Guiding companies and their new concepts from idea to commercialisation

A guide on biobased product development and evaluation by the multicriteria decision making tool prepared in the frame of the BioModels4Regions project

Johan Börjesson
RISE Processum

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RISE Processum, Sweden

Authors: Pietro Bartocci, Jonas Markusson, Johan Börjesson, Eleonora Borén

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List of Abbreviations

CAPEX	Capital Expenditures
DFCCF	Discounted free cash flow to firm
DSP	Downstream processing
GHG	Greenhouse gases
ISBL	Inside battery limits
IRR	Internal Rate of Return
MCDM	Multicriteria Decision Making
NPD	New Product Development
NPV	Net Present Value
OPEX	Operating Expenditures
OSBL	Outside Battery Limits
SCP	Single cell protein
TEA	Techno-economic Analysis
TRL	Technology Readiness Level

1 EXECUTIVE SUMMARY

In this report, RISE Processum uses its recently developed MultiCriteria Decision-Making (MCDM) tool which analyses potential in a whole innovation value chain to produce biobased products set in a regional context. The MCDM tool helps evaluate and prioritize alternatives by assessing six key criteria factors simultaneously, allowing for more balanced and informed decision-making in complex scenarios. MCDM integrates diverse criteria like cost, sustainability, and performance to guide strategic choices, which through comprehensive analysis, can identify strengths and weaknesses early on, allowing resources to be allocated where they add the most value.

This report will go through the theory of MCDM and a stage gate process of new product development for designing new biobased products. MCDM is complementary to business model analysis and can be generally applied to other value chains in other regions across Europe, by providing direct guidance to the different steps from idea to start-up and identifying required steps towards commercialisation.

To showcase the strengths of MCDM, the tool has been applied to a case study of building a biorefinery in North Sweden, in the country of Västernorrland, for production of market competitive end-products from forest residues. In the case study, a base case as business is run today is built and evaluated against five different business scenarios, e.g. with shifting product prices and uses for the lignin for biobased products. The case study 1) predicts and evaluates biomass availability in the form of forest residues, 2) conducts a market analysis of competitive biobased chemicals and products, 3) assesses and matches technology and infrastructure to processing routes, and 4) conducts a technoeconomic assessment of the complete biorefinery.

The biorefinery builds on a system where forest residues in the form of sawdust are fractioned by steam explosion into a hemicellulose stream of C5/C6 sugars in the form of a liquid stream and one solid fraction composed of lignin and cellulose. The liquid stream fermented to produce so called single cell protein, SCP, a possible feed or food ingredient. The solid stream can undergo a further step of hydrolysis, where cellulose in broken down to C6 sugars, which are further fermented to produce 2,3-butanediol. The fermentation liquid can be separated once again from the solid residue, which in this case is composed mainly of lignin.

The market analysis of cost competitive biobased productions of the lignocellulosic feedstock fractions rendered five case study scenarios, a Base case where the lignin fraction sold for combustion for energy recovery and five scenarios in areas indicated by the evaluation (lignin valorisation, reduced 2,3 BDO price (2000 EUR/ton), reduced 2,3-BDO price (1500 EUR/ton) for a polymer market, reduced steam consumption in downstream processing of 2,3-BDO and a 5th scenario that combined several scenarios.

The evaluation highlighted the robustness of the Multi-Criteria Decision-Making (MCDM) tool in assessing the different scenarios. The tool revealed how key criteria—strategic alignment, market attractiveness, technical feasibility, and potential for reward—interacted to shape overall viability. For example, while the scenario 5 scored higher on market attractiveness, lowered market dependency and increased potential reward, it also incurred greater risks in terms of technical feasibility. These trade-offs emphasize the importance of aligning project design with market dynamics and technological readiness.

The analysis reinforced the need for flexible strategies that can adapt to evolving market conditions. While the base case provides a reasonably stable foundation, the alternative scenarios offer a pathway to greater long-term competitiveness, provided the technology risks can be mitigated. This dual approach allows stakeholders to navigate uncertainties while maximizing potential returns.

In conclusion, the scenario-building and evaluation underlined the economic and strategic feasibility of the proposed biorefinery. Several scenarios are viable, but the choice between them depends on the project's risk tolerance and strategic objectives. The alternative scenarios represent a compelling opportunity to capture higher market value, albeit with associated risks that require careful management through innovation, policy alignment, and market development.

Overall, the case study led to some key insights:

- **Lignin Valorisation Enables Competitive Pricing for biobased chemicals**: Scenario 5 demonstrates that by valorising lignin into high-value applications and optimizing downstream processing of the biobased chemical, 2,3 butanediol (2,3-BDO), achieving and exceeding fossil-based pricing for 2,3-BDO is feasible. The pricing of 2,3-BDO can approach levels comparable to 1,4 butanediol (1,4-BDO), making it a competitive alternative in the market.

- **Trade-Off Between Market Opportunities and Technical Challenges**: Lignin valorisation enhances several key evaluation criteria, including product advantage, financial performance, and market attractiveness. However, it at the same time lowers technical feasibility due to the advanced processes and market dependencies required for high-value lignin products.

- **Policy Gaps in Biobased Chemicals and Materials**: The biobased chemicals and materials sector lacks the robust market incentives granted to biofuels. This discrepancy persists despite the European High-Level Group identifying the need for stronger policy support for biobased industries over 12 years ago. Addressing this gap is crucial for fostering market growth and large-scale commercialization.

- **Dynamic Scenario Adaptability**: The evaluation underscores the importance of strategic flexibility. While the Base Case offers a lower-risk pathway from a technological perspective, it does not mitigate market risks as effectively. The scenarios are designed to reduce market risks while aiming for higher market value, increased market penetration, and enhanced competitiveness. The scenarios further build on this by presenting opportunities for greater market rewards, requiring proactive management of technical challenges and alignment with evolving market dynamics.

- **Regional Advantages as a Key Enabler**: Leveraging the regional infrastructure and biomass availability in the country of Västernorrland, proved instrumental in supporting the biorefinery concept. Proximity to sawmills and regional expertise provided critical support for the feasibility of the scenarios.

By using the MCDM tool the base case has evolved into a business case (scenario 5 that introduce lignin valorisation to create a more diverse product portfolio, introduce a reduced price for 2,3-butanediol (2,3-BDO) to promote market growth and market penetration and introduced improvements in downstream processing (DSP) of 2,3-BDO to reduce a large cost in steam) that has increased market penetration and market growth potential, while creating a more diverse product portfolio. Thereby drastically lowered the market risks, while somewhat increasing the technology risks. The effect of the MCDM analysis and changes to the business case create a more balanced income portfolio where the income share of lignin is increased and the income of 2,3-BDO is reduced, the cost of steam is drastically reduced, and we can also see an increase in Net Income. These changes are visually represented in a waterfall diagram, (Figure 1) and scenario 5 (Figure 2), showing the income to the left in green bars building to the total income of the business case, the costs is represented by teal bars and finally ending in a blue bar representing the Net Income.

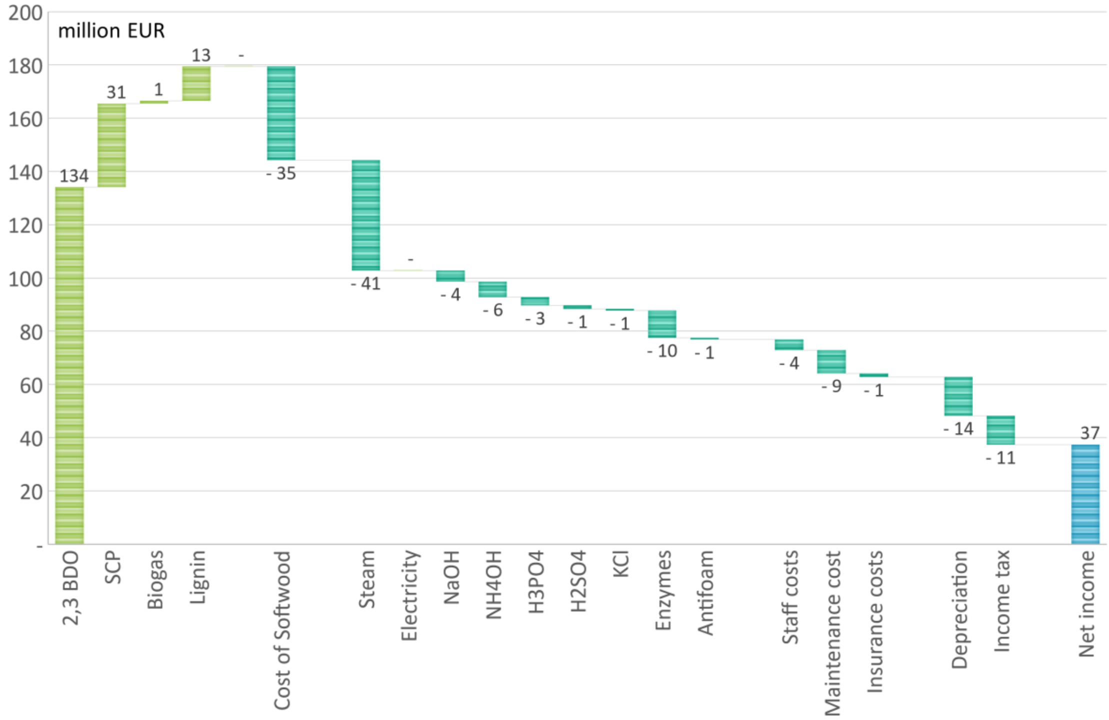

Figure 1 Waterfall diagram of the base case

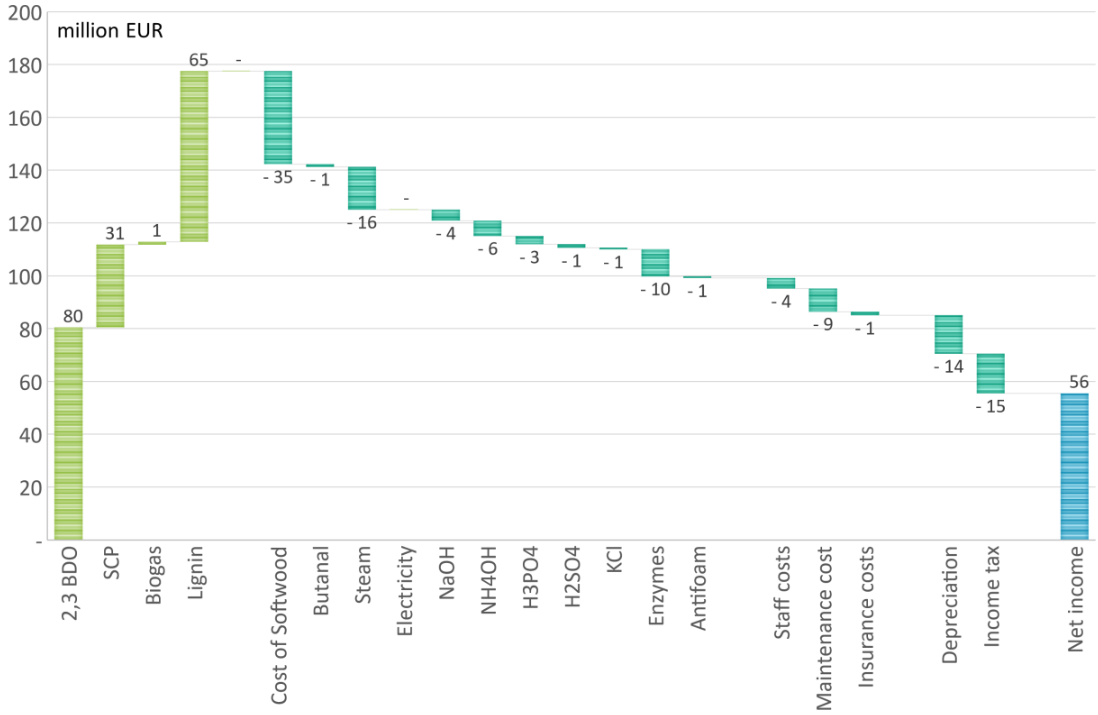

Figure 2 Waterfall diagram of scenario 5

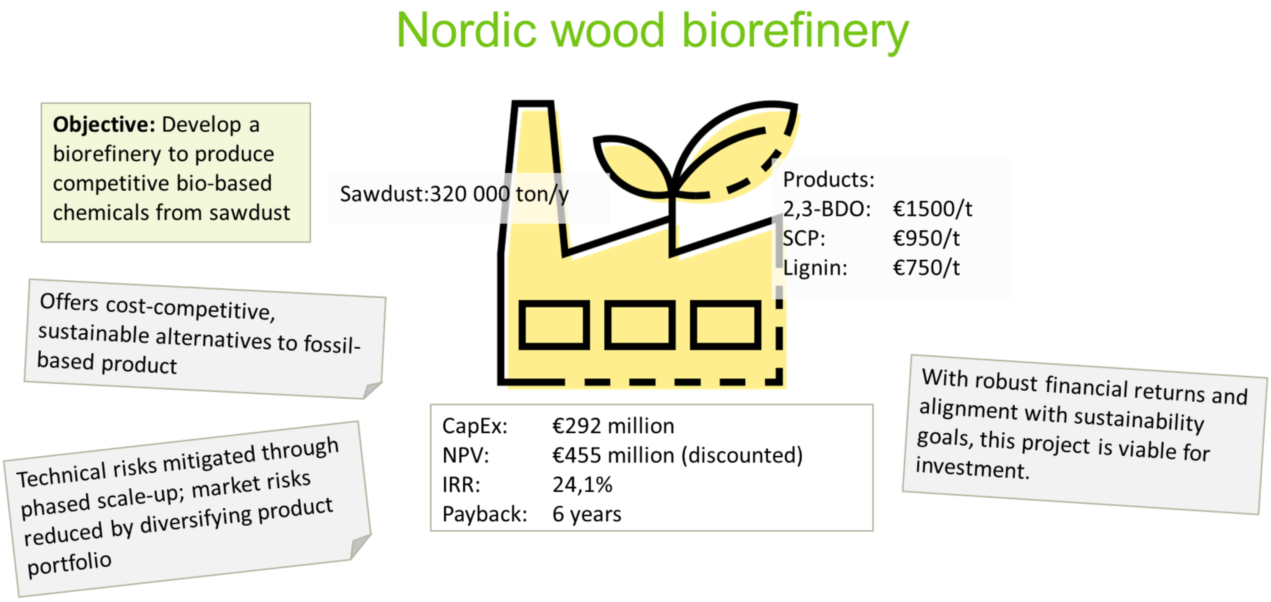

Figure 3 Scenario 5 – winning.

By applying the full methodology of the MCDM tool on a biorefinery case in a specific regional context, the market analysis, feedstock, technology and policy and strategy landscape influences the results. However, the use of the MCDM tool is universal, both to product markets, feedstock, technology and regional context.

To further provide reading and guidance for applying the MCDM methodology to other regions and biorefinery concepts, four appendixes have been included for the reader: Appendix A: New product development, Appendix B: Regional Biomass assessment in EU through Corine landscape maps, Appendix C: Technoeconomic assessment, Appendix D: Sustainability assessments, Appendix E: Business Analysis of a Nordic Biorefinery

2 OBJECTIVE AND AIMS

The main objective of this report is two-fold, firstly the report provide general methodology for companies which can be used in EU countries to develop new biobased concepts e.g. biorefineries projects from idea to commercialisation using the MCDM tool, and secondly, to show the implementation of the methodology, to apply it to a case study of building a biorefinery, tailored to the county of Västernorrland in North Sweden, taking into consideration regional feedstock availability and five different market scenarios.

Within the case study, the subobjectives are the following:

- show a theoretical and practical applicable approach to biomass estimates
- design a plant layout to produce innovative biobased products
- estimate capital costs (CAPEX)
- estimate variable costs (OPEX) and revenues
- calculate financial indexes of economic performance
- evaluate environmental sustainability
- analyse the risk

The scope of the case study can be analysed according to different views:

- there is a geographical scope which is tailored to the analysed country/region
- there is a temporal scope, which is linked to the date in which the report is completed
- there is a technological and process scope linked to the technology advancements relative to the time being
- there is a product scope, the case study focuses on sugar production that are converted into bioproducts, where the specifics of the final product and its competitiveness are linked to the current market.

The limitations of the case study are linked with the scope above, but particular attention has been paid to develop a general methodology which can be applied to different regions in EU notwithstanding the feedstock material which is used and the technology readiness level (TRL) of the chosen technology solutions.

3 METHODOLOGY, INNOVATION GUIDANCE TOOL

3.1 NEW PRODUCT DEVELOPMENT METHODS

New Product Development (NPD) is a set of design, engineering, and research processes which combine to create and launch a new product to market. Unlike regular product development, NPD is specifically about developing a brand-new idea and seeing it through the entire product development process, based on the work performed by Robert G. Cooper on Stage Gate theory.

In today's competitive market, the ability to offer products that meet customers' needs and expectations has never been more important. Customer requirements and behaviours, technology, and competition are changing rapidly, and businesses cannot rely on existing products to stay ahead of the market. They need to innovate, and that means to develop and successfully launch new products.

NPD refers to the complete process of bringing a new product to market. This can apply to developing 1) an entirely new product, 2) improving an existing one to keep it attractive and competitive, or 3) introducing an old product to a new market.

The emergence of new product development can be attributed to the needs of companies to maintain a competitive advantage on the market by introducing new products or innovating existing ones. While regular product development refers to building a product that already has a proof of concept, new product development focuses on developing an entirely new idea – from idea generation, to development, to launch.

When it comes to new product development, each journey to a finished product is different. Although the product development process can vary from company to company, it is possible to break it down into seven main stages (Figure 4).

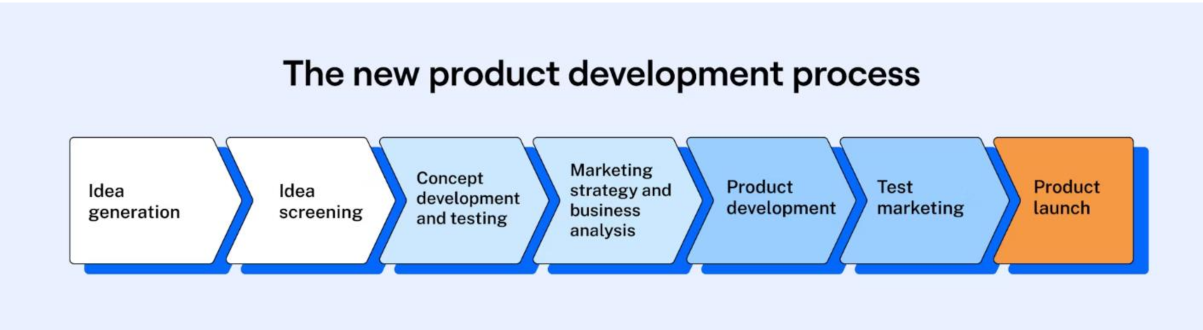

Figure 4 The 7 phases of new product development1

[1] https://maze.co/collections/product-development/new/

The seven phases of the stage gate theory are illustrated in detail in Appendix A - PRODUCT DEVELOPMENT THEORY: from idea generation to idea screening to concept development and testing, to marketing strategy and business analysis to product development, test marketing and product launch, including the best practices to manage each phase. For each of the phases, there is a gate which must be passed to access the following phase. These stage gates will be used also in the assessment of the Case study - A Nordic Wood Biorefinery in combination with the MCDM tool.

3.2 Multi Criteria Decision Making tool

A multicriteria decision-making (MCDM) tool helps evaluate and prioritize alternatives by assessing multiple factors simultaneously, allowing for more balanced and informed decision-making in complex scenarios (Table 1). MCDM integrates diverse criteria like cost, sustainability, and performance to guide strategic choices.

Table 1 The sex key MultiCriteria Decision Making criteria

MCDM Criteria	Criteria description
Strategic alignment	The degree of fit with strategy
Competitive advantage	Perceived value for money, Competitive advantage, unique benefits
Market attractiveness	Ability to penetrate market, Rate of growth for the market
Leverage competence	Ability to leverage core competences
Technical feasibility	Degree of new technology required for business model
Potential for reward	Degree of financial return based on financial indicator

Products/Innovations are broadly evaluated, starting at an early phase of the concept. Thereby, through comprehensive analysis, strengths and weaknesses can be identified early on, allowing resources to be allocated where they add the most value.

The product/innovation is scored on how well it performs in each section. This allows to modulate an aspect of the innovation/product and evaluate its overall effect. For example, a lower score in technical feasibility might be offset by higher scores in competitive advantage or potential reward. This iterative evaluation allows decision-makers to explore whether added risks are justified. By comparing the overall score, insights will be gained if the added risk by introducing a new technology is worth it or not. The scoring process provides actionable insights into the trade-offs and synergies between criteria.

Each criterion is scored from 0 to 10, reflecting performance against expectations:

- 0: No or negative alignment with criteria
- 4: Modest alignment with criteria
- 7: Good alignment with criteria
- 10: Excellent alignment with criteria

In the following sections the different evaluations criteria are explained one by one.

3.2.1 Strategic alignment

Strategic alignment is an evaluation criterion that ensures that a product/innovation aligns with organizational objectives and external opportunities (Table 2). This alignment can be assessed through various approaches that examine both internal coherence and external fit.

From an internal perspective the evaluation is meant to ensure that the product/innovation support the overall business strategy and contribute to the organization's goals. To meet criteria for strategic alignment the product/innovation needs to be consistent with the company long-term vision and strategic goals.

The product must be aligned with the market needs, other potential partnering company's needs, potential synergies, and horizontal and vertical integration possibilities in the value chain of the product developed at company level. Also, the classical PESTEL (Political, Economic, Social, Technical, Environmental, Legal) factors must be considered when evaluating external alienation of the product.

Table 2 MCDM for Strategic alignment

Criteria	0	4	7	10
The degree of fit with strategy	Not aligned with strategy	Somewhat aligns with strategy	Supports strategy	Aligns very well with strategy

3.2.2 Product advantage

The competitive advantage that the company can gain through the development of the product is analysed by evaluating the following aspects (

Table 3):

- Perceived value for money,
- Product characteristics and specifics respect to other competing solutions,
- unique benefit.

Competitive advantage refers to factors that allow a company to produce goods or services better or at a lower cost than its competitors.

Table 3 MCDM for Product advantage

Criteria	0	4	7	10
Perceived value for money	Maintains current competitive position	Modestly improves current competitive position	Provides good advantage to current competitive position	Provides excellent advantage to current competitive position
Competitive advantage	Customer perceives limited or no value	Customer perceives modest value	Customer perceives good value	Customer perceives superior value

3.2.3 Market attractiveness

Market attractiveness refers to how desirable and profitable a market is for your business (Table 4). It depends on various factors, such as the demand, competition, growth, profitability, and risks of the market. It can be measured by evaluating different aspects like:

- ability to penetrate market,
- rate of growth for the market.

Table 4 MCDM for Market attractiveness

Criteria	0	4	7	10
Ability to penetrate market	Limited or no ability to penetrate the market	Modest ability to penetrate the market	Good ability to penetrate market	Strong ability to penetrate market
Rate of growth for the market	No or limited market growth	Modest market growth	Reasonable market growth	High market growth

3.2.4 Leverage competence

Leveraging core competencies for competitive advantage is one of the key objectives of any business (Table 5). Core competencies are the unique capabilities that enable a company to deliver superior value to its customers and differentiate itself from its competitors. These can be both companies' competencies or the competencies which are available in the area in which the company operates that can be generated by universities partnering with the company, startup incubators, and other companies which participate in the value chain creation.

Table 5 MCDM for Leverage competence

Criteria	0	4	7	10
Ability to leverage core competences	Limited or no ability to leverage core competences	Modest ability to leverage core competencies	Good ability to leverage core competencies	Strong ability to leverage core competencies

3.2.5 Technical feasibility

Technology feasibility can be analysed by breaking down the value chain in the single unit processes and analysing the technology readiness level of the technical operations that are performed in the plant, the degree of new technology required for business model, and establishing a continuous improvement process based on innovation of existing processes performed in the company (Table 6). This is key to promote an increase in production efficiency and developing reliable processes which can limit error generation and rework.

Table 6 MCDM for Technical feasibility

Criteria	0	4	7	10
Degree of new technology required	Completely new technology required	Significant new technology required	Some new technology required that will leverage current technology	No new technology required; available in-house

3.2.6 Potential for reward

Potential for reward refers to the financial return that can be expected from a product or innovation, evaluated through key financial indicators (Table 7). This criterion assesses how well the product or innovation aligns with the organization's profitability goals and its potential to generate economic value. A thorough analysis of potential reward helps prioritize initiatives that offer the highest returns while aligning with strategic objectives.

The evaluation of potential reward involves diverse factors:

- Revenue Generation

- The capacity of the product or innovation to drive sales and capture market share. This includes estimating demand, pricing potential, and market penetration rates.

- Cost Efficiency
  - Analysing production costs, raw material requirements, and operational expenses. A competitive cost structure significantly impacts the potential for financial success.
- Feedstock Analysis
  - Examining the availability, cost, and sustainability of feedstocks used in production. Feedstock selection influences not only costs but also the overall marketability and environmental impact of the product.
- Utility Pricing
  - Understanding the costs associated with utilities such as energy, water, and other resources essential to production. Variations in utility pricing can substantially affect profit margins.
- Scalability and Economies of Scale
  - Evaluating whether the innovation or product can scale up efficiently to reduce costs per unit while meeting market demands. Scalability can improve profitability over time.
- Risk Assessment
  - Identifying financial risks, such as market volatility, regulatory challenges, and supply chain disruptions, which could impact expected returns.
- Market Growth
  - Estimating the growth trajectory of the target market and how well the product can capitalize on expanding opportunities.

Accurately evaluating potential for reward requires robust business model development. This requires insights from:

- Technical feasibility Studies
  - To determine the readiness and efficiency of technologies involved.
- Market analysis
  - To understand customer needs, market size, and competitive landscape.
- Financial modelling
  - To forecast revenues, costs, and profitability under various scenarios.
- Scenario analysis
  - To test different market conditions and assess resilience to risks.

Table 7 MCDM for Potential for reward

Criteria	0	4	7	10
Degree of financial return based on financial indicator	**Negative return**	**Modest return**	**Good returns**	**Very positive returns**

3.3 FEEDSTOCK AVAILABILITY ASSESSMENT

With any biorefinery process the feedstock is a key factor in that there are enough volumes for the process and of sufficient quality. Feedstock availability in terms of biomass or biomass by-products can be divided into its theoretical and practical availability, which will be subject to geographic location and availability of national resources, databases for monitoring.

3.3.1 Theoretical biomass availability

The theoretical estimates will depend on the biomass type that is considered, for agricultural biomass it is in many cases referred to national and regional statistics identifying first the cultivated areas and then using production coefficients which state the yields of residues in tons per hectare.

For estimating the forest surface of European regions, the Corine Landcover data can be used. According to the European Environmental Agency: "the Coordination of information on the environment (Corine) is an inventory of European land cover split into 44 different land cover classes"[2].

Corine has been historically used as an input in more complex model aiming at the estimate of forest biomass and carbon stock[3]. This corresponds to the potentially available biomass quantity, while the practically obtainable quantity is determined by the application of sustainable forest management practices[4]. In the Corine Landcover data of for ex Sweden forests are divided in three main categories, broad leaf, mixed leaf and mixed forests, from which estimates can be made of their land coverage.

3.3.2 Practical biomass availability

Both in the case of agricultural land and forestry land the potential biomass availability is very different from that which can be practically used. The vast difference between agricultural

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[2] https://www.eea.europa.eu/en/about/contact-us/faqs/what-is-corine-land-cover

[3] Barredo, J. I., San-Miguel-Ayanz, J., Caudullo, G., & Busetto, L. (2012). A European map of living forest biomass and carbon stock. Reference Report by the Joint Research Centre of the European Commission. EUR–Sci. Tech. Res, 25730(4), 5.

[4] Latterini F, Stefanoni W, Venanzi R, Tocci D, Picchio R. GIS-AHP Approach in Forest Logging Planning to Apply Sustainable Forest Operations. Forests. 2022; 13(3):484. https://doi.org/10.3390/f13030484

areas and forestry areas is that while agricultural areas are harvested on an annual basis, forestry areas are harvested every 70 years, meaning different forest areas will be harvested on an annual basis. Therefore, it is needed not only to know the potential availability but also the effective felling which is operated by forestry companies. This can be determined for example by a model by the Swedish Forest Agency. The model is based on consumption statistics, import and export statistics, stocks statistics and data on felled, but not removed whole trees.

When assessing practical forest residual availability there are two main residual fractions to consider, 1) logging residues: the tops and branches of the trees left behind in the forest, cut on the harvest site, and 2) the residual forest by-products that come from valorisation of the trees, e.g. sawdust and shavings from sawmills and bark from debarking at pulp and paper mills (Figure 5).

Figure 5 Assortments of sawmill by-products, A = Bark, B = Cellulose-Chips, C = Sawdust and D = Shavings[5]

The volumes of logging residues are connected to tree species and handling process. Logging residues are a heterogeneous product fraction from its inherent variations in tree types, number of branches, tops, number of needles and leaves, bark, and contamination of soil etc. Instead, the sawmill by-products will be a more homogenous assortment but qualities will vary from sawmill to sawmill by variations by season, variation by storage time of the byproducts (seen as waste and stored outside and their differences in particle size, moisture content, ash content.

[5] Grabbe, S. (2020). Assortments [Unpublished]. SEIZE Media.

Finally practical availability also needs to consider the cost based on transportation costs and different approaches to optimize and automatise logistics. This may have a large impact on the placement of a biorefinery, to total distance to feedstock sources.

More information on both theoretical and practical feedstock availability and estimates via Corine database and transport functions are available in APPENDIX B biomass assessment methods.

3.4 TECHNO-ECONOMIC ANALYSIS (TEA)

To determine the cost and revenue of different biorefinery routes, a cost and revenue estimate of the process route need to be calculated, including an estimate of 1) the equipment and infrastructure costs, 2) installation costs and 3) cost escalation, and 4) productions costs (variable and fixed) as well as, 5) revenue estimates.

There are several potential technology risks associated with sugar platform biorefinery projects and their integration with pulp mills, which can be categorized within:

Scale-up risks involve discrepancies between the current and planned capacities of the technology, the degree of operational integration, accumulated operating hours, the maturity of design, and the mix of new versus established technologies.

Integration risks address the compatibility of waste flows, residue management, energy consumption types, resource demands like steam, power, and water, as well as impacts on existing pulp mill systems, and CO_2 emissions.

Technology-related risks focus on biomass versatility, feedstock specifications, multi-provider technology combinations, specialized process requirements, including high-pressure operations, advanced fermentation techniques, reliance on feedstock-specific or genetically modified organisms, and energy-efficient purification methods. The table emphasizes evaluating these factors to assess feasibility and mitigate potential challenges in such projects.

A step-by-step guide on calculating cost and revenue estimate of the process route is presented in APPENDIX C COST and REVENUES ESTIMATE as well as more information on risk assessment.

3.5 SUSTAINABILITY ANALYSIS

Sustainability assessment is most often performed using Life Cycle Assessment, LCA. The LCA methodology is standardised by ISO norms ISO 14040 and ISO 14044. The analysis is performed according to four phases: goal and scope, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and Interpretation (Figure 6).

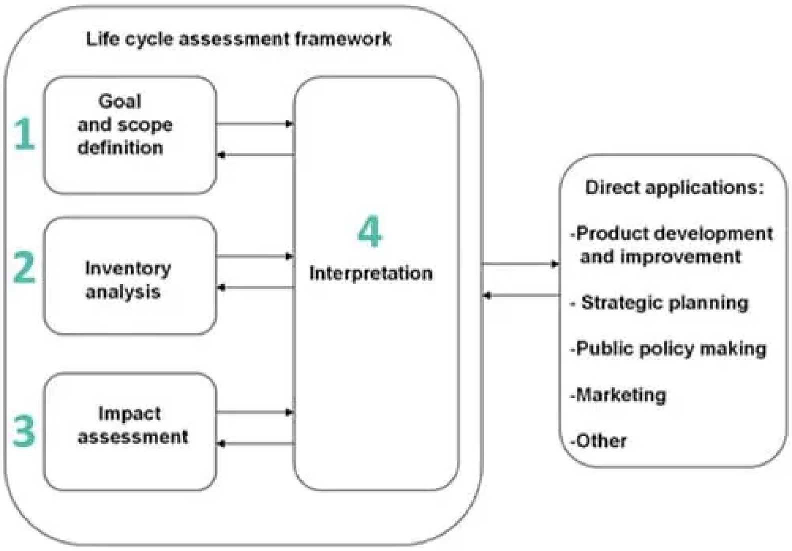

Figure 6 Life Cycle Assessment stages and applications[6]

Today, sustainability analysis incorporates many other aspects that were not present in the initial ISO 14040 and ISO 14044 norms, such as social aspects, safe and sustainable by design framework, and product digital passport and taxonomy aspects referring to EU policies. Further information on the different aspects of sustainability assessment is proposed in Appendix D.

[6] https://circularecology.com/lca.html

4 CASE STUDY - A NORDIC WOOD BIOREFINERY

4.1 SCOPE OF THE CASE STUDY

To showcase the MCDM methodology on a biobased business, the MCDM tool is applied to a case study of building a biorefinery in North Sweden. This provides methodology guideline and an example of how the methodology can be used. However, the tool can be generally applied to multiple regions and types of biobased businesses such as other biorefineries across Europe.

The region of North Sweden is made up of the four most northern counties (Figure 7) of Sweden, the county of Västernorrland, Jämtland-Härjedalen, Västerbotten, and Norrbotten. In this case study, the county of Västernorrland was selected.

Figure 7 Northern Sweden counties[7]

In this case study, biomass feedstock availability is mapped by both theoretical and practical availability. In additions, feedstock suitability and geographical location is considered.

[7] https://www.lansstyrelsen.se/vasternorrland/om-oss/nyheter-och-press/nyheter---vasternorrland/2023-11-14-norra-civilomradet-ovar-och-starker-det-civila-forsvaret.html

The case study also includes a market analysis with the purpose of identifying examples of biobased products that are predicted to grow on the market, targeting market competitive products for all the fractionated parts of lignocellulosic feedstock.

To assess potentially viable conversion technologies for the case study a technology screening is conducted by assessing TRL maturity of the conversion processes and combined technologies that are a good match for the targeted biobased products.

Thereafter the final scenarios are set for a base case and for five different market scenarios. Technoeconomic assessments are made for biorefinery case study and scenarios and they are evaluated according to the MCDM methodology to assess their business potential (Figure 8).

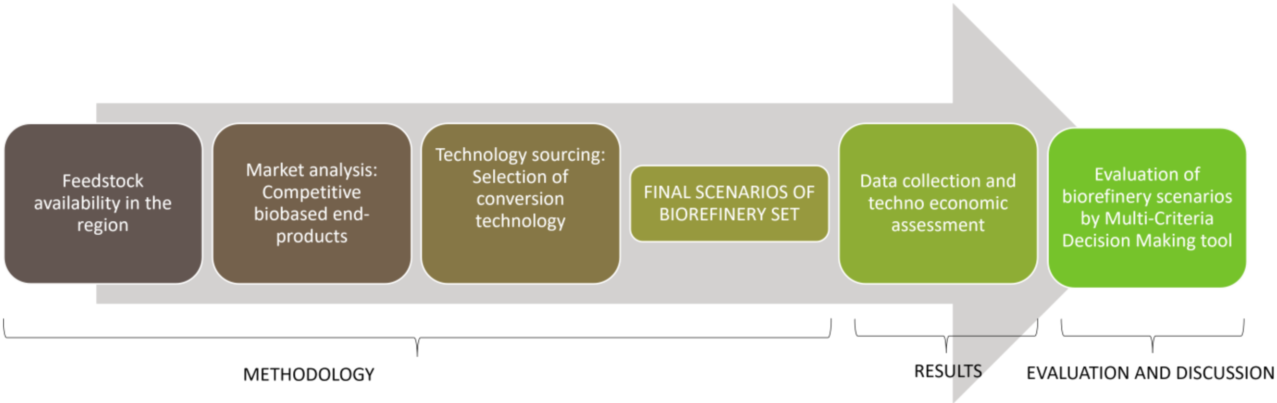

Figure 8 Case study workflow

4.2 SELECTION OF BIOMASS FOR THE CASE STUDY

4.2.1 Assessment of theoretical availability in region of Västernorrland

The county of Västernorrland (Figure 9) covers 5.3 % of the land area in Sweden. The population density is 11.2 inhabitants per square kilometre, which is half the national level. The coastal area and Sundsvall/Timrå have the highest population density[8]. The largest cities are Sundsvall, Örnsköldsvik and Härnösand. More than half (56%) the of the county is covered by large boreal forests.

[8] County Administrative Board of Västernorrland, 2011

Figure 9 The county of Västernorrland[9]

There is 1 672 000 ha of productive forest land in Västernorrland and about 186 000 ha of unproductive forest land. The entrepreneurial projects in Västernorrland proposing new biorefinery concepts can be also influenced by the availability of biomass in close-by counties, such as Jämtland-Härjedalen and Västerbotten.

According to the Corine Land Cover map[10], applied to the county of Västernorrland landcover in the form of forests show a broad coverage of the whole region (Figure 10). The land coverage is divided into three categories (Table 8), denoted in the map as purple (mixed forests), green (coniferous) and red (broad leaves), which shows that is predominantly covered by coniferous forests.

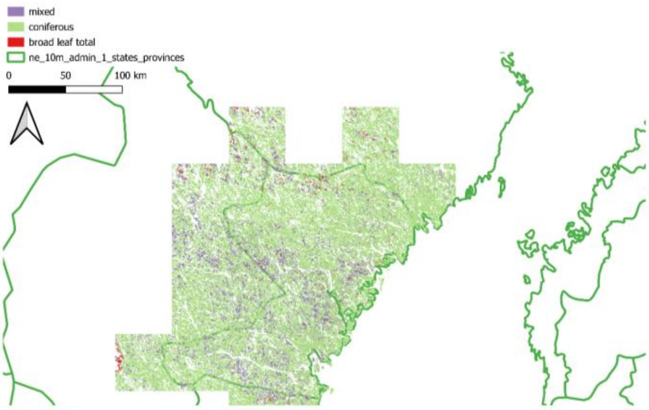

Figure 10 Forests distribution by type in Region of Västernorrland

[9] https://en.wikivoyage.org/wiki/V%C3%A4sternorrland_County

[10] https://www.lantmateriet.se/contentassets/703ae721445f4398a2fd3c890472bbf8/e_clcshmi.pdf

Table 8 Landcover categories, relative to forestry area

Landcover categories	Definition in Corine Landcover of Sweden[11]
Broad leaf	Tree covered areas with a total crown cover of more than 30% of the surface, where more than 75% of the crown cover consist of broadleaved forest. Tree height is more than 5 metres except for natural low growing forest where lower tree height is allowed.
Mixed Forest	Trees with a total crown cover of more than 30% of the surface, where neither broad-leaved forest nor coniferous forest constitute more than 75% of the crown cover. Tree height is more than 5 metres except for natural low growing forest where lower tree height is allowed.
Coniferous forests	Trees with a total crown cover of more than 30% of the surface, where more than 75% of the crown cover consist of coniferous forest. Tree height is more than 5 metres apart from natural low growing forest where lower tree height is allowed.

To conclude the largest available theoretical feedstock is in coniferous forests. However, most of the tree trunk is used for timber production or for pulp and paper production. Instead, residues of the trees are available for further conversion to biobased products, the logging residues and the sawdust, bark and fine shavings at sawmills and pulp mills.

4.2.2 Assessment of practical availability of feedstock in the region of Västernorrland

To assess the availability of sawdust produced by sawmills and pulp mills in the county of Västernorrland, the data was elaborated from the study of Persson 2022[12] (Figure 11). Although these are annual numbers the amounts of sawdust will vary by volumes and quality dependent on sawn materials between sites, variation by season over the year and to an extent of biological degradation during their storage time (oftentimes outside as they are considered a waste).

An in-house optimization strategy was developed to estimate the transportation costs of logging residues using a linear optimization model. The model characterizes the optimization problem as a resource allocation challenge, wherein a finite number of resources must meet the demand at various units. The objective function is designed to calculate the total minimized transportation cost for each assortment, transferring by-products from supply units to demand units (APPENDIX B biomass assessment methods).

[11] https://www.lantmateriet.se/en/geodata/geodata-products/international-cooperation/corine-land-cover/

[12] Persson, L. (2022). Mapping the market of unrefined forest industry by-products in northern Sweden.

To formulate a function that minimizes transportation costs, the following variable were taken into account: the cost of a truckload of by-products, the transport distance between sites, and amount transported in one truckload. The input variables were incorporated into the objective function and constraints to address the cost-effectiveness of biomass transport under specified resource limitations.

Figure 11 Availability of forestry residues in the form of sawdust, provided [13]

The minimization of the objective function was achieved through linear programming techniques. The results of the costs for sawdust from sawmills and pulp mills are displayed in Table 9, and the amount and costs of logging residues in Table 10. In grey of both tables, the municipalities located in Västernorrland are indicated.

Table 9 Sawmills and pulp mills residues availability and costs

Site	**By-products from sawmills/ pulp mills (t dry matter)**	**Total cost M€**	**Cost per unit of mass (€/t)**
Östersund	45583	1.23	27
Malå	17662	0.41	23
Sundsvall	95263	2.49	26
Piteå	89830	2.29	26
Sollefteå	121644	3.53	29
Umeå	93075	2.63	28
Örnsköldsvik	98417	2.90	29

[13] Provided by personal communication with Swedish Agricultural University (SLU), in the person of Dimitris Athanassiadis

Table 10 Logging residues availability and cost

Site	Logging residues (t dry matter)	Total cost (M€)	Cost per unit of mass (€/t)
Östersund	109246	9.59	88
Malå	11026	0.97	89
Sundsvall	102375	9.06	89
Piteå	13587	1.23	88
Sollefteå	114987	10.12	88
Umeå	31371	2.82	88
Örnsköldsvik	65231	5.72	88

The results of the two feedstocks show that there is a small price variation between sawdust dependent on location (Table 9) but the cost of logging residues (Table 10) is very similar between the sites. However, the sawdust cost is only about 30% of the price of logging residues. Within the region of Västernorrland there are three sites, with a total of approximately 315 000 tonnes of biomass on dry basis. This represents a realistic feedstock volume for a biorefinery.

4.2.3 Conclusion of feedstock selection

In between the two feedstock options of logging residues and sawdust there are several factors that favour the option of sawdust, notably sawdust is almost of one third of the price of logging residues (Table 9, Table 10), but also due to its physiochemical characteristics, it is more homogenous in its lignocellulosic composition and has a minimal ash content compared to logging residues.

4.3 Selection of end products

The focus was to identify markets for bio-based products with clear commercial potential, avoiding those dependent primarily on regulatory support, such as biofuels. By targeting high-value markets, the aim is to demonstrate the feasibility of bio-based chemicals and materials in applications that address sustainability challenges and drives innovation. The chapter explore opportunities for products derived from lignocellulosic biomass fractions, emphasising chemicals, materials and feed applications

4.3.1 Market for bio-based chemicals

The bio-based chemicals market is a very important sector to address in the transition towards a circular bioeconomy. This market leverages biomass-derived feedstocks to produce chemicals and materials that can replace the fossil-based counterparts and introduce innovative chemicals and materials capable of replacing fossil components in a large range of applications. Bio-based chemicals encompass a diverse range of products, including polymers, solvents, specialty chemicals, and applications in the food and feed sectors, all derived from renewable biological resources. This market is characterized by the integration of bio-based production within biorefinery systems, enabling the co-production of chemicals, biofuels, and ingredients for food and animal feed. Such integrated systems enhance economic viability by maximizing the utilization of biomass, diversifying product streams, and improving process efficiencies. The biobased share of total EU production and the consumption of biobased products for each category in 2019 are shown in Figure 12[14]. The dimension of the bubbles indicates the total market of the chemicals in the EU (given by the sum of the production of both fossil and biobased chemicals). The largest EU markets for chemical products are platform chemicals, polymers for plastics and paints, coatings, inks and dyes.

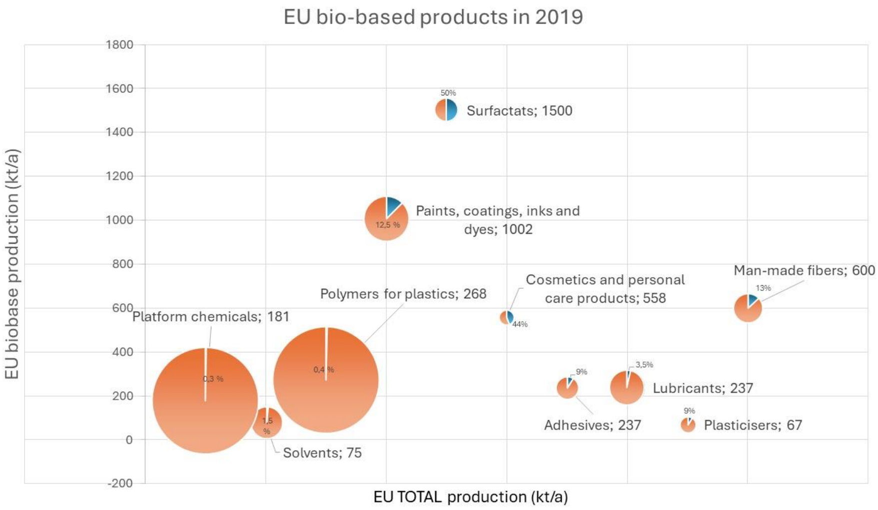

Figure 12 EU biobased products in 2019, adapted from Ed de Jong (2020)[15].The y-axis represents the dimension of the current biobased market (2019) in kt, while x-axis represents the dimension of the total market for the same chemical. The bubbles are also designed as a pie chart in which once again the dimension of the biobased market is visualized, in percentage (blue). The figure shows low penetration of biobased products in bigger dimensions markets; while in some specific niche markets, like surfactants, the penetration is quite high.

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[14] Spekreijse, J., Lammens, T., Parisi, C., Ronzon, T., Vis, M., 2019. Insights into the European market of bio-based chemicals. Analysis based on ten key product categories, EUR 29581 EN, Publications Office of the European Union, Luxembourg, 2019, ISBN 978-92-79-98420-4, https://doi:10.2760/549564, JRC112989.

[15] Ed de Jong, Heinz Stichnothe, Geoff Bell, Henning Jørgensen, Bio-Based Chemicals A 2020 Update, chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.ieabioenergy.com/wp-content/uploads/2020/02/Bio-based-chemicals-a-2020-update-final-200213.pdf

The global bio-based chemicals market has witnessed steady growth, driven by increasing consumer awareness, supportive government policies, and advancements in biotechnological processes. Key product categories include bio-based polymers such as polylactic acid (PLA) and bio-polyethylene (Bio-PE), bio-based solvents like ethanol, and platform chemicals such as succinic acid and 1,3-propanediol. Many of these products have found applications in packaging, agriculture, and automotive sectors, reflecting their versatility and growing acceptance. However, within these large markets, it is evident that the share of bio-based products remains marginal. Notably, about 12.5% of the paints, coatings, inks, and dyes market consists of bio-based alternatives, as illustrated by the blue segments in market pie charts (Figure 12), highlighting opportunities for further growth in these sectors.

Despite the promise of bio-based chemicals, their market share remains relatively modest when compared to the total chemicals market. High production costs and competition with established petrochemical processes are key factors limiting their wider adoption. However, specific segments, such as paints, coatings, inks, and dyes, show greater bio-based penetration, with approximately 12.5% of this market consisting of bio-based alternatives. Premium pricing for bio-based products in niche markets, such as biodegradable packaging and sustainable cosmetics, has further driven their demand [16]. Moreover, bio-polyethylene and polylactic acid have shown robust growth rates, with bioplastics experiencing significant market expansion globally. According to European Bioplastics, the global production capacity for bioplastics was approximately 2.4 million tonnes in 2022, with projections indicating growth to 7.5 million tonnes by 2027 [17]. A large portion of this growth lies in the market for biodegradable bioplastics, driven by their increasing use in packaging applications where environmental regulations and consumer preferences favour compostable materials (Figure 13). Additionally, non-biodegradable bioplastics, such as bio-based PET and PE, continue to expand in durable applications like textiles and automotive components. Bio-based polyamides and other innovative materials are also gaining traction as industries seek sustainable alternatives. Policies incentivizing the adoption of low-carbon products, combined with continuous investments in R&D to enhance production efficiencies and expand feedstock options, are expected to further accelerate the growth of bio-based chemicals in these high-value markets.

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[16] Ed de Jong, Heinz Stichnothe, Geoff Bell, Henning Jørgensen, Bio-Based Chemicals A 2020 Update, chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.ieabioenergy.com/wp-content/uploads/2020/02/Bio-based-chemicals-a-2020-update-final-200213.pdf

[17] European Bioplastics, www.european-bioplastics.org, 2024, https://www.european-bioplastics.org/bioplastics-market-development-update-2024/

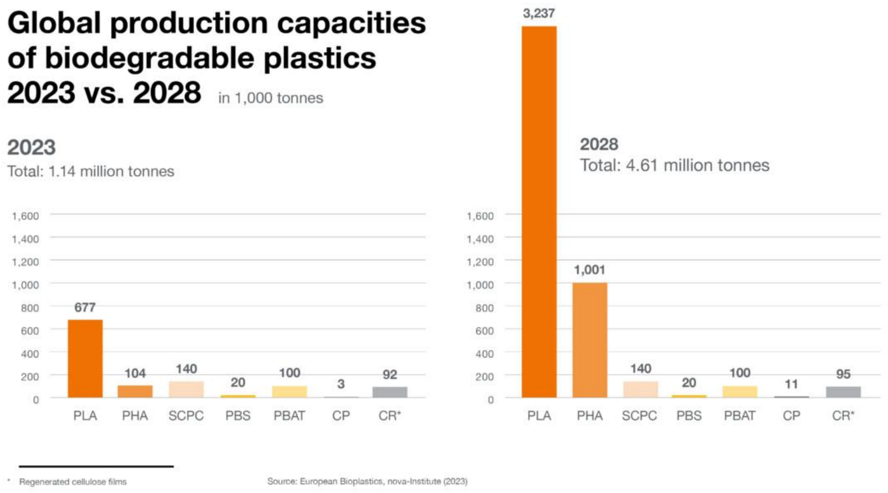

Figure 13 Global production capacities of biodegradable plastics[17]

The bio-based chemicals market represents a significant opportunity for advancing sustainable industrial practices. While challenges related to cost and scalability persist, ongoing innovation and supportive policy frameworks are expected to accelerate market penetration. Glucose serves as the primary substrate for many biological fermentation processes providing access to a variety of important chemical building blocks (alcohols, organic acids, lipids and hydrocarbons) but also very high value fine chemicals and products, current market and estimated growth are shown in Table 11[18].

Table 11 Bio-based market size and estimated annual increase (Compound annual growth rate, CAGR)[19]

Biochemical Category	Market Size (USD)	Estimated CAGR
Alcohols	110 billion	4.4%
Amino acids	11 billion	5.6%
Organic acids	3.5 billion	8.8%
Polymers	0.6 billion	13.5%
Vitamins	0.7 billion	2.6%
Antibiotics	0.8 billion	4.0%
Industrial enzymes	0.3 billion	8.0%

[18] Kohli, K., Prajapati, R., & Sharma, B. K. (2019). Bio-based chemicals from renewable biomass for integrated biorefineries. *Energies*, *12*(2), 233.

[19] Ed de Jong, Heinz Stichnothe, Geoff Bell, Henning Jørgensen, Bio-Based Chemicals A 2020 Update, chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.ieabioenergy.com/wp-content/uploads/2020/02/Bio-based-chemicals-a-2020-update-final-200213.pdf

As the industry evolves, bio-based chemicals are poised to play an increasingly central role in shaping a sustainable and circular global economy.

4.3.2 Viability and product options available for the caste study

The case study will utilize a technology for fractionation of lignocellulosic biomass into three different intermediate products:

- Sugar hydrolysate (higher quality)
- Sugar hydrolysate (lower quality)
- Lignin hydrolyate

The sugar hydrolysate (higher quality) will contain less by-products from the disintegration of biomass and will contain a larger portion of the cellulose sugars (glucose).

The sugar hydrolysate (lower quality) will contain more of the by-products from the disintegration of biomass and will contain a larger portion of the hemicellulose sugars (Xylose, Arabinose, …). The lignin hydrolysate will be a lignin of a comparably higher quality when compared to a lignin from a traditional 2G ethanol plant, with a lignin purity between 80-90% instead of between 60-70%.

4.3.2.1 Product options for Sugar hydrolysate (higher quality)

The higher-quality sugar hydrolysate is well-suited for high-value applications such as the production of bio-based chemicals, including lactic acid for bioplastics, succinic acid for green solvents, and 1,3-propanediol for biodegradable polymers. It can also be utilized in advanced biofuels production or as a fermentation substrate for microbial production of specialty products like vitamins, enzymes, and pharmaceutical precursors.

4.3.2.2 Product options for Sugar hydrolysate (lower quality)

The lower-quality sugar hydrolysate, containing little C5 sugars when using softwood, is suitable for applications where high purity is not essential. It can be used for producing ethanol through fermentation, animal feed additives, or as a feedstock for microbial production of single-cell proteins or bulk biochemicals such as acetic acid and butanol. Additionally, it may serve as a precursor for biogas production.

4.3.2.3 Product options for Lignin hydrolysate

The lignin hydrolysate, with higher purity levels, opens opportunities for advanced material applications. It can be used for advanced material applications. It can be used to produce high-performance lignin-based resins for adhesives, carbon fivers for lightweight materials, and polyurethane foams for insulation. Additionally, it holds potential as precursor for vanillin and phenolic compounds, as well as functional fillers in rubber and plastic applications. Depolymerisation strategies can further enhance its value by enabling the production of polyols, which can be utilized in the production of flexible and rigid polyurethane materials.

4.3.3 Results on the selection of end-products

For the selection of end-products of the case study, the aim has been to focus on products and markets that has rendered little attention, therefore avoiding biofuel products. The targeted end-products has markets in food and feed, in polymer and plastics. The selection of end-products is shown in Table 12.

Table 12 Selection of end-products

End-products	Markets	Estimated market value[1]
2,3-Butanediol, 2,3-BDO	Solvent, plasticizers and as a food additive precursor (potential to grow as a biodegradable polymer in the polymer market)	2500 EUR/t
Single Cell Protein, SCP	Food/feed market	950 EUR/t
Lignin hydrolysate	Energy (potential plastic/composite market)	150 EUR/t
Biogas	Heat and power	250 EUR/t

[1]The prices of the end products are taken from internal data available at RISE

2,3-Butanediol (2,3-BDO) was chosen since it is a chemical that has garnered some interest though articles and commercial activities. 2,3-BDO has garnered interest due to its diverse industrial applications and potential for sustainable material development. Traditionally, 2,3-BDO has been utilized as a solvent, plasticizer, and food additive. Its efficacy as a solvent is noted in various chemical processes, and it serves as a plasticizer in the production of materials like cellulose nitrates, polyacrylates, and polyvinyl chlorides. Additionally, 2,3-BDO is employed in the food industry as a flavouring agent, particularly when converted to diacetyl.[20]

Beyond these established uses, 2,3-BDO holds promise in the synthesis of biodegradable polymers. Research has explored its incorporation into polyesters, aiming to enhance thermal properties and reduce crystallinity, thereby contributing to the development of sustainable

[20] Chan Woo Song, et. Al. (2019). Microbial production of 2,3-butanediol for industrial applications, Journal of Industrial Microbiology and Biotechnology, Volume 46, Issue 11, 1 November 2019, Pages 1583–1601

materials. For instance, studies have investigated the synthesis of terephthalate-based polyesters combining 2,3-BDO with ethylene glycol, achieving notable molecular weights and glass transition temperatures.[21]

Single cell protein (SCP) was chosen because of its potential use in the feed market where its beneficial amino acid composition makes it a prime candidate to replace fish meal in feed application. SCP derived from filamentous fungi has been identified as a promising alternative to fish meal in animal feed due to its favourable amino acid profile, which closely resembles that of fish meal. Fungal SCP sources are rich in essential amino acids such as lysine, methionine, and threonine, making them well-suited for aquafeed formulations.[22]

Land-based fish farms market is increasing and simultaneously the price of fish meal has increased drastically.

Lignin hydrolysate was chosen because it is a natural by-product from the fractionation of biomass. Lignin potential as an energy product has been evaluated in numerous studies[23]. Adopting a modern biorefineries approach to enhance lignins value has gained interest and reached commercial stages. For instance, UPM is producing UPM BioMotion™ Renewable Functional Fillers, UPM BioMotion™ renewable functional filler with the potential to replace carbon black in applications for rubber and plastics[24].

4.4 SELECTION OF CONVERSION PROCESSES

The selection of the conversion process derives directly from the selection of the end products. Given that the choice has been oriented toward the sugar fermentation platform, the potential unit processes that will be:

- pretreatment
- fermentation
- downstream processing units
- cogeneration unit
- handling of residual streams (biogas, wastewater treatment).

[21] Marian Blom, et. Al. (2024), Terephthalate Copolyesters Based on 2,3-Butanediol and Ethylene Glycol and Their Properties, Polymers 2024, 16(15), 2177

[22] Sajjad Karimi, et. Al (2021), Evaluation of Nutritional Composition of Pure Filamentous Fungal Biomass as a Novel Ingredient for Fish Feed, *Fermentation* **2021**, *7*(3), 152

[23] Anne Beaucamp, et. Al, 2022, Lignin for energy applications – state of the art, life cycle, technoeconomic analysis and future trends, Green Chemistry, Issue 21, 2022

[24] UPM Biochemicals, 2024, https://www.upmbiochemicals.com/renewable-functional-fillers/

A theoretical process flow diagram is presented in Figure 14. The biorefinery presented in the case study is assumed to be fed with sawdust produced from softwood in the sawmills which are present in the county of Västernorrland. After being stored outside the sawdust is conveyed to a buffer vessel where it joins some steam recovered from the biomass pre-treatment section.

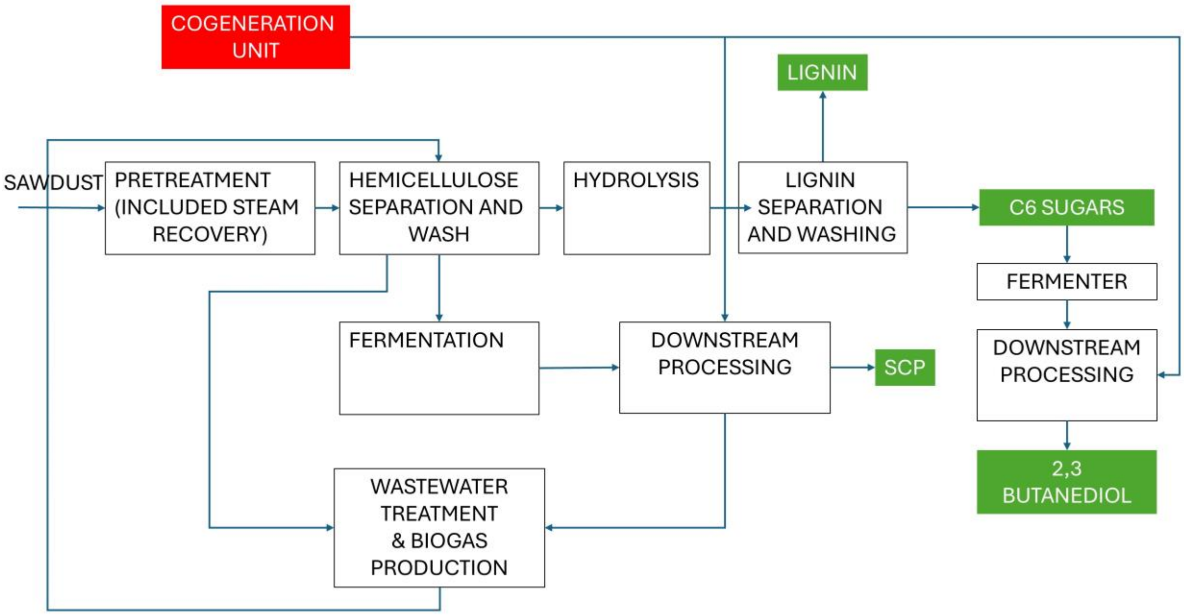

Figure 14 Biorefinery process layout

After this step the sawdust is transported through a screw conveyor to a vessel where the wood is mixed with sulphuric acid. Then the material undergoes the process of steam explosion, which is a thermomechanical process to break down the structural components of cellulose. In general, steam explosion is a process in which biomass is treated with hot steam (180 to 240°C) under pressure (1 to 3.5 MPa) followed by an explosive decompression of the biomass to atmospheric pressure that results in a rupture of the biomass fibers rigid structure, changing the starting material into a fibrous dispersed solid[25]. Mixing sulphuric acid with sawdust can help to achieve already the hydrolysis of hemicellulose to C5 sugars[26] during the steam explosion process. In this way, a liquid stream is obtained which is mainly composed

[25] Ghosh, S. B., & Sain, M. (2014). The use of biobased nanofibers in composites. *Biofiber reinforcements in composite materials*, 594-595.

[26] De Bari, I., Giuliano, A., Petrone, M. T., Stoppiello, G., Fatta, V., Giardi, C., ... & Novelli, A. (2020). From cardoon lignocellulosic biomass to bio-1, 4 butanediol: an integrated biorefinery model. *Processes*, *8*(12), 1585.

by C5 and C6 sugars and a solid stream, which contains lignin and cellulose, which has not been hydrolysed yet. The liquid stream can be separated by means of pressurised filters and then fermented to produce single cell protein. The solid stream can undergo a further step of hydrolysis, where cellulose in broken down to C6 sugars. Those can be further fermented to produce 2,3-butanediol. The fermentation liquid can be separated once again from the solid residue, which in this case is represented mainly by lignin. The drying condensates and the wastewaters can be sent to wastewater treatment with the production of biogas. The heat and electricity needs are provided by a cogeneration plant which can burn biomass residues or use other sources of renewable energy.

4.4.1 Pretreatment technology market

Within the pretreatment phase, there are a few processes and process configurations that can produce lignocellulosic sugars, with its own strengths and weaknesses. Common for each process is the importance of valorising by-products and each process will yield sugars of different qualities. The processes with highest TRL levels are Organosolv (Figure 15) and steam explosion (Figure 16). For both organosolv and steam explosion there are process suppliers and machine suppliers with capabilities and resources for commercial implementation.

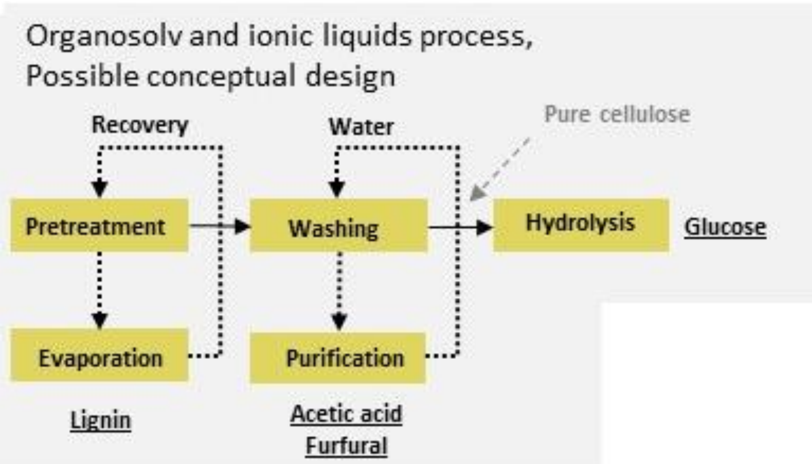

Figure 15 Overview of the organosolv process

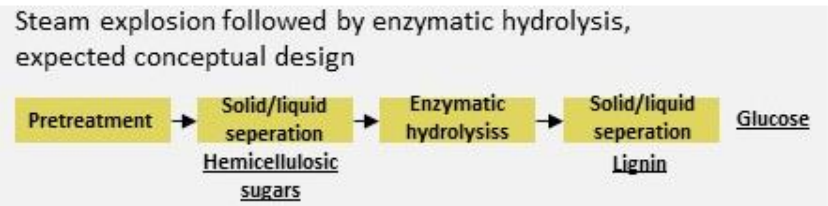

Figure 16 Overview of steam explosion process

4.4.2 Results on the selection of pretreatment technology

Steam explosion was selected as the pretreatment technology for fractionation of biomass based on its specific advantages:

- Steam explosion causes lignin to break down and hemicellulose to dissolve, making the cellulose more accessible for enzymatic hydrolysis.
- Compared to other pretreatment methods, steam explosion has a lower cost and avoids the use of chemicals.
- Steam explosion has high yield of glucose, hemicellulose and lignin.

While steam explosion was chosen, other pretreatment methods, like organosolv, could also be suitable in certain situations; Organosolv is effective at separating high-purity fractions, especially lignin, which can be valuable for specific applications. However, it often involves higher chemical costs and more complex solvent recovery systems, which can make it less cost-effective in some cases. The choice of steam explosion was made because it balances cost, simplicity, and yield. However, the benefits of other methods like organosolv are acknowledged and could be considered for specific needs or products[27]:

4.4.3 Fermentation technology (high quality sugar hydrolysate)

<u>Production of 2,3-BDO</u>

The production of 2,3-BDO is facilitated through microbial fermentation process that can utilize various feedstocks, including glucose and sucrose, and other carbohydrate-rich substrates. This process relies on microorganisms capable of metabolizing sugars under anaerobic conditions to produce 2,3-BDO as a primary product. Commonly used production strains include natural producers of 2,3-BDO such as *Klebsiella pneumoiae* and *Bacillus subtillilts* or genetically modified production strains engineered for enhanced yield and substrate specificity[28].

The fermentation process involves the microbial conversion of sugars through the glycolytic pathway, leading to the formation of pyruvate. Pyruvate is then metabolized into acetoin, which

[27] Maurya, D. P., Singla, A., & Negi, S. (2015). An overview of key pretreatment processes for biological conversion of lignocellulosic biomass to bioethanol. *3 Biotech*, *5*, 597-609.

[28] Kaloyan Petrov, Penka Petrova, (2021), Current Advances in Microbial Production of Acetoin and 2,3-Butanediol by Bacillus spp, Fermentation 2021, 7(4), 307

is subsequently reduced to 2,3-BDO. The process parameters, such as pH, temperature, and oxygen levels, are carefully controlled to optimize microbial growth and product yield.

Advances in fermentation technology have focused on strain improvement through metabolic engineering, process optimization to minimize by-product formation, and the utilization of renewable and cost-effective feedstocks.

4.4.4 Downstream processing of 2,3-BDO

Downstream processing is a critical component of 2,3-BDO production to achieve the required purity and quality for industrial applications. The process typically includes the following steps:

1. Cell Separation: Solid-liquid separation technologies are employed to remove microbial biomass from the fermentation broth.
2. Product recovery: Recovery methods often involve liquid-liquid extraction or adsorption to isolate 2,3-BDO from the fermentation broth.
3. Purification: Purification is done using distillation technologies or using membrane-bases technologies to obtain required specification of product purity.

The main methodology for recovering 2,3-BDO investigated in literature, in the short and medium term, is conventional vacuum distillation. In the long term, solvent extraction is identified as an industrially promising methodology. Other possible processes such as membrane separation, ion exchange, salting out and sugaring out[29]. Based on what is reported in literature, distillation was chosen as the most appropriate method for downstream processing of 2,3-BDO fermentation broth[30].

4.4.5 Fermentation technology (sugar hydrolysate low quality)

Production of SCP

SCP production involves the cultivation of microorganisms such as yeast, bacteria, algae and filamentous fungi to generate protein-rich microbial biomass for applications in animal content and some have amino acid profiles that are very similar to that of fishmeal. Filamentous fungi, such as species from the *Aspergillus*, *Fusarium* and *Rhizopus* are particularly used for

[29] Tinôco, D., Borschiver, S., Coutinho, P. L., & Freire, D. M. (2021). Technological development of the bio-based 2, 3-butanediol process. *Biofuels, Bioproducts and Biorefining*, *15*(2), 357-376.

[30] Sánchez-Ramírez, E., Quiroz-Ramírez, J. J., Hernández, S., Hernández, J. G. S., Contreras-Zarazúa, G., & Ramírez-Márquez, C. (2019). Synthesis, design and optimization of alternatives to purify 2, 3-Butanediol considering economic, environmental and safety issues. *Sustainable Production and Consumption*, *17*, 282-295.

production of SCP due to their ability to grow on diverse substrates and their high protein content. SCP can be produced using residual streams from the forest industry and this offers an attractive concept of turning forest raw material into a protein-rich component for animal feed[31]. In addition to addressing global environmental issues and providing a steady protein supply, local production of protein feed could generate local and regional job opportunities and strengthen the bioeconomy sector. For the biomass stream used in this case study a protein content of 63% are assumed. Key parameters for the fermentation or SCP using filamentous fungi are controlling pH, temperature, oxygen transfer, and nutrient availability, which can be carefully regulated to optimize fungal growth and protein yield. During fermentation, the fungi utilize carbon sources such as glucose, lactose, or complex carbohydrates, and nitrogen sources like ammonium salts of urea as nutrient.

4.4.6 Downstream processing of SCP

Downstream processing for SCP production involves several steps to ensure quality:

1. Biomass Harvesting: The fungal biomass is separated from the fermentation broths using filtration technologies.
2. Cell Washing and Processing: Harvested biomass is washed to remove residual substrates or impurities. This can be done using membrane filter press on the same unit operation as the biomass harvesting.
3. Drying and preservation: The processed biomass is spray dried to increase temperature to inactivate toxins and to improve storage stability and increase shelf life.

Efforts to optimize downstream processing focus on reducing energy consumption, maintaining protein quality, and ensuring the final product complies with regulatory standards for feed or food use.

4.5 Final scope of Biorefinery case study

Given the available data on North Sweden counties, the market analysis and technology selection, the scope of the innovative biorefinery base case has been set. The biorefinery is

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[31] Birgir Örn Smárason, Björn Alriksson, Ragnar Jóhannsson, Safe and sustainable protein sources from the forest industry – The case of fish feed, Trends in Food Science & Technology, Volume 84, 2019, Pages 12-14, ISSN 0924-2244, https://doi.org/10.1016/j.tifs.2018.03.005. (https://www.sciencedirect.com/science/article/pii/S0924224417303655)

fed with sawdust from coniferous wood from sawmills in the county of Västernorrland, to produce multiple outputs: 2,3-BDO, single cell protein, lignin and biogas. The price of the feedstock includes the transport to the final biorefinery facility and a term which considers possible increase of raw material price over time. The total amount of sawdust available at the three locations within the county of Västernorrland (Table 10), sum up to ca 315,000 t/year. Within the case study it is assumed that there is sufficient sawdust to supply a biorefinery at scale of 320,000 t/year. To weight transport costs over the sawmill's location, it was assumed to establish the biorefinery in Örnsköldsvik which is in the middle between Sollefteå and Sundsvall. The transport of all the sawdust from Sollefteå and Sundsvall to Örnsköldsvik will increase raw materials costs and it has also to be considered that a further increase will be foreseen due to the need to have long-term contracts which can cover for all the plant life, which is set to be 20 years. For the case study, the capital expense was calculated for the proposed plant layout with a final accuracy of over 30%, with main costs assumptions are reported in Table 13. CAPEX and OPEX was calculated according to the procedures in APPENDIX C COST and REVENUES ESTIMATE. Data was also checked with equipment providers, and they are mostly confidential for this reason they are not shown in this report.

Table 13 Main input data used in the economic modelling of the biorefinery case study

Financial	
Discount rate	10%
Total Investment Cost, CAPEX	292 MEUR (100% equity)
Corporate tax	22%
Inflation	2%
Utilities	
Steam	45 EUR/t
NaOH	809 EUR/t
NH4OH	600 EUR/t
H3PO4	650 EUR/t
H2SO4	250 EUR/t
KCl	400 EUR/t
Enzymes	1500 EUR/t
Antifoam	2575 EUR/t
Feedstock	
Sawdust	130 EUR/t
Products	
2,3-BDO	2600 EUR/t
SCP	950 EUR/t
Biogas	250 EUR/t
Lignin	150 EUR/t
*Disclaimer: Reported prices of materials are based on previous studies performed by RISE Processum.	

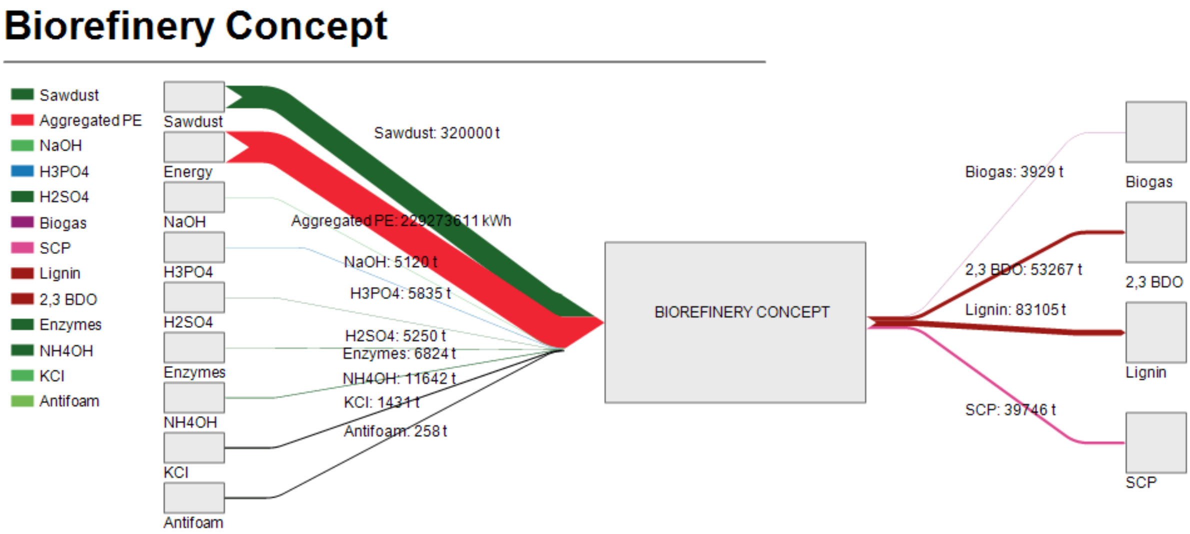

Figure 17 Biorefinery mass and energy balance

A simplified mass balance of the biorefinery concept is shown in Figure 17. Data presented are on a dry basis. Together with sawdust also steam, electricity and chemicals are used. Steam and electricity are coupled in a unique arrow which expresses mainly primary energy consumption. The outputs consist of 2,3-butanediol, single cell protein, lignin, and biogas. The biorefinery has a significant consumption of energy, accounting for 500,000 GJ. The mass balance is shown on dry basis, excluding the water additions through washing procedures as well as addition of water added with the biomass. Certain components are calculated as being 100% (e.g., lignin are calculated as being 100% lignin, whereas the actual solid intermediate component is assumed to contain 84% lignin and 11% glucan, the remaining 5% is a mix of sugars, by-products and residual components). Furthermore, biogas is produced as a result of the addition of a wastewater treatment plant where water are assumed to be recirculated and used as washing water in different process positions. The water circulation are based on general assumptions and with potential for a lot of optimization. Treated wastewater that is not being recirculated are assumed to meet the specifications and regulatory demands in Sweden and can be sent back to the recipient (sea).

From this a biorefinery base, the base case was set and evaluated with the MCDM tool. To compare the base case against alternative market scenarios, e.g. of varying end-product prices and optimization of downstream processing, five scenarios were developed and benchmarked against the base case.

- Base case, lignin is used for energy
- Scenario 1, valorisation of lignin

- Scenario 2, reduction of 2,3-BDO price on current market
- Scenario 3, reduction of 2,3-BDO price to reach polymer market growth
- Scenario 4, more effective downstream processing of BDO to lower steam cost
- Scenario 5, a combination of lignin valorisation (scenario 1), lower 2,3-BDO market price (scenario 3), and improved downstream processing (scenario 4).

4.6 ANALYSIS OF THE BASE CASE

This section provides a comprehensive evaluation of the case study using the multi-criteria decision-making (MCDM) tool. The scoring framework assesses the sex key factors: strategic alignment, product advantage, market attractiveness, Leverage competence, technical feasibility, and potential financial rewards. Each criterion is analysed to understand its contribution to the overall viability of the scenarios. The evaluation highlights trade-offs between market potential and technological challenges, offering insights into how different strategies align with regional strengths and broader bioeconomy goals. This structured approach ensures informed decision-making and prioritization of measures to optimize outcomes.

4.6.1 Strategic alignment (strategic fit and importance)

Table 14 MCDM for Strategic alignment

Criteria	0	4	7 **(7)**	10
The degree of fit with strategy	Not aligned with strategy	Somewhat aligns with strategy	Supports strategy	Aligns very well with strategy

4.6.2 Reasoning behind scoring

In the case study, the strategic alignment cannot be evaluated from an internal viewpoint since RISE is governmentally owned research institute with no plans to extend its operation towards production of chemicals or materials. A scoring based on alignment with RISE internal strategy would naturally be very low. Therefore, the scoring is based solely on alignment with external strategic factors (regional, national and EU).

The proposed Swedish Bioeconomy strategy is focused on transitioning from a fossil-based to a circular, biobased economy, leveraging the country's rich forest resources, advanced technologies, and commitment to sustainability. It is rooted in the principles of resource efficiency, reducing greenhouse gas emissions, and increasing the use of renewable materials. Key goals include promoting sustainable production, enhancing value-added products from biological resources, fostering innovation, and ensuring long-term competitiveness for industries such as forestry, agriculture, and biorefining.

From a regional perspective, northern Sweden, has tailored its strategies to harness its abundant forest resources and robust industrial infrastructure. The counties within the region are leaders in promoting biobased industries, particularly within the forest bioeconomy, which emphasizes sustainable forestry practices and advanced bio-refining processes. Västernorrland, for example, focuses on diversifying its traditional forestry sector to include innovative uses for biomass, such as green chemicals, bioenergy, and renewable materials, all supported by a robust network of research institutions and collaborative clusters like RISE Processum[32].

The regional innovations strategy for smart specialisation of Västernorrland prioritize several key areas:

- Sustainable Resource Management –Maximizing the value from forest and agricultural residues.
- Industrial Collaboration – Strengthening partnerships between academia, industry, and government to advance innovation in biorefining and forest-based materials.
- Circular Economy – Encouraging the use of side streams and residues from industries for new biobased products.
- Decarbonization – Supporting the transition to renewable energy and biobased alternatives to fossil fuels, thereby contributing to Sweden's climate goals.

By fostering regional strategies, biorefineries in northern Sweden can position themselves as key players in the green transition, aligning with both national and EU climate targets.

However, the lack of comprehensive policy support for the bioeconomy presents a significant challenge. Despite Sweden's commitment to sustainability and the EU's broader bioeconomy objectives, the alignment between industrial innovation in biorefineries and the regulatory framework remains fragmented. This is particularly evident in the development of biobased materials and chemicals, where clearer and more targeted policies are needed to promote large-scale commercialization and innovation.

Lack of Policy Coherence

[32] Västernorrlands innovationsstrategy för smart specialisering, 2022-01-12, https://www.rvn.se/globalassets/_rvn/utveckla-vasternorrland/naringslivsutveckling/smart-specialisering/en_smart-specialiseringsstrategi-220112.pdf

The Swedish government is working on developing a national strategy for a sustainable and competitive bioeconomy. There are policy measures already in place for a subsection of the bioeconomy (biofuels), while the absence of robust, sector-specific policies, particularly for biorefineries, creates uncertainty. This is especially problematic in northern Sweden, where biorefineries rely on regional forest resources and contribute significantly to rural economies. Here, policy clarity is crucial for ensuring long-term investment, innovation, and alignment with broader EU goals.

The Mandate for CEN/TC 411 on Biobased Products

A key example of the need for stronger policy support in Europe lies in the CEN/TC 411 mandate (M/491), which was established by the European Commission to develop standards for biobased products. This technical committee (CEN/TC 411) within the European Committee for Standardization (CEN) is responsible for creating a framework that defines the quality, sustainability, and performance metrics for biobased materials. Its goal is to ensure that biobased products, including monomers and polymers, meet rigorous criteria for environmental benefits and technical performance.

However, Mandate M/491 has not yet been fully translated into enforceable regulations or clear market incentives for biorefineries. While the standards developed under TC 411 provide an important foundation for defining biobased products, their adoption remains largely voluntary. This leaves a significant policy gap between the development of these standards and their widespread implementation in the market. For biorefineries in northern Sweden, this lack of regulatory enforcement means they are not strongly incentivized to prioritize biobased chemicals over traditional fossil-based alternatives. Without national or EU-wide mandates that require the use of certified biobased products, biorefineries face difficulties in scaling up production and achieving consistent market demand.

This situation contrasts sharply with the approach taken in the United States, where the BioPreferred Program, initiated by the 2002 Farm Bill, predates CEN/TC 411's efforts and provides a more direct model for policy-driven market creation. The BioPreferred Program mandates that U.S. federal agencies give preference to purchasing biobased products in a wide range of categories, including chemicals, plastics, and construction materials. By requiring federal procurement of biobased goods, the U.S. has created a guaranteed market for biobased products, fostering innovation and growth in the bioeconomy.

In comparison, Europe's current framework, including the CEN/TC 411 mandate, lacks such strong enforcement mechanisms. There is no comparable, binding requirement for public procurement or private sector use of biobased products, leaving biorefineries, especially in rural and forest-rich regions like northern Sweden, at a disadvantage. This absence of regulatory support hinders their ability to attract investment and scale up operations, despite the promising standards developed by CEN/TC 411.

For biorefineries to realize their full potential, policies must go beyond voluntary standards. Clear mandates, such as those that enforce the use of biobased materials in key industries like packaging, construction, and automotive, are essential to drive demand. Furthermore, integrating biobased products into public procurement at the EU level, like the BioPreferred Program in the U.S., would provide biorefineries with the market confidence needed to invest in innovation and scale-up production.

High-Level Group on the Bioeconomy

Further highlighting this gap, the High-Level Group on the Bioeconomy, a key advisory body to the European Commission, has emphasized the need for more integrated policy frameworks to foster the bioeconomy. Their documentation has called for cohesive regulatory measures that encourage investment in biobased innovations across the EU. The High-Level Group stresses that policies must not only support research and development but also create demand through public procurement and fiscal incentives.

Despite these recommendations, the policy environment for biobased industries remains inconsistent across Europe, including Sweden. For biorefineries in northern Sweden, this lack of strong, binding policies translates into difficulties in securing long-term investments and aligning their business strategies with both national and EU goals. Without clearer directives or financial incentives for transitioning from fossil-based to biobased products, these biorefineries face challenges in fully leveraging their regional resources and contributing to Sweden’s and Europe’s bioeconomy goals.

Strategic Alignment and Policy Needs

To achieve better strategic alignment, biorefineries in northern Sweden need policies that:

- Provide Investment Security: Policies that incentivize investments in biobased technologies, such as tax reliefs or subsidies for biobased chemical production, would help biorefineries mitigate financial risks.
- Create Market Demand: Regulations mandating a minimum percentage of biobased products in specific industries (e.g., packaging, plastics, or construction) would drive market demand, aligning production with long-term sustainability goals.
- Support Standardization and Certification: While CEN/TC 411 sets voluntary standards, enforcing these through national policies or within the EU Green Deal would create a level playing field, ensuring that biobased products are prioritized over fossil-based ones in key markets.

- Incentivize Public Procurement: Public procurement policies that favour biobased materials in government projects (such as infrastructure or public buildings) would create significant demand, encouraging biorefineries to scale up production and innovate further. A very large portion of nations budgets are usually used for public procurement of services and goods.

Conclusion Strategic alignment (strategic fit and importance)

While Sweden has demonstrated strong leadership in sustainability, its bioeconomy policies need to be more specific and enforceable, especially for biorefineries in northern Sweden. Drawing from frameworks like the CEN/TC 411 and the recommendations of the High-Level Group on the Bioeconomy, policymakers must develop coherent strategies that not only support innovation but also drive market demand for biobased products. Without these policy mechanisms, the full potential of biorefineries in the region risks being underutilized.

Figure 18 MCDM scoring for Supports strategy, with a score: 7

Taken together, the scoring for the strategic alignment of establishing a biorefinery in the county of Västernorrland is scored a 7 (Figure 18, Table 14), supported by certain strategies but still lack long term policy framework for biobased products.

4.6.3 Product advantage

The scoring for product advantage is described in Table 15.

Table 15 MCDM score scale for Product advantage

Criteria	0	4	7 (**8**)	10
Perceived value for money	Maintains current competitive position	Modestly improves current competitive position	Provides good advantage to current competitive position	Provides excellent advantage to current competitive position
Competitive advantage	Customer perceives limited or no value	Customer perceives modest value	Customer perceives good value	Customer perceives superior value

4.6.3.1 Reasoning behind scoring

The portfolio of biobased 2,3-butanediol, single-cell protein, and lignin-derived products delivers a significant competitive advantage through its focus on sustainability, diverse applications, and alignment with evolving market needs. By addressing environmental challenges and enabling industries to meet sustainability goals, these products exemplify innovation in renewable materials and resource efficiency.

Perceived value: Eco-friendly products command higher prices due to their environmental benefits. The portfolio's biobased origin enhances perceived value, making it an attractive choice for industries and consumers prioritizing sustainability.

Environmental benefits: All products are derived from renewable feedstocks, resulting in significantly lower greenhouse gas (GHG) emissions and reduced ecological impact compared to fossil-based alternatives. This inherent sustainability supports compliance with environmental regulations and aligns with global efforts to mitigate climate change.

Corporate sustainability goals: Industries are increasingly investing in biobased solutions, such as monomers and feed ingredients, to achieve their corporate sustainability targets. Products like 2,3-BDO and SCP enable companies to demonstrate tangible progress in reducing environmental footprints and transitioning to circular economy practices.

Brand reputation: Utilizing biobased and eco-friendly products enhances brand loyalty by signalling a commitment to environmental responsibility. This positive impact on brand reputation is particularly valuable in consumer-facing industries, such as packaging, food, and personal care, where sustainability is a key purchasing criterion.

Biobased 2,3-Butanediol:

Versatility and applications: 2,3-BDO serves as a key intermediate in producing specialty chemicals, including biodegradable plastics, cosmetics, and pharmaceutical products. Its biobased production method positions it as a premium alternative in markets seeking sustainable solutions.

Reduced environmental impact: Its renewable origin significantly lowers carbon emissions compared to fossil-derived counterparts, making it a preferred choice for industries focused on reducing their ecological footprint.

Single-Cell Protein:

Sustainable protein source: SCP offers a scalable and sustainable solution for animal feed, particularly in aquaculture and livestock production. Its production process minimizes reliance on agricultural land, water, and other resources.

High nutritional value: With its rich protein content and essential amino acids, SCP provides a high-performance feed ingredient that meets the growing global demand for alternative proteins.

Market potential: SCP addresses the increasing need for environmentally friendly feed solutions, offering a competitive edge in a rapidly expanding market.

Lignin-Derived Products:

Energy applications: Lignin's calorific value provides a renewable, low-carbon alternative for generating heat and power, reducing reliance on fossil fuels.

Polyols for green polymers: Lignin-based polyols are integral to producing biobased polyurethanes, supporting the development of sustainable materials for industries like construction and automotive.

Plastic fillers and bio composites: Lignin enhances plastics' performance as a filler, providing improved UV resistance and mechanical properties. It is also a valuable component in bio composites, contributing to lightweight, durable, and eco-friendly material alternatives.

Diverse Product Range

The portfolio's breadth addresses both market and environmental demands. It spans high-value chemicals like biobased monomers, sustainable food and feed additives, and eco-friendly fillers, ensuring relevance across various industries and applications.

This combination of sustainability, performance, and market alignment positions the portfolio as a leading choice for industries transitioning to greener practices, meeting both immediate needs and long-term goals for environmental stewardship.

- Perceived Value: Higher prices for eco-friendly products due to environmental benefits.
- Environmental Benefits: Derived from renewable feedstocks. Lower GHG emissions and reduced ecological impact.
- Corporate Sustainability Goals: Companies invest in biobased monomers to meet sustainability targets.
- Brand Reputation: Enhances brand loyalty by signalling environmental responsibility.
- Competitive Advantage: Diverse product range addressing market and environmental demands. Focus on biobased monomers, food/feed additives, and eco-friendly fillers.

Environmental sustainability aspects

Here we propose a quantitative calculation of how the sustainability contributes to product value. The first part in the life cycle of biomaterials produced from sawdust is the logging process. Trees are grown in the forest and harvested and transported to the sawmill. Saw dust is obtained from waste wood flows from a sawmill plant (Figure 19).

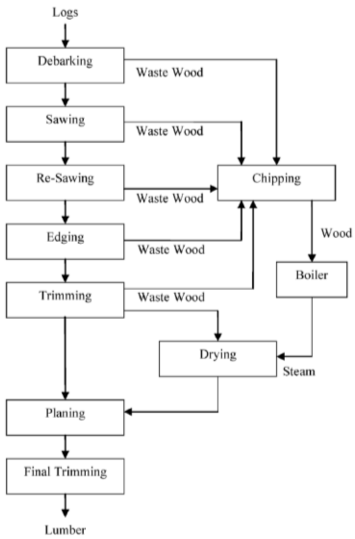

Figure 19 Sawmill processes[33]

[33] Gopalakrishnan, B., Mardikar, Y., Gupta, D., Jalali, S. M., & Chaudhari, S. (2012). Establishing baseline electrical energy consumption in wood processing sawmills for lean energy initiatives: A model based on energy analysis and diagnostics. Energy engineering, 109(5), 40-80.

Sawmill operations include debarking, sawing, edging, trimming, chipping, and drying. These operations require energy-consuming equipment and machinery. Typical sources of energy utilized in sawmills are electricity, natural gas, wood waste, and fuel oil. Electricity is required to operate motors in equipment such as the debarker, head saw, re-saw, edger, trimmer, chipper, planer, fans, and pumps, as well as in material handling equipment such as conveyors and belts.

The last part of the life cycle in the cradle to gate approach is the biorefinery model, which mass and energy balance can be derived directly from the economic cash flows dividing variable costs for the costs per unit of energy and mass. To model sawdust's environmental impact, the following process has been selected from the Ecoinvent database: "1 kg Sawdust, loose, wet, measured as dry mass {Europe without Switzerland}| sawing, softwood | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)". The final impact on the Climate Change category of the process is 0.00849 kgCO_2eq/kg of saw dust. The calibration of the model was done mainly based on the production of BDO, which is reported also in Forte er al, (2016) [34].

Table 16 Comparison of BDO impacts between Forte et al. 2016 and this case study

Impact Category	**Unit**	**Forte et al. 2016**	**This case study**
Climate Change	kgCO_2 eq	1.6	0.961
Ozone Depletion	Kg CFC-11eq	$2.7 * 10^{-7}$	$9.8 * 10^{-8}$
Photochemical oxidant formation	Kg NMVOC eq	$3.6 * 10^{-3}$	$6.69*10^{-4}$
Fossil Depletion	Kg oil eq	$5.3*10^{-1}$	$5.92* 10^{-3}$
Terrestrial Acidification	kgSO_2 eq	$1.2 * 10^{-2}$	$1.41*10^{-2}$
Freshwater Eutrophication	Kg N eq	$4.8 * 10^{-4}$	$2.81*10^{-1}$
Marine Eutrophication	Kg P eq	$9.2 * 10^{-5}$	$1.25*10^{-2}$
Water depletion	m^3	$8.4 * 10^{-1}$	$4.43*10^{-3}$
Particulate Matter Formation	Kg PM10 eq	$2.4 * 10^{-3}$	$3.34*10^{-3}$

In the study of Forte et al. 2016, wheat straw was the feedstock for production of 1,4 BDO, while in the case study saw dust is selected. The case study was expected to have lower

[34] Forte A, Zucaro A, Basosi R, Fierro A. LCA of 1,4-Butanediol Produced via Direct Fermentation of Sugars from Wheat Straw Feedstock within a Territorial Biorefinery. Materials. 2016; 9(7):563. https://doi.org/10.3390/ma9070563

impacts in general because it produces more output from the biorefinery and in this way the final impact is allocated among different products, however three categories to have a higher impact, freshwater eutrophication, marine eutrophication and particulate matter formation (Table 16).

Particulate matter formation is a category in which sawdust can have a higher impact during the transport and handling phases. Marine and freshwater eutrophication is mainly due to the production of enzymes, while photochemical oxidation is due to the production of heat and electricity in the cogeneration system, together to the production of enzymes. The results obtained in the case study are also better than those obtained by Tiwari et al[35], which report a carbon footprint for 2,3 BDO of 3.19 kgCO2eq/kg of product. There are more than one end-product of the biorefinery so below we indicate also the impacts of the other products obtained together with BDO. The comparison of the 4 end products obtained in this study in a single graph is shown in Figure 20.

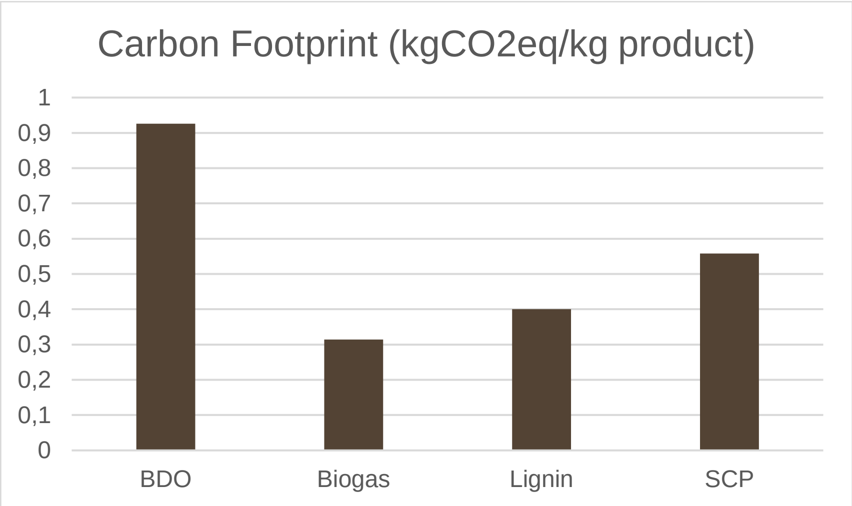

Figure 20: Carbon footprint of the biorefinery products

4.6.4 Market attractiveness

The scoring for market attractiveness is described in Table 17.

[35] Tiwari, B. R., Maity, S. K., Brar, S. K., Chew, K. W., Kumar, G., & Kumar, V. (2024). Comprehensive techno-economic and environmental assessment for 2, 3-butanediol production from bread waste. *Chemical Engineering Journal*, *500*, 157003.

Table 17 MCDM score scale for market attractiveness

Criteria	0	4 (6)	7	10
Ability to penetrate market	Limited or no ability to penetrate the market	Modest ability to penetrate the market	Good ability to penetrate market	Strong ability to penetrate market
Rate of growth for the market	No or limited market growth	Modest market growth	Reasonable market growth	High market growth

4.6.4.1 Reasoning behind scoring

2,3-Butanediol (BDO)

Market Penetration: Moderate to High

Biobased 2,3-butanediol is positioned as a potential substitute for its fossil-derived counterpart, but its adoption is primarily driven by price competitiveness. While the biobased version offers sustainability benefits, it struggles to compete on cost without substantial regulatory support, particularly in Europe. Market penetration has been growing, especially within sectors like packaging, textiles, and consumer goods, which are increasingly prioritizing sustainable alternatives. The penetration rate is improving as more companies in these industries explore biobased options. However, for broader adoption, the biobased monomer needs to reach cost parity with fossil-based BDO, which will drive further market adoption, especially in more price-sensitive sectors.

Market Growth Rate: Moderate to High

The current global market for 2,3-BDO (fossil) is estimated to 236 million EUR and is expected to grow to 284 million EUR in the next five years[36]. The demand for biobased chemicals like 2,3-butanediol is experiencing rapid growth, spurred by the rising consumer demand for sustainable products and tightening environmental regulations. Governments and industries worldwide are under increasing pressure to adopt greener production methods, which accelerates the shift towards biobased monomers. As the market for sustainable materials grows, biobased 2,3-BDO is expected to capture a larger share, particularly as technological advancements help lower production costs and improve scalability. If 2,3-BDO starts being used in production of polymers a rapid growth is expected dedicated for bio-based 2,3-BDO.

[36] 2,3-Butanediol Market Analysis: Growth, Size, Share & Future Trends (2024-2029), https://horizon-markets.com/chemicals-materials/2-3-butanediol-industry/, august 15 2024

Single Cell Protein

Market Penetration: Moderate

The market penetration of SCP is gaining momentum but remains somewhat limited by regulatory hurdles and consumer awareness. In the food and feed sectors, adoption is dependent on the approval of novel food regulations and the perceived nutritional benefits of SCP. Despite these challenges, interest in SCP is growing, particularly as sustainability becomes a more significant factor in the food industry. However, SCP faces strong competition from traditional ingredients like soy and animal-based proteins, which have established supply chains and consumer trust.

Market Growth Rate: Steady

While growth in SCP production is steady, it is slower compared to other biobased materials. The demand for alternative protein sources is undeniably increasing due to growing concerns about food security, sustainability, and the environmental footprint of conventional animal farming. However, the pace of growth in SCP is tempered by the need for regulatory approvals and consumer education. As more sustainable and nutritious alternatives emerge and gain acceptance, SCP is expected to see gradual growth, but it may take longer to achieve widespread adoption compared to other biobased materials.

Lignin for energy recovery

Market Penetration: Low

Lignin-based energy products like biopellets have limited market penetration. These biopellets could potentially replace coal in coal-fired power plants, but no such plants currently exist in the region of interest. The primary application for lignin-based energy products is within local markets, where biomass-based energy generation is established. These products are being considered by energy-intensive industries aiming to reduce their reliance on fossil fuels by utilizing waste lignin as a renewable, carbon-neutral energy source. However, the market penetration remains low due to the absence of infrastructure for large-scale lignin-based energy production and limited regional demand for lignin as a replacement for coal.

Market Growth Rate: Slow

The growth rate for lignin-based energy products is currently slow. As a niche market, lignin's role as a renewable energy source faces challenges in competing with other established renewable energy options, such as wind and solar power. The potential for growth in local energy production exists, but it is confined by the lack of coal-fired plants that could accommodate lignin-based biopellets as a replacement for coal. Without significant infrastructure investment or technological advancements that enhance the scalability and cost-effectiveness of lignin as an energy source, growth will remain limited. However, as demand for renewable energy solutions rises, lignin could see increased interest if the infrastructure for its utilization expands, or new applications emerges.

Figure 21 MCDM scoring for market attractiveness, with a score: 6

Taken together, the market attractiveness score of 6 reflects the combination of good but constrained penetration potential due to the challenges faced by lignin as energy products and SCP (Table 17, Figure 21). Reasonable market growth rates, particularly for biobased 2,3-butanediol, driven by sustainability demands and regulatory pressures. This balanced score represents opportunities for growth while acknowledging current limitations in cost competitiveness, infrastructure, and market readiness for specific products.

4.6.5 Leverage competence (synergies)

The scoring for leveraging competence is described in Table 18.

Table 18 MCDM for Leverage competence

Criteria	0	4	7	10 **(10)**
Ability to leverage core competences	Limited or no ability to leverage core competences	Modest ability to leverage core competencies	Good ability to leverage core competencies	Strong ability to leverage core competencies

4.6.5.1 Reasoning behind scoring

The case study demonstrates the importance of competences that are critical to the project and regional biorefinery development. These competences include forestry, pulp and paper, mechanical/engineering, research & development, innovation, and some chemical industry experience. Together, they allow for progress in biorefinery technologies and processes while enabling collaboration with related industries.

The project shows a strong ability to leverage competence when dealing with innovative technologies. Industries in the region already use similar technologies, which supports knowledge sharing, process adaptation, and scale-up of biorefinery methods. For example, combining competences in forestry and pulp and paper improves material handling, process efficiency, and sustainability. Mechanical/engineering competences further support adapting infrastructure and equipment for biorefinery operations.

There is also a strong ability to leverage competence in manufacturing. The workforce already has skills in production and process management that can easily adapt to biorefinery needs. This ensures that new production methods are implemented efficiently without compromising quality. The established manufacturing competences in the region promote resilience to changes in technology and markets.

Regarding marketing and sales competences, the region demonstrates strong general sales skills. However, to develop markets for biobased chemicals and materials globally, there may be a need to import senior personnel with specific experience in international markets. This could strengthen the ability to target main market areas, overcome market challenges, and meet the demands of biobased products.

Core Competences Summary

Diverse Skill Sets: The region's workforce has strong competence in forestry, pulp and paper, mechanical/engineering, research & development, innovation, and some chemical industry experience. These competences work together to support biorefinery processes and innovation.

Technology Transfer Capability: With competences in forestry and pulp and paper, the biorefinery can easily transfer technologies to improve efficiency and integrate new methods into existing processes.

Adaptability of Manufacturing Skills: Manufacturing skills are highly adaptable to biorefinery needs. This flexibility supports efficient production and the use of advanced manufacturing processes.

Need for Specialized Sales Expertise: General sales competences are strong, but senior expertise with experience in biobased product markets may be required to support entry into main global market areas.

Figure 22 MCDM scoring for leverage competence, with a score: 10

Taken together, the case study displays a strong ability to leverage competencies in the region to support the development of biorefinery technologies, and therefore is given a score of 10 (Figure 22). Strengthening specialized sales skills will be important for long-term success and competitiveness in global markets.

4.6.6 Technical feasibility

The scoring for technical feasibility is described in Table 19.

Table 19 MCDM for Technical feasibility

Criteria	0	4 **(6)**	7	10
Degree of new technology required	Completely new technology required	Significant new technology required	Some new technology required that will leverage current technology	No new technology required; available in-house

4.6.7 Reasoning behind scoring

The evaluation of technical feasibility is very important when developing biorefinery concepts from research scale to industrial application. To make sure progress is systematic, the biorefinery process is divided into five different technological areas (Figure 23), each at different TRL, described below:

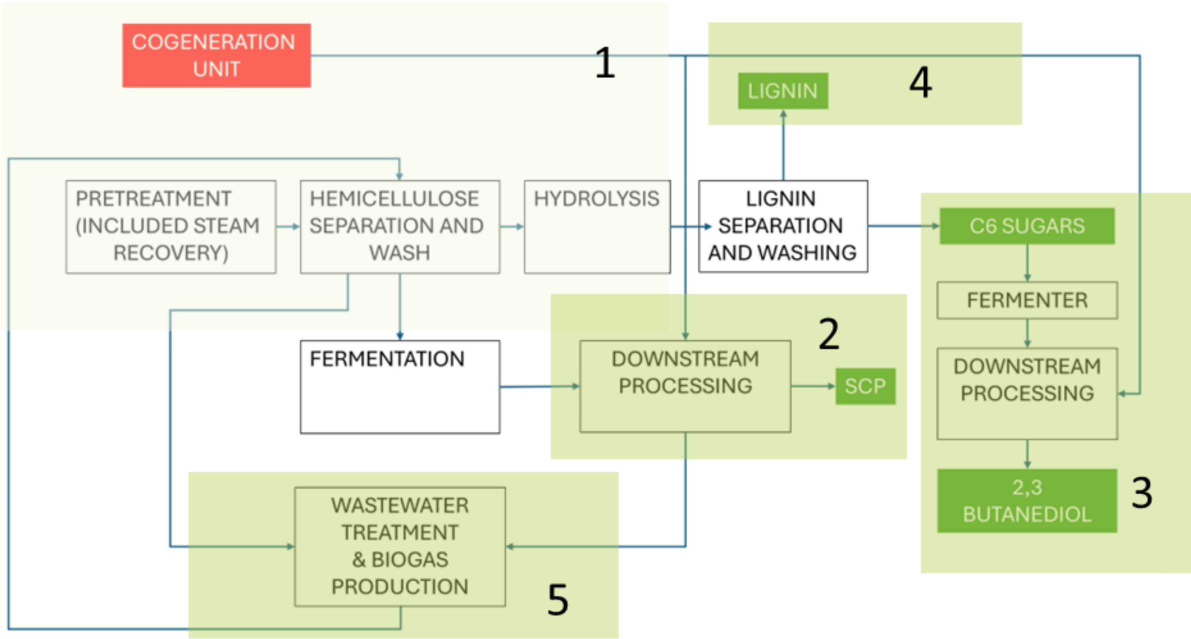

Figure 23 Simplified process diagram

1. **Fractionation of Lignocellulosic Biomass (TRL 7)**: The separation of lignocellulosic biomass into its main components like cellulose, hemicellulose, and lignin is done using advanced fractionation processes. This step is well developed, and pilot-scale tests show that the technology is ready for scaling up to industrial use.

2. **Production of Single-Cell Protein (TRL 5–6)**: Hydrolysed sugars are fermented to produce SCP with microorganisms. The technology is between pilot and demonstration scale, and current efforts focus on improving efficiency and scaling the process further.

3. **Production of 2,3-Butanediol (TRL 3–5)**: Hydrolysed sugars are also fermented to produce 2,3-BDO, a valuable chemical. This process is still at a lower TRL, with testing mainly in the laboratory or small-scale setups.

4. **Lignin drying (and pelletation) (TRL 7-9):** Lignin, a by-product from biomass separation, is being studied for use in high-value products. In the base case, lignin will be used as an energy product where the technologies are well known and has widespread use. Lignin valorisation is still under development, and research is ongoing but has found potentially cost-effective and scalable applications. Efforts to valorise lignin would result in a TRL 3-5.

5. **Wastewater Treatment and Handling (TRL 9)**: Systems for treating wastewater from the biorefinery process are fully developed and already in commercial use. These systems are reliable and meet strict environmental requirements.

This structured way of evaluating helps to focus on the areas that need improvement, while also ensuring that the technologies being developed are environmentally and economically sustainable. It also helps align the development process with market demands, making commercialization more likely.

Figure 24 MCDM scoring for technical feasibility, with a score: 6

Taken together, by reviewing at the TRLs of each area, it is possible to see where the challenges are, what needs more investment, and what can be scaled up. A score of 6, is given as new technology will be required that will leverage current technology. This structured way of evaluating helps to focus on the areas that need improvement, while also ensuring that the technologies being developed are environmentally and economically sustainable. It also helps align the development process with market demands, making commercialization more likely.

4.6.8 Potential for reward

The scoring for potential for reward (financial feasibility) is described in Table 20.

Table 20 MCDM for Potential for reward (Financial feasibility)

Criteria	0	4 (6)	7	10
Degree of financial return based on financial indicator	Negative return	Modest return	Good returns	Very positive returns

4.6.8.1 Reasoning behind scoring

The product has the potential to generate steady revenues, supported by its ability to target emerging markets with growing demand for sustainable alternatives. However, the overall revenue potential is impacted by competition from established fossil-based or alternative products that may offer lower costs or higher scalability. The reliance on renewable feedstocks is an advantage, as it supports sustainability and reduces exposure to volatile fossil-based input prices. However, supply chain dependencies and the cost of securing consistent feedstock streams introduce some risk to the financial model. The pricing strategy is moderately competitive but is somewhat reliant on premium markets that value sustainability. In broader, more cost-sensitive markets, achieving cost parity with traditional alternatives is a key hurdle. The economic performance for the base case gives an IRR of 18,9% and the a NPV of 294 MEUR, with a discounted payback for the investment of around 8 years (Figure 25).

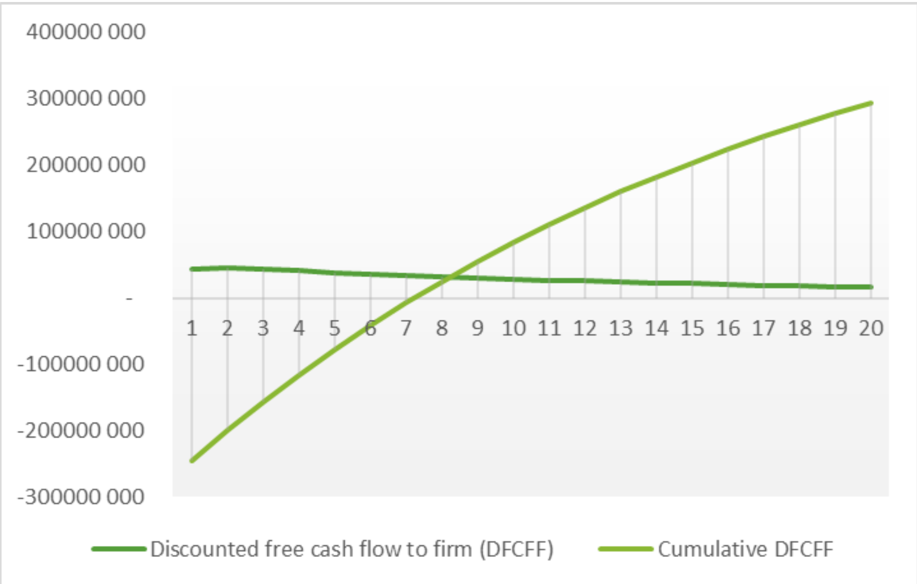

Figure 25 Cashflow analysis of base case, y-axis: EUR, x-axis: years.

The business case is highly reliant on the income from 2,3-BDO, as shown in the income statement in (Figure 26). When reviewing income and cost sources the reliance on 2,3-BDO as main income source is evident. It is also clear that a main cost source lies in the downstream processing (DSP) of 2,3-BDO (Figure 27). Steam consumption for DSP of 2,3-BDO account for 65% of the steam costs shown in the figure below.

Income Statement [EUR]	**year 1**	**year 5**	**year 10**	**year 15**	**year 20**
Specified income	179 433 500	194 224 591	214 439 642	236 758 693	261 400 728
2,3 BDO	134 092 500	145 146 034	160 252 950	176 932 206	195 347 452
SCP	31 424 100	34 014 456	37 554 708	41 463 433	45 778 980
Biogas	982 250	1 063 219	1 173 880	1 296 058	1 430 953
Lignin	12 934 650	14 000 881	15 458 104	17 066 996	18 843 343
Variable costs	- 102 569 370	- 111 024 385	- 122 579 892	- 135 338 105	- 149 424 204
Gross margin	76 864 130	83 200 206	91 859 751	101 420 587	111 976 523
Fixed costs	- 14 102 515	- 15 265 016	- 16 853 811	- 18 607 969	- 20 544 701
EBITDA	62 761 615	67 935 190	75 005 940	82 812 618	91 431 822
Depreciation	- 14 446 450	- 14 446 450	- 14 446 450	- 14 446 450	- 14 446 450
EBIT	48 315 165	53 488 740	60 559 490	68 366 168	76 985 372
EBT	48 315 165	53 488 740	60 559 490	68 366 168	76 985 372
Income tax	- 10 629 336	- 11 767 523	- 13 323 088	- 15 040 557	- 16 936 782
Net income for the period	**37 685 829**	**41 721 218**	**47 236 402**	**53 325 611**	**60 048 590**

Figure 26 Income statement base case

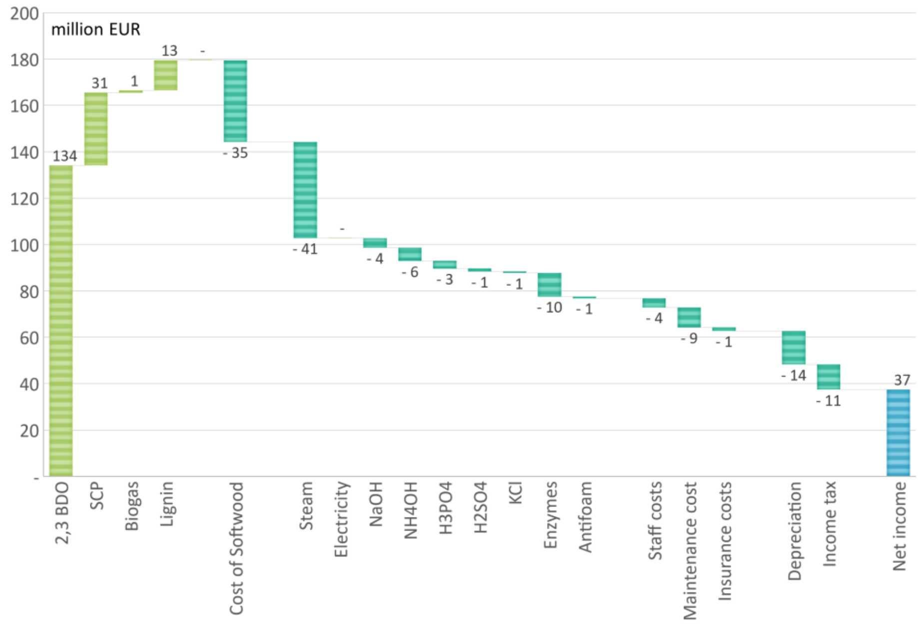

Figure 27 Waterfall diagram, income and cost structure of base case

Figure 28 MCDM scoring for potential for reward, with a score: 6

Taken together, the score of 6 for potential for reward reflects a moderate to good level of financial return based on the current business model and market conditions. While the potential for financial gain is promising, certain challenges and risks slightly temper the overall assessment.

4.6.9 Summary of base case

For the base case (Figure 29), the overall evaluation yielded a score of 43 points, reflecting a balanced trade-off between market stability and manageable risks. Analysing the base case scoring it can be concluded that the proposed biorefinery scores above average in all sex key categories, but with a score on the lower side (6) for market attractiveness, technical feasibility and financial risk vs. reward. Highest score was given for synergies, leverage of competences.

Figure 29 DCMC final base case scoring, with a total score of 43 points.

In terms of income and cost sensitivity, 2,3-BDO needs to carry the weight of the business and the business case is therefore very sensitive to changes in the BDO market (price/volume). **A solution** for this is adding lignin valorisation that would lessen the burden for BDO to carry the business case.

There is room for increased process optimization, the cost analysis revealed that more effective DSP of BDO is required. **A solution** would be to lower the steam consumption rate but most of those options will lower the sustainability since those strategies involve using fossil solvents.

The market penetration is valued as low using current price. **A solution** for increased market growth and penetration, would be to lower the base case assumed price at 2500 EUR/ton to 2000 EUR/ton. This will price 2,3-BDO closer to the lower expected prices for 2,3-BDO and should increase market penetration.

The product portfolio and the market growth rate are limited, this could be increased by targeting and build a polymer market for BDO and by valorising lignin. **A solution** would be valorising lignin, this will increase costs but vastly increase income. **Also**, targeting a polymer market will require lower prices and development of new downstream processing strategy will need to account for the increased specification demands.

Based on these possible solutions, a total of five scenarios are set up and evaluated for their effect on the business case and how their scoring compared to each other and to the base case.

4.7 SCENARIO ANALYSIS COMPARED TO THE BASE CASE

The scenario-building process combines insights from technical, economic, and sustainability analyses to evaluate the feasibility and impact of different pathways. By applying a systematic scoring framework, assessment can be made for how various strategies align with market opportunities, technological challenges, and regional strengths.

Based on the conclusions from analysing the base case, five different scenarios have been set up to address solutions of increased market penetration, increased market growth, reduce cost and create a more diversified product portfolio (see Table 21).

Table 21 Overview of biorefinery cases

Case	Description
Base case	Lignin is used for energy recovery
Scenario 1	Lignin is valorised to create a more diversified product portfolio
Scenario 2	Price of 2,3-BDO lowered from 2500 EUR/t to 2000 EUR/t to increase market penetration
Scenario 3	Price of 2,3-BDO lowered from 2500 EUR/t to 1500 EUR/t to increase market penetration and to increase market growth
Scenario 4	More effective downstream processing of 2,3-BDO reducing cost by lowering the steam consumption
Scenario 5	A combinatory scenario that incorporate scenario 1, scenario 3 and scenario 4

4.7.1 Scenario 1 – Lignin valorisation

In this scenario the focus is on valorising lignin to biobased products instead of energy recovery. The scenario assumes a 90% yield of lignin, reducing total product flow from 158 000 tons/year to 77 600 tons/year and increased pricing from 150 EUR/ton to 750 EUR/ton, with total variable costs increase by 5%. The assumption is that market can be accessed where lignin is a functional filler in some applications, replacing carbon black with a reduced price. The economic performance of the case demonstrates strong financial viability. With an Internal Rate of Return (IRR) of 30% and a Net Present Value (NPV) of 646 MEUR, the project offers a compelling investment opportunity. As illustrated in **Fel! Hittar inte referenskälla.**, the discounted payback period is approximately 5 years, highlighting a rapid return on investment.

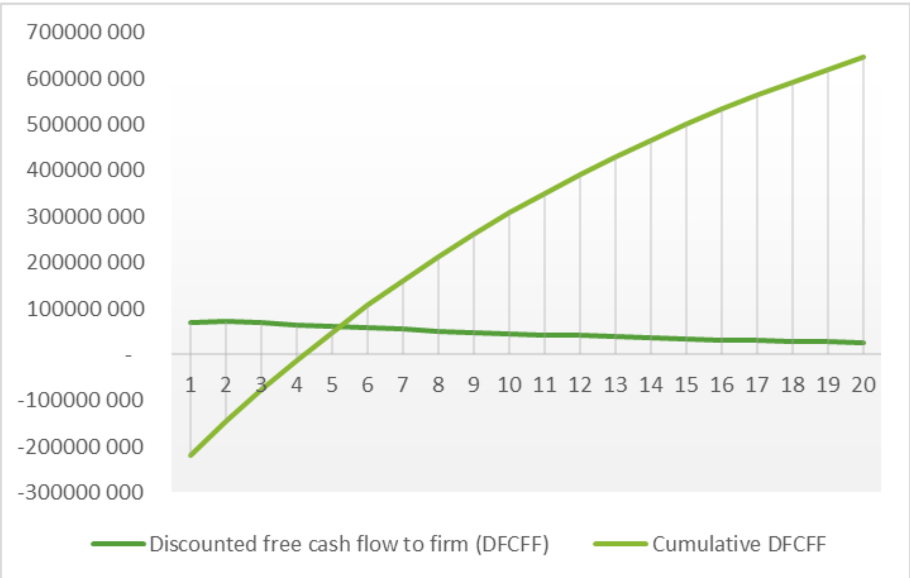

Figure 30 Cashflow analysis for Scenario 1 – lignin valorisation. Discounted payback period is 5 years. y-axis, EUR, x-axis, years.

These metrics emphasize the robustness of the scenario, driven by value-added product streams and market-aligned strategies, ensuring both profitability and competitiveness. The difference between the scenario and base case is shown in Figure 31 and Table 22.

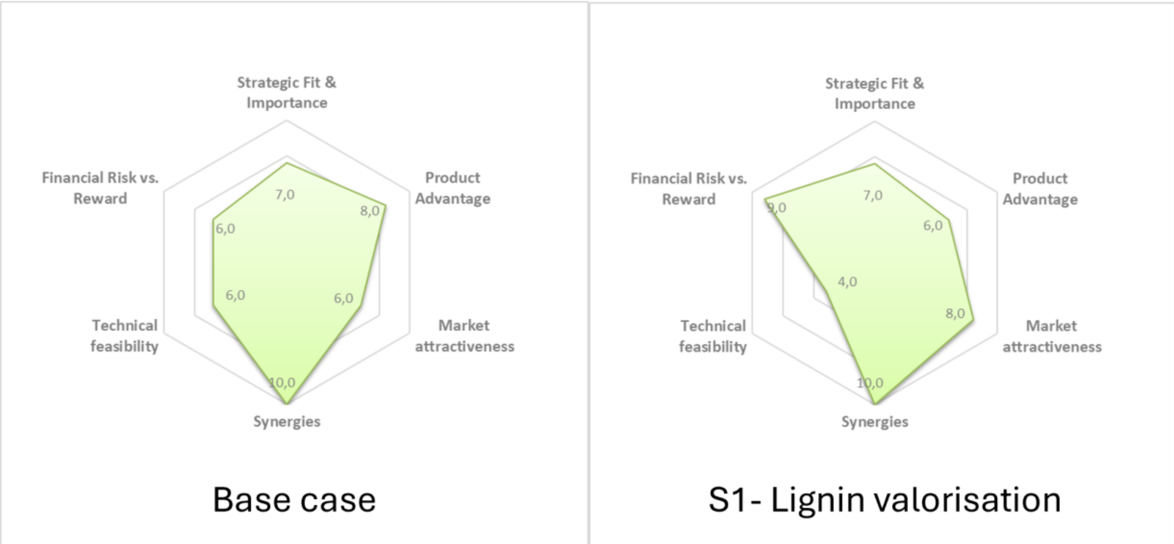

Figure 31 Comparative scoring of (left) base case with total score 43p to (right) scenario 1 – lignin valorisation with total score 44p.

Table 22 Changes in scoring comparing base case and scenario 1

Criteria	Base Case Score	Updated Score	Reason for Change
Financial Risk vs Reward	6	9	Significant financial improvement: IRR increased to 30% compared to 18.9% in the base case, indicating very good returns.
Market Attractiveness	6	8	Lignin valorization diversifies the product portfolio, increases market penetration, and enhances market growth potential.
Technological Feasibility	6	4	Lignin valorization requires new, unproven technologies, reducing the overall technical feasibility.

4.7.2 Scenario 2 – Mild lowering of 2,3- BDO market price

In this scenario the price of 2,3 BDO is reduced to increase market penetration and to potentially stimulate growth. The scenario assumes that the price is reduced from 2500 EUR/ton to 2000 EUR/ton. The economic performance of the case reflects the impact of a strategic price reduction for 2,3-BDO aimed at increasing market penetration and stimulating market growth. By lowering the price from 2500 EUR/ton to 2000 EUR/ton, the scenario achieves an Internal Rate of Return (IRR) of 10% and a Net Present Value (NPV) of 58.5 MEUR, close to breaking even. However, as shown in Figure 32, the discounted payback period extends to approximately 16 years. These metrics highlight the trade-off between achieving long-term market expansion and the immediate financial returns of the investment, indicating a need for careful market strategy alignment to ensure sustainable growth.

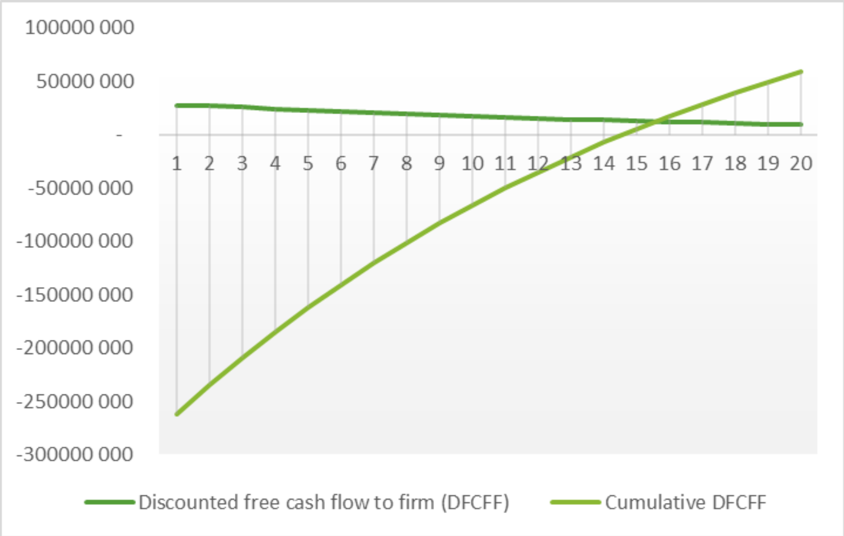

Figure 32 Cashflow analysis for Scenario 2 – lowered 2,3-BDO market price. Discounted payback period is 16 years. y-axis, EUR, x-axis, years

The following aspects changed in this scenario, 1) the scoring on financial risk vs reward was reduced from good returns towards very modest returns, from 6 to 4 (IRR lowered to 10% compared to 18,9% in the base case) and 2) the scoring on market attractiveness for the portfolio increased from 6 to 8 (By moving from a high tier market price for 2,3-BDO to a low tier price we expect a much increased market penetration) (Figure 33) (Table 23).

Table 23 Changes in scoring comparing base case and scenario 2

Criteria	Base Case Score	Updated Score	Reason for Change
Financial Risk vs Reward	6	4	IRR lowered to 10% compared to 18.9% in the base case, indicating a shift from good returns to very modest returns.
Market Attractiveness	6	8	Moving to a low-tier market price for 2,3-BDO is expected to significantly increase market penetration.

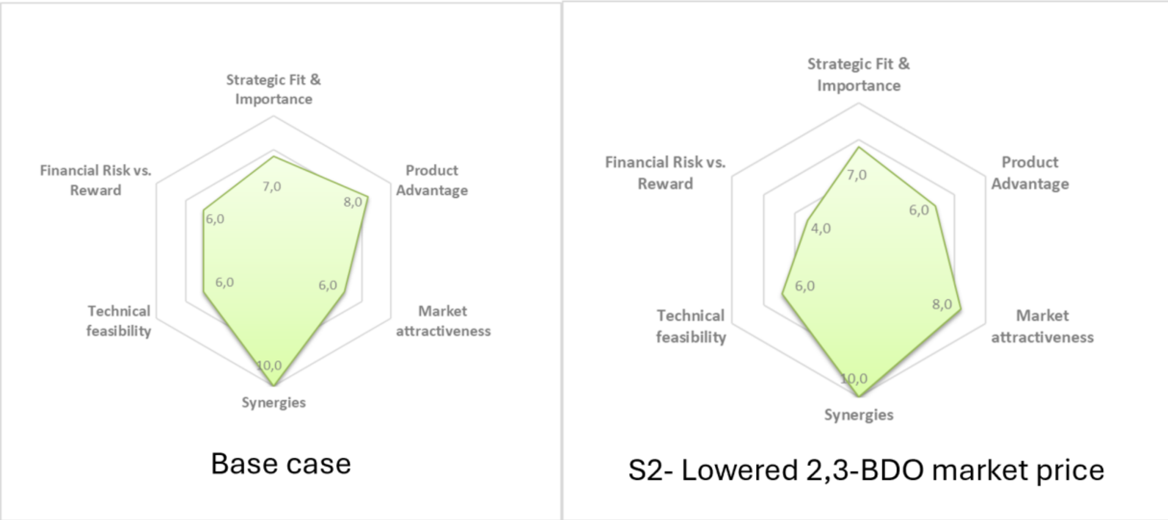

Figure 33 Comparative scoring of (left) base case with total score of 43p to (right) scenario 2 – lowered 2,3-BDO market price with total score of 41p.

4.7.3 Scenario 3 - Very low 2,3-BDO market price

In this scenario the price for 2,3-BDO is lowered from 2500 EUR/ton to 1500 EUR/ton. This would reflect a market price which closer resembles the market price of 1,4-BDO a chemical currently in use for production of biopolymers. Scenario 3 aims to construct a scenario reflecting the potential price demand for a polymer market to facilitate market growth as a biobased polymer component.

The economic performance of the case reflects the impact of a strategic price reduction for 2,3-BDO aimed at increasing market penetration and stimulating market growth by accessing and promoting growth in the biopolymer market. By lowering the price from 2500 EUR/ton to 1500 EUR/ton, the scenario achieves an Internal Rate of Return (IRR) of -3% and a Net Present Value (NPV) of -185 MEUR, a non-viable business caste. These metrics highlight that achieving long-term market expansion and facilitating market growth will require other measures to improve the financial viability of the business case. As shown in Figure 35, Scenario 3 received a score of 40 points, while the financial analysis indicate that the scenario is not financially viable. Therefore, reducing the price of 2,3-BDO to 1500 EUR/ton to make it potentially competitive for use in biopolymers will be evaluated within the combinatory of Scenario 5. The results of the cash flow analysis shows that this approach is not economically feasible on its own (Figure 34).

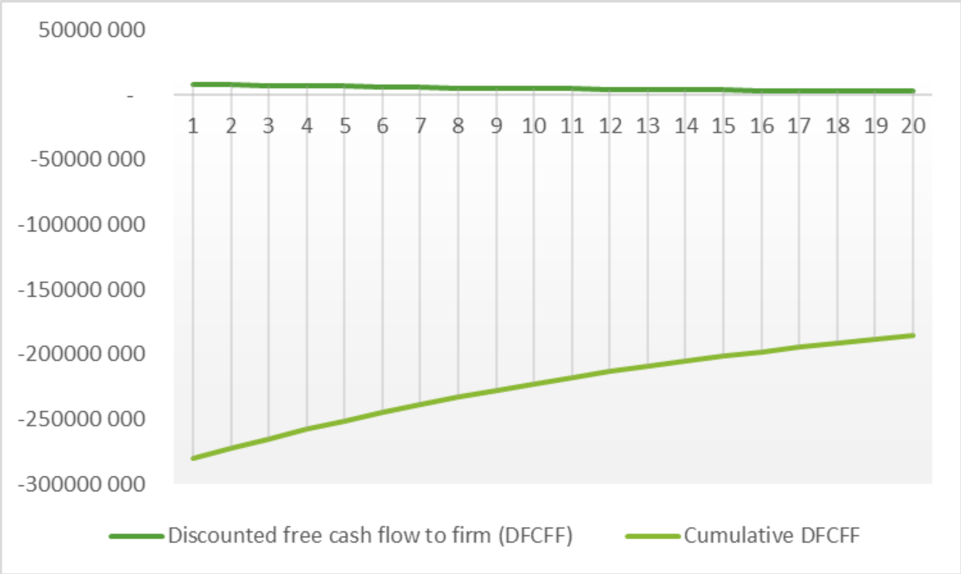

Figure 34 Cashflow analysis for Scenario 3 – lowered 2,3-BDO market price to stimulate market growth. Not financially viable. y-axis, EUR, x-axis, years

The following aspects changed in this scenario, 1) the scoring for product advantage was increased to 8 from a 6 compared to the base case (by reducing price to facilitate both growth and market penetration) 2) the scoring for financial risk vs rewards was reduced to 0 from a 6 compared to the base case (-2% IRR is well below the 8% IRR required to reach break-even and shows that it's not financially viable) (Table 24), rending a total of 40p for scenario 3 (Figure 35).

Table 24 Changes in scoring comparing base case and scenario 3

Criteria	Base Case Score	Updated Score	Reason for Change
Product Advantage	6	8	Reduced price to facilitate growth and market penetration improved the product's competitive advantage.
Financial Risk vs Reward	6	0	-2% IRR, well below the 8% IRR required to break even, indicating the project is not financially viable.

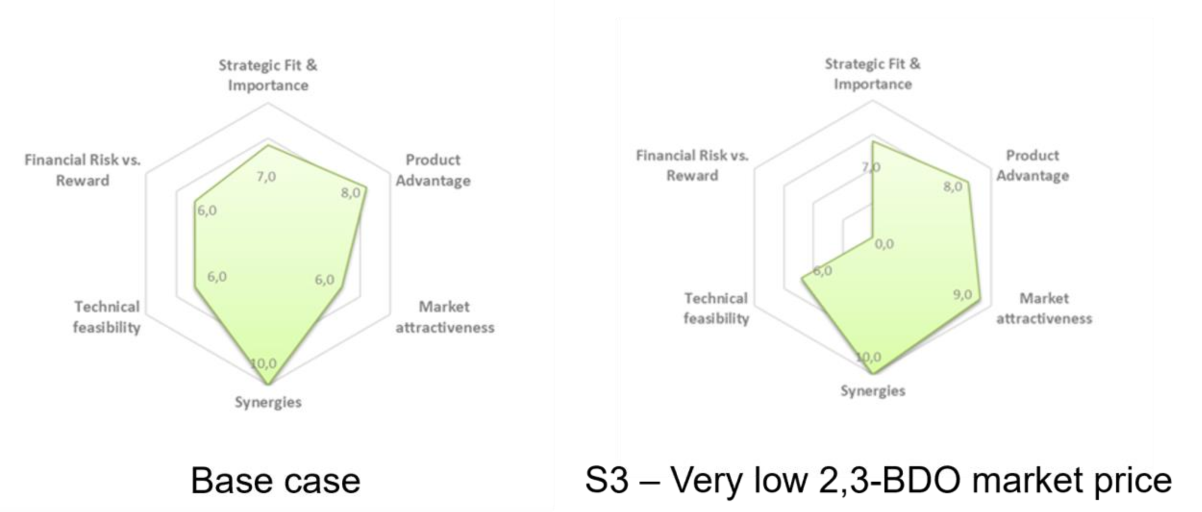

Figure 35 Comparative scoring of (left) base case with total score of 43p to (right) scenario 3 – very low 2,3-BDO market price with total score of 40p.

4.7.4 Scenario 4 - Improved DSP for 2,3-BDO

In scenario 4 a new downstream processing of BDO is added. The scenario assumes a move away from cascade vacuum distillation towards reactive extraction using butanal as solvent. It is assumed that the steam consumption can be roughly 7 times lower for the BDO downstream processing than for base case. It is assumed that recovery rate at 98% for the butanal are achieved and that the volume ratio between BDO and butanal usage in the extractive recovery is 1 to 1. This will drastically reduce the steam consumption - which was the major cost in the downstream processing (Figure 27) - but the chemical costs will increase and result in a slightly reduced overall sustainability (minor effect).

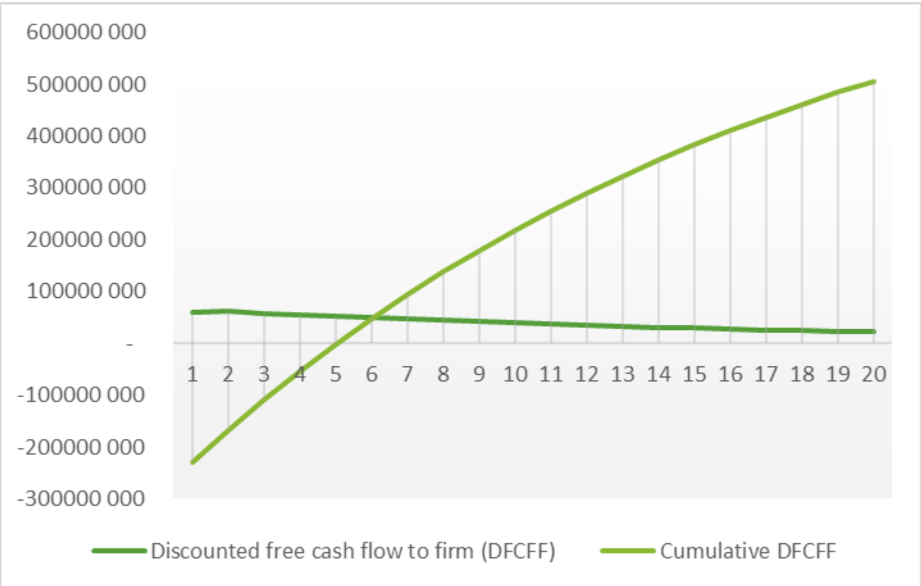

Figure 36 Cashflow analysis for Scenario 4 – improved DSP for 2,3 BDO as process optimization. Discounted payback period is 6 years. y-axis, EUR, x-axis, years

The financial metrics reflect a strong outcome, with an Internal Rate of Return (IRR) of 25.7% and a Net Present Value (NPV) of 506 MEUR. As shown in **Fel! Hittar inte referenskälla.**, the discounted payback period is approximately 6 years, indicating a balance between operational efficiency improvements and financial performance. This scenario underscores the potential of innovative processing methods to enhance profitability while requiring careful consideration of sustainability impacts.

The economic performance of scenario 4 highlights the benefits of adopting a new downstream processing method for 2,3-BDO. By replacing cascade vacuum distillation with reactive extraction using butanal as a solvent, steam consumption for 2,3-BDO downstream processing is reduced by a factor of seven compared to the base case. While the reduced steam consumption significantly lowers energy costs, it is slightly offset by increased chemical costs and potential sustainability trade-offs.

Table 25 Changes in scoring comparing base case and scenario 4

Criteria	Base Case Score	Updated Score	Reason for Change
Financial Risk vs Reward	6	9	IRR increased to 25.7% compared to 18.9% in the base case, indicating a shift from good returns to very good returns.
Technical Feasibility	6	5	Addition of a new downstream process for production lowered the overall Technology Readiness Level (TRL), reducing feasibility.

The following aspects changed in this scenario: 1) The scoring on financial risk vs reward was increased from good returns towards very good returns, from 6 to 9 (*IRR increased to 25,7% compared to 18,9% for the base case) 2*) The Technical feasibility was reduced from 6 to 5 (*the addition of a new downstream process for production will lower the overall TRL*), leading to a total score of 44 points (Figure 37)(Table 25).

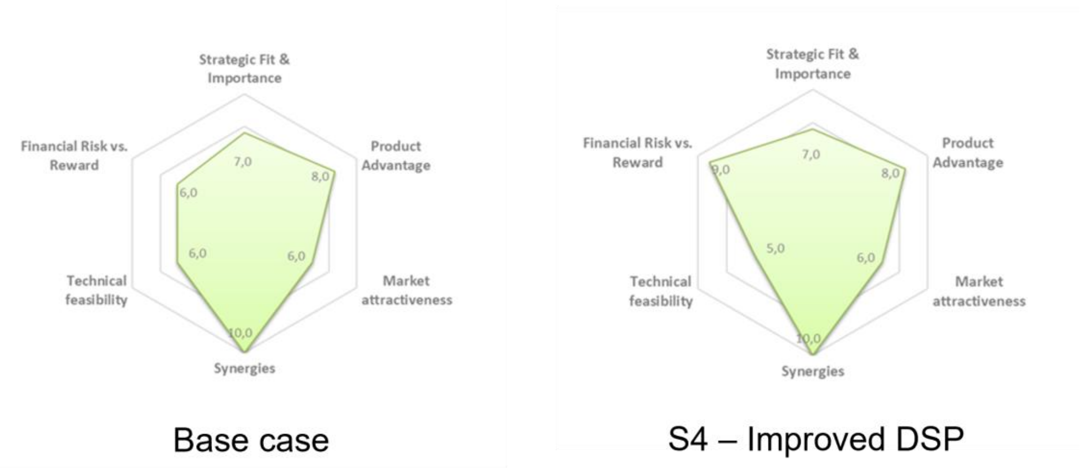

Figure 37, Comparative scoring of (left) base case with total score of 43p to (right) scenario 3 – very low 2,3-BDO market price with total score of 44 p.

4.7.5 Scenario 5 – Lignin valorisation, Low 2,3-BDO market price, Improved DSP

Scenario 5 combines the strategies outlined in Scenario 1 (lignin valorisation), Scenario 3 (very low 2,3-BDO market price), and Scenario 4 (improved DSP) to capture the synergistic effects of multiple measures. By integrating these approaches, the scenario addresses the limitations of Scenario 3, which lacked financial viability when analysed independently, and leverages the enhanced efficiencies and market opportunities provided by the other scenarios. The combined scenario achieves a robust economic performance, with an Internal Rate of Return (IRR) of 24.1% and a Net Present Value (NPV) of 455 MEUR, with a discounted payback period of approximately 6 years (Figure 38).

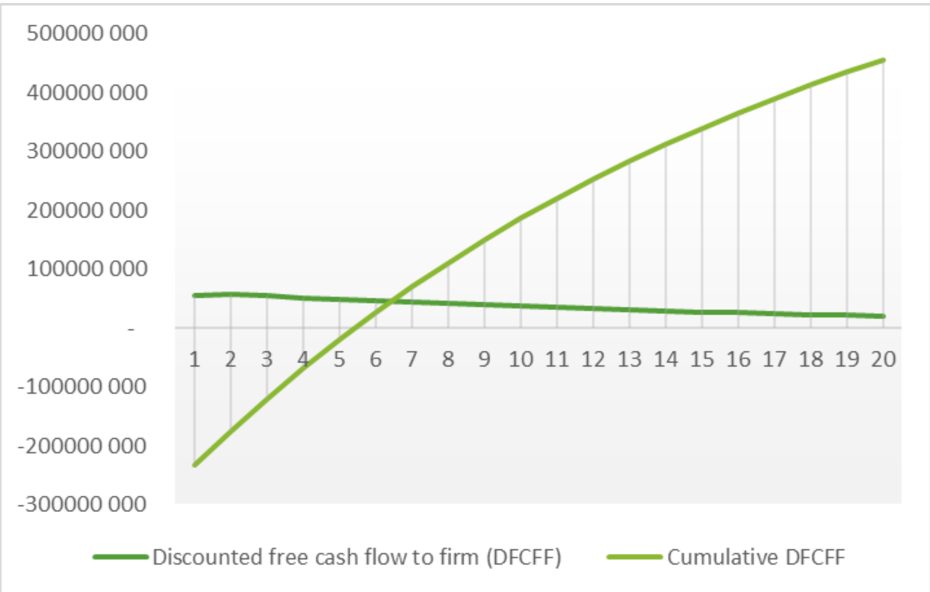

Figure 38 Cashflow analysis for Scenario 5 – lignin valorisation, low 2,3-BDO market price, improved DSP. Discounted payback period is 6 years. y-axis, EUR, x-axis, years

This scenario demonstrates the value of a holistic approach, combining individual measures that, when integrated, result in a financially viable and strategically competitive outcome. However, the cumulative impacts on operational complexity and sustainability metrics require careful monitoring and further optimization. The following aspects changed in this scenario: the scoring on financial risk vs reward was increased from good returns towards very good returns, from 6 to 9 (IRR increased to 24,1% compared to 18,9% for the base case) 2) the scoring on market attractiveness was increased from 6 to 9 (the scenario is diversifying the product portfolio through lignin valorisation, taking measures to increase market penetration by reducing price of 2,3-BDO and increasing market growth potential by meeting expected price demand to access a polymer market) and 3) the technical feasibility was reduced from 6 to 5 (including lignin valorisation and a new DSP of 2,3-BDO the technical feasibility is lowered compared to base case), leading to a total score of 46 points (Figure 39) (Table 26).

Table 26 Changes in scoring comparing base case and scenario 5

Criteria	Base Case Score	Updated Score	Reason for Change
Financial Risk vs Reward	6	9	IRR increased to 24.1% compared to 18.9% in the base case, indicating a shift from good returns to very good returns.
Market Attractiveness	6	9	Diversification of the product portfolio through lignin valorization, price reduction for 2,3-BDO, and increased market penetration by accessing the polymer market.
Technical Feasibility	6	5	Inclusion of lignin valorization and a new downstream process (DSP) for 2,3-BDO reduced technical feasibility.

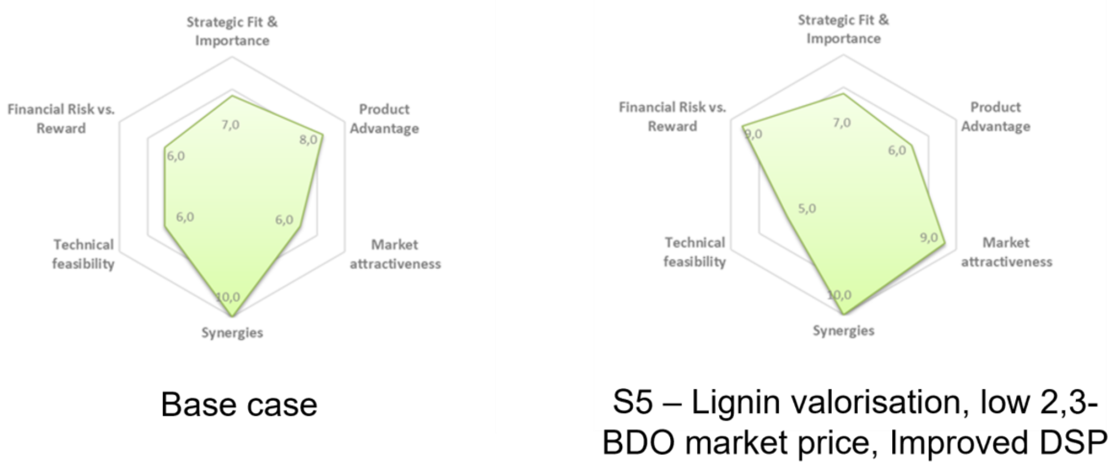

Figure 39 Comparative scoring of (left) base case with total score of 43p to (right) scenario 5 – lignin valorisation, low 2,3-BDO market price and improved DSP, with total score of 46 p.

4.7.6 Evaluation of the Scenarios

The scenario analysis highlights the varied impacts of strategic decisions. Each scenario explored distinct pathways to improve the viability and competitiveness of the biorefinery, with notable trade-off between financial returns, market attractiveness and technological feasibility (Table 27).

Table 27 Overview of results of scenario analysis. Abbreviations: IRR, Internal rate of return, NPV, net Present value, DPP, Discounted payback period

Case	Description	IRR [%]	NPV [MEUR]	DPP [years]	DCDM [score]
Base	Lignin is used for energy recovery	18,9	294	8	43
1	Lignin is valorised to create a more diversified product portfolio	30	646	5	
2	Price of 2,3-BDO lowered from 2500 EUR/t to 2000 EUR/t to increase market penetration	10	58,5	16	44
3	Price of 2,3-BDO lowered from 2500 EUR/t to 1500 EUR/t to increase market penetration and to increase market growth	-3	-185	N.A.	38
4	More effective downstream processing of 2,3-BDO reducing cost by lowering the steam consumption	25,7	506	6	44
5	A combinatory scenario that incorporate scenario 1, scenario 3 and scenario 4	24,1	455	6	46

When comparing scenario 4 and scenario 5, we observe similar financial metrics for the investment, yet the two scenarios differ significantly in their approaches and implications. Scenario 4 focuses solely on cost reduction within the downstream process of 2,3-BDO production. In contrast, scenario 5 builds upon the cost-reduction measures of scenario 4 and incorporates additional strategies, including diversifying the product portfolio through lignin valorization, fostering market growth, and increasing market penetration by reducing the sales price of 2,3-BDO from 2500 EUR/ton to 1500 EUR/ton. Scenario 4 exhibits higher risks due to its narrow business model, it receives a lower score compared to scenario 5 when analysed.

Scenario 5 demonstrates a more balanced and comprehensive strategy, which is reflected in its better score.

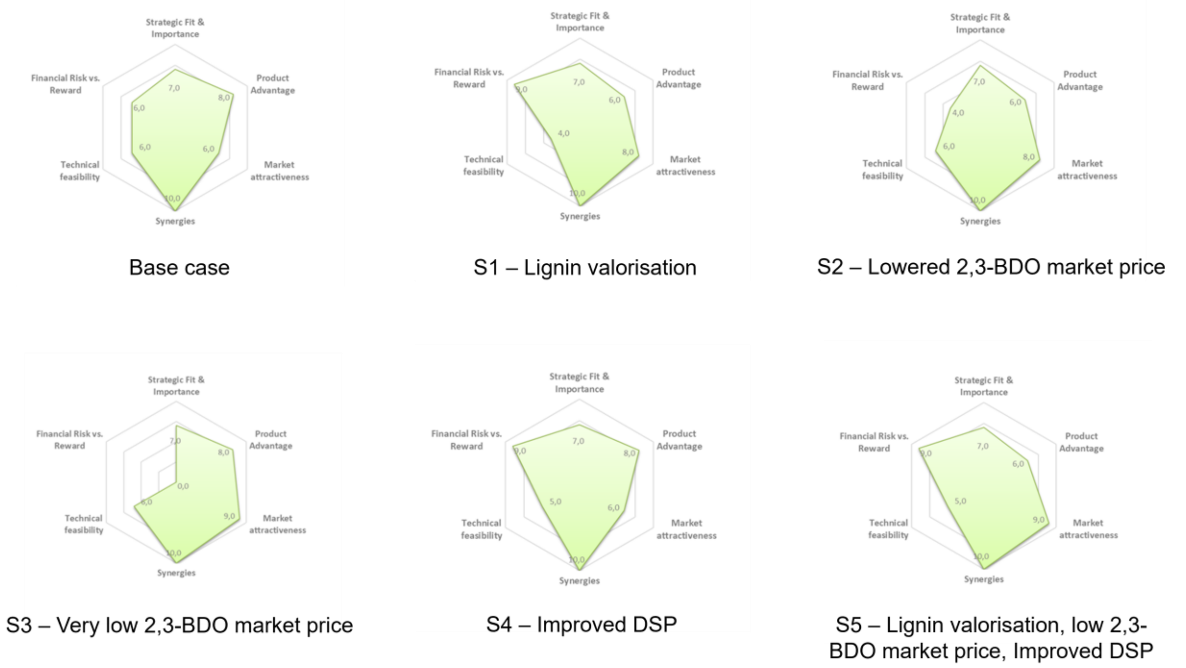

Figure 40 DCDM scores for all scenarios including base case.

Scenario 1: Demonstrates strong financial viability through lignin valorisation, achieving an impressive IRR of 30% and an NPV of 646 MEUR. However, the trade-off is reduced technological feasibility due to the increased complexity of valorising lignin streams.

Scenario 2: Focused on price reduction for 2,3-BDO to increase market penetration, but the economic outcome, an IRR of 10% and an NPV of 58.5 MEUR, reflects modest financial returns, coupled with extended payback periods. The limited immediate profitability makes it less appealing unless paired with broader market strategies.

Scenario 3: Explores further price reductions for 2,3-BDO but fails to achieve financial viability independently.

Scenario 4: Introduces a DSP approach for 2,3-BDO using reactive extraction. This scenario demonstrates strong financial performance (IRR of 25.7% and NPV of 506 MEUR) driven by significant reductions in energy costs, with slight sustainability trade-offs. Scenario 5: Combines the strengths of Scenarios 1, 3, and 4, leveraging lignin valorisation, price adjustments for 2,3-BDO, and advanced DSP. With an IRR of 24.1%, an NPV of 455 MEUR, and a discounted payback period of 6 years, Scenario 5 represents the most balanced and strategically viable approach. It captures synergies from multiple measures, addressing market penetration, product diversification, and operational efficiencies.

Scenario 5 with the highest score of 46 points, performing better than base case (43p) and all other scenarios (Figure 40). This result shows the benefit of a holistic strategy, where integration of lignin valorisation, competitive pricing, and innovative DSP unlocks both economic and market potential, highlighting the importance of an integrated approach to strategy development in biorefinery operations. The scenario 5 delivers robust financial and market outcomes while addressing key operational challenges. By using the MCDM tool the base case has evolved into a business case that has increased market penetration and market growth potential, while creating a more diverse product portfolio. Thereby drastically lowered the market risks, while somewhat increasing the technology risks. The effect of the MCDM analysis and changes to the business case is shown by comparing the cost and income structure of base case (Figure 41) and scenario 5 (Figure 42). An illustration of the scenario 5 business case is shown in (Figure 43).

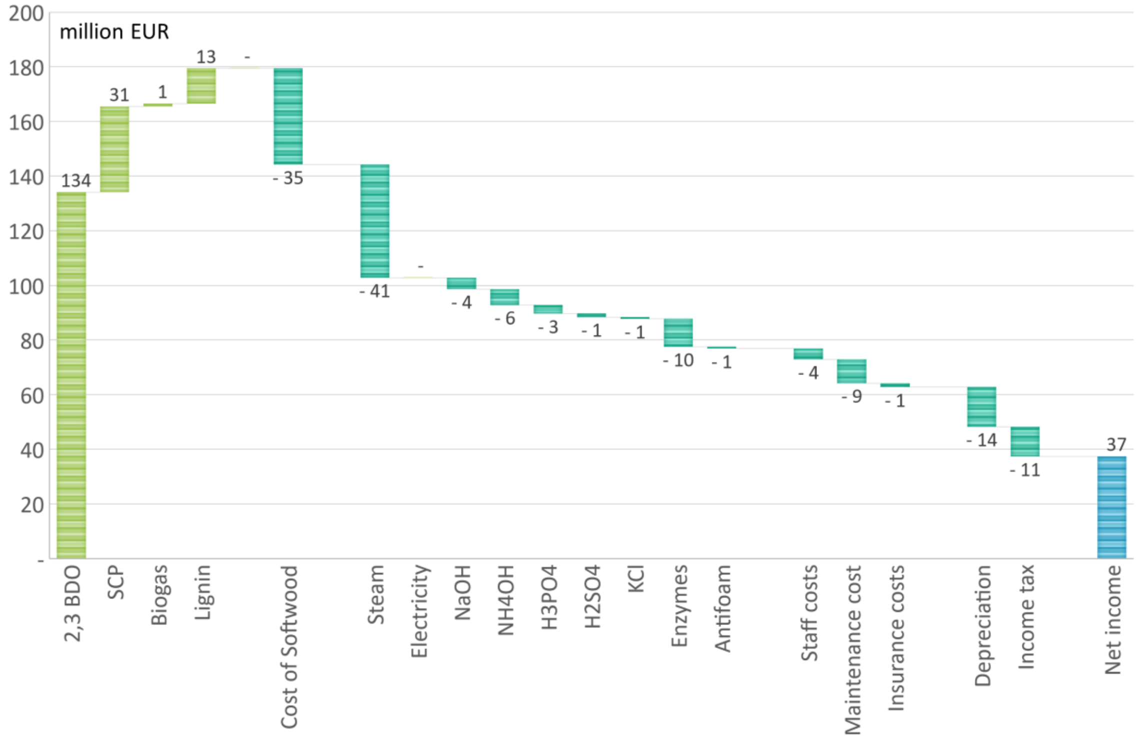

Figure 41 Waterfall diagram of the base case

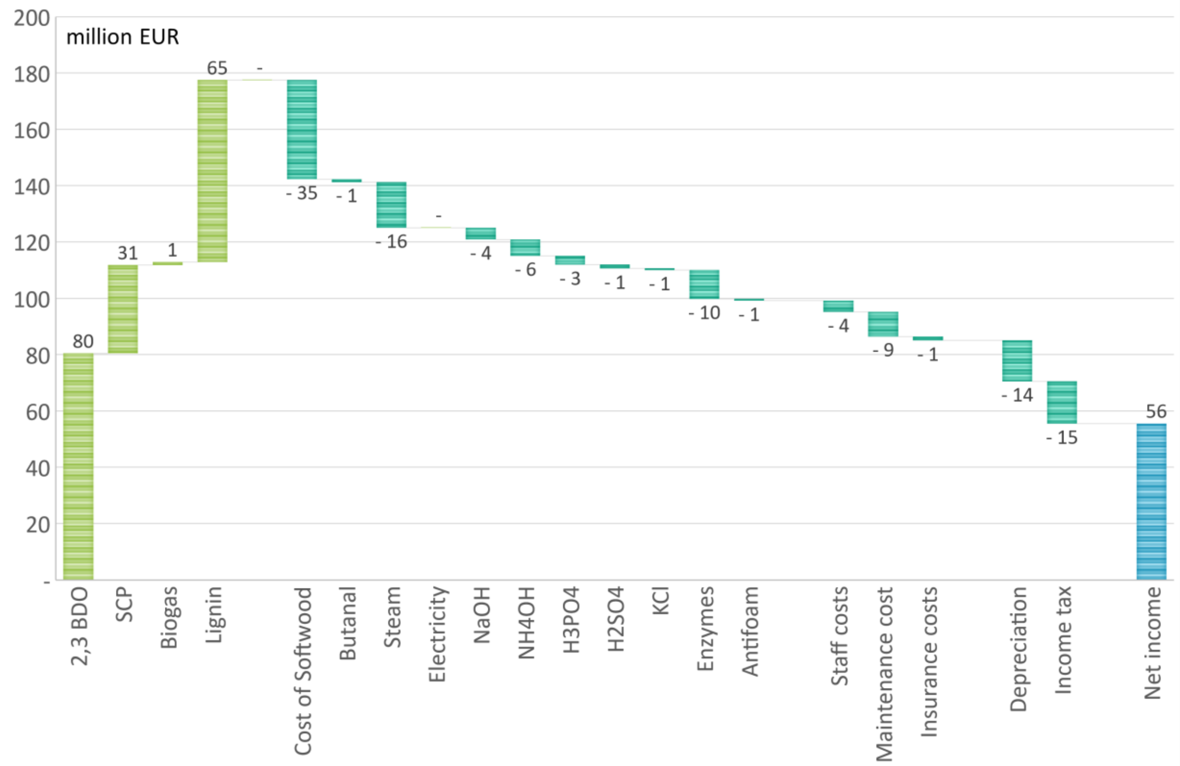

Figure 42 Waterfall diagram of scenario 5

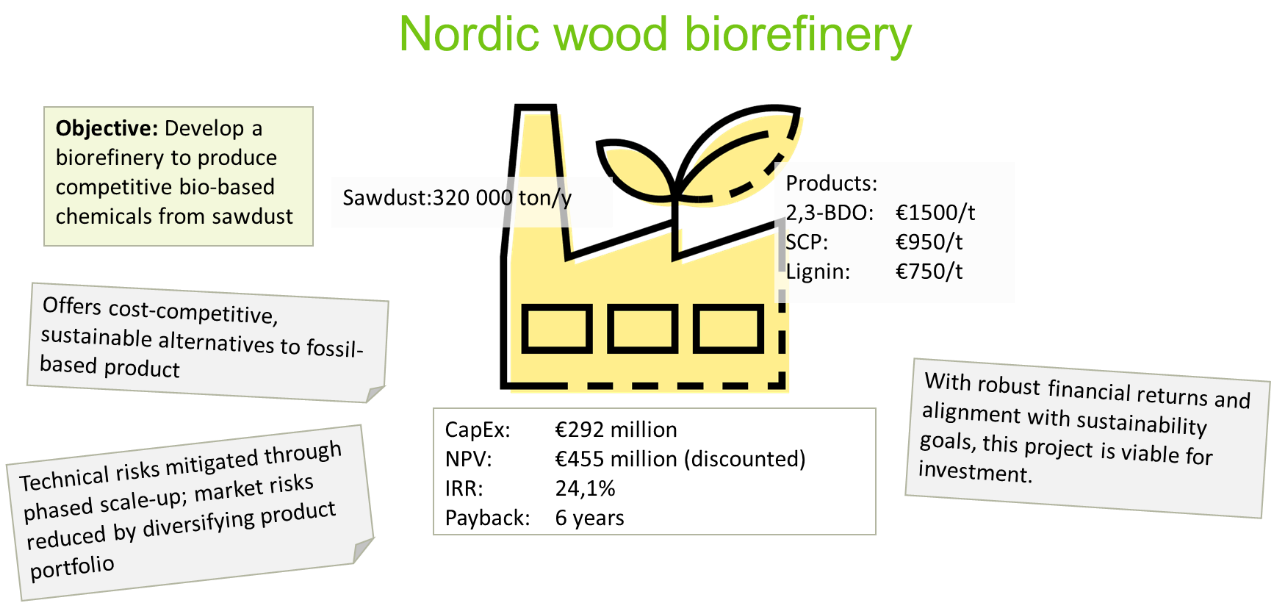

Figure 43 Scenario 5 – winning.

4.8 Conclusions

4.8.1 Multi-Criteria Decision Making (MCDM) tool

The evaluation highlighted the robustness of the Multi-Criteria Decision-Making (MCDM) tool in assessing the scenarios. The tool revealed how key criteria—strategic alignment, market attractiveness, technical feasibility, and potential for reward—interacted to shape overall viability. For example, while the scenario 5 scored higher on market attractiveness, lowered market dependency and potential reward, it also incurred greater risks in terms of technical feasibility. These trade-offs emphasize the importance of aligning project design with market dynamics and technological readiness.

The integration of techno-economic analysis (TEA) and sustainability metrics demonstrated the tool's capacity to address complex decision-making needs. By incorporating diverse evaluation perspectives, MCDM supported data-driven prioritization, enabling stakeholders to align investments with regional and strategic objectives. The universal adaptability of the methodology positions it as a valuable tool for evaluating similar bioeconomy projects in varied contexts.

4.8.2 Case study

The analysis reinforced the need for flexible strategies that can adapt to evolving market conditions. While the base case provides a reasonably stable foundation, the alternative scenarios offer a pathway to greater long-term competitiveness, provided the technology risks can be mitigated. This dual approach allows stakeholders to navigate uncertainties while maximizing potential returns.

Key insights

- **Lignin Valorisation Enables Competitive Pricing for Biobased Products**: Scenario 5 demonstrates that by valorising lignin into high-value applications and optimizing downstream processing of 2,3-BDO, achieving and exceeding fossil-based pricing for 2,3-BDO is feasible. The pricing of 2,3-BDO can approach levels comparable to 1,4-BDO, making it a competitive alternative in the market.
- **Trade-Off Between Market Opportunities and Technical Challenges**: Lignin valorisation enhances several key evaluation criteria, including product advantage, financial performance, and market attractiveness. However, it concurrently lowers technical feasibility due to the advanced processes and market dependencies required for high-value lignin products.
- **Policy Gaps in Biobased Chemicals and Materials**: The biobased chemicals and materials sector lacks the robust market incentives afforded to biofuels. This

discrepancy persists despite the European High-Level Group identifying the need for stronger policy support for biobased industries over 12 years ago. Addressing this gap is crucial for fostering market growth and large-scale commercialization.

- **Dynamic Scenario Adaptability:** The evaluation underscores the importance of strategic flexibility. While the Base Case offers a lower-risk pathway from a technological perspective, it does not mitigate market risks as effectively. The scenarios are designed to reduce market risks while aiming for higher market value, increased market penetration, and enhanced competitiveness. The scenarios further build on this by presenting opportunities for greater market rewards, requiring proactive management of technical challenges and alignment with evolving market dynamics.
- **Regional Advantages as a Key Enabler**: Leveraging the regional infrastructure and biomass availability in Västernorrland proved instrumental in supporting the biorefinery concept. Proximity to sawmills and regional expertise provided critical support for the feasibility.

In conclusion, the scenario-building and evaluation underlined the economic and strategic feasibility of the proposed biorefinery. All but one scenario is viable, but the choice between them depends on the project's risk tolerance and strategic objectives. The alternative scenarios represent a compelling opportunity to capture higher market value, albeit with associated risks that require careful management through innovation, policy alignment, and market development.

5 APPENDIX A - PRODUCT DEVELOPMENT THEORY

5.1 THE PRODUCT DEVELOPMENT PROCESS

New Product Development (NPD) is a set of design, engineering, and research processes which combine to create and launch a new product to market. Unlike regular product development, NPD is specifically about developing a brand-new idea and seeing it through the entire product development process. In today's competitive market, the ability to offer products that meet customers' needs and expectations has never been more important. Customer requirements and behaviours, technology, and competition are changing rapidly, and businesses cannot rely on existing products to stay ahead of the market. They need to innovate, and that means to develop and successfully launch new products.

NPD refers to the complete process of bringing a new product to market. This can apply to developing 1) an entirely new product, 2) improving an existing one to keep it attractive and competitive, or 3) introducing an old product to a new market.

The emergence of new product development can be attributed to the needs of companies to maintain a competitive advantage on the market by introducing new products or innovating existing ones. While regular product development refers to building a product that already has a proof of concept, new product development focuses on developing an entirely new idea - from idea generation, to development, to launch.

5.1.1 The 7 stages of product development

When it comes to new product development, each journey to a finished product is different. Although the product development process can vary from company to company, it is possible to break it down into seven main stages (Figure 44)[37].

Figure 44 The 7 phases of new product development

[37] https://maze.co/collections/product-development/new/

Idea generation

Idea generation involves brainstorming for new product ideas or ways to improve an existing product. During product discovery, companies examine market trends, conduct product research, and dig deep into users' wants and needs to identify a problem and propose innovative solutions.

A SWOT Analysis is a framework for evaluating your Strengths, Weaknesses, Opportunities, and Threats. It can be a very effective way to identify the problematic areas of your product and understand where the greatest opportunities lie.

There are two primary sources of generating new ideas. Internal ideas come from different areas within the company - such as marketing, customer support, the sales team, or the technical department. External ideas come from outside sources, such as studying your competitors and, most importantly, as feedback from your target audience.

Some methods you can use are:

- Conduct a market analysis
- Work with product marketing and sales to check if your product's value is positioned correctly
- Collect user feedback with interviews, focus groups, surveys, and data analytics
- Run user tests to see how people are using your product and identify gaps and room for improvement.

Ultimately, the goal of the idea generation stage is to come up with as many ideas as possible while focusing on delivering value to your customers.

Idea screening

This second step of new product development revolves around idea screening all your generated ideas and picking only the ones with the highest chance of success. Deciding which ideas to pursue and discard depends on many factors, including the expected benefits to your consumers, product improvements most needed, technical feasibility, or marketing potential.

The idea screening stage is best carried out within the company. Experts from different teams can help you check aspects such as the technical requirements, resources needed, and marketability of your idea. Logic trees can help you visualize and chart the best path to your desired outcome.

Concept development and testing

All ideas passing the screening stage are developed into concepts. A product concept is a detailed description or blueprint of your idea. It should indicate the target market for your product, the features and benefits of your solution that may appeal to your customers, and the proposed price for the product. A concept should also contain the estimated cost of designing, developing, and launching the product. Developing alternative product concepts will help you determine how attractive each concept is to customers and select the one that would provide them the highest value. Once you have developed your concepts, test each of them with a select group of consumers. Concept testing is a great way to validate product ideas with users before investing time and resources into building them. Concepts are also often used for market validation. Before committing to developing a new product, share your concept with your prospective buyers to collect insights and gauge how viable the product idea would be in the target market.

Marketing strategy and business analysis

Now that you have selected the concept, it is time to put together an initial marketing strategy to introduce the product to the market and analyse the value of your solution from a business perspective:

- The marketing strategy serves to guide the positioning, pricing, and promotion of your new product. Once the marketing strategy is planned, product management can evaluate the business attractiveness of the product idea.
- The business analysis comprises a review of the sales forecasts, expected costs, and profit projections. If they satisfy the company's objectives, the product can move to the product development stage.

Product development

The product development stage consists of developing the product concept into a finished, marketable product. Your product development process and the stages you will go through will depend on your company's preference for development, whether it is agile product development, waterfall, or another viable alternative.

This stage usually involves creating the prototype and testing it with users to see how they interact with it and collect feedback. Prototype testing allows product teams to validate design decisions and uncover any flaws or usability issues before handing the designs to the development team.

Test marketing

Test marketing involves releasing the finished product to a sample market to evaluate its performance under the predetermined marketing strategy.

There are two testing methods you can employ:

- Alpha testing is software testing used to identify bugs before releasing the product to the public,
- Beta testing is an opportunity for actual users to use the product and give their feedback about it.

The goal of the test marketing stage is to validate the entire concept behind the new product and get ready to launch the product.

Product launch

At this point, you are ready to introduce your new product to the market. Ensure your product, marketing, sales, and customer support teams are in place to guarantee a successful launch and monitor its performance.

Here are some aspects to take care of in this phase:

- Customers: Understand who will be making the final purchasing decisions and why they will be purchasing your product. Create buyer personas and identify their roles, objectives, and pain points,
- Value proposition: Identify what makes you different from the competition and why people should choose to buy your product,
- Messaging: Determine how you will communicate your product's value to potential customers,
- Channels: Pick the right marketing channels to promote your products, such as email marketing, social media, SEO, and more.

You will need to constantly track and measure the success of your product launch and adjust if it does not achieve the desired goals.

5.1.2 Phase gate analysis applied to bioproducts

An example of the implementation of the phase gate process to biorefineries in the paper industry is presented by the work of E. Johannesson (2006)[38]. The objective with a Stage-Gate Companies or divisions can involve different number of Stages, usually between three to seven (Cooper, 1990)[39]. Figure 45 illustrates a typical 5-Stage process, and each stage consists of prescribed activities and a cross-functional inclusion of employees. The workflow is to break down the process of project development into a predetermined set of stages. Before

[38] Johannesson, E. (2016). Implementing a Stage-Gate Process for R&D and Innovation Projects- Challenges and Enablers.

[39] Cooper, R. G., 1990. Stage-Gate Systems: A New Tool for Managing New Products. Business Horizons.

entering a new stage, the project needs to pass through a checkpoint, a “Decision Gate” where a Go/Kill/Hold/Recycle decision is taken[53].

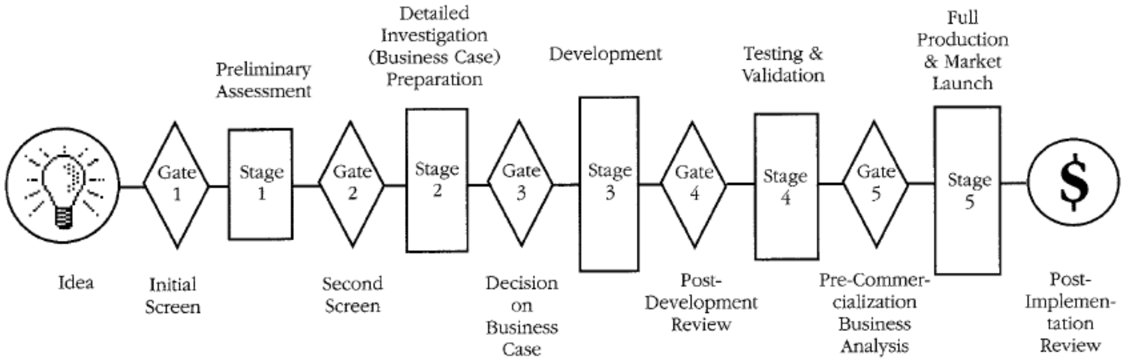

Figure 45 Overview of Cooper Stage-Gate Process[55]

Product innovation often requires involvement of cross-functional specialty units, both within the affected division and across the organization. Integration of knowledge will allow the product innovation to be designed, developed, and finally launched[40]. The aim with multifunctional inclusion of experiences is to keep the project moving forward at a higher pace. The comparative contrast would be having one Stage for each activity such as marketing or technical investigations[41]. As the required resource investment increases, as well as the amount of information, for each Stage as the project passes through Gates, risk is managed. Each Gate is supposed to serve as a quality checkpoint and include “must-meet” project requirements and “should meet” desirable characteristics[54]. The input to each Gate is the deliverables that the project leader is responsible for delivering within the ongoing Stage. The must-meet criteria are the variables the project will be judged on and needs to be fulfilled to pass the Gate. Should-meet characteristics are not as obligatory but can make a difference if resources are limited. The decisions during the Gate make the output, typically a Go/Kill/Hold/Recycle decision and a defined and accepted action plan for the upcoming Stage[42]. The decision makers in the Gates are usually cross-functional senior management from different units responsible for the resources the projects require[54]. The decision makers

[40] Dougherty, D. et al., 2013. Whose Time is It? Clock-time Pacing and Event-time Pacing in Complex Innovations. *Management & Organizations Review,* 9(2), pp. 233-263.

[41] Cooper, R. G. & Kleinschmidt, E. J., 1993. Stage Gate Systems for New product Success. *Marketing Management,* pp. 20-29.

[42] Cooper, R. G., 1990. Stage-Gate Systems: A New Tool for Managing New Products. *Business Horizons.*

can also be referred to as "Gate-keepers". The project leader is the person responsible for carrying the process through the different Stages and must be aware of the demands and requirements obligatory to pass each Gate (Cooper, 1990)[55].

In summary, the description of the phases and the gates considered in the original Cooper model is the following:

Ideation phase consists in the formulation of the first idea.

- **Gate 1**: Initial screen, in this gate the project idea is evaluated based on strategic alignment, project feasibility, magnitude of opportunity, differential advantage, synergy with company core business, resources available and market attractiveness.

Stage 1: Preliminary assessment, in which project costs and timeframe are analysed, together with market size, potential and acceptance.

- **Gate 2**: Second screen, in gate 2 a simple financial assessment is calculated.

Stage 2: Definition, in this phase customer needs, aspirations and preferences are better analysed and measured; a competitive analysis is performed; a technical assessment is assigned to evaluate the do-ability of the project; intellectual property landscaping is realized; financial analysis detail is deepened.

- **Gate 3**: Decision on business case, the financial model is analysed together with definition of the market, product concept, positioning strategy and agreement of desired product benefits. During Gate 3, plans regarding development, operations and marketing are reviewed and approved.

Stage 3: Development, stage 3 consists of continuous development of the product as well as extended work with the operational, marketing and financial plans. During Stage 3 the IP-landscaping is revised and finished.

- **Gate 4**: Post development review. The financial plan is revised with the new data and marketing and operational plans are reviewed in advance for future execution.

Stage 4: Validation. In this phase a series of activities are performed, as for example in-house product tests, user trials, pilot production, pretesting of the market and finally a revision of the financial analysis.

- **Gate 5**: Pre-commercialization decision. Gate 5 is also the final point where the project can be killed. Important inputs are the results of the validation Stage, financial projections, the final revisions, and approvals of both operations- and marketing plans.

Stage 5: The last Stage includes implementation of the marketing launch plan and the operations plan.

- **Post-implementation review**: After commercialization, when the developed product is considered a fixed member in the organization's line, it is time for a post-implementation review. At this point, the project and the developed products will be reviewed both with a critical audit and with a summary of learnings during the project work. The critical audit includes the result of all the data put in the project, such as costs, profits, timing and the products performance. Learnings of the project group's strengths, weaknesses and improvement areas are documented and marks the end of the project.

5.1.3 Product development process in the bioeconomy

In Figure 46 a scheme is displayed which explains how the product development interacts with the current strategy of the company and the current product portfolio. Of the different product ideas which are mainly generated in the labs of the company by the R&D Department, only some ideas are selected. This process consists of the development of a product Pipeline (Figure 46, marked box). This involves identifying the types of products that are most likely to succeed in the market, as well as the resources and processes needed to bring those products to market. This may involve conducting market research, analysing customer needs and preferences, and identifying potential competitors. Once a product pipeline strategy has been developed, it can be used to guide the development of individual products and ensure that they align with the overall strategic vision of the company. In this context the Innovation strategy (Figure 46, marked box) can be driven by the stage gate method which has previously been introduced and that for the case of bioeconomy products is simplified in 3 gates.

Figure 46 Product development process (RISE Processum illustration)

6 APPENDIX B BIOMASS ASSESSMENT METHODS

With any biobased business case, the feedstock is a key factor - that there are enough volumes for the process and of sufficient quality. Feedstock availability in terms of biomass or biomass by-products can be divided into its theoretical and practical availability, which will be subject to geographic location and availability of national resources, databases for monitoring.

6.1 THEORETICAL AVAILABILITY

To estimate the forest surface of European regions the Corine Landcover data can be used. According to the European Environmental Agency: “the Coordination of information on the environment (Corine) is an inventory of European land cover split into 44 different land cover classes”[43]. CORINE Land Cover (CLC) is one of the projects in CORINE (Coordination of Information on the Environment), which was initiated by EU with the aim to facilitate the planning and implementation of the EU environmental policy. Corine has been historically used as an input in more complex model aiming at the estimate of forest biomass and carbon stock[44]. This corresponds to the theoretically available biomass, while the practically obtainable quantity is determined by the application of sustainable forest management practices[45]. To showcase the tool, data from Sweden has been used to demonstrate the tool but it is applicable to any region of Europe.

6.1.1 Corine Forest Landcoverage in County of Västernorrland

The complete distribution of forests in the county of Västernorrland, in Northern Sweden, has been traced by using QGIS software coupled with Corine Land Cover maps[46]. QGIS functions as geographic information system (GIS) software, allowing users to analyse and edit spatial information, in addition to composing and exporting graphical maps.

[43] https://www.eea.europa.eu/en/about/contact-us/faqs/what-is-corine-land-cover

[44] Barredo, J. I., San-Miguel-Ayanz, J., Caudullo, G., & Busetto, L. (2012). A European map of living forest biomass and carbon stock. Reference Report by the Joint Research Centre of the European Commission. EUR–Sci. Tech. Res, 25730(4), 5.

[45] Latterini F, Stefanoni W, Venanzi R, Tocci D, Picchio R. GIS-AHP Approach in Forest Logging Planning to Apply Sustainable Forest Operations. Forests. 2022; 13(3):484. https://doi.org/10.3390/f13030484

[46] https://www.lantmateriet.se/en/geodata/geodata-products/international-cooperation/corine-land-cover/

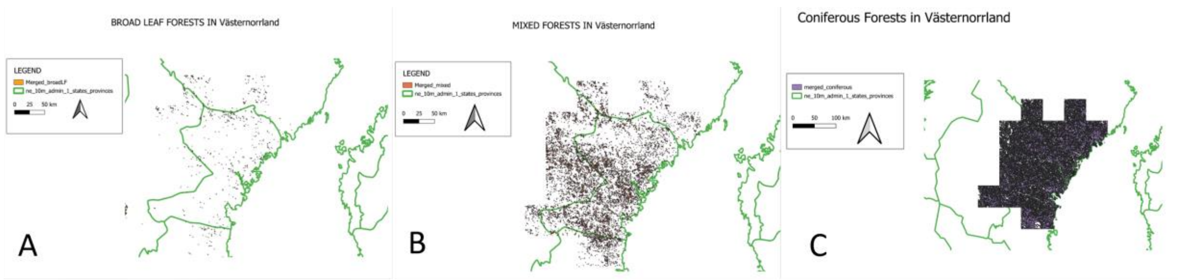

Figure 47 Corine Forest land coverage of county of Västernorrland, a) share of broad leaf forests, b) share of mixed forest, and c) share of coniferous forest.

The coverage of broad leaves forests is very reduced in the county of Västernorrland (Figure 47 A), while the coverage of mixed forests is larger, predominantly through to birch trees (Figure 47 B). Birch has for a long time been taken down to promote monocultures, however this practice is long outdated and nowadays birch trees are left for both the wood and biodiversity. However, what is clearly predominant forest type category is coniferous forests, composed of pine and spruce (Figure 47 C).

6.2 PRACTICAL AVAILABILITY

Northern Sweden is defined by its vast forest resources, cold climate, and low population density. Forests dominate the bioeconomy, covering 67% (148,920 km²) of the region's 221,800 km² land area. The total forest stock is 1,314 million m³, growing annually by 45 million m³, while average annual harvests reach 31 million m³. Approximately 20% (42,990 km²) of productive forest land is protected, with additional areas voluntarily set aside by private forest owners. Imported roundwood also supplements the regional market.

The forest industry has been central to northern Sweden for centuries, initially producing ships and tar. Industrial development accelerated in the 19th century with sawmills and technologies to convert forest biomass into pulp, paper, fuels, and textiles. Since 1903, Swedish law has mandated reforestation after logging, a principle that, combined with improved forestry methods, has doubled forest biomass since 1923, despite increased harvesting. Sweden is now the world's fifth-largest exporter of forest products, with 80% of output exported.

The efficient use of the entire tree follows a cascading principle: the best wood becomes sawn timber, smaller parts and by-products feed pulp and paper production, and residues like branches, treetops, bark, and sawdust are used for energy recovery (Figure 48). Sawn timber, critical to the bioeconomy, provides most forest owners' income, making efficient sawmills essential. Meanwhile, the paper industry has adapted to digitalization by focusing on packaging and tissue production, while graphic paper has declined. Swedish industries have led in transitioning to high value bioproducts. Many pulp mills now operate as advanced biorefineries, converting residues into materials like plastics, chemicals, fuels, and textiles. Innovations continue as efficiency improves, maximizing value from Sweden's vast forest resources.

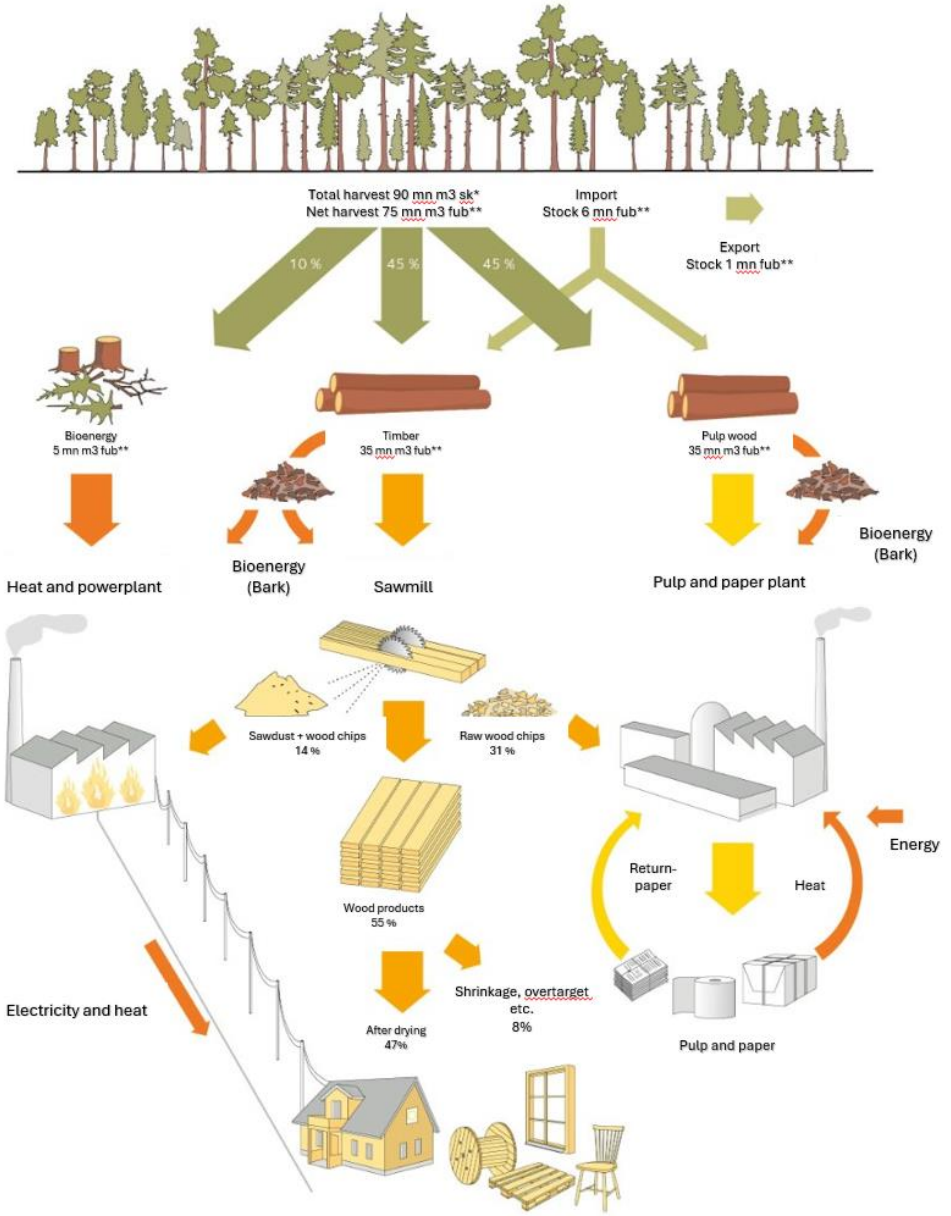

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Figure 48 The value chain of the forests from tree to timber industry, pulp and paper industry, and residue for bioenergy production for energy recovery (*Svenskt trä*)

Yet, there are underutilized forest by-products from a biobased product perspective. Three abundant feedstocks residual feedstocks are *logging residues*, known as top and branches (*in Swedish, Grenar Och Toppar, abbreviated: GROT*), sawdust and wood chips from sawmills and bark from debarking at pulp and paper mills.

Logging residues of the logging industry are dispersed in large areas of the harvested areas, it can be compared to the straw of agricultural residues. The costs needed to collect dispersed residues are always higher respect to the costs needed to collect residues which are localised adjacent plants.

6.2.1 Practical availability of logging residues

Once the quantity available of the theoretical availability of feedstock has been estimated, the practical availability must be estimated. For example, when assessing biomass availability from boreal forests in a region, e.g. county of Västernorrland in Sweden, it is essential to consider existing studies on biomass potential availability and growth modelling of forestry above-ground biomass. These studies have explored various aspects related to forest biomass, as documented in the literature[47,48].

However, here the focus lies on practical biomass availability, which in this case would correspond to a volumes available with the annual felling of trees, which for example can be found national forestry websites, e.g. the Swedish Forest Agency (Skogsstyrelsen) website[49].

Harvesting of logging residues: The harvesting of branches and tops for energy purposes on the final felled area was carried out on average on 81,000 hectares per year during the period 2018–2022; corresponding to approximately 33 % of the total harvested area.

The practice of harvesting branches and tops declined until 2015, especially in north of Sweden and is still more common in southern based Götaland and Svealand than in northern Sweden, Norrland: in Götaland, during the period 2018–2022, branches and tops was extracted on 64 percent of the final felled area and in Svealand on 44 percent of the area. In Southern Norrland and Northern Norrland, the corresponding proportions were 19 and 7 percent, respectively.

In north of Sweden there is today a surplus of tops and branches. The surplus amounts to nearly 14 TWh per year, while sustainably harvesting around 21 TWh of logging residues annually is feasible (the degradation of the tops and branches contribute to nutrients and

[47] Thurner, M., Beer, C., Santoro, M., Carvalhais, N., Wutzler, T., Schepaschenko, D., ... & Schmullius, C. (2014). Carbon stock and density of northern boreal and temperate forests. *Global Ecology and Biogeography*, *23*(3), 297-310.

[48] Avitabile, V., & Camia, A. (2018). An assessment of forest biomass maps in Europe using harmonized national statistics and inventory plots. *Forest ecology and management*, *409*, 489-498.

[49] https://www.skogsstyrelsen.se/en/statistics/subject-areas/felling/

minerals to the soil as it decomposes, benefiting biodiversity). Through to mild winters the early 10' the market declined in the north and with that the logistic system disappeared. What needs to be managed today is rebuilding the capacity for machinery and logistics systems in the region. The later has found a new interest in recent years following increase in energy prices and a predicted higher demand of electricity in the north of Sweden.

The amount of residual feedstock depends on the type of species the residues come from i.e logging residues volumes are dependent on the tree species and felling technique. Table 28 summarizes the potential yields of tops and branches yields per hectare based on available literature.

Table 28 Amount of residual feedstock (tops and branches) per tree species[50]

Species	Yields (t d.m./ha)
Scots pine	24.5
Norway Spruce	11.7
Silver Birch	28.6
Black Alder	15.8

6.2.2 Practical availability of sawmills by-products

Feedstocks that are concentrated to a production site have several practical aspects to consider when assessing the practical availability of the residual feedstock, which may differ from the those collected in the field.

As with the volumes of logging residues that are dependent of tree species and handling process, the volumes of by-products from sawing wood at a sawmill are also connected to the volume of the sawmill processes and species[51] For examples, from roundwood volume, around 50% becomes sawn wood products, 20% sawdust, 10% bark, 20% chips and 1 ton shavings/10m^{3}sw product[52].

While logging residues may struggle with a largely heterogeneous product fraction of variations in branches, tops, needles, leaves, bark etc, the sawmill by-products will most often be a homogenous fraction.

[50] KURVITS, Vahur, et al. Assessment of load and quality of logging residues from clear-felling areas in Järvselja: a case study from Southeast Estonia. Central European Forestry Journal, 2020, vol. 66, no 1, p. 3-11.S

[51] Fridh, M. & Christiansen, L. (2015). Rundvirkes- och skogsbränslebalanser för år 2013 – SKA 15. (SKA 15). Jönköping. https://www.skogsstyrelsen.se/globalassets/statistik/skogligakonsekvensanalyser/rundvirkes--och-skogsbranslebalanser-for-ar-2013-ska-meddelande-3-2015.pdf [2020-08-17]

[52] Staffas, L., Hansen, K., Sidvall, A. & Munthe, J. (2015). Råvaruströmmar från skogen-tillgång och samband. (C 116). Stockholm: Svenska Miljöinstitutet.

To assess the availability of sawdust produced by sawmills and pulp mills in the country of Västernorrland, data was elaborated from the study of Persson 2021[53]. To understand the analysis performed we need to first describe what we classify as unrefined forestry by-products.

Oftentimes fractions/assortments for sawmill by-products encompass cellulose-chips, dry chips, sawdust, bark, and shavings (Figure 49) and vary in quality by:

- Variation in volumes and quality dependent on sawn materials between sites
- Variation by season
- Variation by storage time of the byproducts (seen as waste and stored outside)

Figure 49 Assortments of sawmill by-products, A = Bark, B = Cellulose-Chips, C = Sawdust and D = Shavings[54]

6.2.3 Cost estimate

An in-house optima strategy has been developed to identify biomass costs by use of linear optimization models[55]. The model showcases that the real optimization problem is characterized as a resource problem. This means there is a finite number of resources for the demand units. The objective function has calculated the total minimized cost of transport for each assortment from supply units to demand units.

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[53] Persson, L. (2022). Mapping the market of unrefined forest industry by-products in northern Sweden.

[54] Grabbe, S. (2020). Assortments [Unpublished]. SEIZE Media.

[55] Persson, L. (2022). Mapping the market of unrefined forest industry by-products in northern Sweden.

An objective function can be described as f(x) where, x= (x1, x2…xn) is a vector of decision variables.

The values x could take defines the number of allowed solutions that exist. Constrains set the terms of how the objective function should be optimized. For example, one possible constraint could be built on resources available at supply nodes. Constraints restricts the possible values that x could take in the target function.

In this context, the function can be used to calculate total feedstock costs by maximizing available biomass at minimal transportation costs. Minimization of the objective function (*1*) was used when solving the linear programming problem.

To formulate the general, minimize transportation cost the following terms must be described[56]:

$xij = transported\ units\ from\ supply\ unit\ i\ to\ customer\ j$,

$i = 1, \dots , m\ j = 1, \dots , n$

$cij = transport\ cost\ (per\ unit)\ from\ supply\ unit\ i\ to\ demand\ unit\ j$,

$i = 1, \dots , m\ j = 1, \dots , n$

$si = supply\ at\ unit\ i,\ i = 1, \dots , m$

$dj = demand\ at\ unit\ j,\ j = 1, \dots , n$

$z = The\ objective\ function\ (total\ minimized\ transport\ cos$

Then the model can be formulated as:

$$Min\ z = \sum_{i=1}^{m}\sum_{j=1}^{n} cij\ xij \quad (1)$$

Under the constraints,

- $\sum_{j=1}^{n} xij \leq si, i = 1, \dots, m\ (supply)$
- $\sum_{i=1}^{m} xij = dj, j = 1, \dots, n\ (demand)$

[56] Lundgren, J., Rönnqvist, M. & Värbrand, P. (2008). Optimeringslära. 3. ed. Malmö, Sweden: Holmbergs’. [2020-12-04]

- $X_{ij} \geq 0$ i =1, …, n

To finally calculate the transportation cost a transport cost function[57](**2**) was used.

$$c = 12.533\, x + 0{,}692 y * x \qquad (2)$$

Where,

c is the cost in SEK (1 Euro= 11.42 SEK, 2024-07-10) for transport of one truck load of by-products,

y is transportation distance in km

x is amount transported in one truckload (tons).

The different values that x can take are illustrated in Table 29.

Table 29 Input data for the calculation of biomass costs[58].

Variable	Sawdust	Bark	C-Chips	Dry Chips	Shavings
Loading volume (tons)	41.50	41.50	41.50	22.50	22.50
Basis for payment (tons)[59]	41.50	41.50	41.50	41.50	41.50
SEK/km	0.69	0.69	0.69	0.69	0.69
One time cost SEK/ton	12.53	12.53	12.53	12.53	12.53

The methods for practical assessment are different depending on what kind of feedstock residue is considered in the region, sawdust or logging residues. In the case of sawdust this is determined through questionnaires to the sawmill's plants on their main products and subproducts.

- in the case of logging residues, these are dependent on the number of felled trees annually, this information is often available at national forestry websites, e.g. the Swedish Forest Agency

[57] Persson, L. (2022). Mapping the market of unrefined forest industry by-products in northern Sweden.

[58] Persson, L. (2022). Mapping the market of unrefined forest industry by-products in northern Sweden.

[59] We consider the basis for payment to be set at 41.5 tons, this is because the transport company takes out full payment even if the load weighed less than the capacity of the truck

(Skogsstyrelsen) website[60]. Data granularity is at a county level, if more detailed data are needed maps, satellites earth observation, and questionnaires can be used.

As with the volumes of tops and branches are connected to tree species and handling process, the volumes of by-products from sawing wood at a sawmill are also connected to the volume of the sawmill processes and species[61] For examples, from roundwood volume, around 50% becomes sawn wood products, 20% sawdust, 10% bark, 20% chips and 1 ton shavings/10m^{3}sw product[62].

While logging residues may struggle with a largely heterogeneous product fraction of variations in branches, tops, needles, leaves, bark etc, the sawmill by-products will most often be homogenous fractions/assortment but may vary from sawmill to sawmill.

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[60] https://www.skogsstyrelsen.se/en/statistics/subject-areas/felling/

[61] Fridh, M. & Christiansen, L. (2015). *Rundvirkes- och skogsbränslebalanser för år 2013 – SKA 15*. (SKA 15). Jönköping. https://www.skogsstyrelsen.se/globalassets/statistik/skogligakonsekvensanalyser/rundvirkes--och-skogsbranslebalanser-for-ar-2013-ska-meddelande-3-2015.pdf [2020-08-17]

[62] Staffas, L., Hansen, K., Sidvall, A. & Munthe, J. (2015). *Råvaruströmmar från skogen-tillgång och samband*. (C 116). Stockholm: Svenska Miljöinstitutet.

7 APPENDIX C COST AND REVENUES ESTIMATE

To determine the cost and revenue of different biorefinery routes, a cost and revenue estimate of the process route need to be calculated. In sections below an approach is step by step presented for estimating the equipment and infrastructure costs, installation costs and cost escalation, and productions costs (variable and fixed) as well as revenue estimates.

7.1 CAPEX

According to the Association for the Advance of Cost Estimating International (AACE International)[63] capital costs estimates can be classified into five types according to accuracy and purpose (Table 30).

Table 30 Overview of methods for capital cost estimates and their accuracy[78]

Estimate Type	Accuracy	Purpose
Order of Magnitude	30-50%	Based on similar processes, no design information
Preliminary	30%	Coarse choices between design alternatives
Definitive	10-15%	Authorization of funds
Detailed	5-10%	Project cost control, estimates for fixed-price contracts
Check	5-10%	Based on completed design and procurement negotiations for specialized items

The order of magnitude estimates is typically used in very early planning for rough estimates. The preliminary estimates are useful for makes coarse choices and to compare different design options, for example to make a choice of process route. The definitive estimates include detailed process design and at this point, requesting quotations. The detailed estimates are on a level of breakdown of construction costs and the final check is used for validation and for choices of specific items.

7.1.1 Estimating purchased equipment costs

When more design information is available the cost of the plant can be worked up from the cost of individual items of process equipment. Costs of single pieces are also often needed for minor revamp and debottlenecking projects.

63 AACE International Recommended Practice No. 18R-97 COST ESTIMATE CLASSIFICATION SYSTEM – AS APPLIED IN ENGINEERING, PROCUREMENT, AND CONSTRUCTION FOR THE PROCESS INDUSTRIES AACE-Cost-Estimate-Classification-System.pdf

Sources of equipment cost data

The best source of purchased equipment costs is recent data on actual prices paid for similar equipment. Engineers working for the Engineering, Procurement and Construction (EPC) companies (often referred to as contractors) have access to large amounts of high-quality data. Engineers working in operating companies may have access to data from recent projects, but unless they work for a large company that carries out many capital projects, they are unlikely to be able to develop and maintain current cost correlations for more than a few basic equipment types. Most large companies recognize the difficulty of making reliable cost estimates and employ a few experienced cost engineering specialists who collect data and work closely with the EPC companies on project budgets. Those design engineers who are outside the EPC sector and do not have the support of a cost estimating department must rely on cost data from the open literature or use cost estimating software e.g. Aspen Technology Inc. Aspen ICARUS^{TM} Technology estimates: equipment costs, bulk costs and installation costs from the costs of materials and labour, following the practice used by cost engineers for detailed estimating.

There is abundance of equipment cost data and cost correlations in the open literature, but much of it is of insufficient quality.

Some of the most reliable information on equipment costs can be found in the professional cost engineering literature:

1. Correlations based on recent data are occasionally published in "Cost Engineering", which is the journal of the Association for the Advancement of Cost Engineering International (AACE), which has also a useful website (www.aacei.org), which has cost models that can be used by members.
2. The U.K. Association of Cost Engineers (ACostE) publishes the journal "The Cost Engineer" and prints a guide to capital cost estimating[64]. The International Cost Engineering Council (www.i-coste.org) provides links to 46 international cost engineering societies, several of which maintain databases of local costs.
3. Current prices for new and used equipment can be found on resale web sites such as: www.equipnet.com. These websites can be used to confirm the results of the cost estimation equations.
4. Many cost correlations can be found in chemical engineering texts books.

[64] Gerrard, A. M. (Ed.). (2000). Guide to capital cost estimating. IChemE.

Cost curves for purchased equipment costs

For those design engineers who lack access to reliable cost data or estimating software, the correlations given in Table 31 can be used for preliminary estimates. The correlations presented in the table are in the form of:

$$Ce = a + bSn \quad (3)$$

Where,

- Ce = purchased equipment cost on a U.S. Gulf Coast basis, Jan 2010 (CPCI = 532.9, NF refinery inflation index = 228.6).
- a,b = cost constants.
- S = size parameter.
- n = exponent for that type of equipment.

The correlations shown in the Table 31 are only valid between the lower and the upper value of S indicated. The prices are all for carbon steel equipment, except where noted Table 31.

Table 31: Equipment cost correlations[65]

Equipment	**Units for Size, S**	S_{lower}	S_{upper}	**a**	**b**	**n**	**Notes**
Agitators and mixers							
Propeller	Driver power, kW	5.0	75	17,000	1,130	1.05	
Spiral ribbon mixer	Driver power, kW	5.0	35	30,800	125	2.0	
Static mixer	litres/s	1.0	50	570	1,170	0.4	
Boilers							
Packaged, 15 to 40 bar	Kg/h steam	5,000	200,000	124,000	10,0	1.0	
Field erected, 10 to 70 bar	Kg/h steam	20,000	800,000	130,000	53	0.9	
Centrifuges							
High speed disk	Diameter, m	0.26	0.49	57,000	480,000	0.7	
Atmospheric suspended basket	Power, kW	2.0	20	65,000	750	1.5	
Compressors							
Blower	m^3/h	200	5,000	4,450	57	0.8	
Centrifugal	Driver power, kW	75	30,000	580,000	20,000	0.6	
Reciprocating	Driver power kW	93	16,800	260,000	2,700	0.75	
Conveyors							

[65] Towler, G., & Sinnott, R. (2021). Chemical engineering design: principles, practice and economics of plant and process design. Butterworth-Heinemann.

Belt 0.5 m wide	Length, m	10	500	41,000	730	1.0	
Belt, 1.0 m wide	Length, m	10	500	46,000	1,320	1.0	
Bucket elevator, 0.5 m bucket	Length, m	10	30	17,000	2,600	1.0	
Crushers							
Reversible hammer mill	t/h	30	400	68,400	730	1.0	
Pulverizers	Kg/h	200	4,000	16,000	670	0.5	
Jaw crusher	t/h	100	600	-8,000	62,000	0.5	
Gyratory crusher	t/h	200	3,000	5,000	5,100	0.7	
Ball mill	t/h	0.7	60	-23,000	242,000	0.4	
Crystallizers							
Scraped surface crystallizer	Length, m	7	280	10,000	13,200	0.8	
Distillation columns **(**See pressure vessels, packing and trays)							
Direct contact Rotary	m^2	11	180	15,000	10,500	0.9	1
Atmospheric tray batch	Area, m^2	3.0	20	10,000	7,900	0.5	
Spray dryer	Evap rate kg/h	400	4,000	410,000	2,200	0.7	
Evaporators							
Vertical Tube	Area, m^2	11	640	330	36,000	0.55	
Agitated falling film	Area, m^2	0.5	12	88,000	65,500	0.75	2
Exchangers							
U-tube shell and tube	Area, m^2	10	1,000	28,000	54	1.2	
Floating head shell and tube	Area, m^2	10	1,000	32,000	70	1.2	
Double pipe	Area, m^2	1.0	80	1,900	2,500	1.0	
Thermosiphon reboiler	Area, m^2	10	500	30,400	122	1.1	
U-tube Kettle reboiler	Area, m^2	10	500	29,000	400	0.9	
Plate and frame	Area, m^2	10	500	1,600	210	0.95	2
Filters							
Plate and frame	Capacity, m^3	0.4	1.4	128,000	89,000	0.5	
Vacuum drum	Area, m^2	10	180	-73,000	93,000	0.3	
Furnaces							
Cylindrical	Duty, MW	0.2	60	80,000	109,000	0.8	
Box	Duty, MW	30	120	43,000	111,000	0.8	
Packings							
304 ss Raschig rings	m^3			0	8,000	1.0	
Ceramic intalox, saddles	m^3			0	2,000	1.0	
304 ss Pall rings	m^3			0	8,500	1.0	
PVC structured packing	m^3			0	5,500	1.0	
304 ss structured packing	m^3			0	7,600	1.0	3
Pressure vessels							

Vertical, cs	Shell mass, kg	160	250,000	11,600	34	0.85	4
Horizontal, cs	Shell mass, kg	160	50,000	10,200	31	0.85	4
Vertical 304 ss	Shell mass, kg	120	250,000	17,400	79	0.85	
Horizontal 304 ss	Shell mass, kg	120	50,000	12,800	73	0.85	
Pumps and drivers							
Single stage centrifugal	Flow, litres/s	0.2	126	8,000	240	0.9	
Explosion proof motor	Power, kW	1.0	2,500	-1,100	2,100	0.6	
Condensing steam turbine	Power, kW	100	20,000	-14,000	1,900	0.75	
Reactors							
Jacketed, agitated	Volume m^3	0.5	100	61,500	32,500	0.8	2
Jacketed, agitated, glass lined	Volume m^3	0.5	25	12,800	88,200	0.4	
Tanks							
Floating roof	Capacity m^3	100	10,000	113,000	3,250	0.65	
Cone roof	Capacity m^3	10	4,000	5,800	1,600	0.7	
Trays							
Sieve trays	Diameter, m	0.5	5.0	130	440	1.8	5
Valve trays	Diameter, m	0.5	5.0	210	400	1.9	
Bubble cap trays	Diameter, m	0.5	5.0	340	640	1.9	
Utilities							
Cooling tower and pumps	Flow litres/s	100	10,000	170,000	1,500	0.9	6
Packaged mechanical refrigerator evaporator	Duty, kW	50	1,500	24,000	3,500	0.9	
Water ion exchange plant	Flow m^3/h	1	50	14,000	6,200	0.75	

Notes:

1. Direct heated
2. Type 304 stainless steel
3. With surface area 350 m^2/m^3
4. Not including heads, ports, brackets, etc.
5. Cost per tray, based on a stack of 30 trays.
6. Field assembly
7. All costs are U.S. gulf Coast basis, Jan 2010 (CEPCI Index = 532.9, NF refinery inflation index = 2281.6)

The final estimates were doubled checked by using vendor data cost estimates. A large amount of vendor information is now available online and can easily be found using any of the major search engines or by starting from directories such as the Chemical Engineering Buyer´s Guide (www.che.com/buyersguide/public/). Online costs are usually manufacturer´s catalogue prices for small-order quantities. Large order sizes (as filled by contractors) are often heavily discounted. When a vendor is contacted directly the quality of the estimate that they can provide depends very much on the quality of the information that they are given.

7.1.2 Estimating installed costs: the factorial method

Inside battery limits (ISBL) is the area within a plant where the primary process equipment is located. The ISBL includes all process units, equipment, and facilities that are necessary to produce the final products, for a biorefinery this would include i.e. reactors, distillation columns, pumps, and compressors.

Capital cost estimates for chemical process plants are often based on an estimate of the purchase cost of the major equipment items required for the process, the other costs being estimated as factors of the equipment cost. The accuracy of this type of estimate will depend on what stage the design has reached at the time the estimate is made, and on the reliability of the data available on the equipment costs. In the later stages of the project design, when detailed equipment specifications are available and firm quotes have been obtained from vendors, a more and more thorough estimate of the capital cost can be made by this method.

Lang factors

Lang[66] proposed that the ISBL fixed capital cost of a plant is given as a function of the total purchased equipment cost by the equation:

$$C = F(\sum Ce) \tag{4}$$

Where,

C = total plant ISBL cost (including engineering cost).

∑Ce = total delivered cost of all the major equipment items: reactors, tanks, columns, heat exchangers, furnaces, etc.

F = an installation factor, later widely known as Lang Factor.

Lang originally proposed the following values of F, based on 1940s economics:

F = 3.1 for solids processing plant.

F = 4.74 for fluids processing plant.

F = 3.63 for mixed fluids-solids processing plant.

[66] Lang, H. J. (1948). Simplified approach to preliminary cost estimates. Chemical Engineering, 55(6), 112-113.

Hand[67] suggested that better results are obtained by using different factors for different types of equipment (Table 32). Hand also observed that this approach should only be used in the earliest stages of process design in the absence of detailed design information.

Table 32: Installation Factors Proposed by Hand[68]

Equipment type	**Installation factor**
Compressors	2.5
Distillation columns	4
Fixed heaters	2
Heat exchangers	3.5
Instruments	4
Miscellaneous equipment	2.5
Pressure vessels	4
Pumps	4

Both Lang and Hand included home office costs but not offsite costs or contingency in their installation factors, so be cautious of double counting Engineering Procurement, and Construction (EPC) costs when using this approach. The relative cost of materials and labour have changed substantially from when these factors were developed, and the accuracy of the correlation probably never warranted three significant figures for F. Most practitioners using this method therefore use a Lang factor of 3,4 or 5, depending on the plant scale (larger plant = smaller factor) and type.

Detailed factorial estimates

Equation (**4**) can be used to make a preliminary estimate once the flowsheet has been drawn up and the main plant equipment has been sized. When more detailed information is available, the installation factor can be estimated somewhat more rigorously, by considering the cost factors that are compounded into the Lang factor individually.

The direct-cost items that are incurred in the construction of a plant, in addition to the cost of equipment are:

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[67] Hand, W. E. (1958). From flow sheet to cost estimate. Petroleum Refiner, 37(9), 331-337.

[68] Towler, G., & Sinnott, R. (2021). *Chemical engineering design: principles, practice and economics of plant and process design*. Butterworth-Heinemann.

1. Equipment erection, including foundations and minor structural work.
2. Piping, including insulation and painting.
3. Electrical, power and lighting.
4. Instruments and automatic process control (APC) systems.
5. Process buildings and structures
6. Ancillary buildings, offices, laboratory buildings, workshops (if not costed separately as offsites)
7. Storage for raw materials and finished product (if not costed separately as offsites)
8. Utility, provision of plant for steam, water, air, firefighting services (if not costed separately as offsites).
9. Site preparation.

The contribution of each of these items to the total capital cost is calculated by multiplying the total purchased equipment cost by an appropriate factor. As with the basic Lang factor, these factors are best derived from historical cost data for similar processes. Typical values for the factors are given in several references, including Happle and Jordan[69] and Garrett[70]. Guthrie[71] splits the costs into the material and labour portions and gives separate factors for each.

The accuracy and reliability of an estimate can be further improved by dividing the process into subunits and using factors that depend on the function of the subunits. In Guthrie´s detailed method of cost estimation the installation, piping, and instrumentation costs for each piece of equipment are costed separately. Detailed costing is only justified if the cost data available are reliable and the design has been taken to the point where all the cost items can be identified and included. Gerrard[72] gives factors for individual pieces of equipment as a function of equipment cost and complexity of installation.

Typical factors for the component of the capital cost are given in Table 33. These can be used to make an approximate estimate of capital cost using equipment cost data published in the literature.

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[69] Happel, J., & Jordan, D. G. (1975). Chemical process economics. (No Title).

[70] Garrett, D. E. (2012). Chemical engineering economics. Springer Science & Business Media.

[71] Guthrie, K. M. (1969). Capital cost estimation. Chem. Engng., 24, 114–142.

[72] Gerrard, A. M. (Ed.). (2000). Guide to capital cost estimating. IChemE.

Table 33: Typical factors for estimation of project fixed capital cost

Item	Process type		
	Fluids	Fluids-Solids	Solids
Major equipment, total purchase cost	C_e	C_e	C_e
f_{er} Equipment erection	0.3	0.5	0.6
f_P Piping	0.8	0.6	0.2
f_i Instrumentation and control	0.3	0.3	0.2
f_{el} Electrical	0.2	0.2	0.15
f_e Civil	0.3	0.3	0.2
f_S Structure and buildings	0.2	0.2	0.1
f_L Lagging and paint	0.1	0.1	0.05
ISBL Cost, C = ∑Ce X	3.3	3.2	2.5
Offsites (OS)	0.3	0.4	0.4
Design and Engineering (D&E)	0.3	0.25	0.2
Contingency (X)	0.1	0.1	0.1
Total fixed capital cost C_{FC} = C(1 + OS)(1+D&E+X)			
= Cx	1.82	1.89	1.82
= $\sum C_e X$	6.00	6.05	4.55

Material factors

The installation factors given in Table 34, Table 31 and Table 32 are for plants build up with carbon steel. When more expensive materials are used then a materials factor, f_m , should also be introduced.

F_m = purchased cost of item in exotic material / purchased cost of item in carbon steel (5)

Note that f_m, is not equal to the ratio of the metal prices, as the equipment purchase cost also includes labour costs, overheads, fabricator´s profit, and other costs that do not scale directly with metal price.

Equation (**4**) can then be expanded for each piece of equipment, to give:

$$C = \sum_{i=1}^{i=M} C_{e,i,CS}\left[(1+f_p)f_m + (f_{er} + f_{el} + f_i + f_c + f_s + f_L)\right] \tag{6}$$

Equation (**6**) should be used when the purchased cost has been found on a carbon steel basis and the designer is estimating the cost for alloy construction. If the purchased equipment cost has been obtained on an alloy basis, then the designer should instead correct the other installation factors so as not to overestimate the cost of installation:

$$\boldsymbol{C = \sum_{i=1}^{i=M} C_{e,i,A}\left[(1 + f_p) + (f_{er} + f_{el} + f_i + f_c + f_s + f_L)/f_m\right]} \tag{7}$$

Where,

$C_{e,I,CS}$ = purchased equipment cost of equipment I in carbon steel.

$C_{e,iA}$ = purchased equipment cost of equipment I in alloy.

M = total number of pieces of equipment.

f_p = installation factor for piping.

f_{er} = installation factor for equipment erection.

f_{el} = installation factor for electrical work.

f_i = installation factor for instrumentation and process control.

f_c = installation factor for civil engineering work.

f_s = installation factor for structures and buildings.

f_L = installation factor for lagging, insulation, or paint.

Failure to properly correct installation factors for materials of construction is one of the most common sources of error with the factorial method. Typical values of the material factor for common engineering alloys are given in Table 34.

Table 34: Materials cost factors, f_m, relative to plain carbon steel

Material	**f_m**
Carbon steel	1.0
Aluminium and bronze	1.07
Cast steel	1.1
304 stainless steel	1.3
316 stainless steel	1.3
321 stainless steel	1.5
Hastelloy C	1.55
Monel	1.65
Nickel and Inconel	1.7

Current material prices can be found in websites reported in Table 35.

Table 35: Current metal prices sources[73]

Source	Material
www.steelonthenet.com www.steelonthenet.com	Free site with monthly carbon steel prices
www.steelbb.com www.steelbb.com	Steel Business Briefing – subscription site with weekly carbon steel and stainless steel prices
www.steelweek.com www.steelweek.com	Subscription site with weekly international prices
http://metalprices.com http://metalprices.com	Great alloy calculator – 3 month old prices are free, current prices need a subscription.

Summary of the factorial method

Many variations of the factorial method are used. The method outlined below can be used with the data available to make a quick, approximate estimate of the fixed capital investment needed for a project:

Prepare Material and Energy Balances

- Develop preliminary flowsheets.
- Size major equipment items.
- Select materials of construction.

Estimate Purchased Equipment Costs

- Determine the cost of major equipment items.

Calculate ISBL Installed Capital Cost

- Use factors from Table 32
- Correct for materials of construction using (6**)** (7**)** with materials factors from Table 34

2. Calculate Outside Battery Limits, OSBL, Engineering, and Contingency Costs:

[73] Towler, G., & Sinnott, R. (2021). *Chemical engineering design: principles, practice and economics of plant and process design*. Butterworth-Heinemann.

    - Refer to auxiliary infrastructure and utilities necessary to support the ISBL but which are not part of the core production process
    - Some of these factors are included in the base case (wastewater treatment, cooling systems, storage facilities, pipelines and admin building)
    - Other factors are referred as outside site utilities supplying to the investment (e.g., steam, power generation)
3. Fixed Capital Investment:
    - Sum ISBL and OSBL costs along with engineering and contingency costs.
4. Estimate Working Capital:
    - Typically, 10-20% of the fixed capital investment.
    - Alternatively, calculate it based on estimated production costs (preferred is available).
5. Total Investment:
    - Add fixed capital and working capital

7.1.3 Cost escalation

All cost-estimating methods use historical data and are themselves forecasts of future costs. The prices of materials of construction and the costs of labour are subject to inflation. Some method must be used to update old cost data for use in estimating at the design stage and to forecast the future construction cost of the plant.

The method usually used to update historical cost data makes use of published cost indices. These relate present costs to past costs and are based on data for labour, material, and energy costs published in government statistical digests.

$$\text{Cost in year A} = \text{Cost in year B} * \text{Cost index in year A} / \text{Cost index in year B} \quad (8)$$

To get the best estimate, each job should be broken down into its components and separate indices should be used for labour and materials. It is often more convenient to use the composite indices published for various industries in the trade journals. These are weighted average indices combining the various components of costs in proportions considered typical for the specific industry.

1. A composite index for the United States process plant industry is published monthly in the journal of Chemical Engineering; this is the Chemical Engineering Plant Cost Index (CEPCI) often referred to as the CE index. Chemical Engineering also publishes the Marshall and Swift index (M&S Equipment Cost Index).

2. For oil refinery and petrochemicals projects, the Oil and Gas Journal publishes the Nelson-Ferrer Refinery Construction Index (NF Index). This index is updated monthly and indices for forty types of equipment are updated quarterly. The Nelson-Farrer index is on a U.S. Gulf Coast basis rather than U.S. average, and it is more reliable than the CE index for the types of equipment used in hydrocarbon processing.

3. The journal Engineering News Record publishes monthly construction cost index. This is based on civil engineering projects, and it sometimes used for updating offsites costs. This index has been published since 1904 and is the oldest of all indices. For international projects, the journal Process Engineering publishes monthly cost indices for several countries, including the United States, United Kingdom, Japan, Australia, and many EU countries.

7.2 OPEX AND REVENUES

Estimation of the product revenues and costs of production is a key step in determining the profitability of a process. An understanding of the breakdown of production costs is critically important to process optimization, regardless of whether the project is a new grassroots design or a revamp or expansion of an existing plant. Several companies regularly publish economic analyses of chemical processes. Nexant publishes the Process Evaluation and Research Planning (PERP) reports. Roughly ten new reports are issued each year and almost two hundred processes have been analysed. The PERP reports provide estimates of capital and operating costs, usually for two or three process alternatives, as well as an overview of the current market conditions for the product. SRI publishes the Chemical Economics Handbook (CEH) series, which contains 281 reports on a range of commodity and specialty chemicals. The CEH reports provide an overview of production technologies and analyses of several regional markets, but do not provide the level of production cost detail given in the PERP reports. Various consulting firms also carry out paid economic studies of “state of the art” technology.

Variable costs of production

For most chemicals, the major variable costs are the costs of raw materials and utilities. In addition, consumables and waste handling (effluent post treatment) can amount to larger costs in complex processes. Variable costs are proportional to the plant output or operation rate. These include costs of:

- **Raw materials** - consumed in the process.
- **Utilities** - fuel burned in process heaters, steam, cooling water, electricity, raw water, instrument air, nitrogen, and other services brought in from elsewhere on the site.
- **Consumables** - solvents, acids, bases, inert materials, corrosion inhibitors, additives, catalysts, and adsorbents that require continuous or frequent replacement.
- **Effluent disposal** - air, water and soil
- **Packaging and shipping** - drums, bags, tankers, freight charges, etc.

Variable costs are mainly determined by the choice of feedstock, process chemistry, and plant location, and can usually be reduced by more efficient design or operation of the plant.

Raw material: For raw materials, the annual cost of each raw material is the annual consumption multiplied by the price. Raw materials prices will be discussed in the next session on revenues. For an existing plant the volumes of raw materials consumed per kg of product can be easily determined from plant purchasing records. In a new plant the volumes of raw materials required to make the desired product is usually estimated using a process model to determine the overall plant material balance. Whenever possible the process model should be benchmarked against an existing plant or pilot plant.

Plant utilities: Plant utilities include fuel, process steam, cooling water, other heating or cooling fluids, electricity, process water, nitrogen, instrument air, and other service streams. Most utility costs are based on the cost of fuel (typically natural gas) and electricity. Determining utility costs is more difficult than determining raw materials costs, although utilities usually are less than 15% of the cash cost of production and typically account for about 5% to 10% of cost of production (COOP), i.e. the total expense of manufacturing the product. The use of energy recovery and heat integration methods means that determination of the utility consumption of a proposed design requires not only a completed mass and energy balance of the process, but also a preliminary design of the heat recovery network.

The cost of providing heat to a process is often reduced by using process waste streams as fuel. When waste streams are used as fuel there is a double benefit, as both fuel costs and waste-handling costs are reduced.

Consumables: Consumables, including acids, bases, sorbents, solvents, and catalysts are key chemicals in chemical production. These materials gradually deplete or degrade during the process and require replacement. In terms of replacement strategies, some consumables follow continuous purge and make-up procedures (e.g., acids and bases), while others are periodically replaced in entire batches (e.g., sorbents, chromatography media, and catalysts). When calculating costs, it is essential to include expenses related to neutralizing spent streams for process acids or bases. Prices for adsorbents and catalysts exhibit significant variability based on material characteristics. Although small in quantity and typically costing less than 3% of the Cash Cost of Production (CCOP), consumables can add a lot of capital cost and complexity to a plant. The plant must be designed with systems for handling, storing, metering, and disposing of all the consumables used. In many chemicals plants over half of the total pieces of equipment are associated with consumables handling.

Waste handling and disposal: Waste disposal costs are relative to materials produced by the process that cannot be recycled or sold as by-products must be disposed of as a waste. In some cases, additional treatment is required to concentrate the waste stream before sending it to final disposal. Dilute aqueous streams are sent to wastewater treatment unless the contaminants are toxic to the bacteria in the wastewater plant. Acid or basic wastes are neutralized prior to treatment. Neutralization is usually carried out using a base or acid that will form a solid salt that can be precipitated from the water, so that the total dissolved solids load on the wastewater plant is not excessive. The costs of hazardous waste disposal depend strongly on the plant location, proximity to waste disposal plants, and the nature of the hazardous waste, and must be evaluated on a case-by-case basis.

Packaging and Shipping Costs: Packaging and shipping costs are essential components of variable production expenses and can be divided into 1) packaging costs; packaging materials (such as drums, bags, and containers) and expenses related to acquiring, storing, and handling packaging materials and costs of transporting the packing material onsite, 2) shipping costs; covering the transportation of finished products from the production facility to distribution centres or customers including freight charges, transportation mode (e.g., truck, rail, air), and distance, as well as additional costs if specialized/hazardous handling or expedited shipping is required, and 3) storage and handling; storage costs for storing packaged products before shipment and labour costs related to handling, loading, and unloading shipments.

Fixed production costs are costs that are incurred regardless of the plant operation rate or output. Even if the plant cuts back its production, these costs are not reduced.

Labor costs

Labor costs are the wages paid to plant operators and supervisors. Plant operation requires experience and safety training, and it is not practical to ramp the force up and down with short-term changes in demand. Direct salary overhead costs are the costs of providing employee benefits and training. These include such non-salary costs as health insurance, contribution to employees' savings plans, training courses, and benefits such as subscriptions and professional society membership. Direct salary overhead typically varies between 40% and 60% of labour plus supervision costs.

Maintenance

A plant must be kept in good working conditions, notwithstanding the level of production. Maintenance costs include the cost of replacing or repairing parts and equipment as well as the cost of labour needed to carry out the maintenance work. Maintenance costs are typically estimated as a fraction of Inside Battery Limits (ISBL) investment, ranging from 3% for a process that handles liquids and gases to 5% for a process that involves solids handling or other large mechanical equipment. If a process is known to require regular equipment replacement, the design engineer should make an estimate of the annualized replacement cost and add this to the maintenance costs.

Site costs

Many new plants are built on sites that were previously occupied by other process operations. Local governments often provide incentives for companies to redevelop abandoned industrial sites, while chemical companies themselves often encourage other companies to locate plans on unoccupied parts of their site so, as to defray some of their own utility and infrastructure costs. The costs of land or building rental vary widely between locations and play a strong role in determining plant location. As a first approximation, the cost of land is typically taken as 1% of the Inside Battery Limits (ISBL) investment plus Outside Battery Limits capital cost for a plant that has few buildings, or 2% of ISBL plus OSBL capital cost if the plant is to be located indoors. Some local, regional, state, or provincial governments charge property taxes on commercial land or buildings. The level of property tax should be determined in consultation with local authorities. For a preliminary analysis, 1% of ISBL plus OSBL capital cost can be assumed.

All plants require an insurance to cover third party liability as well as potential plant damage. Most chemical companies maintain insurance coverage through insurance brokers, although some choose to self-insure, essentially setting aside a part of their operating income to cover liabilities. Insurance premiums are based on prior performance and risk assessments carried out by specialist risk management companies and are typically about 1% of ISBL plus OSBL capital cost per year.

If the project is financed by bonds or loans, the regular payments of interest (or interest plus amortization of principal) are a fixed cost of the project. Creditors have a primary claim on earnings over shareholders, so payments on debt must be made as a cost of production rather than set aside to be paid out of retained earnings. Most companies do not break out the relative proportion of debt and equity financing on a project-by-project basis and instead evaluate projects using an overall average cost of capital. Repayment of debts associated with the fixed capital investment is therefore included with the overall expected return on capital of the project. It is, however, common to assume that working capital will be funded entirely by the debt, as the value of the working capital is always sufficient to repay the principal of the loan and the cost of maintaining the working capital is then equal to just the annual interest due. The annual interest payment is then equal to the working capital[74] multiplied by the interest rate, which can be estimated from the interest rate paid on corporate bonds by similar companies. When a company has only one plant, for example, when a new venture is being considered, then it is best to separate debt financing from equity financing and calculate the cost of servicing the debt as a fixed cost of production. This gives a more accurate picture of the likely return on equity from the project.

Corporate overhead charges

Corporate overhead varies widely depending on the industry sector. Company financial reports can be used to gain insights into the typical distribution of overhead costs in different companies and industries. These reports are freely available and easily obtained over the internet.

General and administrative costs include all the costs of administering a corporation: general management, human resources, purchasing and procurement, finance, accounting, strategic planning, business development, property management, information technology, health, safety and environment, corporate communications, and legal services. In smaller companies some of these functions may be outsourced to consultants, but the costs must nonetheless be borne by the company, and a share of these costs is attributed to any new project. General and administrative costs can be assessed by looking at the annual income statement of a company. G&A costs are usually allocated based on either revenue or headcount. A typical estimate using a headcount-based approach might be 65% of labour cost plus supervision and overhead, while a revenue-based approach would assume the same proportion of revenues as in the overall corporate income statement.

A plant that makes use of proprietary technology must hold a license or royalty payments to the owner of the technology. If a company practices technology that is under patent protection without obtaining a license to use the technology, the patent holder can sue them for

[74] Working capital, also known as net working capital (NWC), is the difference between a company's current assets—such as cash, accounts receivable/customers' unpaid bills, and inventories of raw materials and finished goods—and its current liabilities, such as accounts payable and debts. It's a commonly used measurement to gauge the short-term health of an organization. See also: https://www.investopedia.com/terms/w/workingcapital.asp

infringement. In the process industries, patents typically cover processes, compositions of matter, chemical and biological routes, process conditions, catalysts, enzymes, genetically modified organisms, processing equipment, and control strategies and algorithms. Patent holders often include royalty fees in the pricing of a product such as a catalyst, enzyme, or piece of equipment, and warrant the customer that their product does not infringe on anyone else´s patent. When the royalty is not included in the price of a product, license fees are negotiated between the patent holder (the licensor) and the company that wants to practice the technology (the licensee). The pricing of the royalty payment depends on the availability of alternatives, the licensee's desire to acquire the technology and the patent holder´s desire to sell. Royalties can be set as percentage of revenues, but the most common method is a fixed rate per kg of product based on total production capacity. Although the royalty rate is proportional to plant capacity, royalties are a fixed cost and must usually be paid regardless of whether the plant operates at full capacity.

Research and development costs: R&D costs cover the costs of fundamental discovery projects, new product development, scale-up and testing, clinical trials for new medicines, and applications testing to develop new markets for existing products. Research and development costs range from less than 1% of revenues for operating companies in the fuels and bulk petrochemicals sectors to as much as 15% of revenues for some biotech and pharmaceutical companies.

Selling and marketing costs include costs of paying the sales force, advertising costs including promotional materials, travel to visit customers and trade shows, and other costs associated with closing sales. Additional marketing expenses include the costs of market research and analysis, competitive studies, branding, and any other costs associated with developing an understanding of customers' needs and preferences and using this understanding to guide new product development and product positioning and pricing. Selling and marketing costs are very dependent on the type of product. Bulk commodities that are produced to ASTM standards have almost zero selling and marketing costs, whereas consumer and specialty products can have selling costs as high as 5% of total cost of production.

7.2.1 Revenues

The revenues for a project are the income earned from sales of main products and by-products (Figure 50). The production rate of the main product is usually specified basis (production rate is set determined by certain criteria) such as predictions of overall market growth.

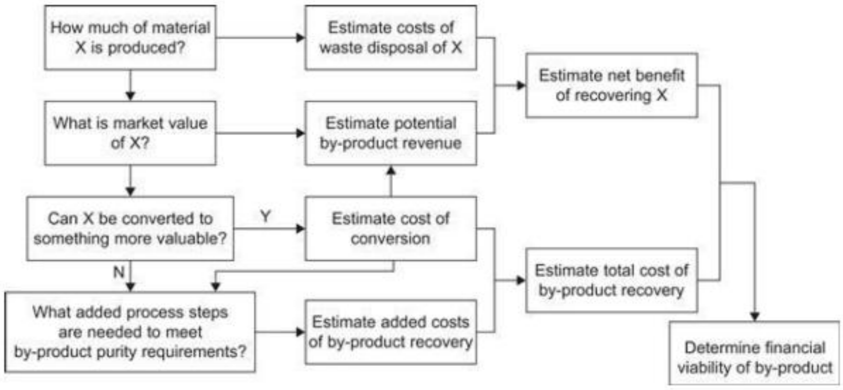

Figure 50 Algorithm for assessing the economic viability of by-product recovery[75]

Determining which by-products to recover, purify, and sell is usually more difficult than determining the main product. The decision to recover, purify and sell; recycle or otherwise attenuate; or dispose of by products as waste is an important design optimization problem. Substantial efforts can be put into addressing process design and analysing by-product recovery.

Potentially valuable by-products include:

- Materials produced in stoichiometric quantities by the reaction that form the main product. If these are not recovered as by-products, the waste disposal costs may be excessive.
- Components that are produced in high yield by side reactions.
- Components formed in high yield from feed impurities.
- Components produced in low yield that has a high value.
- Degraded consumables such as solvents that have reuse value.

For the byproduct to have value, it must meet the specifications for that material, which may entail additional costs. The design engineer must therefore assess whether the additional cost of recovering and purifying the by-product is justified by the by-product value and avoided waste disposal cost, before deciding whether to value the material as a by-product or as a waste stream.

It is important to consider not only the cost of purifying the by-product, but also whether it can be converted into something more valuable. This would include recycling the by-product within the process if that might be expected to lead to a higher yield of main product or formation of

[75] Towler, G., & Sinnott, R. (2021). Chemical engineering design: principles, practice and economics of plant and process design. Butterworth-Heinemann.

a more valuable by-product. Note also that when analysing whether to recover a by-product, the value created by recovering it includes not only the revenue from by-product sales, but also the avoided by-product disposal cost. If the by-product has fuel value, the fuel value should be subtracted from the revenue instead.

In addition, recovering by-products plays a crucial role in adhering to the principles of the waste hierarchy and fostering a circular bioeconomy. The waste hierarchy prioritizes waste management practices in the following order: prevention, reduction, reuse, recycling, recovery, and disposal. By focusing on recovering and converting by-products into valuable materials or energy, businesses can significantly reduce the environmental impact associated with waste disposal. This approach not only aligns with the waste hierarchy by minimizing the need for landfill use but also promotes resource efficiency and sustainability, which may be important selling point for marketing.

Furthermore, recovering by-products supports innovation and economic growth by opening new market opportunities and creating additional revenue streams. It encourages the development of new technologies and processes that can efficiently convert waste into valuable products, thus enhancing the overall competitiveness of businesses. By fostering a circular bioeconomy, industries can not only achieve environmental benefits but also improve their economic performance and contribute to a more sustainable future.

7.2.2 Margins and profits

The sum of product and by-product revenues minus raw material costs is known as the gross margin (or sometimes product margin or just margin) (9):

$$\text{Gross margin} = \text{Revenues} - \text{Raw material costs} \tag{9}$$

Margins vary widely between different sectors of the chemical industry. For commodities margins are usually very low, less than 10% of revenues. For regulated products such as food additives and pharmaceutical products margins can be comprised from 40% to 80%. The variable contribution margin is the sum of revenues minus variable costs (10):

$$\text{Variable contribution margin} = \text{Revenues} - \text{Variable Costs of production} \tag{10}$$

The cash cost of production (CCOP) is the sum of the fixed (FCOP) and variable production costs (VCOP) (11).

$$COOP = VCOP + FCOP \quad (11)$$

Where,

VCOP = sum of all variable costs of production minus by-product revenues.
FCOP = sum of the fixed costs of production.

The cash cost of production is the cost of making product, not including any return on the equity capital invested. By convention, by product revenues are usually taken as a credit and included in the VCOP. This makes it easier to determine the ¤/lb of producing the main product. The gross profit is (12):

$$\text{Gross profit} = \text{Main product revenues} - CCOP \quad (12)$$

Net profit is gross profit minus taxes.

7.2.3 Product and raw material prices

The revenues and variable costs of production are obtained by multiplying the product, feed, or utility rates for appropriate prices. The prices used in economic analysis of a plant design should reflect the market conditions that the company expects to face over the life of the project. It is therefore necessary to make also long-term forecast of prices. The chemical and process industries handle a very broad range of materials. Some of the most basic materials are traded on commodity exchanges and their price can fluctuate significantly on a daily or even hourly basis. Materials that are supplied in large bulk quantities are usually sold under long-term contracts. The contract price may be pegged to the price of a commodity such as natural gas, corn, or crude oil, or may be subject to periodic renegotiation, typically on a quarterly or annual basis. Materials that are supplied in smaller quantities have a list price specified by the supplier, but in many cases, prices can be the results of a negotiation between the purchasers´ procurement department and the supplier´s sales department and can depend on the quantity, delivery terms and other factors.

With pricing operations, it needs to be considered that the price of any substance is determined by the balance between its supply and its demand, this can be determined through different options:

- **Internal Company Forecast**: In many large companies the marketing or planning department develops official forecasts of prices for use in internal studies. These forecasts sometimes include multiple price scenarios, and projects must be evaluated under every scenario. Companies' forecasts are occasionally made available to the public.

- **Trade journals**: Several journals publish chemicals and fuel prices on a weekly basis. See for example the ICIS Chemical Business Americas, which is available online through subscription. The Oil and Gas journal (Pennywell) publishes prices for several crude oils and a range of petroleum products on the USA, Europe, Southeast Asia. The Oil and Gas Journal also publishes formula estimates of gross and net margins for refineries, natural gas liquids recovery, and ethylene plants on a monthly basis. Chemical Week (HIS) gives spot and contract prices for 22 commodity chemicals in United States and Northwest Europe markets.
- **Consultants**: There are many companies that can be hired as consultants to provide economic and marketing information. The information provided includes market surveys and technical and economic analyses of competing technologies as well as price data forecasts. Some of the most used are Purvin and Gertz, Cambridge energy research associates; Chemical Market Associates Inc. (CMAI); SRI: The Chemical Economics Handbook series of reports published by SRI.
- **Online brokers and suppliers**: A lot of price data is available online from suppliers web sites that can be found through directory sites such as those listed here[76]. Some caution is needed when using price data from the web.

In many cases it is needed to forecast prices, because in most cases, it will take between one and three years for a project to go through the phase of design, procurement, and construction before the plant can begin operations. The plant will then operate for the next 10 or 20 years. The design engineer in that case needs to carry out the economic analysis using prices forecasted over the next twenty or so years. Most price forecasts are based on an analysis of historic price data and have expanded with the development of data analytics tools.

7.3 Financial indicators

In the case study presented in this report in fact we consider these main financial indicators:

- Cash flows.
- Net Present Value (NPV).
- Internal Rate of Return (IRR)
- Payback Period.

[76] https://blog.agchemigroup.eu/the-top-online-marketplaces-for-industrial-chemicals/

Cash flows can be pre-taxes and after-taxes. For year zero, the pre-tax cash outflow Cout,0 is equal to the project equity, that is, the portion of the total investment required to finance the project that is funded directly and therefore not incorporated in the financial leverage (e.g. not included in the debt):

$$C_{out,0} = C\,(1-f_d) \qquad (12)$$

Where,

f_d is the financial leverage.

While $C_{out,n}$ is defined as:

$$C_{out,n} = C_{O\&M}(1+r_i)^n + C_{rm} + D + C_{per}(1+r_i)^n \qquad (13)$$

Where,

n is the year,

$C_{O\&M}$ is the yearly operation and maintenance costs incurred by the bioeconomy project,

r_i is the inflation rate,

C_{rm} is the annual cost of the raw material,

D is the annual debt payment

C_{per} is the periodic costs or credits incurred by the system.

During cash inflows for year zero, the pre-tax cash inflow $C_{in,0}$ is simply equal to incentives and grants IG:

$$C_{in,0} = IG \qquad (14)$$

For subsequent years, the pre-tax cash inflow $C_{in,n}$ is represented by the sales (given by the product of Product Price -PP- times Quantity -Q-):

$$C_{in,n} = (PP*Q)^n \qquad (15)$$

The pre-tax cash flow C_n for year n is simply the difference between the pre-tax cash inflow and the pre-tax cash outflow:

$$C_n = C_{in,n} - C_{out,n} \qquad (16)$$

To define the IRR and the NPV we need to calculate the Discounted Cash Flows (DCF), with the following equation[77]:

[77] https://www.investopedia.com/terms/d/dcf.asp

$DCF = CF_1/(1+r)^1 + CF_2/(1+r)^2 + CF_n/(1+r)^n$ (17)

Where r is the discount rate. The calculation of the discount rate or its estimate is a complex topic and requires the introduction of the Capital Asset Pricing Model (CAPM), which can be used to calculate the risk-adjusted discount rate[78].

Based on what has been explained above, the NPV is defined as the value of all future cash flows, discounted at the discount rate, in today's currency. It is calculated by discounting all cash flows as given in the following formula:

$$NPV = \sum_{n=0}^{N} \frac{C_n}{(1+r)^n} \quad (18)$$

Where r is the discount rate.

The internal rate of return IRR is the discount rate that causes the Net Present Value (NPV) of the project to be zero. It is calculated by solving the following formula for IRR:

$$0 = \sum_{n=0}^{N} \frac{C_n}{(1+r)^n} \quad (19)$$

where N is the project life in years, and C_n is the cash flow for year n (note that C0 is the equity of the project minus incentives and grants; this is the cash flow for year zero). The pre-tax IRR is calculated using pre-tax cash flows, while the after-tax IRR is calculated using the after tax cash flows. Note that the IRR is undefined in certain cases, notably if the project yields immediate positive cashflow in year zero.

The payback period is the number of years it takes for the cash flow (excluding debt payments) to equal the total investment (which is equal to the sum of the debt and equity):

$PB = (C-IG)/(PP*Q-C_{O\&M}-C_{rm})$ (20)

Where, C is the initial investment and the other parameters are described above.

[78] https://www.investopedia.com/articles/budgeting-savings/083116/guide-riskadjusted-discount-rate.asp

8 APPENDIX D – SUSTAINABILITY ASSESSMENT

Integrating Techno-Economic Analysis (TEA) and sustainability assessment has become a common practice in the development of biorefinery projects. TEA typically involves process modelling and design using process systems engineering tools, such as simulation and optimization methods, but lacks a standardized methodology. In contrast, sustainability assessment is often conducted using Life Cycle Assessment (LCA), a standardized tool outlined in ISO 14040 and ISO 14044. However, while LCA is effective for evaluating specific systems, it has limitations when assessing the broader sustainability of the bioeconomy. To address this gap, Karvonen et al. (2017) proposed a customized set of indicators specifically for evaluating the sustainability impacts of the forestry bioeconomy (Table 36).

Table 36: Sustainability indicators for forestry based bioeconomy[92]

Indicator	Dimension	Unit	Data source
Greenhouse gases (GHG)	Environmental	tCO_2eq, GWP	National statistics
Fossil fuel use	Environmental	Tons, % - of all fuels	National statistics, industry
Fine particle emission	Environmental	Particle sizes > 10, 1-10 and < 1 µm	Industry, literature, derivable from other indicators
Water contamination	Environmental	m3	Industry
Land use and land use change	Environmental	ha	National statistics, industry (e.g. wood use)
Biodiversity	Environmental	Area protected/area used, species richness	Experts, Industry
Gross domestic production (GDP)	Economic	€, %-change in GDP	National statistics
Gross and/or local value added (G/LVA)	Economic	€ added to product per m3 wood used	Industry, (Inter)National statistics
Trade	Economic	Import/export change	National statistics
National supply security and self-reliance	Social	Import/Total energy use	National statistics, industry
Employment	Social	Person years	National statistics, industry
Human health and wellbeing	Social	N/A	Questionnaires, industrial accounting
Accidents and work related diseases	Social	Person days-off/working days	National statistics, industry, insurance institutions
Equity	Social	Paid salaries, Gini-index	National statistic, industry
Capacity and freedom	Social	Disposable income, free time	Questionnaires
Participation	Social	Number of participants, number of hearings	Public documentation
Rural development	Social	Rural/urban jobs	National statistics, industry

8.1.1 CEN/TC 411[79] biobased products

The European Standardization Committee CEN/TC 411 has the following objectives:

i. Development of standards for biobased products covering horizontal aspects. This includes consistent terminology, sampling, certification tools, biobased content, application of and correlation towards life cycle analysis, sustainability criteria for biomass used and for final products, and aspects where further harmonization is needed on horizontal level.
ii. Development of standards for bio-solvents, covering product functionality, biodegradability and, if necessary, product specific aspects not covered under i.

The Committee CEN/TC 411 has been divided into 5 workgroups:

- CEN/TC 411/WG 1 - Terminology
- CEN/TC 411/WG 2 - Bio-solvents
- CEN/TC 411/WG 3 - Biobased content
- CEN/TC 411/WG 4 - Sustainability criteria, life cycle analysis and related issues
- CEN/TC 411/WG 5 - Certification and declaration tools

The most interesting one for the sustainability assessment is the WG4, which has developed the following norms:

- CEN/TR 16957:2016 (WI=00411010), Biobased products - Guidelines for Life Cycle Inventory (LCI) for the End-of-life phase.
- CEN/TR 17341:2019 (WI=00411014), Biobased products - Examples of reporting on sustainability criteria.
- EN 16751:2016 (WI=00411005), Biobased products - Sustainability criteria
- EN 16760:2015 (WI=00411006), Biobased products - Life Cycle Assessment
- prEN 18027 (WI=00411019), Biobased products - Life cycle assessment - Additional requirements and guidelines for comparing the life cycles of biobased products with their fossil-based equivalents (under approval)

The assessment of sustainability for biobased products is generally well-standardized, following established norms. Particular attention must be given when comparing the environmental impacts of biobased products with their fossil-fuel-based alternatives to ensure accurate and meaningful comparisons.

[79] https://www.cencenelec.eu/news-and-events/news/2021/briefnews/2021-06-29-standards-biobased-products-new-infographic-nen/

8.1.2 Circularity indicators

Circularity indicators for forestry biobased products and processes are aligned with the following circular economy standards[80]:

▪ ISO 59004 – Vocabulary, principles and guidance for implementation)

▪ ISO 59010 – Guidance on the transition of business models and value networks)

▪ ISO 59020 – Guidance on the transition of business models and value networks

In addition to these standards, the H2020 project, Biological Resources Certifications Schemes (BIORECER) [81] has introduced new methods and indicators applicable to biological resources and bioeconomy products. This project places a strong emphasis on traceability, supported by innovations such as blockchain technology.

8.1.3 Safe and Sustainable by Design (SSbD) criteria

The SSbD framework[82], developed by the European Commission, aims to:

- Guide the innovation process toward a green and sustainable industrial transition.
- Substitute or minimize the production and use of substances of concern, addressing both current and future regulatory requirements.
- Reduce impacts on human health, climate, and the environment during sourcing, production, use, and end-of-life phases of chemicals, materials, and products.

The framework consists of an iterative process encompassing a (re-)design phase and an assessment phase, which evolves as new data becomes available. As outlined in the recently published *Methodological Guidance*, the SSbD assessment (Figure 52) follows four main phases:

- Assessment of **hazard properties** of the chemical or material.
- Evaluation of **human health and safety** during production processes.
- Analysis of **environmental and human health risks** in the use phase.
- Quantification of **environmental impacts** across the entire life cycle.

[80] https://www.delegationcirkularekonomi.se/49bfdd/contentassets/ed47754bb0104cf996dc829e7ef0cec1/pressrelease---cirkular-ekonomi---iso-59000-serien.pdf

[81] https://biorecer.eu/

[82] https://research-and-innovation.ec.europa.eu/research-area/industrial-research-and-innovation/chemicals-and-advanced-materials/safe-and-sustainable-design_en

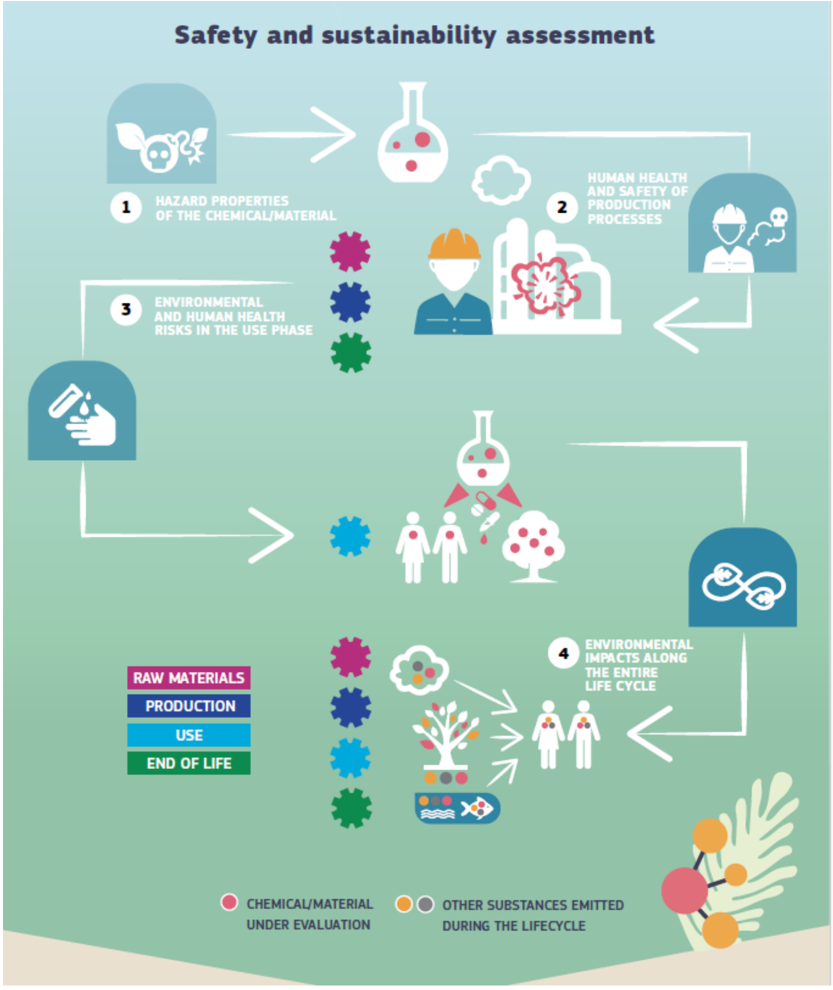

Figure 51 Safe and Sustainable by Design framework

Sustainability assessment plays a central role within the SSbD framework. It aligns closely with the impact categories and methodologies established under the European Union's Product Environmental Footprint (PEF) initiative.

9 APPENDIX E - BUSINESS ANALYSIS OF A NORDIC BIOREFINERY

Understanding and managing the environmental, social, and economic impacts of biorefinery operations is crucial to attract investors, demonstrate sustainability, and foster positive change in the biobased industry. Biobased business has been studied for their adoption factors, challenges and impacts of biobased business models within the Biomodel4regions project by Wageningen University, by performing in-depth interviews with three biobased companies in different regions across Europe. which have been analysed for their drivers, barriers, sustainability outcomes and strategic factors. The same set of questions have been asked for the theoretical Nordic biorefinery case study, to further analyse the business case from a regional bioeconomic perspective.

9.1 Adoption Factors and barriers

A summary of the adoption factors from a political, economic, technological, supply chain and organizational perspective show that there are several barriers but also drivers (Table 37)

Table 37 Summary of adoption factors

	Barriers	Drivers
Political/ institutional	**Policy Risks:** EU-level debates on forestry usage and biodiversity protection potentially restricting resource extraction.	**Policy Support:** National and regional bioeconomy strategies promoting the valorization of forest resources.
Economic	**Market Integration:** Challenges in marketing new bio-based products and achieving competitive pricing compared to fossil-based counterparts.	**Market Demand:** Interest in sustainable products such as bio-based textiles, food applications, and composite materials.
Technological/ informational	**Technology Scale-Up Challenges:** Adapting lab-scale technologies for industrial-scale applications while maintaining economic feasibility.	**Technological Advancement:** Development of processes for converting lignocellulosic biomass into value-added semi-products like sugar and fibers
Supply chain	**Logistics Costs:** High transportation costs for raw materials from remote areas.	**Resource Availability**: Ample forestry residues such as sawdust and branches, with proximity to sawmills for reduced transportation costs.
Organisational		1) Partnerships with universities for data collection on resource availability and technological development. 2) Collaboration with sawmills and potential investors for joint ventures in bio-refinery operations.

9.1.1 Adoption factors

The adoption factors for a business to thrive can be further broken down into these:

Availability of Raw Materials: Northern Sweden has abundant forest resources, including sawdust and forestry by-products, which serve as essential feedstocks for biorefineries.

Public Support for Sustainability: Strong societal support for sustainable technologies and bioeconomic solutions acts as a key driver for biorefinery development. Also, there is a strong local support of the population for sustainable technologies. The work on the national Bioeconomy Strategy in Sweden is ongoing, with clear set goals for bioeconomic growth, aligning well with the establishment of biorefineries. This strategy will also trickle down to regional levels, further supporting initiatives.

Resilience and preparedness: An important part of the proposed strategy is increased regional resilience and preparedness. Increased domestic production of chemicals, fuels, and food enhances regional and national resilience, reducing dependence on imports and improving preparedness for future challenges.

Herein, the biorefinery also contribute to increased resilience by food and feed ingredients by the production of single-cell proteins for animal feed or human consumption, using forestry by-products like sawdust as feedstock.

Increased Value from Forest Products: Processing of forest resources into high-value-added products (e.g., biochemicals, biofuels) is more profitable than traditional timber export, driving bioeconomic development.

Rural Development and Employment: A biorefinery would stimulate employment in rural areas where sawmills and forestry activities are already established, fostering economic growth outside urban centers. There is extensive know-how on pulp and paper technologies and extension into textile industry

9.1.2 Barriers

The barriers and challenges for for a business to thrive can be further broken down into these:

Technological Barriers: Scaling up processes like fermentation to industrial levels is challenging due to changes in parameters affecting feasibility. Existing infrastructure incompatibility and intellectual property constraints further limit the adoption of biobased technologies.

Market Barriers: Biobased products face high costs, low consumer awareness, and limited market acceptance. Commercialization struggles with product positioning, distribution, and the need for standardization and certification to compete with fossil-based alternatives. Low awareness of biobased products slows market demand. Education and promotion are vital to highlight and educate about biobased products.

Value Chain Barriers: Inefficient resource flows and the lack of policies supporting by-product utilization hinder the transition to circular resource systems. Effective regulations are needed to improve waste valorisation.

Feedstock Quality and Availability: Ensuring consistent biomass supply is challenging due to variability, seasonal constraints, and regional differences. Addressing feedstock heterogeneity is essential for process efficiency.

Geographical Barriers: Transportation logistics for feedstock and products require optimization to reduce costs and environmental impacts. Efficient national and international distribution systems are necessary.

Economic Barriers: High production costs, reliance on subsidies, and limited economies of scale undermine profitability. Competing with established fossil-based economies remains a significant obstacle.

Policy and regulatory Barriers: Misaligned policies and lengthy permitting processes across the EU complicate feedstock supply and market incentives. Uncertainty over forestry management practices adds complexity. Debates over forest use and differing forestry traditions across the EU create regulatory uncertainty, impacting investment and strategic decision-making.

Organizational Barriers: Dependence on skilled labor and resistance to change in legacy business models hinder innovation. Technological lock-in and path dependence limit adaptability.

9.1.3 Actions needed to overcome barriers

Specific actions must be put in place for each of the barriers which have been identified. Below the actions identified to address the above identified barriers are provided:

Table 38: Actions required to overcome the identified barriers

Barrier	Actions to Address the Barrier
Technological Barriers	- Pilot plant providers, such as the Bioeconomy Arena at RISE, can provide complementary infrastructure, expertise, and test beds to facilitate the scaling up of biorefinery projects. Integration into an industrial biorefinery cluster can further maximize these benefits. - Intellectual property (IP) challenges can be mitigated through the development and implementation of a comprehensive IP strategy, particularly tailored for startups to safeguard innovation.
Market Barriers	- Tailored go-to-market strategies should be developed for start-ups, small and medium enterprises (SMEs), and large companies, depending on their specific objectives, such as substituting fossil-derived products, introducing new products, or delivering bioeconomy-related services. - Marketing costs for innovative biobased products can be partially offset by collaborating with industry associations and implementing public awareness campaigns to enhance the visibility and acceptance of bioeconomy products.
Value Chain Barriers	- Addressing supply chain inefficiencies requires ensuring the reliable and cost-effective availability of raw materials. Establishing robust distribution channels is essential to penetrate new markets and compete effectively with fossil-based products.
Feedstock Quality and Availability Barriers	- Certification systems are critical for addressing product quality and availability concerns. For instance, the BIORECER Horizon Europe project, in which RISE Processum is a partner is developing indicators to assess the sustainability and circularity performance of bioeconomy products.
Geographical Barriers	- Regional supply chains and localized markets should be promoted to reduce transport distances and associated environmental impacts. - Developing raw material collection platforms and implementing traceability systems can ensure that feedstock originates from short and sustainable supply chains.
Economic Barriers	- Reducing production costs for biofuels and biochemicals is essential to enhance competitiveness with fossil-based alternatives. This can be achieved through continued research and development (R&D) in biotechnologies, such as precision fermentation, which offer significant cost-saving opportunities.

Regulatory Barriers	- Regulatory frameworks should further incentivize the adoption of biobased materials, building on existing policies and initiatives. - Consumer awareness campaigns should be implemented to promote biobased products and their environmental benefits. - The European Commission's *Safe and Sustainable by Design (SSbD)* framework should be leveraged to support regulatory alignment, encourage sustainable development, and streamline approval processes.
Organizational Barriers	- Organizational barriers can be addressed by fostering collaboration with industrial associations and encouraging active participation in bioeconomy exhibitions and networking events, including those organized by EU-funded projects. - Capacity-building initiatives, such as those supported by Horizon Europe projects, should be leveraged to develop skilled workforces and provide targeted support for SMEs and startups in the bioeconomy sector.

9.2 BUSINESS LEVEL

9.2.1 Description of what the business entails

In this business case a biorefinery has been established in Northern Sweden, in the county of Västernorrland was selected due to its strategic geographical location and biomass feedstock availability. The availability of biomass feedstock was mapped based on both theoretical and practical considerations, assessing feedstock suitability and geographical distribution. Sawdust derived from coniferous wood produced by local sawmills was identified as the primary feedstock for the biorefinery. In Västernorrland, the total available sawdust from three key locations—Sollefteå, Sundsvall, and Örnsköldsvik—amounts to approximately 315,000 tonnes per year. For the proposed biorefinery, it is assumed that feedstock availability is sufficient to meet an operational scale of 320,000 tonnes per year.

To optimize transport logistics and balance costs, the biorefinery is proposed to be located in Örnsköldsvik, which is geographically central between Sollefteå and Sundsvall. This location minimizes transport distances and associated costs. However, transport costs, as well as the potential for increased feedstock prices over time, were factored into the analysis, particularly for securing long-term contracts over the projected plant lifespan of 20 years.

A market analysis was conducted to identify biobased products predicted to experience significant growth and competitive demand. The biorefinery will target multiple marketable outputs from lignocellulosic sawdust, including:

- 2,3-Butanediol (2,3-BDO),
- Single Cell Protein (SCP),
- Lignin
- Biogas.

This product portfolio was selected based on both market competitiveness and the potential to maximize the value of all feedstock fractions.

With a production of not final end products, joint venture or partnership agreement need to be arranged with a company capable to develop the intermediate products into a final products e.g into fish feed of SCP and to organize the distribution channels and marketing operations.

The value delivered to the customer

The biorefinery in the country of Västernorrland will provide value to the region by producing sustainable products locally, contributing to self-sufficiency of biobased commodities. The key value propositions include:

- Production of Butanediol: This platform chemical can replace fossil-derived materials, such as in the production of polyesters and polyurethanes, where it serves as a chain extender.
- Production of Single Cell Protein: This protein can be used in food and feed applications, providing an alternative to animal-derived proteins.
- Production of Biogas: Biogas can substitute natural gas for energy production, contributing to a reduction in fossil fuel use.
- Production of Lignin: Lignin can be used as a carbon raw material, replacing fossil-based materials (energy and biobased products)

The development of innovative materials can lead to the production of higher-value products. The primary value proposition lies in substituting fossil-based materials, which has significant positive environmental impacts. Additionally, the development of innovative materials can lead to the production of higher-value products. A key technological challenge is to produce butanediol at lower costs through precision fermentation, compared to traditional chemical production methods.

The possibility to produce more sustainable products with reduce carbon emissions or even negative carbon emissions due to the use of renewable organic carbon raw materials:

- The availability or waste streams which can be used according to the principles of the circular bioeconomy as low-cost raw materials for producing added value products.
- The development or new biotechnologies which can decrease the production costs of these added value raw materials.
- The possibility to produce completely new products which do not substitute current fossil based markets but create new ones.

Business weaknesses

There are several business weaknesses of establishing a biorefinery in northern Sweden. One major challenge is the need for high sales prices and low costs to maximize return on investment, along with the necessity for affordable infrastructure to lower fixed production costs. Additionally, the authorization/permitting process can be complex (national) and time-consuming. Biorefineries require substantial funding, particularly for CAPEX, to begin operations. A well-targeted marketing strategy is essential to reach the right customer segment. Furthermore, competition from fossil-derived chemicals is constantly present, as decreasing demand for fossil fuels may lower their prices, making them more competitive. Therefore, policies and public procurement such as mandatory quotas for biomaterials or carbon taxes could help make bio-based products more attractive in comparison.

Within a business model canvas there are several building blocks:

Value Proposition: Sustainable semi-products such as bio-based sugars and fibers with applications in textiles, food, and composite materials.

Customer Segments: Primarily business-to-business markets for industries needing bio-based intermediate products. Therefore, the costumers for the products of the biorefinery case study are mainly other businesses. The applications of butanediol can be polymers (PET, PTT, PBT), fuels, fine chemicals, cosmetics, pharmaceuticals83,84.

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[83] Zhang, Y., Liu, D., & Chen, Z. (2017). Production of C2–C4 diols from renewable bioresources: new metabolic pathways and metabolic engineering strategies. *Biotechnology for biofuels*, *10*, 1-20.

[84] Bai Y, Feng H, Liu N, Zhao X. Biomass-Derived 2,3-Butanediol and Its Application in Biofuels Production. *Energies*. 2023; 16(15):5802. https://doi.org/10.3390/en16155802

Key Resources:

- **Core Technology**: Technology provider and machine suppliers.
- **Processing Infrastructure**: For scale-up and large scale tests.
- **Market Analysis**: Insights into polymer, plastic, rubber, and feed industry demands.
- **Research Partnerships**: Collaboration with research institutions for innovation.
- **Techno-Economic Analysis**: Evaluation tools to assess process viability and cost-efficiency.
- **Sustainability Framework**: Metrics for environmental impact and circular economy integration.
- **Regulatory Support**: Compliance with regional and global standards for chemicals and materials.
- **Investment**: Long-term funding for R&D, scaling, and operational expansion.

Key Activities: Process development, feasibility studies, and certification for market readiness.

Key Partners: Universities, regional authorities, feedstock suppliers, and investors, Incubators, Research Institutes

Cost Structure: Major costs include raw material procurement, transportation, and technology scale-up. The value chain has been analysed in detail in the case study. It has been shown clearly that the value generated is interesting for the partners involved and for the region, based a biorefinery concept which produces multiple outputs which are able to generate value and cover abundantly the production costs.

Revenue Streams: Sales of products to industries, with potential for premium pricing based on sustainability certifications.

Promotion of circular economy principles by utilizing industrial residues and supporting recycling practices.

Implementation of certification and traceability systems for bio-based products to ensure environmental and consumer confidence.

9.2.2 Strengths and weaknesses of the business case

Table 39 presents a summary of the main weaknesses and strengths of the analysed case study.

Table 39: Strengths and weaknesses summary

Strengths	Weaknesses
Previous experience on chemistry industry	Limited public awareness and marketing strategies for bio-based products.
Cheap raw materials	High initial costs for technology scale-up and infrastructure development.
Innovation environment	Competitive fossil derived market
Optimized logistics	Insufficient support and clarity from policy makers
Territorial biorefinery case study	Dependency on high-value markets to offset competition from cheaper fossil-based alternatives.
Demand for food and feed products	
Proximity to raw material sources reduces logistics costs.	
Support from national and regional bioeconomy strategies.	
Advanced methodologies for techno-economic and sustainability assessments.	

Overcoming weaknesses

The weaknesses identified in the biorefinery sector, such as limited public awareness, high initial costs, competitive fossil-derived markets, and insufficient policy support, can be addressed by focusing on several key areas: business development, product and process development, legal framework optimization, and improved support policies. Effective marketing strategies, joint ventures with biotech companies, and partnerships with universities can all play a crucial role. Key players who are needed to overcome these weaknesses include business developers, project managers, engineers (product and process developers), and policymakers who can streamline regulations and provide necessary support.

9.3 Sustainability Impact

Table 40 presents a summary of the main weaknesses and strengths of the analysed case study.

Table 40 Main positive and negative effecton social, environmental and economic impact

Category	Positive	Negative
Social Impact	- Job creation and economic growth in rural areas.	- Risk of uneven economic benefits, potentially exacerbating local inequalities.
	- Rural development and community engagement.	
	- Strengthened food security through efficient biomass utilization.	
Environmental Impact	- Reduction in greenhouse gas emissions (reduced footprint compared to fossil counterparts).	- Extensive water usage.
	- Promotion of biodiversity and utilization of renewable resources.	- Transportation emissions.
	- Biodegradable products (e.g., production of biodegradable biopolymers reduces plastic pollution).	- Slight acidity in waterways.
Economic Impact	- Potential for long-term profitability through sustainable product development and market positioning.	- High initial investment and operational costs pose financial risks.
	- Export opportunities and increased value creation from biomass (tripling turnover per kg of biomass).	- Potentially negative impact on traditional fossil industries and associated jobs.

Positive Impact on society

The establishment of a biorefinery in a rural area could have a significant positive impact on society by creating jobs and stimulating economic growth. It can contribute to the development of local communities and offer long-term benefits through the involvement of small and medium-sized enterprises (SMEs) within the supply chain. The biorefinery can support the forest sector and other local industries while fostering networks with other companies. The initiative can also improve work safety, job satisfaction, and gender equality, and provide opportunities for education. Moreover, it can enhance the sustainable use of forests, promote social innovation, and involve communities in decision-making processes, contributing to rural development and collective action.

Positive Impact on environment

When biochemicals and bioproducts replace fossil-derived materials, they can significantly reduce greenhouse gas emissions. The positive environmental impacts include a reduction in greenhouse gas emissions, support for biodiversity, and the use of renewable resources, contributing to a more sustainable future. And a more efficient use of feedstock resources, meaning more from every tree.

Positive (local) financial Impact

The establishment of a biorefinery can offer significant local financial benefits. By diversifying into bioenergy and bioproducts, companies can increase their resource efficiency, especially through retrofits that utilize residues for bioenergy products. The shift toward sustainable product development enhances market positioning, offering potential for long-term profitability while contributing to a more resilient and diverse local economy. Also, the biorefinery would bring employment opportunities and jobs for entrepreneurs in connection to the plant that would boost the local bioeconomy.

Negative impacts on financial, economy, society, environment,

The establishment a biorefinery, while beneficial, may also result in negative impacts across several areas. Environmentally, the extensive water usage and transportation emissions can contribute to resource depletion and air pollution. Socially, economic inequality might arise if the economic benefits of the biorefinery are not evenly distributed, potentially worsening existing disparities within communities. Economically, traditional fossil industries and associated jobs could suffer, creating resistance and disruption. Technologically, the shift may require significant adaptation.

Actions taken to address impact on the environment/society/economy

Environmental Impact: Implement water treatment and conservation technologies and optimize transportation logistics to reduce emissions. Additionally, use feedstock raw materials in a sustainable manner.

Social Impact: Ensure equitable distribution of economic benefits by promoting community engagement, investing in local workforce development, and addressing income disparities.

Economic Impact: Facilitate a just transition for workers in traditional fossil industries by supporting retraining programs and fostering economic diversification in affected regions.

Monitoring and measuring the impact

Environmental Monitoring: Water usage: Install meters and sensors to track water consumption and wastewater discharge. Use real-time data analytics to identify inefficiencies. Enforce a good sampling programme to understand physicochemical characteristics of the wastewater and its variation, find alternative applications. Regularly monitor water pH levels near discharge points and establish thresholds for corrective actions.

Transportation emissions: Utilize GPS tracking and emissions sensors to monitor transport routes and emissions. Implement fuel consumption tracking for fleet management.

Social Monitoring: Economic inequality: Track the distribution of local employment and income through surveys and interviews with community members. Measure the impact of community engagement programs. Local workforce development: Track job creation, training program participation, and employment retention in affected communities using HR and social impact data.

Economic Monitoring: Impact on traditional fossil industries: Conduct economic assessments to monitor job losses in fossil industries and track the success of retraining programs. Use industry-specific indicators to assess economic transitions.