DEGREE PROJECT

Techno-economic assessment of biooil production in a small-scale biomass conversion facility

A comparative evaluation of forest bark and cereal straw at different production scales

Hanna Hellsén

Sustainable Energy Engineering, master's level
2026

Luleå University of Technology
Department of Engineering Sciences and Mathematics

Förord

Detta examensarbete har utförts som en del av civilingenjörsutbildningen i Hållbar energiteknik på Luleå tekniska universitet. Arbetet har genomförts i samarbete med Votion Biorefineries, där studien har haft fokus på tekno-ekonomisk utvärdering av småskalig produktion av bioolja från olika biomassor.

Jag vill rikta ett stort tack till min handledare vid universitetet, Joakim Lundgren, för värdefull vägledning, konstruktiv återkoppling och stöd under arbetets gång. Jag vill även tacka min handledare på Votion Biorefineries, Anders Edling Hultgren, för insikter kring processdesign, dataunderlag och industriella perspektiv som varit avgörande för studiens genomförande. Ett särskilt tack riktas även till Bio4Energy och plattformen för Systemanalys och bioekonomi för det finansiella stödet, som har varit värdefullt för genomförandet av detta arbete. Tills sist vill jag rikta ett tack till Sveriges Ingenjörer och deras Miljöfond för det finansiella stöd som har varit värdefullt för genomförandet av studien.

Arbetet har gett mig en fördjupad förståelse för hur tekniska och ekonomiska faktorer samverkar vid utvecklingen av bioraffinaderikoncept, samt hur viktiga systemgränser och antaganden är vid utvärdering av nya energisystem.

Luleå, juni 2026
Hanna Hellsén

Sammanfattning

Detta examensarbete syftar till att utvärdera den tekniska och ekonomiska genomförbarheten av att etablera en småskalig anläggning för produktion av bioolja vid Votion Biorefineries i norra Sverige. Studien jämför två biomassabaserade råvaror, skogsbark och spannmålsstrå, och identifierar viktiga designmässiga, operativa och ekonomiska faktorer som påverkar genomförbarheten av decentraliserad biooljeproduktion.

En teknoekonomisk analys genomförs för två produktionsskalor: Fall A (1 000 ton bioolja/år) och Fall B (5 000 ton bioolja/år). Analysen omfattar råvarulogistik, anläggningslayout, massa- och kolbalanser samt ekonomiska nyckeltal såsom nettonuvärde (NPV), internränta (IRR) och återbetalningstid (PBT).

Resultaten visar att biomassans fysikaliska egenskaper har en betydande påverkan på processdesignen, främst genom skillnader i bulkdensitet och därmed varierande lagringsbehov. Spannmålsstrå kräver betydligt större lagringsytor och en större total anläggningsyta än skogsbark, vilket gör lagringsegenskaper till en viktig begränsande faktor vid både processutformning och val av råvara. Kolflödesanalysen visar att skogsbark har en högre kolutnyttjandeeffektivitet, där 82% av råvarans kol återfinns i biooljan jämfört med 72,5% för spannmålsstrå. För spannmålsstrå innebär detta att en större andel av kolet fördelas till reströmmar.

Ur ett ekonomiskt perspektiv är ingen av råvarorna lönsam vid en produktionsskala på 1 000 ton/år, vilket resulterar i negativa NPV-värden. Vid 5 000 ton/år blir skogsbark marginellt lönsam med ett NPV på cirka 9 MSEK, en IRR på 9% och en återbetalningstid på 10 år. Spannmålsstrå förblir däremot olönsamt och kräver en uppskattad produktionsskala på cirka 7 000 ton/år för att nå lönsamhet. De dominerande kostnadsdrivarna identifieras som CapEx-relaterade installationsfaktorer (Langfaktor), enhetskostnader för S1 samt priset på Kemikalie A. Känslighetsanalysen visar att kapitalrelaterade parametrar och priset på Kemikalie A har störst påverkan på de ekonomiska resultaten, där konfigurationen med skogsbark vid 5 000 ton/år uppvisar den mest robusta ekonomiska prestandan mellan analyserade scenarier.

Sammantaget är skogsbark den mest lämpliga råvaran under de utvärderade förutsättningarna, tack vare högre kolutnyttjandeeffektivitet, lägre logistiska krav och bättre ekonomisk prestanda. Småskaliga decentraliserade bioraffinaderier kan dock fortfarande bidra med ett bredare systemvärde genom ökad regional energisäkerhet, förbättrad infrastrukturresiliens och bidrag till långsiktiga klimatmål utöver konventionella teknoekonomiska mått.

Abstract

This master thesis aims to assess the technical and economic feasibility of establishing a small-scale bio-oil production facility at Votion Biorefineries in northern Sweden. The study evaluates two biomass feedstocks, forest bark and cereal straw, and identifies key design, operational and economic factors influencing the feasibility of decentralized bio-oil production.

A techno-economic assessment is conducted for two production scales: Case A (1,000 tonnes bio-oil/year) and Case B (5,000 tonnes bio-oil/year). The analysis covers feedstock logistics, facility layout design, mass and carbon balances and economic performance indicators including Net Present Value (NPV), Internal Rate of Return (IRR) and payback time (PBT).

Results show that biomass physical properties significantly influence process design, primarily through differences in bulk density and resulting storage requirements. Cereal straw requires substantially larger storage areas and overall plant footprint than forest bark, making storage characteristics a key design and feedstock selection constraint. Carbon flow analysis indicates that forest bark achieves higher carbon utilization efficiency, retaining 82% of feedstock carbon in the bio-oil compared to 72.5% for cereal straw, which directs a larger fraction of carbon to residual streams.

Economically, neither feedstock is viable at 1,000 tonnes/year, yielding negative NPVs. At 5,000 tonnes/year, forest bark becomes marginally viable with an NPV of approximately 9 MSEK, an IRR of 9% and a payback time of 10 years, while cereal straw remains unprofitable and requires an estimated scale of 7,000 tonnes/year to reach breakeven. The dominant cost drivers are identified as CapEx-related installation factors (Lang factor), unit S1 costs and the price of Chemical A. The sensitivity analysis confirms that capital-related parameters and Chemical A pricing are the strongest influences on economic outcomes, with the forest bark Case B configuration showing the most robust performance across scenarios.

Overall, forest bark is the more suitable feedstock under the evaluated conditions due to better carbon efficiency, lower logistical burdens and improved economic performance. Small-scale decentralized biorefineries may still provide broader system value through enhanced regional energy security, improved infrastructure resilience and contributions to long-term climate mitigation goals beyond conventional techno-economic metrics.

Contents

1 Introduction

The global energy system remains strongly dependent on fossil fuels, both in terms of energy supply and economic structure. Although the transition toward renewable energy sources is underway, it is a complex process constrained by both technical limitations and political and economic factors.

Today, the majority of global energy demand is still met by oil, coal and natural gas, and despite the growing share of renewables, fossil fuels are projected to remain dominant in the foreseeable future. Current trends indicate that they may still account for around 78% of global energy consumption in 2040. This continued reliance is partly explained by their high energy density, established infrastructure and their critical role in sectors such as transport, heavy industry and power generation, particularly in developing economies (Millinger et al., 2025).

In addition to technical and infrastructural factors, fossil fuels are deeply embedded in the global economy. Many countries depend on fossil fuel production and export revenues for economic stability. This dependence is further reinforced by long-standing industrial structures, government subsidies and lobbying activities, which collectively contribute to maintaining fossil fuels as a relatively cost-competitive energy source compared to many renewable alternatives (Millinger et al., 2025).

Against this background, bioenergy has emerged as one of the key renewable energy pathways in the transition toward net zero emissions (NZE) by 2050. Currently, bioenergy accounts for approximately 6% of the total global energy supply. In the NZE scenario, this share is projected to increase to around 13% by 2030 and further to 18% by 2050 (International Energy Agency, 2023).

This expansion is expected to rely on sustainable sourced biomass in order to minimize negative impacts on biodiversity, soil health and water resources. To avoid competition with food production, the total global use of bioenergy is limited to approximately 100 EJ in the NZE pathway. At the same time, a structural shift is anticipated, moving away from conventional feedstocks toward advanced bioenergy sources such as forest residues, agricultural residues and organic waste (International Energy Agency, 2023).

1.1 Aim and objectives

This project aims to assess the technical and economic feasibility of establishing a small commercial facility for bio-oil production at Votion Biorefineries. To achieve this aim, this report will:

- Evaluate operational considerations for the selected feedstocks, including availability, feedstock demand from competing industries, seasonal variability, upscaling logistics and storage requirements. The feedstocks considered are:
  - Forest bark (woody biomass)
  - Cereal straw (agricultural residue).
- Determine the required land area and layout for two production scales:

  - Case A: 1,000 tons of bio-oil per year
  - Case B: 5,000 tons of bio-oil per year.
- Establish mass balances for bio-oil production at both scales and for each feedstock.
- Estimate Capital Expenditure (CapEx), including equipment sizing, cost scaling and installation factors, for all scenarios.
- Estimate Operating Expenditure (OpEx), including feedstock costs, energy consumption, labour, maintenance and utilities, for all scenarios.
- Evaluate key economic indicators, Net Present Value (NPV), Payback Time (PBT) and Internal Rate of Return (IRR), for each scenario.
- Perform a sensitivity analysis to evaluate how variations in key CapEx and OpEx parameters affect profitability.
- Assess carbon flows within the process.
- Identify the most promising pathway and key parameters for further development.

1.2 Scope and limitations

This study evaluates the technical and economic performance of a bio-oil production facility located in northern Sweden, using forest bark and cereal straw as feedstocks sourced from Swedish forestry and agricultural systems. Two production scales are analysed: Case A (1,000 tonnes/year) and Case B (5,000 tonnes/year). Key operational factors include feedstock availability, competing demand, seasonal variability, logistics and storage requirements.

The analysis includes mass balances, carbon flow assessment and process design for each case. Facility layouts are created to estimate space requirements and support equipment sizing. Capital expenditure (CapEx) is estimated using equipment cost scaling and installation factors, while operating expenditure (OpEx) includes feedstock, energy, labour, maintenance and utilities. Economic performance is evaluated using Net Present Value (NPV), Payback Time (PBT) and Internal Rate of Return (IRR). A sensitivity analysis is conducted to assess the impact of key cost parameters.

The system boundary covers biomass collection, transportation, on-site handling and storage, conversion and storage of the produced bio-oil. Downstream processes such as distribution and end-use are excluded as well as biomass production.

The study has several limitations. The analysis is based on pilot-scale data and simplified assumptions, including fixed yields and estimated carbon distributions, which may not reflect industrial-scale performance. CapEx is approximated using the Lang factor method and does not account for site-specific conditions or detailed design.

Uncertainties also exist in the carbon flow analysis where it relies on simplified parameters and should be interpreted as indicative. Data availability and time constraints have required assumptions regarding feedstock properties, process performance and cost parameters, which may affect the accuracy of the results.

2 Theoretical framework for bio-oil production systems

This chapter presents the theoretical background for the technical, economic and environmental aspects of bio-oil production. It explains the basic principles of biomass conversion technologies and describes the main types of feedstocks used for producing bio-oil. The chapter also discusses small-scale commercial production and the challenges of scaling up processes from laboratory or pilot scale to full industrial operation.

In addition, a techno-economic assessment is explained as a tool for evaluating financial feasibility and overall system performance. Finally, climate impacts and carbon flows in bioenergy systems are discussed to place bio-oil production in a wider sustainability context. Together, these sections provide the foundation for the analysis and discussion presented later in this study.

2.1 Bio-oil and biomass conversion technologies

Bio-oil is a complex liquid mixture of many organic compounds, mainly composed of carbon, hydrogen and oxygen. It can be produced by thermally decomposing biomass such as woody residues, agricultural waste or algae. Biomass itself is mainly built up of cellulose, hemicellulose and lignin. The most common production methods are thermochemical conversion processes, especially pyrolysis and hydrothermal liquefaction (HTL) (Baloch et al., 2018).

2.1.1 Pyrolysis

Pyrolysis is a thermochemical process where biomass is heated in the absence of oxygen. During pyrolysis, rapid heating breaks down the biomass into unstable vapours, which are quickly removed from the reactor to reduce secondary cracking reactions and then condensed into liquid bio-oil. A key limitation of pyrolysis is the requirement for low moisture content in the feedstock, which often require energy-intensive drying before the process (Baloch et al., 2018).

Different types of pyrolysis are defined by temperature, heating rate and residence time. Fast pyrolysis uses rapid heating rates (10–200 °C/s) and temperatures of 500–650 °C, producing the highest bio-oil yield, typically 60–70 wt%. Slow pyrolysis operates at lower heating rates (0.1–1 °C/s), temperatures of 400–600 °C, longer residence times and mainly produces biochar rather than bio-oil. Other variants, such as vacuum pyrolysis and flash pyrolysis, use reduced pressure or extremely high heating rates (up to 1000 °C/s) to increase bio-oil yield and improve product quality (Baloch et al., 2018).

2.1.2 Hydrothermal liquefaction

Hydrothermal liquefaction (HTL) is often considered as an alternative to pyrolysis because it can process wet biomass without prior drying. The process is carried out in a solvent, usually water, at temperatures of 220–380 °C and pressures of 5–25 MPa, although organic solvents such as ethanol, methanol or acetone may also be used. Under these high-temperature and high-pressure conditions, biomass breaks down into smaller molecular fragments. These fragments are reactive and undergo further reactions such as polymerisation, condensation and cyclisation, forming more stable compounds that together constitute the final product, bio-oil (Baloch et al., 2018).

2.2 Feedstocks for bio-oil production

Forest bark and cereal straw represent two fundamentally different types of biomass. They differ in origin, chemical composition, typical applications and seasonal availability, as well as logistics and storage requirements.

2.2.1 Forest bark as a biomass resource

Forest bark are the outer layers surrounding the vascular cambium of a tree and is generally divided into inner bark (living tissue) and outer bark (dead tissue), as illustrated in Figure 1. It is a natural by-product generated during forest harvesting and wood processing. In 2021, the global availability of bark from the wood-processing sector was estimated at approximately 200 million cubic meters (Supriyadi et al., 2025).

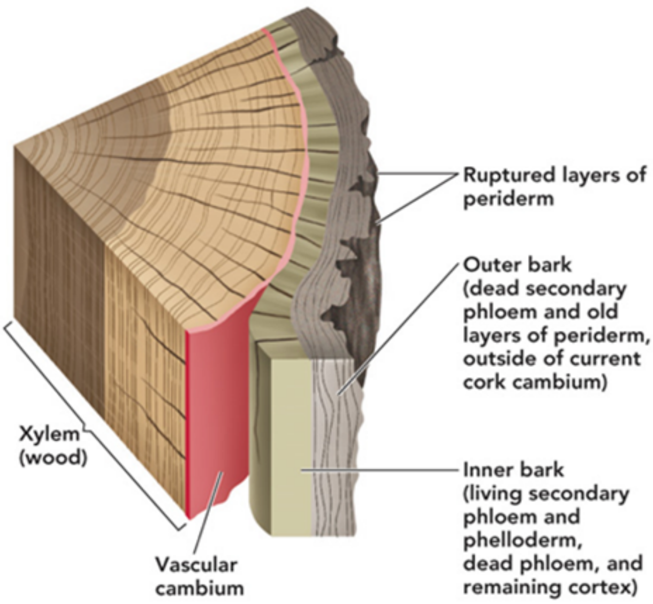

Figure 1: Structural representation of bark anatomy and layer composition (Plantscience4u, n.d.).

Bark is a heterogeneous material mainly composed of cellulose (around 30%), lignin, extractives and inorganic components such as ash, typically ranging between 1–10%. Because of its relatively high lignin and extractive content, bark often has a higher calorific value than wood, which makes it an attractive renewable energy source. However, its performance in combustion systems is strongly influenced by moisture content. High moisture levels reduce energy efficiency and the relatively high ash content can create operational challenges, including slag formation, corrosion and deposit build-up in boilers and incineration systems (Supriyadi et al., 2025).

Industrial and environmental applications

The utilization of bark spans from traditional medicinal use to modern industrial applications. In Sweden, its primary use is as biofuel. Bark is commonly processed into pellets, providing a lower-cost alternative to pure wood fuels. Spruce and pine bark have a relatively high calorific value, typically ranging from 17 to 25 MJ/kg, which makes them more suitable for energy production (Pásztory et al., 2016).

Beyond energy applications, bark is also used in the construction sector as insulation boards and particleboard materials. Bark also has environmental and chemical applications. It can serve as a bioindicator of air pollution, as its surface accumulates pollutants over long exposure periods. In addition, bark is a source of valuable chemical extracts with potential medical applications, including immune-stimulating compounds (Pásztory et al., 2016).

Seasonal variability in biomass availability

Forest fellings in Sweden are mainly carried out during winter or summer, depending on soil bearing capacity, moisture conditions and machine accessibility. Winter operations are often preferred on soft or wet soils, as frozen ground reduces the risk of soil damage. Summer harvesting is more suitable on stable and well-drained terrain. The decision to harvest is guided by forest management plants. Trees are typically felled when they reach a predefined rotation age, target diameter or economic maturity (Meraskog, 2021).

Supply chain logistics

Harvested timber is primarily transported by truck from forest sites to industrial facilities (Holmen, n.d.). At these facilities, different debarking methods are used to separate the bark from the stems (Skogsindustrierna, 2026). The resulting woody biomass residues, including bark, are then transported to relevant industries for further utilization (Pohjanen & Ström Transport, n.d.).

Storage conditions and requirements

Forest bark contains a high proportion of parenchyma cells, which results in a relatively high concentration of accessible sugars and increased heat generation during storage. This cellular structure also makes bark more susceptible to microbial activity, particularly fungal degradation. Material losses of approximately 5–10% have been reported for storage periods of two to five months. In addition, bark emits volatile organic compounds during the first weeks of storage and when stored in piles, the concentrations have been observed to decline to undetectable levels within about four weeks (Anerud et al., 2019).

To reduce storage-related degradation, several handling measures are recommended. Pile height should not exceed approximately seven meters in order to limit excessive heat build-up and the risk of self-heating. Bark should be stored under breathable covers that allow ventilation of heat and moisture while protecting against precipitation. Mixing bark from different tree species, especially with varying moisture contents, should be avoided, as this may accelerate uneven microbial activity and temperature development. Storage time should preferably be limited to three to four months and significant internal temperature increases should be expected in larger piles. Mechanical pressing or dewatering to reduce the moisture content below approximately 50% can further improve storage stability and extend the safe storage period (Anerud et al., 2019).

2.2.2 Cereal straw as a biomass resource

Cereal straw is an agricultural residue from grain crops such as wheat, barley, rye, oats and triticale. It consists mainly of organic material and can contain up to about 60% organic carbon. As a lignocellulosic feedstock, straw is suitable for conversion into various biofuels and bio-based products. However, removing straw from the field instead of allowing it to decompose can negatively affect soil quality by reducing the return of organic carbon and nutrients. To maintain long-term soil fertility, additional fertilization may therefore be required (Bentsen et al., 2016).

Compared to most forest biomass, straw generally has higher ash content, which increases the risk of slagging and contamination in combustion systems. It also has a lower bulk energy density than denser fuels such as wood pellets, which affect transportation efficiency and storage logistics. Despite these limitations and due to its complex chemical composition straw remains a flexible resource for energy production as well as for the manufacture of biomaterials and biochemicals (Bentsen et al., 2016).

Industrial and environmental applications

In Sweden, approximately 60% of cereal straw is left in the field, while about 40% is collected for further use. Most of the harvested straw is used in animal production, where around 60% serves as bedding material and about 30% is used as feed. Additionally, straw is applied as protective mulch for crops such as strawberries and carrots, while straw bales can function as structural wall elements in agricultural storage buildings (Casimir and Gunnarsson, 2020).

Farmers willingness to sell straw varies and is largely influenced by the balance between economic incentives and concerns about soil fertility. Many farmers, especially those focused on specialised crop production, are concerned that extensive straw removal may reduce long-term soil quality. These farmers tend to harvest smaller quantities. In contrast, those who view straw as an additional income source are more likely to remove larger volumes. In contradiction to this, the regions with the greatest potential for industrial straw supply, mainly in southern Sweden, also show higher levels of concern regarding soil fertility (Casimir and Gunnarsson, 2020).

Livestock producers are generally more willing to sell straw, as they are already experienced in handling and managing it. Other influencing factors include access to direct contracts, a preference for short contract periods due to harvest uncertainty, and the structure and variability of pricing mechanisms (Casimir and Gunnarsson, 2020).

Season variability in biomass availability

Grain harvesting typically occur from late summer to early autumn, depending on crop species and regional climate. Yields are strongly affected by annual weather conditions, including temperature, precipitation and extreme events such as drought or heavy rainfall. As a result, total harvest volumes can vary significantly between years, directly influencing the availability of straw as an agricultural residue (Jordbruksverket, 2025).

Supply chain logistic

Baling is often outsourced to agricultural contractors, particularly on large-scale crop farms. Smaller farms, especially those with integrated livestock production, commonly perform baling themselves. Increased industrial demand could create shortages in baling capacity, requiring additional contractors or new market actors. Bale collection is usually carried out by the farmers, who generally have sufficient equipment to manage this even at larger scales. Transport from field to customer is typically performed by tractor, although in about 30% of cases the customer is responsible. At an industrial scale, longer transport distances reduce the cost-effectiveness of tractor-based logistics. Therefore, larger cooperatives or industry actors (e.g., Lantmännen) would likely need to provide coordinated transport and logistics solutions to ensure efficient supply chains (Casimir and Gunnarsson, 2020).

Storage conditions and requirements

Straw is normally stored at a moisture content below 20%, with recommended levels of 15–16% to minimise biological degradation. Higher moisture increases the risk of mould growth, internal heat generation, dry matter losses and safety hazards. In Nordic climates, achieving sufficiently low moisture can be challenging due to unstable autumn weather. If moisture content exceeds approximately 20%, plastic wrapping is recommended, typically with three layers for winter storage and up to six layers for storage longer than one year. For outdoor storage, wrapping is generally required to prevent moisture from being introduced. If straw is not wrapped, it should be stored indoors or under a roof with good ventilation and moisture maintenance. Chemical preservatives may further improve storage stability (Lötjönen and Joutsjoki, 2016).

2.3 Small-scale commercial bio-oil production

Small-scale commercial production is an intermediate phase between technology development and full-scale industrial deployment. To understand its role in scale-up, it is necessary to distinguish it from pilot and demonstration plants, which serve different purposes in the development process.

Industrial technologies typically progress through several plant scales. Pilot plants operate periodically and are used to test and validate specific technical aspects of a process. They are not fully integrated into the value chain. Demonstration plants operate continuously over longer periods and represent a complete production process. These are integrated into the value chain and aim to verify technical performance under realistic conditions, build stakeholder confidence and support the development of standards. Commercial-scale plants are designed for full-scale production, with a focus on improving performance and reducing costs through operational experience and learn-by-doing (Hellsmark et al., 2016).

Small-scale commercial operations often face significant economic challenges, mainly due to limited access to financial capital. Banks and other financial institutions tend to view these ventures as high-risk, since they often lack sufficient collateral, have short credit histories and involve technological uncertainty. Small-scale producers are also more sensitive to market fluctuations, which can quickly affect revenues and liquidity. They must also compete with larger, more established companies that benefit from economies of scale, as well as stronger financial and operational capacity (Bakri, 2024).

2.4 Techno-economic assessment of bioenergy systems

A techno-economic assessment (TEA) is a structured framework used to evaluate the technical and economic performance of a process, product or service. It combines process modelling, engineering design and financial analysis to connect technical feasibility with economic viability in a production system (Mishra et al., 2023; Mirkouei et al., 2017).

A TEA provides decision-makers with a quantitative basis for strategic planning. It evaluates key factors such as investment costs, operating expenses, revenues, risks, uncertainties and time frames to assess the economic potential of emerging technologies. By doing so, it helps stakeholders, including biomass owners, investors and policy makers in making informed decisions about resource allocation and investments (Mishra et al., 2023).

2.4.1 Technical metrics

Technical metrics are important components in a techno-economic assessment (TEA), as they are used to evaluate process performance, scalability and resource efficiency. Two central aspects are mass balancing and process scale-up.

Mass balancing is a fundamental method used to describe and control material flows within a system. It is based on the principle of conservation of mass, meaning that the total mass entering a process unit must equal the total mass leaving the unit (Wills and Finch, 2016).

Another important aspect in a TEA is process scale-up, which refers to the transition of a process from laboratory or pilot scale to industrial production. The objective is to increase production capacity while maintaining performance, safety, product quality and economic feasibility. This stage is technically demanding because physical and chemical properties do not scale proportionally, requiring careful engineering design to ensure stable and predictable operation (Cleaver, 2023).

2.4.2 Financial metrics

Several financial metrics are commonly used within a TEA to assess investment performance. Capital Expenditures (CapEx) refers to long-term investments in physical assets intended to generate future benefits, such as machinery, buildings or vehicles. These costs are associated with expansion, modernization or efficiency improvements and typically have a lifespan exceeding one year. The total capital investment can then be estimated by multiplying the total equipment cost by a Lang factor. The Lang factor is an empirical coefficient used to account for additional costs associated with plant construction, including piping, installation, instrumentation, civil works, engineering and other indirect costs. This approach provides a simplified method for approximating the capital investment cost of the facility during early design stages (Dahmen et al., 2026). In contrast, Operational Expenditures (OpEx) represent the recurring costs required for day-to-day operations. These include costs such as salaries, utilities, maintenance and administrative costs (Ross, 2025).

Net Present Value (NPV) measures the profitability of an investment by calculating the present value of expected future cash flows and subtracting the initial investment. Future cash flows are discounted using a chosen discount rate to account for the time value of money. A positive NPV indicates that the project is expected to generate value above its cost and is therefore considered financially feasible (Sinaga et al., 2023).

Internal Rate of Return (IRR) is the discount rate at which the NPV equals zero. It represents the expected annual rate of return of the investment. A project is generally accepted if its IRR exceeds the required rate of return. However, IRR may be difficult to interpret when cash flows change sign more than once, potentially leading to multiple internal rates of return (Sinaga et al., 2023).

Payback Time (PBT) indicates the time required for cumulative cash inflows to recover the initial investment. It provides a simple measure of liquidity risk and capital recovery speed. However, it does not account for the time value of money and ignores cash flows after the payback period. Therefore, it should be used alongside more comprehensive metrics such as NPV or IRR (Sinaga et al., 2023).

3 Methodology

The study was conducted using a structured methodology combining process modelling, a techno-economic assessment and a carbon flow analysis. The aim was to evaluate how production scale and feedstock choice affect plant design, economic performance and carbon distribution within the defined system boundaries.

3.1 System boundaries and scenario definition

The system boundaries were defined from biomass collection to the end of production of bio-oil at the facility. This includes biomass harvesting, transportation to the production site, on-site storage, the conversion process and the storage of bio-oil. Activities downstream of the production facility were excluded such as further upgrading, distribution and end-use of the bio-oil, illustrated in Figure 2.

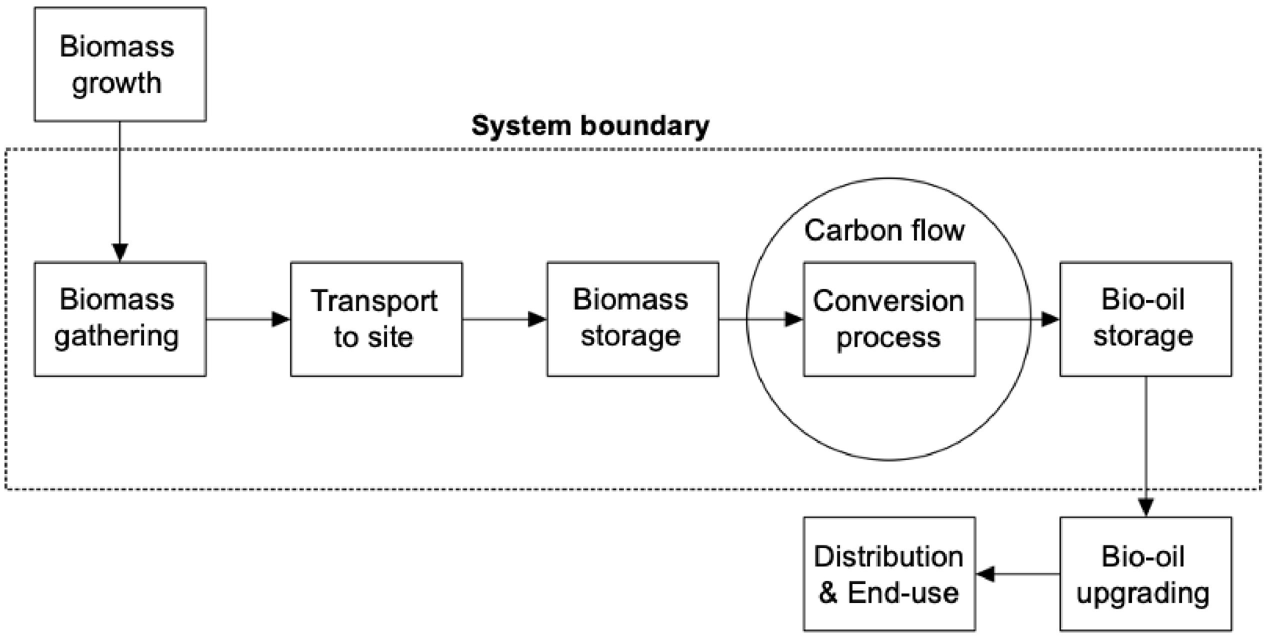

Figure 2: System boundary illustrating included processes and excluded flows. The carbon flow assessment is limited to the conversion process.

Two production cases were defined in order to analyse the effect of scale, on plant design and layout. Case A represents a facility with an annual production capacity of 1,000 tonnes of bio-oil, while Case B represents a scaled-up configuration with a production capacity of 5,000 tonnes per year. The plant was assumed to operate 300 days per year and the same operating assumptions were used for both cases to allow comparison.

Two types of feedstock were analysed: forest bark and cereal straw. The same methodology was applied to both to ensure comparability.

The process consists of 9 units, S1–S9, where S1 is the main input and S9 is the main output. The inputs consists of biomass, Chemical A and B as well as water and a solvent, where the solvent is recycled from S8 to S3. The output consists of bio-oil, Chemical C and outputs from residual streams (from S5 and S7). The process is illustrated in Figure 3.

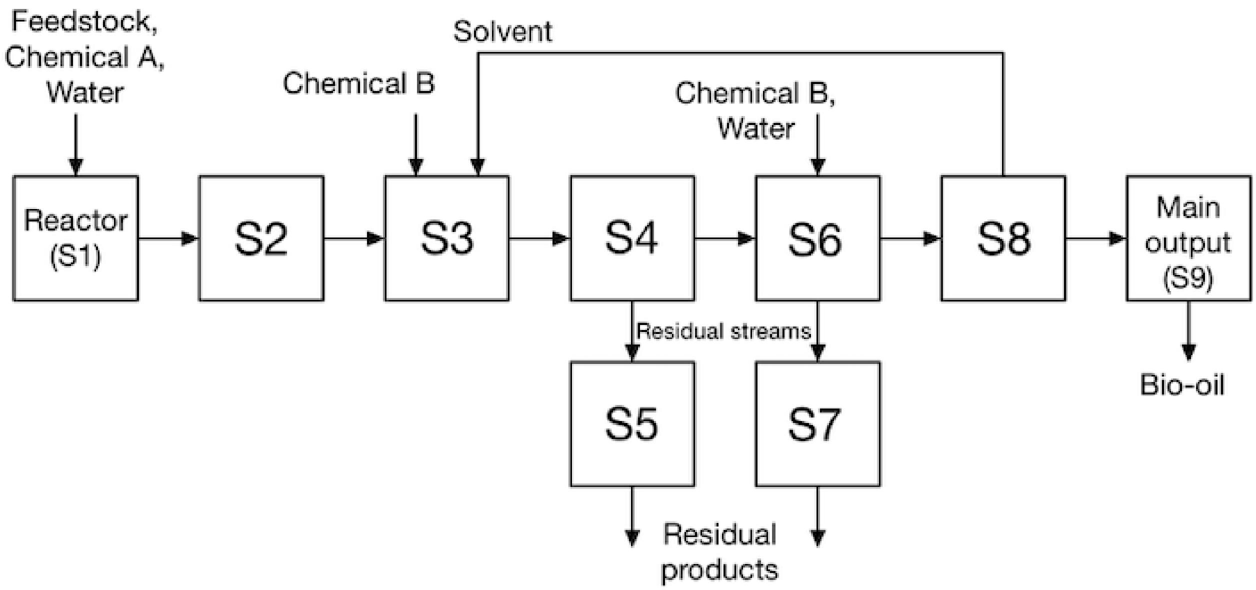

Figure 3: The conversion process illustrating the different units and flows between them.

3.2 Feedstock characterization and analysis

The feedstock analysis was carried out to evaluate the suitability of forest bark and cereal straw for bio-oil production, considering practical aspects affecting their use.

3.2.1 Availability calculations and other operational aspects

The availability of forest bark and cereal straw was estimated based on simplified resource fractions representing the portion of biomass that could be collected for industrial use.

The annual volume of harvested roundwood in Sweden was estimated at 70.3 million m^3fub (2024) (Skogsstyrelsen, 2024a). The theoretical bark availability was calculated using a bark fraction of 0.13 (Håkansson, 2000) and the volume was converted to mass using a density of 525 kg/m^3 (Petráš et al., 2020). To estimate the practically available resource, 90% was deducted to account for current uses, while the remaining 10% was assumed to represent the fraction that is practically available (Larsbrink, 2024). This fraction excludes material that remains in the forest or is otherwise not collected.

A similar approach was used for cereal straw. The total grain harvest in Sweden was estimated at 5.2 million tonnes (2024) (Karlsson, 2025). A straw-to-grain ratio of 0.5 was applied (Nilsson and Bernesson, 2009), and the result was reduced by 90% to reflect current use, with the remaining 10% assumed to be available for utilization (Casimir and Gunnarsson, 2020; Björnsson and Prade, 2021).

To analyse regional availability, data on forestry and agricultural production were collected and grouped into three geographical regions in Sweden. The northern part is Norrland, the central part is Svealand, and the southern part is Götaland, as illustrated in Figure 4.

Figure 4: Map of Sweden showing its three main regions: Norrland (north), Svealand (central) and Götaland (south) (Wikipedia, 2025).

Operational aspects related to the use of bark and straw were analysed to identify practical limitations including feedstock demand from competing industries, seasonal variability, upscaling logistics and storage requirements. Literature and industry sources were used to describe the operational considerations with a summarizing traffic light evaluation.

3.2.2 Traffic light evaluation

The traffic light assessment is based on a three-colour system: green, yellow and red. Green represents low risk, favourable conditions and minimal obstacles to large-scale implementation. Yellow represents moderate risk, with manageable challenges requiring reasonable technical or logistical measures. Red represents high risk, indicating significant operational constraints that may compromise technical feasibility, economic viability or stable operation. The specific evaluation criteria for each operational consideration are described below.

Availability of biomass

- 🟢 Stable and sufficient supply at local or regional level. Availability exceeds or reliably meets demand.
- 🟡 Limited or uncertain supply. May require sourcing from multiple suppliers or regions.
- 🔴 Insufficient, highly uncertain or inconsistent supply.

Resource demand from competing industries

- 🟢 Limited competition from other industries. Feedstock is not widely demanded.
- 🟡 Moderate competition. Availability and pricing may be affected.
- 🔴 High competition from other industries, significantly impacting availability and cost.

Season variability in biomass availability

- 🟢 Minimal or no seasonal variation in supply.
- 🟡 Moderate seasonal fluctuations. Requires planning or buffer storage.
- 🔴 Strong seasonal dependency. High risk of supply shortages without extensive storage solutions.

Upscaling logistics

- 🟢 Straightforward to scale up. Compatible with existing infrastructure and logistics systems.
- 🟡 Some logistical challenges. Requires additional investment or system adjustments.
- 🔴 Significant logistical barriers to scaling (e.g., transport limitations, low bulk density, handling complexity).

Storage conditions and requirements

- 🟢 Easy to store with minimal requirements and low risk of degradation.
- 🟡 Requires controlled storage conditions (e.g., moisture, temperature).
- 🔴 Complex storage requirements. High risk of degradation, biological activity or safety issues (e.g., self-heating).

3.3 Facility design and scale-up methodology

The facility was divided into blocks representing different process and storage areas, and preliminary calculations were performed to estimate the space requirements of each block. A storage capacity corresponding to 14 days of operation was assumed for all storage units and a minimum spacing of four meters was assumed between blocks to allow for access and safety. The layout is developed with consideration of the main road network and railway lines.

For Case A, pilot data was used to estimate the daily biomass demand for bark and straw. Based on these values, storage volumes were calculated using assumed bulk densities of 500 kg/m³ for bark and 100 kg/m³ for straw (Petráš et al., 2020; Narra et al., 2012). Storage heights of three meters for bark and six meters for straw were applied. The process design required 12 tanks (according to pilot data) and their dimensions were estimated assuming cylindrical geometry with the height exceeding the diameter. A minimum clearance of two meters was maintained between tanks and to the surrounding boundaries.

Bio-oil storage was also based on a 14-day capacity, corresponding to approximately two process tanks, with similar spacing assumptions. The storage requirement for chemical components, A, B and C was estimated from pilot data and also assumed to be cylindrical and designed with the same clearance distances. In addition, truck access roads were assumed to be six meters wide to comply with vehicle regulations (maximum truck width of 2.6 meters) (Transportstyrelsen, n.d.). The road layout was designed to ensure efficient traffic flow and minimize the need for reversing or turning during loading and unloading operations.

For Case B, the system was scaled up based on the same design principles. Biomass storage capacity was increased proportionally to the higher production rate, while maintaining the same storage heights. Process and storage units were scaled in volume to match the increased throughput, while keeping spacing requirements unchanged. Due to an increase in total facility area, internal road lengths were also increased.

3.4 Mass balance calculations

The mass balance was established by first identifying all input and output streams and assigning them to the respective process units. Pilot data was then used to define the relationship between biomass input and product yield, which served as the basis for estimating the required feedstock input as well as the relationship with other process inputs.

For Case A, the biomass demand was determined based on a target production of 1,000 tonnes of bio-oil per year. All input and output streams were then calculated and combined to ensure mass conservation within the system boundaries. The balance was verified by confirming that total inputs equalled total outputs. Units S1 and S2 were expressed as daily mass flows, while downstream units were represented in kg/h to enable estimation of volumetric flow rates and equipment sizing. The same calculation procedure was applied to Case B and repeated for cereal straw to allow comparison between feedstocks.

3.5 Simplified climate assessment and carbon flow

Pilot data were used to estimate the carbon flows in the system. The carbon in the oil was calculated by multiplying the oil yield by its carbon content. The remaining carbon in the process was estimated by comparing the carbon content of the feedstock before and after processing.

It was assumed, based on pilot data, that 5% of the carbon is released as CO_2. This was used to estimate the amount of carbon emitted as gas. The remaining carbon was assumed to stay in non-gaseous products.

The results provide an overview of the carbon distribution within the system and allow for comparative assessment of remaining carbon and emissions between scenarios. However, the results should be interpreted as indicative rather than absolute, as they are based on pilot-scale data and simplifying assumptions, including a fixed CO_2 emission fraction. Consequently, the model does not capture full process variability or detailed distribution of carbon in non-gaseous residues.

3.6 Economic analysis

The economic analysis was conducted to evaluate the financial feasibility of the proposed bio-oil production system. The analysis included estimation of capital expenditure (CapEx), operating expenditure (OpEx) and the economic performance of the system using indicators such as Net Present Value (NPV), Internal Rate of Return (IRR) and Payback Time (PBT). The calculations were performed for both production scales and feedstock scenarios in order to compare their economic performance.

3.6.1 Capital expenditure estimation

The volumes of the process units were estimated based on the results from the mass balance calculations. These volumes were used to determine the required capacities of the process equipment.

A market survey was conducted to identify used industrial equipment with capacities corresponding to the calculated process requirements. The purchase costs of selected equipment were used as the basis for estimating the equipment investment cost. The total equipment cost was calculated by multiplying the unit cost by the number of units required according to the estimated process volumes. All storage units were combined into one category called *Storage*, including storage for biomass, bio-oil and Chemical A, B and C. Forest bark biomass storage was assumed to require breathable covers, whereas cereal straw was assumed to require 3 layers of plastic wrapping.

To estimate the total capital investment, the total equipment cost was multiplied by a Lang factor of four. The calculation procedure was applied to both cases and feedstocks.

3.6.2 Operating expenditure estimation

The operating expenditure (OpEx) includes all costs associated with the operation of the facility, including feedstock and process inputs, electricity, personnel, maintenance and other operational costs.

Feedstock and input material prices were obtained from publicly available sources. Due to the small production scale, a higher solvent price was assumed, reflecting limited purchasing volumes and the absence of bulk discounts.

The energy content of both forest bark and cereal straw was assumed to be 5 MWh/tonne (Belbo and Talbot, 2014; Ojanguren, 2008). Electricity consumption was estimated using mass flow calculations combined with pilot plant data to determine the specific energy demand of the process. The total electricity consumption was then calculated for each scenario.

Personnel costs were estimated per employee per year, including salary and associated employment costs. Maintenance costs were assumed to correspond to 2.5% of total CapEx per year, while other operational costs were estimated as 1% of CapEx (Edling Hultgren, 2026).

3.6.3 Profitability indicators

The economic performance of the scenarios was evaluated using NPV, IRR and PBT. A project lifetime of 20 years and a discount rate of 8% were applied, consistent with values commonly used in techno-economic assessments of emerging energy technologies (Zetterholm et al., 2020). CapEx was assumed to occur in year 0, while OpEx was applied annually from year 1. Revenues were based on the sale of the main product, bio-oil, as well as the secondary product, Chemical C, see Table 1.

Table 1: Financial inputs for calculations.

Category	Price [SEK/kg]
Biomass	0.75[1]
Chemical A	11.72[2]
Chemical B	1.07[3]
Solvent	26.63[4]
Bio-oil	8.52[1]
Chemical C	8.10[1]

[1](Edling Hultgren, 2026), [2](in-house data), [3](in-house data), [4](in-house data).

NPV was calculated by discounting the annual net cash flow over the project lifetime and adding them to the initial investment:

$$NPV = -C_0 + \sum_{t=1}^{n} \frac{C_t}{(1+r)^t} \tag{1}$$

where:

$C_0 =$ Initial investment

$C_t =$ Net cash flow in period t

$r =$ Discount rate

$t =$ Number of time periods

$n =$ Total number of periods.

IRR was determined as the discount rate at which the NPV equals zero:

$$IRR = \frac{FV}{PV}^{\frac{1}{n}} - 1 \tag{2}$$

where:

$FV =$ Initial investment

$PV =$ Net cash flow in period t

$n =$ Total number of periods.

PBT was estimated from the cumulative cash flow, defined as the time required for the initial investment to be recovered:

$$\text{Payback time} = \frac{\text{Initial investment}}{\text{Annual cash flow}} \tag{3}$$

Full production capacity was assumed from year 1 and did not account for potential ramp-up periods, which may lead to an underestimation of the payback time. These indicators were calculated for each feedstock and production scale to enable a comparative evaluation of economic feasibility.

3.7 Sensitivity and risk analysis

Three parameters were selected for the sensitivity analysis: the Lang factor (in CapEx), solvent waste, and the price of Chemical A. Base values were defined based on previous calculations, with the Lang factor set to 4, solvent waste to 4% and the price of Chemical A to 1,100 EUR per tonne. The range of variations applied to these parameters is presented in Table 2.

Table 2: Base values and variation ranges of the selected parameters used in the sensitivity analysis.

Scenario	**Lang factor [-]**	**Solvent waste [%]**	**Price of Chemical A [EUR/tonne]**
Optimistic	2	2%	900
Realistic	4	4%	1,100
Pessimistic	6	6%	1,300

The base case was set as the reference (0) and the results for the other cases were expressed as variations from this value to illustrate the impact of parameter variations.

4 Results and discussion

This section presents and discusses the results of the techno-economic and process analysis, including feedstock comparison, mass and carbon flows, cost and economic performance across different scales, sensitivity analysis and a broader system-level interpretation of the findings.

4.1 Comparative analysis of biomass feedstocks

This section compares the two selected feedstocks, forest bark and cereal straw, in terms of their suitability for bio-oil production. The comparison focuses on availability of biomass, feedstock demand from competing industries, seasonal variability in biomass availability, upscaling logistics and storage conditions and requirements. These factors provide an overview of the main practical conditions affecting the feasibility of each feedstock at an industrial scale.

4.1.1 Availability of biomass

The annual available biomass is presented in Table 3. The quantity of bark was 46% higher than that of straw.

Table 3: Calculated annual available biomass from bark and straw.

Biomass	Available amount [tonnes/year]
Bark	500,000
Straw	260,000

The results indicate that the theoretical availability of forest bark is higher than that of cereal straw and that both feedstocks meet the annual biomass requirement under all considered cases (1,700–10,000 tonnes per year). Forest bark availability is influenced by forest operations and collection efficiency and may vary depending on regional conditions. Cereal straw is limited by agricultural constraints, as a share of residues must remain in the field and additional fractions are typically retained in practice.

Although bark shows a higher theoretical availability under these assumptions, both feedstocks are subject to competing uses. Bark is commonly used as a biofuel within the forest industry, while straw is primarily used in agriculture for bedding and animal feed. Consequently, the practical availability for bio-oil production is likely lower than the theoretical values presented in Table 3. From a supply perspective, forest bark may therefore represent a more stable industrial feedstock, whereas straw availability is more sensitive to agricultural constraints and seasonal variability.

Amount of source material per region

The northern region of Sweden accounts for the largest share of annual gross fellings, representing 36%, followed by the southern region at 35% and the central region at 30%. The corresponding gross felling volumes are shown in Table 4.

Table 4: Distribution of annual gross fellings across Swedish regions (Skogsstyrelsen, 2024b).

Region	Annueal gross fellings [million m^3/year]
Northern	31
Central	26
Southern	30

The distribution of gross fellings across Sweden is relatively balanced between the three regions. This indicates that bark as a by-product of wood processing is geographically widespread. As a result, several regions may have the potential to supply bark for bio-oil production facilities.

The southern region of Sweden accounts for the largest share of annual grain harvest, representing 71%, followed by the central region at 28% and the northern region at 2%. The grain harvest volumes in tonnes are presented in Table 5.

Table 5: Regional distribution of annual grain harvest in Sweden (Statistikdatabasen, n.d.).

Region	Grain harvest [tonnes/year]
Northern	87,000
Central	1,400,000
Southern	3,600,000

In contrast to bark, grain production is strongly concentrated in southern Sweden. The southern region accounts for more than 70% of the total grain harvest, while the northern region contributes only a small fraction. This concentration implies that straw-based bio-oil production would likely be most feasible in southern Sweden, where feedstock availability and transportation distances are more favourable.

4.1.2 Feedstock demand from competing industries

The level of competition for biomass resources affect their long-term availability for bio-oil production. Bark is primarily generated as a by-product within the forest and wood-processing industries and is therefore often available at industrial sites. However, bark is already used as a biofuel within the forest industry, which may limit the amount available for alternative applications.

In contrast, cereal straw is mainly used within the agricultural sector, particularly as animal bedding and feed. Farmers may therefore be reluctant to sell large volumes of straw, especially if straw removal is perceived to negatively affect soil fertility. As a result, competition for straw may be more strongly influenced by agricultural practices and farmer preferences.

4.1.3 Season variability in biomass availability

Seasonal availability differs significantly between the two feedstocks. Bark is generated continuously as a by-product of forestry operations and wood processing throughout the year. Although harvesting intensity may vary seasonally, bark supply to industrial facilities is generally stable.

Straw availability on the other hand, is strongly seasonal. Grain harvesting typically occurs during late summer and early autumn, which means that large quantities of straw become available within a limited time period. Long-term storage is therefore required to ensure year-round supply for industrial processing.

4.1.4 Upscaling logistics

Logistics also differ between the two feedstocks. Bark is typically handled within established forestry supply chains, where transportation from forest sites to industrial processing facilities is already well developed. This existing infrastructure may simplify the integration of bark into bio-oil production systems.

Straw logistics are more decentralized, as the resource originates from numerous farms. Collection, baling and transportation are therefore often carried out by farmers or agricultural contractors. At larger industrial scales, coordination of transportation and logistics may become more complex and could require additional organizational structures or dedicated logistics providers. Straw also has a low bulk density, which increases transportation requirements and reduces logistical efficiency when supplying large volumes to the facility.

4.1.5 Storage conditions and requirements

Storage requirements differ significantly due to the physical properties of the feedstocks. Bark often has a relatively high moisture content and may be susceptible to biological degradation during long-term storage. Self-heating and microbial activity may also occur if bark is stored in large piles.

Straw is typically stored at lower moisture contents but is highly sensitive to moisture uptake during storage. If the moisture content exceeds recommended limits, the risk of mould formation and biological degradation increases significantly. Proper storage conditions, such as covered storage or plastic wrapping, are therefore essential to maintain straw quality.

4.1.6 Traffic light evaluation

The traffic light evaluation is presented in Table 6. The results show that Case A and Case B do not affect the qualitative outcome of the assessment.

A clear difference is observed between the two feedstocks. Forest bark shows an overall more favourable performance, with mainly green indicators and no red categories. This suggests that bark is better aligned with the process requirements. In contrast, cereal straw shows a less favourable profile, with mostly yellow indicators and only a single green category, indicating a higher degree of constraint or uncertainty across several evaluation criteria.

Table 6: Traffic light assessment of operational considerations for the evaluated scenarios. Colours indicate the level of operational risk and feasibility.

Operational considerations	Case A: Bark	Case A: Straw	Case B: Bark	Case B: Straw
Availability	🟢	🟢	🟢	🟢
Resource competition	🟡	🟡	🟡	🟡
Seasonal variability	🟢	🔴	🟢	🔴
Upscaling logistics	🟢	🔴	🟢	🔴
Storage requirements	🟡	🟡	🟡	🟡

It should be noted that the table does not account for economic differences between Case A and Case B, which may significantly influence the most suitable option.

4.2 Facility design and scale-up results

This section presents the results related to facility design and scale-up for both forest bark and cereal straw as feedstocks. It includes the overall layout configuration, area distribution between blocks and non-block sections, and the impact of scaling to Case A or to Case B.

4.2.1 Forest bark as feedstock

The total area requirements for the two plant scales processing forest bark are primarily driven by biomass storage capacity. Scaling up the facility from Case A to Case B results in an approximate 115% increase in total facility block area and a 40% increase in total facility area, as shown in Table 7.

Table 7: Estimated total facility area for Cases A and B based on forest bark as feedstock.

Facility block	**Case A** Area required [m²]	**Case B** Area required [m²]
- Biomass storage	112	560
- Process	260	528
- Bio-oil storage	84	144
- Chemical A storage	84	144
- Chemical B storage	84	144
- Chemical C storage	98	168
- Housing	120	120
Facility block area (total)	842	1,808
Non-block area	3,526	4,351
Total facility area	**4,212**	**6,160**

The process design layout for Case A is illustrated in Figure 5, while the corresponding layout for Case B is shown in Figure 6. Together, the figures provide an overview of the spatial arrangement of facility blocks and illustrate how the total facility area is distributed between blocks and non-block sections.

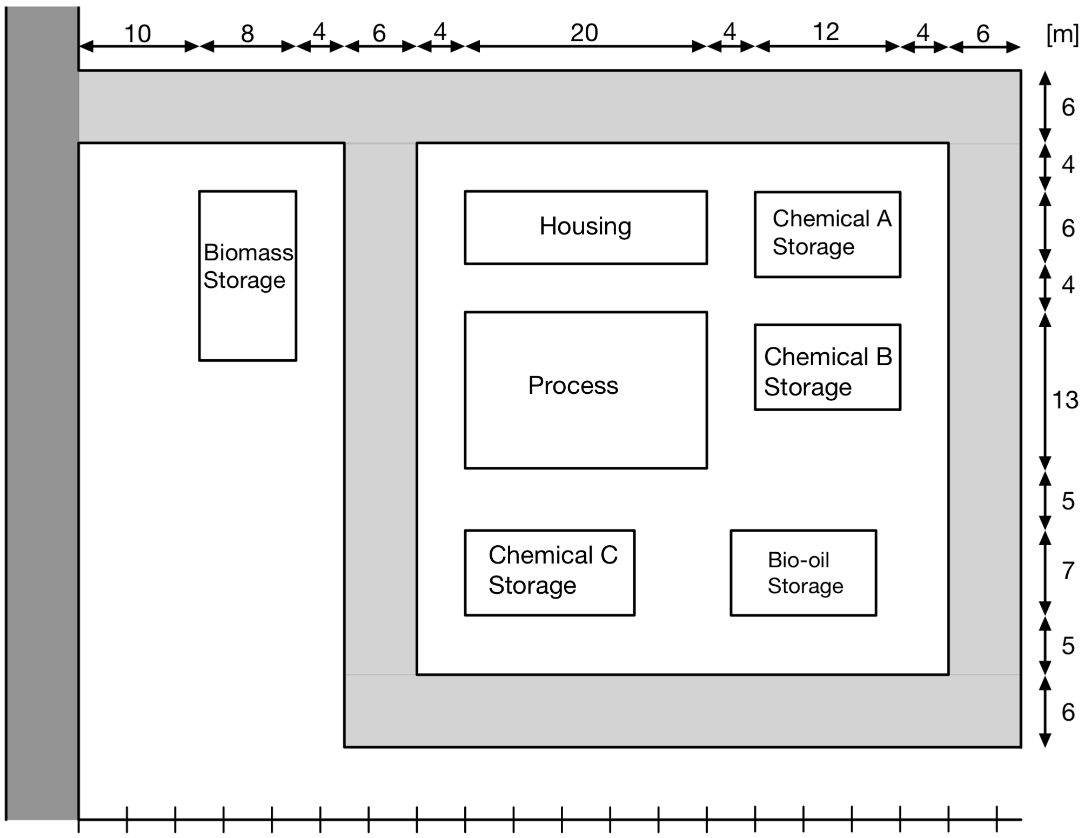

Figure 5: Process design layout for Case A, showing the spatial arrangement of facility blocks and the distribution of the total facility area between blocks and non-block areas.

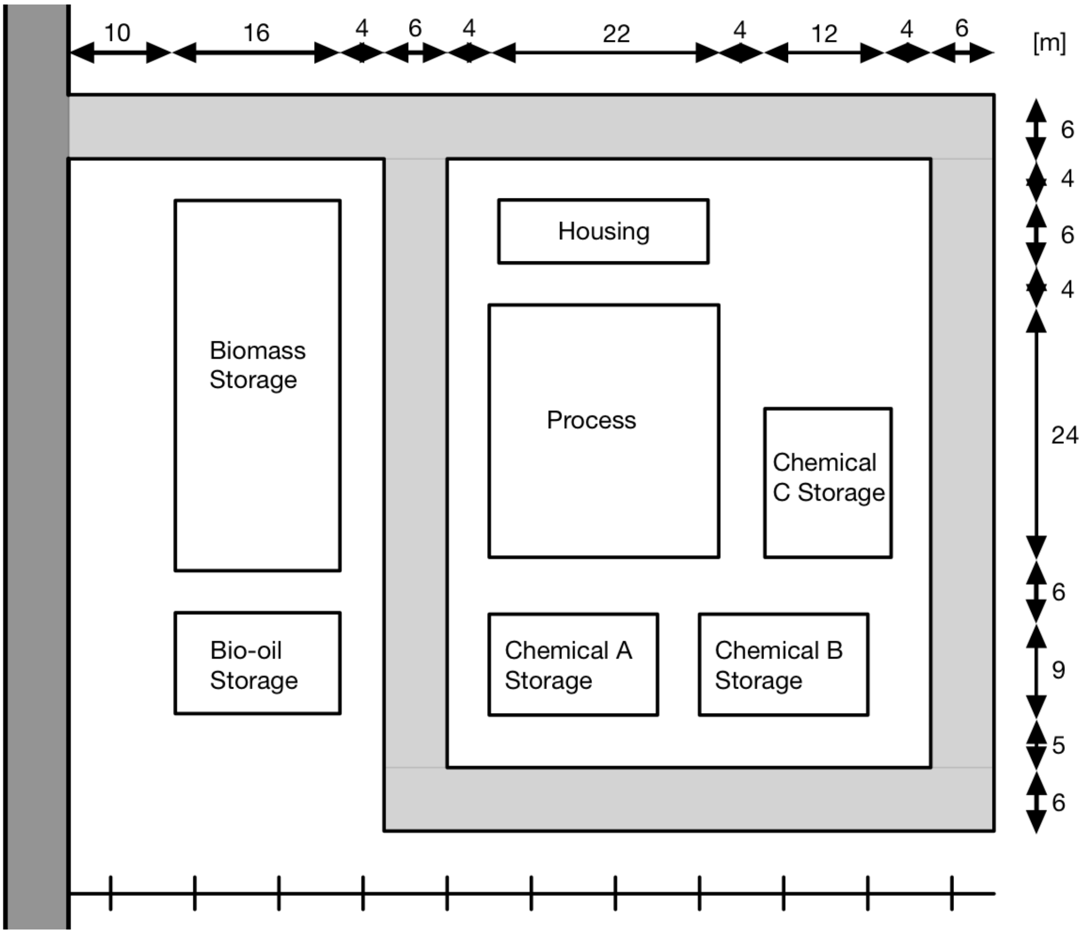

Figure 6: Process design layout for Case B, showing the spatial arrangement of facility blocks and the distribution of the total facility area between blocks and non-block areas.

4.2.2 Cereal straw as feedstock

A similar trend was observed for cereal straw, with total facility block area requirements again being largely driven by biomass storage capacity. Scaling up the facility, from Case A to Case B, resulted in an approximate 180% increase in total facility block area and a 41% increase in total facility area, see Table 8.

Table 8: Estimated total facility area for Cases A and B based on cereal straw as feedstock.

Facility blocks	**Case A** Area required [m²]	**Case B** Area required [m²]
- Biomass storage	350	1,750
- Process	260	528
- Bio-oil storage	84	144
- Chemical A storage	84	144
- Chemical B storage	84	144
- Chemical C storage	98	168
- Housing	120	120
Facility block area (total)	1080	2,997
Non-block area	4,200	4,443
Total facility area	**5,280**	**7,440**

The process design layout for Case A is illustrated in Figure 7, while the corresponding layout for Case B is shown in Figure 8. Together, the figures provide an overview of the spatial arrangement of facility blocks and illustrate how the total facility area is distributed between blocks and non-block sections.

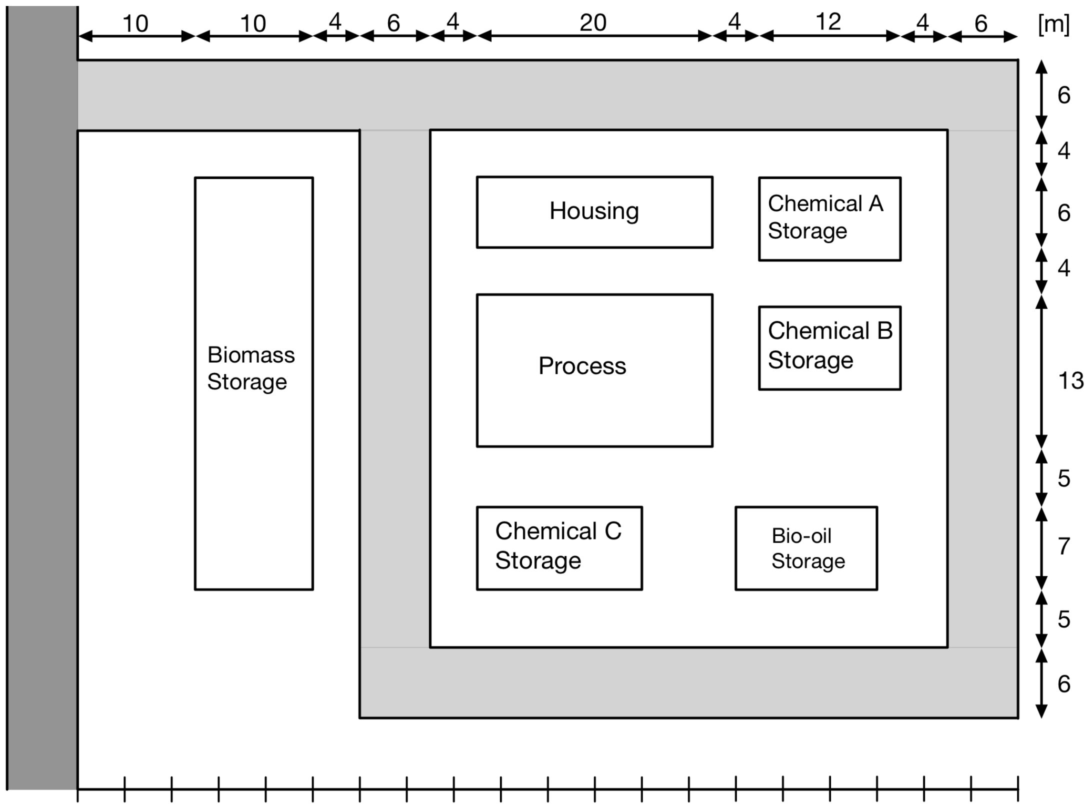

Figure 7: Process design layout for Case A, showing the spatial arrangement of facility blocks and the distribution of the total facility area between blocks and non-block areas.

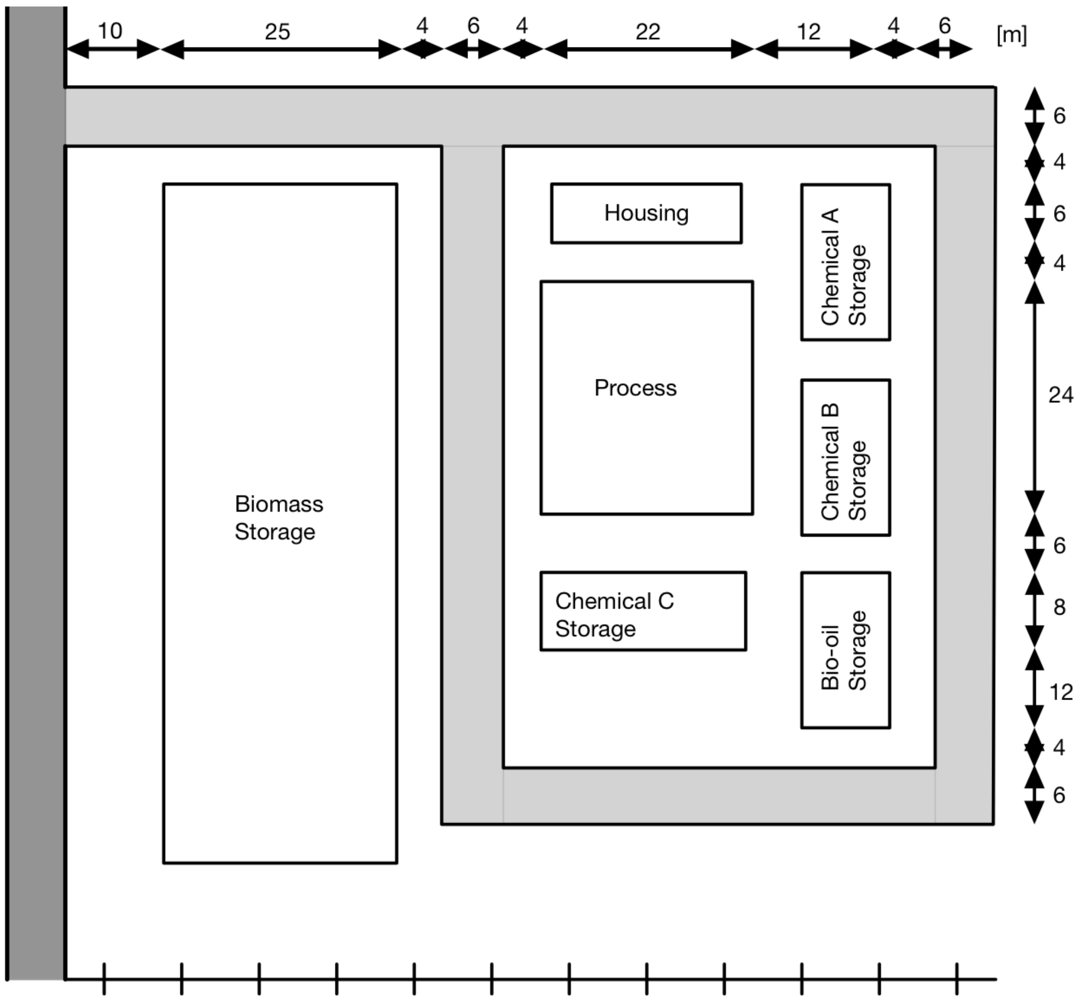

Figure 8: Process design layout for Case B, showing the spatial arrangement of facility blocks and the distribution of the total facility area between blocks and non-block areas.

Overall, the results indicate that biomass storage is the primary factor determining the total facility area for both feedstocks. While the other facility blocks remain relatively similar between the two feedstocks, the required storage area for raw biomass differs significantly. Straw requires considerably larger storage areas than bark due to its lower bulk density, resulting in substantially larger facility area.

In addition, the scale-up from Case A to Case B does not lead to a proportional increase in total area. While production capacity increases by a factor of five, the total facility area increases by approximately 40% for bark and 41% for straw. This suggests that certain facility blocks benefit from scaling effects, whereas biomass storage requirements remain closely linked to the volume of feedstock required.

These results highlight the importance of considering physical properties of feedstock when designing bio-oil production facilities, as storage requirements may strongly influence overall facility layout and land use.

4.3 Mass balances

The mass balance results for the process are presented as normalized input and output mass flows, where the final product flow has been set to 1 tonnes/day as the reference basis for each process unit. Figure 9 presents the mass distribution for forest bark and cereal straw.

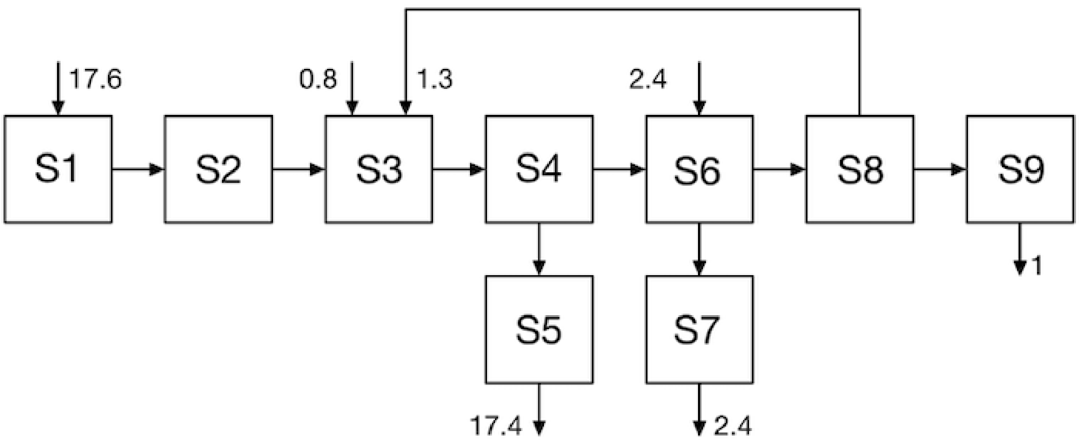

Figure 9: Normalized mass balance for each process step where the final product flow has been set to 1 tonnes/day as reference.

The results show that the mass balances for both feedstocks are internally consistent, as the normalized input and output mass flows are balanced within the defined system boundaries.

The distribution of mass across the process units is the same for both forest bark and cereal straw, indicating that the process behaves similarly for the two feedstocks. The majority of the mass entering the system originates from the biomass feedstock and other process inputs in unit S1, which accounts for approximately 17.6 tonnes per day. On the output side, the primary product stream leaves the system through unit S9, while other fractions are distributed to units S5 and S7, representing intermediate or residual streams. The lack of differences between forest bark and cereal straw suggests that feedstock type has a limited influence on the overall mass distribution within the process.

4.4 Carbon flow in the process

The carbon flow with forest bark as feedstock shows that 82% of the carbon remains in the bio-oil. A small fraction of 1.4% leaves the process as CO_2 from unit S3, while the remaining 16.6% is discharged as part of the residual stream (S5), illustrated in Figure 10.

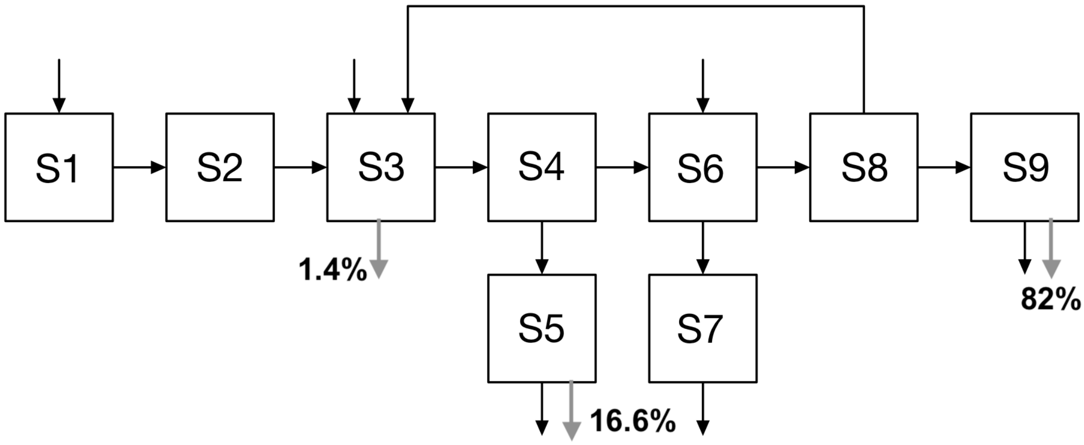

Figure 10: Carbon flow for forest bark shown as grey arrows of CO_2 from S3 and as parts of residual stream (S5) and oil (S9).

The carbon flow with cereal straw as feedstock shows that 72.5% of the carbon remains in the bio-oil. A small fraction of 1.4% leaves the process as CO_2 from unit S3, while the remaining 26.1% is discharged as part of the residual stream (S5), illustrated in Figure 11.

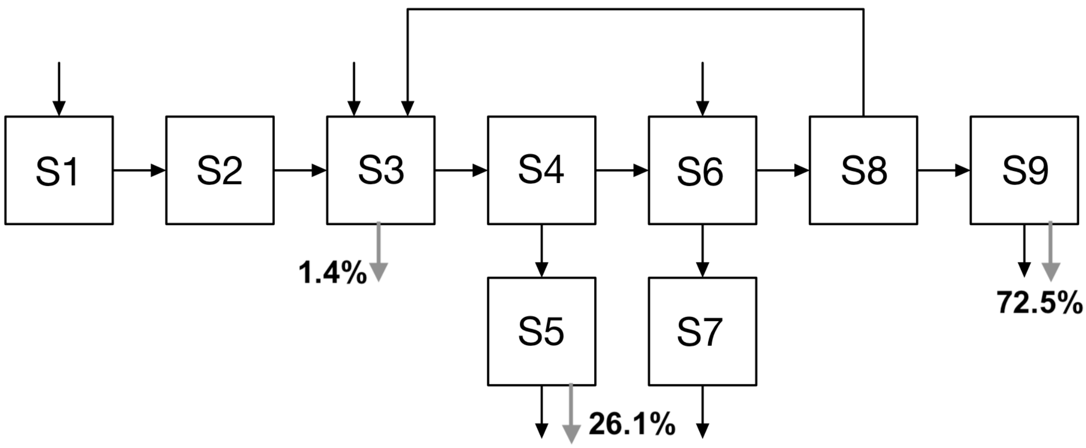

Figure 11: Carbon flow for cereal straw shown as grey arrows of CO_2 from S3 and as parts of residual stream (S5) and oil (S9).

Compared to the previous case, cereal straw shows a lower share of carbon in the bio-oil (72.5% vs. 83.7%). At the same time, the residual stream increases noticeably from 14.9% to 26.1%. This indicates that more carbon is directed to the residual fraction and less ends up in the bio-oil. The

CO_2 fraction remains unchanged at 1.4%, suggesting that gas formation in unit S3 is not affected by the feedstock. Overall, the results show that changes in feedstock mainly influence the distribution between bio-oil and residual streams.

Uncertainties also exist in the carbon flow analysis, as it is based on simplified process parameters and model assumptions rather than detailed operational data. As a result, the calculated carbon flows should be interpreted as indicative estimates rather than precise values.

4.5 Capital investment costs (CapEx)

The estimated capital investment costs for the different process units are presented in Appendix A.1, with a summary presented in Table 9.

Table 9: Estimated capital investment costs for each scenario.

Scenario	Capital investment cost [SEK]
Case A: Bark	52,300,000
Case A: Straw	55,500,000
Case B: Bark	160,200,000
Case B: Straw	175,200,000

The results show that the capital investment costs increases significantly with production scale. Increasing the production capacity from Case A to Case B results in an approximately three- to fourfold increase in estimated capital investment costs. This increase reflects the larger process equipment and storage capacity required for higher production volumes.

A comparison between the feedstocks indicates that the capital investment for straw-based production is slightly higher than for bark. This difference is mainly related to the higher mass of straw required to achieve the same production capacity as bark. The yield of straw is assumed to be 0.5, while the yield of bark is 0.6. As a result, a larger amount of straw is required to produce the same annual amount of bio-oil.

Across all scenarios, the largest share of the equipment cost is associated with the initial processing units, particularly unit S1, which handles the primary input stream. This reflects the importance of feedstock handling and preprocessing in determining the overall capital cost of the system. However, when the Lang factor is applied, it represents the largest contribution to the total capital expenditure. This indicates that indirect costs related to installation and infrastructure dominate the overall investment rather than the equipment cost alone. Consequently, strategies for reducing capital cost should not only focus on equipment optimisation, but also on minimising installation complexity, such as simplifying plant layout, reducing piping requirements and improving process integration.

4.6 Operating costs (OpEx)

The estimated operating costs for the different cost units are presented in Appendix A.2, with a summary presented in Table 10.

Table 10: Estimated operating costs for each scenario.

Scenario	Operating cost [SEK]
Case A: Bark	22,600,000
Case A: Straw	26,400,000
Case B: Bark	100,800,000
Case B: Straw	120,000,000

The results show that operating costs increase with production scale. Increasing the production capacity from Case A to Case B leads to higher overall OpEx, mainly due to the increased demand for feedstock, energy and other process inputs required to sustain a larger production volume. A comparison of the feedstocks indicates that straw-based production results in slightly higher operating costs than bark, primarily due to the lower conversion yield of straw, which requires a larger input mass to achieve the same bio-oil output. Across all scenarios, the largest share of operating costs is associated with Chemical A amount, indicating that this parameter is a key driver of overall OpEx. Consequently, efforts to reduce operating costs should focus on optimising the use of Chemical A and reducing its unit cost where possible.

4.7 Economic performance of the scenarios

The economic performance of the scenarios are precented in Table 11.

Table 11: Economic performance indicators across four scenarios.

Scenario	NPV [MSEK]	PBT [years]	IRR [%]
Case A: Bark	-42	51	-7.6
Case A: Straw	-53	262	-17.5
Case B: Bark	9	10	9
Case B: Straw	-46	14	4

The economic performance of the scenarios varies significantly with both production scale and feedstock. At the smaller scale (Case A), both feedstocks result in negative NPV, long payback times and negative IRR, indicating that the process is not economically viable under these conditions. Increasing the production scale to Case B improves the economic performance, particularly for forest bark, which achieves a positive NPV, positive IRR and a shorter payback time. Although cereal straw still results in a negative NPV at this scale, the payback time is reduced and the IRR becomes positive, while a positive NPV can be achieved at a production capacity of 7,000 tonnes of bio-oil per year.

A clear difference is observed between the feedstocks, where bark consistently outperforms straw across all indicators. The poorer performance of straw is mainly linked to its lower conversion yield, resulting in higher feedstock demand and increased capital and operating costs. Despite the improvement at larger scale, straw-based production remains economically unattractive and remains highly negative NPV with low IRR. Overall, the results indicate that both feedstock selection and production scale are key factors in determining economic feasibility, with bark at larger scale representing the most promising scenario among those evaluated.

4.8 Sensitivity analysis results

This chapter presents the results of the sensitivity analysis, where key economic and operational parameters are varied to assess their impact on the overall system performance.

4.8.1 Variating the Lang factor

The sensitivity analysis shows that CapEx, represented by the Lang factor, has a strong influence on all economic indicators across the evaluated scenarios. An increase in the Lang factor leads to a decrease in NPV and IRR, while increasing the PBT. Conversely, a lower Lang factor improves all economic performance indicators, highlighting the importance of capital intensity in the overall feasibility of the process.

The impact of the Lang factor is more clear at the larger production scale (Case B), where changes in NPV are higher compared to the smaller scale (Case A). This indicates that larger facilities are more sensitive to capital cost variations. The differences between the feedstocks are small, with straw being slightly more sensitive than bark at both production scales, see Figure 12.

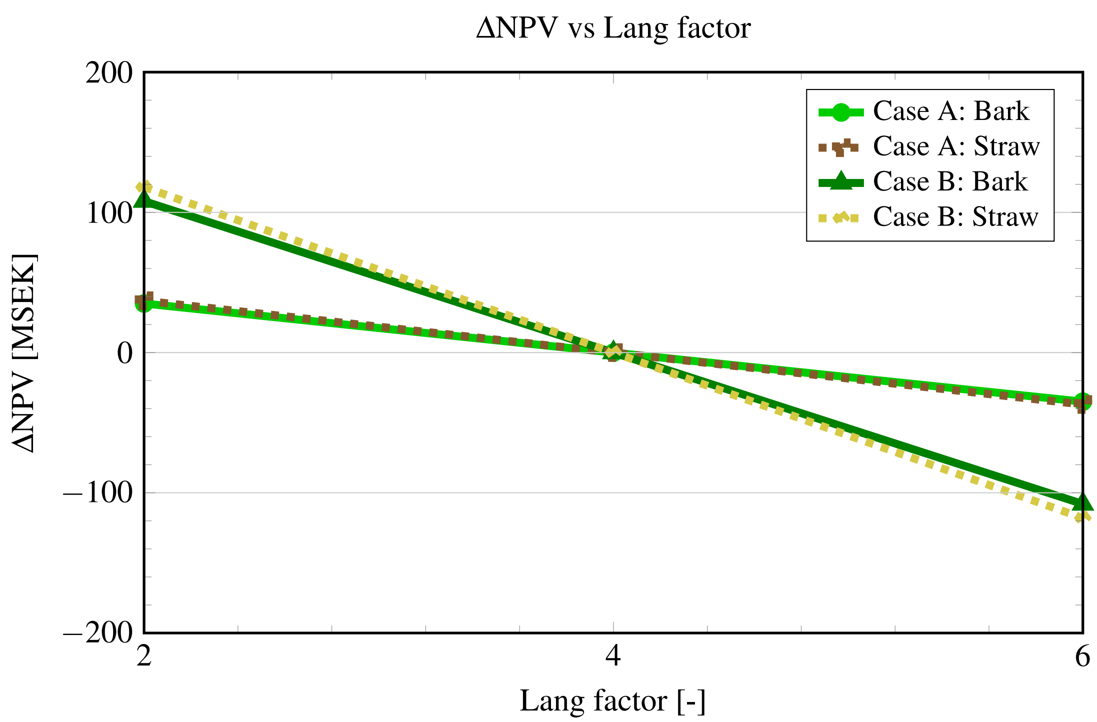

Figure 12: Sensitivity of NPV to variations in Lang factor for different process configurations.

PBT is highly sensitive to changes in the Lang factor. Higher Lang factor result in significantly longer PBT, while lower values improve capital recovery time. The effect is most clear in the smaller-scale scenarios, where even small increases in the Lang factor lead to very long PBT, indicating low economic robustness. At higher Lang factor values, Case A with cereal straw as feedstock does not reach payback at all, see Figure 13.

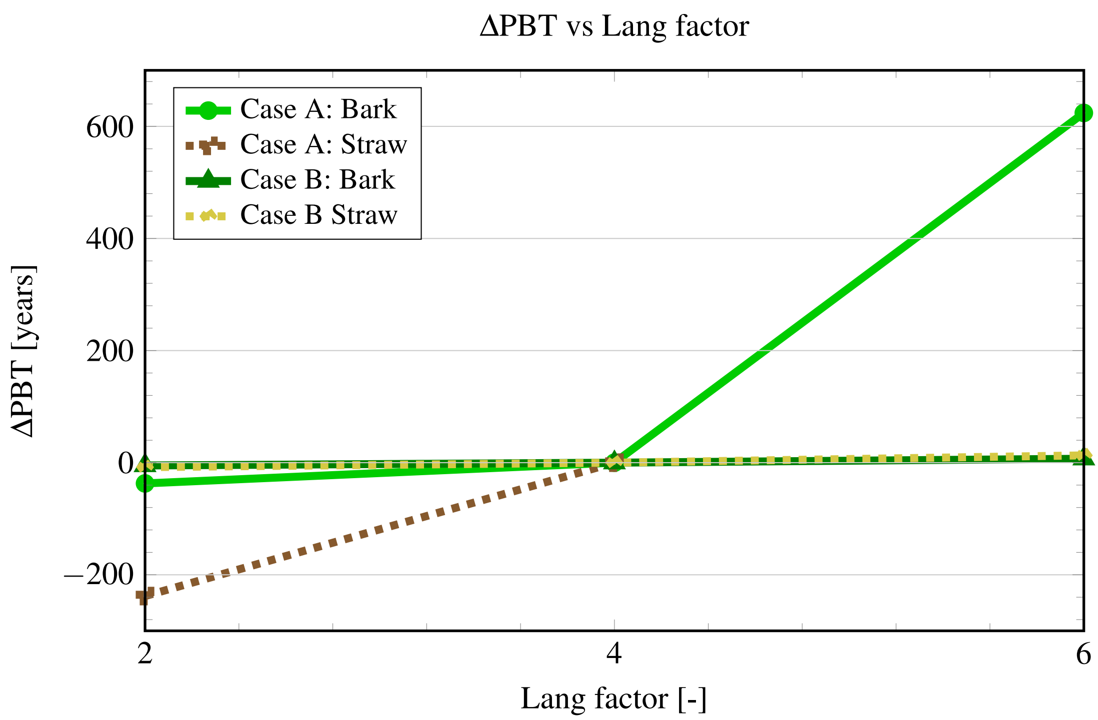

Figure 13: Sensitivity of PBT to variations in Lang factor for different process configurations.

The IRR follows the same general trend as NPV, decreasing with increasing Lang factor across all scenarios. The effect is most severe for the low-scale scenarios, where IRR becomes highly negative at higher Lang factor. Case A, using cereal straw as feedstock, does not achieve a calculable IRR within the project lifetime, see Figure 14.

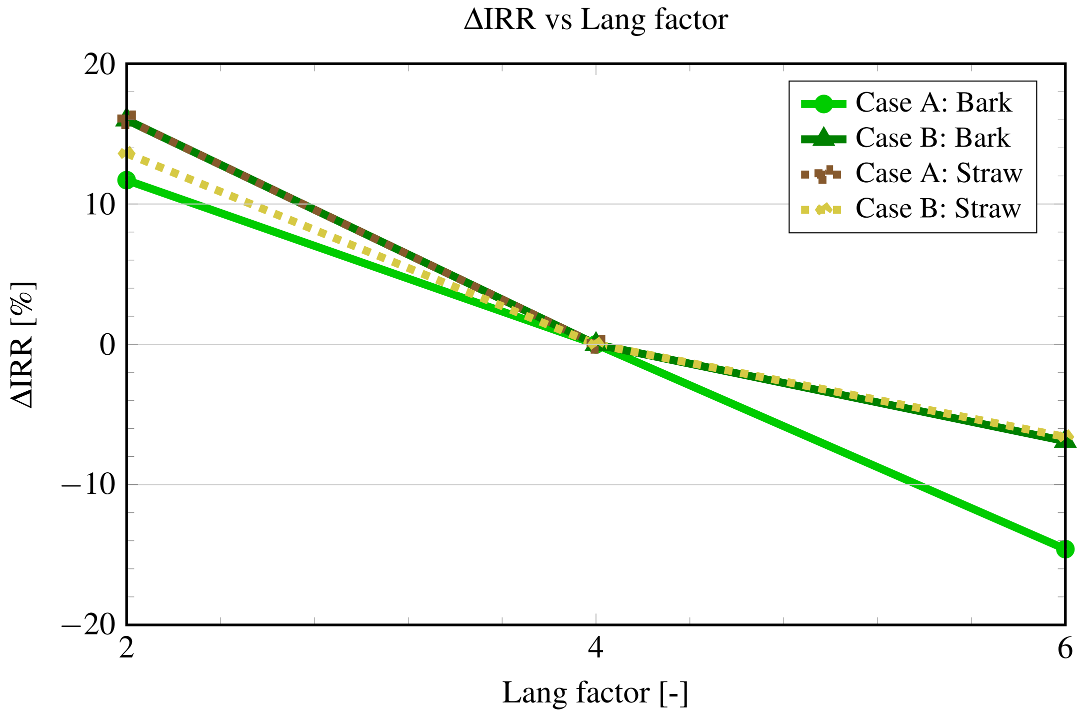

Figure 14: Sensitivity of IRR to variations in Lang factor for different process configurations.

Overall, the results show that capital cost assumptions have a dominant influence on economic feasibility, and that reducing installation complexity and indirect costs is critical for improving project viability.

4.8.2 Variating solvent waste amount

The sensitivity analysis shows that solvent waste has a moderate influence on the economic performance of the process across all evaluated scenarios. An increase in solvent waste leads to a decrease in both NPV and IRR, while also increasing the PBT. Conversely, lower solvent waste levels improve all economic indicators, highlighting the importance of efficient solvent recovery for overall process profitability.

The impact of solvent waste is more pronounced at the larger production scale (Case B), where changes in NPV is significantly larger compared to the smaller scale (Case A). This indicates that larger facilities are more sensitive to inefficiencies in solvent handling. The differences between feedstocks follow the same general trend as for the Lang factor, with straw showing slightly higher sensitivity than bark at both production scales, see Figure 15.

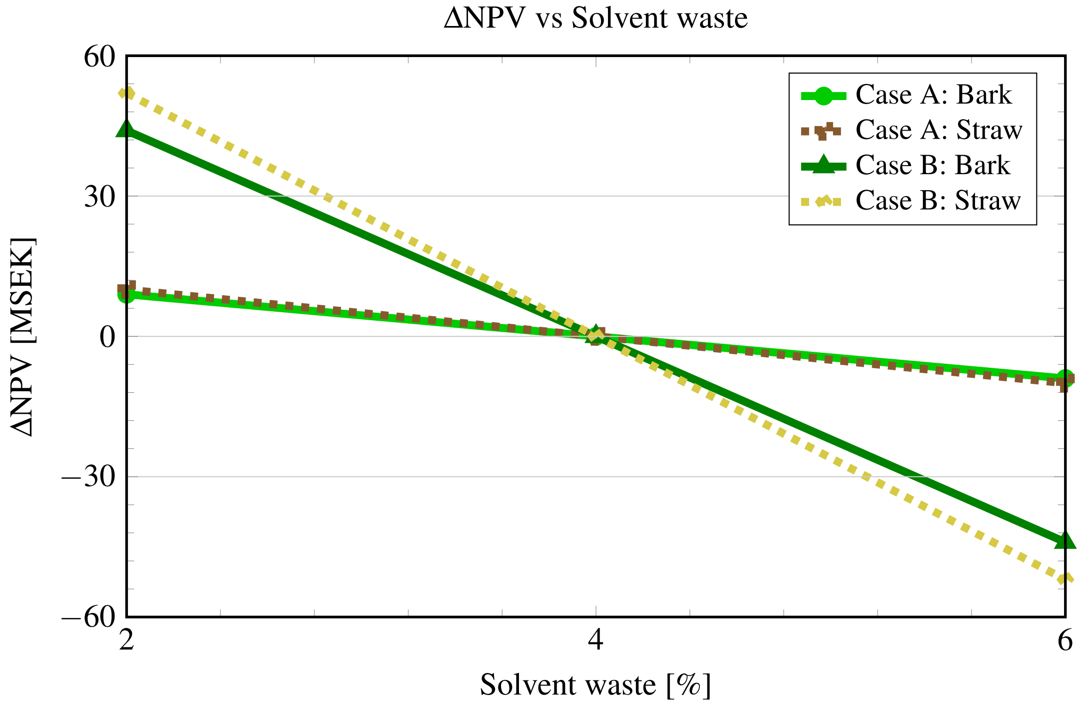

Figure 15: Sensitivity of NPV to variations in solvent waste levels for different process configurations.

The PBT is highly sensitive to changes in solvent waste. Higher solvent losses result in longer PBT, while lower waste levels improve capital recovery. The effect is most clear in the smaller-scale cases, where even small increases in solvent waste can greatly increase the PBT, showing that the process becomes less economically robust when solvent recovery is inefficient. At higher solvent waste values, Case A with cereal straw as feedstock does not reach payback at all, see Figure 16.

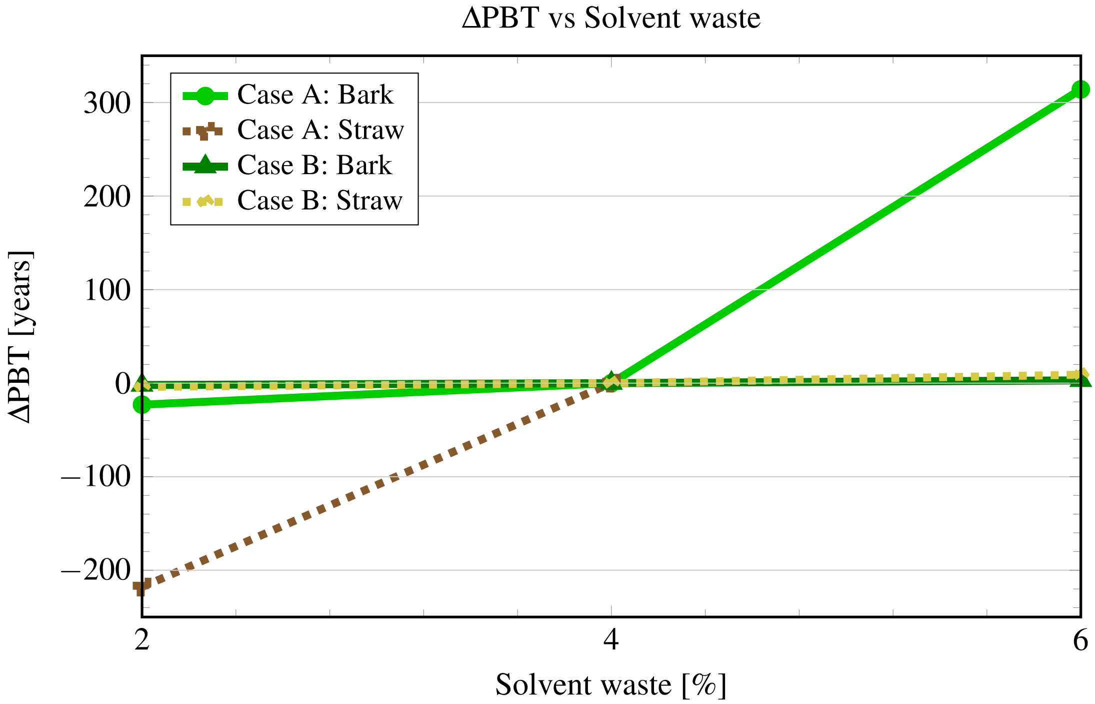

Figure 16: Sensitivity of PBT to variations in solvent waste levels for different process configurations.

The IRR follows the same general trend as NPV, decreasing with increasing solvent waste amount across all scenarios. The effect is most severe for the low-scale scenarios, where IRR becomes highly negative at higher solvent waste amount. Case A, using cereal straw as feedstock, does not achieve a calculable IRR within the project lifetime at higher solvent waste levels, indicating that the economic performance becomes insufficient under these conditions, see Figure 17.

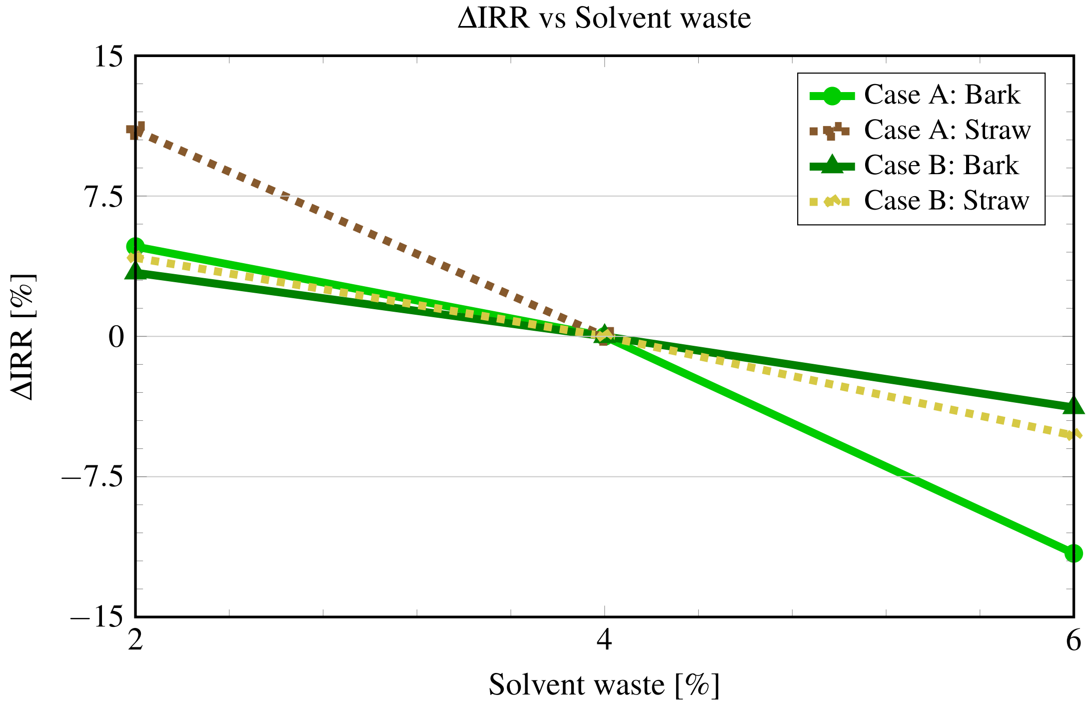

Figure 17: Sensitivity of IRR to variations in solvent waste levels for different process configurations.

Overall, the results show that solvent management is an important factor influencing economic feasibility, although its impact is less dominant than the Lang factor. Still, improvements in solvent recovery and reductions in waste streams can contribute meaningfully to improved project viability.

4.8.3 Variating the price of Chemical A

The sensitivity analysis shows that the price of Chemical A has a clear influence on the economic performance of the process across all evaluated scenarios. An increase in Chemical A price leads to a decrease in NPV and IRR, while also increasing the PBT. Conversely, lower prices improve all economic indicators, highlighting the importance of raw material cost stability for overall process feasibility.

The impact of Chemical A price is more pronounced at the larger production scale (Case B), where the changes in NPV is significantly greater compared to the smaller scale (Case A). This indicates that larger facilities are more sensitive to variations in operating costs linked to Chemical A input. The differences between feedstocks follow the same general pattern as in previous cases, with straw showing slightly higher sensitivity than bark in all scenarios, see Figure 18.

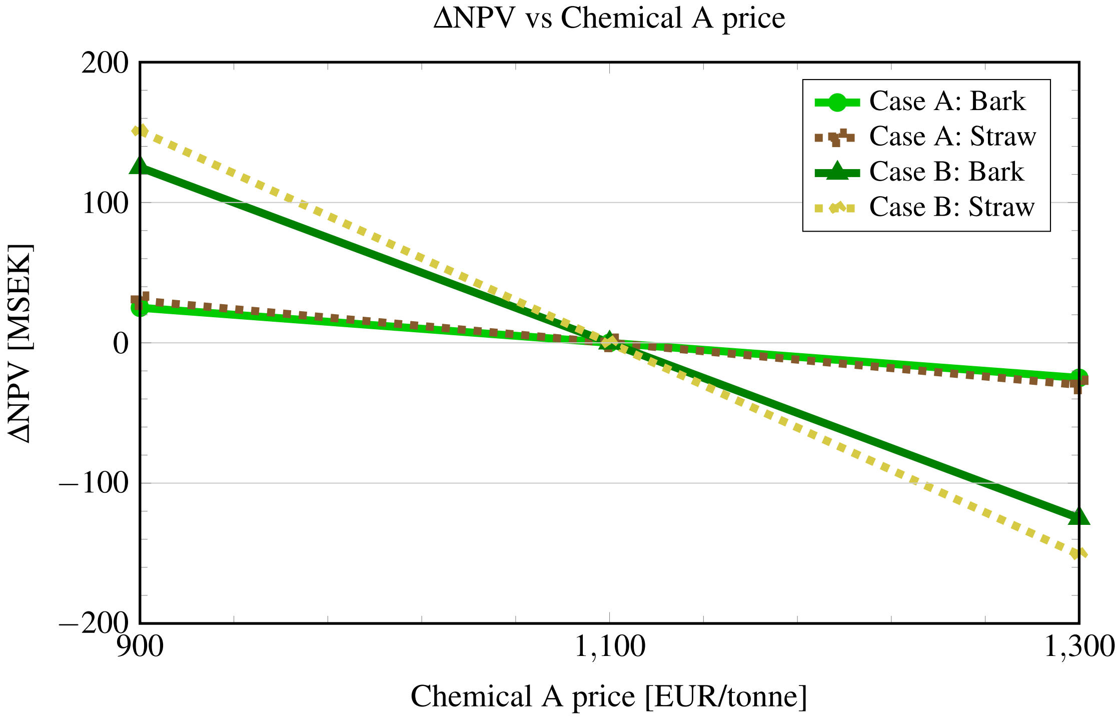

Figure 18: Sensitivity of NPV to variations in Chemical A price for different process configurations.

The PBT is strongly affected by changes in Chemical A price. Higher prices lead to longer PBT, while lower prices significantly improve capital recovery. The effect is most evident in the smaller-scale scenarios, where cost increases in Chemical A can lead to very long PBT, indicating reduced economic robustness under unfavourable market conditions. Case B, using forest bark as feedstock, is the only viable scenario at higher Chemical A prices, see Figure 19.

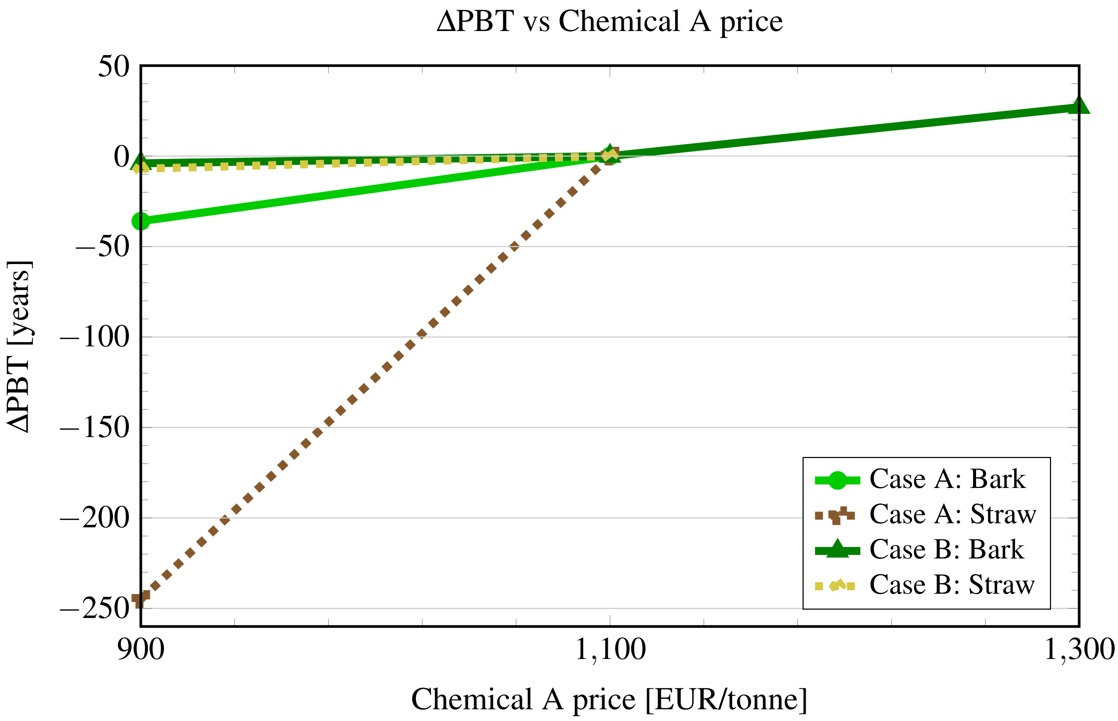

Figure 19: Sensitivity of PBT to variations in Chemical A price for different process configurations.

The IRR follows the same general trend as NPV, decreasing with increasing Chemical A price across all scenarios. The effect is most severe for the low-scale scenarios, where IRR becomes highly negative at higher Chemical A price. Case B, using forest bark as feedstock, is the only scenario that achieves a calculable IRR within the project lifetime at higher Chemical A prices, indicating that the economic performance of the other scenarios becomes insufficient under these conditions, see Figure 20.

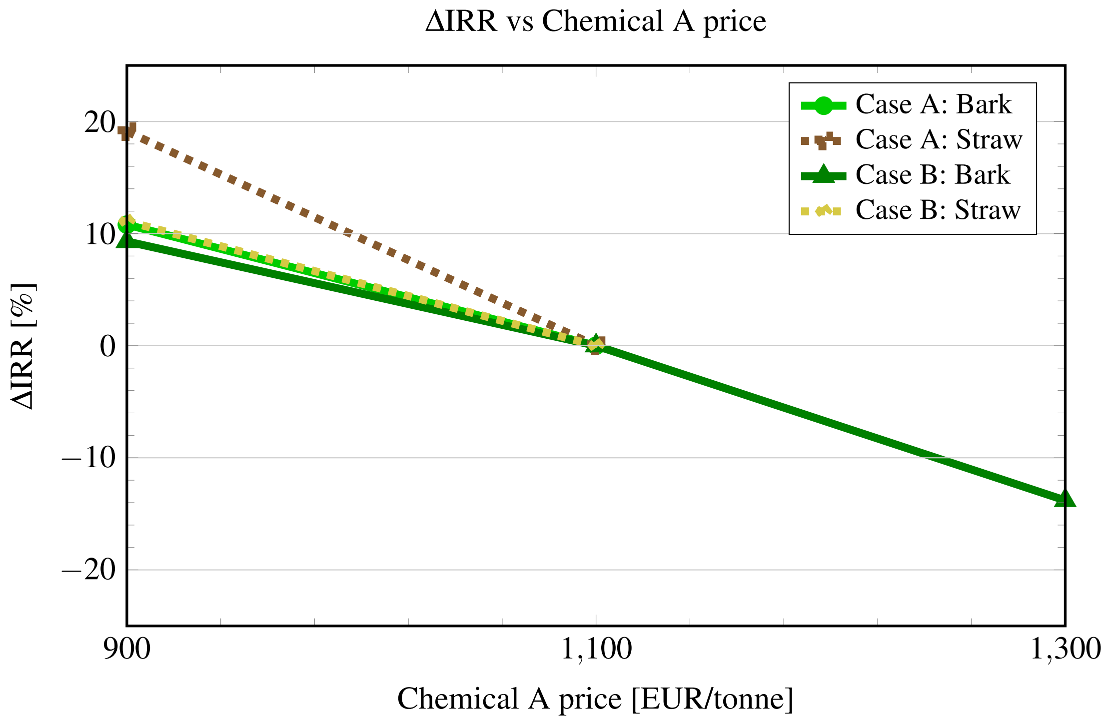

Figure 20: Sensitivity of IRR to variations in Chemical A price for different process configurations.

Overall, the results show that Chemical A price is a major economic driver, with an impact that is comparable to or in some cases greater than the Lang factor. This highlights that fluctuations in chemical pricing can strongly affect project viability.

4.9 Economic interpretation and system value

The techno-economic results indicate that the studied bio-oil production system is economically challenging under the assumed conditions. High investment and operating costs result in negative or weak values for key economic indicators such as NPV, PBT and IRR, suggesting limited profitability under current market assumptions. However, these indicators primarily reflect investors perspective and do not capture broader system-level benefits. The results should therefore also be interpreted from an energy systems perspective.

4.9.1 Energy security

Local fuel production reduces dependence on imports and decreases exposure to price volatility and supply disruptions. This value is not reflected in conventional techno-economic assessments but can be interpreted as avoided costs associated with fuel price fluctuations and, in particular, rare but high-impact supply crises. Consequently, evaluations based only on average market conditions may underestimate the value of improved energy security.

4.9.2 Enhanced resilience

A decentralized production structure consisting of several smaller units reduces the risk of single points of failure compared to large centralized refineries. This decreases both the likelihood and the consequences of disruptions, such as geopolitical events or attacks on critical infrastructure. The value of increased resilience can be interpreted as risk reduction or avoided outage costs and is often assessed through scenario analyses comparing centralized and decentralized systems under disturbance conditions.

4.9.3 Climate and resource objectives

The system may contribute to reduced greenhouse gas emissions and increased utilization of local resources. These benefits can generate economic value through policy instruments such as carbon pricing, which improves the competitiveness of low-emission fuels, as well as investment subsidies or operational support schemes that reduce capital requirements and production costs.

4.9.4 Summary of system value

Despite limited profitability in the base scenario, the system provides value through improved energy security, enhanced resilience and contributions to long-term sustainability and transition goals. An assessment based only on direct economic costs therefore risks underestimating the overall socio-economic value of the system.

5 Conclusion

The analysis of the two biomass feedstocks shows that forest bark is the more suitable option of the two considered in this study. However, it is important to note that forest bark may compete with existing and future applications in other industries and requires proper storage conditions to minimize degradation and material losses. Cereal straw may instead be more attractive in the southern parts of Sweden, where most production is located, but its large storage requirements may increase facility size and associated costs, reducing its overall attractiveness. This is further reflected in the facility layout, where biomass storage has a significant influence on total plant area, making storage characteristics an important selection criteria for the feedstock.

The mass balance analysis shows that the choice of biomass has a limited effect on the overall mass balance, but a more pronounced effect is observed in the carbon distribution. Forest bark results in a higher fraction of carbon preserved in the bio-oil, whereas cereal straw leads to more carbon in residual streams, making forest bark the more favourable option from a carbon utilization perspective.

From an economic perspective, cereal straw consistently results in higher capital and operating costs than forest bark, mainly due to its lower bio-oil yield. The main cost drivers are unit S1, the additional Lang-factor-related costs and Chemical A, indicating that these components are critical targets for cost reduction. The economic analysis further shows that a production capacity of 1,000 tonnes of bio-oil per year is not economically feasible. At 5,000 tonnes per year, forest bark becomes a potentially viable option, although with a relatively low NPV, while cereal straw requires a higher scale of around 7,000 tonnes per year to achieve a positive NPV. The sensitivity analysis supports these findings, showing that CapEx-related additional costs and the price of Chemical A are the most influential parameters, while the 5,000 tonnes per year case shows the most robust performance across scenarios.

Finally, although the system shows limited economic attractiveness under base-case assumptions, a small-scale biorefinery may still provide important value from a broader systems perspective. Benefits such as improved energy security, enhanced resilience and contributions to long-term sustainability goals increase the overall socio-economic value beyond what is captured by conventional techno-economic indicators.

5.1 Recommendations for future work

Future work should focus on integrating technology maturity effects into the economic assessment, including learning curves, future cost reductions and changing market conditions that may affect the competitiveness of small-scale biorefineries over time.

Additional studies should focus on process optimization to improve bio-oil yield and reduce dependency on Chemical A, which was identified as one of the main operating cost drivers. Further investigation of greater production capacities from 7,000 tonnes of bio-oil per year is also recommended to better identify the economic threshold for profitability. To complement the techno-economic analysis, future work should include a full life cycle assessment (LCA) covering greenhouse gas emissions, energy efficiency and resource use, as well as comparisons with fossil-based alternatives under different policy scenarios. Finally, opportunities for integration with existing industrial and energy systems, such as CHP plants or pulp and paper mills, should be investigated to assess the potential for improved efficiency, reduced infrastructure costs and increased system resilience.

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A Appendix

A.1 Estimated capital investment costs

Table 12: Estimated capital investment costs for each process unit for forest bark processing at a production scale of Case A.

Process unit	Equipment cost [SEK]
S1	7,960,000[1]
S2	580,000[2]
S3	120,000[3]
S4	1,410,000[4]
S5	800,000[5]
S6	6,400[6]
S7	3,200[6]
S8	1,050,000[7]
S9	700,000[8]
Storage	330,000[9]
Housing	108,000[10]
Total equipment cost	13,100,000

[1](Edling Hultgren, 2026), [2](in-house data), [3](in-house data), [4](in-house data), [5](in-house data), [6](in-house data), [7](in-house data), [8](in-house data), [9](MCR, n.d.;Machineseeker, n.d.;BigBagStore.eu, n.d.;dm-folien, n.d.;Lötjönen and Joutsjoki, 2016), [10](Mascus, n.d.).

Table 13: Capital cost estimation based on the Lang factor method for forest bark at a production scale of Case A.

Total equipment cost [SEK]	Lang factor [-]	Capital investment cost [SEK]
13,100,000	4	52,300,000

Table 14: Estimated capital investment costs for each process unit for cereal straw processing at a production scale of Case A.

Process unit	Equipment cost [SEK]
S1	8,430,000[1]
S2	870,000[2]
S3	120,000[3]
S4	1,420,000[4]
S5	1,400,000[5]
S6	6,400[6]
S7	3,200[6]
S8	1,050,000[7]
S9	700,000[8]
Storage	380,000[9]
Housing	108,000[10]
Total equipment cost	13,900,000

[1](Edling Hultgren, 2026), [2](in-house data), [3](in-house data), [4](in-house data), [5](in-house data), [6](in-house data), [7](in-house data), [8](in-house data), [9](MCR, n.d.;Machineseeker, n.d.;BigBagStore.eu, n.d.;dm-folien, n.d.;Lötjönen and Joutsjoki, 2016), [10](Mascus, n.d.).

Table 15: Capital cost estimation based on the Lang factor method for cereal straw at a production scale of Case A.

Total equipment cost [SEK]	Lang factor [-]	Capital investment cost [SEK]
13,900,000	4	55,500,000

Table 16: Estimated capital investment costs for each process unit for forest bark processing at a production scale of Case B.

Process unit	Equipment cost [SEK]
S1	24,900,000[1]
S2	2,610,000[2]
S3	410,000[3]
S4	1,460,000[4]
S5	3,200,000[5]
S6	16,000[6]
S7	9,600[6]
S8	3,150,000[7]
S9	2,700,000[8]
Storage	1,530,000[9]
Housing	108,000[10]
Total equipment cost	40,000,000

[1](Edling Hultgren, 2026), [2](in-house data), [3](in-house data), [4](in-house data), [5](in-house data), [6](in-house data), [7](in-house data), [8](in-house data), [9](MCR, n.d.;Machineseeker, n.d.;BigBagStore.eu, n.d.;dm-folien, n.d.;Lötjönen and Joutsjoki, 2016), [10](Mascus, n.d.).

Table 17: Capital cost estimation based on the Lang factor method for forest bark at a production scale of Case B.

Total equipment cost [SEK]	Lang factor [-]	Capital investment cost [SEK]
40,000,000	4	160,200,000

Table 18: Estimated capital investment costs for each process unit for cereal straw processing at a production scale of Case B.

Process unit	Equipment cost [SEK]
S1	26,900,000[1]
S2	2,900,000[2]
S3	470,000[3]
S4	1,470,000[4]
S5	3,200,000[5]
S6	22,400[6]
S7	9,600[6]
S8	4,200,000[7]
S9	2,700,000[8]
Storage	1,780,000[9]
Housing	108,000[10]
Total equipment cost	43,800,000

[1] *(Edling Hultgren, 2026), [2] (in-house data), [3] (in-house data), [4] (in-house data), [5] (in-house data), [6] (in-house data), [7] (in-house data), [8] (in-house data), [9] (MCR, n.d.;Machineseeker, n.d.;BigBagStore.eu, n.d.;dm-folien, n.d.;Lötjönen and Joutsjoki, 2016), [10] (Mascus, n.d.).*

Table 19: Capital cost estimation based on the Lang factor method for cereal straw at a production scale of Case B.

Total equipment cost [SEK]	Lang factor [-]	Capital investment cost [SEK]
43,800,000	4	175,200,000

A.2 Estimated operating costs

Table 20: Estimated operating costs for each cost component for forest bark processing at a production scale of Case A.

Cost component	Cost (SEK/year)
Bark	1,250,000[1]
Chemical A	14,100,000[2]
Chemical B	1,300,000[3]
Solvent	1,800,000[4]
Electricity	400,000[1]
Personnel	2,000,000[1]
Maintenance	650,000[1]
Other	260,000[1]
Total operating cost	22,600,000

[1](Edling Hultgren, 2026), [2](in-house data), [3](in-house data), [4](in-house data).

Table 21: Estimated operating costs for each cost component for cereal straw processing at a production scale of Case A.

Cost component	Cost (SEK/year)
Straw	1,500,000[1]
Chemical A	16,900,000[2]
Chemical B	1,500,000[3]
Solvent	2,100,000[4]
Electricity	450,000[1]
Personnel	2,000,000[1]
Maintenance	700,000[1]
Other	280,000[1]
Total operating cost	26,400,000

[1](Edling Hultgren, 2026), [2](in-house data), [3](in-house data), [4](in-house data).

Table 22: Estimated operating costs for each cost component for forest bark processing at a production scale of Case B.

Cost component	**Cost (SEK/year)**
Bark	6,300,000[1]
Chemical A	70,300,000[2]
Chemical B	6,300,000[3]
Solvent	8,900,000[4]
Electricity	1,500,000[1]
Personnel	2,000,000[1]
Maintenance	2,300,000[1]
Other	930,000[1]
Total operating cost	100,800,000

[1](Edling Hultgren, 2026), [2](in-house data), [3](in-house data), [4](in-house data).

Table 23: Estimated operating costs for each cost component for cereal straw processing at a production scale of Case B.

Cost component	**Cost (SEK/year)**
Straw	7,500,000[1]
Chemical A	84,400,000[2]
Chemical B	7,600,000[3]
Solvent	10,700,000[4]
Electricity	1,700,000[1]
Personnel	2,000,000[1]
Maintenance	2,600,000[1]
Other	1,000,000[1]
Total operating cost	120,000,000

[1](Edling Hultgren, 2026), [2](in-house data), [3](in-house data), [4](in-house data).