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BIOTRANSFORM
TRANSITION PATHWAYS TO CIRCULAR BIO-ECONOMY

# Circular bioeconomy transformation for regions by enabling resource and governance networks

## D2.2 Report on each subsystem assessment methodology: environmental, economic, socio-cultural

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# List of Terms and Definitions

*Table 1: Terms and Definitions*

| Abbreviation | Definition |
|---|---|
| **ASR** | Absolute sustainability ratio |
| **BL** | Black liquor |
| **BSF** | Black soldier fly |
| **CAPEX** | Capital expenditure |
| **CBE** | Circular bioeconomy |
| **CO2** | Carbon dioxide |
| **EU** | European union |
| **FDCA** | 2,5-Furandicarboxylic acid |
| **FU** | Functional unit |
| **GHG** | Greenhouse gas |
| **GWP** | Global warming potential |
| **IAT** | Impact assessment tool, provided by LIST |
| **JRC** | Joint Research Centre - European Commission |
| **LA/ PLA** | Lactic acid/poly-lactic acid |
| **LCA** | Life cycle assessment |
| **LCI** | Life cycle inventory |
| **LCIA** | Life cycle impact assessment |
| **MAA** | Multi-actor approach |
| **MCDA** | Muticriteria decision analysis |
| **MDF** | Medium-density fiber board |
| **MEA** | Multicriteria environmental analysis |
| **MooV** | logistics optimization tool, provided by VITO |
| **NIMBY** | Not in my backyard |
| **NRW** | North Rhine-Westphalia |
| **OFMSW** | Organic fraction of municipal solid waste |
| **OPEX** | Operational expenditure |
| **OTP** | Olive tree pruning |
| **PB** | Planerary boundaries |
| **PEF** | Product environmental footprint |
| **PHA** | Polyhydroxyalkanoate |
| **RF** | Response factor |
| **RFA** | Resource flow analysis |
| **SBP** | Sugar beet pulp |
| **SDGs** | Sustainable Development Goals by the United Nations |

| | |
|---|---|
| **SIA** | Social impact assessment |
| **SOS** | Safe operating space |
| **SME** | Small and medium enterprise |
| **TCP** | Transfer collection points |

# Executive Summary

This report presents a structured framework for assessing the sustainability of the bioeconomy transition across six diverse European pilot regions, each focusing on a distinct sector/ feedstock. The assessment addresses the environmental, economic, and social dimensions of transitions and is grounded in the integrated evaluation framework developed in Deliverable D2.1. This assessment builds upon prior feedstock mapping and stakeholder engagement efforts conducted under Work Packages 1 and 3. It supports the development of tailored circular bioeconomy transition roadmaps for pilot regions that align with local capacities and limitations.

The assessment employs three tools:

- **Resource Flow Analysis (RFA):** This tool utilises Sankey diagrams to trace biomass flows and transformation pathways, enabling the identification of opportunities for material efficiency gains, resource cascading, and the adaptive reuse of infrastructure.
- **Logistics Optimisation (MooV):** This tool enhances the efficiency of regional transport systems, supports multimodal logistics strategies, and facilitates the redesign of bio-based supply chains to reflect local geographical and infrastructural constraints.
- **Impact Assessment Tool (IAT):** Developed through participatory processes, the IAT offers a transparent and systematic means of comparing transition scenarios across environmental, social, and economic dimensions, incorporating both quantitative and qualitative data.

The integrated assessment enables the co-design of transition strategies relevant to regions with limited data availability by capturing context-specific complexity through stakeholder engagement, including participation from experts in environmental, economic, and social assessments. The assessment highlights the crucial role of stakeholder engagement and contextualised knowledge in evaluating the transition pathways. The framework's strengths lie in its adaptability, inclusiveness, and transparency.

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# 1. Introduction

The BIOTRANSFORM project supports the transition from linear fossil-based to circular bio-based systems by equipping European policymakers and regional stakeholders with practical tools, methodologies, and co-created solutions. Operating at the intersection of circular economy and bioeconomy transitions, the project facilitates systemic change across six diverse case-study regions: Andalusia (Spain), Northern Burgenland (Austria), Western Macedonia (Greece), North Rhine-Westphalia (Germany), the Charles Spa Region (Czechia), and Finland. These regions represent a spectrum of sectors including agri-food, forestry, water ecosystems, chemical industry, and energy production. All these sectors need to transition towards circular bio-bioeconomy to become (more) sustainable.

This deliverable D2.2 applies the integrated assessment framework detailed in D2.1, comprising Resource Flow Analysis (RFA), Logistic optimisation, and an Impact Assessment Tool (IAT), to evaluate the co-defined regional bioeconomy transition pathways. Building on the regional feedstock mapping and stakeholder engagement activities conducted in Work Package 1, the assessment framework supports region in identifying optimal pathways that are contextually robust, technically feasible, and aligned with regional priorities to derive the regional bioeconomy transition roadmap (WP3). To ensure that regional transition pathways are consistent with both the European Union's Bioeconomy Strategy and the Circular Economy Action Plan, we have developed a integrated assessment framework that integrates resource flows, supply chain optimisation, key sustainability and circularity dimensions. The transition pathways were identified through a multi-actor participatory process, as detailed in Deliverable D3.1.

From a policy perspective, the EU Bioeconomy Strategy[1] emphasizes the sustainable use of biological resources and bio-based materials to foster regional economic development and support decarbonization goals and the Circular Economy Action Plan[2] prioritizes waste reduction, resource efficiency, and the decoupling of economic growth from environmental degradation, thus addressing key stages of the product lifecycle and promoting system-level circularity. To reconcile and integrate the objectives of both strategies, our assessment framework encompasses: environmental sustainability, economic sustainability, social sustainability and circularity dimensions. The assessment approach aimed to combine stakeholder knowledge with quantitative assessment tools to co-create actionable and tailored circular bioeconomy strategies for each region such that socio-economic challenges and long-term environmental resilience is achieved.

**Key resources from the BIOTRANSFORM project:**

**D1.4 Literature review comparing impact assessment methodologies for linear fossil and circular bio-based economies**

**D2.1 Report on the framework for assessment and methodology applied in the impact tool**.
Framework for the planned assessment and methodology applied in the BIOTRANSFORM assessment tool.

[1] Strategy, U. B. (2018). A sustainable bioeconomy for Europe: strengthening the connection between economy, society and the environment. *European Commission.–2018*
[2] https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en

## 1.1 Environmental assessment

To ensure that sustainability transitions do not worsen existing environmental challenges in the pilot region, a comprehensive environmental impact assessment (Task 2.2) is essential. The current framework utilizes a three-tiered approach to environmental assessment aimed at identifying key contributors to impacts and hotspots, which will guide decision-making in the pilot regions.
Tier 1 consists of a multi-criteria environmental assessment for cases where adequate data for a full LCA are unavailable. This tier incorporates stakeholder values and expert knowledge through a participatory process. Environmental criteria—such as climate change, land use change, and fossil resource use—were collaboratively defined and evaluated. Tier 2 uses Life Cycle Assessment (LCA) for proposed transition pathways when sufficient data is available. Tier 3 involves an absolute sustainability assessment based on the planetary boundary framework. This assessment is conducted at a coarse regional scale to contextualize environmental performance within the limits of Earth's systems, providing a perspective on the absolute ecological impacts of the proposed transitions

## 1.2 Economic assessment

The economic assessment of regional bioeconomy transition pathways (T2.3) evaluates the economic feasibility and systemic impacts using various categories. The first step involves monetizing life cycle environmental impacts by applying valuation coefficients from CE Delft[3], which translates emissions, pollution, and resource use into economic terms for direct comparability with fossil-based alternatives. This assessment also considers labour market dynamics, including projected job creation and displacement, wage stratification (i.e., whether new jobs fall into the categories of minimum, average, or high income), and regional skill readiness by identifying the training needs necessary for workforce reallocation. It quantifies value creation and resource efficiency through indicators such as unit product prices, feedstock-to-product conversion rates, and capital expenditures related to infrastructure. The evaluation investigates how to optimize economic viability in the region by scaling and sizing bio-based value chains. From a trade perspective, these transitions affect the balance of locally consumed versus exported bio-based products and reduce fossil fuel imports, thus assessing the region's progress towards strategic autonomy. Finally, the assessment incorporates adaptation costs for retrofitting or repurposing underutilized infrastructure to capture the necessary investments for the shift to a bioeconomy.

## 1.3 Social assessment

The social impact assessment (T2.4) of the regional bioeconomy transition is grounded in survey data from Task 1.5 and informed by the region-specific social limitations identified through desk research and stakeholder interviews. Stakeholder interviews across the pilot regions revealed shared concerns such as the ageing population, loss of skilled labour due to migration, unemployment, etc. Other social concerns for the transition were the emotional value of forests in Finland and the strong consumer interest in sustainability in North Rhine–Westphalia (Germany) and Andalusia (Spain). To understand how bioeconomy transitions intersect with regional social structures, support regional capacities and avoid regional vulnerabilities, a set of social categories was used to evaluate the societal implications, as mentioned in Task 2.4. These include income, work-life balance, housing, health, education, governance, environment, and security (in line with bioeconomy strategy dimensions: food, water, and energy), as well as self-reported life satisfaction. By applying these indicators, both the benefits

[3] Delft, C. E. (2023). Handboek milieuprijzen 2023. *Methodische onderbouwing van kengetallen gebruikt voor waardering van emissies en milieu-impacts*.

(e.g., increased environmental awareness, citizen engagement with sustainability, and potential for rural revitalization) and the risks (e.g., labour shortages, housing shortage, not in my backyard (NIMBY) were systematically assessed.

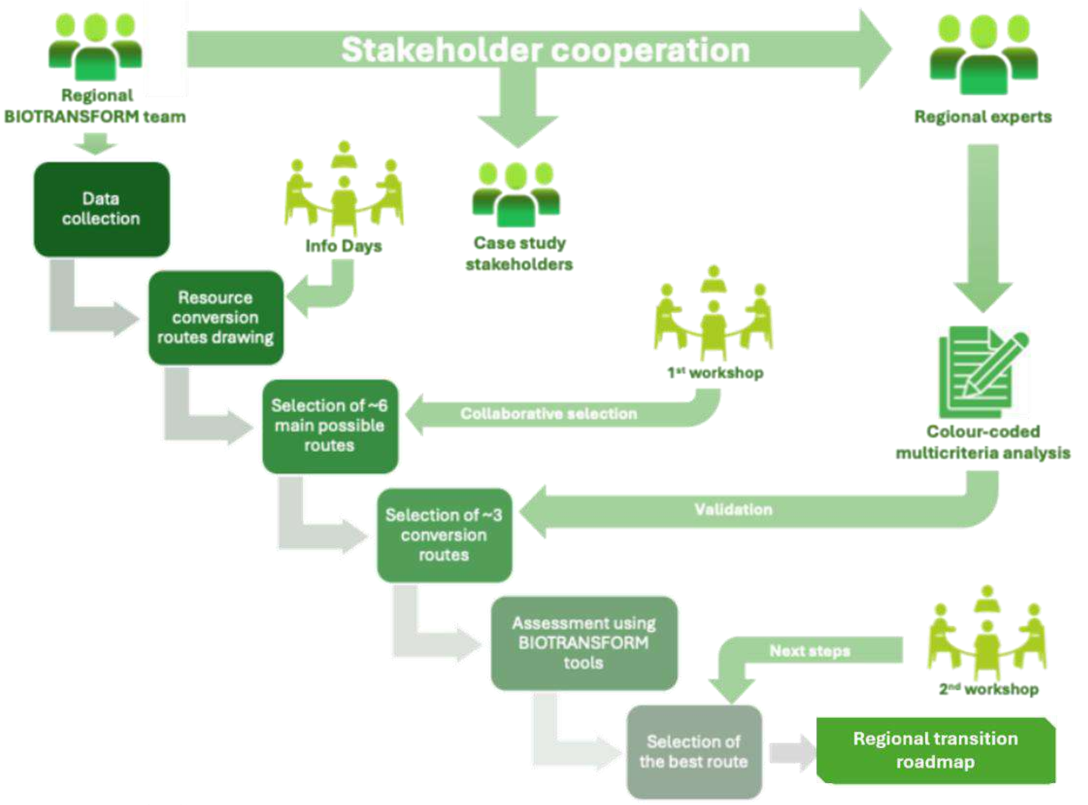


*Figure 1: Six step methodology starting from mapping regional feedstocks, sustainability limitations (data collection) to using three BIOTRANSFORM tools and selecting optimal pathway for each pilot regions.*

The report combines both quantitative and qualitative analyses to evaluate the resource available, logistic, sustainability and circularity potential of the proposed regional transition pathways, providing support for informed regional decision-making for circular bioeconomy. The report is structured as follows: Section 2 presents the assessment framework and the methodology that describes the three-tier environmental impact assessment, economic assessment and the social impact assessment of the transition methodology, along with the circularity assessment. Section 3 illustrates how the regions effectively applied the integrated assessment framework, engaging stakeholders and experts throughout the process

# 2. Methods

## 2.1 Assessment framework

Developing effective policies prioritising sustainability and resource efficiency requires a thorough understanding of resource flows, consumption patterns, environmental and socio-economic limitations. In the BIORANSFORM pilot regions ranging from Andalusia's olive groves to Finland's forestry landscapes and Burgenland's lake-vineyard ecosystems, regional economies face the shared challenge of transitioning from linear, fossil-dependent models towards more sustainable, circular, and bio-based economies. Despite the diversity of six pilot regions, common issues include underutilised local biomass, fragmented value chains, limited investment in bio-based innovation, involvement of multiple stakeholders and divergent value systems. Addressing these challenges requires a systemic approach by integrating various analytical tools to guide, inform, and monitor the transition and to develop transition roadmaps. Transition roadmaps act as strategic tools, simplifying complex bioeconomy transitions into understandable narratives and scenarios and support an effective communication with stakeholders, enabling evidence-based progress monitoring, and help identify necessary steps over time. It also provides a guideline to include the various stakeholder's perspective in making informed decisions, the BIOTRANSFORM regional assessments is shown in section 9, this integrated approach lays the foundation for robust, evidence-based transition roadmaps, translating regional aspirations into measurable impacts and actionable strategies (as detailed in Deliverable D3.2) by translating regional aspirations into measurable impacts and actionable strategies.

## 2.2 BIOTRANSFORM tools

The BIOTRANSFORM methodology for assessing the pilot region transition consists of three tools as shown in Figure 2:

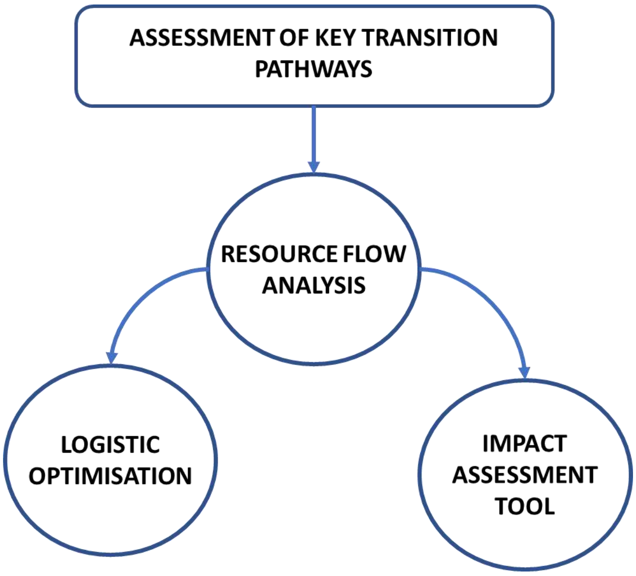


*Figure 2: BIOTRANSFORM tools used for the regional assessment of the proposed transition pathway*

### 2.2.1 Resource flow analysis

To represent and evaluate the current and proposed uses of feedstock within each pilot region, Resource Flow Analysis (RFA) was conducted, primarily using Sankey diagrams as visual tools to provide an overall picture of resource and mass flows. These diagrams were created using quantitative inputs derived from available regional datasets, calculations (e.g., conversion efficiencies), and, where necessary, assumptions based on expert interviews and stakeholder consultations during pathway co-definition. For each selected transition pathway - from raw material acquisition and transport to final outputs - a step-by-step process was mapped to illustrate the sequence of activities, technological requirements, and resource dependencies. This process explicitly considered both the implementation of new technologies and infrastructure and the repurposing of existing or underutilised regional assets, such as decommissioned industrial facilities or logistics networks, to minimise capital investment and environmental footprints. The resulting Sankey diagrams visually underscore the significance of the proposed circular bioeconomy scenarios compared to the current state and serve as a foundational basis for the subsequent environmental, economic, and social impact assessments. To ensure replicability, these diagrams were generated using freely available web-based tools (https://sankeymatic.com/ and https://sankeydiagram.net/), with an example of their creation provided in Appendix 1 of this report.

### 2.2.2 Logistic optimisation tool: MooV

MooV[i] is VITO's supply chain optimisation service dedicated to optimising logistics, supply chain design and mobilisation strategies.

MooV can be applied to the design of entirely new supply chains as well as the evaluation and optimisation of existing ones, with the overarching goal of improving efficiency while minimising logistical risks and costs. Insights and results are delivered to clients in a clear and accessible format, providing valuable decision support for shaping their logistics and mobilisation strategies.

As part of the BIOTRANSFORM project, MooV was applied to evaluate regional biomass mobilisation strategies and to address key logistical and transportation challenges in the transition toward a circular bio-based economy. The analysis considered every step of the logistics chain—including transport, storage, chipping, drying, loading, and unloading—to identify the most effective strategies tailored to the specific needs of each region.

Figure 3 presents the MooV methodology, with a brief explanation of each step provided below.

**Supply Chain**

We begin with a comprehensive analysis of the supply chain, covering all relevant stages from feedstock production, harvesting, and storage to preprocessing and final product processing. This includes all forward and reverse logistics steps, such as first-mile pick-up and last-mile delivery. Where applicable, circularity principles are integrated into the design to align with sustainability objectives.

**Parameters**

Key characteristics of the supply chain are identified, including origin and destination points, timing and scheduling, quality and grading requirements, transported volumes or masses, and any client-specific constraints. These parameters guide the development of tailored supply chain configurations suited to operational and strategic needs.

**Goals**

The optimal supply chain setup depends on client-specific goals. These may include minimizing costs, reducing environmental impact, enhancing circularity, or strengthening strategic partnerships. Often, a combination of these objectives informs the evaluation and decision-making process.

**Scenarios**

In close collaboration with the client, we develop alternative scenarios that reflect different supply chain configurations. Examples include centralized versus decentralized storage systems, variations in fleet composition or capacity, and different pick-up or delivery routing strategies.

**Impact**

Each scenario is assessed using key logistics performance indicators. Evaluations consider economic aspects (e.g., costs and benefits), environmental factors (e.g., fleet emissions), and social dimensions (e.g., job creation). This allows for a comparative analysis of the alternatives.

**Results**

Results are communicated through one-on-one consultations and presented using detailed reports, interactive dashboards, and spatial visualizations. These tools provide clear insight into the implications of each design and support well-informed decision-making.

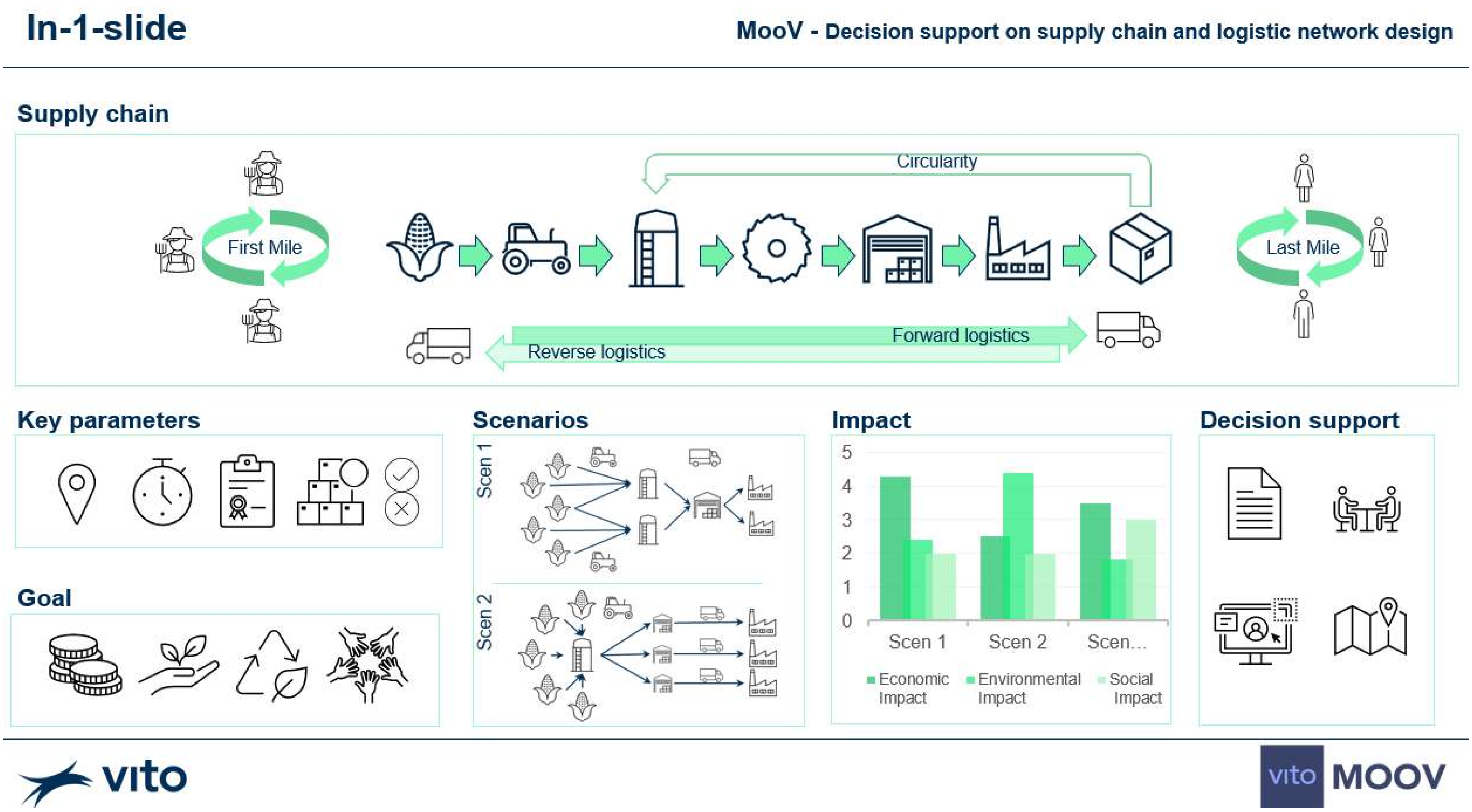


*Figure 3: MooV - explained in one slide*

### 2.2.3 Impact assessment tool

The Impact Assessment Tool (IAT) is an Excel-based, multi-criteria decision-support framework developed to assess the sustainability of regional bioeconomy transition pathways, particularly under limited data availability. It provides a systematic, adaptable, and expert participatory approach to guiding bioeconomy transitions in diverse regional contexts. The IAT integrates quantitative and semi-quantitative assessment methods, combining environmental assessment (LCA) where primary or secondary data are available, with multi-criteria analysis to evaluate socio-economic impacts in data-scarce contexts. Designed to facilitate the first solid step transition from fossil-based to a sustainable bio-based economy, the IAT evaluates pathways across three pillars of sustainability: environmental, economic, and social. It enables the comparative assessment of transition scenarios by scenario-specific resource and energy flows to assess the relative performance of proposed bioeconomy transition (bio-products). Each pillar is further disaggregated into subcriteria, such as greenhouse gas emissions (environmental), job creation (economic), and life satisfaction (social), with weights assigned to each based on stakeholder input, making it inclusive and contextual. IAT uses a transparent and participatory weighting system, which allocates an initial 1,000-point sustainability budget across the three pillars. This allocation is done by stakeholders' workshops and experts' engagement, reflecting processes' representation, regional priorities, and contextual relevance. In a second round, a structured workshop assesses how each subcategory will impact the proposed transition pathway. Using a low-burden assessment method, participants indicated whether the transition would likely have a positive, neutral, or negative impact on each criterion. These qualitative insights were translated into a semi-quantitative scale for comparative analysis to support regional transition. The framework facilitates comparison of the proposed pathway and the identification of synergies and trade-offs among sustainability pillars and subcriteria. Thus, highlights the primary idea of sectoral hotspots and helps co-design optimised transition strategies in collaboration with stakeholders

#### *Environmental assessment*

The environmental sustainability assessment aimed to evaluate the potential environmental benefits and trade-offs associated with regions transition to replace the fossil-based with the bio-based product across different sectors in the pilot regions. One of the widely accepted methods for quantifying environmental impacts across the entire product lifetime is Life Cycle Impact Assessment (LCIA)[4]. However, the assessment of products derived from secondary streams of biorefineries presents specific methodological challenges, including data scarcity and the complexity of allocating environmental burdens among co-products[5]. Conducting a robust LCA is a time-consuming, iterative process that demands high quality data and may not be compatible with the timeframes when rapid decisions are needed. Also, LCA are product based and cannot always capture system-level changes

##### *Multicriteria environmental assessment*

**Tier 1**: A hybrid approach combining literature-derived data with engineering-based assumptions to estimate the energy, water, and material requirements associated with each activity represented in the process diagram. In cases where direct data were unavailable, proxy values or analogous processes were applied to ensure consistency, methodological transparency, and to maintain the comparability across scenarios. For the multicriteria environmental analysis (MEA), six key environmental impact categories were selected, encompassing all regional pathways analyzed:

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[4] Zuiderveen, E. A., Kuipers, K. J., Caldeira, C., Hanssen, S. V., van der Hulst, M. K., de Jonge, M. M., ... & Huijbregts, M. A. (2023). The potential of emerging bio-based products to reduce environmental impacts. *Nature Communications*, *14*(1), 8521.

[5] Gaffey, J., Collins, M. N., & Styles, D. (2024). Review of methodological decisions in life cycle assessment (LCA) of biorefinery systems across feedstock categories

climate change (global warming potential, GWP-total), particulate matter formation, land use change, water use and Resource use – fossil fuels. Each environmental impact was mapped to the most relevant activities ensuring a systematic link between process steps and environmental consequences, as detailed in Table 2.

*Table 2: Environmental impact assessment categories and activities contributing to the categories*

| Environmental indicators | Key activities |
|---|---|
| Climate change (GWP-total) | • Fossil fuel combustion (coal, oil, gas) [6]<br>• Deforestation and land-use change [7]<br>• Industrial processes (cement, steel, chemicals) [8]<br>• Agriculture (livestock, fertilizer use) [9]<br>• Emissions of fluorinated gases from equipment and products[10] |
| Particulate matter formation | • Fossil fuel combustion (vehicles, industry) [11]<br>• Biomass burning and agriculture [12]<br>• Construction and mining activities [13]<br>• Industrial emissions (manufacturing, power generation)[14] |
| Land use change | • Deforestation for agriculture and urbanization [15]<br>• Conversion to cropland or pasture[16]<br>• Urban and infrastructure development[17]<br>• Afforestation and reforestation initiatives[18] |
| Water use | • Agricultural irrigation[19]<br>• Industrial processes and cooling[20]<br>• Domestic and urban water consumption[21]<br>• Energy production[22] |
| Resource use – fossil (ADP-fossil) | • Extraction and consumption of coal, oil, and gas<br>• Plastic and synthetic material production<br>• Fuel consumption in the transport sector<br>• Electricity generation from fossil sources |
| Resource use – minerals and metals (ADP-min&met) | • Mining and extraction of minerals and metals<br>• Manufacturing of electronics and batteries<br>• Use of construction materials |

6 https://www.ipcc.ch/report/ar6/wg1/
7 https://www.ipcc.ch/srccl/
8 https://www.iea.org/reports/tracking-industry-2022
9 https://www.ipcc-nggip.iges.or.jp/public/2019rf/index.html
10 https://www.ipcc.ch/report/ar5/wg3/industry/
11 https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health
12 Johnston, H. J., Mueller, W., Steinle, S., Vardoulakis, S., Tantrakarnapa, K., Loh, M., & Cherrie, J. W. (2019). How harmful is particulate matter emitted from biomass burning? A Thailand perspective. *Current Pollution Reports*, *5*, 353-377.
13 https://www.epa.gov/air-emissions-factors-and-quantification/ap-42-compilation-air-emission-factors
14 https://www.eea.europa.eu/data-and-maps/dashboards/air-pollutant-emissions-data-viewer-2
15 https://www.ipcc.ch/srccl/
16 https://www.fao.org/documents/card/en/c/cb9360en
17 https://www.eea.europa.eu/airs/2018/natural-capital/land-take
18 https://ipbes.net/assessment-reports/ldr
19 https://www.fao.org/3/i7959e/i7959e.pdf
20 https://unesdoc.unesco.org/ark:/48223/pf0000367306
21https://www.epa.gov/watersense/how-we-use-water
22 https://doi.org/10.1088/1748-9326/7/4/045802

| | |
|---|---|
| | • Industrial processes requiring specific minerals or metals |

***Life cycle assessment***
**Tier 2**: Life Cycle Assessment (LCA) is a standardized method defined by ISO 14040 and ISO 14044 for assessing the environmental impacts associated with all stages of a product's life cycle from raw material extraction, production, and use, to disposal or recycling. It translates resource use and emissions into quantifiable environmental impacts (e.g., climate change, water depletion) using scientific models and category indicators. Several LCA methods[23] are available, each reflecting specific scientific models, regional contexts and differ in their selection endpoint vs. midpoint modelling approaches[24]. There are four phases of the LCA

- Goal and Scope Definition: Defines purpose, system boundaries, and functional unit
- Life Cycle Inventory (LCI): Compiles energy/material inputs and emissions
- Life Cycle Impact Assessment (LCIA): Evaluates environmental impacts
- Interpretation: Analyse results against goals, and support conclusions or improvements

To translate the life cycle inventory into environmental impacts, impact categories such as climate change, eutrophication, human toxicity are selected. According to the recommendation by JRC sixteen standardized impact categories (ILCD handbook, JRC)[25] are mandatory and their weighting and normalization are optional.

*Table 3: Sixteen recommended environmental impact categories (European context) for LCIA by ILCD along with the abbreviation and unit*

| Impact category | Abbreviation | Unit |
|---|---|---|
| Climate change 1 | CC | kg $CO_2$ eq |
| Ozone depletion | ODP | kg CFC-11 eq |
| Human toxicity, non-cancer | HTOX_nc | CTUh |
| Human toxicity, cancer | HTOX_c | CTUh |
| Particulate matter | PM | Disease incidence |
| Ionising radiation | IR | kBq U-235 eq. |
| Photochemical ozone formation | POF | kg NMVOCeq. |
| Acidification | AC | mol $H^+$ eq |
| Eutrophication, terrestrial | TEU | mol N eq |
| Eutrophication, freshwater | FEU | kg P eq |
| Eutrophication, marine | MEU | kg N eq |
| Land use | LU | Pt |
| Ecotoxicity freshwater | ECOTOX | CTUe |
| Water use 1 | WU | $m^3$ water eq |

[23] https://doi.org/10.1007/978-3-319-56475-3
[24] Huijbregts, M. A., Steinmann, Z. J., Elshout, P. M., Stam, G., Verones, F., Vieira, M., ... & Van Zelm, R. (2017). ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. *The international journal of life cycle assessment*, *22*, 138-147
[25] https://eplca.jrc.ec.europa.eu/uploads/ILCD-Handbook-Recommendations-for-Life-Cycle-Impact-Assessment-in-the-European-context.pdf

| | | |
|---|---|---|
| Resource use, fossils | FRD | MJ |
| Resource use, minerals and metals | MRD | kg Sb eq |

*Planetary boundaries*

**Tier 3:** The planetary boundaries framework (PBs) presents an absolute sustainability assessment framework that is based the earth system thresholds. The concept suggests that the Earth is constrained by biophysical limits referred to as carrying capacity, which indicates how much environmental disturbance the Earth system can sustain without irreversible damage to its function. Hence, defining Safe Operating Space (SOS) for humanity (Table 4). The framework includes nine Earth system processes referred to as boundaries and fourteen control variables that defines the nine key earth system processes, which are responsible for keeping the planet in a stable and functional condition: climate change, stratospheric ozone depletion, ocean acidification, biosphere integrity, biogeochemical flows (nitrogen and phosphorus cycles), land-system change, freshwater use, atmospheric aerosol loading, and novel entities (chemical pollution), and thirteen different quantitative indicators (control variables) for the nine boundaries (such as nitrogen and phosphorous flows as indicators of biogeochemical flows boundary).

*Table 4: Latest values of the minimum and maximum value of the planetary boundaries framework as retrieved from (Richardson et al., 2023)*

| Planetary boundary | Unit | Zone of uncertainty (min-max) | Natural background level | Full SOS (min-max) |
|---|---|---|---|---|
| Climate change (Energy imbalance) | W/m² | 1–1.5 | 0 | 1–1.5 |
| Climate change (CO2 concentration) | ppm CO2 | 350–450 | 280 | 70–170 |
| Ocean acidification | Ωaragonite | 2.75–2.408 | 3.44 | 0.69–1.032 |
| Stratospheric ozone depletion | DU | 275–260 | 290 | 15–30 |
| Atmospheric aerosol loading - global | - | 0.1–0.25 | 0.03 | 0.07–0.22 |
| Biogeochemical flows - Nitrogen global | Tg N/yr | 62–82 | 0 | 62–82 |
| Biogeochemical flows – Phosphorus global | Tg P/yr | 11–100 | 0 | 11–100 |
| Land system change - global | % | 75–54 | 100 | 25–46 |
| Freshwater use - global | km³ | 4000–6000 | 0 | 4000–6000 |
| Change in biosphere integrity - functional diversity | % BII loss | 10–70 | 0 | 10–70 |

## Economic assessment

The economic assessment was conducted in two stages. In the first stage, we calculated environmental prices by monetizing the environmental impacts estimated using LCA based on established valuation methods. In the second stage, we performed a semi-quantitative evaluation using a set of economic indicators applied at the value chain level for each.

*Environmental prices*

The CE Delft Environmental Prices Handbook[26] provides a structured methodology to estimate the social costs of environmental pollution by assigning monetary values called as "environmental prices" to emissions. These prices are expressed in euros per kilogram of pollutant and represent the economic welfare loss associated with additional pollution. The methodology operates on three levels: pollutant level (specific substances), midpoint level (environmental themes like climate change), and endpoint level (impacts on human health or ecosystems). Valuation is grounded in welfare economics, utilizing approaches such as damage-cost methods, willingness-to-pay studies, and impact pathway modelling to ensure consistent valuation across impact categories, facilitating integration into LCA impacts. The average monetary value for each kg of the pollutant as shown in the table below[27].

***Table 5: Environmental prices per life cycle impact category[28], the central is calculated using hierarchist perspective[29]. The environmental impacts are estimated using ReCiPe method LCIA***

| Impact category | Unit | Central (€) |
|---|---|---|
| Climate change | €/kg $CO_2$-eq. | 0.13 |
| Ozone depletion | €/kg CFC-11-eq. | 29.1 |
| Radiation | €/kBq Co-60-eq. | 0.00422 |
| Smog formation, human health | €/kg $NO_x$-eq. | 1.7 |
| Smog formation, terrestrial ecosystems | €/kg $NO_x$-eq. | 0.043 |
| Particulate matter formation | €/kg $PM_{2.5}$-eq. | 168 |
| Acidification | €/kg $SO_2$-eq. | 6.46 |
| Eutrophication, freshwater | €/kg P-eq. | 5.53 |
| Eutrophication, marine | €/kg N-eq. | 14.25 |
| Ecotoxicity, terrestrial | €/kg 1,4-DCB-eq. | 0.00095 |
| Ecotoxicity, freshwater | €/kg 1,4-DCB-eq. | 0.0309 |
| Ecotoxicity, marine | €/kg 1,4-DCB-eq. | 0.0047 |
| Human toxicity, cancer-related | €/kg 1,4-DCB-eq. | 5.25 |
| Human toxicity, non-cancer-related | €/kg 1,4-DCB-eq. | 0.097 |
| Land use | €/$m^2$·year crop-eq. | 0.146 |
| Resource depletion, mineral | €/kg Cu-eq. | 0.014 |
| Resource depletion, fossil | €/kg oil-eq. | 0.028 |
| Water use | €/$m^3$ | 0.137 |
| $NO_2$-mortality* | €/kg $NO_x$-eq. | 9.32 |

***Qualitative assessment***

[26] https://cedelft.eu/wp-content/uploads/sites/2/2021/03/CE_Delft_7N54_Environmental_Prices_Handbook_2017_FINAL.pdf

[27] Delft, C. E. (2023). Environmental Prices Handbook 2024: EU27 version. *Report*.

[28] https://cedelft.eu/wp-content/uploads/sites/2/2021/03/CE_Delft_7N54_Environmental_Prices_Handbook_2017_FINAL.pdf

[29] Huijbregts, M. A., Steinmann, Z. J., Elshout, P. M., Stam, G., Verones, F., Vieira, M., ... & Van Zelm, R. (2017). ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. *The international journal of life cycle assessment*, *22*, 138-147

A structured qualitative assessment approach based on stakeholders and experts' engagement to evaluate the economic implications of the proposed bioeconomy transition pathways. A semi-quantitative methodology was developed to systematically assess the potential economic impacts of each transition pathway. This approach was grounded in a set of predefined economic indicators, which were initially outlined in the project proposal. These indicators captured both potential benefits and risks and are summarized in Table 6.

*Table 6: Key economic criteria and associated perspective (risks/opportunities) in the development of a regional bio-based value chain*

| Economic category | Contextual focus |
|---|---|
| Job Creation / Loss | Anticipated employment shifts, including job creation potential and risks of job displacement or uneven regional distribution. |
| Wages | Evolution of wage structures, potential for wage disparity between bio-based and fossil-based sectors, risk of stagnation or decline. |
| Training needs | Identification of skill gaps and retraining requirements for the transitioning workforce; risks include misalignment between skills demand and availability. |
| Value creation | Potential revenue generation from new value chains, contingent on feedstock availability and value chain development; risks include value capture by large firms or failed upscaling. |
| Added value | Net added value across supply chains; concerns include poor conversion efficiency and overreliance on subsidies. |
| CAPEX (Capital Expenditure) | Investment costs for establishing new facilities; risk of high capital requirements potentially acting as a barrier. |
| OPEX (Operational Expenditure) | Costs associated with feedstock procurement, logistics, and labour; vulnerable to supply variability and price volatility. |
| Sizing and scaling | Appropriateness of facility scale given feedstock availability and market proximity; potential drawbacks include infrastructure strain and displacement of small actors. |
| Export | Opportunities to generate exportable, high-value bio-based products; risks involve prioritization of export over domestic material needs. |
| Import | Reduction in reliance on fossil-based imports, enhancing regional resilience; potential downside includes new dependencies on imported biomass feedstocks. |

**Indicator weighting**

Relevant regional stakeholders from academia, industry, civil society, and local governance were identified and engaged. They were asked to assign relative weights to each economic criteria based on the contextual priorities and specificities of the region's transition pathway ensuing that the assessment reflects economic concerns and strategic interests of the region as shown in Figure 4

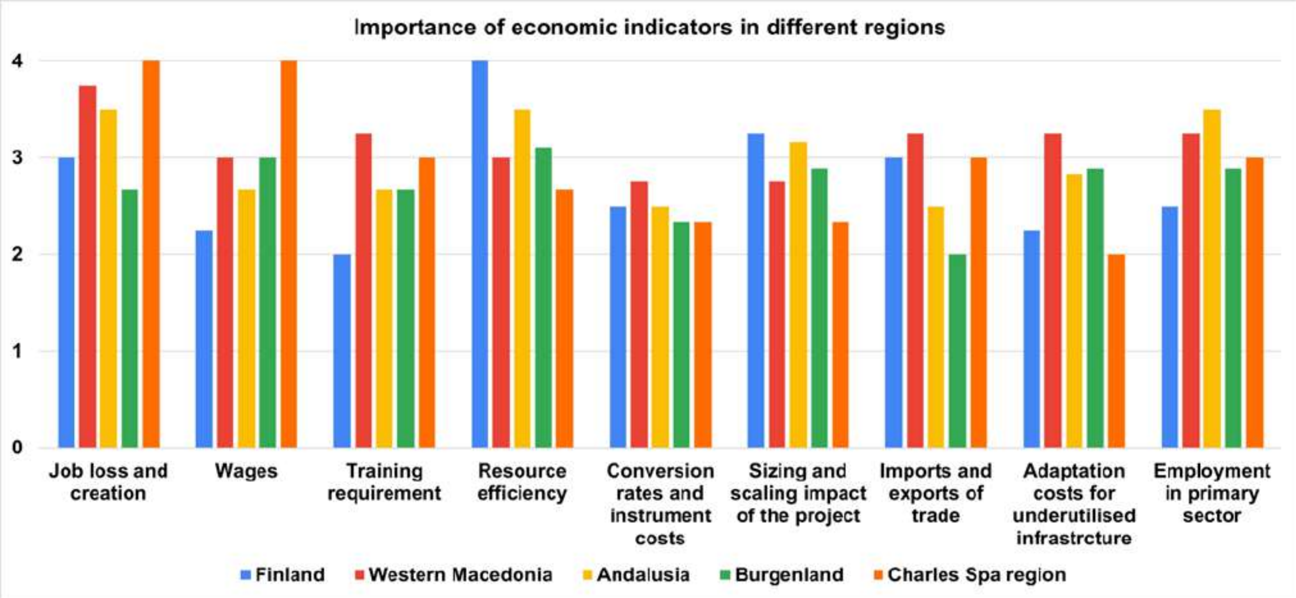


*Figure 4: Importance of economic assessment categories across pilot regions based on stakeholder survey responses using a Likert scale (1 = least important, 4 = most important). This bar plot illustrates the relative significance attributed to each category, highlighting regional variations in stakeholder priorities.*

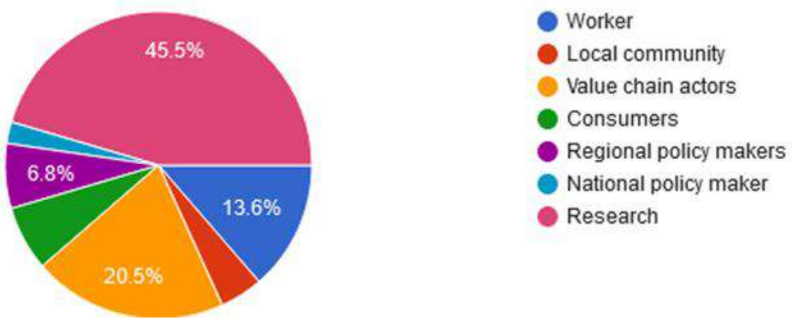


*Figure 5: Stakeholders group that participated in the survey*

## Impact evaluation

In a second round, stakeholders assessed the expected impact of the proposed transition pathway for each indicator. Using a low-burden elicitation method (e.g., short surveys or structured interviews), participants indicated whether the transition would likely result in a **positive**, **neutral**, or **negative** impact for each criterion. These qualitative insights were translated into a semi-quantitative scale for comparative analysis:

a. Positive impact = 1
b. Neutral impact = 0.5
c. Negative impact = 0

This conversion enabled aggregation and comparison of stakeholder perceptions across different economic categories, thereby supporting a more comprehensive understanding of the anticipated economic trade-offs of the bioeconomy transition.

### *Social assessment*

The goal of the social assessment was to understand stakeholder perspectives from different pilot regions on the potential social implications of proposed bioeconomy transition pathways. A structured, multi-step approach was adopted to ensure stakeholder input was meaningfully integrated into the evaluation process.

For each pilot region, stakeholders were identified based on their relevance to the selected transition pathways and their potential exposure to social impacts (Task 1.5). The process emphasized inclusivity from stakeholders and context-specific regional relevance. Stakeholder engagement was carried out through regional workshops and an online survey. Due to limited project funding for engagement activities, a low-burden approach was adopted to collect stakeholder insights efficiently. Stakeholders consulted by region included:

- Greece: Lignite mine workers, academic researchers, wastewater utility representatives
- Finland: Forestry value chain actors
- Czech Republic: Restaurant owners, biogas/composting operators, policymakers
- Spain: Value chain actors, consumers, researchers
- Austria: Farmers, regional policymakers, biomass processors, business support agencies
- Germany: Farmers, representatives from sugar/chemical industries, academia, food producers, innovation clusters

Step 1: Indicator-based stakeholder survey
A set of social impact indicators was selected based on relevance to different stakeholder groups. Each stakeholder was asked to rank the importance of specific indicators, to ensure the pathways support socially just transitions.
The survey assessed stakeholder priorities across different domains[30]:

- Workers: Knowledge creation, capacity building, inclusion of vulnerable groups
- Local communities: Cultural heritage, local employment, community engagement, safe and healthy working/living conditions
- Value chain actors: Fair competition, social responsibility
- Consumers: End-of-life product responsibility, transparency

An initial survey conducted during the first stakeholder workshops helped identify which social indicators were prioritized in each region. These preferences are illustrated in Figure 6

[30] Traverso, M., Valdivia, S., Luthin, A., Roche, L., Arcese, G., Neugebauer, S., ... & Zamagni, A. (2021). Methodological sheets for subcategories in social life cycle assessment (S-LCA) 2021. *United Nations Environment Programme (UNEP)*.

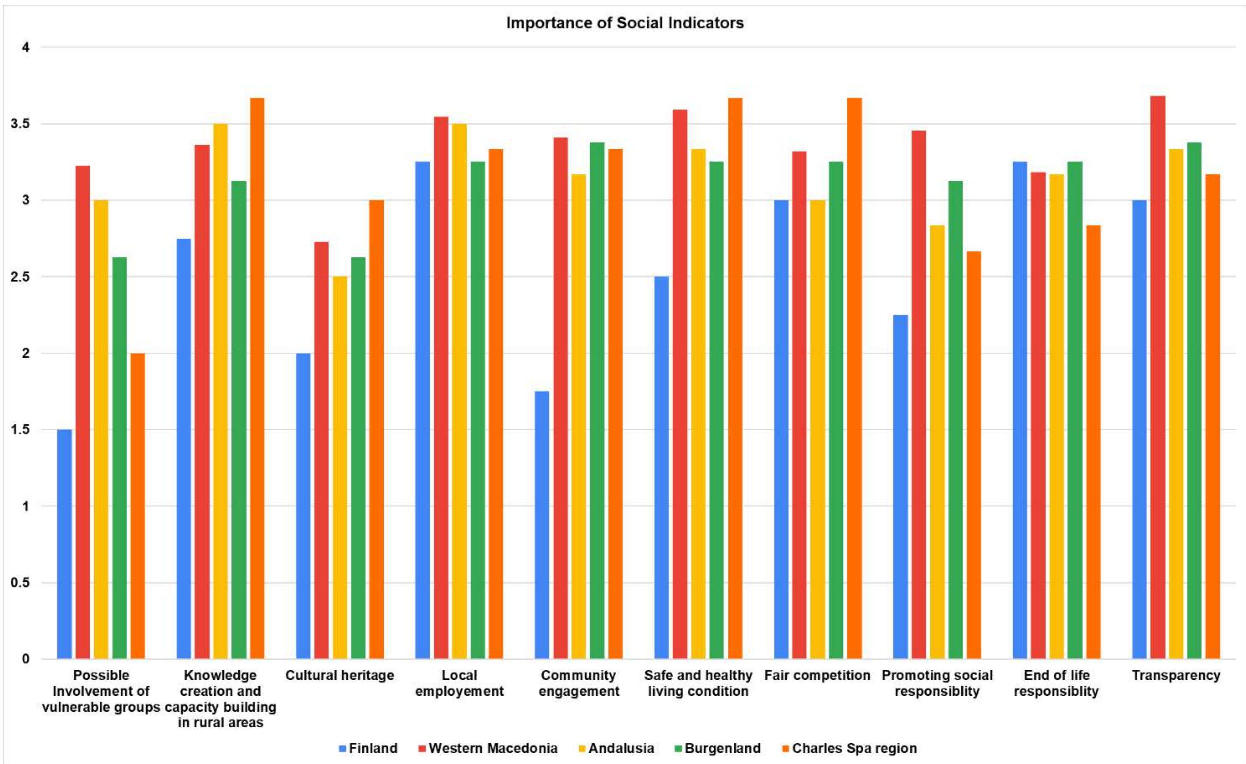


*Figure 6: Importance of social assessment categories across pilot regions based on stakeholder survey responses using a Likert scale (1 = least important, 4 = most important). This bar plot illustrates the relative significance attributed to each category, highlighting regional variations in stakeholder priorities.*

Step 2: Assessment of social categories
Stakeholders were then invited to assess the proposed transition pathways against a defined set of social categories, which were contextualized to reflect regional and stakeholder-specific realities. The table below summarizes each category and its contextual meaning:

*Table 7: Key social category and the contextual focus used to assess the social impact of the bio-based value chain*

| Social category | Contextual focus |
|---|---|
| Employment | Job quantity, type, and flexibility. Flexible jobs accommodate aging workers, women, and caregivers, supporting equal opportunities[31]. |
| Work-life Balance | Effects of transition on time management, proximity to work, and part-time/flexible schedules that support family and community life[32]. |
| Income | Impacts on income generation, distribution, diversification, and stability to ensure inclusive socio-economic benefits[33] |
| Housing | Affordability, availability, quality, and sustainability of housing. Sustainable construction and community planning are seen as positive impacts.[34] |

[31] Ecker, F., Philippidis, G., Sinabell, F., & Toppinen, A. (2023). The social pillar of bioeconomy sustainability: A review of socio-economic indicators and assessment frameworks
[32] https://www.ilo.org/resource/news/flexible-working-hours-can-benefit-work-life-balance-businesses-and
[33] Marting Vidaurre, N. A., Vargas-Carpintero, R., Wagner, M., Lask, J., & Lewandowski, I. (2020). Social aspects in the assessment of biobased value chains. *Sustainability*, *12*(23), 9843.
[34] Chan, S. M., Wong, H., Tang, Y. K., & Li, S. N. (2023). Social impact assessment of transitional social housing and service interventions for low-income families: the case of Hong Kong. *Sustainability*, *15*(15), 12061.

| | |
|---|---|
| Health | Effects on physical and mental well-being of workers and communities, considering risks (e.g., exposure to bio-waste) and benefits (e.g., green jobs, ecosystem restoration)[35]. |
| Governance | Stakeholder perceptions on policy coherence, responsibility allocation, financial inclusion, and the effectiveness of multi-level governance[36]. |
| Security | Impacts on the food-water-energy nexus: availability, stability, and sustainability of essential resources. |
| Environment | Effects on land-use changes and biodiversity as part of the social dimension of the transition.[37] |
| Life Satisfaction | Perceptions of well-being, leisure time, and community belonging. Indicators include cultural participation, shared values, and a sense of identity.[38] |

Step 3: Criteria weighting and pathway Evaluation
In the next step, stakeholders assigned weights to the various social criteria based on their perceived importance within their regional context. They then evaluated the expected impact of the proposed bioeconomy transition pathway for each criterion, indicating whether it would have a positive, negative, or neutral effect. These responses were translated into numerical values to enable comparison: positive = 1, neutral = 0.5, and negative = 0.

### *Sustainability assessment*

To assess and compare the overall sustainability of proposed transition scenarios across different pilot regions, we applied a multi-criteria decision analysis (MCDA) framework. This method integrates quantitative environmental life cycle impacts with semi-quantitative MEA, economic and social indicators, and places stakeholder engagement at the core of the decision-making process. The structure and weighting system are inspired by the Battelle Environmental Evaluation System [39].

**Weighting of sustainability criteria by stakeholders**
In the first step, local stakeholders from each pilot region were engaged to define the relative importance of the three sustainability criteria: environmental, economic, and social. Each region allocated a total score of 1000 points across these three categories based on their perceived importance for the sustainability of the transition scenario in that context.

**Example:**

*Table 8: Example showing the sustainability criteria weighting and the score distribution*

| Sustainability criteria | Weight (%) | Score |
|---|---|---|
| Environmental | 35% | 350 |
| Economic | 35% | 350 |
| Social | 30% | 300 |

[35] Rebolledo-Leiva, R., Moreira, M. T., & González-García, S. (2023). Progress of social assessment in the framework of bioeconomy under a life cycle perspective. *Renewable and Sustainable Energy Reviews*, *175*, 113162.
[36] European Commission: Directorate-General for Research and Innovation, *Enhancing stakeholder involvement in EU bioeconomy policy*, Publications Office of the European Union, 2024, https://data.europa.eu/doi/10.2777/361410
[37] https://wedocs.unep.org/20.500.11822/45332
[38] https://doi.org/10.1787/9789264191655-en

[39] https://uon.sdsu.edu/the_battelle_ees.html

**Subcriteria selection and weighting**

Within each main sustainability category, a set of subcriteria's were identified to capture specific aspects of environmental, economic, and social performance. These subcriteria were also weighted by stakeholders, who rated each one based on its relevance to the success and sustainability of the proposed transition pathway.

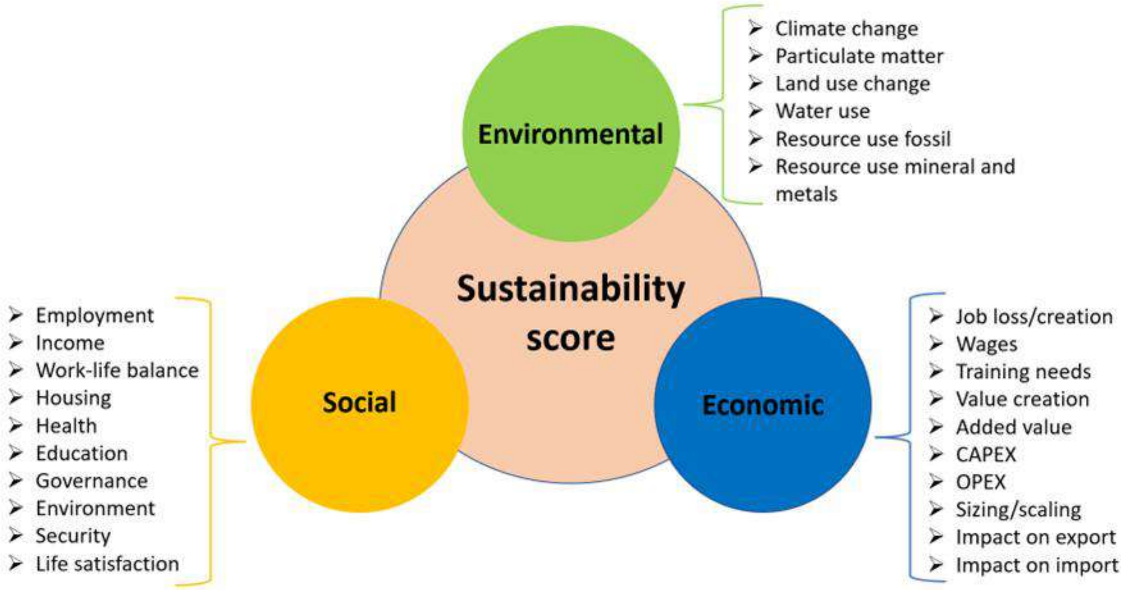


*Figure 7: Showing the impact categories considered for assessing the sustainability of the proposed transition pathways under environmental, social, and economic criteria*

Participants assessed subcriteria using:

- A Likert scale (from 1 = most important to 4= least important), or
- Qualitative assessments (positive, same, negative), which were quantified numerically (positive = 1, same = 0.5, negative = 0).

These responses were normalized and used to determine **percentage weights** for each subcriterion within its sustainability category.

**Example (Environmental subcriteria):**

*Table 9: Example of subcriteria weighting by stakeholders based on activities contributing to environmental impact (Table 2) and their relevance to the conversion root process diagram for informed decision-making*

| Subcriterion | Weight (%) | Subunit |
|---|---|---|
| Climate change (GWP-total) | 20% | (20/100)*350 |
| Particulate matter | 15% | (15/100)*350 |

Calculating Preliminary Subcriteria Score (PSS) & overall sustainability scores

In step 3 we quantify the contribution of each subcriteria to the overall sustainability score:

Each PSS is calculated as:

PSS = (Weight of Subcriterion100)×Score of Sustainability Criterion

To reflect stakeholder views about the direction of impact for each category, subunit score is multiplied by a response factor, defined as follows:

- Positive impact → response factor = 1
- No change → response factor = 0.5
- Negative impact → response factor = 0

For example, if stakeholders believe that the proposed pathway will positively affect climate change, the subunit score for climate change is multiplied by 1. If the impact is negative, it is multiplied by 0, effectively removing it from the score. If the impact is expected to remain unchanged, the subunit score is halved (multiplied by 0.5).

The sustainability score is estimated by summing the subunits factored for all the criterion shown in Figure.8:

*Total Sustainability Score=∑(Subunit ×Stakeholder Response Factor)*

This adjustment ensures that the sustainability evaluation reflects both the importance of each Sub criterion and the expected impact of the transition pathway, as perceived by regional stakeholders.

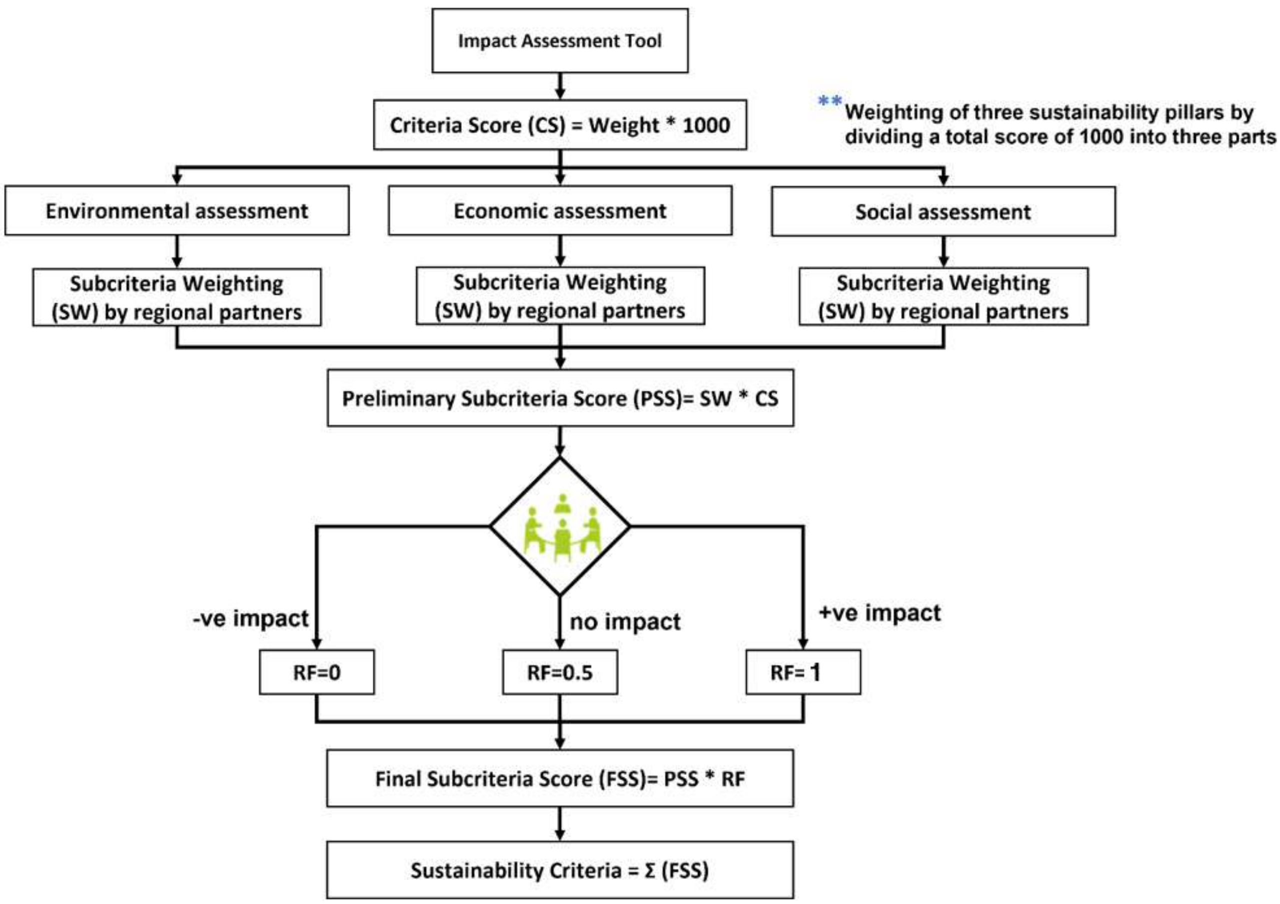


*Figure 8: Flowchart illustrating the three-tiered sustainability assessment approach incorporating expert perspectives. The subcriteria for each tier are detailed in Figure 7*

### *Circularity assessment*

To evaluate the circularity potential of the proposed transition pathway, which remains largely at the pilot scale, a structure-based approach is developed, drawing on the work of Geng et al. (2012)[40]. The framework facilitates a systematic appraisal of resource and material flow efficiencies across production and consumption systems, particularly in data-scarce environments. It provides a qualitative yet methodologically rigorous means to assess systemic circularity performance and guide strategic decision-making. Instead of calculating fully quantified circularity metrics, the assessment relied on macro-level indicators and qualitative visualisation tools as provisional yet informative proxies for quantifying performance across key circularity metrics, aiming to identify performance trends, potential hotspots, and systemic bottlenecks along the transition pathway. The framework is organised around four primary dimensions of circular economy performance: resource output rate, resource consumption rate, integrated resource utilization rate, and waste disposal and pollutant emissions. Each dimension was analysed using a curated set of macro-level indicators (Table 10,11,12,13) selected for their ability to reflect material and energy productivity, system circularity, and environmental leakage. A traffic-light visualisation scheme was integrated into the assessment process. This visual diagnostic tool categorises circularity performance as follows:

- **Green** – indicative of favourable or efficient circular performance
- **Yellow** – reflective of moderate performance or areas requiring improvement
- **Red** – denoting inefficiencies or environmentally unsustainable practices

#### 1. Resource output rate

This dimension evaluates the economic productivity derived from the consumption of primary mineral and energy resources. The aim is to capture how effectively bioeconomy activities generate value while minimizing extraction pressure on ecosystems.

*Table 10: Indicators to estimate resource output calculation and the explanation*

| Indicator | Formula | Explanation |
|---|---|---|
| Output of main mineral resources | GDP / Total mineral resource consumption | Assesses value generation per unit of extracted mineral resource (e.g., iron, copper, zinc). |
| Output of energy | GDP / Total energy consumption | Measures economic output per unit of energy input across all sources. |

#### 2. Resource consumption rate

This set of indicators reflects the intensity of energy and water use across the economy and industrial production systems. Lower values are preferred, indicating a decoupling of economic output from resource inputs.

*Table 11: Indicators to calculate resource consumption rate, formula and explanation*

[40] Geng, Y., Fu, J., Sarkis, J., & Xue, B. (2012). Towards a national circular economy indicator system in China: an evaluation and critical analysis. *Journal of cleaner production*, *23*(1), 216-224

| Indicator | Formula | Explanation |
|---|---|---|
| Energy consumption per unit of GDP | Energy consumption / GDP[41] | Evaluates national energy efficiency. |
| Energy consumption per added industrial value (AVI) | Industrial energy consumption | Focuses on energy performance in industrial sectors. |
| Energy consumption of key industrial products | Energy consumption of steel, copper, aluminum, cement, fertilizer,paper)/steel production (copper, aluminium, cement, fertilizer, paper) | Sector-specific assessment (e.g., steel, cement). |
| Water withdrawal per GDP | Total freshwater withdrawal / GDP | Indicates water use intensity of the economy. |
| Water withdrawal per industrial value added | Industrial water withdrawal / AVI[42] | Captures efficiency of water use in industry. |
| Water consumption per unit of key product | Freshwater consumed / Amount of Product production ($10^8$ $m^3$/ton) | Sector-specific water use. |
| Coefficient of Irrigation water utilization | Actual amount of irrigation water consumption/total amount of irrigation water consumption | Evaluates efficiency of agricultural water use. |

**3. Integrated resource utilization rate**

This category measures how effectively materials are reused, recycled, or safely treated—key proxies for loop closure and circularity performance.

*Table 12: Indicators to calculate integrated resource utilization rate, formula and explanation*

| Indicator | Formula | Explanation |
|---|---|---|
| Recycling rate of industrial solid waste | (waste quantity integrated utilization/ Industrial solid waste generation) × 100% | Indicates the closure of industrial material cycles. |
| Industrial water reuse ratio | (industrial repetitive water use Q[43] / Industrial water consumption) × 100% | Assesses industrial reliance on water reuse. |
| Wastewater reuse rate | (Treated waste water reuse Q / Total treated wastewater Q) × 100% | Evaluates circularity in wastewater management. |
| Safe treatment rate of domestic waste | (Safely treated domestic waste / Total collected domestic waste) × 100% | Reflects robustness of municipal waste systems. |
| Recycling rate of iron scrap | (amount of Recycled iron scrap / Total production of iron) × 100% | Indicates circular use of ferrous materials. |
| Recycling rate of non-ferrous metals | (Amount of recycled non-ferrous metal/ total amount | Captures reuse of high-value metals. |

[41] Gross Domestic Product
[42] Annual added industrial production value

[43] Quantitity

| | | |
|---|---|---|
| | of non-ferrous metal / Total production) × 100% | |
| Recycling rate of paper | Amount of recycled paper / Total production of paper × 100% | Reflects bio-based material recovery. |
| Recycling rate of plastic | Amount of recycled / Total production × 100% | Tracks progress on persistent plastic waste. |
| Recycling rate of rubber | Amount of recycled rubber / total amount of rubber production × 100% | Relevant for circularity in mobility sectors. |

**4.Waste disposal and pollutant emissions**

This final dimension evaluates residual outputs and emissions that represent system leakages and environmental risks. Indicators are essential to assess whether circularity efforts are effectively reducing ecological burdens.

*Table 13: Indicators used to quantify waste disposal and pollutant emissions*

| Indicator | Unit | Explanation |
|---|---|---|
| Industrial solid waste for final disposal | Tons | Measures unrecovered industrial residues. |
| Industrial wastewater discharge | Tons | Indicates volume of untreated or unreused wastewater. |
| $SO_2$ emissions | kg | Proxy for fossil fuel dependence and air pollution. |
| COD discharge | kg | Reflects organic pollutant load in aquatic systems. |

# 3. Results - Pilot region assessment

**Key resources from the BIOTRANSFORM project:**

**D1.1 Report on limits of the linear fossil economies**. Baseline report on environment, economic & social limits of linear fossil-based economies exemplifying our 6 case-study regions.

**D1.2 Report on current status of development of EU regional circular bioeconomies.** Baseline report on current circular bioeconomy, measurement indicators, assessment of technologies & solutions.

**D1.3 Database of suitable circular bioeconomy solutions.** This database includes >40 circular bioeconomy solutions, which are suitable for our pilot areas and sectors.

**D3.1 Report on the different pathway analysis and selection of the optimal transition pathway from linear fossil-based to circular bioeconomy.** This deliverable describes the process of co-defining the pathways of the individual case study regions within the BIOTRANSFORM project.

**D3.2 Transition roadmaps from linear fossil based to a circular bioeconomy of our case-studies.** Deliverable D3.2 presents detailed transition roadmaps developed collaboratively with regional stakeholders in each of the case-study regions.

## 3.1 Austria

The Northern Burgenland region around Lake Neusiedl presents a unique opportunity for circular bioeconomy innovation. Rich in biomass resources such as reed from lake maintenance and sediments from dredging activities, the region faces ecological challenges (e.g. sedimentation, water balance) that simultaneously offer bio-based innovation potential. Within BIOTRANSFORM, a set of transformation scenarios was developed and evaluated using a combined approach of resource flow analysis and a structured multi-criteria assessment, targeting sustainability and circularity impacts across environmental, economic, and social dimensions.

### 3.1.1 Transition pathway

**Route 1: Sediments as construction materials**
This pathway explores the use of lake sediments from Lake Neusiedl as raw material for construction products, such as bricks or plaster. The multicriteria assessment highlighted strong environmental and economic potential, particularly in reducing resource extraction and landfill disposal. It showed positive social impacts through local job creation and regional value retention. Challenges remain in legal classifications and handling logistics.

**Route 2: Sediments in agriculture**
This route investigates the application of sediments as soil improvers or fertiliser supplements. Environmental results indicate high nutrient recycling potential, though stakeholder concerns about contamination and public acceptance slightly reduced its social score. Economically, the route is promising due to the avoided costs of artificial fertilisers and sediment disposal.

**Route 3: Reed as construction materials**
Reed biomass is considered for insulation or fibreboard production. The environmental profile is very positive, with high carbon storage and renewable material substitution effects. Economically and socially, the route is competitive if supply chains and processing capacity can be developed locally. Stakeholders appreciated the added value for habitat management and ecosystem restoration.

**Route 4: Reed for mycelium-based materials**
This innovative pathway combines reed substrates with fungal growth for packaging or building materials. The assessment showed good social and environmental potential, especially due to the biodegradable nature of the end-products and potential for SME innovation. However, the route is still at low TRL and economically less mature.

**Route 5: Reed for energy**
This scenario focuses on using reed biomass for combustion or pellet production. It received mixed scores in the assessment: while providing immediate use for biomass and reducing fossil fuel dependency, stakeholders raised concerns about emissions and lower circularity compared to material use. Economically, the route is viable under existing biomass feed-in tariffs, but less preferred in long-term circular bioeconomy visions.

### 3.1.2 Resource flow analysis

Three major biogenic resource streams were examined:

- **Reed**: In the current scenario, ~3,640 t/year of reed are harvested, with 99% exported for roof thatching. Only ~1% is used domestically. Alternative processing into reed mats, insulation panels, and mycelium-based products remains marginal shown in Figure 9.
- **Sediments**: Approximately 60,000 m³/year are dredged, mainly disposed of without added value as shown in Figure 10.
- **Vineyard residues**: Around 85,000 t/year are still underutilized as shown in Figure 11.

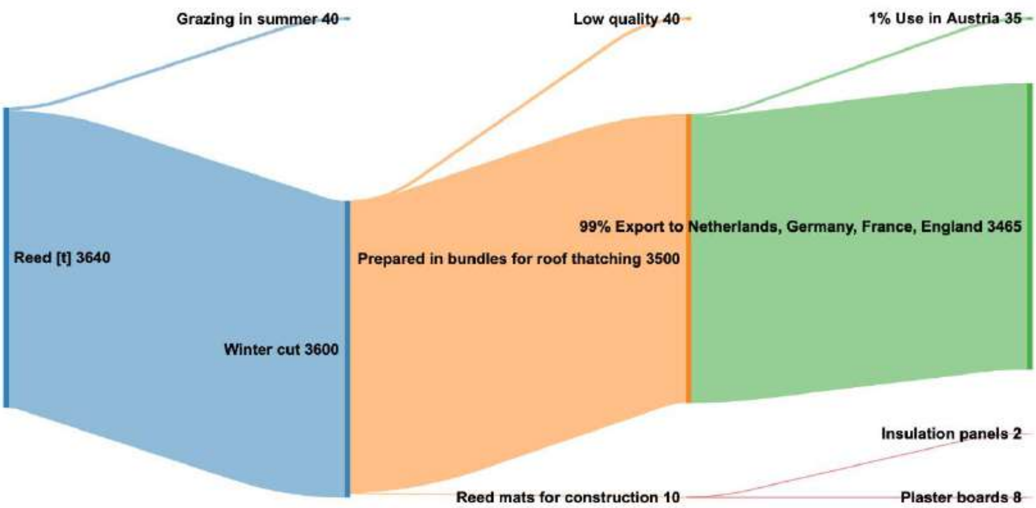


*Figure 9: Current approximate utilisation of reed in Northern Burgenland (extrapolated from reports, interviews, images & calculated based on interview with reed cutter)*

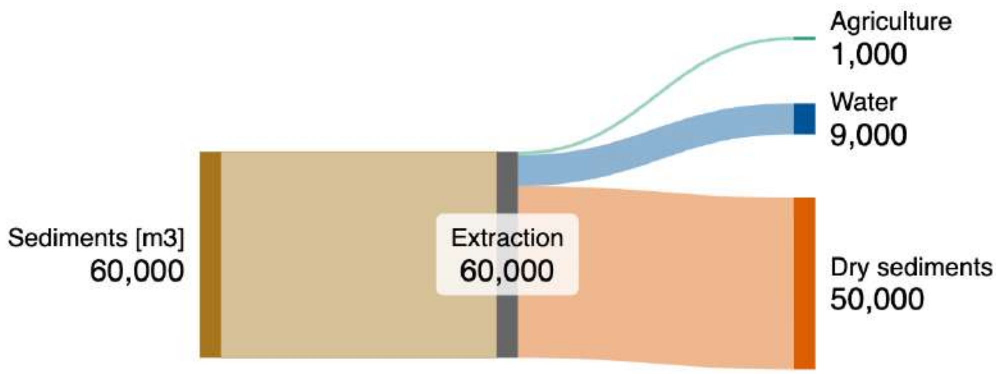


*Figure 10: Current resource flow for extracted sediments (specific utilisation of material not clear even after interview)*

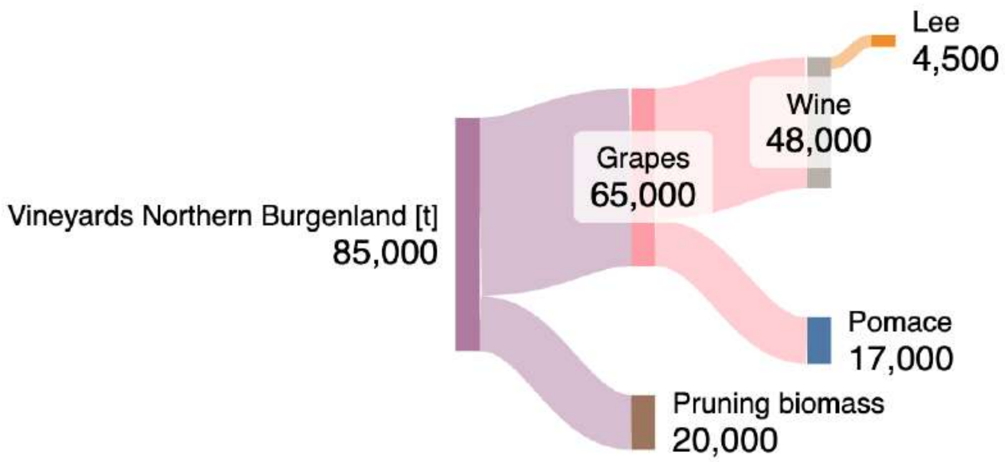


*Figure 11: Current resource flow for vineyards in Burgenland (based on regional statistics and residue amounts per ha derived from calculations done in 2014)*

The data for the Sankey diagrams representing current and proposed scenarios in Northern Burgenland were compiled through a triangulated approach combining:

- Local reports and natural park documents (e.g., reed harvesting amounts)
- Published newspaper entries concerning reed management and lake infrastructure (e.g., sediment extraction amount)
- Data from the Austrian Statistics Office and Chamber of Commerce
- Satellite images to estimate harvestable areas (e.g., 60 km² reedbed area)
- Expert interviews and stakeholder consultations, which validated key flow assumptions
- Quantitative inputs from the regional case study workshop, held on 5 March 2024 with approximately 15 stakeholders including lake managers, policymakers, and biomass processors

The numeric estimates (i.e., sediment volume of 100,000 m³/year, 42,000 t/year of harvestable reed) were discussed in that workshop and agreed upon as realistic targets. The vineyard residue scenario was not further elaborated as the focus and stakeholder selection was put on lake residues. The diagrams were created using online tools (Sankeymatic and Sankeydiagram), using consistent units (tons per year or m³/year) and scaled to reflect the proposed shift in biomass valorisation strategies.
In the proposed scenarios, reed harvesting is scaled to 20,000 t/year and sediment extraction to 100,000 m³/year. Reed is diversified into building products (panels, plaster boards) and mycelium substrates; sediments are valorised into bricks, soil improvers, and 3D printing materials.
(See Figures 9 for reed and 10 for sediments)

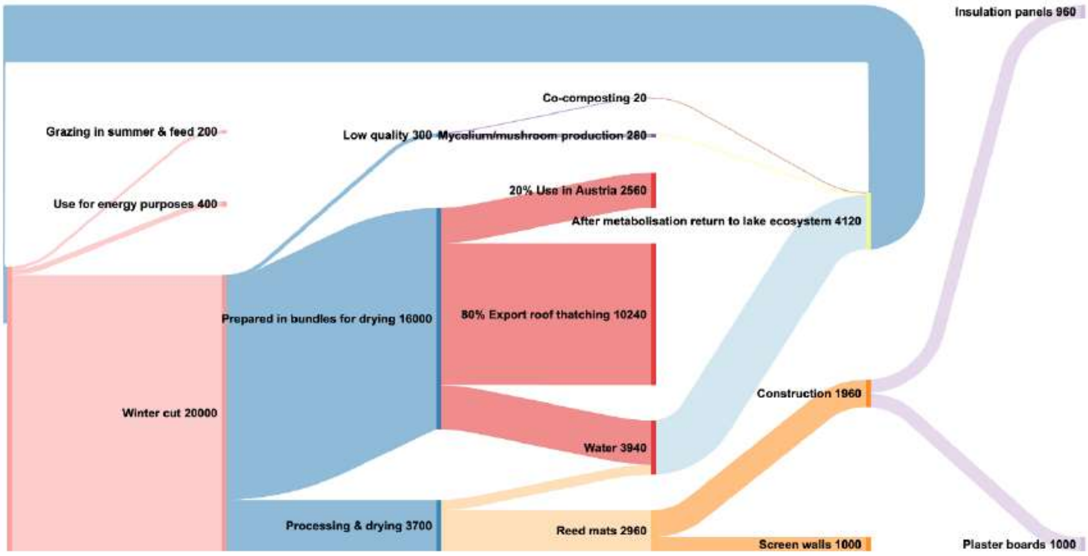


*Figure 12: Sankey scenario for scaling reed utilisation in Northern Burgenland*

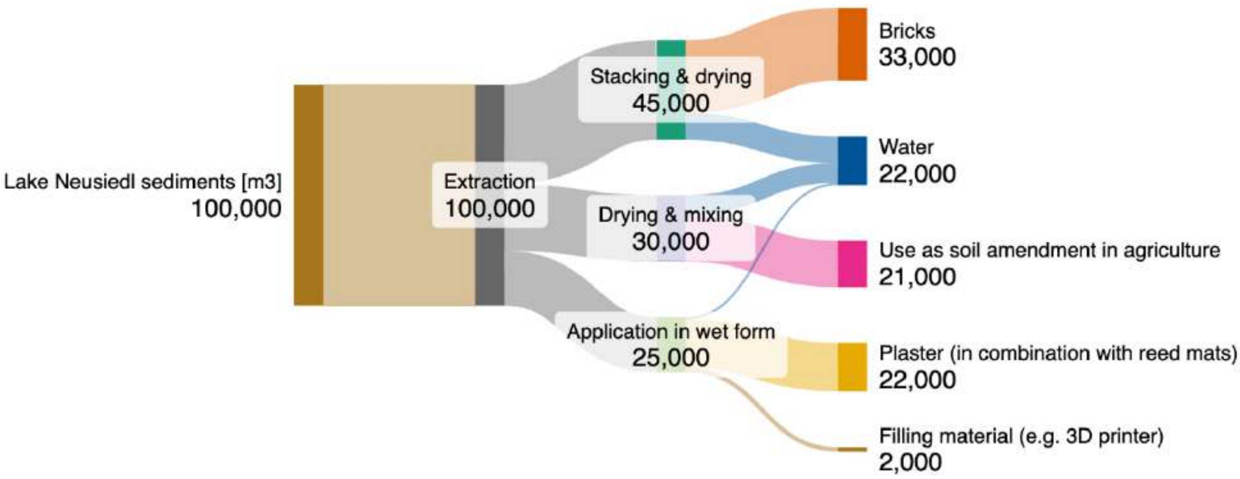


*Figure 13: Scenario for scaling sediment utilisation in Northern Burgenland*

### 3.1.3 Environmental assessment

The weights were assigned on perceived importance of the environmental sub criteria by the expert accounting for the regional challenges and remined constant for all the routes as shown in Table 14.

*Table 14: Weighting the different environmental criteria for the Northern Burgenland case*

| Main Criteria | Weight | Units | Subcriteria | Weight | Sub-Units |
|---|---|---|---|---|---|
| Environmental Impact | 33% | 230 | Climate change (GWP-total) | 20% | 80.00 |
| | | | Particulate matter | 15% | 35.00 |
| | | | Land use change | 15% | 60.00 |
| | | | Water use | 20% | 40.00 |

| | | | | | |
|---|---|---|---|---|---|
| | | | Resource use fossil (ADP-fossil) | 15% | 70.00 |
| | | | Resource use mineral and metals (ADP-min&met) | 15% | 45.00 |
| | | | Subtotal environmental impact | 100% | 330.00 |

### *3.1.4 Economic assessment*

The weights were assigned on perceived importance of the economic subcriteria by the expert accounting for the regional challenges and remined constant for all the routes as shown in Table 15.

*Table 15: Weighting the different economic criteria for the Northern Burgenland case*

| Main Criteria | Weight | Units | Subcriteria | Weight | Sub-Units |
|---|---|---|---|---|---|
| Economics | 34% | 340 | Job loss / Job creation | 18% | 70.00 |
| | | | Wages | 16% | 45.00 |
| | | | Training needs | 14% | 35.00 |
| | | | Value Creation | 14% | 30.00 |
| | | | Added Value | 13% | 30.00 |
| | | | CAPEX | 5% | 35.00 |
| | | | OPEX | 5% | 35.00 |
| | | | Sizing/scaling | 5% | 20.00 |
| | | | Impact on export | 5% | 20.00 |
| | | | Impact on import | 5% | 20.00 |
| | | | Subtotal economical | 100% | 340.00 |

### *3.1.5 Social assessment*:

The weights were assigned on perceived importance of the economic subcriteria by the expert accounting for the regional challenges and remined constant for all the routes as shown in Table 16.

*Table 16: Weighting the different social criteria for the Northern Burgenland case*

| Main Criteria | Weight | Units | Subcriteria | Weight | Sub-Units |
|---|---|---|---|---|---|
| Social aspects | 33% | 330 | Employment | 19% | 70.00 |
| | | | Income | 17% | 60.00 |
| | | | Work-Life Balance | 17% | 45.00 |
| | | | Housing | 16% | 55.00 |
| | | | Health | 5% | 20.00 |
| | | | Education | 5% | 20.00 |
| | | | Governance | 5% | 15.00 |

| | | | | | |
|---|---|---|---|---|---|
| | | | Environment | 5% | 15.00 |
| | | | Security | 5% | 15.00 |
| | | | Life satisfaction | 5% | 15.00 |
| | | | Subtotal social impact | 100% | 330.00 |

The experts scored each indicator for 5 different proposed scenarios. The detailed results of the evaluation of environment, economic and social criteria are shown in Figures 14 to 16.

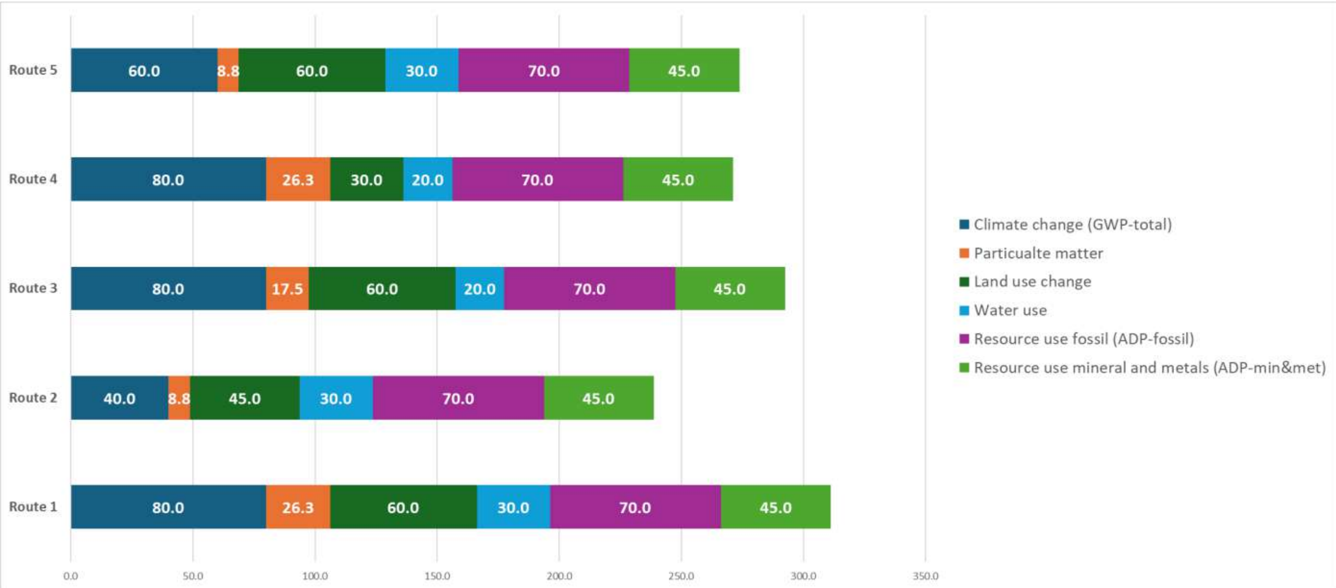


*Figure 14: Evaluation of environmental criteria for the 5 proposed pathways in Northern Burgenland*

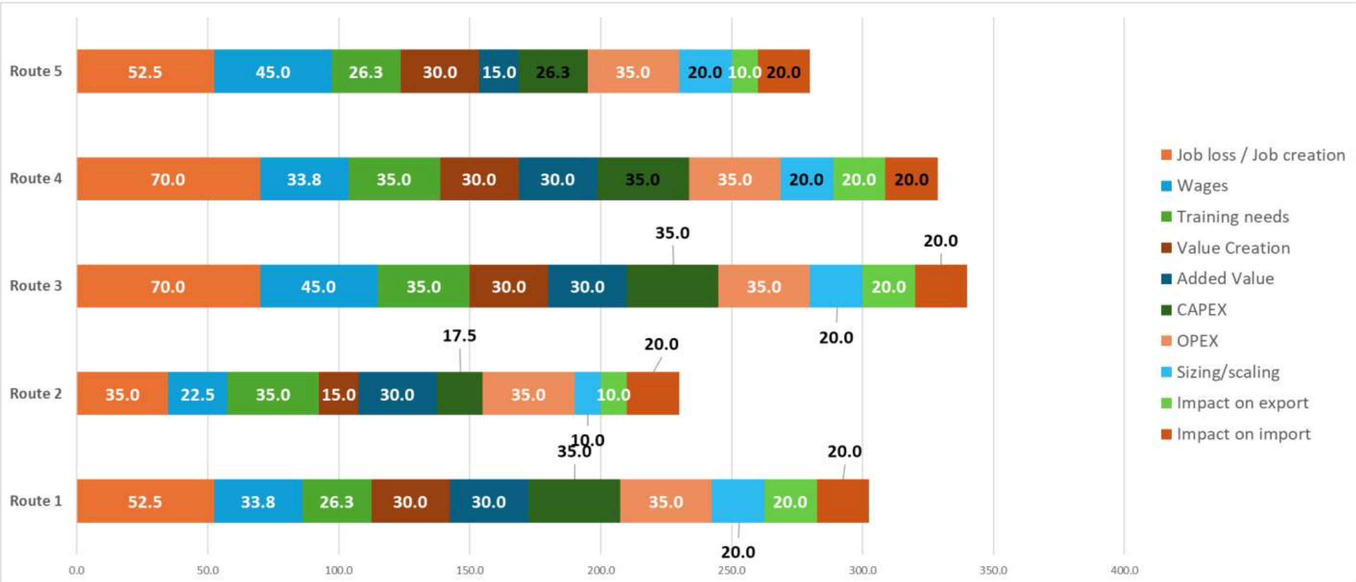


*Figure 15: Evaluation of economic criteria for the 5 proposed pathways in Northern Burgenland*


*Figure 16: Evaluation of social criteria for the 5 proposed pathways in Northern Burgenland*

## 3.1.6 Sustainability assessment

The multi-criteria assessment of the five proposed valorisation routes for lake reed and sediments in Northern Burgenland revealed distinct profiles for each. Overall, pathways focusing on material use, such as route 1 (Sediments as construction materials) and route 3 (Reed as construction materials), tended to score favourably in environmental and potentially social aspects, offering benefits like resource efficiency, carbon storage in products, and local value creation. Route 2 (Sediments in agriculture) showed promise for nutrient recycling, though its overall score might be influenced by considerations like potential contaminants. The more innovative route 4 (Reed for mycelium-based materials) likely highlighted good circularity potential and innovation as well as or employment opportunities but might have presented higher economic uncertainty or lower TRL at this stage. In contrast, route 5 (Reed for energy), while offering an immediate use for biomass, may have scored lower on overall sustainability and value addition compared to material applications, reflecting a common trade-off in bioeconomy pathways. It is noteworthy that findings related to vineyard residue valorisation, including the Sankey diagrams of the status quo, were also presented during the final stakeholder meeting; however, the primary focus for the stakeholder interaction and the detailed MCA assessment detailed here centred on lake residue valorisation, as this was identified as an even more significantly underutilised resource with pressing ecological implications for the Neusiedler See region.

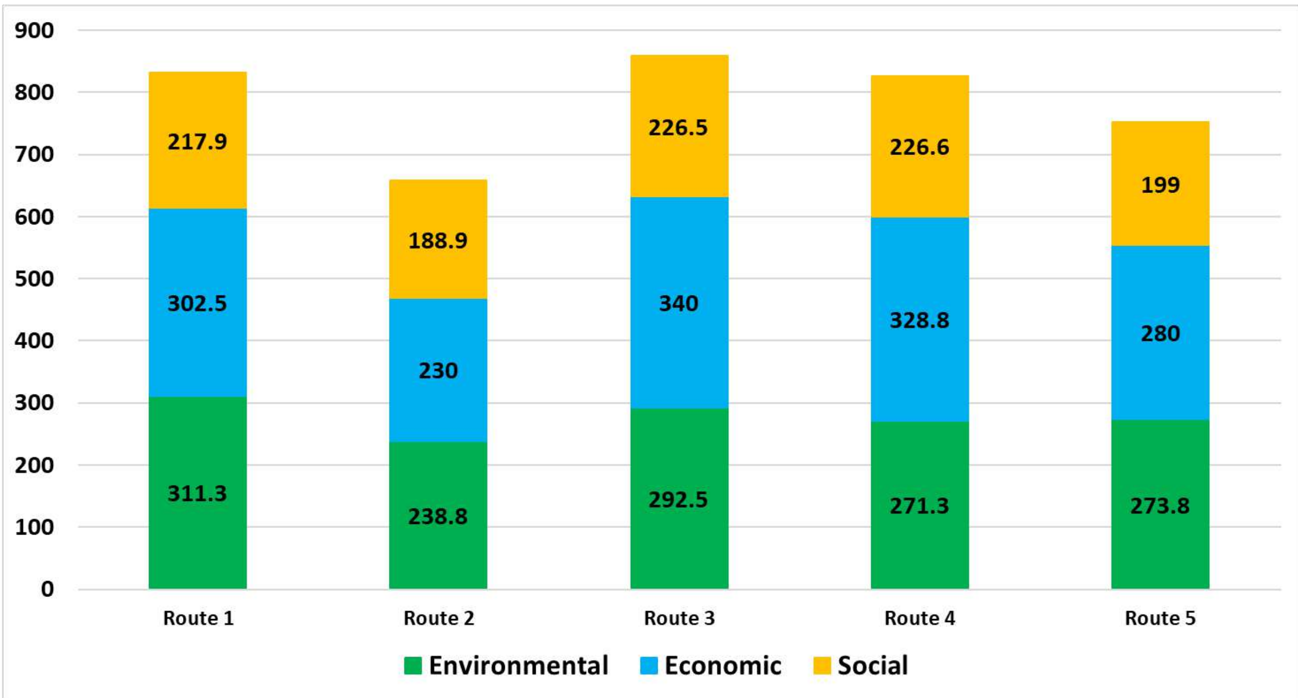


*Figure 17: Sustainability score for the 5 proposed pathways in Northern Burgenland*

It is important to emphasize that the multicriteria sustainability assessment results (Figure 17), while indicative, are not exhaustive or definitive. The primary value of this exercise in the Northern Burgenland case study was the process of engaging diverse stakeholders, confronting them with a structured approach to evaluate different options, and thereby illuminating future possibilities. This served as a crucial preparatory step to foster dialogue and lay the groundwork for potential follow-up projects and more detailed feasibility studies

### 3.1.7 Circularity assessment

In Northern Burgenland, the circularity assessment evaluates pathways designed to create value from currently underutilised local resources: lake reed, dredged lake sediments, (and vineyard residues). The focus is on establishing local material cycles that address both ecological management needs (e.g., for Lake Neusiedl) and opportunities for sustainable products in construction, agriculture, and innovative bio-based materials.

*Table 17: Circularity assessment of construction material production using lake reed and dredged sediments in Northern Burgenland, Austria*

| Product | Resource Output rate | Resource consumption rate | Integrated Resource Utilisation rate | Waste disposal and pollutant emissions |
|---|---|---|---|---|
| **Reed for construction materials** (panels, roofing) | Utilises rapidly renewable, locally abundant biomass for durable products. High value from managed natural resource contributing to lake health. | Low processing energy for traditional uses (thatching); moderate for panels. Water use for reed growth is part of the natural lake ecosystem. | Uses significant portion of harvested reed; different qualities for different products. Addresses ecological need for reed management, contributing to ecosystem health. | Replaces energy-intensive conventional materials (e.g., insulation). Biodegradable if untreated. Sequesters carbon in buildings for their lifetime. |
| **Reed for mycelium-based products** | Innovative valorisation of reed into novel, high-potential materials. Economic output depends on market development for mycelium products. | Energy required for substrate preparation and controlled mycelium cultivation. Water for reed growth is natural. | Utilises reed, including potentially lower quality fractions not suitable for traditional construction, for a new bio-based value chain. By-products from mycelium process can be composted. | Products are typically biodegradable and compostable. Replaces fossil-based plastics/foams. Potentially low processing emissions. |
| **Sediments for construction materials** (bricks, plaster) | Transforms dredged material into valuable construction inputs. High resource output from a problematic "waste" stream. | Energy for drying/firing bricks can be significant, but potentially less than virgin clay extraction/processing. High initial water content of sediment. | Full valorisation of dredged sediment for this product line. Directly addresses lake management needs by finding use for removed material. | Reduces need for landfilling sediment. Emissions from brick firing. Potential for contaminant leaching from products needs careful assessment and management if sediments are polluted. |
| **Sediments for agricultural use** (soil improver) | Recycles nutrients and organic matter from the lake ecosystem back to agricultural land. High value if it replaces synthetic fertilisers. | Low energy input for application. Water content of sediments can be beneficial for application on dry soils. | Direct use of dredged material, effectively closing local nutrient loops and enhancing soil organic matter. | Reduces need for synthetic fertiliser production (which is energy-intensive and has GHG emissions). Risk of contaminant transfer from sediment to soil requires rigorous testing and quality control. |
| **Reed for energy** | Lower value application compared to material uses; energy output per ton of reed is the primary measure. | Energy for harvesting, transport, pelletising/combustion. Replaces fossil fuels for energy but is a less efficient use of biomass carbon than material use. | Utilises reed biomass but does not cascade carbon into long-lived products; primarily a recovery option. | Combustion emissions ($CO_2$, particulates, NOx, SOx), even if $CO_2$ is biogenic. Ash requires disposal or further valorisation. Less circular than material uses. |

# 3.1 Czechia-Charles Spa

## 3.2.1 Transition pathway

As established in D3.1, the Charles Spa region of the Czech Republic opted to propose a transition path by combining local biomass from the tourism industry (food waste from restaurants and households) to produce biogas and composting. The path was co-defined by stakeholder consultations, expert suggestions, and supported by the local strategies for energy transition. The decision to follow this route was taken by taking into consideration the limited biomass options for the region (low agricultural activity and forestry), existing infrastructure and activities, but primarily the region's priorities for energy efficiency and shift toward sustainable energy production. Considering the blooming tourism sector in Charles Spa, the selected route can be an example for other regions with similar production models. The analysis for the regions entails a biomass flow analysis, supported by Sankey diagrams, a sustainability assessment, circularity assessment based on the traffic light approach and logistics tool optimization to figure out the best strategies for biomass transportation and location of processing facilities.

The first part showcased the differences between the current and future scenario through Sankey diagrams, including also the calculations for mass balances based on bibliography since not all data was publicly available. Then the sustainability assessment is analysed step by step, including the logic behind each rating from the local experts

### 3.2.2 Resource flow analysis

The Sankey diagram of the “current scenario” showcases the mass flows of gastro and food waste currently treated in Charles Spa. The data reflect specifically the Karlovy Vary and Marianske Lazne cities of the Charles Spa region, as these were selected for the analysis due to their intense tourist activities. The Sankey has as a starting point the collected waste destined for composting. According to the MooV provided data estimations, this is 1695.9t yearly. It’s worth mentioning that some of the Food Waste (Here represents both the domestic and the restaurant's “gastro waste”) is lost due to the law allowing the gastro waste fraction to be home-shredded and dumped despite the existence of paid collection services. Therefore, it’s difficult to estimate the total amount of food waste (compostable municipal waste + gastro waste from restaurants). The available data only concerns the amount collected. Therefore, the amount ending up in the waste dump might vary. Estimations for this branch of the Sankey are based on literature and are used for visualization purposes, and do not reflect the exact numbers.

For the amount collected and headed to the composting plant, it is estimated that 60% is turned into compost while 40% is lost in the process, according to the literature. A part is also separated and sent to the waste dump at the collection points.

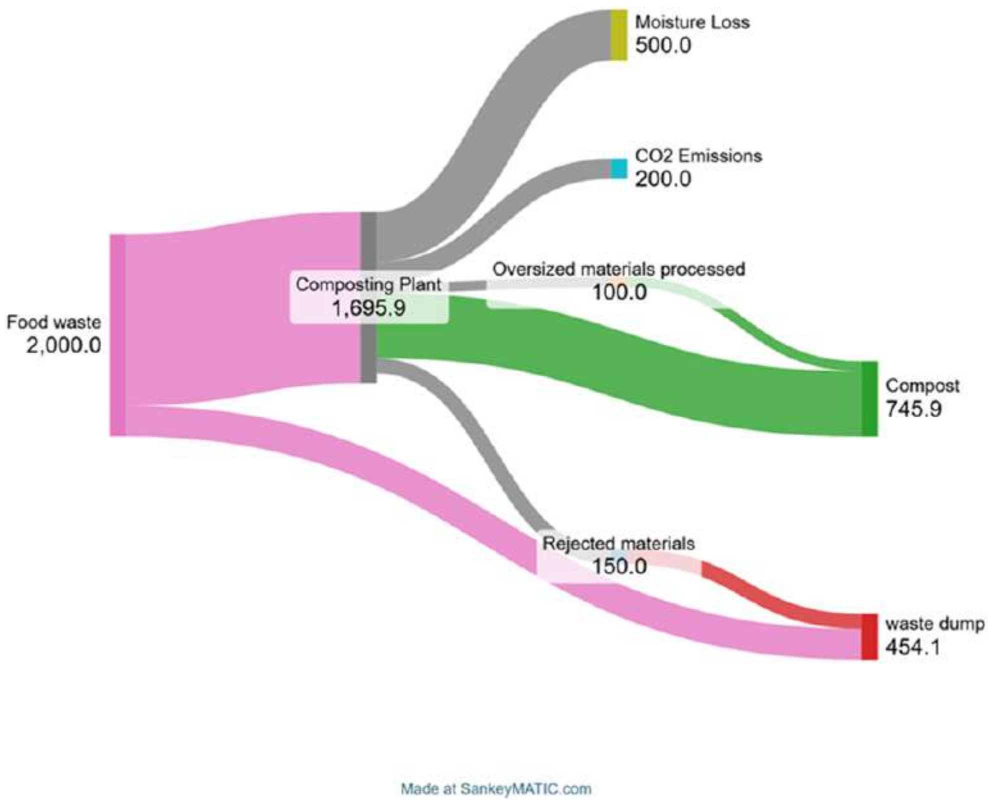


*Figure 18: Sankey diagram showing the mass flow in tonnes in the current scenario for Charles Spa*

*Table 18: Flow breakdown of food waste processing: inputs, losses, and final compost output*

| Initial input | Food waste: 1,695.9 tons (100%) |
|---|---|
| Pre-processing [44] | Rejected Material: ~150 tons (8.8%)<br>Non-compostables (plastics, glass, bones, etc.) removed during sorting. |
| Composting Process[45] | Moisture Loss (Evaporation): ~500 tons (29.5%)<br>Water evaporates due to microbial heat generation and environmental exposure. |
| | $CO_2$ Emissions: ~200 tons (11.8%)<br>Carbon is lost as $CO_2$ through microbial respiration during decomposition. |
| | Recirculated Oversized Material: ~100 tons (5.9%)<br>Large, underprocessed pieces are reintroduced to the process. |
| Final Output | Finished Compost: ~745.9 tons (44%) [46] |

Given the simplified block diagram below, two scenarios are possible, apart from the composting of the currently non-valorized waste.

- We can also generate fertilizer and biomethane instead of just compost from the amounts of food waste currently collected.
- Or fertilizer and biogas, which can be directly fed into a cogeneration unit to produce heat and electricity.

Option 1 and Option 2 present small differences in the production of biomethane, showing a big loss of volume at the end. Biomethane is denser, performs better compared to biogas, and is promising for sale at a better price.

[44] Haug, R.T. (1993), The Practical Handbook of Compost Engineering, Lewis Publishers.
[45] Zhou et al. (2018). Mass and Energy Balances of a Large-Scale Composting Facility, Waste Management, 74, 193–200, DOI: 10.1016/j.wasman.2017.11.049

[46] FAO (Food and Agriculture Organization of the United Nations), “Manual on Composting.”, http://www.fao.org/3/x9501e/x9501e00.htm

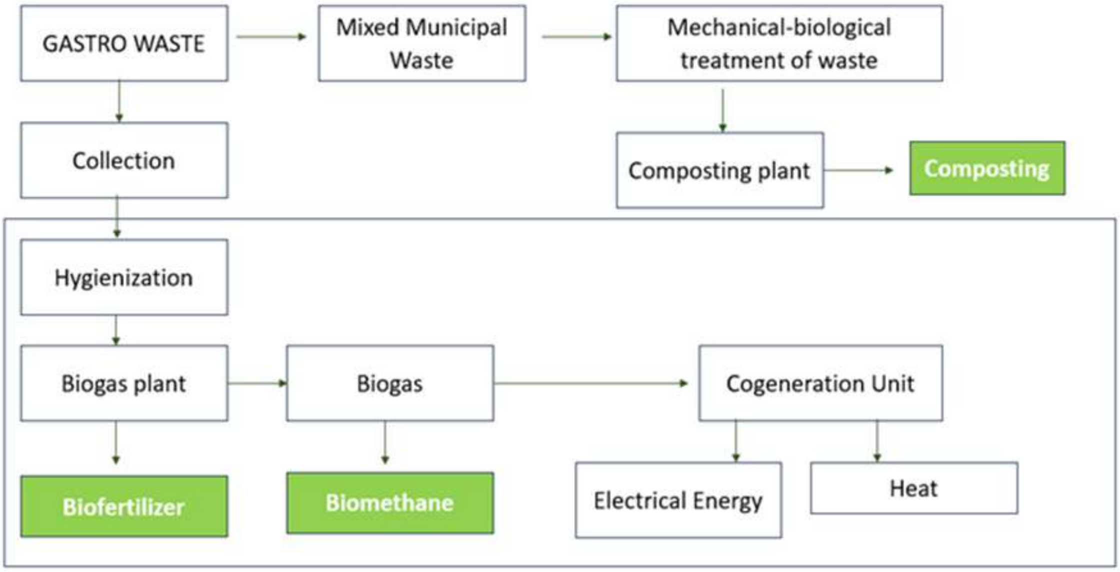


*Figure 19: Process diagram for the future scenario*

Route 1: Production of fertilizer, composting, and biomethane (bigger loss with more purified gas). For the analysis, literature has been used with estimations upon the baseline of the 1695.9 tons of food and gastro waste collected, starting from the point “Collection”. The analysis on the upper part of the diagram, starting from “Food waste” up to “Composting” and “CO2, H2O,” is indicative for visualization purposes and does not reflect exact numbers due to a lack of data. Generally, the proposal follows the logic of **Food Waste → Biogas → Biomethane + $CO_2$,** while the remaining material → **Digestate → Solids (Fertilizer) + Water.**

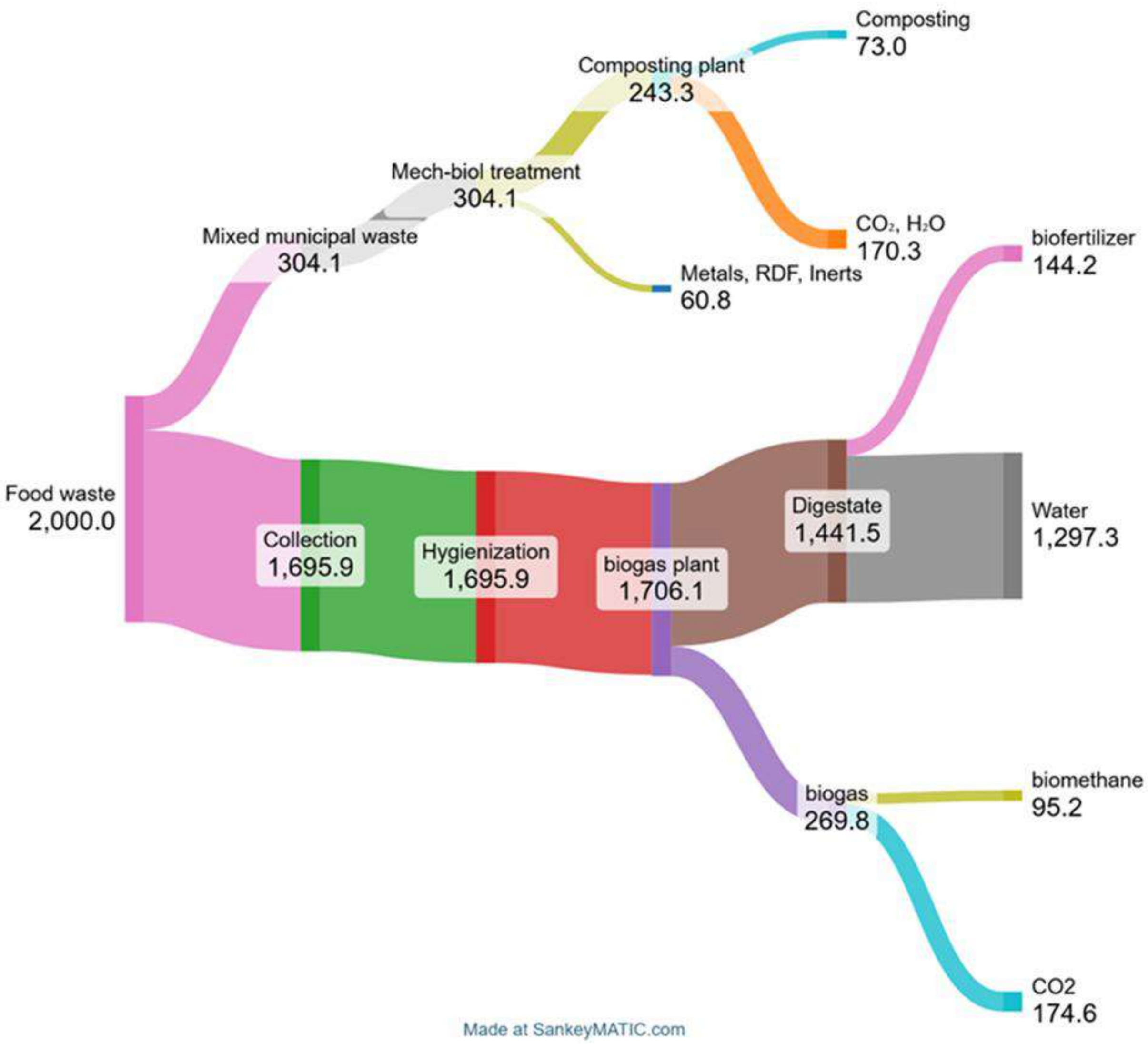


*Figure 20: Flows of food waste in tonnes through collection, treatment, and recovery processes in Charles Spa*

*Table 19: Mass balance estimations used in Sankey for food waste conversion into bio-compost*

| Assumptions for mass balance estimations | | Calculations |
|---|---|---|
| Food Waste = 1695.9 tons | | |
| Anaerobic Digestion[47] | Biogas yield: 130 m³/tonne<br>Biogas composition: ~60% $CH_4$ (methane), 40% $CO_2$<br>Biogas density: ~1.2 kg/m³ | Volume: 1695.9 × 130 = 220,467 m³<br><br>Mass: 220,467 × 1.2 = 264.6 tons |

[47] Biogas yield from food waste: *Koch, K., et al. (2015). "Biogas from Food Waste – A Review on Recent Developments." Bioengineering, 2(2), 93–106.* **&** *FAO (2013). "Technical Compendium: GHG Emissions from the Food System"*

| | | |
|---|---|---|
| Biogas Upgrading to Biomethane | Biomethane ($CH_4$) = 60% of biogas volume<br>Mass of $CH_4$: ~0.72 kg/m³<br>$CO_2$ is separated and may be vented or captured | Methane ($CH_4$): 60% → 132,280 m³ → 132,280 × 0.72 = 95.2 tons<br><br>$CO_2$: 40% → 88,187 m³ → 88,187 × 1.98 = 174.6 tons<br><br>(Note: $CO_2$ is denser than $CH_4$.) |
| Digestate Output[48] | 85% of original food waste<br>10% total solids[5] → Fertilizer | Mass: 85% of input → 1441.5 tons<br><br>Solids (Fertilizer): 10% = 144.2 tons<br><br>Water: 1297.3 tons |
| Mixed Municipal waste: 304.1 tons | | |
| Mechanical Pre-Treatment (sorting, separation)*<br><br>* These values are conservative and based on typical MBT plant reports and studies. | Metal content, 2% of input<br>Combustible fraction (light), 15% of input<br>Inerts sorted, 3% of input<br>Fine fraction to composting, 80% of input<br>Final compost yield, 30% of organic matter → ~25% of compost input mass | •Metals: 2% → 6.1 t<br><br>•Combustibles (light fraction): 15% → 45.6 t<br><br>•Inerts: 3% → 9.1 t<br><br>•Remaining for biological treatment: 80% → 243.3 t |
| Biological Treatment (Aerobic composting) | Rapid degradation in first 10 weeks: 60% of organic content degraded<br>Slower degradation continues: final organic content is ~30% of original<br>Cellulose degraded: 85%<br>Organic carbon degraded: 95%<br>Non-cellulosic sugars: 94% | •Organic degradation: ~70% of organics lost<br><br>→ Final compost yield ≈ 30% of 243.3 t = 73.0 t |

[48] Digestate yield: *Mönch-Tegeder, M., Lemmer, A., et al. (2013). "Efficiency of a two-stage anaerobic digestion process for the energy recovery of food waste." Waste Management, 33(4), 806–811.* & *WRAP (UK) – "Digestate and Compost in Agriculture" (2016)*

*Table 20: Mass balance estimations used in Sankey for food waste conversion into biogas*

| Stream | Mass (tons) | % of Input |
|---|---|---|
| **Food Waste (Input)** | 1695.9 | 100% |
| Biogas (Total) | 264.6 | 15.6% |
| Biomethane ($CH_4$) | 95.2 | 5.6% |
| $CO_2$ (byproduct) | 174.6 | 10.3% |
| Digestate (Total) | 1441.5 | 84.9% |
| Fertilizer (Solids) | 144.2 | 8.5% |
| Water | 1297.3 | 76.5% |
| **MSW (Input)** | **Mass (tons)** | **% of Input** |
| Metals (recovered) | 6.1 | 2.0% |
| Combustible fraction (RDF) | 45.6 | 15.0% |
| Inerts | 9.1 | 3.0% |
| To composting | 243.3 | 80.0% |
| Final compost product | 73.0 | 24.0% |
| Degraded/lost ($CO_2$, $H_2O$) | 170.3 | 56.0% |

Route 2 entails producing fertilizer and biogas, which can be directly fed into a cogeneration unit to produce heat and electricity. The electrical energy generated can reach up to 40%, and the heat 20%. The efficiency of a cogeneration unit is almost 87%, depending on several parameters[49].
The Sankey diagram, as before, keeps the upper branch for visualization purposes, which remains the same as in Option 1. The difference is showcased at the lowest branch of the Sankey. All values are expressed in tons apart except energy, heat, and energy losses.

[49] *EBA European Biogas Association. (n.d.). About biogas and biomethane. European Biogas Association. Retrieved April 16, 2025, from https://www.europeanbiogas.eu/about-biogas-and-biomethane/*

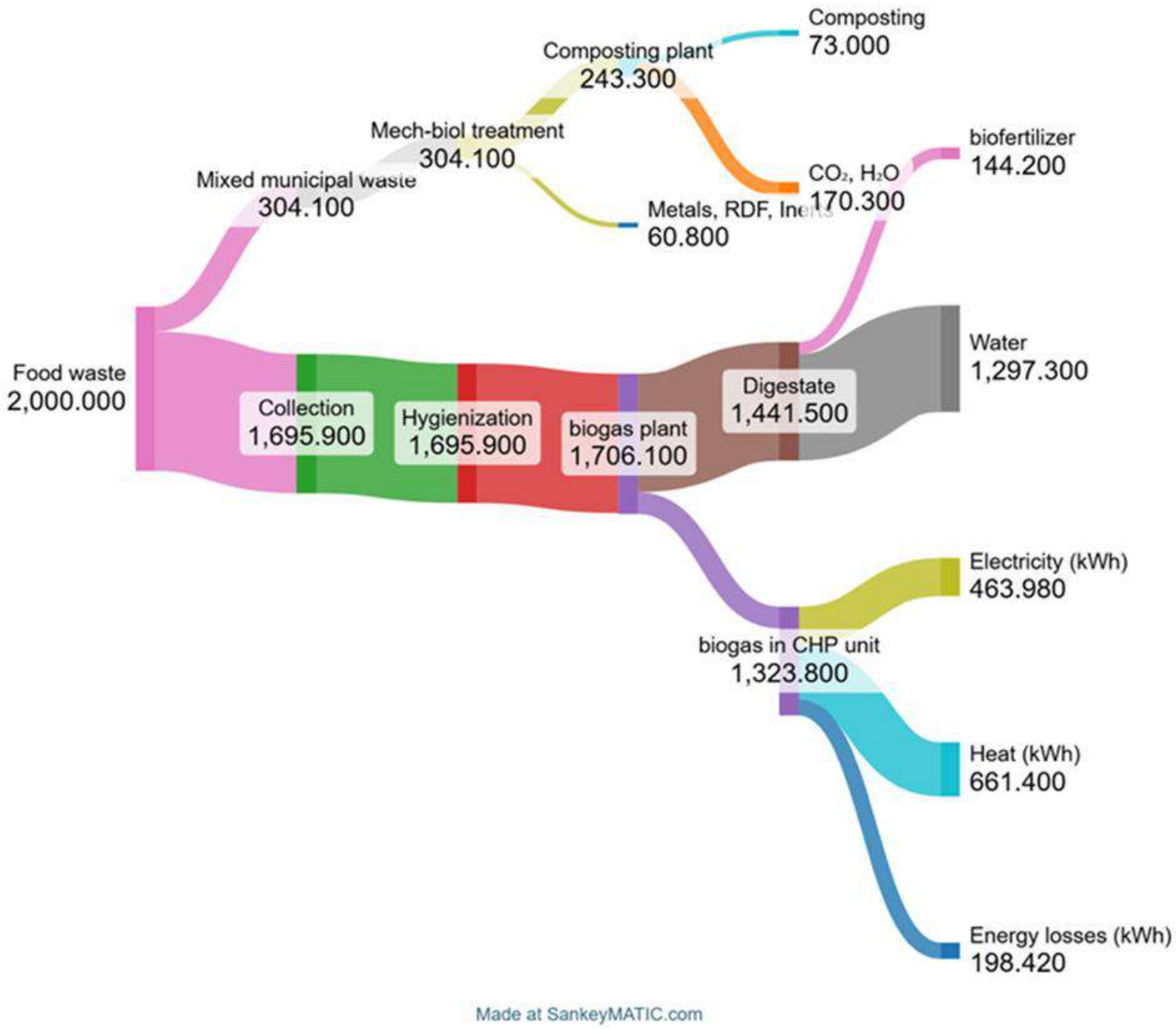


*Figure 21: Sankey representing conversion of food waste in tonnes producing fertilizer and biogas, which can be directly fed into a cogeneration unit to produce heat and electricity*

*Table 21: Assumptions used for mass balance estimations for waste for producing fertilizer and biogas*

| Assumptions for mass balance estimations | | Calculations |
|---|---|---|
| Anaerobic Digestion[50] | **Biogas yield**: 130 m³/tonne of food waste → Total = **220,467 m³** **Biogas density**: 1.2 kg/m³ → **264.6 tons** **$CH_4$ content**: ~60% → 132,280 m³ methane | |

[50] Appels, L., et al. (2008). "Principles and potential of the anaerobic digestion of waste-activated sludge." & Koch, K., et al. (2015). "Biogas from food waste – A review on recent developments." Bioengineering, 2(2), 93–106.

| | | |
|---|---|---|
| **Energy Content**[51] | Methane calorific value: **~10 kWh/m³** → Energy in $CH_4$ = **1,322,800 kWh** | |
| Cogeneration Unit (CHP)[52] | •Electrical efficiency: 35%<br>•Thermal efficiency: 50%<br>•Losses: 15% | **Electricity**: 35% of 1,322,800 kWh = **463,980 kWh**<br>**Heat recovered**: 50% = **661,400 kWh**<br>**Energy losses**: 15% = **198,420 kWh** |
| **Digestate**[53] | 85% of food waste = 1441.5 t<br>Solids (10% of digestate) = 144.2 t<br>Water = 1297.3 t | |

*Table 22: Table showing the mass and energy balance produced, as depicted in the Sankey diagram.*

| Stream | Mass / Energy | Unit | % of Input |
|---|---|---|---|
| **Food Waste (Input)** | 1695.9 | tons | 100% |
| Biogas | 264.6 | tons | 15.6% |
| to CHP unit | 264.6 | tons | |
| Electricity | 463,980 | kWh | — |
| Heat | 661,400 | kWh | — |
| Energy losses | 198,420 | kWh | — |
| Digestate (Fertilizer) | 1441.5 | tons | 84.9% |
| Solids (Fertilizer) | 144.2 | tons | 8.5% |
| Water | 1297.3 | tons | 76.5% |

### 3.2.3 Environmental assessment

For the environmental assessment, the following subcriteria were considered: Climate change (GWP-total), Particulate matter, Land use change, Water use, Resource use fossil (ADP-fossil), Resource

[51] *IEA Bioenergy Task 37 (2020). "Biogas Upgrading – Technical Brochure." & Perry's Chemical Engineers' Handbook, 8th Ed.*
[52] *IEA Bioenergy Task 37 (2021). "Cogeneration of heat and power (CHP) from biogas and biomethane." & Scarlat, N., Dallemand, J.-F., et al. (2018). "Biogas: Developments and perspectives in Europe." Renewable Energy, 129, 457–472.*
[53] W *RAP (UK), 2016. "Digestate and Compost in Agriculture – Good Practice Guide." & Mönch-Tegeder, M., Lemmer, A., et al. (2013). "Efficiency of a two-stage anaerobic digestion process for energy recovery of food waste." Waste Management, 33(4), 806–811.*

use mineral and metals (ADP-min&met). Each of the subcriteria was given a different weight based on the methodology.

*Table 23: Weighting of environmental subcriteria for food waste valorisation into biogas and compost in Charles Spa, Czechia, based on stakeholder responses*

| Main criteria | Weight (%) | Units | Subcriteria | Subcriteria weight (%) | Sub-units | Biogas average | Compost average |
|---|---|---|---|---|---|---|---|
| Environmental | 40% | 400 | Climate change (GWP-total) | 20% | 80.00 | 0.9 | 0.8 |
| | | | Particulate matter | 15% | 60.00 | 1.0 | 0.6 |
| | | | Land use change | 15% | 60.00 | 0.6 | 0.7 |
| | | | Water use | 20% | 80.00 | 1.0 | 0.6 |
| | | | Resource use - fossil (ADP-fossil) | 15% | 60.00 | 1.0 | 0.5 |
| | | | Resource use - minerals & metals (ADP-min&met) | 15% | 60.00 | 0.5 | 0.7 |
| | | Total | Subtotal Environmental | 100% | 400.00 | | |

Five local experts evaluated each environmental subcriterion to assess its relevance to the Charles Spa region in Czechia, as shown in Figure 22. Among the three pillars of sustainability, environmental criteria received the highest weighting and the most evaluation units (40%). Between the two treatment pathways, the biogas route received the most favourable ratings for climate change, particulate matter, water use, and fossil resource use. These positive ratings were primarily due to its avoidance of fossil fuel combustion, non-reliance on agricultural biomass, and efficient water use in energy production. The composting route also performed reasonably well, with average ratings across all subcriteria ranging from neutral to positive

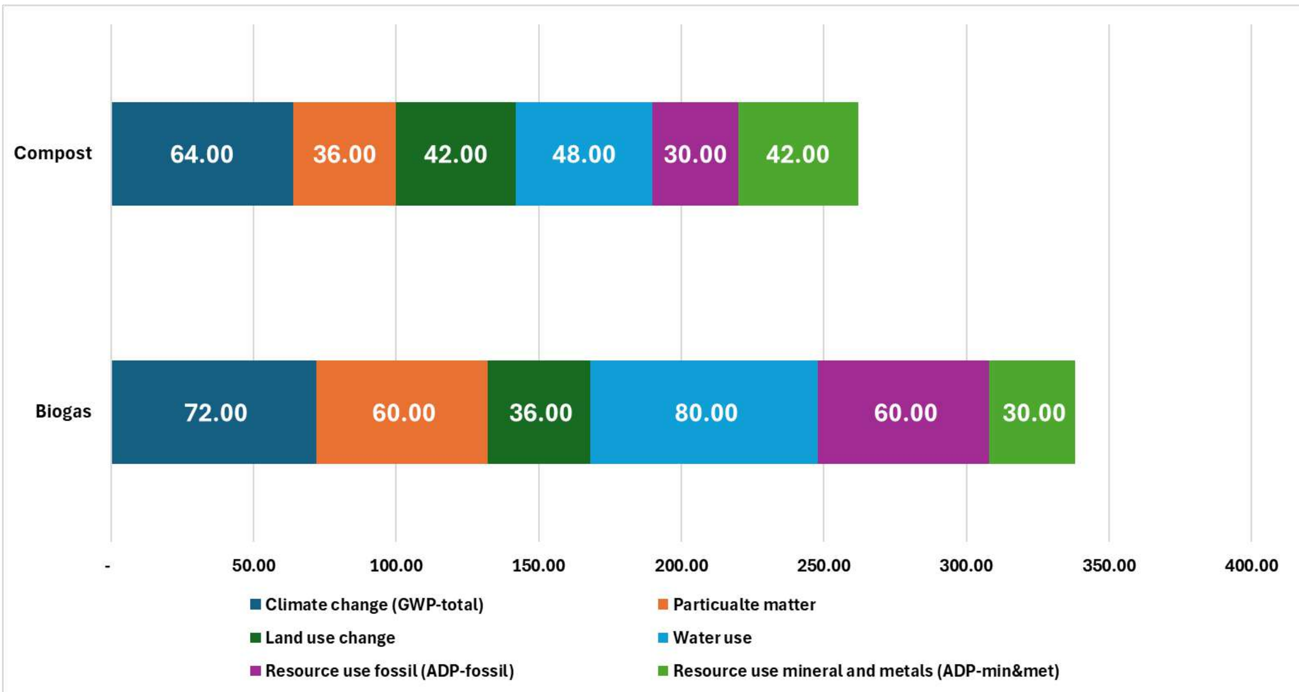

*Figure 22: Environmental assessment for using food waste as biogas and compost route for Charles Spa region of Czechia*

For biogas, the Climate change (GWP-total) subcriterion received the most units, mostly avoiding fossil fuel burning. For the same criterion, Compost is considered for use in agriculture. For particulate matter, biogas also received a positive rating since biogas production is linked with diverting from fossil fuel combustion and reduced emissions. Land use change was considered neutral for biogas but slightly positively rated for compost due to the compost's positive effect in agriculture. Water use received a better score for biogas under the considerations for energy production, biogas systems can be water-efficient, particularly when designed for recycling and using moisture-rich feedstocks like food waste. Resource use fossil (ADP-fossil) was also rated positively for biogas, while resource use mineral and metals (ADP-min&met) was neutral. For the same subcriterion, compost received a more positive score due to composting replacing mineral mining for fertilizer production.

Overall, the two routes do not feel contradictory and present small differences, mostly linked to their nature. Their positive impact and alignment with local policies and priorities were reflected in the experts' rating, even though it was commented that due to the region's structural economic challenges, it is unlikely that the change will be disruptive.

### 3.2.4 Economic assessment

For the economic assessment, the following subcriteria described in the methodology (economic assessment) were considered. Each subcriterion was assigned a different weight for the two pathways, as the economic implications of using food waste varied between them as shown in Table 24.

***Table 24: Weighting of economic subcriteria for food waste valorisation into biogas and compost in Charles Spa, Czechia, based on stakeholder responses***

| Main criteria | Weight | Units | Subcriteria | Weight | Sub-Units | Biogas average | Compost average |
|---|---|---|---|---|---|---|---|
| Economic | 35% | 350 | Job loss / Job creation | 18% | 62.93 | 0.7 | 0.6 |
| | | | Wages | 16% | 57.53 | 0.8 | 0.5 |
| | | | Training needs | 14% | 48.54 | 1 | 0.9 |
| | | | Value Creation | 14% | 48.54 | 0.9 | 0.9 |
| | | | Added Value | 13% | 44.95 | 0.8 | 0.9 |
| | | | CAPEX | 5% | 17.50 | 0.2 | 0.1 |
| | | | OPEX | 5% | 17.50 | 0.3 | 0.1 |
| | | | Sizing/scaling | 5% | 17.50 | 0.7 | 0.6 |
| | | | Impact on export | 5% | 17.50 | 0.7 | 0.6 |
| | | | Impact on import | 5% | 17.50 | 0.8 | 0.8 |
| | | | Subtotal economic | 100% | 350.00 | | |

Five local experts rated each economic subcriterion on a scale from 0 to 1 to reflect the perceived impact of the two pathways on the Charles Spa region. The average response factor for the two food waste valorisations is shown in Table 23. The most influential subcriteria for the area—job creation and loss, wages, and training needs—generally show average scores close to 1, suggesting a positive economic impact. An exception is the wages subcriterion for the composting route, where stakeholders anticipated no significant change. The final scores for each subcriterion were calculated by multiplying the assigned weights with the expert ratings, and the results are shown in Figure 23

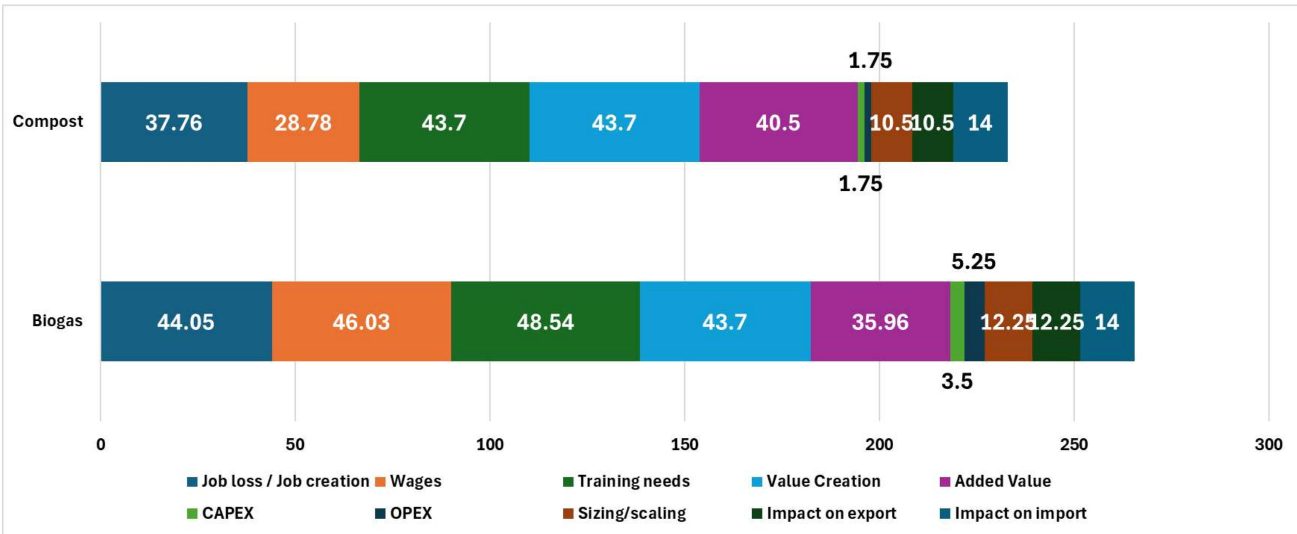


*Figure 23: Economic assessment results and comparison between the biogas and compost routes*

Commenting on the overall score results (calculating the units), we see that for biogas, training needs and wages were slightly more influential since biogas workers receive a higher salary and are trained within the companies. The same subcriteria also received a high score in compost, but still lower than biogas. Job creation was positively perceived in both routes, even though experts commented that the jobs generated might not be that attractive. Value creation received the same score in both cases, while added value was better in compost due to its contribution to agriculture. CAPEX and OPEX, in both cases, were rated either neutral or negative due to the additional cost of installing a new facility. Sizing/scaling was slightly better perceived in biogas, while import and export were almost the same in both cases.

### 3.2.5 Social assessment

For the social impact assessment, the subcriteria outlined in Figure 7 are considered. The average response factors for the two food waste valorisation routes are summarised in Table 25. All subcriteria indicate a generally positive effect (RF close to 1), except work-life balance and housing, where the pathways show a negative impact.

*Table 25: weighting of social subcriteria for food waste valorisation into biogas and compost in Charles Spa, Czechia, based on stakeholder responses*

| Main criteria | Weight | Units | Subcriteria | Weight | Sub-units | Biogas average RF | Compost average RF |
|---|---|---|---|---|---|---|---|
| Social | 25% | 250 | Employment | 19% | 47.48 | 0.7 | 0.6 |
| | | | Income | 17% | 43.41 | 0.8 | 0.7 |
| | | | Work-Life Balance | 17% | 43.41 | 0.5 | 0.5 |
| | | | Housing | 16% | 40.70 | 0.5 | 0.5 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | Health | 5% | 12.50 | 1 | 0.7 |
| | | | Education | 5% | 12.50 | 0.9 | 0.8 |
| | | | Governance | 5% | 12.50 | 0.8 | 0.8 |
| | | | Environment | 5% | 12.50 | 0.8 | 0.8 |
| | | | Security | 5% | 12.50 | 0.9 | 0.7 |
| | | | Life satisfaction | 5% | 12.50 | 0.7 | 0.6 |
| | | | Subtotal social impact | 100% | 250.00 | | |

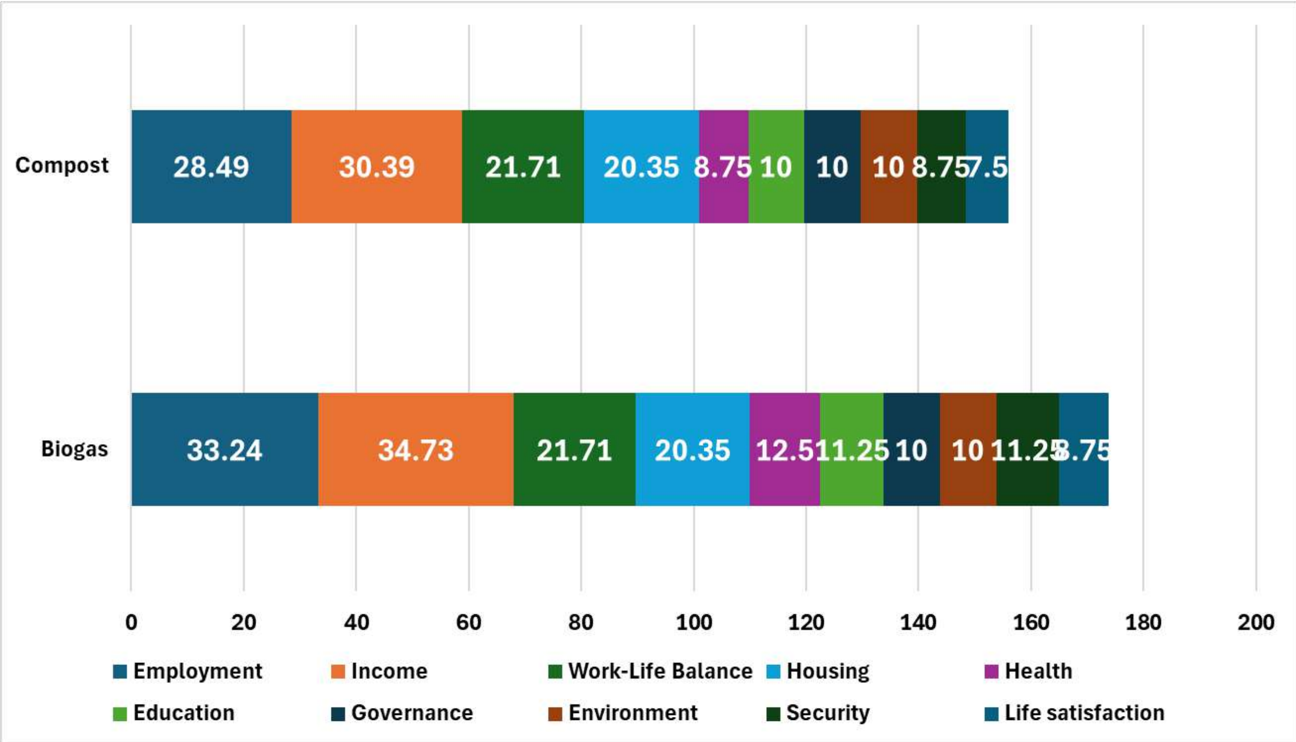


*Figure 24: Social assessment for using food waste as biogas and compost route for Charles Spa region of Czechia*

Notably, the biogas route shows substantial benefits in several areas: income, as employees in biogas plants earn wages above the national average; education, due to company-led training programs for workers; and governance–environment–security, where the route contributes to efficient resource management and supports the well-being of the community in alignment with local policy objectives at the same time, work-life balance and housing were considered neutral. In health, route one was supposed to have a more positive influence due to the transition from mining to sustainable energy. The same applies to education, with route 1 requiring special training from biogas production companies. In governance and environment, both routes received the same score, as they are aligned with local strategies for energy, and no significant changes in land use are expected, except perhaps in the case of creating a new facility. In terms of security, route 1 performed better, aligning with the energy security perspective. Life satisfaction, on the other hand, was not considered relevant and was ranked as no change (0.5).

### 3.2.6 Sustainability assessment

The sustainability assessment summarizes the total environmental, economic, and social scores for the two routes. It is important here to point out that Options 1 and 2 generate both products (value chains), which will be referred to as 1. Biogas Production and 2. Composting.

The goal is to visually highlight the best sustainability performance between the two products. Each main criterion – Economic, Social, Environmental – has been weighted with the help of local experts, taking into consideration the pathway particularities and the local priorities. The following table displays the main criteria weight. Most important was considered the Environmental impact (35%), given the region's recovery from mining activities and efforts for energy shifting to greener sources. Then, economics follows with 30%, considering the region's low economic performance compared to the whole country. Traditional economic activities are in decline, and a new economic shift is necessary for local development. Social aspects land in the 3rd place with a 20%, reflecting the brain and workforce drain of the region and the low educational background, which forces young people to search for more career opportunities in other areas of the Czech Republic.
Circular aspects fall into the last place with a 15%, primarily because of the limited circularity potential of the 2 routes, as only fertilizer returns into the system in agriculture, while energy is eventually lost. Eventually, the overall assessment should gather 100% (or 1000 units) to make the comparison between the 2 routes possible.

***Table 26: Weighting of the sustainability assessment criteria by experts for conversion of food waste into biogas and compost in Charles spa region of Czechia***

| Main criteria | Weight | Units |
|---|---|---|
| Environmental impact | 40% | 400 |
| Economics | 35% | 350 |
| Social Aspects | 25% | 250 |
| Total | 100% | 1000 |

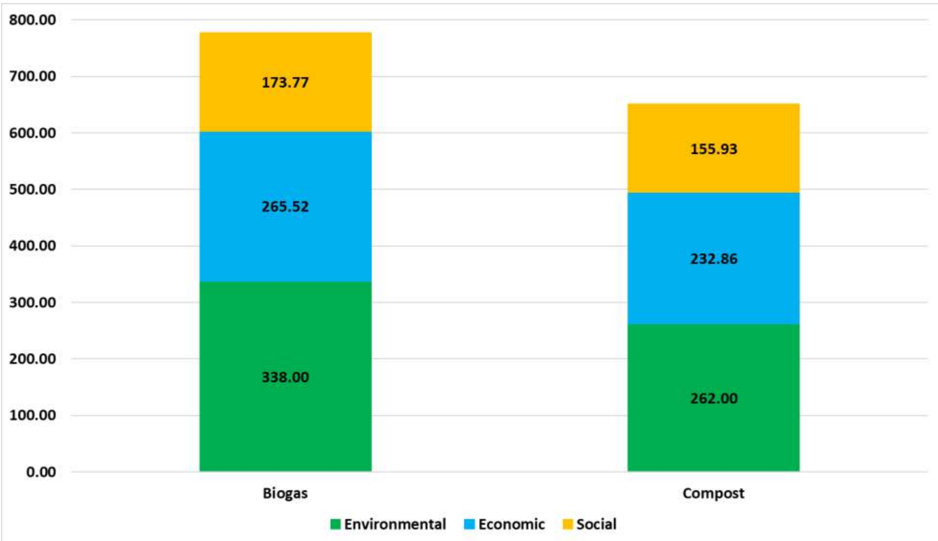


***Figure 25: Sustainability assessment of comparing the food waste as biogas or compost for Charles Spa region of Czechia***

In the above figure, we see that biogas production has a better overall sustainability score than compost, reflecting the region's strategic priority for energy efficiency and reducing carbon emissions, enhancing environmental sustainability, of course, compared to brown coal mining.

Reflection on sustainability assessment methodology

The methodology for the sustainability assessment attempted to address several of the challenges identified in WP1. Particularly for Charles Spa, the limited data availability was compensated by the participation of local specialists and stakeholders were this was feasible. The significance attributed to the criteria followed the findings of WP1, given that environmental challenges were crucial for the regional transition (gradually abandoning the mining activities and opting for sustainable energy options), followed by the economic factor (traditional activities in decline), and finally the social factors as challenged by local brain drain and lack of education options.

The methodology was flexible enough to include measurable assessments where access to data was difficult, and allowed more in-depth analysis when possible. Qualitative elements like the rating of the impact of each subcriterion provided a more insightful thought from the stakeholders' perspective.

### 3.2.7 Circularity assessment

The circularity assessment for the Charles Spa Region centres on the valorisation of food waste, a significant organic stream, particularly from its tourism sector. The pathways aim to transform this urban biowaste into valuable resources like biogas for energy and compost for soil improvement, thereby reducing landfill dependency and closing local nutrient and energy loops.

*Table 27:Circularity assessment for the biogas and compost from food waste in Charles Spa (Czechia)*

| Product | Resource Output Rate | Resource Consumption Rate | Integrated Resource Utilisation Rate | Waste Disposal and Pollutant Emissions |
|---|---|---|---|---|
| Food waste to biogas (incl. digestate use) | High value from a problematic urban/tourism waste stream – produces renewable energy (biogas) and a valuable soil conditioner (digestate). | Anaerobic digestion is often net energy positive. Reduces reliance on fossil fuels for energy and synthetic fertilisers. Water is co-digested within the process. | Effectively processes food waste, generating two valuable outputs. Digestate application closes nutrient loops, returning organic matter and nutrients to agriculture. | Significantly reduces landfill methane emissions (a potent GHG) from food waste. Biogas combustion is cleaner than direct fossil fuel use. Digestate reduces the need for synthetic fertiliser production and its associated emissions. |
| Food waste to compost | Good value from waste (soil conditioner), but less energy recovery compared to anaerobic digestion. | Low direct energy input for the composting process itself. Reduces the need for synthetic fertilisers and peat-based soil conditioners. | Effectively processes food waste into a useful soil product, closing nutrient loops and enhancing soil health. | Reduces landfill methane emissions. Compost improves soil carbon sequestration. Generally lower GHG impact than landfilling or unmanaged decomposition. |

### 3.2.8 Supply chain optimisation and logistic network design

***Reader's note:*** *This section provides a comprehensive overview of the supply chain optimisation and logistics network design results. For full details, see Appendix 2 – Section 1: Food Waste in Karlovy Vary (Czech Republic).*

The **Karlovy Vary in the Czech Republic** is a key centre for tourism and related industries, leading to substantial **food waste** generation during peak seasons. The cities of Karlovy Vary and Mariánské Lázně are in focus.

The region's existing food waste collection and processing system was analysed from a logistics perspective, aiming to identify opportunities for reducing costs and transport distances.

Alternatively, improvement scenarios (TO BE) are explored with a focus on introducing alternative processing methods such as anaerobic digestion (AD), centralising the treatment process, combining composting with AD, and bypassing transfer collection points (TCP) (Figure 26).

This case study explores the **impact of introducing alternative logistic and processing scenarios** on the **transport distance** (Figure 27) and **mobilisation cost** (Figure 28).

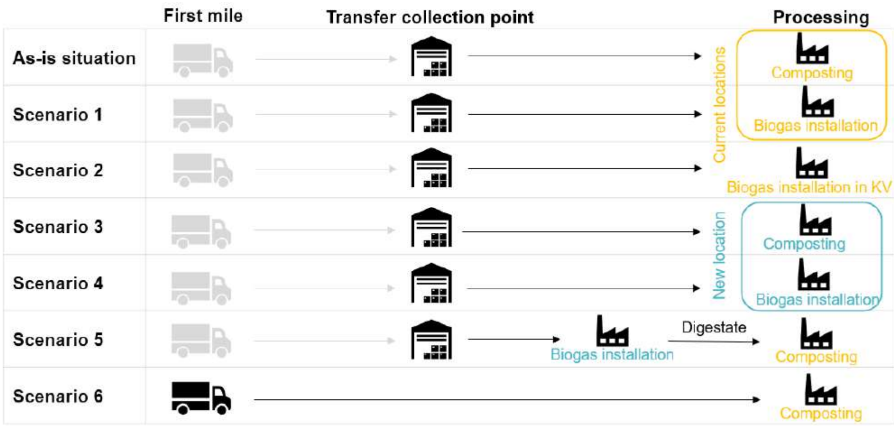


*Figure 26: Food waste in Karlovy Vary - Scenario overview*

Currently (AS IS), food waste from both cities is collected via first-mile pick-up and brought to intermediate transfer collection points (TCPs), from where it is transported to their respective composting facility. In total, 1,689 tons of food waste are processed annually, resulting in a transport distance of ca. 15.000 km a total annual logistic cost of €286.726—equating to roughly 9 km and €170 per processed ton. Of the total cost, 37% is attributed to the first-mile collection and transport to the TCPs, 56% to transport from TCPs to the composting facility, and only 6% to the composting OPEX costs.

**Scenario results**

**Scenario 1 retains the existing two processing locations but shifts the treatment method from composting to AD.** Since the locations remain unchanged, transport costs are unaffected; however, a 12% increase in total costs is observed, driven by higher operational expenses associated with AD.

**Scenario 2 shifts treatment method from composting to AD while centralising processing** at the Karlovy Vary plant. This increases transport distance by 8% and total costs by 14%. However, the additional transport cost is expected to be offset resulting from the consolidation of activities into a single end-processing facility, rather than the two facilities currently in operation.

**Scenario 3 proposes the establishment of a new centralised composting facility**, with the flexibility to select the optimal location within the region. This approach results in a 39% reduction in total transport distance and a 48% decrease in overall costs, highlighting the efficiency gains from strategic centralisation.

**Scenario 4 builds upon Scenario 3 by introducing an AD** in place of a composting installation. Despite the higher OPEX costs associated with AD, the scenario still achieves a 37% overall cost reduction, owing to lower transport costs.

**Scenario 5 builds on Scenario 4 by further processing the digestate from the AD facility at the existing composting sites**, while both TCPs remain operational. This introduces an additional transport leg, increasing the overall transport distance by 19%. However, when considering the mass balance, the transport distance per processed ton decreases by 31%. The transport cost per processed ton decreases by 39% in Scenario 5, due to a higher total processed volume compared to the AS-IS scenario

To end, Scenario 6 eliminates the TCPs, directly transferring food waste to a centralised composting facility, reducing the total transport distance by 46% and cutting overall costs by 50%.

**In conclusion**

As this case study focused on minimising mobilisation costs, the results demonstrate that the greatest cost savings are achieved by consolidating operations at a centralised facility, particularly when the location is optimised to minimise transport distances.

To further refine the results towards a robust business case, the following aspects require additional attention:

- **CAPEX Costs**: The capital expenditure (CAPEX) associated with new installations was excluded from this analysis. Future evaluations should incorporate these costs to provide a complete financial picture.
- **OPEX Costs**: Operational expenditure (OPEX) was assumed to remain unchanged within the current study scope. However, consolidation scenarios — merging two operational sites into a single optimally located site — could potentially reduce OPEX through efficiency gains and should be assessed.
- **Revenues**: No additional revenues were considered from biogas production or digestate valorisation. Exploring potential revenue streams could improve the business case.
- **Policy Framework**: The potential impact of regulatory and policy developments, particularly government incentives for biogas, needs to be evaluated to understand financial and operational implications.
- **Social Framework**: Stakeholder consultations are recommended to assess the feasibility of transitioning to a centralised facility and to evaluate its potential effects on local communities.
- **Additional Scenarios**: Based on the current findings, a combined scenario could be explored where:
  i) Direct transport is organised to an optimally located composting site (Scenario 6), ii) AD is integrated at this location (Scenario 2), iii) Composting of digestate occurs on-site, eliminating the need for additional transport (Scenario 5).
- **Phased CAPEX Investments**: To ease financial planning, CAPEX investments for the new composting and AD facilities could be staggered over time, allowing depreciation of the first facility before investing in the second

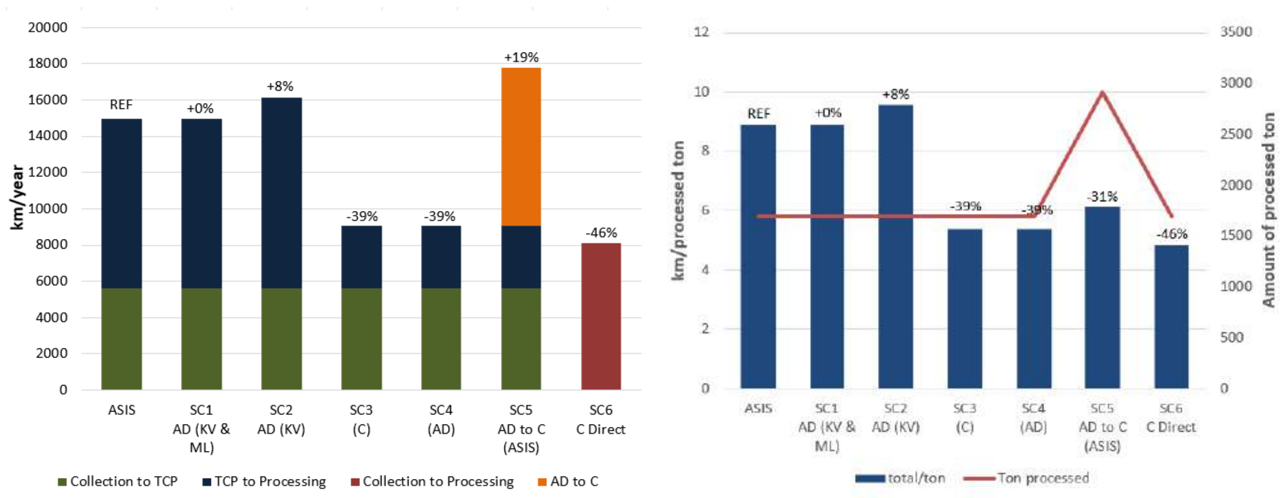


*Figure 27: Food waste in Karlovy Vary - Transport distance [km/year (L) and €/ton (R)]*

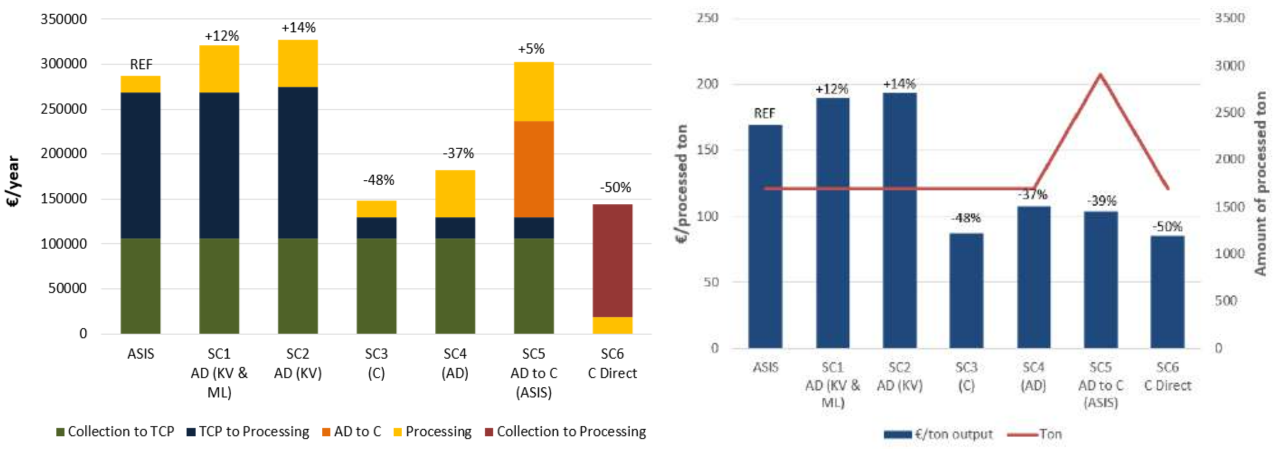


*Figure 28: Food waste in Karlovy Vary - Mobilisation cost [€/year (L) and €/ton (R)]*

## 3.3 Finland

### 3.3.1 Transition pathway

These Sankeys evaluate lignin-based alternatives for three applications: anode materials, adhesives, and plasticizers. Lignin was selected by researchers based on discussions with stakeholders in workshops backed up by literature survey that identified several possible secondary streams that were: lignin, green liquor dregs, bark and sawdust, hemicellulose, ash and post-consumer wood. Then mass flows of these were identified. Current scenario is based on current pulp production using kraft-pulping. One of the main reasons why this was selected was that the Finnish pulp industry is a cornerstone of the Finnish economy producing 9.2 million metric tonnes of pulp (Finnish Forest industries federation, 2023[54]), is partially circular, and the transitions can be accelerated by valorizing side streams such as black liquor (BL). Of the BL organic material, over 50% is lignin, that has high calorific value and most of the time it is incinerated in the recovery boiler. During this process inorganic chemicals are recovered, generating bioenergy[55]. Many pulp mills especially in Finland are already

[54] https://www.metsateollisuus.fi/tilastot
[55] https://publications.vtt.fi/pdf/technology/2016/T258.pdf

free (such as bioproduct mill, Finland[56]) or close to free from fossil fuels consumption thanks to bioenergy. In addition, some mills are even producing heat and power for external use, the excess heat produced cannot be exploited if the site is remotely located in such cases exploiting BL for lignin extraction (high value products) can increase the overall resource-efficiency. Kraft pulping is also the mainstream technology in current pulp production globally, meaning that this type of approach could be replicated.

### *3.3.2 Resource flow analysis*

Currently lignin is incinerated to energy and by using this approach surplus electricity can be sold outside the mill.

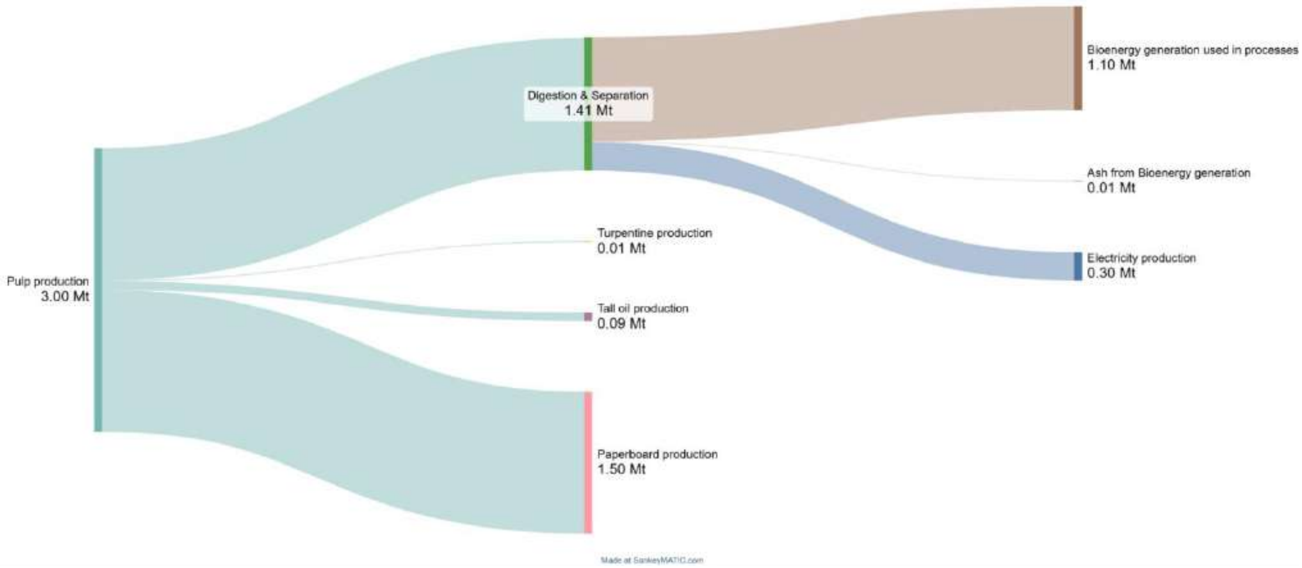


*Figure 29. Current scenario. Lignin incineration to energy*

**Proposed scenario**

In the proposed scenario, lignin incineration is reduced, and several products can be created from lignin. The lignin-based alternatives were considered for three applications: anode materials, adhesives, and plasticizers

56 https://www.ymparisto.fi/sites/default/files/documents/LAPPI_YVA_Metsa_Fibre_Arviointiselostus_15_9_2019.pdf

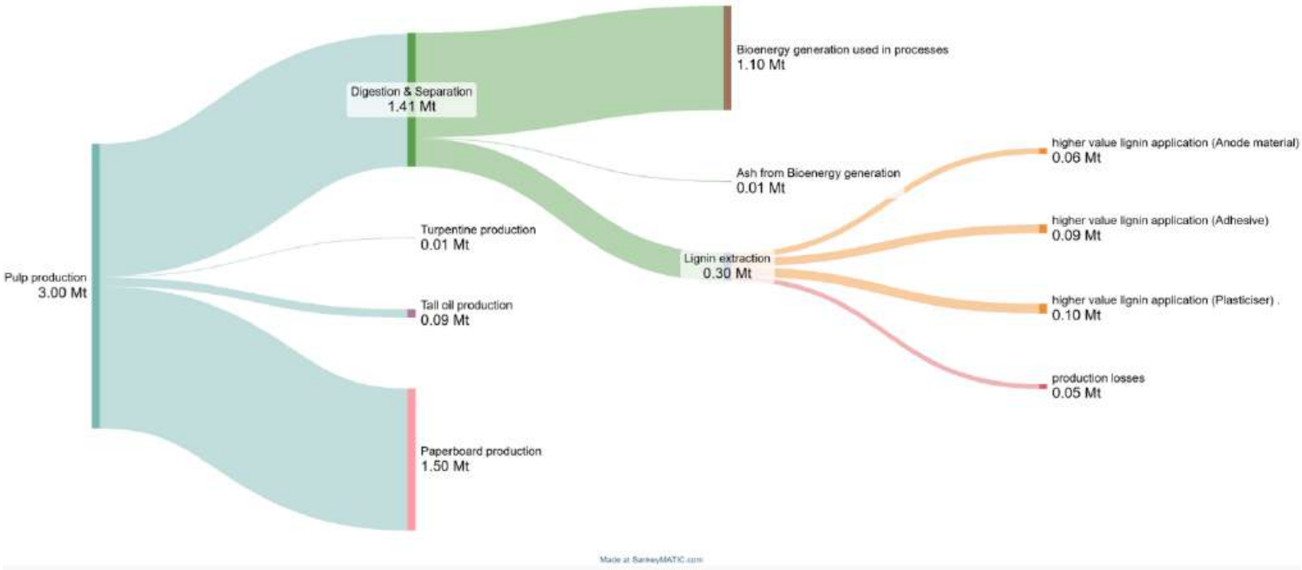


*Figure 30. Proposed scenario. Lignin conversion to products*

### 3.3.3 Environmental assessment

To assess the environmental sustainability of substituting fossil-based materials with lignin-derived alternatives in Finland. The assessment covered the substitution for fossil-based graphite anode in lithium-ion battery production, lignin-based adhesives for phenol in phenolic resins, lignin-based plasticizers for sulfonated melamine formaldehyde used in concrete admixtures. The study follows the principles and requirements of the ISO 14040:2006 and ISO 14044:2006 standards, as well as the International Life Cycle Data System Handbook guidance (JRC-IES, 2010)[57]. The LCA was performed using the open-source tool Brightway 2. Both attributional and consequential LCA perspectives were considered, with background data sourced from ecoinvent v3.9.1[58]. Environmental impacts were characterized using the Product Environmental Footprint (PEF) method, version 3.1, in line with European Commission guidelines[59]. The sections below describe LCA, the allocation of environmental impact to black liquor, the impact assessment details.

**LCA**

Given the early-stage development of lignin valorisation technologies, we explore how technological improvements and allocation methods influence life cycle impacts across three lignin-derived products where Finland is currently investing: anodes, adhesives, and plasticizers with an attributional LCA.

**Goal and scope**

The goal was to evaluate the relative performance of lignin-based product, and the functional unit is to compare the environmental impact for producing 1 kg of lignin-based products extracted from paper and pulp industry in Finland and to compare them to fossil-based alternatives produced elsewhere. For lignin extraction we use is the basis for commercial lignin extraction methods such as the

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[57] Wolf, M., Chomkhamsri, K., Brandao, M., Pant, R., Ardente, F., Pennington, D., Manfredi, S., De Camillis, C. and Goralczyk, M.. International Reference Life Cycle Data System (ILCD) Handbook - General guide for Life Cycle Assessment - Detailed guidance. EUR 24708 EN. Luxembourg (Luxembourg): Publications Office of the European Union; 2010. JRC48157
[58] https://support.ecoinvent.org/ecoinvent-version-3.9.1
[59] https://eplca.jrc.ec.europa.eu/EnvironmentalFootprint.html

Lignoforce process [21], economic allocation method is used to allocate the impact of environmental impacts as shown in section 2.1. The amount of lignin and electricity used in the Mill is shown below

**Life cycle inventory**

The life cycle inventory (LCI) for the lignin-based products was modelled analogously to their fossil-based counterparts using data primarily sourced from ecoinvent v3.9.1 (cutoff data set) For the anode production, the activity "anode production, graphite, for Li-ion battery, RoW" was used. In the lignin-based scenario, fossil graphite was substituted with lignin on a mass-equivalent basis. For the replacement of fossil-based adhesives in medium-density fibreboard (MDF), the activity "phenolic resin production, RoW" was selected. Lignin replaced phenol at a 1:1 mass ratio, and additional electricity inputs were included to account for the processing of extracted lignin into a form suitable for adhesive application. For plasticizers, the reference fossil-based activity was "plasticizer production, for concrete, based on sulfonated melamine formaldehyde." In the lignin-based case, fossil-derived formaldehyde was replaced by lignin in 1:1 ratio. For the transportation of lignin-based products produced in Finland a 200 km transport distance was assumed via "transport, freight, lorry, 16–32 metric ton, EURO6", and for fossil-based alternatives produced elsewhere we assumed a transport distance of 20,000 km using the activity "market for transport, freight, sea, container ship". The input amounts of electricity and lignin required to produce 1 kg of lignin-based product are presented in Table 28 and the details of inventory in given in and the allocation of environmental impact of lignin in explained under the heading 'Allocation of lignin environmental impact'.

*Table 28: Details of lignin and electricity used to produce lignin-based product*

| Lignin pathway | Amount of lignin | Electricity required (KWh) |
|---|---|---|
| Anode | 2 kg | 7.5 |
| Adhesives | 1 kg | 1 |
| Plasticizer | 1 kg | 2.47 |

**Allocation of lignin environmental impact**

Pulping is a multi-output industrial process mainly used to manufacture a variety of paper, board, and conducting LCA of such a system requires the environmental burdens to be appropriately allocated among its by-products. In the ecoinvent 3.9.1 database, the default pulping dataset includes by-products: bark chips, electricity, heat, sawdust, tall oil, and turpentine to which environmental impacts are distributed but BL is not explicitly listed, although it is primarily used on-site to generate heat and electricity for internal use with surplus electricity being sold. To assess the environmental impact of lignin extracted from BL, we modified the dataset, assuming that the electricity previously exported is no longer sold, and the equivalent amount of BL is redirected toward lignin extraction without affecting the overall function of the mill. Although primary operational data from mills were not available, consultation with an industrial stakeholder provided insight into realistic extraction rates. Based on this input, we assumed an extraction of 150 grams of lignin per kilogram of pulp it allows us to isolate lignin as an additional co-product from the existing pulping process. To be consistent with ecoinvent's allocation methodology, we applied economic allocation based on the market prices of the co-products. Table 29 summarizes the product quantities, associated prices, income per product, and resulting allocation factors.

*Table 29: Economic allocation used to allocate the environmental impact to the by-product of pulping process*

| Product | Quantity | Price in ecoinvent, €/unit | Income per product, € | Economic Allocation(%) |
|---|---|---|---|---|
| Pulp, kg | 1 | 0.355 | 0.355 | 75.64693042 |
| Barkchips, kg | 0.19 | 0.034 | 0.00646 | 1.376561044 |
| Sawdust, kg | 0.0151 | 0.101 | 0.0015251 | 0.324983475 |

| | | | | |
|---|---|---|---|---|
| Tall oil, kg | 0.0485 | 0.653 | 0.0316705 | 6.748665098 |
| Turpentine, kg | 0.00239 | 1.83 | 0.0043737 | 0.931991492 |
| High voltage, electricity, kWh | 0.141 | 0.0977 | 0.0179 | 3.185289804 |
| District heat or industrial, MJ | 1.68 | 0.0106 | 0.017808 | 3.794705738 |
| Extracted lignin, kg | 0.15 | 0.25 | 0.0375 | 7.990872931 |

**Life cycle impact assessment**

The life cycle impact assessment performed using PEF and sixteen environmental indicators were estimated, the indicators the abbreviation used and the unit of measurement is shown below in the table:

*Table 30: Sixteen Environmental impacts considered for Life cycle impact assessment*

| Impact category | Abbreviation | Unit |
|---|---|---|
| Climate change 1 | CC | kg $CO_2$ eq |
| Ozone depletion | ODP | kg CFC-11 eq |
| Human toxicity, non-cancer | HTOX_nc | CTUh |
| Human toxicity, cancer | HTOX_c | CTUh |
| Particulate matter | PM | Disease incidence |
| Ionising radiation | IR | kBq U-235 eq. |
| Photochemical ozone formation | POF | kg NMVOCeq. |
| Acidification | AC | mol $H^+$ eq |
| Eutrophication, terrestrial | TEU | mol N eq |
| Eutrophication, freshwater | FEU | kg P eq |
| Eutrophication, marine | MEU | kg N eq |
| Land use | LU | Pt |
| Ecotoxicity freshwater | ECOTOX | CTUe |
| Water use 1 | WU | $m^3$ water eq |
| Resource use, fossils | FRD | MJ |
| Resource use, minerals and metals | MRD | kg Sb eq |

**Results**

presents the comparative results for 1 kg of lignin-based anode, adhesive, and plasticizer relative to their fossil-based (conventional) counterparts using sixteen midpoint environmental impact categories as defined by the EF 3.1 method. Across 13 out of 16 categories, the lignin-based alternatives consistently exhibit lower environmental burdens than the fossil-based products.

In the climate change category, the lignin-based anode demonstrates a substantial reduction in global warming potential (GWP), with emissions of 2.1 kg $CO_2$-equivalents, compared to 4.8 kg $CO_2$-equivalents for the fossil-based anode showing a 56% decrease. Similar trends are observed for plasticizers and adhesives: fossil-based plasticizers have a GWP of 1.5 kg $CO_2$-equivalents, whereas lignin based only emits 1.0 kg $CO_2$-equivalents. For adhesives, the fossil-based system yields 6.4 kg $CO_2$-equivalents, while the lignin-based results in 3.4 kg $CO_2$-equivalents.

Despite these advantages, the lignin-based anode exhibits higher impacts in three categories: ionizing radiation (IR), water use (WU), and land use (LU). These elevated impacts are primarily linked

to the upstream energy and feedstock supply chains. The production of lignin-based anodes relies on high-voltage electricity in Finland, where the national grid includes a nuclear energy share of 21%. Nuclear energy is a major contributor to both ionizing radiation and water use impacts, thereby amplifying the environmental footprint in these categories. In contrast, the fossil-based anode is produced using a medium-voltage electricity mix in regions without nuclear input, leading to comparatively lower IR and WU impacts.
The land use impact of lignin-based products is predominantly driven by the forestry operations associated with pulp production as in the current study environmental burden from pulping is allocated to lignin, treated as a by-product. Pulping requires wood coming from pulping has a substantially higher land use change compared to the fossil-derived graphite, which is primarily produced from petroleum coke with relatively lower land use intensity. Moreover, water use is further elevated in the lignin pathway due to the combined contributions from both nuclear electricity generation and pulping operations.

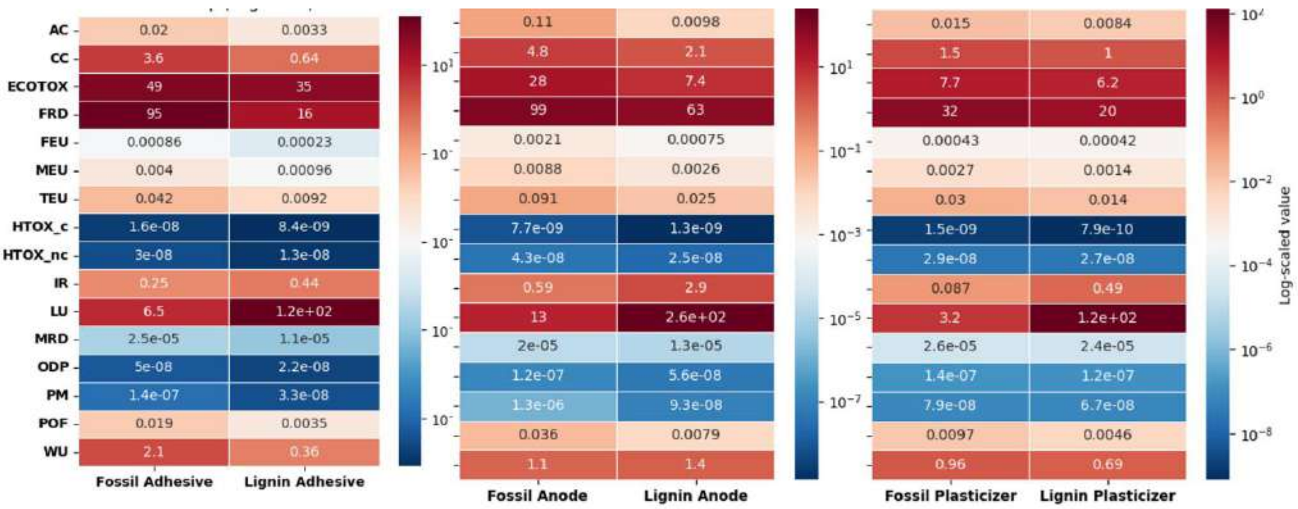


*Figure 31: Plot illustrates the environmental impact for 1kg of lignin-based anode, adhesive and plasticizer across 16 impact categories. Since each impact category has a different unit, y-axis of the plot is a logarithmic axis*

## Planetary boundary

The emergence of the planetary boundary's framework initiated a paradigm shift in sustainability assessments; from relative to absolute assessments. Hence, evaluating what the earth system can tolerate from a given activity or product system. Therefore, while the LCA previously discussed highlighting relative results of how the three product systems score against each other, the environmental performance of these valorisation pathways when assessed against global sustainability thresholds, represented by planetary boundaries remains insufficiently understood. To this end, this section applies an absolute environmental sustainability assessment to anode, plasticizer and adhesive valorisation pathways to assess how they operate against a fair share of planetary boundaries hence, defining their contribution to remaining within the safe operating space.

### *LCA*

#### Goal and scope

The functional unit (FU) was defined as 1 kg of the reference flow, so that the end-product fulfils the yearly need for the Finnish economy at a given year. This was estimated by identifying three parameters: the projected market volume, the assigned share of the safe operating space to the valorisation pathway at a given year, and the impact associated to 1 kg of reference flow. We adopted the FU in annual scale as it provides better interpretation of the absolute assessment results, by facilitating the choice of a fair share of the safe operating space. Moreover, our impact assessment for the absolute assessment relied on PB-LCIA method, which requires the scaling of the inventory to the annual amount to comply with the planetary boundaries' framework. We chose this method as it enables representing the inventory in the metrics of the PB framework, by applying a conversion through characterization models. The characterization factors used in the study were retrieved from[60] for the following seven boundaries (climate change, stratospheric ozone depletion, ocean acidification, biogeochemical flows, land-system change, freshwater use, and atmospheric aerosol loading) and from[61] for biodiversity loss. This enabled us to include eight out of the nine planetary boundaries, where novel entities planetary boundary was excluded due to the lack of a quantitative indicator that enables its characterization, as the current definition of boundary is conceptualized only in the unit of emission of untested synthetics[62].

**Absolute environmental impact assessment**

The modelling in this study followed an attributional approach following the recommendations prescribed by the (ILCD Handbook), where this approach has been described as more appropriate for absolute assessments. For conducting an absolute assessment, we relied on the recommendations by[63]. The absolute assessment encompasses three main steps (i) impact assessment using lifecycle perspective, (ii) assigning a science-based target to evaluated system as a share of safe operating space, (iii) and finally evaluate target fulfilment. To simulate our AESA, we modelled our first step using PB-LCIA. This method enables linking impact results to the planetary boundaries framework[64]. This is achieved by applying metrics conversion from life cycle inventory into planetary boundaries control variables[65]. For the second step, we started by (a) the definition of global earth system boundaries; by relying on the planetary boundaries framework (b) then, we translated global boundaries to the products level by assigning a fair share to the Finnish sector and each products' future demand. The application of this step is typically affected by many factors including data availability and translation level[66] (c) therefore; to guarantee the quality of results, we screened different allocation principles for sharing the safe operating space. The three products in our study mainly relied on the allocation principles highlighted in the table below. (d) These steps were then operationalized using enacting metrics which represent the parameters needed for assigning a share of the safe operating space and operationalize an allocation approach commonly used parameters in our study were (Population, GDP, market share and emissions contribution in end-product).

*Table 31: Allocation approach used for the PB analysis*

| Allocation approaches | Description |
|---|---|

[60] Ryberg, M., Laurent, A., & Hauschild, M. Z. (2018). *Introducing the Environmental Footprint into the Planetary Boundaries Framework*. *Environmental Science & Technology*, 52(5), 2054–2062
[61] Galán-Martín, Á., Tulus, V., Díaz, I., Pozo, C., Pérez-Ramírez, J., & Guillén-Gosálbez, G. (2021). Sustainability footprints of a renewable carbon transition for the petrochemical sector within planetary boundaries. *One Earth*, 4(4), 565–583.
[62] Persson, L., Carney Almroth, B. M., Collins, C. D., Cornell, S., de Wit, C. A., Diamond, M. L., Fantke, P., Hassellöv, M., MacLeod, M., Ryberg, M. W., Søgaard Jørgensen, P., Villarrubia-Gómez, P., Wang, Z., & Hauschild, M. Z. (2022). Outside the Safe Operating Space of the Planetary Boundary for Novel Entities. *Environmental Science & Technology*, 56(3), 1510–1521.
[63] Bjørn, A., Richardson, K., Hauschild, M. Z., & Olsen, S. I. (2020). *The role of planetary boundaries in assessing absolute environmental sustainability across scales*. Environment International, 137, 105611.
[64] Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., ... & Sörlin, S. (2015). Planetary boundaries: Guiding human development on a changing planet. *science*, *347*(6223), 1259855
[65] Clausen, C. A., Bjørn, A., Sanyé-Mengual, E., & Ryberg, M. (2024). Applying environmental sustainability boundaries for climate change in life cycle assessment: A review of approaches and implications for policymaking. *Journal of Industrial Ecology*, *28*(3), 617-630.
[66] Bai, X., Hasan, S., Andersen, L. S., Bjørn, A., Kilkiş, Ş., Ospina, D., ... & Zimm, C. (2024). Translating Earth system boundaries for cities and businesses. *Nature Sustainability*, *7*(2), 108-119

| | |
|---|---|
| (4) Egalitarian approach | The distribution of resources shall follow an equal per capita principle. |
| (4) Economic throughput | Correlated the assigned share of carrying capacity to the economic throughput of the activity |
| (4) Economic capacity and efficiency | Assigns a share of the safe operating space based on the economic capacity of the activity. |
| (4) Historical justice and grandfathering principles | The reduction target drives from historical emissions. |

**Calculation summary**

*Table 32. overview of criteria and methods used for assessing absolute sustainability of valorised pathways using the planetary boundaries life cycle impact assessment (PB-LCIA) approach*

| Criteria | Description |
|---|---|
| Method | PB-LCIA method, which applies metric conversion to Life cycle inventory to represent results in PBs metrics. |
| Functional unit | 1 kg of reference flow of valorisation pathway (anode, plasticizer and adhesive) |
| Reference global boundary | PBs framework |
| Translating boundary to evaluation level | Harmonized amongst the three products by translating from (i) global to regional scale, (ii) regional to Finland, (iii) assigning a share to Finnish market demand of end-product (iv) economic or emissions contribution analysis of valorised pathway in end-product. (E.g. anode valorisation in battery end-product) |
| Uncertainty handling | We applied different sharing principles to retrieve (minimum and maximum) share, so that our absolute result reflects a probabilistic range instead of a definitive uncertain value. Red |
| Absolute sustainability equation (Target fulfilment) | Impact per kg/ allocated share per kg<br>ASR ≤ 1 → indicates absolute sustainability for the PB<br>ASR > 1 → indicates the target is unfulfilled for the PB |

**Results**

The radar plots below illustrate the absolute sustainability performance of each valorisation pathway across selected planetary boundaries (PBs). Each axis is labelled with a specific environmental indicator: FW represents freshwater use, while *N flow* and *P flow* refer to the biogeochemical flows of nitrogen and phosphorus, respectively. *CC (*W/m²*)* and *CC (*ppm*)* denote the climate change boundary, expressed as radiative forcing and atmospheric $CO_2$ concentration.

In the plots:

- The green hexagon marks the Absolute Sustainability Ratio (ASR) = 1, which defines the threshold for remaining within the safe operating space for each environmental dimension.
- The yellow area represents performance under the least conservative scenario, where the product is allocated the maximum feasible share of the safe operating space.
- The red area reflects performance under the most conservative scenario, where the product is assigned the minimum feasible share of the safe operating space.

Values exceeding the green boundary indicate transgression of the planetary threshold, highlighting areas where environmental performance must improve to ensure absolute sustainability.

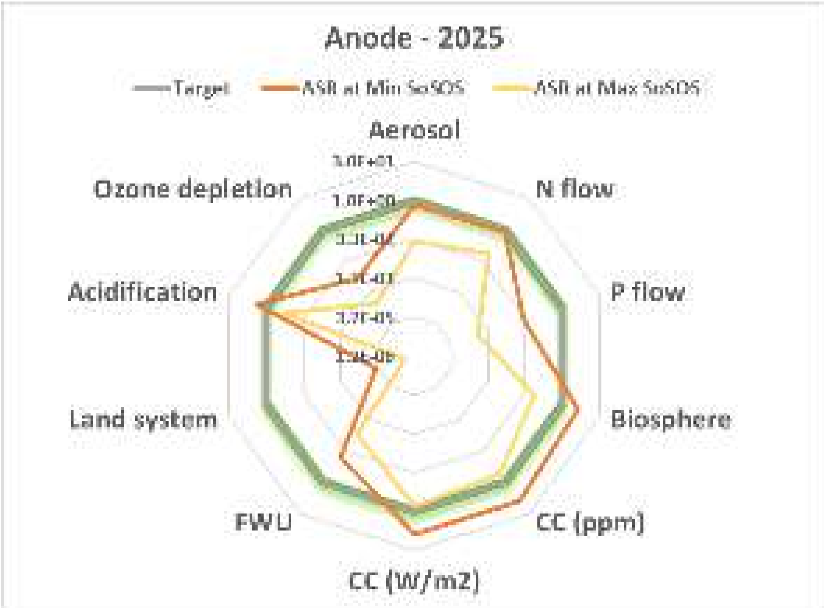


*Figure 32: PB estimated for anode used in the electric vehicle sector in Finland*

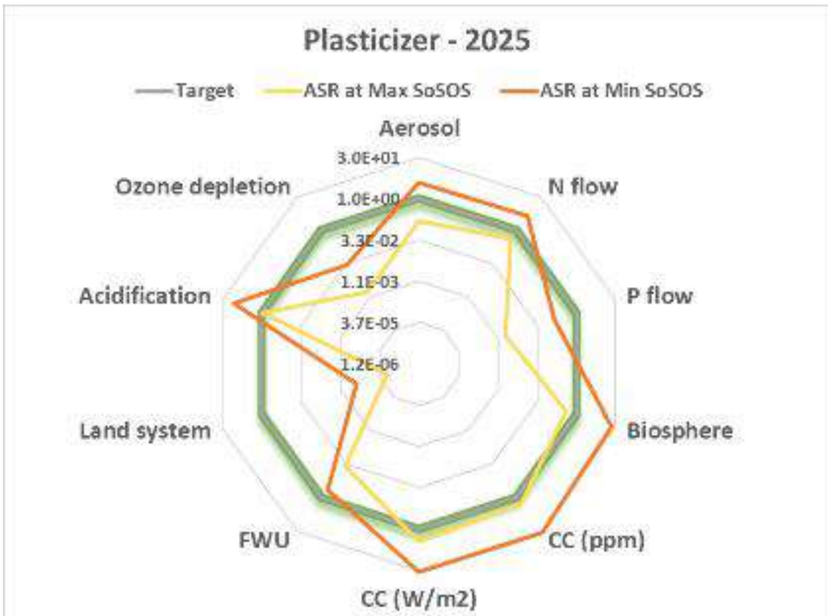


*Figure 33: PB estimated for plasticizer used in the construction sector in Finland*


*Figure 34: PB estimated for adhesives used in the wood-board sector in Finland*

**Reflection and outlook**

Under the most conservative scenario, none of the three valorisation pathways achieves absolute sustainability based on current market conditions. This indicates an urgent need for trajectory-based analysis to assess prospective sustainability and to define technology-specific environmental targets.

In contrast, the least conservative scenario presents a more optimistic outlook. The anode pathway demonstrates compliance with all considered planetary boundaries (PBs), followed by the adhesive and plasticizer pathways, both of which meet all boundaries except for a marginal exceedance of the climate change boundary—specifically in terms of radiative forcing and $CO_2$ concentration.

When considering the median scenario, the adhesive and anode pathways transgress two and three PBs respectively, while the plasticizer pathway significantly exceeds five of the eight considered boundaries. Specifically:

- **Adhesive** exceeds:
  - Climate Change: $CO_2$ concentration (3.1×), Radiative forcing (4.62×)
  - Acidification (1.51×)
- **Anode** exceeds:
  - Climate Change: $CO_2$ concentration (4.1×), Radiative forcing (3.91×)
  - Acidification (1.31×)
  - Biosphere integrity (2.16×)
- **Plasticizer** exceeds:
  - Aerosol loading (2×)
  - Nitrogen flow (2.43×)
  - Biosphere integrity (10.82×)
  - Climate Change: $CO_2$ concentration (18.75×), Radiative forcing (17.96×)
  - Acidification (5.99×)

Overall, climate change and acidification consistently emerge as the most critical boundaries across all scenarios. To remain within the safe operating space, future research should prioritize prospective scenario modelling to define absolute environmental targets and guide technological innovation, especially for boundaries showing recurrent exceedance.

*Table 33: Future projection for PB for lignin case*

| Lignin Products | Usage details/sector | Mass information | Future projection |
|---|---|---|---|
| Anode | Automobile- EV batterry | 1kg for 1kwh<br>Assume: car of 60kwh | 1.5 M EV by 2040<br>and 50% will have lignin anode |
| Adhesives | Furniture (MDF)or particle board | 2.4% of the weight can be from lignin Adh. without changing its functionality of the current product | *Partial replacement.* Lifetime same as in current products (10-15 y furniture) |
| Plasticizers | Used in the construction sector | 2% for bitumen road and 0.5% in cement concrete | *Partial replacement*. Lifetime same as in current products (50y for concrete) |

67

## 3.3.4 Economic assessment

**Eco-Cost**: The economic assessment was done in two steps in the first step we calculated Environmental prices which is based on the valuation of the environmental quality meaning expressing the value society assigns to environmental quality in monetary terms. Since in many cases that value cannot be directly established via market prices therefore, prices are constructed for the social cost or pollution, expressed in Euros per kilogram pollutant. Environmental prices thus indicate the loss of economic welfare that occurs when one additional kilogram of the pollutant finds its way into the environment. External costs are characterized based on an individualist perspective value is equal to the 'Pigovian tax' required to internalize external impacts[68]. Other things being equal, internalization of external costs, so they can be included in policy deliberations, leads to greater economic welfare. For environmental impacts estimation the ReCiPe method[69] is used. We used the attributional LCA inventory in Brightway 2 with ecoinvent data set to calculate the impacts and when impacts were calculated it was multiplied by the cost values to estimate the environmental prices.
For environmental impacts estimation the ReCiPe method is used. We used the attributional LCA inventory in Brightway 2 with ecoinvent data set[70] to calculate the impacts and when impacts were calculated it was multiplied by the cost values to estimate the environmental prices. The eco-cost saving for 1kg of anode, adhesives and plasticizers are given below:

*Table 34: Environmental costs estimated for 1 Kg of Anode, Adhesives and Plasticizer*

| Product (kg) | Anode | Adhesives | Plasticizer |
|---|---|---|---|
| Eco-cost saving (€) | 67 | 54 | 11 |

For the economic assessment, a ranking was made, highest rank was given to for the most important one. Most important one was seen to be value creation, followed by added value and profitable investment, that is run profitably. Reasonable scale for profitable operation that also suits for export market were the following subcriteria. Jobs creation potential were seen quite low in amounts, thus having also low impact on wages for the regional economy. Least impacting subcriteria seen were import need and training needs from the economic viewpoint.

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67 https://pypi.org/project/brightway2/
68 Pigou, A. (2017). *The economics of welfare*. Routledge.
69 Huijbregts, M. A., Steinmann, Z. J., Elshout, P. M., Stam, G., Verones, F., Vieira, M. D. M., ... & van Zelm, R. (2016). ReCiPe 2016: a harmonized life cycle impact assessment method at midpoint and endpoint level report I: characterization
70 https://support.ecoinvent.org/ecoinvent-version-3.9.1

*Table 35: Weighting of economic sub criteria for three lignin valorisation pathways using lignin sourced from the pulp and paper industry in Finland*

| Economic Subcriteria | Anode | Plasticizers | Adhesive |
|---|---|---|---|
| Job loss / Job creation | 4 % | 5 % | 5 % |
| Wages | 4 % | 4 % | 4 % |
| Training needs | 3 % | 3 % | 3 % |
| Value Creation | 34 % | 34 % | 34 % |
| Added Value | 17 % | 17 % | 17 % |
| CAPEX | 11 % | 11 % | 11 % |
| OPEX | 9 % | 9 % | 9 % |
| Sizing/scaling | 7 % | 7 % | 7 % |
| Impact on export | 6 % | 6 % | 6 % |
| Impact on import | 5 % | 4 % | 4 % |

*Figure 35: Economic impact assessment for the lignin valorisation pathway in Finland*

### 3.3.5 Social assessment

For the social assessment, a survey was made, consisting of 3 questions from each of the economic subcriteria are shown in next table. Responses to questions were formulated to be Likert-scale (1-5), giving 3 for equal to current pathway and if change was minor, the change of 1 in Likert-scale and if change was more than minor, then change of 2 in Likert-scale, improvement in positive and vice versa. From the responses a numeric average to each subcriteria was calculated. Then average values were given a subunit sum-weight by giving 0.75 for the lowest and 1 for highest and linearly giving value for the one in between and multiplying the value by subunit points of 300.

*Table 36: Subcriteria estimation for Finnish social impact*

| Social Impact subcriteria | Anode | Adhesive | Plasticizer |
|---|---|---|---|
| Employment | 4 | 4 | 4 |
| Income | 3 | 4 | 2 |
| Work life balance | 3 | 3 | 3 |
| Housing | 4 | 3 | 3 |
| Health | 4 | 5 | 3 |
| Education | 4 | 4 | 5 |
| Governance | 4 | 4 | 4 |
| Environment | 3 | 3 | 3 |
| Security | 5 | 5 | 0 |
| Life satisfaction | 4 | 4 | 4 |
| Total | 38 | 39 | 31 |
| Subunits | 0.969 | 1 | 0.750 |

| | | | |
|---|---|---|---|
| Units (300)*Subunits | 290.6 | 300 | 225 |

Subunits are converted from the weights of previous table via multiplying them by 300. The result is shown in Figure 36.

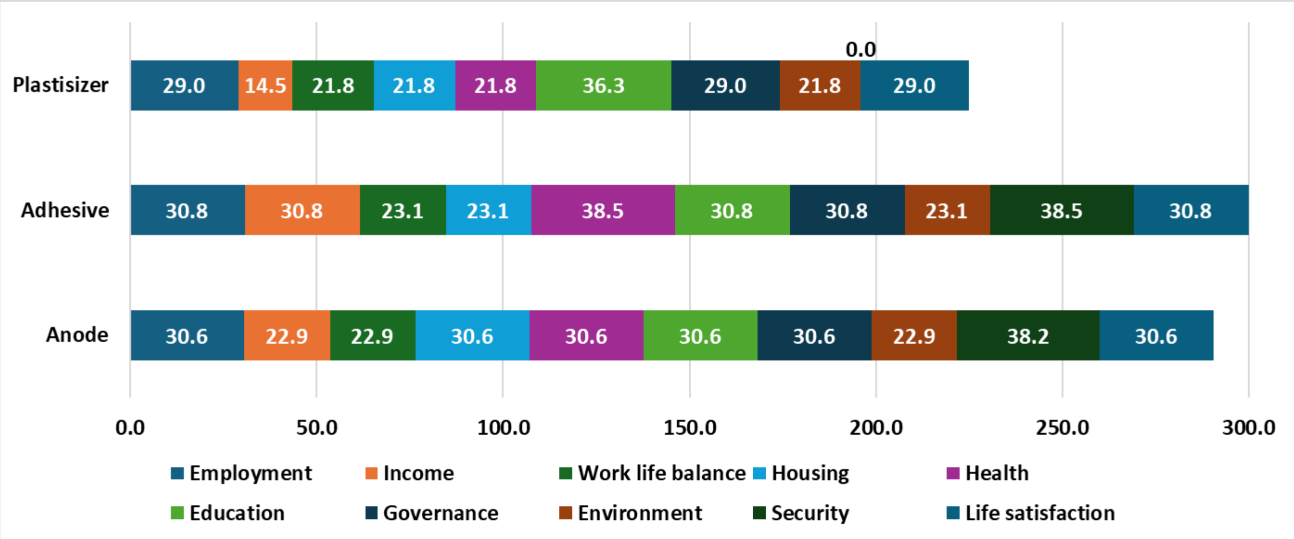


*Figure 36. Subunits of the social impact assessment.*

From these subunits a total sustainability assessment is formulated for each pathway.

### 3.3.6 Sustainability assessment

To ensure robust representation of environmental impact, the weighting of environmental subcriteria incorporated both stakeholder-derived priorities and standardized weights from the EF 3.1 method (Ref). For instance, land use change accounted for 8.7% of the total impact in EF 3.1, whereas stakeholders predominantly from the forestry sector assigned it a 25% weight. To balance general and context-specific perspectives, the final weight used in the analysis was the arithmetic mean of the EF 3.1 and stakeholder-derived values. The final sustainability score for each scenario was obtained by summing the weighted scores across the environmental, economic, and social pillars, thereby providing an integrated metric for comparative evaluation.

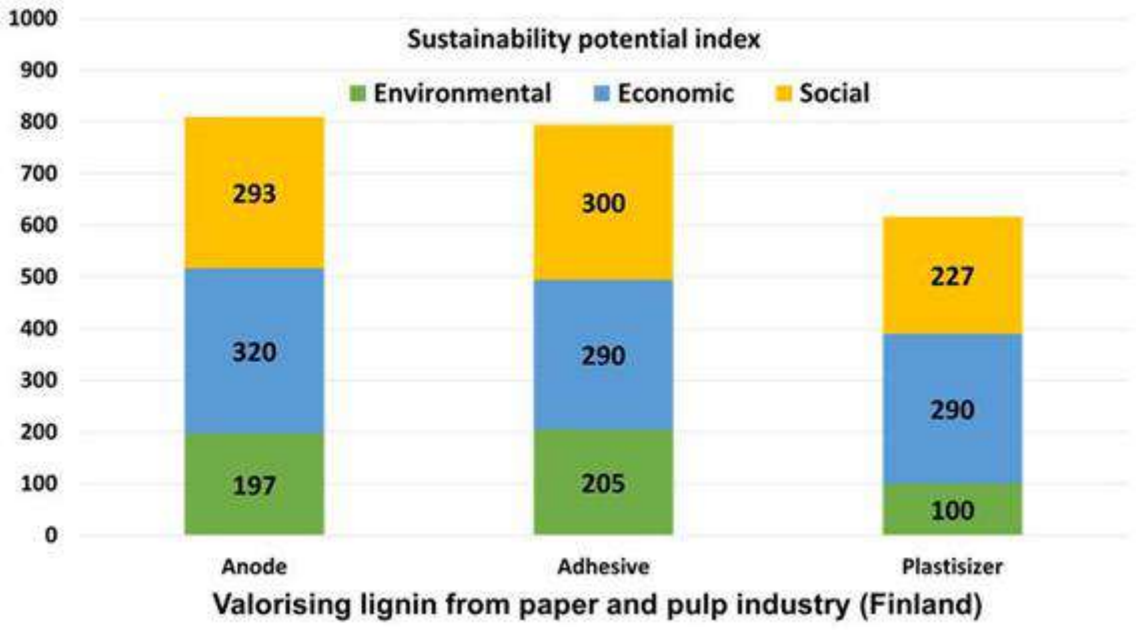


*Figure 37. Sustainability score for converting lignin into anode, adhesives and plasticizers for Finland*

## 3.3.7 Circularity assessment

The circularity assessment for Finland focuses on pathways valorising lignin, a significant side-stream from its extensive pulp and paper industry. The aim is to transition lignin from its current primary use as an energy source towards higher-value, longer-lasting bio-based products, thereby enhancing resource efficiency and replacing fossil-derived materials in applications like battery anodes, adhesives, and plasticizers.

*Table 37: Circularity assessment for lignin valorisation in Finland*

| Product | Resource Output rate | Resource consumption rate | Integrated Resource Utilisation rate | Waste disposal and pollutant emissions |
|---|---|---|---|---|
| Lignin to battery anode material | Valorises lignin (industrial by-product) into a high-value component, replacing mined graphite. Economic output tied to battery market. | Lignin extraction & processing require energy, but avoids energy/resource intensity of graphite mining & purification. | Excellent use of a major industrial by-product (black liquor/lignin), cascading carbon into a durable, high-tech product. | Reduces mining impacts associated with graphite. Lignin is renewable. Battery end-of-life requires specific recycling. |
| Lignin to adhesive | Valorises lignin to replace fossil-based phenols in resins, improving resource output for adhesive/wood panel sector. | Energy for lignin processing versus energy for conventional phenol production; likely medium net impact. | Good utilisation of lignin by-product for a significant material application, enhancing circularity of the forestry sector. | Replaces fossil-derived, potentially more hazardous chemicals (phenols). Reduces emissions from conventional chemical synthesis. Bio-based adhesive. |
| Lignin to plasticizer (in concrete) | Valorises lignin to replace synthetic (often fossil-derived) plasticizers in concrete applications. | Energy for lignin processing versus energy for synthetic plasticizer production. | Good utilisation of lignin by-product, diverting it from primary use as fuel to a material application. | Replaces fossil-derived chemicals. Concrete is a long-life product, effectively sequestering the bio-based carbon. Reduces emissions from synthetic plasticizer. |

## 3.4 North Rhine-Westphalia (Germany)

The case study transition pathway for North Rhine-Westphalia (NRW) focusses on the use of side streams from regional sugar production. The production of sugar is an important economic factor in NRW and contributes to Germany's above-average sugar supply situation overall [71]. In addition to NRW, there are other sugar beet-growing regions in Germany and the production of beet sugar is also the most common form of industrial and household sugar production in neighbouring EU countries. The transformation path under consideration therefore shows potential for replication in both a national and international context [72]. Making use of biogenic side streams is tied in the national strategies as well as the regional NRW bioeconomy strategy that is currently under development with support of the appointed Bioeconomy Council, made up of experts from industry and academia. The

[71] Bericht zur Markt- und Versorgungslage Zucker 2024; BLE
[72] Bericht zur Markt- und Versorgungslage Zucker 2024; BLE, CEFS STATISTICS 2021/22

effective material use of biogenic carbon is both a challenge and an opportunity for the strong chemical industry in NRW. Changing processes from linear fossil-based routes to bio-based practices in connected to large investments and economic uncertainty. However, this can contribute to resource resilience and will help to meet the EU's climate goals. For NRW, moving towards circular bioeconomy practices goes along the structural change process in the Rhenish mining region that faces a large-scale transition process after the fade out of open face lignite mining in 2035. There are numerous activities in the NRW region to form a region with a strong bioeconomy focus. In addition to actors from research and industry, regional innovation clusters, business development organizations and political decision-makers are also involved in this process.

### 3.4.1 Transition pathway

The decisions made towards the final transition pathway for the NRW case study region were made via a series of discussions with regional industry actors and representatives from research and politics. A broader discussion of possible routes took place in regional stakeholder workshops, where the challenges of certain feedstocks and possible products for the chemical industry were considered. These routes and the decision-making process was described in more detail in the deliverables D3.1 and D3.2. The finally chosen pathway, the fermentative production of lactic acid from sugar beet pulp, follows the principle of prioritising the material use of biogenic resources over their energetic use, and presents an alternative use-case of a regional side stream to achieve a higher valorisation.

During the production of sugar, roughly 15 percent of the sugar beet input (mass based, ~ 24 % dry matter, DM) ends up as pressed sugar beet pulp (SBP) that is then dried and pelleted to be used as animal feed. A share of SBP is mixed with molasses, another side stream of the sugar production, to create a more enriched feed with higher caloric value. Besides this, sugar beet pulp is a possible feedstock for biogas plants, however its share in biogas production is relatively small compared to other feedstocks like corn or manure [73]. The use of sugar beet pulp for the energetic requirements of the sugar biorefinery itself is however a scenario discussed by the sugar producers' associations. Although the biorefinery could generate most of its demand in heating energy with a campaign's worth of SBP-derived biogas or biomethane, this requires high investments along with further adjustments of the heaters to convert them to biogas use [74]. The use of sugar beet pulp in the current scenario is depicted in Figure 38.

[73] DBFZ Report Nr. 30, Anlagenbestand Biogas und Biomethan – Biogaserzeugung und -nutzung in Deutschland
[74] Roadmap treibhausgasneutrale Zuckerindustrie in Deutschland; FutureCamp

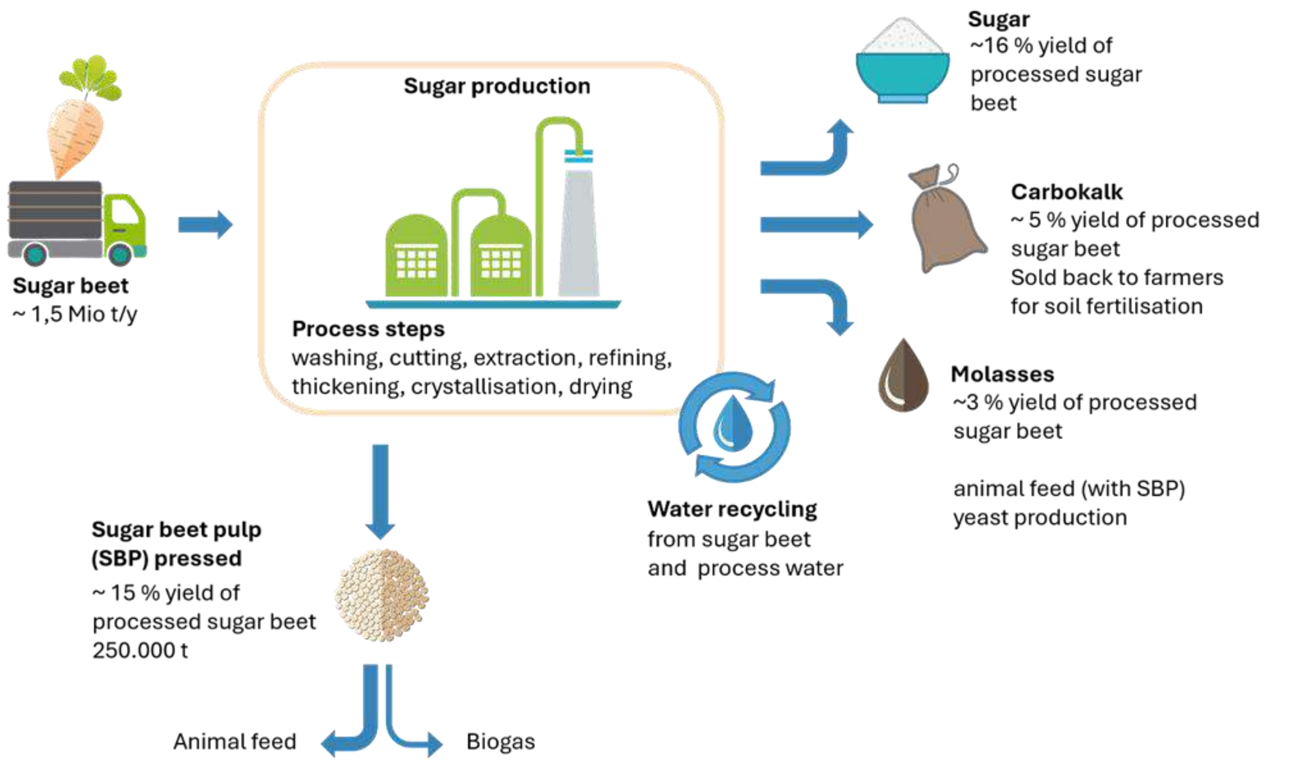


*Figure 38: Current scenario of NRWs sugar production. The volumes of processed beets represent the amount of one regional production facility yielding pressed sugar beet pulp (24 % dry matter) to be further processed to mostly animal feed. The use in biogas plants is possible, however not the standard practice*

Detailed flow charts of sugar production plants vary heavily depending on the plant. A detailed overview for NRW was not available, however, similar reports can be found for other regions[75]. In the NRW case study, production capacities of regional sugar plants were used to estimate the local production. The current scenario shown in Figure 38 is based on the production capacity of one regional plant. Estimations of side streams were made based on literature data, where no numbers were available.

## 3.4.2 Resource flow analysis

As described in D3.2, the future scenario focusses on the implementation of a lactic acid production unit in the process of a running sugar production plant. The analysis and modelling of this process was done with support of the group of Prof. Michael Zavrel of Technical University Munich (TUM). The process was scaled down to match a realisable batch size for preprocessing, hydrolysis, fermentation and downstream processing. Based on the amount of SBP in a single regional plant, several batches of lactic acid could be produced over the duration of a campaign and beyond, provided the right storage concepts for SBP are in place[76].

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[75] Möglichkeiten der Wertschöpfungssteigerung durch Abfallvermeidung (biogener Reststoffe) und Nebenproduktnutzung – Johanneum Research
[76] Wendt & Zhao, 2020; doi.org/10.3389/fbioe.2020.00370

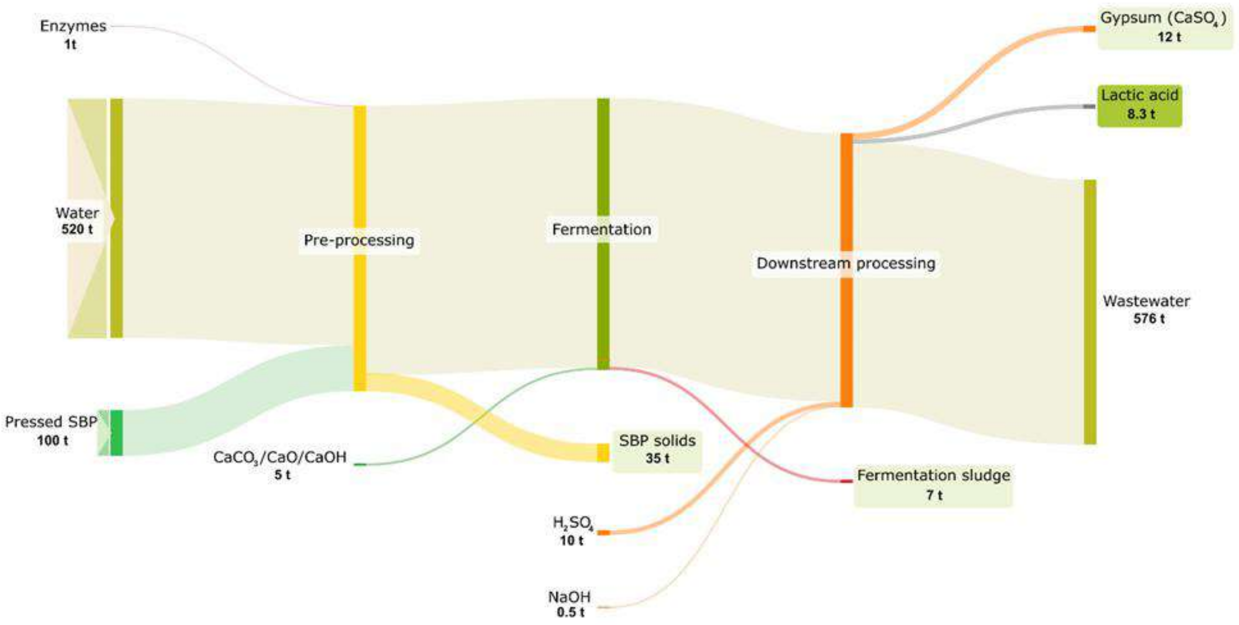


*Figure 39: Sankey diagram of one batch of sugar beet pulp valorisation to lactic acid.*

The depicted process yields lactic acid as its main product that can be further processed into polylactic acid or enter other markets as an ingredient for cosmetics, food and feed applications, or the chemical industry. Side streams of this process (gypsum and biological residues of the fermentation process) can be further utilised in the construction industry or as a feedstock for biogas production, respectively.

The second pathway under consideration for regional implementation in NRW was the valorisation of biogenic side streams via insects (black soldier fly). This was discussed during the stakeholder workshops and the selection of the final pathway. However, because of limited stakeholder availability, a follow up of this pathway was not possible and it was not further analysed in terms of the assessment described in this deliverable. All information concerning the decisions made towards implementation of this pathway can be found in deliverable D3.2.8.4.2 Sustainability assessment

The semi-quantitative assessment of the sustainability factors was carried out for the final transformation path of the case study region NRW as part of a stakeholder workshop. A group of 13 experts from academia, industry, civil society, tech centers, clusters, and funding agencies gave their assessment on the potential impact of the transformation path for the region. The assessment was made after discussing a possible roadmap for this transformation path and assuming a successful implementation. For the three sustainability aspects environment, economy, and social, the experts gaged the influence of the presented pathway on the respective sub criteria. Possible answers included positive influence, no influence, and negative influence. As described before, (see above and D3.1 and D3.2), only one pathway was considered for the sustainability assessment.

The weighting of the sustainability impact was estimated along the regional transformation strategies for NRW[77] and in alignment with the limitations identified in D1.1. The defossilisation of the chemical industry in NRW is challenging, as strong international competition means that economic competitiveness is essential. Even if the transformation pathway discussed here only makes a small contribution to integrating bio-based practices into this industry, this is reflected in the economic weighting criteria. Economic factors were therefore rated as most important, while environmental and

[77] Eckpunkte für eine Bioökonomie-Strategie Nordrhein-Westfalen, Landesregierung Nordrhein-Westfalen

social aspects were given equal importance. The main criteria were ultimately chosen in a 30/40/30 ratio for the environmental, economic, and social assessment, respectively.

The final scores were calculated following the methodology presented in the method section. [78]

### 3.4.3 Environmental assessment

The environmental assessment describes the impact the transformation pathway imposes on the region's ecosystems.

The weighting of the sub criteria was again set according to the region's overall strategies and the relevance for the chosen pathway. The sub criteria "climate change" and "resource use fossil" were deemed most important to produce lactic acid from sugar beet, as these are most relevant for the overall transformation, i.e. defossilisation, of the chemical industry. Lactic acid is a platform chemical and its envisioned product, polylactic acid (PLA) is a bio-based polymer, which can replace fossil-based polymers in a long-term scenario. However, existing regulations, infrastructure, and stakeholder interests are not yet favourable for its recycling or industrial composting. This slows down implementation and therefore the potential of saving fossil resources[79]. This statement was underlined during the stakeholder workshop and is also reflected under the "governance" in the social aspects below. [80]

*Table 38: Weighting for the environmental impact of the Sugar beet pulp to lactic acid pathway of NRW.*

| Main criteria | Weight | Units | Sub criteria | Sub score | Weight |
|---|---|---|---|---|---|
| Environmental impact | 30% | 300 | Climate change (GWP-total) | 75 | 25% |
| | | | Particulate matter | 30 | 10% |
| | | | Land use change | 60 | 20% |
| | | | Water use | 45 | 15% |
| | | | Resource use fossil (ADP-fossil) | 75 | 25% |
| | | | Resource use mineral and metals (ADP-min&met) | 15 | 5% |
| | | | Subtotal environmental impact | 300 | 100% |

Ranked second and third were factors that connect to the impact of the primary production of sugar beet. While sugar beet is primarily grown to produce household sugar, the use of sugar beet pulp presents a 2G feedstock solution (i.e. using side-streams instead of primary biomass) without adding to the land use change or water consumption. This is a benefit because currently, the global lactic acid production is based on glucose as a fermentation feedstock and therefore directly connected to the production of corn or other starch crops, thus contributing to "water use" and "land use change". A more efficient use of the side streams of sugar production should therefore be considered important for the environmental impact.

Lastly, the "particulate matter" sub criterion was given less importance. While sugar beet production as well as the sugar production process contribute to particulate matter generation through several steps during the growing period, transport, and the processing and extraction[81]. By adding a further layer of side stream utilization and production efficiency, the load will be further distributed.

[79] Mosomi et al. 2024; DOI: 10.1002/eng2.12909

[81] Gonzales & Björnsson, 2022; doi.org/10.1016/j.jclepro.2022.131211

### 3.4.4 Economic assessment

The economic impacts of the selected transformation pathway were weighed according to the expected influences for the NRW region. Table 37 shows the classification of the weighting for the economic indicators. Regardless of the transformation paths pursued, the expectations of structural change in NRW are high and the creation of new jobs or the preservation of existing ones is a high priority. Reskilling will also be an important factor to adequately train the existing workforce in the sectors to be phased, so they can find employment in new activities.

*Table 39: Weighting for the economic impact of the sugar beet pulp to lactic acid pathway of NRW*

| Main criteria | Weight | Units | Sub criteria | Sub score | Weight |
|---|---|---|---|---|---|
| Economic impact | 40% | 400 | Job loss / Job creation | 80 | 20% |
| | | | Wages | 28 | 7% |
| | | | Training needs | 60 | 15% |
| | | | Value Creation | 0 | 0% |
| | | | Added Value | 80 | 20% |
| | | | CAPEX | 28 | 7% |
| | | | OPEX | 28 | 7% |
| | | | Sizing/scaling | 28 | 7% |
| | | | Impact on export | 40 | 10% |
| | | | Impact on import | 28 | 7% |
| | | | Subtotal economical | 400 | 100% |

With regards to the transformation pathway under consideration, the additional value creation ("added value") resulting from the production of lactic acid can be an important economic factor for the region. However, sugar beet pulp as a side stream is already utilised as animal feed and marketed alongside other side streams of the beet sugar production. Consequently, the general subcriterion of "value creation" was not considered in the evaluation since a value is already attached to the feedstock. The remaining criteria are related to the construction of new facilities, the employment of technical staff and trade. Although noteworthy, the transformation path under consideration does not pose any particular significance for these sub criteria. These were therefore less impactful. However, the high investment costs attached to production facilities for an economically relevant scale are a mayor cost driver of the transformation in general. As described in D3.2, early cost estimations are usually vague and the influence of capital investment for the region is dependent on the stakeholders involved in setting up the facilities.

### 3.4.5 Social assessment

The assessment of social aspects combines economic and environmental aspects and their impact on the well-being of the population. In North Rhine-Westphalia (NRW), social indicators are recorded and analysed by the State Statistical Office IT.NRW on behalf of the Ministry of Labour, Health and Social Affairs (MAGS NRW). The latest social reports highlight aspects of monetary stability and security as critical. Although employment rates are high and an increase in average wages was reported, the increase in prices for goods and energy can be a problem for people with lower incomes [82]. The indicators listed in Table 38 are only partially addressed by the transformation pathway considered here. For example, while successful implementation could generate additional employment, wages will only be affected indirectly.

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[82] Sozialberichterstattung NRW. Kurzanalyse 04/2023

*Table 40: Weighting for the social impact of the Sugar beet pulp to lactic acid pathway of NRW*

| Main criteria | Weight | Units | Sub criteria | Sub score | Weight |
|---|---|---|---|---|---|
| Social impact | 30% | 300 | Employment | 60 | 20% |
| | | | Income | 24 | 8% |
| | | | Work-Life Balance | 15 | 5% |
| | | | Housing | 45 | 15% |
| | | | Health | 15 | 5% |
| | | | Education | 45 | 15% |
| | | | Governance | 21 | 7% |
| | | | Environment | 30 | 10% |
| | | | Security | 30 | 10% |
| | | | Life satisfaction | 15 | 5% |
| | | | Subtotal social impact | 300 | 100% |

Wages will not be particularly different from comparable occupations in other industries. The same is true for health issues or the impact on work life balance or life satisfaction. Good governance will be important for the whole process of structural change in NRW and its industry. A particular importance for the presented pathway lies within setting up effective regulations for bio-based building blocks and chemicals.

### 3.4.6 Sustainability assessment

The stakeholder survey revealed the social impact scores depicted in Table 40 and Figure 40. Overall, the results showed a lower score for the economic aspects of the pathway impact than the environmental and social aspects. Given that in the weighing the economic aspects were assigned the highest relevance, this result revealed an uncertainty on the part of stakeholders. While “added value” was clearly evaluated positively, the stakeholders were undecided in terms of positive or neutral influence of the subcriterion “job loss/ job creation”. Especially the subcriteria “OPEX” and “CAPEX” were assigned a rather negative impact. This reflects the high investment costs of such a production facility already discussed above.

*Table 41: Scores for the sustainability assessment given by a group of stakeholders in the final workshop for pathway implementation. The theoretical maximum is given according to the weighing of the main criteria as parts from 1.000 points.*

| Scores after stakeholder consideration | | Theoretical |
|---|---|---|
| Total score Environment | 222.32 | 300 |
| Total Score Economic | 194.22 | 400 |
| Total Score Social | 232.43 | 300 |
| Score Impact Assessment | 648.97 | 1000 |

In terms of environmental impact, the assessment by stakeholders aligned well with the previously predefined weighting of the subcriteria. Especially the influence on “climate change” and “resource use fossil” were highly agreed on. Besides several neutral influences, negative impacts did not find a majority.

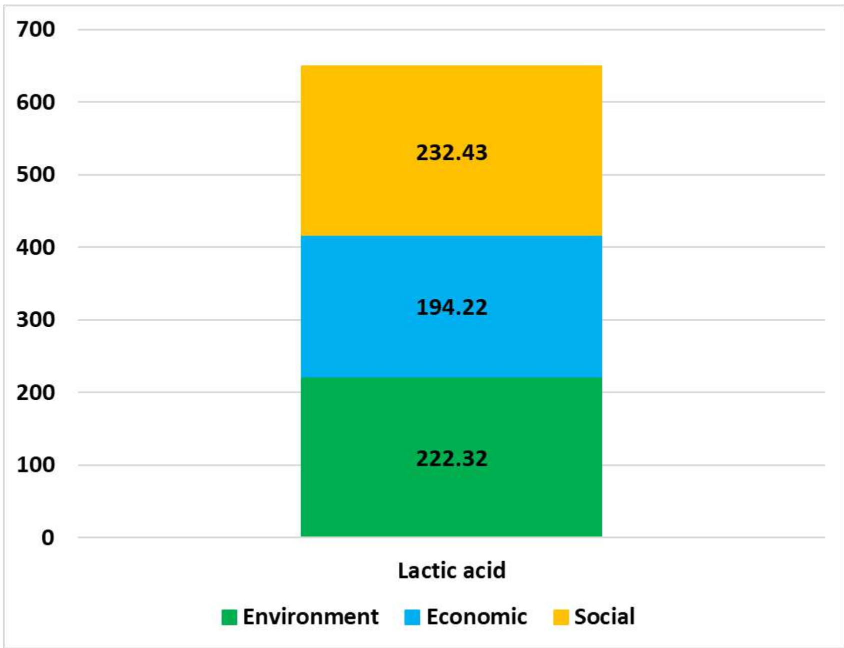



*Figure 40: Visualisation of the sustainability scores for the transformation pathway of valorising sugar beet pulp into lactic acid via fermentation.*

The impact in social subcriteria was voted positive in most cases. Exceptions were the subcriteria “work-life balance”, “housing”, and “health” where no influence was expected.

### 3.4.7 Circularity assessment

For North Rhine-Westphalia, the circularity assessment examines the potential of valorising key agro-industrial side-streams, such as sugar beet pulp, and other biogenic wastes. The selected pathways aim to produce bio-based platform chemicals like lactic acid and other valuable products such as insect-derived lipids and proteins, fostering integration with the region's strong chemical industry and reducing reliance on fossil feedstocks.

*Table 42: Circularity assessment for lactic acid valorisation in North Rhine-Westphalia*

| Product | Resource Output Rate | Resource Consumption Rate | Integrated Resource Utilisation Rate | Waste Disposal and Pollutant Emissions |
|---|---|---|---|---|
| Sugar beet pulp (SBP) to lactic acid (LA) / PLA | Valorises an agro-industrial by-product (SBP) into higher-value chemicals (LA) and bioplastics (PLA), which have a larger market value than animal feed. | Fermentation for LA and subsequent polymerisation to PLA can be energy and water-intensive processes. Requires chemical inputs and significant processing. | Utilises SBP, a major side-stream of sugar production. Further integration and valorisation of by-products from LA fermentation (e.g., microbial biomass, process water) could improve overall resource utilisation. | PLA has the potential to replace fossil-derived polymers, reducing reliance on fossil carbon. However, PLA end-of-life (industrial composting, chemical/mechanical recycling) is still a challenge and can lead to microplastic pollution if not properly managed. Process emissions from fermentation/chemical conversion. |
| Food waste/biogenic side streams to insect oil/lipids (BSF) | Converts diverse, often low-value or problematic organic waste streams (subject to regulation) into high-value products like insect oil and protein meal. | Energy required for insect rearing (e.g., climate control for optimal growth) and processing of larvae. Water use for maintaining substrate moisture. Land use for rearing facilities. | Highly effective conversion of various organic wastes into multiple co-products (oil, protein meal, frass/fertiliser). Demonstrates a strong cascading use of nutrients and organic matter. | Reduces the volume of organic waste. Frass acts as a biofertiliser. Low process emissions if managed well. Has the potential to replaces less sustainable conventional protein and oil sources (e.g., fishmeal, soy, palm oil s). |

Note: In Germany (NRW), the expert felt that the indicators cannot be color coded, so this table provides only the summary.

## 3.5 Greece-Western Macedonia

### 3.5.1 Transition pathway

The Western Macedonia region, which some of the main activities are agriculture, livestock farming, mining, power production, tourism. It is a land of mountains, lakes and rivers, currently is going through an ambitious programme of decarbonisation. This process leads uncertainties by the population, such as job losses, income reduction, outmigration of skilled labourer from the region[83]. A complex structure of possible pathways for the region was prepared, based on literature, observations, and stakeholders consulting, which was identified that the different connections can be interconnected. One key-criteria to select the ones that could generate higher positive impacts and according to the current focuses in the region, such as decarbonisation and socioeconomic impact, as job generation and focus on pathways that can promote high skill educational level.

[83] Ziouzios, D., Karlopoulos, E., Fragkos, P., Vrontisi, Z. Challenges and Opportunities of Coal Phase-Out in Western Macedonia. *Climate* 2021, 9, 115

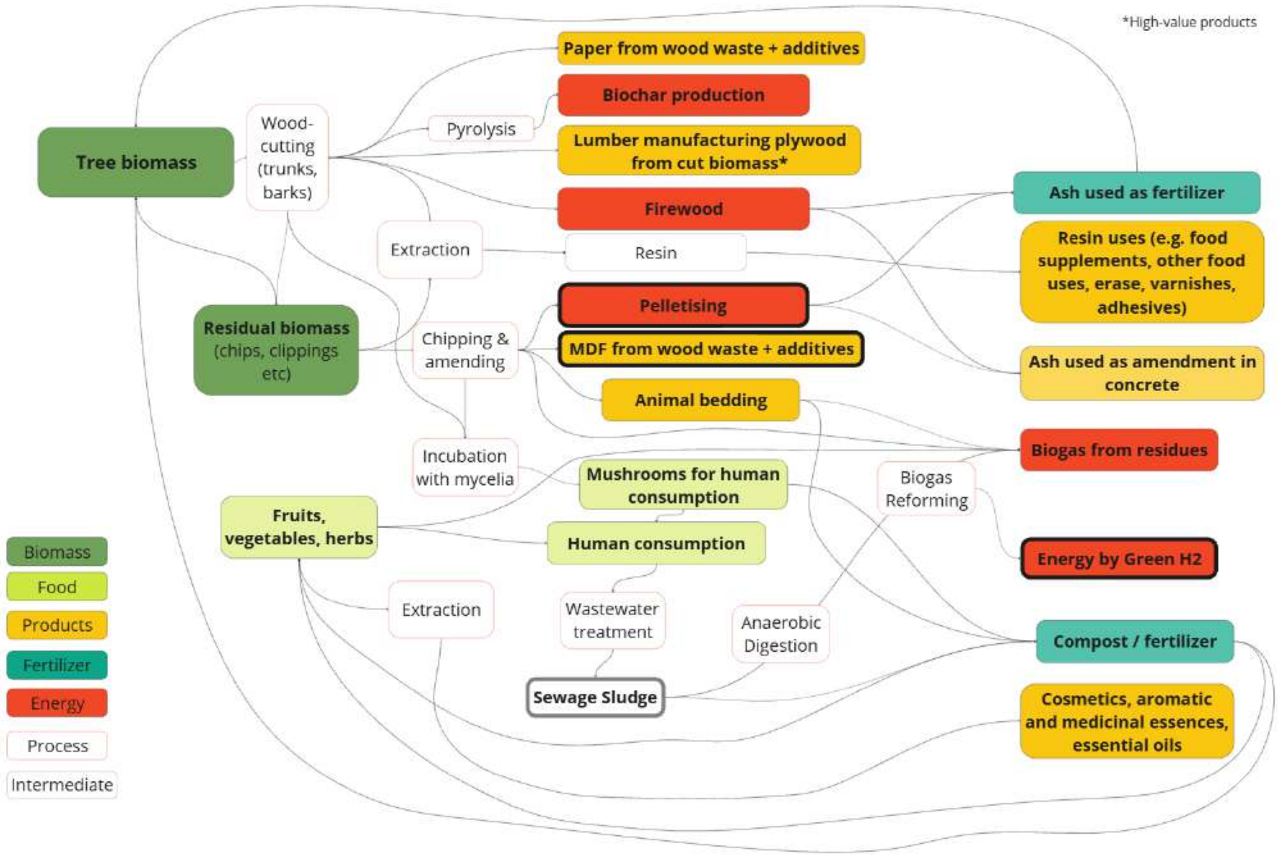



*Figure 41: Diagram of interconnected pathways in the approach of Western Macedonia, Greece*

According also to an alignment with current policies, literature analysis and stakeholders consulting, the pathways selected were chosen on the following way:

**Biomass origin:**

- Scaling up of MDF industry
- Scaling up of Pellets industry

Energy production:

- Hydrogen produced by sewage sludge

On the next topics, they are explained in more details.

## 3.5.2 Resource flow analysis

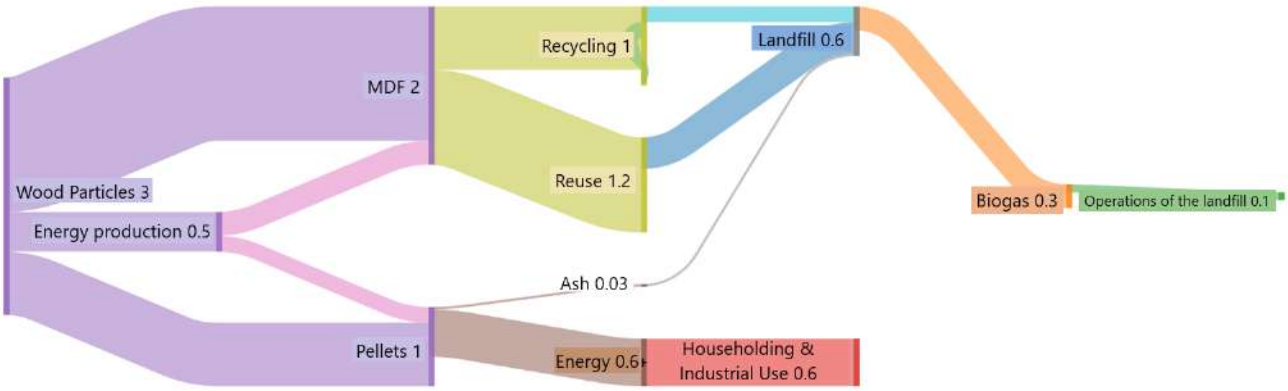
For both pathways analysed in this case-study, the scaling-up of the industry is the focus. Both of them have different end-uses, as for MDF is the use in furniture, building and toys, while Pellets focuses in the heating energy, applied in industries and households.

MDF industry

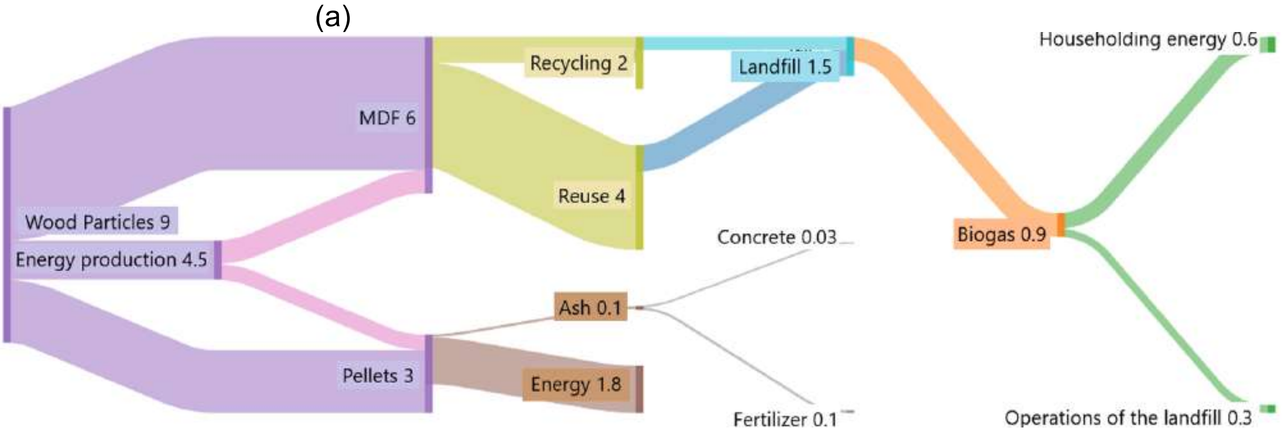
- Scaling-up potential of 500x, but for this study, a conservative scenario of 300x is being considered.
- Increase in the job's generation directly and indirectly, and in rural areas.
- Increase the relevance of Greece in the international trade market of MDF.
- Potential of generation by the industry: currently: 100.000 tons, after the scaling-up: 300.000 tons.
- High quality wood will be used.

Pellets industry

- Scaling-up potential of 300x.
- Increase in jobs generation in rural areas and villages.
- Possibility of decreasing costs in the pellets for low-income families and local industries.
- The ashes are foreseen to be collected in a common point and be destined to fertilizers or concrete industries, promoting circularity, mitigating environmental impacts[84].




(a)




(b)

*Figure 42: Current and previous scenarios foreseen to the biomass pathways through Sankey diagrams (MDF and Pellets)*

The future scenario will allow not only the scaling-up, but also the product generated by pellets, that is ash, for example, to be destined to concrete and fertilizer industries. There are already plans for the collection, which will strengthen the cooperation between communities.

Values given in proportion, considering the scaling up of x300 for both biomass pathways.

[84] Shibu, C., Chandel, S., Vats, P. Scaling Up of Wood Waste Utilization for Sustainable Green Future. *Sustainable Consumption and Production for Greener Economies* 2023, 1, 26.

Green hydrogen ($H_2$) by sewage sludge

The successful transition to hydrogen production from sewage sludge and biomass valorisation will largely depend on early-stage regulatory adaptation, targeted investment support, and the strengthening of stakeholder networks.

- Use of sewage sludge to generate green energy, instead of exclusively destinate it to agricultural soil without any other cascade use[85].
- After the generation of green energy, it will be possible to analyses the quality of the compost in the plant's laboratory and destine it to the fields through donation or sale.
- The green H2 will fuel 14 of the garbage collection trucks that operate in the city.
- Training has a high potential to generate more bioeconomy-related jobs, while increasing the skills of groups that can work in the plant (lignite workers, young people, unemployed people).
- It offers a possibility for the Western Macedonia region to become a reference point in this kind of technology, being able to attract investments and multiplier groups from other regions and countries.

In the next figure, it is possible to analyse in detail the processes needed in the $H_2$ production by sewage sludge, where the use of the raw material as sewage sludge can promote the energy production for fuel garbage trucks.

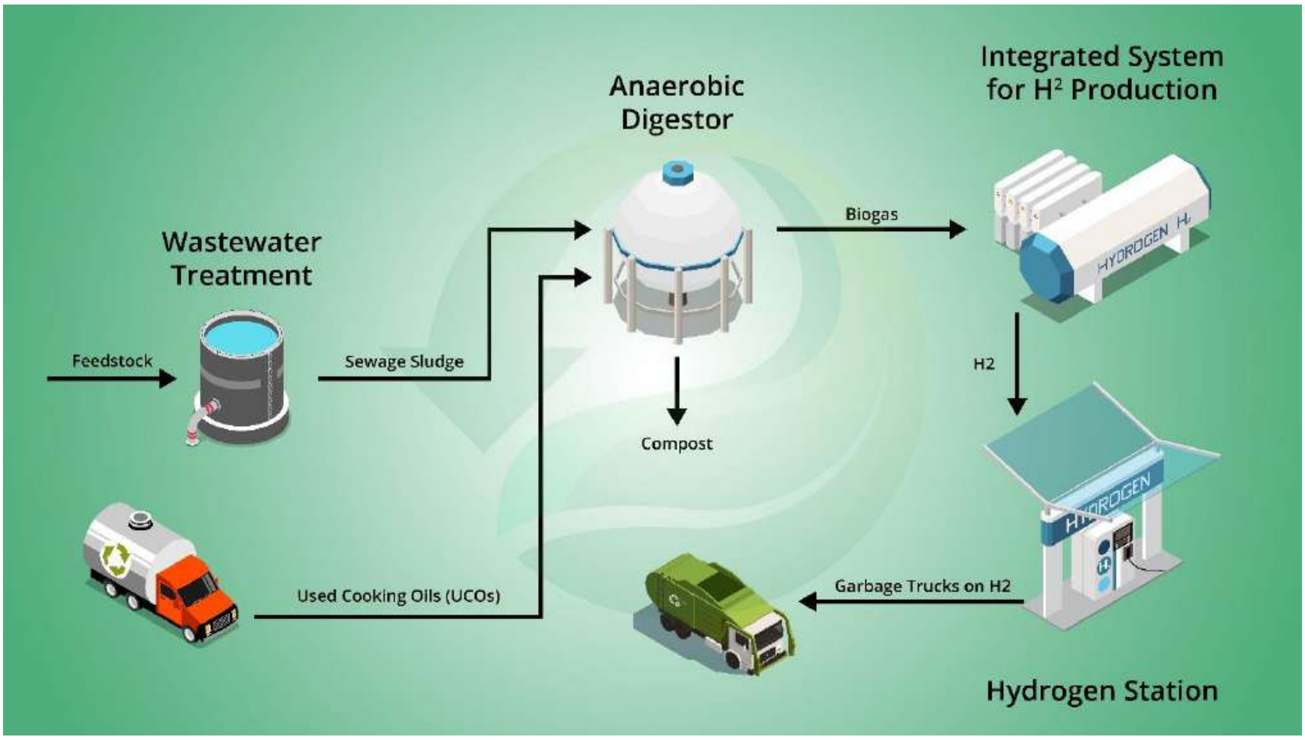



*Figure 43: Schematic representation of $H_2$ production using sewage sludge*

[85] Kostowski, W., Tanczuk, M., Majchrzyk, M., Banasik, A., Klimanek, A. Generation of renewable hydrogen from sewage sludge – Quantitative and energy-based technology evaluation. *International Journal of Hydrogen Energy* 2024, 52, 983-994

Below, the representation of the future scenario of the use of sewage sludge to produce green $H_2$, considering that the current scenario is not clear and the destination of sewage sludge in Greece is not foreseen in recommendations and laws.

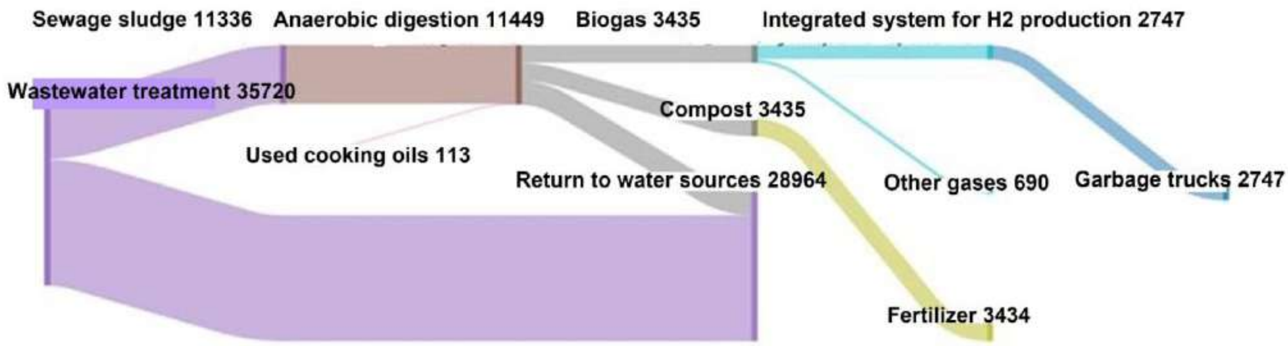



*Figure 44:Western Macedonia case – Sankey diagram for the green hydrogen production  the mass are in tonnes*

It can be confirmed that the process is inherently circular, sustained by the natural flow following wastewater treatment and operating independently of direct anthropogenic interventions.

The current and projected scenarios for biomass pathways—specifically the scaling-up of MDF and pellet production—indicate significant potential for expansion. Depending on investment capacity, the effectiveness of governance, the implementation of supportive environmental policies, and the revision of regional guidelines, production could increase by a factor of 300 to 500.

All the scenarios presented are promising. From that starting point after analysing the main criteria and connections of the pathways, the following step was to analyse which of them could have better impact, following the methodologies proposed by BIOTRANSFORM.

### 3.5.3 Environmental assessment

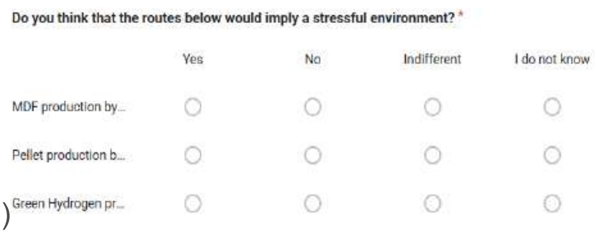
Based on these aspects found in along the project, the Multicriteria Decision Analysis (MCDA) was used to distinguish the pathways and their relevance in the environmental, social and economic approaches. Weights were given to each pathway, according to what was observed along the process of analysis through stakeholder's consensus and literature review. In the table below, we can observe that the three pathways have different weights in the environmental, social and economic criteria.

The sub criteria are crucial to understanding which part of the criteria can count the most for each pathway. Below, it is possible to observe in the table the different weights per sub criteria.

*Table 43: Environmental criteria and weighting for each pathway analysed*

| Environmental Sub criteria | MDF | Pellets | H2 |
|---|---|---|---|
| Climate change (GWP-total) | 15% | 10% | 20% |
| Particulate matter | 25% | 10% | 15% |
| Land use change | 15% | 20% | 15% |
| Water use | 25% | 0% | 20% |
| Resource use fossil (ADP-fossil) | 15% | 25% | 15% |
| Resource use mineral and metals (ADP-min&met) | 5% | 35% | 15% |

Subsequently, the questions and corresponding results were structured to assess stakeholders' perceptions regarding the impact of each pathway on the sub criteria, classified as positive, neutral, or negative. Responses marked as 'I do not know' were assigned a neutral weight for analytical consistency.

a) 


b)

| Subcriteria | Weight | Sub -Units | consider | Positive Improves, adds up | Same Remains, no change | Negative Worsens |
|---|---|---|---|---|---|---|
| Climate change (GWP-total) | 15% | 37,50 | •Burning fossil fuels (oil) along | | | X |
| Particualte matter | 25% | 62,50 | •Combustion of fossil fuels in | | | X |
| Land use change | 15% | 37,50 | •Deforestration for | | X | |
| Water use | 25% | 62,50 | •Industrial processes | | | X |
| Resource use fossil (ADP-fossil) | 15% | 37,50 | •Extraction and consumption | | | X |
| Resource use mineral and metals (ADP-min&met) | 5% | 12,50 | •Use of constructio | | X | |
| **Subtotal environmental** | 100% | 250,00 | - | - | - | - |

*Figure 45: a: Example of question to get the answer and input them into the positive, neutral and negative impact to improve the preliminary sustainability score (b).*

The answers were given anonymously, and each stakeholder were identified only by the order of its answer. It was shared with industry and R&D representatives. The total of 8 answers were given.

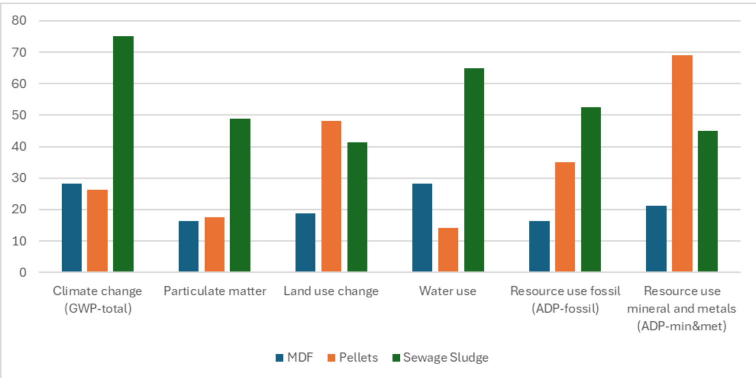



*Figure 46: Comparison of environmental sub criteria analysis for the three pathways.*

## *3.5.4 Economic assessment*

Literature review:

- Low innovation performance
- Challenges of accessing markets and availability of the final product to the consumer.
- Import of raw materials.
- Small primary producers are enough small and cannot cover all regulatory, qualitative or event quantitative requirements of local industries.
- The phasing-out of lignite mines affects the entire economic and business activities.

Interviews:

- Limited development of innovations or competitiveness.
- The phase-out of lignite mining creates a suffocating economic environment in the absence of other developed economic branches because of lack of investments, reduced incomes, no adequate local raw materials and no accessibility to markets.
- Special taxes on pollutants makes the exploitation of lignite unprofitable.

For the economic criteria, weights were given according to the interviews and points given along the WP1.

*Table 44: Economic criteria and weighting for each pathway analysed*

| Economic Sub criteria | MDF | Pellets | H2 |
|---|---|---|---|
| Job loss / Job creation | 2% | 2% | 5% |
| Wages | 11% | 11% | 7% |
| Training needs | 18% | 18% | 4% |
| Value Creation | 13% | 4% | 2% |
| Added Value | 15% | 13% | 11% |
| CAPEX | 5% | 7% | 15% |
| OPEX | 4% | 9% | 9% |
| Sizing/scaling | 7% | 5% | 13% |
| Impact on export | 9% | 15% | 18% |
| Impact on import | 16% | 16% | 16% |

According to the previous methodology applied in the environmental approach, for the economic the stakeholders were also consulted and their opinion about the influence of each sub criteria for the three pathways were given. The results of economic are shown in the plots below:

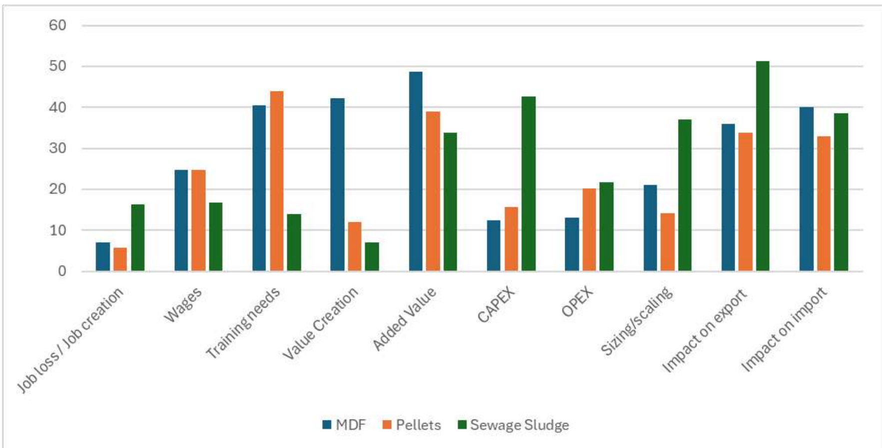



*Figure 47: Results of economic criteria for Western Macedonia*

## 3.5.5 Social assessment

Literature review:

- Focus of the economy on activities that are going obsolete due to environmental and ethical reasons
- Elderly population, with a low level of education and lack of advanced and up-do-date skills

Interviews:

- Reduction and aging of the region's population
- Interest in greener economic models
- Migration of young people to big cities or abroad weakens the Region's qualified human resources
- Consumers are very interested in greener and more sustainable products

The weights were given according to the literature and main results from the discussion with the stakeholders along the project.

*Table 45: Social sub criteria and weighting for the three pathways in Western Macedonia*

| Social Subcriteria | MDF | Pellets | H2 |
|---|---|---|---|
| Employment | 20% | 15% | 18% |

| | | | |
|---|---|---|---|
| Income | 15% | 6% | 18% |
| Work-Life Balance | 5% | 15% | 4% |
| Housing | 5% | 4% | 5% |
| Health | 5% | 10% | 10% |
| Education | 7% | 5% | 8% |
| Governance | 15% | 10% | 5% |
| Environment | 10% | 12% | 20% |
| Security | 10% | 15% | 8% |
| Life satisfaction | 8% | 8% | 4% |

Then, as the previous aspects, the stakeholders were consulted to answer according to their perspective regarding the relevance and impact of each pathway to the given sub criteria.

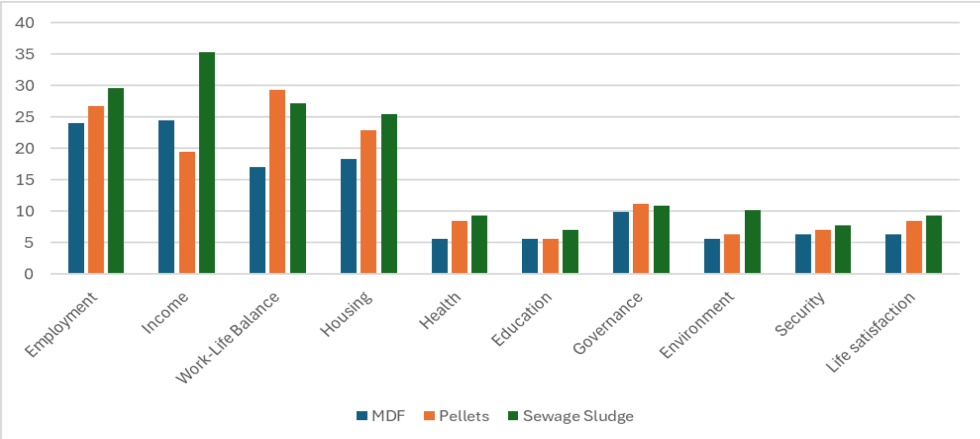



*Figure 48: Social assessment comparing the three pathways in Western Mecedonia*

## 3.5.6 Sustainability assessment

The MCDA was essential to observe the higher impact and relevance of the pathways into the three dimensions criteria observed: environmental, social and economic. According to the figure 47, it is possible to observe that in each dimension, one pathway is highlighted with higher points than the others.

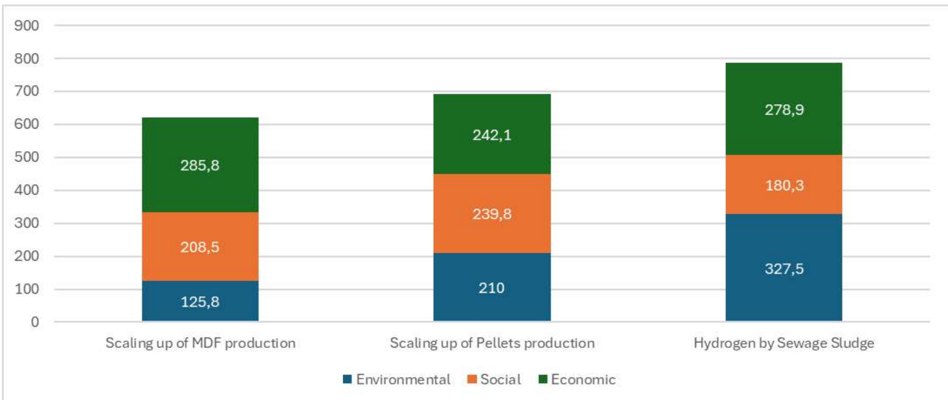



*Figure 49: Sustainability assessment for MDF, Pellets and Green hydrogen in Western Macedonia case study*

It is possible to observe that, besides hydrogen by sewage sludge sum the higher number of points, it was not for all the criteria. While in the environmental aspect it reaches the higher number of points in comparison to the other pathways, the social aspect had a higher positive impact by pellets. At the

same time, when we look to the economic dimension, the scaling-up of MDF industry has higher relevance.
This study is a key to provide to policymakers and decision-makers a complete approach of the different aspects and benefits of each criterion with strong basis from literature and knowledge of the regional situation.

### 3.5.7 Circularity assessment

For Western Macedonia, a region undergoing significant decarbonisation efforts, the circularity assessment reviews pathways aimed at sustainably valorising local resources like wood biomass and sewage sludge. The focus is on scaling up existing bio-based industries (MDF, pellets) and introducing innovative solutions such as green hydrogen production from waste streams, contributing to both economic diversification and environmental objectives.

*Table 46: Circularity assessment for the three pathways in Greece- Western Macedonia*

| Product | Resource Output rate | Resource consumption rate | Integrated Resource Utilization rate | Waste disposal and pollutant emissions |
|---|---|---|---|---|
| **Scaling-up of the MDF industry** | • No mineral resource relevance<br>• It includes the scaling-up, but it does not rethink the methods of energy efficiency in the production. The processes that mainly consume energy are drying, cutting and pressing. | **Energy (current scenario)**: 1MWh, **Heating**: 3MWh, to **produce** 100000 m3/year. No exact data for water consumption and wastewater. Factory works 24/h, full year. | • The recycling rate of industrial solid waste is limited, as wood needs to attend high quality criteria.<br>• Waste along production is avoided to the maximum possible. | • Information about the total amount of industrial wastewater that is discharged is not available, but the quality, as mentioned by stakeholders, is difficult to treat as it is full of chemical components and extremely polluted. |
| **Scaling-up of the Pellets industry** | • No mineral resource relevance<br>• Not exacerbated consumption of energy in the industry, as the peak of production changes along the seasons.<br>• Over 70% of the energy sources in the region are non-renewable (Lambropoulos et al, 2025). The role of bioenergy is still | • No consumption of water and energy consumption is seasonal.<br>• The final product also can produce energy through heating.<br>• The waste product can be reutilized through concrete and fertilizers. | • The total recycling rate will depend on how the final consumers will be engaged with the destination of ashes to the collect points.<br>• Awareness campaigns and good alignment with stakeholders from concrete | • The final disposal of the waste, which will be managed by the consumers (households and industry) can become part of other products, but it depends on good arrangement and organization for the collection in specific points. |

| | | | | |
|---|---|---|---|---|
| | insignificant on a large scale, but the aim of this case-study is the consumption by households and industries. | | industry and fertilizer | |
| **Hydrogen by Sewage Sludge** | • No mineral resource relevance.<br>• The consumption of energy in the production field is foreseen to be green, when it is ready for production. Besides that, the energy consumption is foreseen to be high.<br>• Nevertheless, along its use by garbage trucks, it is neutral. So, it has emission in the 1$^{st}$ and 2$^{nd}$ scope, but not in the final use. | • Energy consumption is high, but it will be consumed from green sources.<br>• The benefits will indirectly have a positive impact to all the citizens but directly will impact the entities involved in waste and wastewater management, educational entities, trucks maintenance. | • Industrial water reuse ratio is not the focus, but the municipal wastewater, originated mainly from residences, can be considered high, as 36,000 m3/d.<br>• The water use is also low, as to fill it only one time is enough for a long-term of Hydrogen production. | • The material for the H2 production is long-lasting, but the final product (H2) does not produce pollutant gases.<br>• The possible waste could be sewage sludge, but after its drying **and quality analysis, it is possible to destine it as a fertilizer product, depending on the available** components. |

## 3.6 Spain-Andalusia

### 3.6.1 Transition pathway

As previously depicted in D3.1 and D3.2, the top 3 routes that were selected as proposed pathways are:

- Reinforcement of polymeric materials from olive pruning debris (route 1)
- Polymeric production and antioxidants production from olive pruning debris (route 2)
- Antioxidants production from olive pomaces (route 7, renamed as route 3 from now on)

The following pictures provides some insights about how these routes are identified among the olive value chain. The new high-value proposed valorisation routes are highlighted in red.

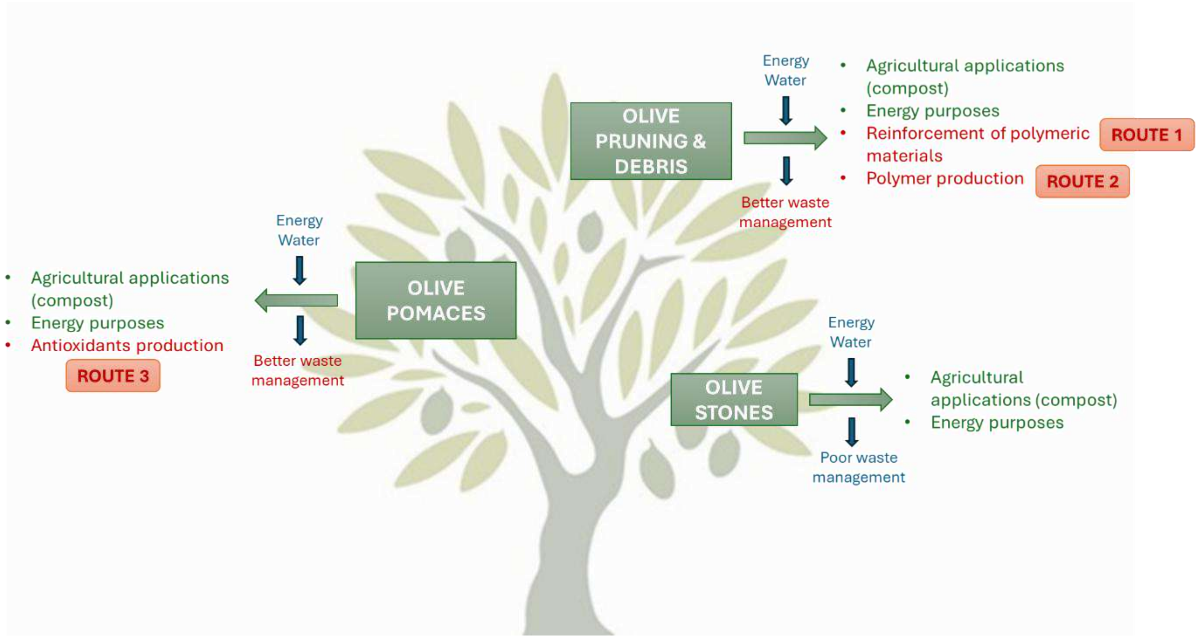



*Figure 50: Top 3 pathways selected - Andalusian regional case*

## Route 1: Reinforcement of Polymeric Materials from Olive Pruning Debris

This pathway aims to produce high-value biocomposites from olive pruning residues (as visualised process chart in *Figure 48*), primarily focused on recycled polypropylene materials. The process, developed by ANDALTEC, has reached a Technology Readiness Level (TRL) of 5-6, supported by the LIFE project COMPOlive [3]. The commercial production of biocomposites has strong market potential, particularly in the automotive and furniture industries, with an estimated annual revenue of over €3.5 billion.

**Key Elements**

- **CAPEX**: Investment is mainly in extrusion lines, biomass processing equipment, and reactors. Using existing machinery reduces capital costs and facilitates integration into current production systems.
- **OPEX**: Operational costs include raw materials, energy, and personnel. These costs are expected to be on par with conventional polymer production, ensuring market competitiveness.
- **Market Potential**: The process can produce up to 3.5 million tons of biocomposites annually, targeting the automotive, furniture, and construction sectors, with projected revenues of €3.5 billion.
- **Business Applications**: Applications in the automotive sector as lightweight biocomposites for car parts (e.g., bumpers, panels) or as durable, eco-friendly furniture. This flexibility allows for easier adoption and scalability across existing facilities, making the transition from laboratory to commercial production more efficient.
- Logistics Strategy:
  - **Collection**: Local collection and processing of pruning residues using shredders and balers, reducing transport costs.
  - **Intermediate Processing**: Material compression and basic treatments at strategically located centres.
  - **Final Production**: Partnership with industries such as automotive, furniture, and urban infrastructure to ensure diverse applications for the biocomposites.
  - **Distribution**: Efficient supply chain management using digital platforms to optimise transport routes and return reusable materials to their points of origin, further enhancing the sustainability of the process.

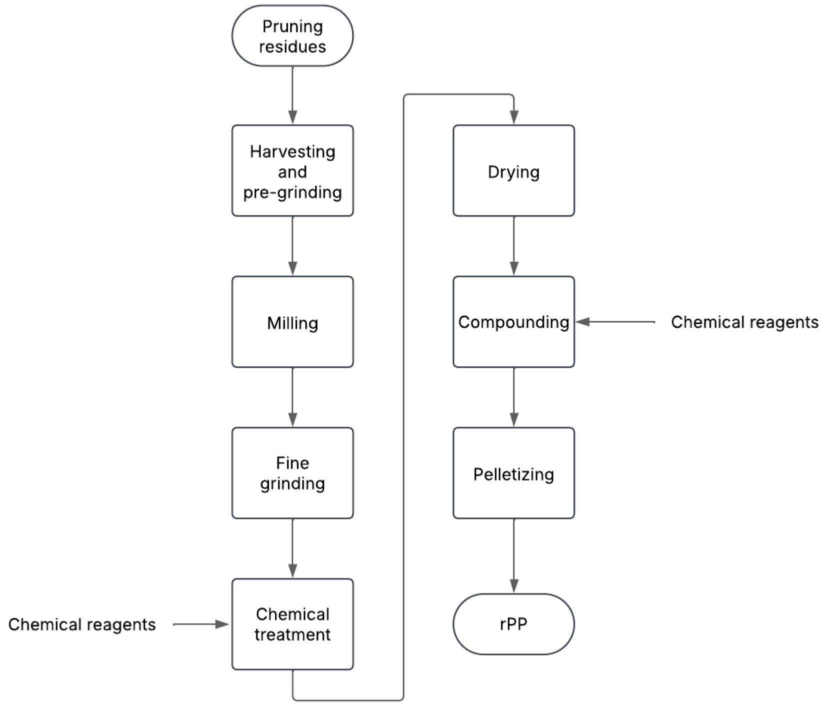



*Figure 51: Andalusian regional case, Route 1 process block diagram*

### Route 2: Polymeric Production and Antioxidants from Olive Pruning Debris

This route targets the production of nanocellulose crystals and cellulose acetate from olive pruning residues, with a TRL of 3-5. These materials have strong applications in the production of biofilms for sustainable food packaging and textiles. The market for cellulosic fibres and bioplastics is growing globally, and this process offers a potential pathway to meet the European demand for sustainable fibres while contributing to the circular bioeconomy.

**Key Elements**

- **CAPEX**: Investment in pulping equipment, chemical reactors, and fibre spinning machinery
- **OPEX**: Raw materials, energy consumption, and labour costs
- **Market Potential**: Significant growth in the global textile and bioplastic industries
- **Business Applications:** Applications include bioplastics for food packaging and eco-friendly textiles. The flexibility of the process supports scaling and adoption in various industries.
- **Logistics Strategy:** Focus on local collection and processing of pruning residues, optimising supply chains and minimising transport costs - same as described in route 1.

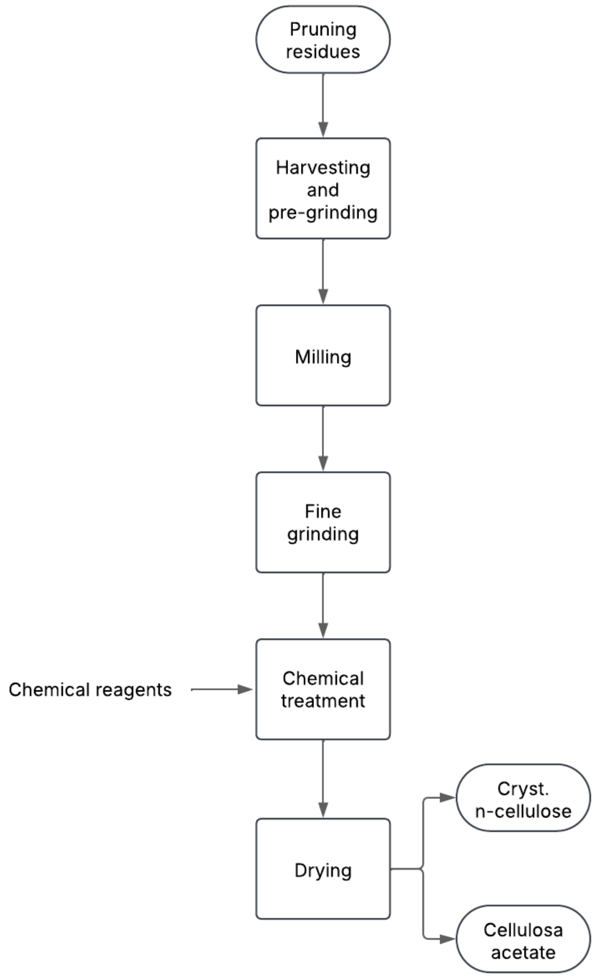



*Figure 52: Andalusian region case, Route 2 process block diagram*

### Route 3: Antioxidants Production from Olive Pomaces

This pathway focuses on the extraction of valuable antioxidants like hydroxytyrosol from olive pomace, a byproduct of olive oil production. Several Andalusian actors, including Naturphenolive and Deretil Nature, are advancing this technology. The extraction of hydroxytyrosol is expected to be highly profitable, with the market for these antioxidants growing rapidly. The total potential of antioxidants from olive pomace in Spain is estimated at around 100,000 tons, including 75,000 tons of hydroxytyrosol. The product has various applications in the pharmaceutical, cosmetic, and nutraceutical industries, with the market for hydroxytyrosol projected to reach $73 billion by 2031.

**Key Elements**

- **CAPEX**: High-cost equipment such as High-Performance Liquid Chromatography (HPLC) systems for antioxidant extraction
- **OPEX**: Raw materials (olive pomace), energy, specialised labour costs
- **Market Potential**: The hydroxytyrosol market is expected to reach $73 billion by 2031
- **Regulation**: The regulatory environment for hydroxytyrosol is complex, requiring careful navigation and investments in compliance and certification processes.
- **Business Applications**: Nutraceuticals (growing demand for natural antioxidants in health products), cosmetics (hydroxytyrosol's anti-aging properties for high-end personal care products), food (antioxidant as a natural preservative and functional ingredient), and pharmaceuticals (hydroxytyrosol's health benefits)

- **Logistics Strategy**: Focus on the distribution of antioxidant products with minimal additional infrastructure

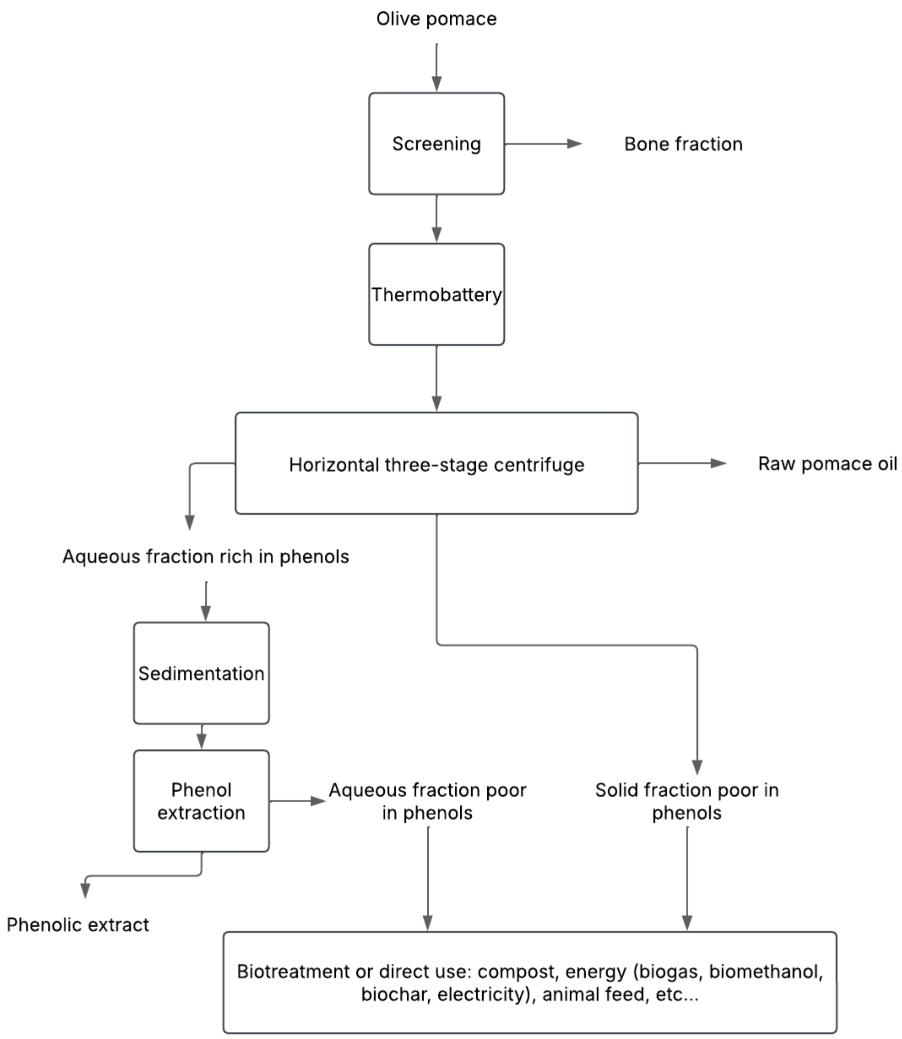



*Figure 53: Andalusian regional case, Route 3 process block diagram*

General Insights for All Routes:

**Sustainability:** These pathways contribute to the valorisation of agricultural residues, promoting circularity by reducing waste and enhancing resource efficiency. Each pathway plays a role in minimising waste and promoting sustainable practices across multiple sectors.

**Economic Impact**: The commercial potential for all three routes is significant. The development of biocomposites, textiles, and antioxidants is expected to create substantial revenue streams while supporting regional job creation and economic growth in Andalusia.

**Regional Benefits**: By integrating these solutions, Andalusia stands to gain new business opportunities, reduce environmental impacts, and foster rural development. The scaling-up of these pathways could enhance regional self-sufficiency and contribute to Spain's broader circular economy objectives.

### 3.6.2 Resource flow analysis

As for the Sankey diagrams (all of them showing figures in tons), the one for the base scenario (current valorisation schemes for the olive value chain) is provided next. This has been elaborated using information provided in regional policy documents [2] such as the Andalusian Strategy for the olive sector (2025).

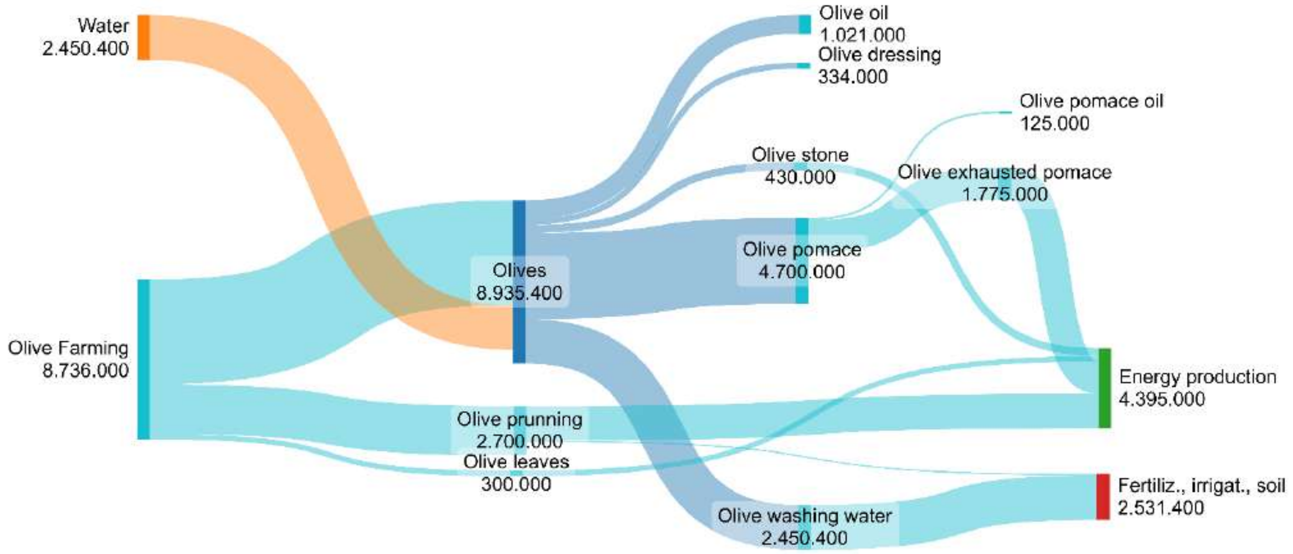



*Figure 54: Andalusian regional case. Sankey diagram for current state (tons)*

Route 1: Reinforcement of Polymeric Materials from Olive Pruning Debris

Figure 53 illustrates the resource flow for this route, showing the mass balance of pruning residues through to biocomposite production. Information used for the mass balance calculation was provided by the Andalusian RTO ANDALTEC, produced through the CompOLIVE project (www.lifecompolive.eu ).

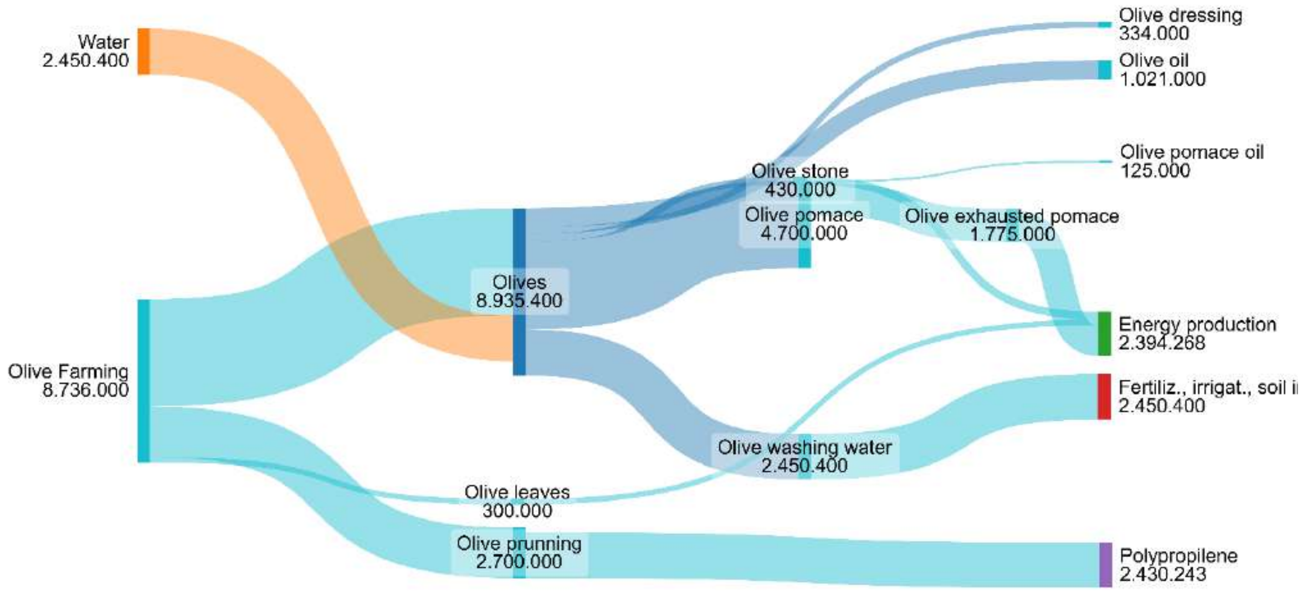



*Figure 55: Andalusian regional case. Sankey diagram for route 1 (tons)*

Route 2: Polymeric Production and Antioxidants from Olive Pruning Debris

The resource flow diagram for this route (Figure 54) illustrates the mass balance of pruning residues and fibre production. Information used for the mass balance calculation comes mainly from peer reviewed publications[86].

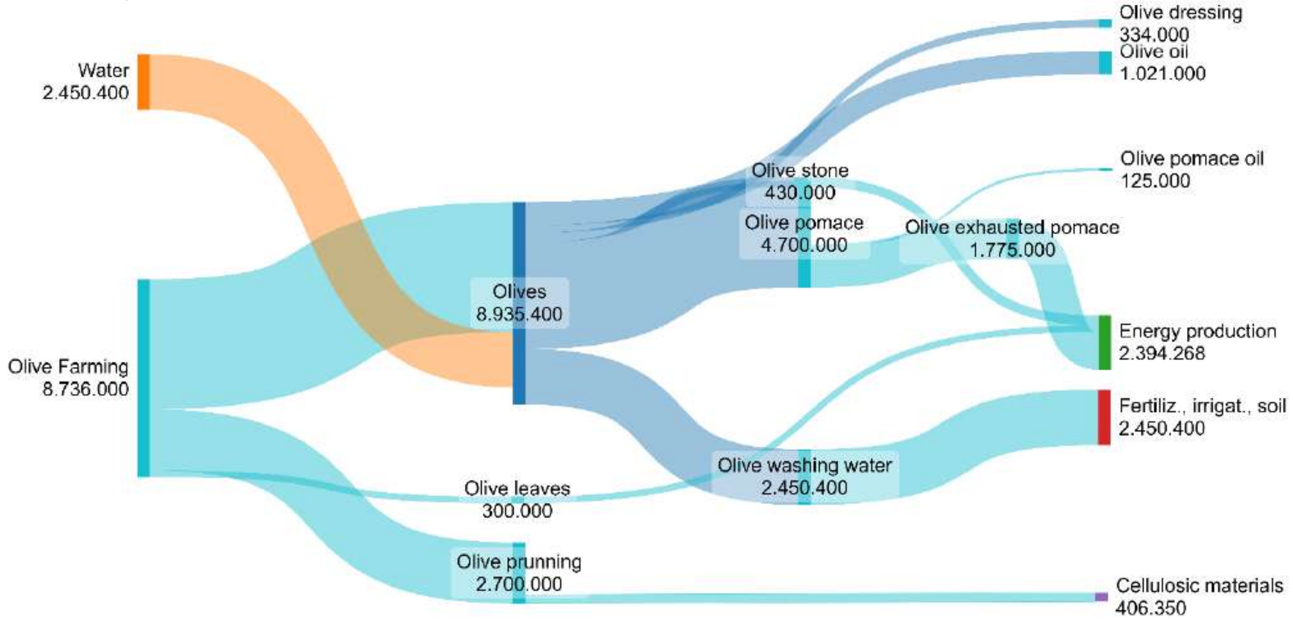



*Figure 56: Andalusian regional case. Sankey diagram for route 2 (tons)*

Route 3: Antioxidants Production from Olive Pomaces

The resource flow diagram for this route (Figure 55) illustrates the mass balance and extraction process for antioxidants from olive pomace. Information used for the mass balance calculation comes mainly from peer reviewed publications[87].

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86 Rodríguez-Liébana, J.A., Robles-Solano, E., Jurado-Contreras, S., Morillas-Gutiérrez, F., Moya, A.J., Mateo, S., Navas-Martos, F.J. and La Rubia, M.D. (2024), Production and characterization of cellulose acetate using olive tree pruning biomass as feedstock. Biofuels, Bioprod. Bioref., 18: 865-882. https://doi.org/10.1002/bbb.2600

Jurado-Contreras, S., Navas-Martos, F. J., García-Ruiz, Á., Rodríguez-Liébana, J. A., & La Rubia, M. D. (2023). Obtaining Cellulose Nanocrystals from Olive Tree Pruning Waste and Evaluation of Their Influence as a Reinforcement on Biocomposites. *Polymers*, *15*(21), 4251. https://doi.org/10.3390/polym15214251

87 Caballero AS, Romero-García JM, Castro E, Cardona CA (2020) Supercritical fluid extraction for enhancing polyphenolic compounds production from olive waste extracts. J Chem Technol Biotechnol 95:356–362

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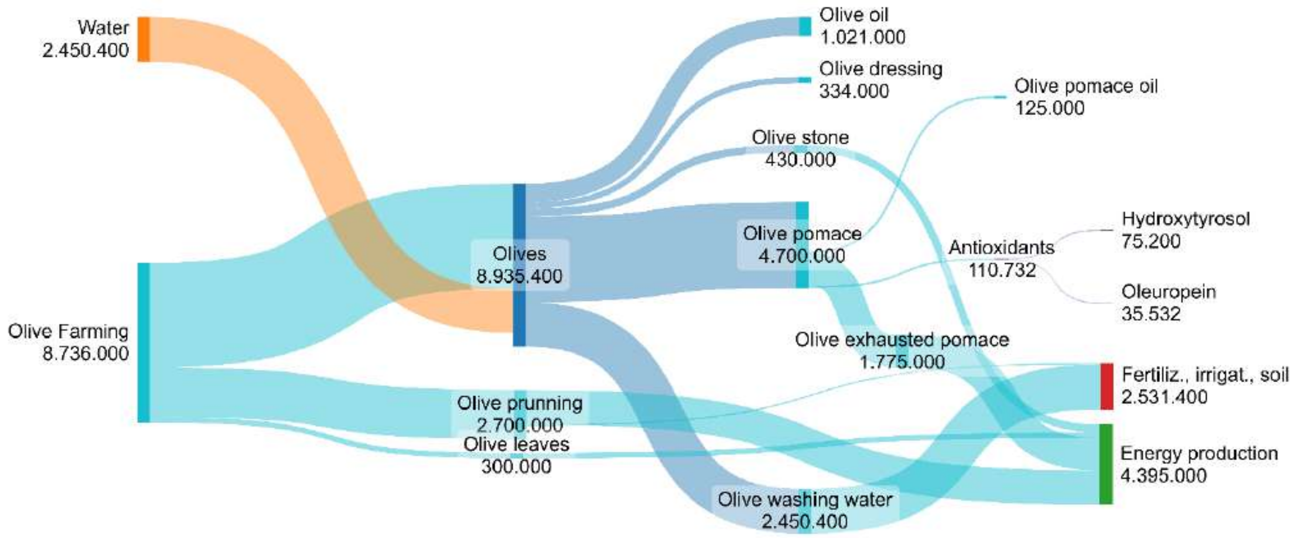



*Figure 57: Andalusian regional case - Sankey diagram for route 3 (tons)*

## 3.6.3 Environmental assessment

*Table 47: Results for the environmental assessment for the Andalusian case*

| | | | | | | Route 1 | | Route 2 | | Route 3 | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Main criteria | Weight | Units | Subcriteria | Weight | Sub -Units | RF | Points | RF | Points | RF | Points |
| Environmental aspects | 38% | 380 | Climate change (GWP-total) | 20% | 76,00 | 0,9 | 68,40 | 0,9 | 68,40 | 0,8 | 60,80 |
| | | | Particualte matter | 15% | 57,00 | 0,9 | 51,30 | 0,9 | 51,30 | 0,7 | 39,90 |
| | | | Land use change | 15% | 57,00 | 0,6 | 34,20 | 0,6 | 34,20 | 0,6 | 34,20 |
| | | | Water use | 20% | 76,00 | 0,5 | 38,00 | 0,4 | 30,40 | 0,6 | 45,60 |
| | | | Resource use fossil (ADP-fossil) | 15% | 57,00 | 0,9 | 51,30 | 0,9 | 51,30 | 0,6 | 34,20 |
| | | | Resource use mineral and metals (ADP-min&met) | 15% | 57,00 | 0,7 | 39,90 | 0,7 | 39,90 | 0,5 | 28,50 |
| | | | Subtotal environmental | 100% | 380,00 | | 283,10 | - | 275,50 | - | 243,20 |

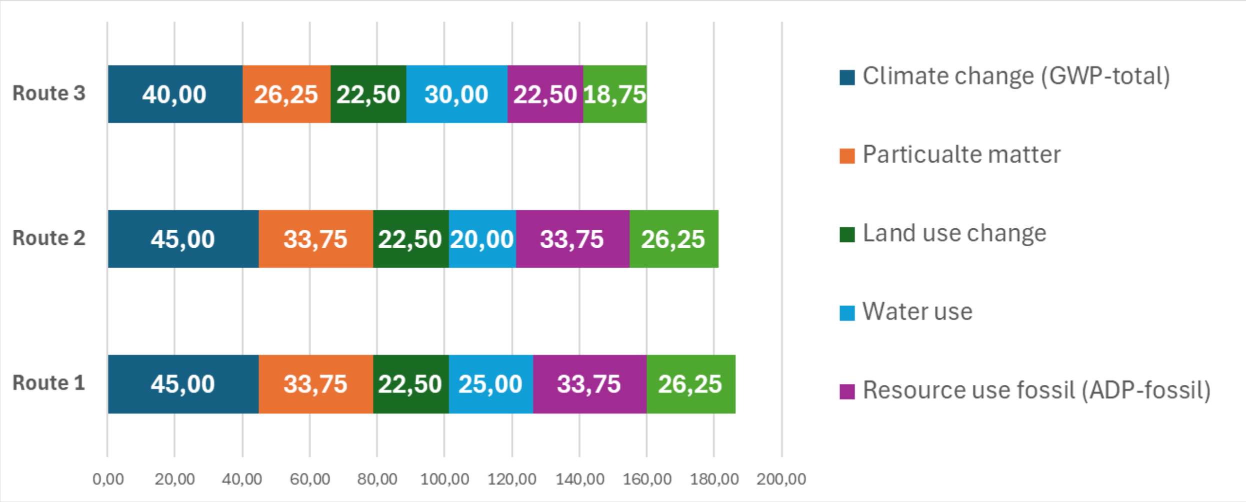



*Figure 58: Andalusian case. Results from the environmental criteria assessment*

## 3.6.5 Economic assessment

*Table 48: Results for the economic assessment for the Andalusian case*

| | | | | | | Route 1 | | Route 2 | | Route 3 | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Main criteria | Weight | Units | Subcriteria | Weight | Sub -Units | RF | Points | RF | Points | RF | Points |
| Economic aspects | 30% | 300 | Job loss / Job creation | 18% | 53,94 | 0,9 | 48,54 | 1 | 53,94 | 1 | 53,94 |
| | | | Wages | 16% | 49,32 | 0,6 | 29,59 | 0,6 | 29,59 | 0,6 | 29,59 |
| | | | Training needs | 14% | 41,61 | 1 | 41,61 | 1 | 41,61 | 1 | 41,61 |
| | | | Value Creation | 14% | 41,61 | 1 | 41,61 | 1 | 41,61 | 1 | 41,61 |
| | | | Added Value | 13% | 38,53 | 1 | 38,53 | 1 | 38,53 | 1 | 38,53 |
| | | | CAPEX | 5% | 15,00 | 0,6 | 9,00 | 0,6 | 9,00 | 0,6 | 9,00 |
| | | | OPEX | 5% | 15,00 | 0,7 | 10,50 | 0,7 | 10,50 | 0,9 | 13,50 |
| | | | Sizing/scaling | 5% | 15,00 | 0,8 | 12,00 | 0,8 | 12,00 | 0,8 | 12,00 |
| | | | Impact on export | 5% | 15,00 | 1 | 15,00 | 0,9 | 13,50 | 1 | 15,00 |
| | | | Impact on import | 5% | 15,00 | 0,7 | 10,50 | 0,7 | 10,50 | 0,8 | 12,00 |
| | | | Subtotal economic | 100% | 300,00 | - | 256,88 | - | 260,77 | - | 266,77 |

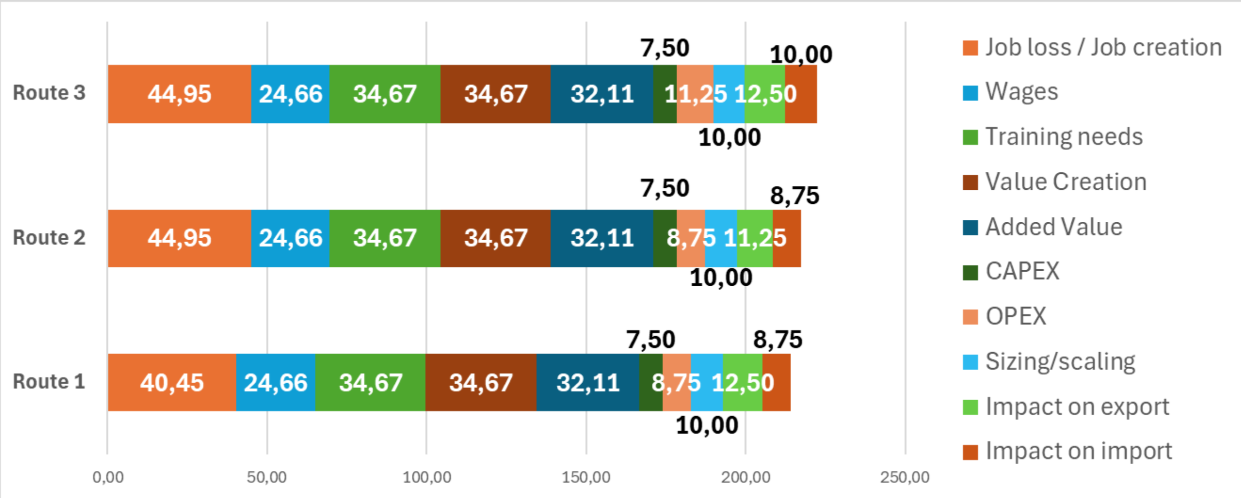



*Figure 59: Andalusian case. Results from the economic criteria assessment*

## 3.6.6 Social assessment

*Table 49: Results for the social assessment for the Andalusian case*

| Main criterio | Weight | Units | Subcriteria | Weight | Sub -Units | Route 1 RF | Route 1 Points | Route 2 RF | Route 2 Points | Route 3 RF | Route 3 Points |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Social aspects | 32% | 320 | Employment | 19% | 60,78 | 0,9 | 54,70 | 0,9 | 54,70 | 0,9 | 54,70 |
| | | | Income | 17% | 55,57 | 0,9 | 50,01 | 0,8 | 44,45 | 0,9 | 50,01 |
| | | | Work-Life Balance | 17% | 55,57 | 0,6 | 33,34 | 0,6 | 33,34 | 0,5 | 27,78 |
| | | | Housing | 16% | 52,09 | 0,7 | 36,47 | 0,8 | 41,67 | 0,7 | 36,47 |
| | | | Health | 5% | 16,00 | 0,6 | 9,60 | 0,6 | 9,60 | 0,7 | 11,20 |
| | | | Education | 5% | 16,00 | 1 | 16,00 | 1 | 16,00 | 1 | 16,00 |
| | | | Governance | 5% | 16,00 | 0,9 | 14,40 | 0,9 | 14,40 | 0,9 | 14,40 |
| | | | Environment | 5% | 16,00 | 0,8 | 12,80 | 0,8 | 12,80 | 0,8 | 12,80 |
| | | | Security | 5% | 16,00 | 0,5 | 8,00 | 0,6 | 9,60 | 0,6 | 9,60 |
| | | | Life satisfaction | 5% | 16,00 | 0,5 | 8,00 | 0,5 | 8,00 | 0,5 | 8,00 |
| | | | Subtotal social impact | 100% | 320,00 | - | 243,31 | - | 244,56 | - | 240,96 |

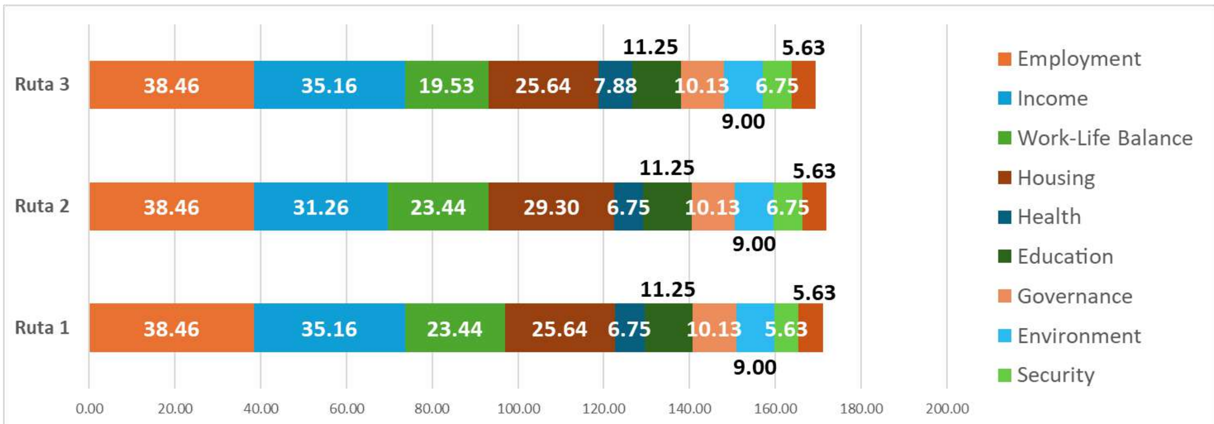



*Figure 60: Andalusian case. Results from the social criteria assessment*

### *3.6.7 Sustainability assessment*

For the selection of the optimal pathway the methodology that has been designed in the frame of the project has been implemented, following from the point already reported in D3.1. Specifically, after producing all the previous information, this was shared with the Andalusian stakeholders in order to jointly select the optimal pathway. The selection was done using a MultiCriteria Decision Analysis (MCDA) tool where individual assessment from each expert was considered. The picture below provides more information on this last step.

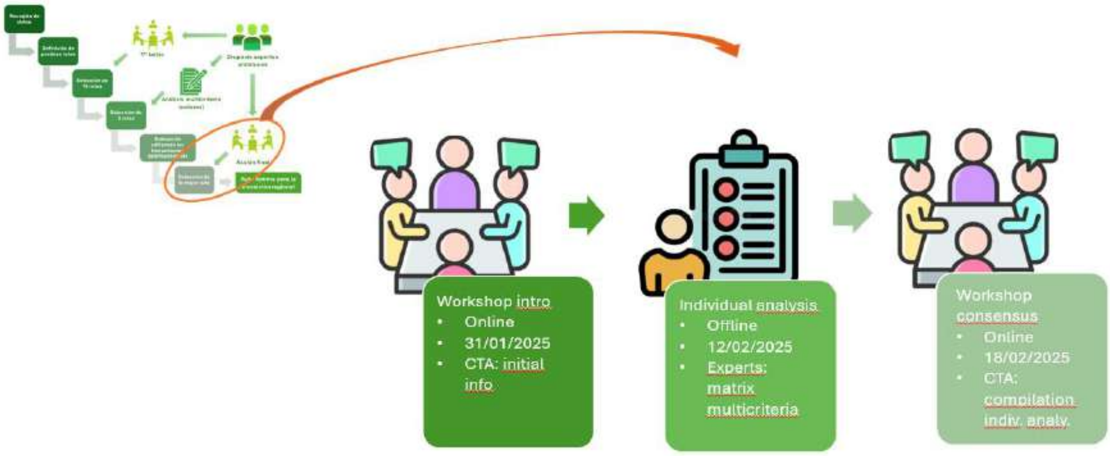
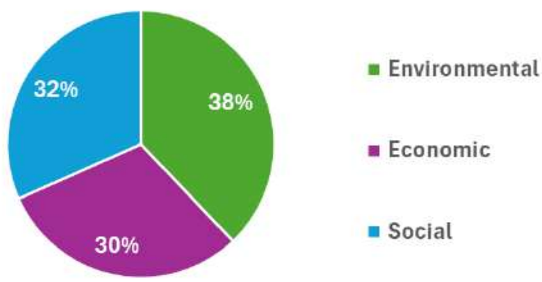



*Figure 61: Andalusian case. Methodology used for the optimal pathway selection*

About the MCDA and how it was designed, this was developed following previous research from Macias Aragonés et al.[88]. Main criteria (or categories as in the Battelle Method (BM) were defined as economic, environmental and social, and weights for these were asked to the Andalusian stakeholders. As for the subcriteria (or components), the weights were allocated according to a survey that was launched to Andalusian stakeholders in the frame of WP2. This survey asked the stakeholders to assess the level of relevance for them for different economic and social indicators. The following picture and tables summarise the results of the different weights allocated to criteria (as a mean value of the weights allocated individually by the actors) and subcriteria. Following the BM approach, 1000 units were divided among these subcriteria.




| Environmental Subcriteria | Weight |
|---|---|
| Climate change (GWP-total) | 20% |
| Particulate matter | 15% |
| Land use change | 15% |
| Water use | 20% |
| Resource use fossil (ADP-fossil) | 15% |
| Resource use mineral and metals (ADP-min&met) | 15% |

| Economic Subcriteria | Weight |
|---|---|
| Job loss / Job creation | 18% |

| Social Subcriteria | Weight |
|---|---|
| Employment | 19% |

[88] Marta Macias Aragonés and others, 'Valorizing Biodiesel and Bioethanol Side-Streams: Sustainability Potential Assessment through a Multicriteria Decision Analysis Framework and Appraisal of Valuable Compound Recovery Prospects', *Energies*, 16.1 (2023), p. 176, doi:10.3390/en16010176.

| | |
|---|---|
| **Wages** | 16% |
| **Training needs** | 14% |
| **Value Creation** | 14% |
| **Added Value** | 13% |
| **CAPEX** | 5% |
| **OPEX** | 5% |
| **Sizing/scaling** | 5% |
| **Impact on export** | 5% |
| **Impact on import** | 5% |

| | |
|---|---|
| Income | 17% |
| Work-Life Balance | 17% |
| Housing | 16% |
| Health | 5% |
| Education | 5% |
| Governance | 5% |
| Environment | 5% |
| Security | 5% |
| Life satisfaction | 5% |

*Figure 62: Andalusian case. Weights for main criteria and subcriteria*

As for the individual reports, stakeholders were asked to fill individual assessment where they were asked to assess for each subcriteria if the proposed routes cause a positive, neutral or negative impact when compared to the fossil and linear solution. These answers were then transformed into the Unit values (which rank from 0-1) according to this rationale: positive impact~1, neutral impact~0,5 and negative imapct~0. For each subcriteria, the mean value of all the individual assessment from the stakeholders was calculated, and then the Sustainability points were calculated following BM approach. This way, the total Sustainability index can be obtained for each route. Results per each main criterion are provided next.

Figure 61 presents the three main criteria results compiled.

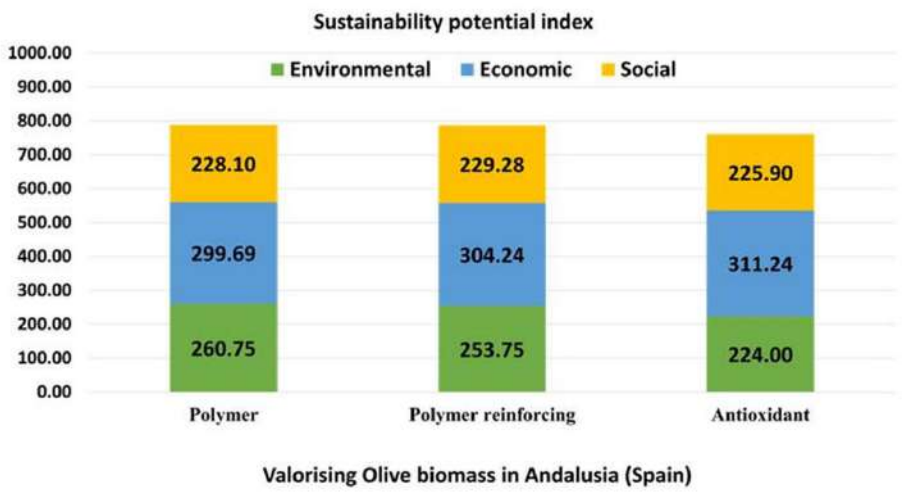



*Figure 63: Sustainability assessment score from Andalusian case*

This way it can be concluded that the optimal pathway for the Andalusian region is route 1 (obtention of biocomposites from olive pruning and debris).

Reflection on sustainability assessment methodology

It is important to note that during the meetings with the stakeholders, new routes were identified and it was discussed another potential route that could be a merger of the three routes following a cascading approach for olive pomace valorisation through a thermos hydrolysis that would deliver 3 phases: oil phase for pomace olive oil production, liquid phase for antioxidants further extraction and purification and solid phase that could be processed following route 1 approach for biocomposite production.

This allows concluding that while the proposed methodology is useful for assessing and identifying new transition pathways it is difficult somehow to grasp all the non-written knowledge among that is available among the stakeholders. Also, even though the network of one BIOTRASFORM project partner is quite big in the region, it is difficult to get onboard all the relevant stakeholders at all times, which can cause that knowledge is not properly captured since the very beginning if a relevant stakeholder does not attend the sessions.

### 3.6.8 Circularity assessment

The circularity assessment for Andalusia investigates pathways focused on the high-value valorisation of abundant residues from its leading olive sector, including olive pruning debris and pomace. The strategic aim is to transform these agricultural side-streams, currently often used for low-value applications, into advanced bio-based products such as biocomposites, polymers, and antioxidants, thereby enhancing resource efficiency and fostering a circular bioeconomy within this key regional industry.

*Table 50: Circularity assessment for the pathway in Andalusia*

| Product | Resource Output rate | Resource consumption rate | Integrated Resource Utilization rate | Waste disposal and pollutant emissions |
|---|---|---|---|---|
| **Reinforcement of polymeric materials** | Not applicable as raw materials and energy are not outputs of the process | Energy consumption might be lower while water might be higher | Only sub criteria applicable is recycling rate of plastics | Lower waste generation |
| **Polymer production** | Not applicable as raw materials and energy are not outputs of the process | Energy Consumption might be lower while water might be higher | Only sub criteria applicable is recycling rate of plastics | Lower waste generation |
| **Antioxidant recovery** | Not applicable as raw materials and energy are not outputs of the process | Energy and water consumption might be lower | Not applicable as all subcriteria refer to non-biomass resources | Lower waste generation |

### 3.6.9 Supply chain optimization and logistic network design

***Reader's note:*** *This section provides a comprehensive overview of the supply chain optimisation and logistics network design results. For full details, see Appendix 2 – Section 2: Olive tree pruning in Andalusia.*

This case investigates the logistic feasibility of valorising olive tree pruning (OTP) from Andalusia's extensive olive groves as a feedstock for bioplastic production.

The region, with over 1.16 million hectares of olive cultivation, generates large volumes of woody biomass that are often underutilised or burned. However, the seasonal nature of pruning, fragmented field distribution, high moisture content of fresh OTP, and lack of suitable infrastructure pose **significant logistical challenges** in valorising them. Efficient collection, storage, and transport in combination with optimal siting strategies are essential to enable the year-round operation of biorefineries and to unlock the economic potential of this biomass stream.

The **logistics chain** unfolds as follows: it begins with the in-field pruning of olive trees, with the pruning chipped into woodchips at the edge of the field. Due to the chipper's limited container capacity, the material is unloaded into a larger transport truck, which then either delivers the chips to a storage facility or transports them directly to the biorefinery (Figure 62).

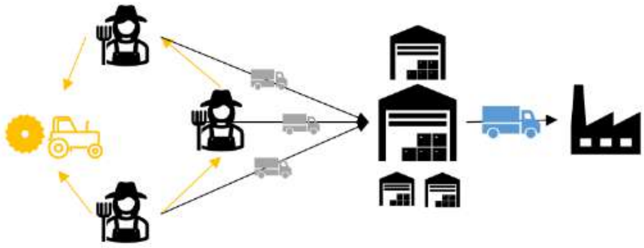


*Figure 64: Network flow diagram.*

To address the supply chain challenges, MOOV investigated a range of OTP collection, storage and transportation scenarios in the Andalusian region.
The scenarios differ in terms of the number, size, and location of storage facilities and biorefineries, as well as the impact of decentralised storage and processing.

- **Scenario 1:** One biorefinery (32 kton capacity) – using existing off-site storage
- **Scenario 2:** One biorefinery (kton capacity) – no off-site storage
  - **Sensitivity 2A:** Impact of multiple biorefineries
  - **Sensitivity 2B:** Impact of multiple off-site storage
- **Scenario 3:** One biorefinery (700 kton capacity) – no off-site storage
  - **Sensitivity 3A:** Impact of multiple biorefineries
  - **Sensitivity 3B:** Impact off-site storage

The analysis results demonstrate the impact of introducing alternative logistics scenarios on the performance indicators: **mobilisation cost** (Figure 63) and **transport distance** (Figure 64).
Mobilisation cost is defined as the sum of the costs for chipping, chipper transport, storage, and all transport between the field, storage facilities, and biorefinery.

<u>**Scenario results**</u>

In **Scenario 1**, the supply chain relies solely on the **existing storage infrastructure** within the region, offering a capacity of 15 kton distributed across approximately 20 locations. This enables a feedstock throughput to the biorefinery of 32 kton/year. Optimal utilisation of storage capacity and optimal selection of the biorefinery location result in a mobilisation cost at the biorefinery gate of 122 €/ton of dry woodchips, with an average transport distance of 18 km/ton.
However, a techno-economic study on woody biorefineries has demonstrated the positive impact of scale on economic feasibility, with a 150 kton/year capacity performing best. Consequently, **Scenario 2** investigates the scaling up to a **150 kton biorefinery** with on-site storage. The biorefinery location is optimally selected in view of minimising the mobilisation cost. This results in an increased mobilisation cost of 143 €/ton, with an average transport distance of 21 km/ton. As fresh woodchips, containing approximately 50% moisture, are transported directly to the refinery in this scenario, transport costs represent a significant fraction of the total mobilisation cost.

- A sensitivity analysis of this scenario shows that the region can supply sufficient OTP feedstock to support **multiple 150 kton/year biorefineries**, with a maximum of four - **Sensitivity 2A**. Mobilisation costs increase by 2%, to 145 €/ton, when two biorefineries are established, and by 13%, to 162 €/ton, when four are operating. In the latter case transport distance rises to 28 km/ton. This can be logically explained by the fact that, as more biorefineries require servicing, feedstock must also be sourced from less optimally located fields, resulting in slightly increased transport distances.
- **Sensitivity 2B** explores the installation of one biorefinery while using **multiple off-site storage facilities** distributed across the region, instead of a centralised storage facility at the biorefinery. Important to note that during storing the fresh woodchips are air dried, resulting in a significant weight loss which positively affects transportation costs.

Storage facilities are also assumed A range of six storage capacities was investigated, from XXL-to-XXS. Results show that opting for extra-small (XS) off-site storage facilities are used, mobilisation costs are reduced by 13%, to 124 €/ton (compared to Scenario 2).
The cost reduction is primarily due to a 25% decrease in field-to-storage transport costs, as the storage facilities are now optimally located near the olive fields, reducing the average transport distance to 16 km/ton.
Additionally, results show that opting for smaller (XXS) or larger (XXL) scale facilities is suboptimal compared to XS-facilities. This is because the benefits of decentralisation are determined by balancing field-to-storage and storage-to-refinery transport costs, as well as by balancing the number of required storage facilities against their associated investment costs.
**Scenario 3** explores a more hypothetical situation in which **all available OTP** in the region is processed at a **single biorefinery with on-site storage**. This raises mobilisation costs to 219 €/ton, driven by high field-to-storage/refinery transport distances, reaching up to 54 km/ton.

- **Sensitivity 3A** explores the **decentralisation of the biorefineries** by introducing 10 smaller biorefineries with on-site storage. This reduces by -33% the overall mobilisation cost to 147 €/ton, and the transport distance to 21 km/ton (compared to Scenario 3). This positive impact is explained as refineries are now located closer to the fields. Note however that investment costs for a biorefinery are not included in this analysis and should be considered when interpreting overall economic feasibility.
- **Sensitivity 3B** investigates the decentralisation of storage facilities using medium-sized (M) storage units. Results show that the benefits are correlated with the degree of decentralisation of the biorefineries: the advantage of decentralised off-site storage diminishes as the decentralisation of the biorefineries increases.

For example, deploying off-site storage with a single central refinery reduces mobilisation costs by 23%, down to 172 €/ton vs. 219 €/ton - Sensitivity 3B(1) vs. Scenario 3. In contrast, when ten biorefineries are deployed, mobilisation costs slightly increase to 151 €/ton vs. 147 €/ton, when adopting off-site storage facilities - Sensitivity 3B(2) vs. Sensitivity 3A.
This suggests that when a higher number of biorefineries is already present, the system is sufficiently decentralised, and the additional benefits of off-site storage are reduced, while higher investment costs for these additional storage facilities are still incurred.

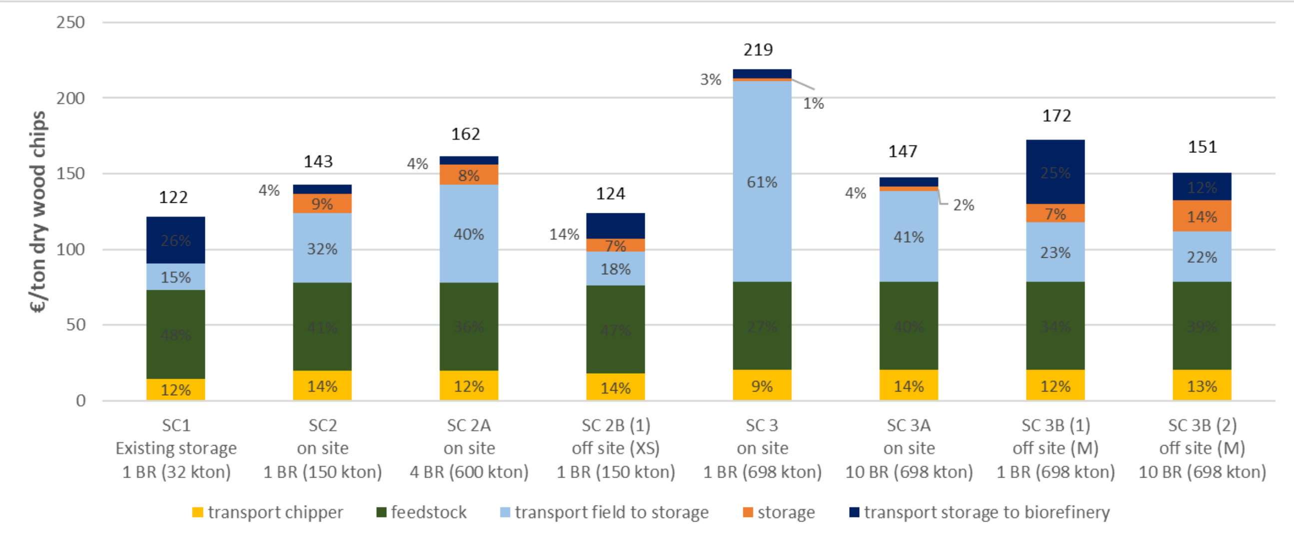



*Figure 65: Olive tree pruning in Andalusia - Mobilisation cost [€/ton dry OTP]*

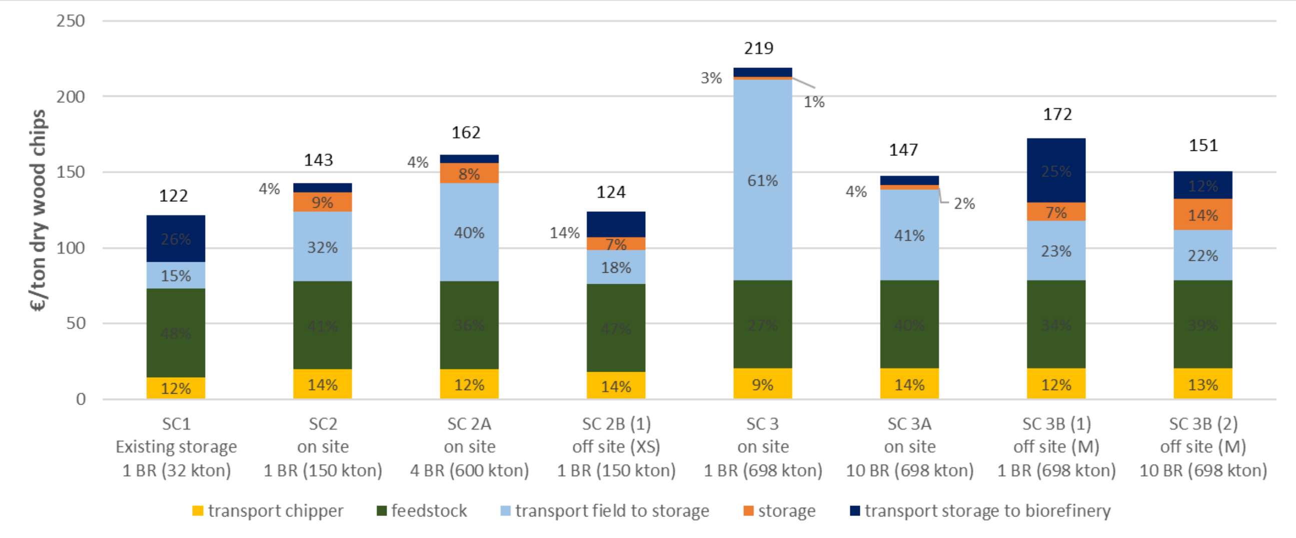



*Figure 66: Olive tree pruning in Andalusia - Transport distance [km/ton dry OTP]*

## In conclusion

- Decentralised systems are consistently more cost-effective.
    - Scenarios involving multiple localised facilities - whether in the form of off-site storage near production zones or distributed biorefineries - outperform centralised configurations by significantly reducing transport distances and leveraging regional OTP availability. The XS off-site storage scenario (124 €/ton) and 10 biorefinery setup (147 €/ton) proved to be the most economically viable strategies, demonstrating that a decentralised network better matches the spatial reality of the OTP supply base. The benefits of decentralisation are determined by balancing field-to-storage and storage-to-refinery transport costs, as well as balancing the number of required storage facilities and related investment, which is influenced by economies of scale.

- Transport of fresh chips from the field to storage facilities or biorefinery is the dominant cost driver.
    - Fresh woodchips possess a high moisture content and low bulk density, leading to higher transport weights and increased transport costs. When direct transport to the biorefinery is used — without drying at storage facilities — transport accounts for between 30% (Scenario 2) and 60% (Scenario 3) of the total mobilisation cost. This underscores the importance of minimising the fresh transport leg to control costs, whether by drying near the source, decentralising storage capacity, or decentralising processing capacity.

- Optimal design balances minimal field-to-storage transport with efficient storage sizing.
    - While maintaining a single biorefinery, increasing the number of storage facilities reduces the transport distance for fresh chips but raises the required investment. For example, the XXS scenario achieved low transport distances but would require 48 facilities, resulting in a mobilisation cost of 134 €/ton. In contrast, the XS configuration required only 10 facilities and achieved a better balance between logistics efficiency and infrastructure investment, with a lower mobilisation cost of 124 €/ton.

- XS off-site storage with a 150 kton biorefinery is the best performing logistic configuration.
    - Among all the reviewed scenarios, the XS off-site storage configuration combined with a 150 kton biorefinery proved to be the best-performing logistics setup. The XS scenario achieved the lowest mobilisation cost across all options, at 124 €/ton.

- It effectively matched storage capacity to the spatial distribution of olive groves, reduced field-to-storage transport distances, and enabled air drying at the storage facility before transporting the lighter, drier chips to the biorefinery. Its modular and scalable design makes it particularly well-suited for incremental rollout and for adapting to future demand growth or processing capacity expansion.

- Investment costs for a biorefinery were not included in this analysis and should be considered when interpreting overall economic feasibility.

# 4 Discussion

This assessment framework proposed was designed to provide rapid, evidence-informed insights that support early-stage decision-making in regional circular bioeconomy transitions. One of its primary strengths lies in its ability to address the challenge of limited data availability in the pilot regions by using a structured qualitative approach. However, it has components that can be implemented to obtain quantitative results when data is available, achieving a pragmatic balance between scientific rigour and feasibility. The assessments can evolve as additional data becomes available, enabling adaptive and iterative decision-making. Through participatory weighting of sustainability criteria and pathway scoring, stakeholders and experts contributed contextual knowledge and compensatory mechanisms for data limitations, enriching the relevance of the assessment. For example, the consistent stakeholder preference for material valorisation pathways over biomass-to-energy options reflects both environmental considerations (e.g., CHG emissions, value retention) and economic resilience objectives. Moreover, regional variability in preferences, such as the prioritisation of underutilised biomass in resource-rich areas versus a focus on high-TRL solutions in economically distressed regions, highlights the value of integrating local perspectives into the sustainability framework.
The Finnish lignin valorisation case exemplifies how linking top-down process-based (PB) analysis with bottom-up multicriteria analysis enhances sustainability through coherent, localised strategies, thereby mitigating the risk of unintended environmental and socio-economic consequences. The use of LCA indicators and integration of planetary boundaries (PB) ensures that regional decisions are evaluated within broader environmental thresholds. Despite these strengths, limitations exist that would remain undetected in purely qualitative evaluations compared to the LCA. Additionally, dedicated stakeholder engagement requires funding. In our case, we opted for a low-burden participatory model, which, while efficient, limited the breadth and representativeness of stakeholder input as in the weighting of sustainability indicators. For instance, we saw potential biases comparing the local weighting with the global weighting used to convert the LCA impacts into a single score. For example, in Finland, a 30% weighting is assigned to the "land use change," compared to the 8% proposed by the JRC, which involved a more diverse set of stakeholders, in contrast to our stakeholder pool, where forestry-sector actors dominate. Such skewed representation can compromise the comparison of the pathway across regions. Sector-specific stakeholder engagement provided grounded, actionable insights, it also risked reinforcing existing institutional or industrial biases, which could hinder the long-term goal of fostering a just and inclusive bioeconomy transition; also, relying on voluntary stakeholder participation without a robust mechanism to ensure diversity or balance may lead to uneven influence over sustainability criteria and trade-off assessments. To address these limitations, future iterations of the framework should prioritise strategies to broaden stakeholder engagement. Even under resource constraints, innovative tools such as online deliberation platforms, structured stakeholder surveys, or partnerships with regional development agencies could help diversify participation without imposing excessive burdens, ensuring they capture a range of values and long-term development priorities. Moreover, by making the value of stakeholder contributions and the impact of empirical data on improving assessment precision transparent, the framework can incentivise more systematic data sharing from both private and public actors. This creates a pathway toward more quantitative, standardised, assessments over time while maintaining the flexibility necessary for decision-making under uncertainty.

# 5 Conclusions

The bioeconomy transition in the six pilot regions, assessed through a combination of Sankey resource flow analysis, sustainability and circularity assessment, and logistics optimization, reveals both opportunities and challenges in aligning bio-based innovation with regional environmental objectives. Our findings underscore that while many biobased products offer significant environmental benefits – particularly in terms of carbon sequestration, reduced fossil carbon emissions, and closed-loop resource use these outcomes are not automatic. They depend critically on the specific implementation strategies and the local ecological and socio-economic context.

In several cases, the substitution of fossil-derived materials with biobased alternatives (e.g., biochar, lignin-derived resins, reed-based insulation) demonstrated clear carbon sequestration potential, particularly when materials are locked in long-life applications or returned to soil. Moreover, the cascading use of biomass and valorization of secondary resources—such as vine pruning, reed biomass, and sediments—highlight the role of bioeconomy in operationalizing circular economy principles and mitigating local environmental pressures, such as landfill dependency and nutrient loss. However, the transition is not without risks. Rising biomass demand can drive deforestation, encourage monoculture cropping, or divert agricultural residues away from their role in soil health maintenance, potentially exacerbating local issues like biodiversity loss and soil degradation. Furthermore, some biobased pathways, especially those involving energy-intensive processing or short-lived products, risk eroding their environmental advantage if powered by fossil energy or poorly integrated into local waste management systems.

To address these risks, regionally tailored subsystem-level environmental assessments are essential. These assessments enable the identification of environmental hotspots, guide resource prioritization, and support adaptive decision-making in alignment with ecosystem boundaries and circularity goals. For example, in regions where bioeconomy transitions increase energy use, concurrent shifts to low-carbon energy sources can be a key mitigation measure. Similarly, selecting end-uses that extend product lifespans or favor reuse, and recycling scenarios can improve carbon retention and reduce environmental burdens. Table 51 shows the carbon sequestration and end of life scenarios for pathways proposed in the pilot regions.

Ultimately, our analysis confirms that a structured, system-oriented assessment methodology is critical for guiding sustainable bioeconomy transitions. By integrating life-cycle data, regional biophysical limits, and feedback from stakeholders, the applied methodology supports transparent, evidence-based policy development. As pilot regions move toward implementation, iterative updates to the assessment—incorporating real-time data and improving circularity indicators—will be vital to ensure that bioeconomy pathways contribute meaningfully to climate goals, environmental protection, and socio-economic resilience.

*Table 51: Carbon sequestration potential of the proposed transition pathway along with the End-of-Life scenarios*

| Product | Fossil Product Replaced | Carbon Content | Life Span | End of Life Scenario |
|---|---|---|---|---|
| Polymers for car pieces (lights) manufacturing | Petro-based plastics | N/A | Not specified | Plastics recycling |
| Antioxidants (from other biomass sources or chemically produced) | Antioxidants from fossil sources | N/A | 6-12 months | Used for animal or human consumption |
| Partial replacement of petro by LPG | Petro-derived fuels | 0.537 kg CO2/l | 10-30 years max storage | $CO_2$ emissions during use |
| Fertilizer replacement | Chemical (fossil-based) fertilizers | 30:1 (likely ratio N/A if C | Storage half a year | Closing loop by entering back into |

| | | | | |
|---|---|---|---|---|
| | | content assumed) | | agricultural production |
| Lignin-based carbon for car battery | Fossil graphite | 99% carbon | 20 years (car battery) | More than 80% recycled |
| Lignin derivative replacing phenol in phenolic resin | Phenol from fossil sources | 55-56% carbon | 10-15 years (furniture use) | Incineration |
| Bio-based admixtures replacing polycarboxylate/naphtalene in concrete | Polycarboxylate or naphtalene-based admixtures | ~50% | 50 years (cement structures) | Part of concrete (locked in matrix) |
| Bio-based lactic acid (incl. first gen bio-based replacing fossil-based) | Fossil-based lactic acid | ~50% | Up to several years (depending on PLA application) | Mechanical/chemical recycling to PLA; composting also possible |
| Bio-based hydraulic oils | Fossil-based hydraulic oils | Depends on formulation | <1 year (highly application dependent) | Biodegradable if fully bio-based, otherwise depends on additives |
| Bio-based combustion products (unspecified) | Fossil-based energy products | Not specified | Yearly production | Ash that can be used as fertilizer or concrete |
| Bio-based products replacing durable materials (unspecified) | Fossil-derived long-life materials | ~50% | Decades (depending on product/application) | Reuse, recycling, repair, refurbish, remanufacture, repurpose, landfill |
| Reed roof thatching | Conventional roofing materials (e.g., bitumen shingles, tiles) | High biogenic carbon (stored from atmosphere) | 20-60 years (depending on quality & maintenance) | Compostable/Biodegradable (if untreated) |
| Reed insulation panels | Fossil-based insulation (e.g., EPS, XPS, mineral wool) | High biogenic carbon | 50+ years (building lifetime) | Compostable (if natural binders), Landfill, potentially energy recovery |
| Mycelium-based materials (from reed) | Polystyrene packaging, some synthetic building components | High biogenic carbon (fungal biomass + reed substrate) | Variable (short for packaging, medium-long for building elements) | Biodegradable, Compostable |
| Sediment bricks/blocks | Conventional clay/concrete bricks | Low embodied energy vs some conventional bricks | 100+ years (building lifetime) | Crushed for aggregate/road base, recyclable into new bricks (potential) |
| Sediment plaster/filler (construction) | Cement/gypsum-based plasters, synthetic fillers | Variable (depends on organic content) | 50+ years (building lifetime) | Inert, soil amendment |

| | | | | |
|---|---|---|---|---|
| Sediment-based soil improver/fertiliser | Synthetic/mineral fertilisers, Peat-based soil conditioners | Variable (organic carbon content contributes to soil health) | Short (consumed seasonally by plants/soil) | Integrated into soil ecosystem, closing nutrient loops |
| Biochar (from vine prunings) | Peat, some synthetic soil conditioners, N/A (for C sink) | Very high stable carbon (~70-90% C) | Centuries to millennia (in soil) | Remains in soil, improving fertility and sequestering carbon |
| Compost/mulch (from prunings/pomace) | Synthetic fertilisers, Peat-based mulch/compost | High biogenic carbon (organic matter) | Short (decomposes over 1-2 years, enriching soil) | Integrated into soil ecosystem |
| Grape seed oil/flour (from pomace) | Other edible oils (some less sustainable), refined flours | Biogenic carbon (food product) | 1-2 years (shelf life) | Human/animal consumption, conversion to energy/fuel if not consumed |
| Pruning-based artisanal construction/fascines | Plastic/metal/concrete erosion control, some landscaping materials | High biogenic carbon | Medium (few years to decades depending on application) | Biodegradable, on-site decomposition |
| Bio-based fuels for garbage trucks | Fossil fuels (diesel/gasoline) used in garbage trucks | Assuming 10 diesel garbage trucks are replaced by 10 H2 garbage trucks: Life-cycle emissions ~142 t CO2-equ. /y - 7.3 t CO2-equ./y = ~34.7 tCO2 equ. /y (or~95%*) | Daily production | Use as vehicle fuel |

** The values for GHG emissions were calculated by utilizing the number of garbage trucks, average diesel consumption per km, the average yearly mileage, and so calculating the yearly diesel demand. Then, these were converted to tons of CO2eq/year, considering the relative diesel and hydrogen life cycle GHG emission factors.*

In contexts where comprehensive, real-time data are not yet available—as is typical during early-stage or pilot-phase bioeconomy transitions—a structured and quantitative circularity assessment framework offers a scientifically sound means to evaluate systemic performance and inform decision-making. The use of macro-level indicators, combined with qualitative visualization tools, facilitates a transparent and policy-relevant evaluation of the circularity potential of the bioeconomy. This approach also enables iterative refinement as more empirical data become available and the pathway matures from concept to implementation.

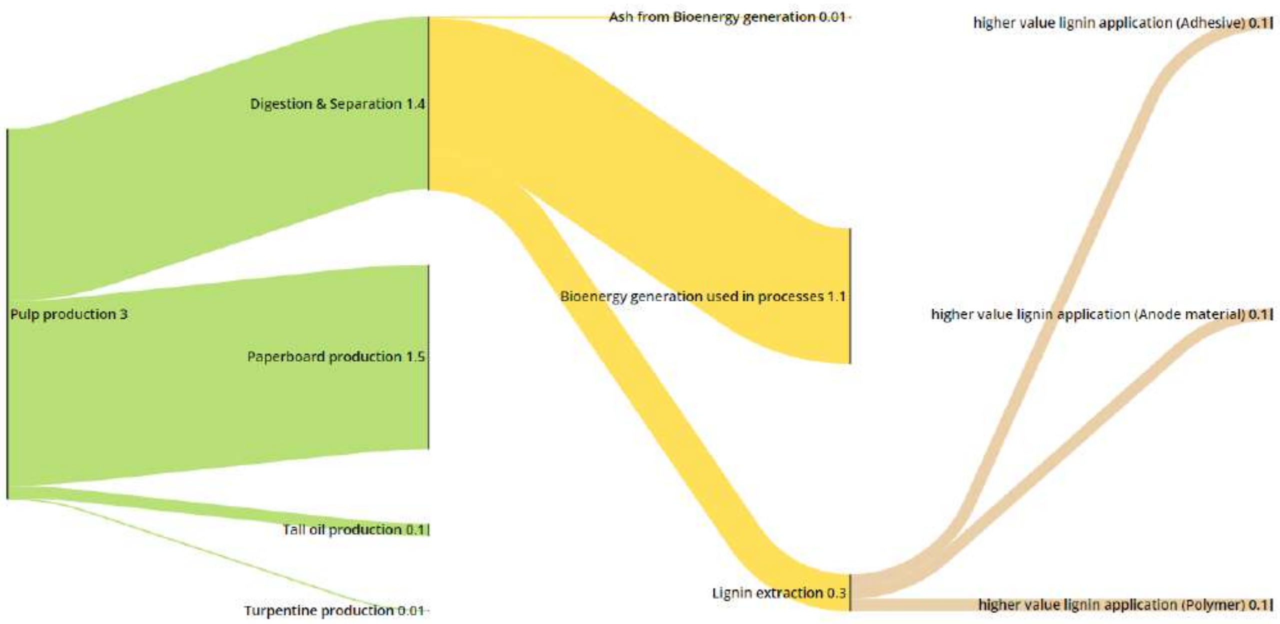
# Appendix 1

How to create a simple sankey with SankeyDiagram Tool: Generate Sankey Diagrams with ease

1. open SankeyDiagram Tool: Generate Sankey Diagrams with ease
2. paste following to box in the webpage (input-tab left)

Pulp production [1.39] Digestion & Separation
Pulp production [0.01] Turpentine production
Pulp production [0.09] Tall oil production
Pulp production [1.5] Paperboard production
Digestion & Separation [1.1] Bioenergy generation used in processes
Digestion & Separation [0.01] Ash from Bioenergy generation
Digestion & Separation [0.3] Lignin extraction
Lignin extraction [0.1] higher value lignin application (Anode material)
Lignin extraction [0.1] higher value lignin application (Adhesive)
Lignin extraction [0.1] higher value lignin application (Plasticiser)

3. take screenshot and save it for later use.




4. modify text to original and paste:

Pulp production [1.39] Digestion & Separation

Pulp production [0.01] Turpentine production

Pulp production [0.09] Tall oil production

Pulp production [1.5] Paperboard production

Digestion & Separation [1.1] Bioenergy generation used in processes

Digestion & Separation [0.01] Ash from Bioenergy generation

Digestion & Separation [0.3] Electricity production

5. take screenshot and save it for later use.


Give credits: Sankey Diagram Generator provided by JonasDoesThings and Open Source contributions.

# Appendix 2

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i https://MooV.vito.be

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# Appendix 2

# 1. Food waste in the Karlovy Vary (Czech Republic)

## 1.1 Framing the challenge

The Karlovy Vary region in the Czech Republic is renowned for its “Spa town triangle”, consisting of Karlovy Vary, Františkovy Lázně and Mariánské Lázně, which together account for over half of the country’s spa industry. The region’s key economic sectors include tourism, glass and ceramics production, mechanical engineering, and food production. The cities Karlovy Vary and Mariánské Lázně – located ca. 60 km apart (Figure 1) – attract a high number of tourists, particularly during peak season. Therefore, these two cities are the cities under consideration in this case-study. The possibility of including one or more German towns near the Czech-German border in Bavaria was considered. However, due to challenges in obtaining the necessary data and legal complexities, it was decided to focus exclusively on the Czech towns.

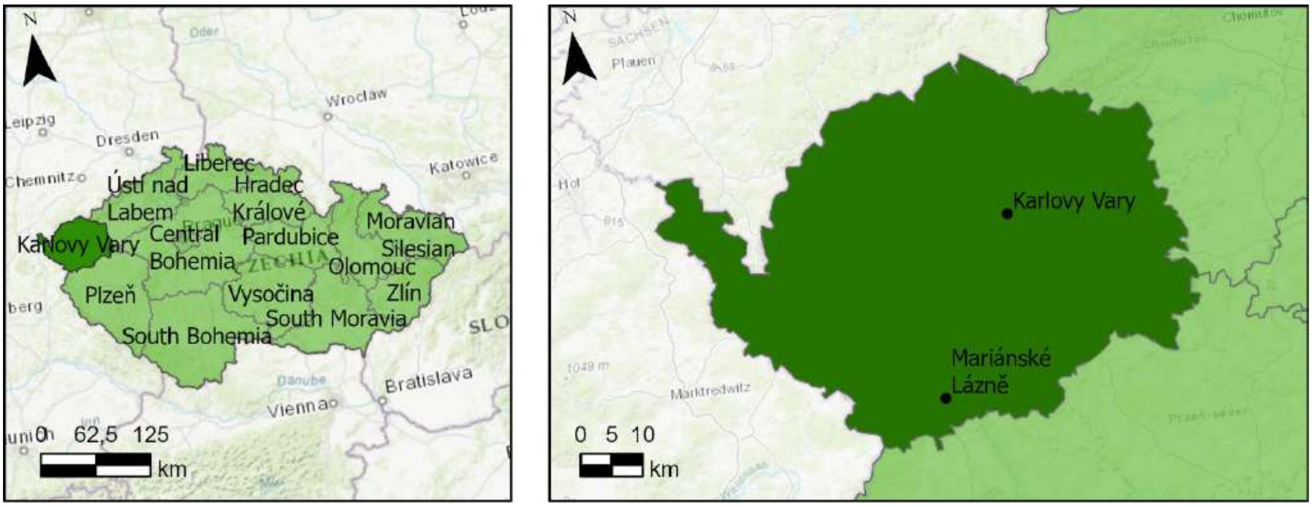


*Figure 1: Food waste in Karlovy Vary - Region of focus (dark green)*

During the touristic peak season, both Karlovy Vary and Mariánské Lázně generate substantial amounts of food waste on a daily basis, primarily due to the high concentration of restaurants and catering establishments. For this reason, the case study focuses on food waste from both the domestic and touristic sector. The touristic sector was included due to its significant economic importance in these cities. It is important to note that the term "food waste" excludes used cooking oil. Although the possibility of analysing cooking oil separately has been discussed, it was deemed unnecessary due to the relatively small quantities involved.

Currently, this biomass source is already structurally collected and composted. However, questions were raised concerning the impacts related to this supply chain and the possibility for optimisation. At VITO, through our MOOV service, we responded to these needs by carrying out an analysis of the current food waste supply chain and possible alternative scenarios. This investigation assessed the impact of the scenarios on total logistic costs and transport distances. This is outlined in the following sections.

## 1.2 Define – Input data and system boundaries

This initial phase centres on identifying the specific needs, characteristics, and objectives in collaboration with key stakeholders. It also includes the collection, processing, and validation of all relevant input data.

In summary, the food waste is collected and centralised in transfer collection points (TCPs) from where it is transported to a composting facility in the region, for both cities separately. For the logistic assessment, the currently applied door-to-door pick-up routes of the waste are considered in the assessment but not optimised since this is already implemented and not questioned (Figure 2).

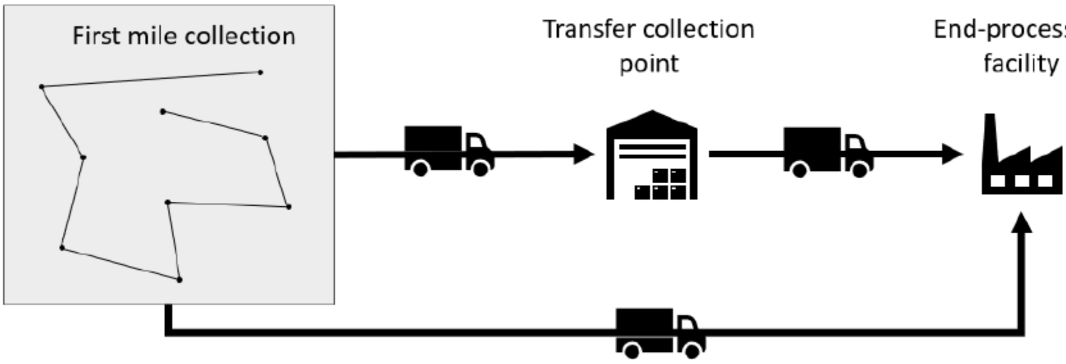


*Figure 2: Food waste in Karlovy Vary region - Stages of focus of the pathway to valorise food waste.*

The following sections provide more detail on the products and activities in this logistic chain.

### 1.2.1 Products and activities

#### Resource collection

The Czech case focusses on food waste from both the domestic and touristic sector in the 2 cities: Karlovy Vary and Mariánské Lázně. In 2023, food waste was collected from April to November, spanning a 35-week campaign. In **Karlovy Vary**, about 41 tons of food waste is collected weekly, leading to a yearly collection of 1429 tons. Four regions in the city are serviced on a specific day (Figure 3 and Table 1), usually requiring 1 or 2 trucks per day. In **Mariánské Lázně** on average 7,6 tons of food waste is collected weekly on one specific day in the week (hence 267 ton/year), requiring 1 truck (Figure 3 and Table 1).

*Table 1: Food waste in Karlovy Vary – Resource collection: Parameters and characteristics*

| City | Total quantity (ton/year) | Collection cost (€/year) | Route | Route distance (km) |
|---|---|---|---|---|
| KV | 1.429 | 253.620 | Monday | 51 |
| | | | Tuesday | 70 |
| | | | Wednesday | 70 |
| | | | Thursday | 51 |
| ML | 267 | 14.158 | A day | 69 |

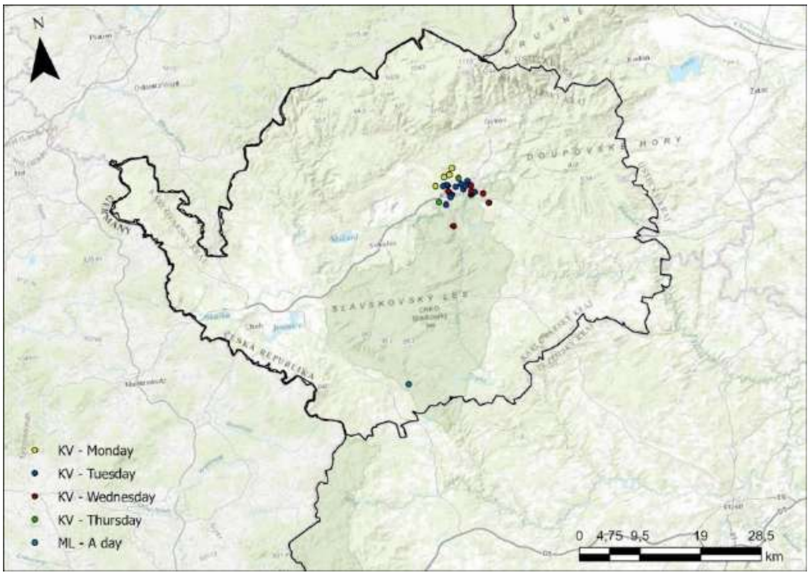


*Figure 3: Food waste in Karlovy Vary – Resource collection: Sourcing locations*

### *Storage at the transfer collection point*

After collecting the food waste, it is transported to a TCP in Karlovy Vary (north) and Mariánské Lázně (south) (Figure 4). The maximum time that food waste can remain at this point typically is 48 hours at maximum.

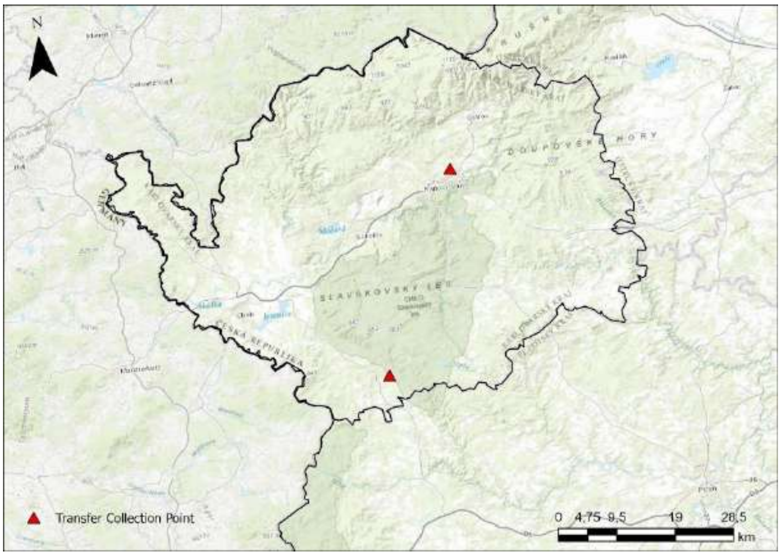


*Figure 4: Food waste in Karlovy Vary – Transfer collection point locations.*

### *Treatment*

According to the regional stakeholder, the food waste is not subjected to any treatment before, during, or after storage at the TCP. As a result, no additional treatment activities have been considered in the analysis.

### *End-processing*

Following storage at the TCP, the two cities individually transport food waste from the TCP to an end-processing facility (Figure 5). Currently, food waste is composted; however, there is growing interest in installing an AD to process food waste from both cities. This initiative aligns with the region's strategic focus on biogas production as part of its broader energy transition goals. By generating biogas and digestate, the facility could not only provide a sustainable solution for organic waste management but also help meet local energy demands. This approach presents economic advantages and supports efforts to reduce reliance on natural gas. The characteristics of both end-processing types are summarised in Table 2.

The operational costs (OPEX) are considered in the scenario analysis for both composting and AD.

However, although MOOV is fully equipped to account for capital expenditure (CAPEX) costs, these are not included in the Czech case study due to the absence of specific regional data on costs and depreciation. This distinction is important, as composting facilities are already operational and may be fully depreciated, whereas AD would require a complete CAPEX investment to be built from scratch. Nevertheless, Table 2 (column 3) provides an estimated CAPEX per processed ton to offer an indicative comparison, allowing the scale of logistical cost components to be weighed against the projected capital costs of new installations.

*Table 2: Food waste in Karlovy Vary – Processing types – Parameters and characteristics [1].*

| Processing type | Capacity (ton per year) | CAPEX[2] (€ per year) | CAPEX* (€ per ton per year) | OPEX (€ per ton) |
|---|---|---|---|---|
| Composting | 30.000 | 195.650 | 6,5 | 11 |
| Anaerobic digestion | 25.000 | 559.650 | 22,3 | 31 |

During processing, water evaporates, biogas is produced and biomass decomposed, leading to changes in the mass balance. Table 3 illustrates the mass conversion rates (input vs. output); for example, composting 1 ton of food waste results in approximately 0,4 ton of compost, while the remaining 0,6 ton are lost through water evaporation and biomass decomposition.

This is particularly important from a logistics perspective, as only the solid mass fraction remains for transport, significantly reducing the volume and weight that needs to be moved after processing.

*Table 3: Food waste in Karlovy Vary – Processing types: conversion coefficients of processing types*

| Processing type | Product type IN | Product type OUT | Conversion rate (out) % |
|---|---|---|---|
| Composting | Food waste | Compost | 40% |
| | | Water (evaporated)/decomposed biomass | 60% |
| Anaerobic digestion | Food waste | Digestate | 80% |
| | | Biogas | 20% |
| Composting | Digestate | Compost | 40% |

[1] https://www.nrel.gov/docs/fy22osti/81024.pdf
[2] Assumed depreciation period: 20 years

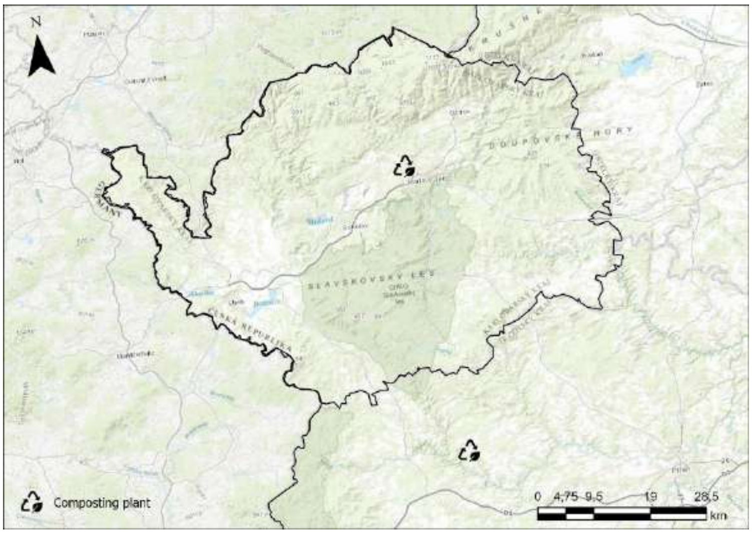


*Figure 5: Food waste in Karlovy Vary region – Current composting locations (AS IS).*

In order to optimise mobilisation costs, an optimal location of the processing facility is determined. This requires the identification of multiple candidate locations, from which the MOOV model selects the most cost-effective option. These candidate locations are selected based on two approaches (Figure 6):

- **Green field approach (GF)**: The region of interest – the Karlovy Vary Region – is overlayed with a raster (5 km x 5 km) in which the centroid of each raster cell is defined as a potential candidate location. Candidate locations within the Natura2000 protected areas have been removed from the selection.
- **Multi-criteria analysis**: a candidate location is determined by the following geographical requirements; the location must be located within an industrial zone defined by Corine land cover (CLC) and Natura 2000 regions are excluded.

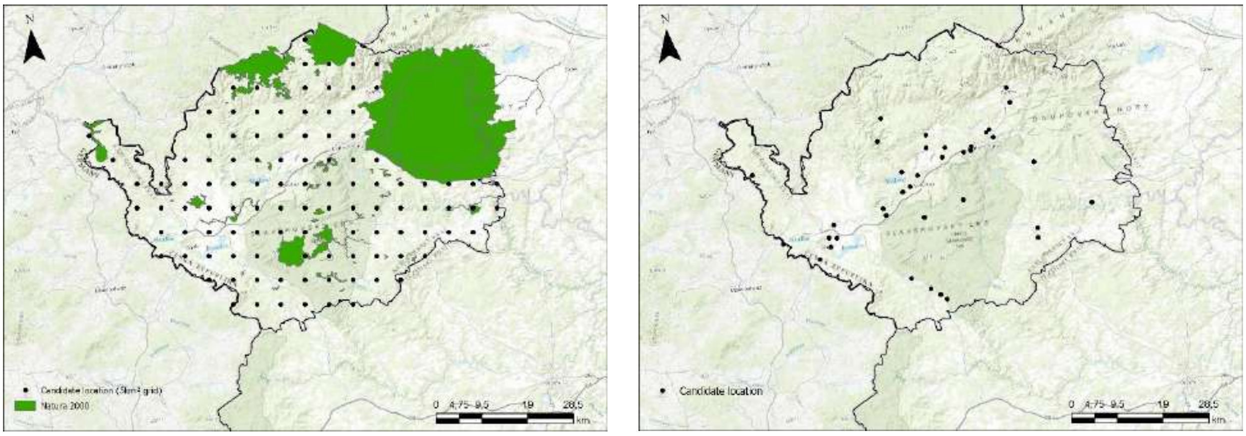


*Figure 6: Food waste in Karlovy Vary – Candidate locations for end-processing based on the GF approach (L) and the multi-criteria analysis (R).*

### *Transport*

For both cities, information on the origin locations of food waste and the corresponding daily collection routes was considered.

The costs related to collect the food waste and bring it to the TCP are based on the information mentioned in Table 1, and is dependent on the city where the biowaste is collected. In Mariánské

Lázně, 1 truck is used to collect the food waste, leading to a cost of 5.9 €/km. In Karlovy Vary, the daily first mile collection is carried out using 1 or 2 trucks each day. Hence, for Karlovy Vary, the assumption is integrated that of the 35 weeks of collection, 1 truck is used for 18 weeks and 2 trucks are used for 17 weeks. This leads to a total kilometre of 12574 km per season and 20.2 €/km for Karlovy Vary (Table 4).

These costs represent the service costs. This implies that all associated costs are considered, including transport (per kilometre), transhipment costs, and loading costs. The same types of costs – depending on the city in question – are also considered for the (bulk) transport of the food waste from the TCP to the processing facility.

*Table 4: Food waste in Karlovy Vary – Transport – Transport types, parameters and characteristics.*

| City | Transport type | Capacity (ton) | Service cost (€/km) |
|---|---|---|---|
| KV | First mile collection | 5 | 20,2 |
| | First mile collection | 9 | 20,2 |
| | TCP to processing (Bulk) | 10 | 20,2 |
| ML | First mile collection | 10 | 5,9 |
| | TCP to processing (Bulk) | 10 | 5,9 |

Figure 7 shows the transportation network in the Karlovy Vary region. Only the main roads are provided on the image to increase readability.

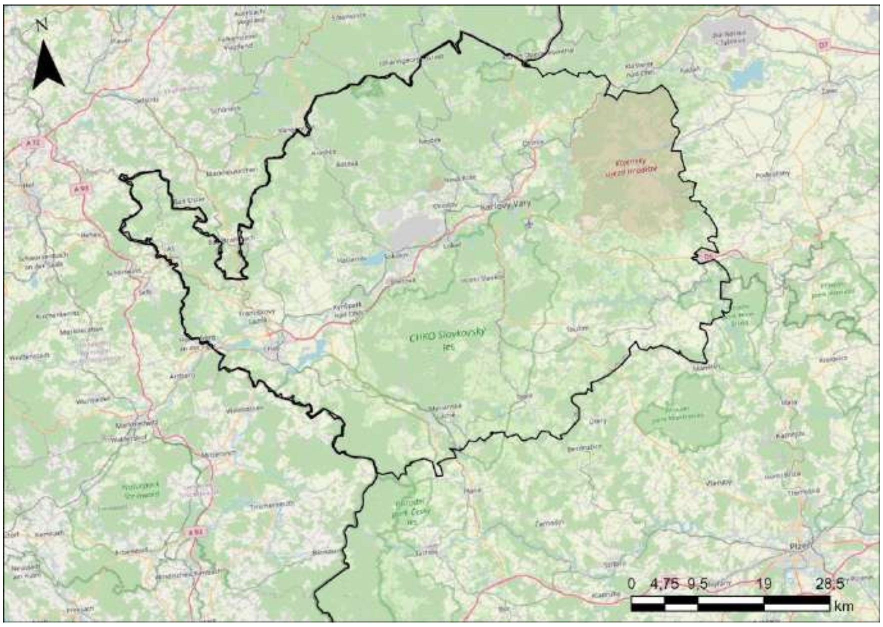


*Figure 7: Food waste in Karlovy Vary – Transport network Network flow diagram[3]*

[3] Source: World Street Map, ESRI, HERE, Garmin, Intermap

After collecting the food waste in the city via a pick-up round (first mile), it is transported to a TCP outside the city by truck. Here it is stored shortly (max. 48 hours) after which it is transferred by truck to the composting facility (Figure 8)

The network flow diagram is the basis for the development of the BIOTRANSFORM MOOV-model for the Czech case and has the ambition to include all potential flows between activities (and locations) in the chain.

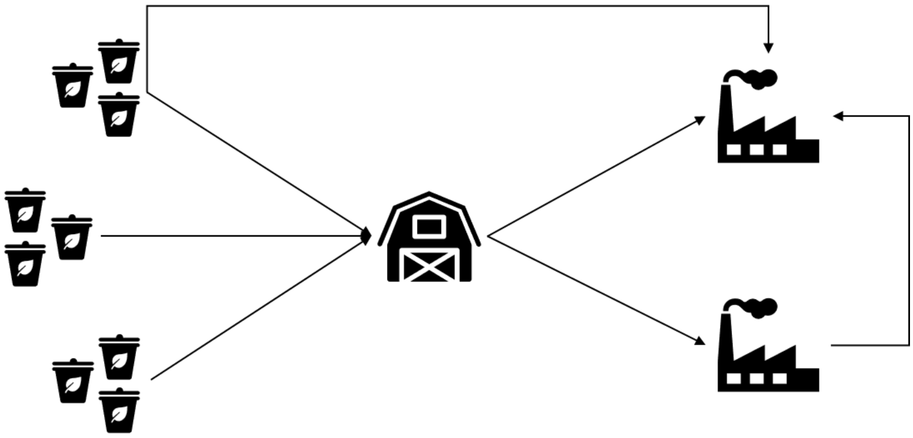

*Figure 8: Food waste in Karlovy Vary – Network flow diagram as a generic representation of the potential resource flows.*

## 1.3 Design –development of the optimisation model

The specifics defined in chapter 1.2 are now transferred to the MOOV model. Such specifics include amongst others:

- The definition of the objective function
- The addition of parameters related to describe the specifics and constraints of the Czech food waste supply chain

The parameters and corresponding values used in the shell model are derived through collaboration with project partners and an extensive review of relevant literature.

### 1.3.1 Objective function

In mathematical modelling, especially in optimisation problems, the objective function is a mathematical expression that defines the goal of the model – what you want to maximise or minimise – while meeting a set of constraints and relationships between the decision variables.

For the Czech case, the focus is on the minimisation of the **logistic costs** of the food waste over the supply chain – from the food waste collection over the storage in the TCPs up to the end-processing facilities. The total mobilisation cost is composed of the following key cost elements, each representing a specific activity in the food waste supply chain (Figure 9). The optimisation is performed collection-side driven (i.e. push), since there is an obligation to process all the collected resources.

The total logistic cost is defined as the sum of the following key cost elements, each representing a specific activity in the food waste supply chain (Figure 9):

1) **Cost for feedstock collection**: cost of the collection, i.e. cost for loading and transport during collection of the resources (defined as a centre point of the district).
2) **Cost for end processing**: cost for end-processing (composting resp. AD), defined by the operational expenditures (OPEX).
3) **Cost for transport**: this cost entails the cost for transport (distance) (i.e. movement of products from one place to another) as well as the cost for transshipment (time) (i.e. unloading and loading of goods) based on the potential food waste flows (Figure 8) for:
    a. Transport between the first mile collection and the TCP,
    b. Transport between the first mile collection and end-processor,
    c. Transport between the TCP and end-processor,
    d. Transport between end-processors mutually.

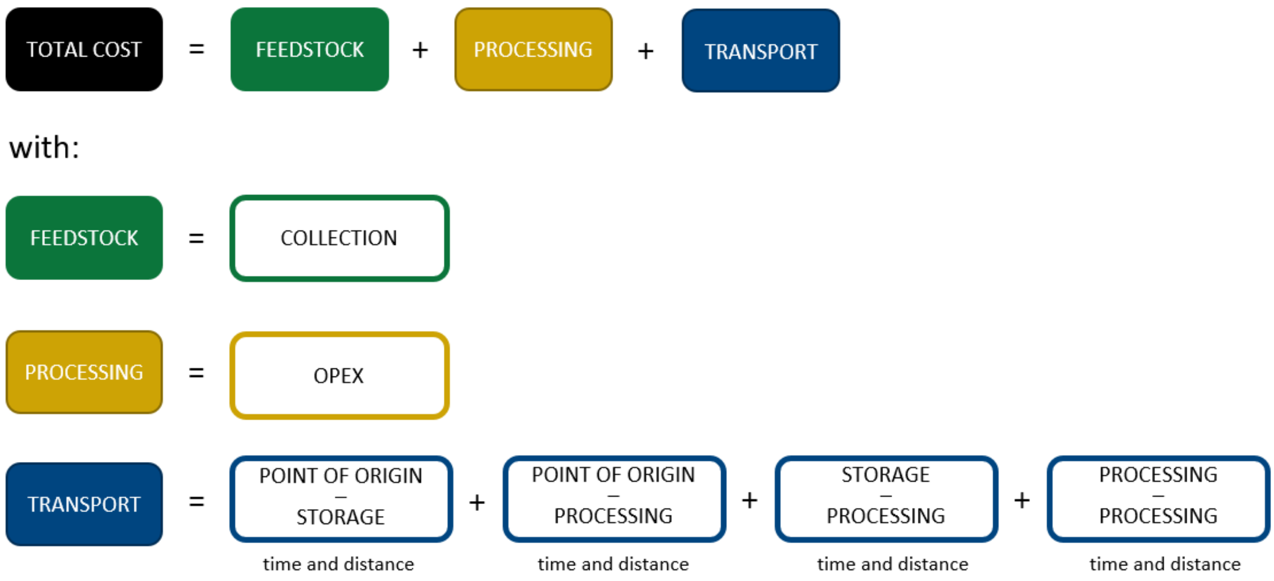


*Figure 9: Food waste in Karlovy Vary – Components of the total mobilisation cost included in the MOOV model.*

In addition to the mobilisation cost, the **total transport distance** (km) needed to mobilise the resources from the collection locations to the end processors is calculated for each scenario.

### 1.3.2 Constraints

The constraints reflect the limitations and conditions which must be fulfilled throughout the supply chain. These constraints are sourced from previous projects and expert knowledge. The most important constraints are listed below.

- **Physical constraints** (e.g. capacity, feedstock quality or origin) imposing limitations on the allowable combinations between feedstock and activities, between activities mutually, and on the allowed activities at the harvest locations, TCP locations and end-processing locations.
- **Product conversion constraints** defining the conversion of a product into another (intermediate or final) product due to an activity (treatment, TCP or end-processing);
- **Network flow constraints** define the mass (and volume) flows between locations. Note that flows between end-processing locations are included to allow scenarios analysis where end-processing by-products are exchanged.

## 1.4 Deliver

### 1.4.1 Scenario Overview

Currently (AS IS), food waste from both cities is collected via first-mile pick-up and brought to intermediate transfer collection points (TCPs), from where it is transported to their respective composting facility. The current logistics, including the existing collection routes, are taken as given and not optimised further.

Improvement scenarios (TO BE) are explored with a focus on introducing alternative processing methods such as AD, centralising the treatment process, combining composting with AD, and bypassing TCPs.

#### *Impact scenarios*

The **AS IS** scenario represents the current method of food waste processing in the Karlovy Vary region. This scenario serves as the baseline for the impact assessment, against which all alternative scenarios are compared.

- **AS IS situation:** currently, food waste is collected, stored in a TCP and delivered to dedicated separate composting facilities for both Karlovy Vary and Mariánské Lázně

The alternative scenarios (TO BE scenarios) were defined in collaboration with BioEast HUB CZ – the local facilitator. In these TO BE scenarios, several dimensions are changed in the supply chain configuration; the end-processing type (scenario 1), the location of the processing facilities (scenario 2 and 3) or a combination of both (scenario 4). These scenarios are visualised in Figure 10.

- **Scenario 1**: Impact of end processing type
  - What if the food waste is anaerobically digested in the current composting locations of Karlovy Vary and Mariánské Lázně?
- **Scenario 2**: Impact of processing type and location
  - What if the food waste is anaerobically digested only in Karlovy Vary?
- **Scenario 3:** Impact of centralisation
  - What if the composting of food waste from both regions takes place in one optimised new location?
- **Scenario 4:** impact of processing type and centralisation
  - What if food waste is anaerobically digested in this new location?
- **Scenario 5:** Impact of processing combination
  - What if the food waste is treated through AD, followed by composting of the resulting digestate as a post-treatment step?
- **Scenario 6**: Impact of excluding intermediate TCPs
  - What if the TCPs would be removed and the trucks drive immediately to the processing plant(s)?

The potential implementation of 'pocket digesters' – very small-scale ADs installed directly at individual restaurants and hotels – was also considered. This approach would allow for on-site treatment of food waste at the point of generation. However, in both Karlovy Vary and Mariánské Lázně, such touristic establishments are generally small in scale. As a result, a large number of pocket digesters would be required to achieve even a modest reduction in food waste, leading to substantial financial investment. Due to the lack of detailed data at this granular level, no MOOV analysis was conducted for this scenario.


*Figure 10: Food waste in Karlovy Vary - Visualisation of the AS IS situation and TO BE scenarios.*

### *Key performance indicators (KPIs)*

KPIs are used to assess the impacts related to the different scenarios, since these enable a data-driven approach to assess trade-offs and identify performance bottlenecks or improvement opportunities. The considered KPIs are 'cost' and 'mileage', which can be found in the result tables in the following paragraphs. The indicators are to be interpreted as follows:

- **Cost:** expresses the logistics cost per ton - including collection, storage at the TCP, end-processing and transport.
- **Mileage:** expresses the transport distance per ton to deliver the resources at the gate of the end-processor. The mileage includes i) transport from collection district to the TCP, ii) transport from collection district directly to end-processors, iii) transport from the TCP to end-processing and iv) transport between end processors.

## *1.4.1 Scenario AS IS: composting at two locations*

Currently, the food waste in Karlovy Vary and Mariánské Lázne is brought via a TCP to a composting plant, but the location of both plants is different for both cities. In Karlovy Vary this includes the transport of 41 ton per week, collected over 4 days for 35 weeks. In Mariánské Lázne this includes the transport of 7,6 ton per week, collected on one specific day for 35 weeks. In Figure 11 the transport routes, the location of the TCP and the composting site are indicated for both Karlovy Vary (L) and Mariánské Lázne (R).

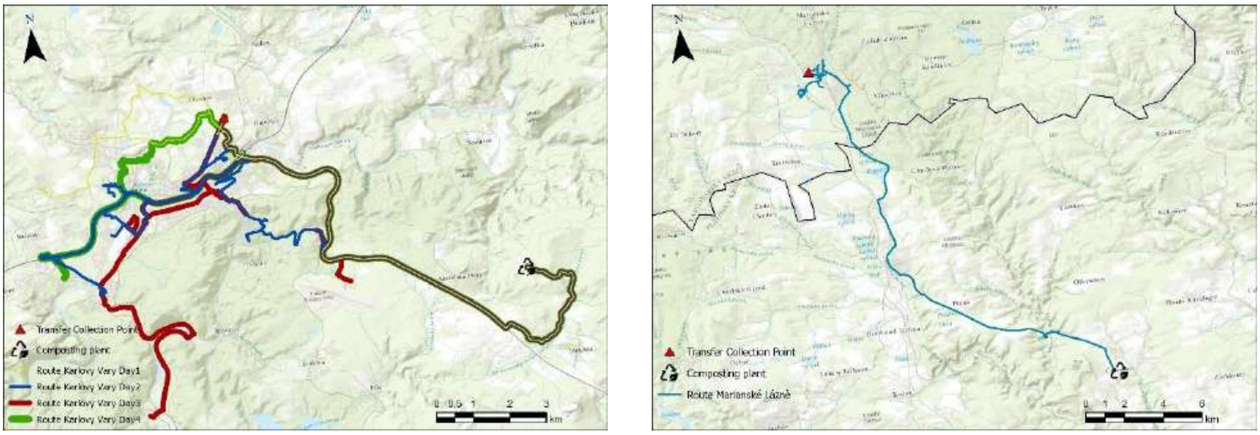


*Figure 11: Food waste in Karlovy Vary – Map of resource flows in the current situation (AS IS) for Karlovy Vary (L) and Mariánské Lázne (R).*

For this AS IS situation, a total of 1.689 ton/year food waste is processed from both cities, with a transport distance of 14.989 km/year and a cost of 286.726 €/year. This implies a transport distance of ca. 9 km/ton and a cost of 170 €/ton per year.

This total annual transport cost (of 14.989 km/year) related to both cities under consideration is for 37% allocated to the transport of the food waste to the storage points (TCPs) and for 63% allocated to the transport from the TCP to the composting facility (Figure 12).

The cost (286.726 €/year) implies the following elements (Figure 12):

- 37% transport to the TCPs including the first mile collection,
- 56% transport between the TCP and composting facility
- 6% processing – composting – itself.

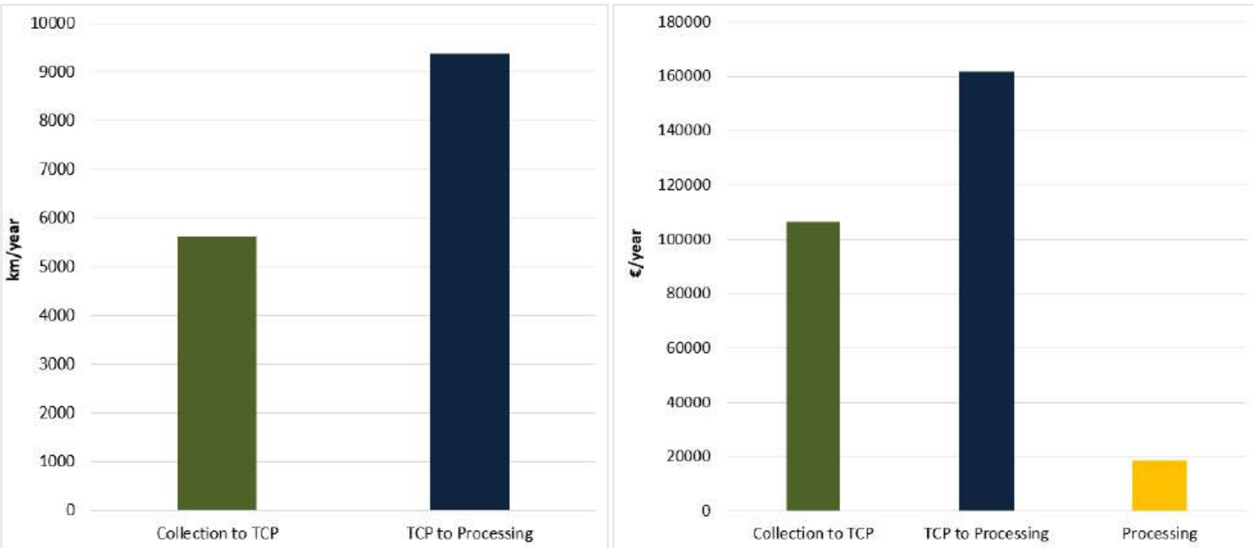


*Figure 12: Food waste in Karlovy Vary region – transport distance (L) and cost (R) in the current situation (AS IS).*

### 1.4.2 Scenario 1 and 2: introducing AD maintaining two resp. one location

Scenarios 1 and 2 examine the impact of the chosen end-processing method. While the current approach involves composting biowaste, these scenarios explore the introduction of AD – which is linked to the upcoming interest in this processing type as part of this region strategic focus on biogas production as part of its broader energy transition goals.

**Scenario 1** assumes that the end-processing sites of both cities remain at the same location as in the AS IS situation, but the end-processing method is changed from composting to AD. The same amount of food waste (1.689 tons/year) is processed, and the collection routes remain unchanged; therefore, the total transport distance is the same as in the AS IS scenario.

**Scenario 2** considers centralisation of the food waste transporting it from both cities to the end-processing site in Karlovy Vary, which is the largest plant. Again, the end-processing method is changed from composting to AD. In this case, the distance between the TCP and the end-processing facility increases by 12%, resulting in a ca. 8% rise in total annual transport distance — from 14.989 km/year to 16.140 km/year. When expressed per ton of processed food waste, this corresponds to an increase from 8,9 km/ton to 9,6 km/ton (Figure 13).

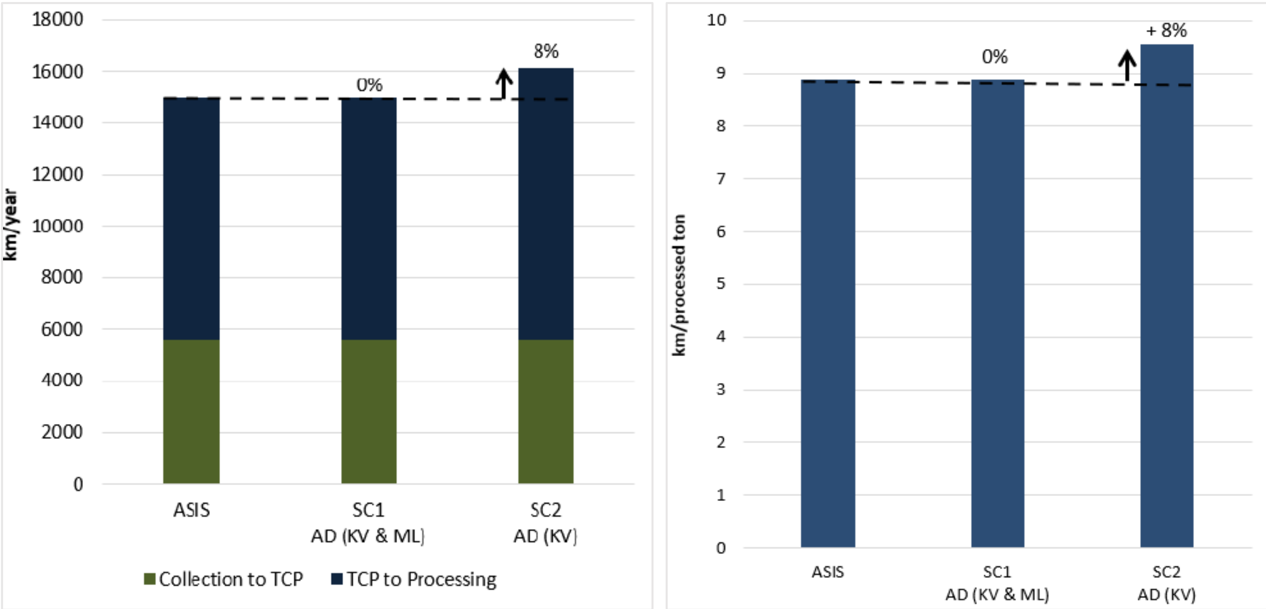


*Figure 13: Food waste in Karlovy Vary region – Transport distance in km/year (L) and km/processed ton (R) of processing type (scenario 1 and scenario 2) in comparison to the current situation (AS IS)*

For **scenario 1**, an additional cost of 33.784 €/year in considered in comparison to the AS IS situation. This surplus is attributed to the shift in the end-processing type from composting to AD, resulting in an increase in OPEX cost from 11 €/ton to 31 €/ton (Table 2). This change corresponds to an approximate 12% rise in total costs (Figure 14).

For **scenario 2**, the same surplus cost of 33.784 €/year related to the change in end-processing type is considered. Additionally, an extra transport cost of 6.750 €/year is included, derived from the extended transport distance as visualised in Figure 13. Combined, both factors contribute to a total cost increase of ca. 14% compared to the AS IS situation (Figure 14).

However, the additional transport cost of €6,750 per year in Scenario 2 is likely to be offset by lower operational (OPEX) and capital (CAPEX) costs, resulting from the consolidation of activities into a single end-processing facility, rather than the two facilities currently in operation.

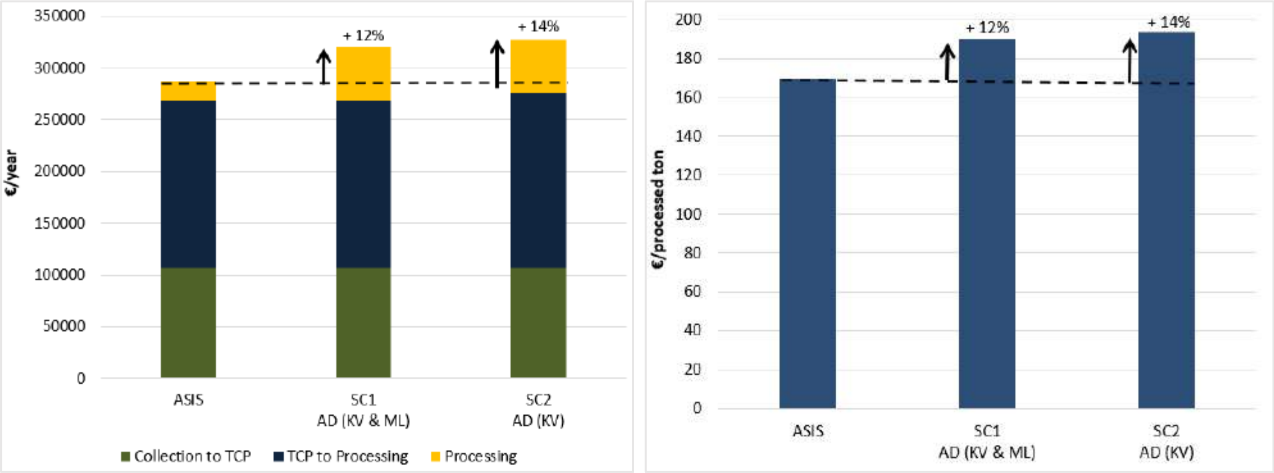


*Figure 14: Food waste in Karlovy Vary region – Mobilisation cost in €/year (L) and €/processed ton (R) of processing type (scenario 1 and scenario 2) in comparison to the current situation (AS IS)*

### 1.4.3 Scenario 3 and 4: selection of the optimal location for composting and AD

Scenarios 3 and 4 evaluate the centralisation of end-processing in a newly established facility, with its location determined by the optimisation model to minimise total costs.

Scenario 3 proposes the development of a composting facility, whereas Scenario 4 explores the construction of an AD.

In both scenarios, food waste from the two cities would be transported from their respective transfer collection points (TCPs) to the selected centralised facility.

Initially, candidate locations for the new centralised facility were identified using two distinct methods: the GF approach and the CLC approach, as outlined in Section 1.2.1 – End-Processing. However, the outcomes of both approaches showed only minor differences. Therefore, only the results of the CLC approach—which is the more restrictive of the two—will be visualised and discussed in the following sections.

The results indicate that the optimal location for the new facility is near the Karlovy Vary transfer collection point (TCP), marked by a green circle icon in Figure 15. This location is favoured due to the substantially higher volume of food waste collected annually in Karlovy Vary, which represents 84% of the total waste from both cities, as shown in Table 1.

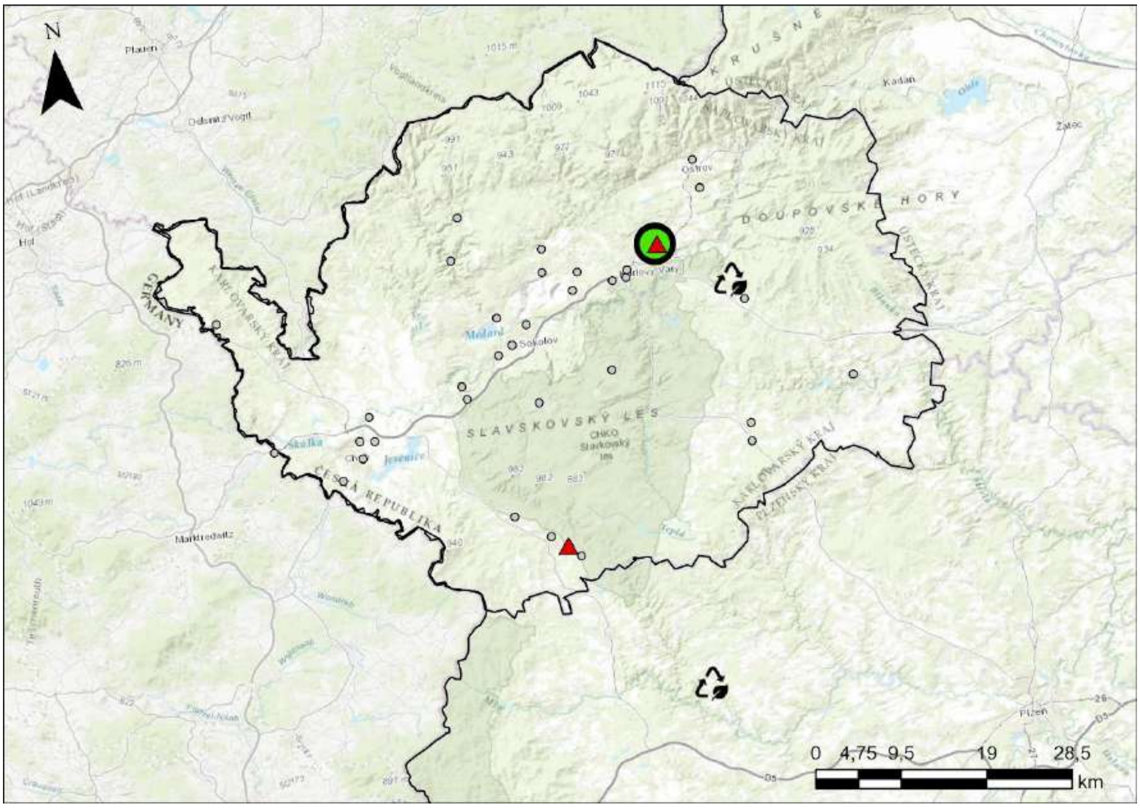


*Figure 15: Food waste in Karlovy Vary – Optimal location for end-processing.*

In both **Scenarios 3 and 4**, the same volume of food waste (1.689 tons/year) is processed as in the AS IS scenario. Selecting the optimal location results in a 63% reduction in transport distance between the TCPs and the end-processing site in both Scenarios 3 and 4. When considering the total transport distance, including both the route from the first mile collection to the TCP and from the TCP to the end-processing facility, this optimisation leads to an total transport distance reduction of 39% (Figure 16).

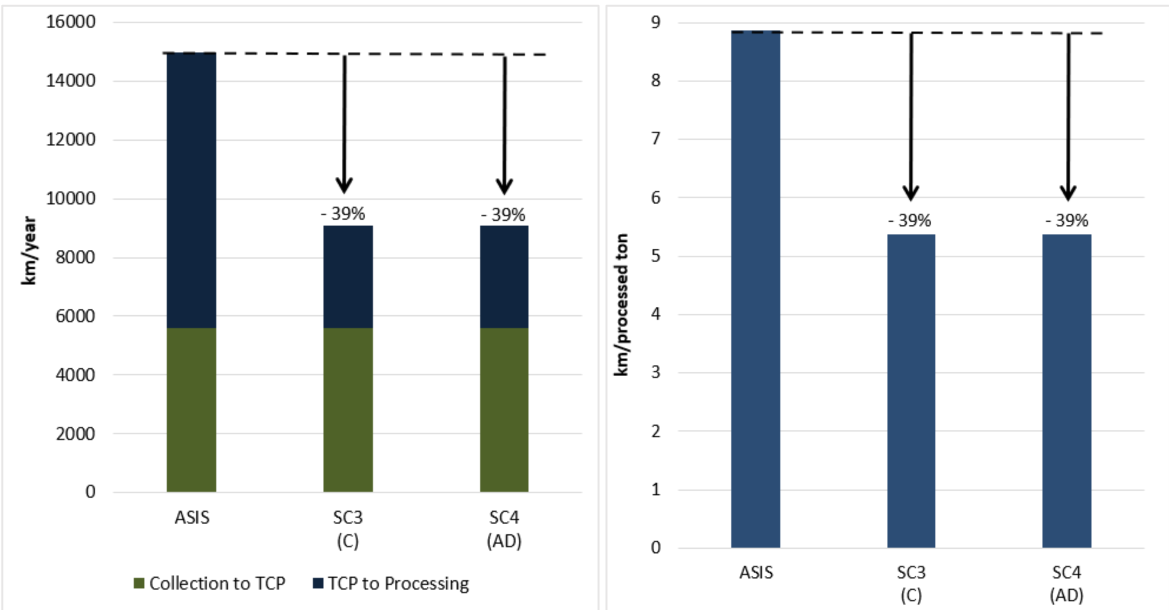


*Figure 16: Food waste in Karlovy Vary region – Transport distance in km/year (L) and km/processed ton (R) of centralisation (scenario 3 and scenario 4) in comparison to the current situation (AS IS).*

For **Scenario 3**, this decrease contributes to a total cost reduction of 138.661 €/year, equivalent to 82 €/processed ton, representing a 48% decrease in total costs – compared to the AS IS situation.

In **Scenario 4**, the introduction of an AD leads to a 182% increase in operational (OPEX) processing costs, rising from €11 to €31 per ton. However, this cost increase is effectively offset by the reduction in transport costs, as previously discussed. As a result, the scenario yields a net annual cost saving of €104.878, or €62 per processed ton, corresponding to a 37% decrease in total costs compared to the current (AS IS) situation (Figure 17).

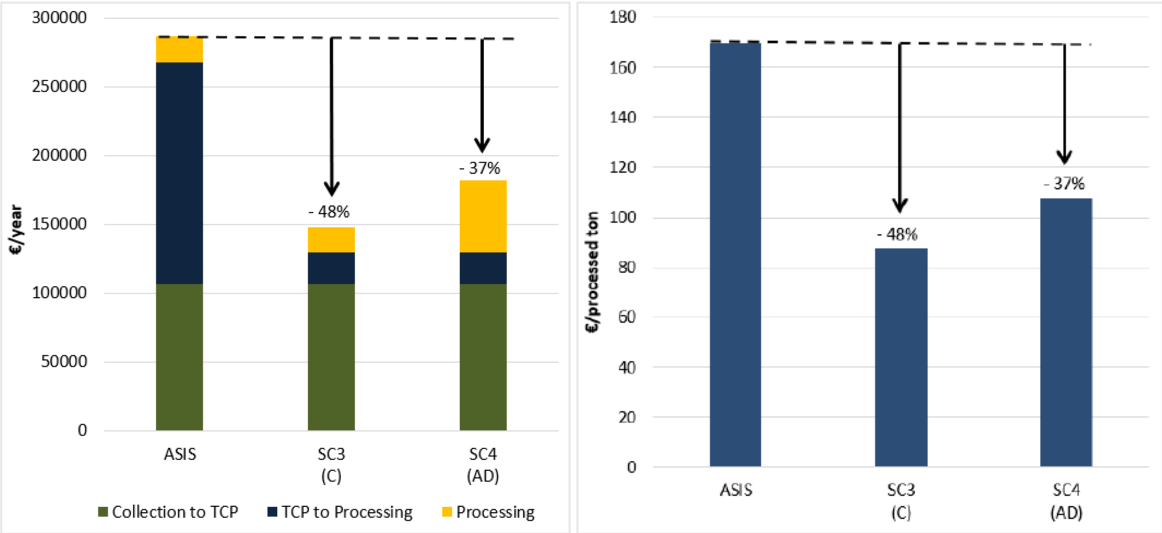


*Figure 17: Food waste in Karlovy Vary region – Mobilisation cost in €/year (L) and €/processed ton (R) of centralisation (scenario 3 and scenario 4) in comparison to the current situation (AS IS).*

## 1.4.1 Scenario 5: introducing composting of the digestate from AD

**Scenario 5** builds upon Scenario 4, but with a key difference: the digestate produced by the AD is further processed at the existing composting facilities. It is assumed that both current transfer collection points (TCPs) remain operational, and the AD is situated at the optimal location identified in Scenario 4 (Figure 15). While the total findings from Scenario 4 still apply,

Scenario 5 introduces an **additional transport leg**, as the digestate must be transferred **from the AD facility to one of the composting sites** for final treatment. This results in an increase of 8.718 kilometres per year, as shown in Figure 18 (left, orange bar section), representing a 19% increase in total transport distance.

The majority of this additional distance is attributed to the transport of digestate to Mariánské Lázně, compared to the smaller contribution from digestate transport to Karlovy Vary. This discrepancy arises because the AD facility is located close to Karlovy Vary, thereby requiring shorter transport distances for that route.

On the other hand, **the first transport leg from the TCP to the AD facility** is significantly reduced, as shown in Figure 18 (left, blue bar section). This is because the optimal location for the AD facility is in Karlovy Vary, situated close to the TCP, minimising transport distance for this segment.

However, when comparing Scenario 5 to the AS IS situation, **the transport distance per processed ton** actually decreases by 31% (Figure 18 – right). This because on mass-balance a higher total volume is processed in Scenario 5—2.910 tons (comprising 1.689 tons of food waste and 1,221 tons of digestate)—versus only 1.689 tons in the AS IS scenario (Figure 17).

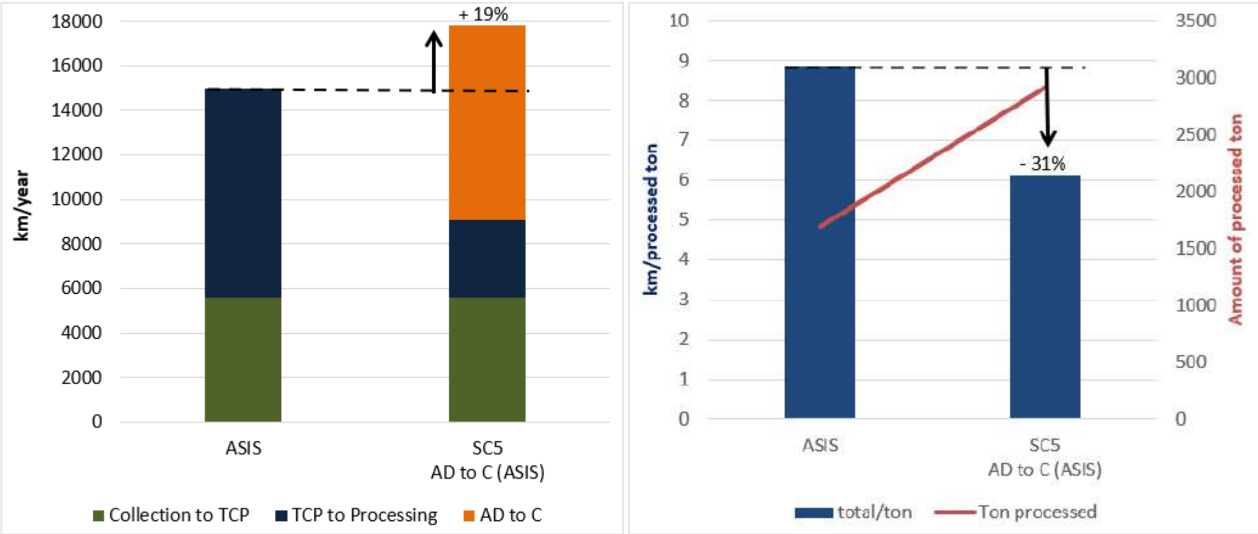


***Figure 18: Food waste in Karlovy Vary – Transport distance in km/year (L) and km/processed ton in comparison to the total amount of processed ton (R) of end-processing combination (scenario 5) in comparison to the current situation (AS IS).***

In terms of total costs, Figure 19 (yellow bar section) illustrates a logical increase in processing costs when combining composting with AD, rising to €65,794 per year, compared to €18,581 per year for composting alone.

However, Figure 19 also shows that the total transport cost in Scenario 5 (blue and orange sections) is reduced compared to the AS-IS situation (blue section), despite the addition of a transport leg for the digestate from the AD facility to the composting sites.

This reduction is primarily because the transport to Mariánské Lázně weighs more heavily in the additional transport distances, and the cost per kilometre for transport to Mariánské Lázně is significantly lower (€5.9/km) compared to transport to Karlovy Vary (€20.2/km) (Table 4). As a result, the transport cost of this leg is reduced, which is reflected in the orange bar of Figure 19.

**The transport cost per processed ton** decreases by 39%. This because on mass-balance a higher total volume is processed in Scenario 5 vs. the AS IS scenario (Figure 19– right).

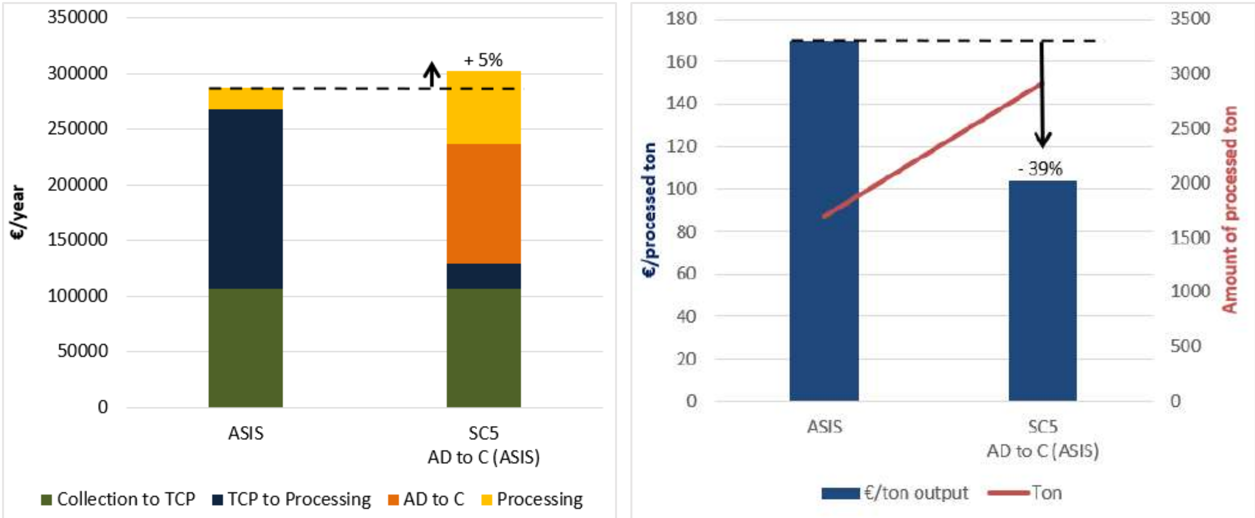


*Figure 19: Food waste in Karlovy Vary – Mobilisation cost in €/year (L) and €/processed ton in comparison to the total amount of processed ton (R) of end-processing combination (scenario 5) in comparison to the current situation (AS IS).*

### 1.4.2 Scenario 6: direct transport to the optimal location for composting

This scenario examines the impact of removing the storage point (TCP), with all food waste being directly transported to the optimally located composting plant. In this case, the total transport distance amounts to 8.133 kilometres per year, representing a 46% reduction compared to the AS-IS situation (Figure 20).[4]

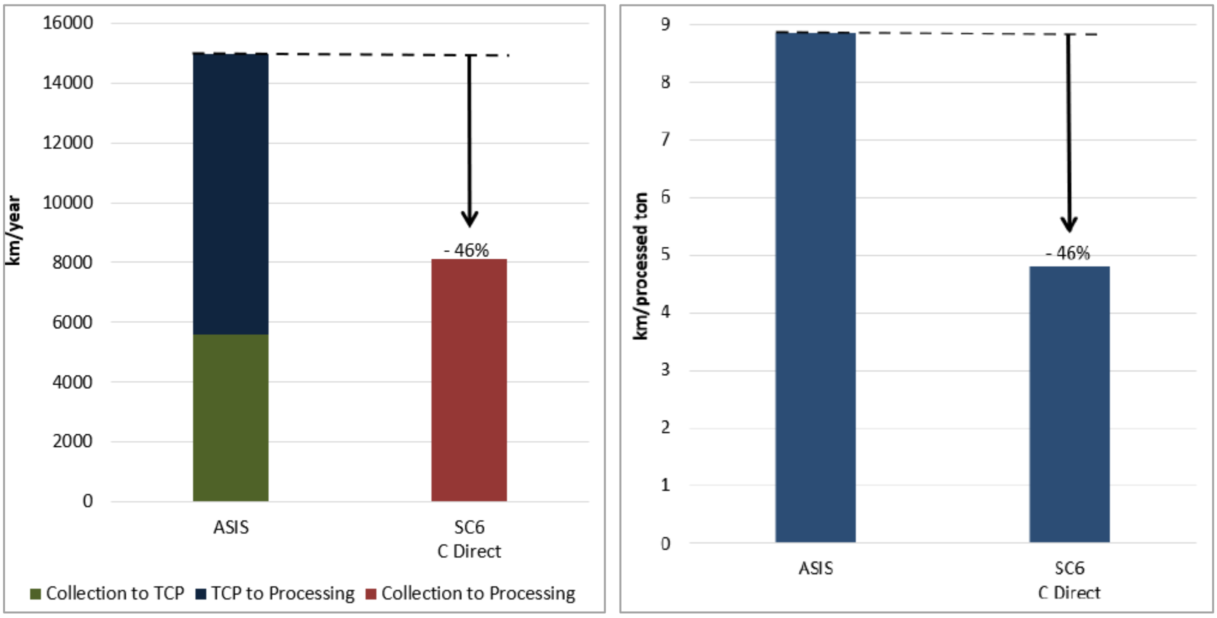


*Figure 20: Food waste in Karlovy Vary – Transport distance in km/year (L) and km/processed ton (R) of decentralisation (scenario 6) in comparison to the current situation (AS IS) in km/year (L) and km/processed ton (R).*

The end-processing cost remains unchanged at €18,581 per year, as the same 1.689 tons of food waste is composted (Figure 21, yellow bar section). However, the annual mobilisation cost drops

[4] Without considering AD

significantly to €125.869 per year, compared to €268.145 per year under the AS-IS scenario — resulting in a 50% reduction in total costs (Figure 21).

The combination of an optimally located composting facility and the elimination of the intermediate transport leg via the respective TCPs in both cities leads to a favourable reduction in transport costs. OPEX costs are assumed to remain unchanged, as composting remains the end-processing method in both the current situation and in Scenario 6. However, this scenario would involve a consolidation from two operational composting sites to a single facility, which could potentially further reduce OPEX costs through efficiency gains.

Finally, it is important to note that the CAPEX costs associated with constructing a new composting installation are excluded from this analysis.

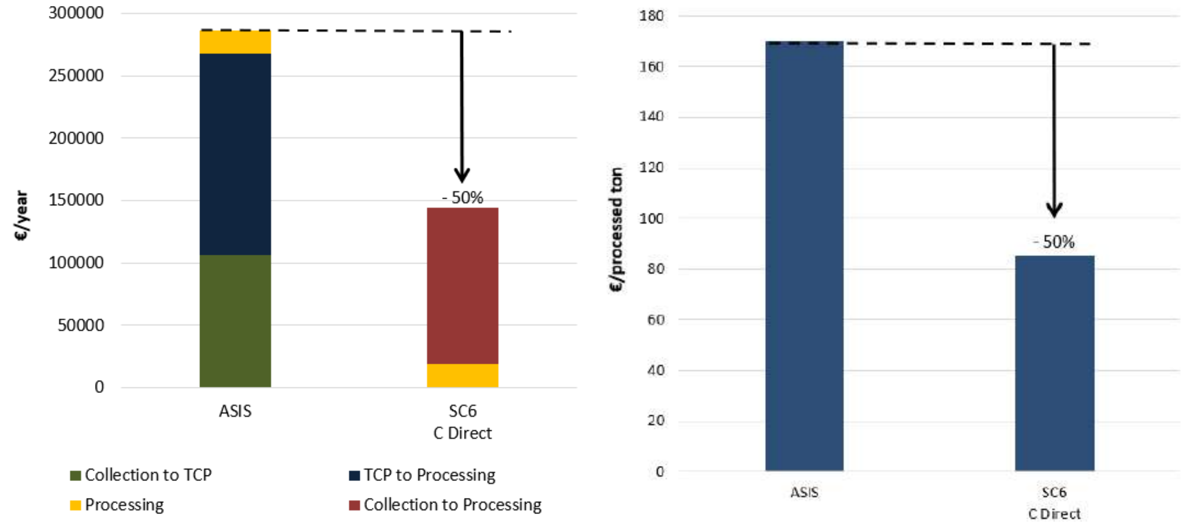


*Figure 21: Food waste in Karlovy Vary – Mobilisation cost in €/year (L) and €/processed ton (R) of decentralisation (scenario 6) in comparison to the current situation (AS IS).*

## 1.5 Conclusions

The Karlovy Vary Region in the Czech Republic is a key centre for tourism and related industries, leading to substantial food waste generation during peak seasons. Through its MOOV service, VITO analysed the region's existing food waste collection and processing system from a logistics perspective, aiming to identify opportunities for reducing costs and transport distances.

Currently (AS IS), food waste from both cities is collected via door-to-door pick-up and brought to intermediate transfer collection points (TCPs), from where it is transported to their respective composting facility. The current logistics, including the existing collection routes, are taken as given and not optimised further.

Improvement scenarios (TO BE) are explored with a focus on introducing alternative processing methods such as AD, centralising the treatment process, combining composting with AD, and bypassing TCPs.

In the current (AS IS) scenario, 1,689 tons of food waste are processed annually, resulting in a transport distance of ca. 15.000 km a total annual logistic cost of €286.726—equating to roughly 9 km and €170 per processed ton. Of the total cost, 37% is attributed to the first-mile collection and transport to the TCPs, 56% to transport from TCPs to the composting facility, and only 6% to the composting OPEX costs.

**Scenario results**

**Scenario 1** retains the existing two processing locations but shifts the treatment method from composting to AD. Since the locations remain unchanged, transport costs are unaffected; however, a 12% increase in total costs is observed, driven by higher operational expenses associated with AD.

**Scenario 2** shifts treatment method from composting to AD while centralising processing at the Karlovy Vary plant. This increases transport distance by 8% and total costs by 14%. However, the additional transport cost is expected to be offset resulting from the consolidation of activities into a single end-processing facility, rather than the two facilities currently in operation.

**Scenario 3** proposes the establishment of a new centralised composting facility, with the flexibility to select the optimal location within the region. This approach results in a 39% reduction in total transport distance and a 48% decrease in total costs, highlighting the efficiency gains from strategic centralisation.

**Scenario 4** builds upon Scenario 3 by introducing an AD in place of a composting installation. Despite the higher OPEX costs associated with AD, the scenario still achieves a 37% total cost reduction, owing to lower transport costs.

**Scenario 5** builds on Scenario 4 by further processing the digestate from the AD facility at the existing composting sites, while both TCPs remain operational. This introduces an additional transport leg, increasing the total transport distance by 19%. However, when considering the mass balance, the transport distance per processed ton decreases by 31%. The transport cost per processed ton decreases by 39% in Scenario 5, due to a higher total processed volume compared to the AS-IS scenario

To end, **Scenario 6** eliminates the TCPs, directly transferring food waste to a centralized composting facility, reducing the total transport distance by 46% and cutting total costs by 50%.

In **conclusion**, as this case study focused on minimising mobilisation costs, the results demonstrate that the greatest cost savings are achieved by consolidating operations at a centralised facility, particularly when the location is optimised to minimise transport distances.

Further considerations for business case refinement

To further refine the results towards a robust business case, the following aspects require additional attention:

- **CAPEX Costs**: The capital expenditure (CAPEX) associated with new installations was excluded from this analysis. Future evaluations should incorporate these costs to provide a complete financial picture.
- **OPEX Costs**: Operational expenditure (OPEX) was assumed to remain unchanged within the current study scope. However, consolidation scenarios — merging two operational sites into

a single optimally located site — could potentially reduce OPEX through efficiency gains and should be assessed.

- **Revenues**:
  No additional revenues were considered from biogas production or digestate valorisation. Exploring potential revenue streams could improve the business case.
- **Policy Framework**: The potential impact of regulatory and policy developments, particularly government incentives for biogas, needs to be evaluated to understand financial and operational implications.
- **Social Framework**: Stakeholder consultations are recommended to assess the feasibility of transitioning to a centralised facility and to evaluate its potential effects on local communities.
- **Additional Scenarios**: Based on the current findings, a combined scenario could be explored where:
  i) Direct transport is organised to an optimally located composting site (Scenario 6), ii) AD is integrated at this location (Scenario 2), iii) Composting of digestate occurs on-site, eliminating the need for additional transport (Scenario 5).
- **Phased CAPEX Investments**: To ease financial planning, CAPEX investments for the new composting and AD facilities could be staggered over time, allowing depreciation of the first facility before investing in the second

# 2. Olive tree pruning in Andalusia (Spain)

## 2.1 Framing the challenge

In this chapter, VITO's supply chain optimisation service, MOOV, explores the collection and transportation strategies of woody olive tree pruning (OTP) from groves to biorefineries in the Andalusian region.

In the region of Andalusia (Spain) there is a growing interest to valorise the woody pruning from olive production to biobased products, such as particleboards [Kougioumtzis et al. 2023], activated carbon [Ramos et al. (2025)] or bioplastics[5].The EU-project SCALE-UP[6], for example, marks that one of the objectives of the Andalusian region is to take advantage of the region's biomass potential however challenges in doing so are associated with the exploitation of this biomass such as its storage and mobilisation or the lack of locally available infrastructures to process biomass [Nieto et al. (2022)].

In this case study, collaboration was established with Andaltec, a Spanish research centre located in Jaén, Andalusia. Andaltec specialises in the development of bioplastic materials for a range of applications, including food packaging and automotive components. More recently, the centre has explored the potential of valorising OTP as a raw material for bioplastic production, aligning with broader circular economy objectives.

The European Union accounts for approximately 67% of global olive oil production. Olive cultivation spans around 4,6 million hectares, predominantly in Mediterranean EU countries such as Spain, Italy, Greece, and Portugal. Spain alone comprises 2,75 million hectares, representing roughly 60% of the EU's total olive production area[7,8].

Within Spain, olive production is concentrated in the Andalusia region in the south (Figure 22). The majority of olive cultivation in Andalusia takes place in the provinces of:

- Jaén: ~570.000 hectares
- Córdoba: ~350.000 hectares
- Sevilla: ~240.000 hectares

These three provinces collectively define the study area for the present case study.

With a combined area of approximately 1,16 million hectares, equating to 27% of the global area under olive cultivation, and encompassing an estimated 76.000 individual fields, this region is considered one of the leading global hotspots for olive production (Table 5 and Figure 22).

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[5] https://renewable-carbon.eu/news/bioplastic-from-olive-tree-pruning-residues/
[6]https://www.scaleup-bioeconomy.eu/Publications/SCALE-UP_D4.1_Overview-of-regionally-suitable-solutions_-rev-.pdf
[7] https://agriculture.ec.europa.eu/farming/crop-productions-and-plant-based-products/olive-oil_en
[8] https://ec.europa.eu/eurostat/web/products-eurostat-news/-/ddn-20190301-1

*Table 5: Pruning in Andalusia – Area of olive production in Cordoba, Jaen and Sevilla[9]*

| | Area of the province (ha) | Area of olive production (ha) | % | N° of fields |
|---|---|---|---|---|
| *Cordoba* | 1.439.000 | 354.000 | 25 | 27.000 |
| *Jaén* | 1.410.000 | 573.000 | 41 | 29.000 |
| *Sevilla* | 1.473.000 | 238.000 | 16 | 20.000 |
| *Total* | 4.322.000 | 1.165.000 | 27 | 76.000 |

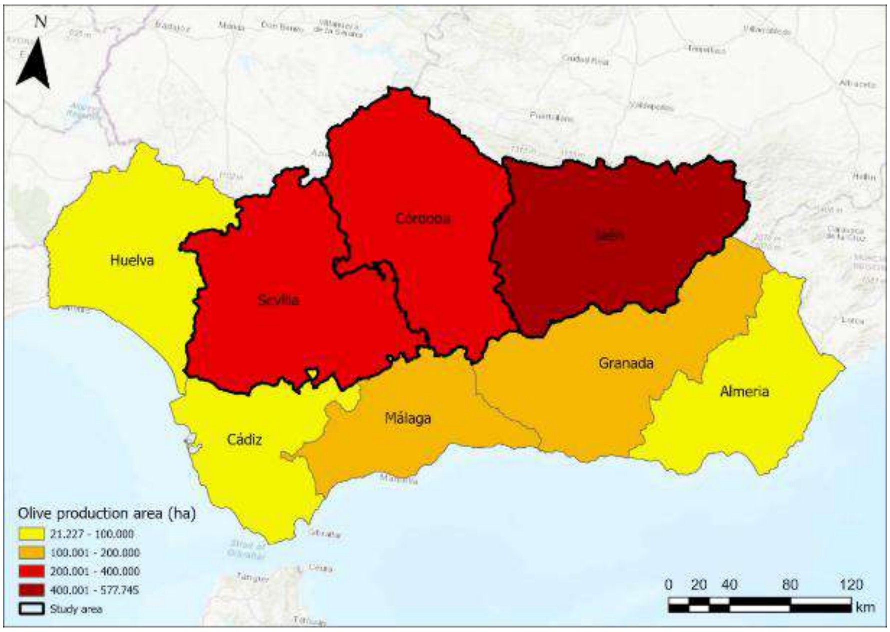


*Figure 22: Pruning in Andalusia – Area of olive production (ha) in Andalusia by province[10]*

Furthermore, this region concentrates most of the **olive processing facilities** nationwide. In 2017, in total, there were 844 oil mills (48% of the national total), 219 table olive industries (45% of the national total), and 45 olive pomace extractors (71% of the national total). [Marquina et al. (2021)].

According to Cardoza et al. (2021), more than 70% of the **olive processing wastes** generated in Spain originates from the provinces Jaen, Cordoba and Sevilla.

Focusing on **OTP valorisation**, these are most commonly shredded and used as organic fertilisers. Or as the costs related to shredding are typically borne by the farmers, small farmers, in particular, often lack the capacity and financial resources to manage these activities. As a result, burning OTP remains a widespread practice. To address this, alternative valorisation strategies that are both economically feasible and environmentally sustainable are essential. OTP has also been explored as an energy source—used as solid fuels for heat and electricity or converted into liquid biofuels such as bioethanol for transport. More recently, emerging opportunities are integrating OTPs within a broader **biorefinery concept**, aiming to optimise biomass use and enhance the production of bio-based products like bioplastics from lignocellulosic materials.

One of the potential pathways is the usage of OTP as a biobased resource for **bioplastic production**. Via pyrolysis the OTP will thermally decompose into three main fractions; a liquid fraction called

[9] Source: Univ. of Jaén
[10] Source: based on data received from Univ. of Jaén

pyrolysis oil which is a bio-oil, a solid fraction or biochar, and a gaseous fraction or syngas The solid fraction can be used e.g. as soil improver while the gas fraction is often used to maintain pyrolysis temperature. The bio-oil fraction can serve as a precursor for bioplastic production and hence is of interest to Andaltec.

The project 'Life CompOlive'[11] – coordinated by Andaltec – concludes that OTP, and especially the woody fraction, is suitable for the development of bioproducts, and quotes that **collecting these OTP** to use as raw material for the several industries could provide additional economic benefits to olive producers and also amortise management operations within the framework of sustainable utilisation.

CompOlive connects the collection of OTP with the **need for optimised strategies for collection and transport**, aligned with appropriate scales and volumes. It concludes that developing an economically viable approach to convert these residues into valuable products requires a thorough assessment of the quantities generated and their regional distribution, in order to determine the scale that minimises collection and transportation costs.

This need is further supported by Fanourakis et al. (2024), who explored the potential of OTP as a resource for biorefinery applications. The authors highlight that "projects require **optimal siting strategies**, considering the proximity to biomass sources, …, **effective logistical planning** including partnerships with biomass suppliers to ensure uninterrupted operations… to ensure project viability."

At VITO, through our MOOV service, we responded to these needs by carrying out an in-depth analysis of various collection and transportation strategies for OTP in the Andalusian region. The analysis also assessed the impact of these strategies on total logistic costs and transport mileage, as outlined in the following sections.

## 2.2 Define – Input Data and System Boundaries

The initial phase focuses on a comprehensive assessment of specific needs, characteristics, and objectives, undertaken in close collaboration with key stakeholders. This stage also encompasses the systematic collection, processing, and validation of all relevant input data to ensure a robust foundation for subsequent activities.

The logistics chain begins with the in-field pruning of olive trees. These pruning are immediately processed into woodchips at the field's edge using a chipper. In field the chipper (Figure 23 - yellow)discharges the fesh woodchips  into a medium-size transport vehicle (Figure 23 - grey). From there, the material follows one of two logistical pathways: it is either delivered to a dedicated storage facility for interim holding and air-drying or transported directly to the biorefinery for further processing.

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[11] COMPOLIVELife CompOlive - LIFE18 ENV/ES/000309 (Del. A.1.1)

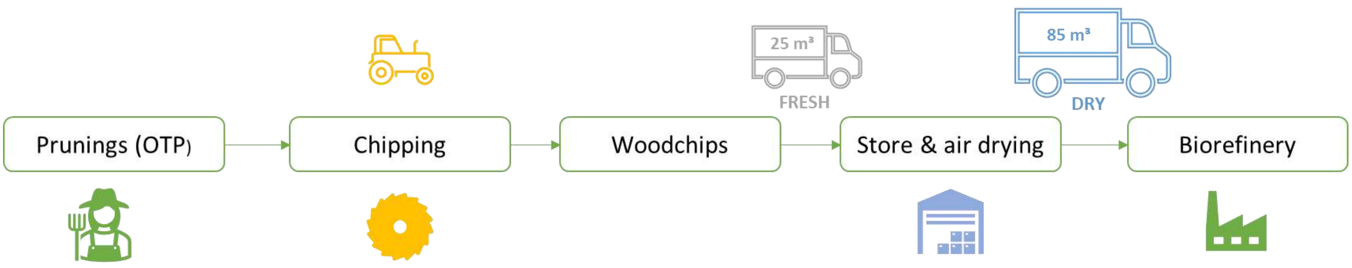


*Figure 23: Pruning in Andalusia – logistics chain.*

The subsequent sections offer a detailed overview of the products and operations involved across each stage of the logistics chain, highlighting key processes, material flows, and associated activities.

### 2.2.1 Products and activities

#### Pruning

The olive pruning campaign typically follows the harvest season, occurring during the late winter to early spring months. In Mediterranean regions such as Andalusia, this generally spans November to March, though it may occasionally extend into April, depending on local climate conditions and olive field management practices. Regional variation is detailed in Table 6, which presents the percentage of OTP generated throughout the campaign period per month.

The availability of OTP is characterised by distinct seasonal peaks. For example, in the province of Jaén, only about 2% of the annual pruning occurs in November, whereas in Sevilla, approximately 30% of the yearly OTP production happens during this month. This uneven temporal distribution contrasts with the operational preferences of biorefineries, which typically require a steady, year-round supply of woodchips. To align the seasonal availability of OTP with this constant demand, storage solutions are necessary to peak-shave the fluctuations and ensure continuous feedstock availability.

*Table 6: Pruning in Andalusia –Distribution of OTP availability per month and region [12].*

| Region | November | December | January | February | March | April |
|---|---|---|---|---|---|---|
| Jaén | 2 | 3 | 15 | 35 | 30 | 15 |
| Córdoba | 5 | 10 | 20 | 30 | 25 | 10 |
| Sevilla | 30 | 25 | 15 | 10 | 15 | 5 |
| | | | | | | |
| % | ≤5 % | 6-10 % | 11-20 % | 21-30 % | 31-40 % | |

#### Chipping

The Andalusian case focuses specifically on the woody fraction of OTP. These pruning, composed of branches (the woody component) and leaves, are generated during the routine pruning of olive trees

[12] University of Jaén

carried out after the harvest season. As illustrated in Figure 24 (a), farmers typically collect the OTP at the edge of the field.

Figure 24: Pruning in Andalusia – Feedstock collection[13].

While there are differences in cropping strategies between table olives and olives grown for oil production, their pruning is treated the same, as no significant differences in their characteristics are observed. However, it is important to note that table olives are pruned annually, whereas olive fields intended for oil production are typically pruned every two years.

In Mediterranean regions—Andalusia included—the average annual yield of OTP from table olive trees is approximately 1,3 tons per hectare. In contrast, olive fields cultivated for oil production generate around 3 ton per hectare every two years, or 1,5 ton fresh[14] per hectare per year on average. Given that oil-producing olive trees account for the vast majority of plantations (90%), with table olives representing only 4% and dual-use trees 6%, an OTP yield of 1,5 ton fresh per hectare per year is used as the reference yield potential [Marquina et al (2021)]

A mobile chipper, equipped with a small trailer simultaneously chips the pruning in the field while separating the leaves. This separation is essential, as the woody component is the primary target for bioplastic production. Additionally, leaves have a low mass density, which would result in higher transport volumes and costs for relatively little usable mass. Therefore, only woodchips are considered suitable feedstock for transportation. The leaves are left on the field, serving as an organic input to enrich the soil, while the woodchips are gathered and transported to the designated storage area.

A chipper can typically chip 1 hectare per hour and has a throughput capacity of 1,5 to 3 tons per hour, or 10 to 11 tons per day. The estimated operating cost of €30–40 per hectare. A mass correction factor of 80% is applied to the throughput to account for losses of around 20% due to fallout, spillage, and other inefficiencies (

*Table 7*).

Based on a total surface area of 1.165.000 hectares (Table 5) and assuming an average yield of 1,5 tons of fresh OTP per hectare, the gross availability amounts to approximately 1.750.000 tons of fresh OTP. Applying a mass correction factor of 80% to account for technical and operational constraints, the usable fresh OTP potential is estimated at around 1.400.000 tons.

[13] Images by Andaltec

[14] Assuming 50% water content

Assuming a drying stage is applied (refer to the 'drying' section below), the water content is reduced from 50% to 10%. This corresponds to a weight loss of approximately 45% due to water evaporation. When expressed on a dry basis, this results in an estimated annual potential of roughly 770.000 tons or 770 kton of dry OTP available in the study region.

*Table 7: Pruning in Andalusia – Feedstock collection, parameters and characteristics[15]*

| Treatment type | Capacity (ton / h) | Capacity (ha / h) | Collection cost (€ / ha) | Coefficient (%) |
|---|---|---|---|---|
| Chipping + collection | 1,5 - 3 | 1 | 30 – 40 | 80 |

Figure 25 (L) displays the olive fields locations as mapped by Cardoza et al. (2021), which are then translated into a field density map (R).

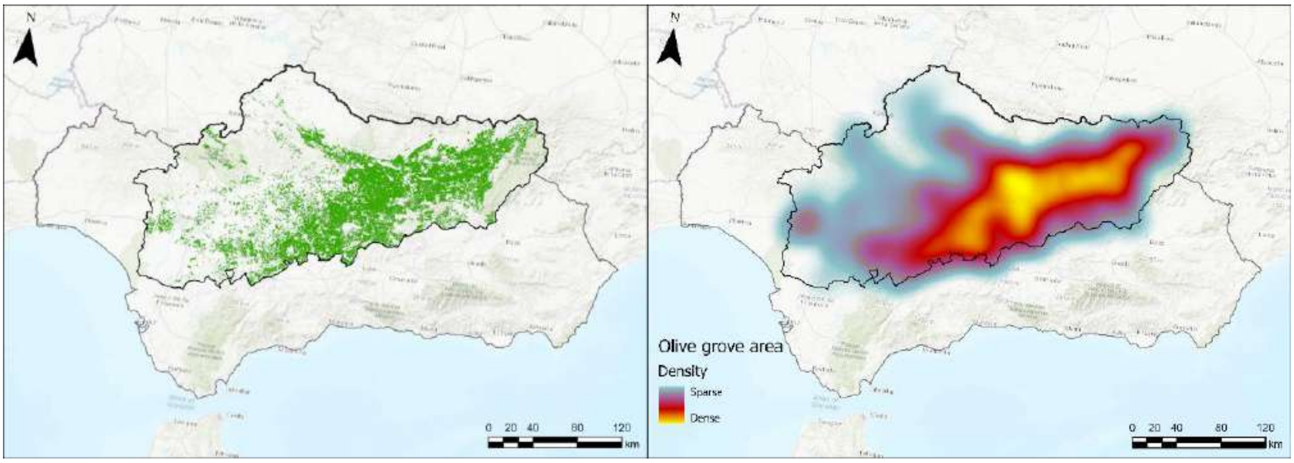


*Figure 25: Pruning in Andalusia – Olive field locations and olive field density[16]*

A strategic analysis such as the MOOV analysis does not require the details of each field independently. Therefore, the data is aggregated on a 10 km² grid (Figure 26). These “aggregated fields” are the starting point of the journey of the feedstock to the storage site or the refinery. The aggregated spatial distribution of olive tree fields (Figure 26) matches the distribution of the olive field density in the area (Figure 25 – R). More densely regions, such as the Jaen region, provide more OTP in absolute numbers than for example in the northern region of Cordoba.

[15] Source: Andaltec
[16] Source: based on data received from Univ. of Jaén

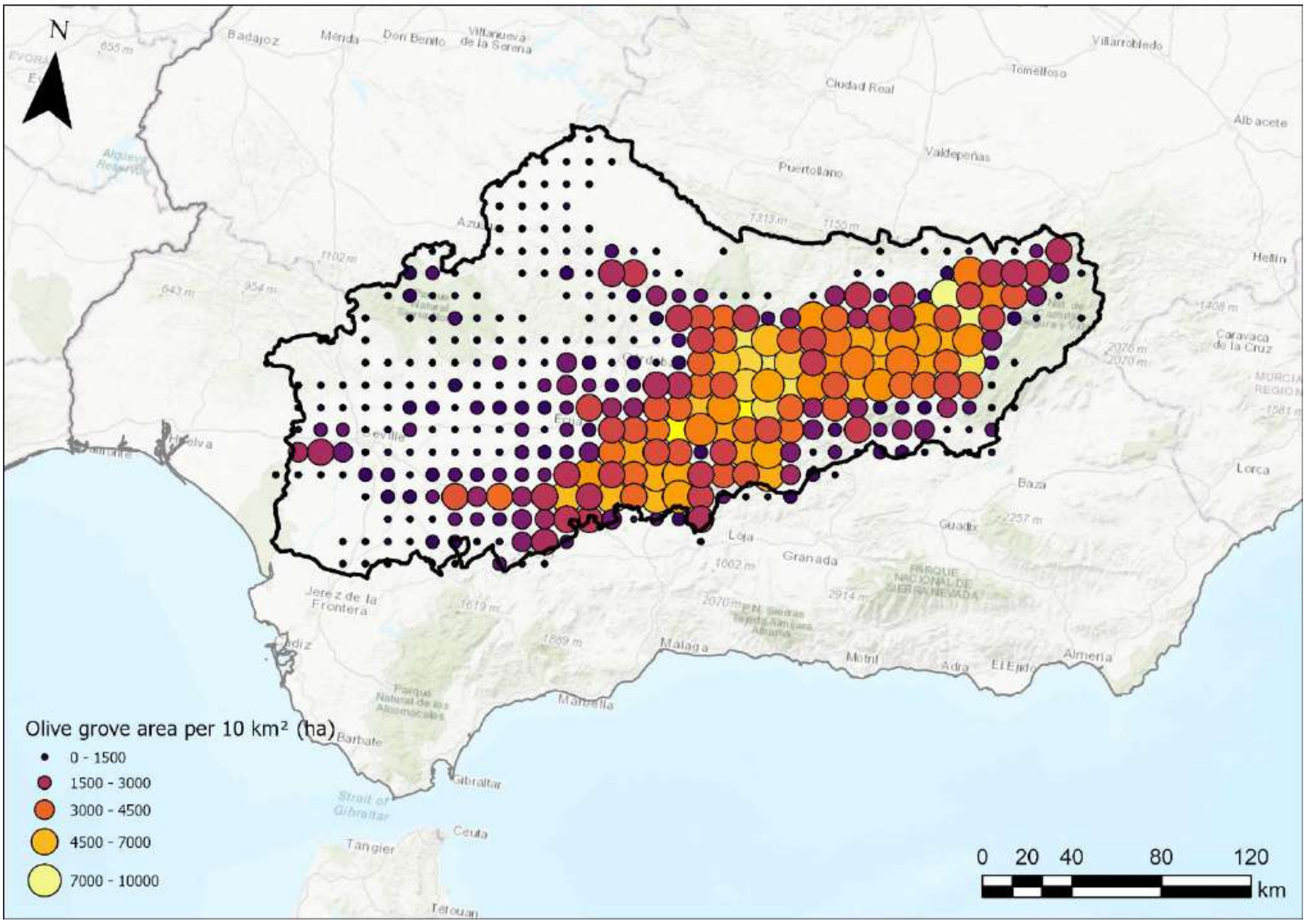


*Figure 26: Pruning in Andalusia – Olive field area aggregated to a grid of 10 km x 10 km.*

### Storage

Since pruning is limited to six months of the year, biorefineries—which typically require a continuous, year-round supply of woodchips—must rely on storage to ensure feedstock availability. This storage can be located either on-site or off-site.

**On-site storage** refers to storing biomass at the same location as the biorefinery. As such, potential on-site storage locations are inherently linked to the candidate sites for the biorefinery itself (Figure 29). This also means that the off-site storage must be dimensioned in relation to the capacity of the refinery. To ensure operational continuity, the storage facility must be capable of holding a minimum of 6 months of feedstock, effectively serving as a buffer against potential supply disruptions as well as to cover the discontinuous supply of OTP.

**Off-site storage** facilities would act as intermediate hubs between the olive fields and the biorefinery. It is assumed that existing roofed storage infrastructure at processing sites - such as olive extraction and drying facilities[17] - can be used as candidate locations for off-site storage (Figure 27)[18].

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[17] Notably, these facilities typically conclude their operations after the olive season (September–March), which coincides with the olive pruning campaign. This temporal alignment makes them particularly suitable for temporary biomass storage during the critical period of OTP collection.

[18] Andaltec and the University of Jaen.

*Figure 27: Pruning in Andalusia – Example of roofed storage facilities*

Figure 28A illustrates the locations and available roofed areas at existing processing facilities in the study area. An estimated 21.000 m² of covered surface is assumed to be available. Based on a storage density of approximately 700 kg/m², this translates to a total storage capacity of ca. 15.000 kton.

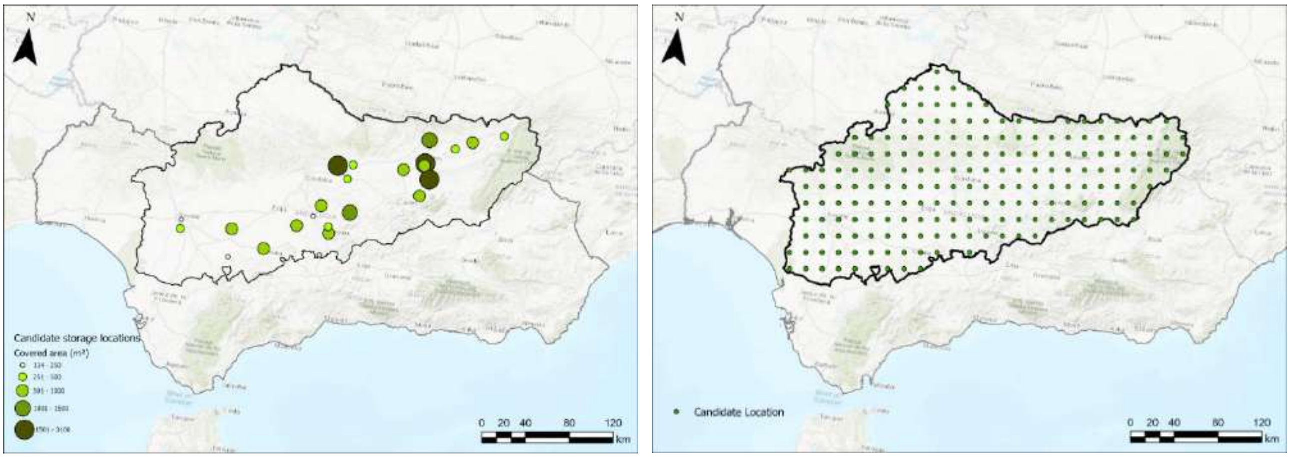



*Figure 28: Pruning in Andalusia – Existing off-site storage locations with indication of roofed area (A) and candidate locations for potential new off-site storage (B).*

In addition to identifying suitable locations for the off-site storage facilities, the scenario analysis also assesses how the number and size of off-site storage sites affect logistics costs (see Section 2.4). Storage types are divided into five categories—extra-small, small, medium, large, and extra-large—with the corresponding capacities outlined in Table 8. The storage sizes are defined as such that the XL storage unit can accommodate the entire OTP volume on its own, requiring only one site. In contrast, the extra-small (XXS) storage size represents the minimum capacity per site that still yields a feasible solution, assuming all candidate locations are utilized, and the total OTP volume is processed.

The CAPEX results from the techno-economic assessment on a woody biorefinery in the Biowood project. To consider the economy of scale, the rule of six-tenths has been applied [Tribe et al. (1986)]. The same capacities and CAPEX are considered to assess the impact of on-site storage linked to the refinery's capacity.

*Table 8: Pruning in Andalusia – Storage size and costs*

| Storage size | Capacity (m³) | CAPEX (€ per year) | OPEX (€ per ton) |
|---|---|---|---|
| Extra extra small (XXS) | 10 000 | 472 968 | marginal |
| Extra small (XS) | 50 000 | 1 242 263 | marginal |
| Small (S) | 200 000 | 2 853 971 | marginal |

| | | | |
|---|---|---|---|
| Medium (M) | 500 000 | 4 945 538 | marginal |
| Large (L) | 1 000 000 | 7 496 034 | marginal |
| Extra large (XL) | 2 225 000 | 12 193 855 | marginal |

### *Drying*

During storage, the woodchips undergo natural air-drying, which allows for the evaporation of moisture and reduces the water content from approximately 50% (fresh) to around 10% (dry)—the level required for bioprocessing. This moisture reduction results in a weight loss of about 45%, which positively affects logistics. With less water content, less mass needs to be transported, and trucks experience reduced payloads, leading to lower fuel consumption and transportation costs.

Note that given the higher ambient temperatures in Andalusia, achieving a moisture content of 10% is reasonable[19]. Exceptionally, during the cooler months - from November to February - forced drying could be necessary. In such cases, residual heat from existing biorefinery or extraction facilities could be utilised to support the drying process. However, in the scenario analysis (see section 2.4) only natural drying is considered.

While natural drying is generally sufficient for reducing moisture content, it often requires substantial storage space. When handling large volumes, woodchips cannot be stacked excessively, as this leads to elevated temperatures within the stack. Higher temperatures stimulate biological activity, which can result in dry matter losses (i.e., fibre) and potential changes in fibre quality. According to Whittaker et al. (2018), temperatures within large woodchip piles can reach up to 60°C, with dry matter losses of up to 20%. A stacking height of 5 meters is assumed leading to a storage density of 700 kg/m².

During the drying process, the woodchips need to be turned periodically to prevent degradation caused by rising temperatures within the stack. It is assumed that existing storage facilities are already equipped with the necessary turning equipment, and therefore, no additional costs are accounted for in these cases. However, for newly established storage facilities, the cost of this equipment is included in the CAPEX estimation.

### *Biorefinery*

At the biorefinery woodchips are processed into biopolymers, involving mechanical operations such as milling and sieving, followed by pyrolysis, as explained in section 2.1. At the biorefinery, the dried woodchips are processed via pyrolysis into three main fractions; a liquid fraction called pyrolysis oil which is a bio-oil, a solid fraction or biochar, and a gaseous fraction or syngas. The solid fraction can be used e.g. as soil improver while the gas fraction is often used to maintain pyrolysis temperature. The bio-oil fraction serves as a precursor for bioplastic production.

While transport costs up to the gate of the biorefinery are assessed in the scenario analysis, costs incurred within the biorefinery itself are excluded, as they fall outside the scope of logistics. Nevertheless, its location is important as the transport distance to the biorefinery directly affects the total logistic cost.

To identify the optimal location(s) for the biorefinery within the study area, a set of candidate sites has been predefined. This set is determined by overlaying a 25 km × 25 km raster grid onto the study area, with the centroid of each grid cell representing a potential site. Only those locations outside

[19] Oral communication Andaltec

Natura 2000 protected areas are considered. The remaining candidate sites are then assigned to the nearest industrial zones, as these areas are more likely to provide an environment conducive to establishing a biorefinery (Figure 29).

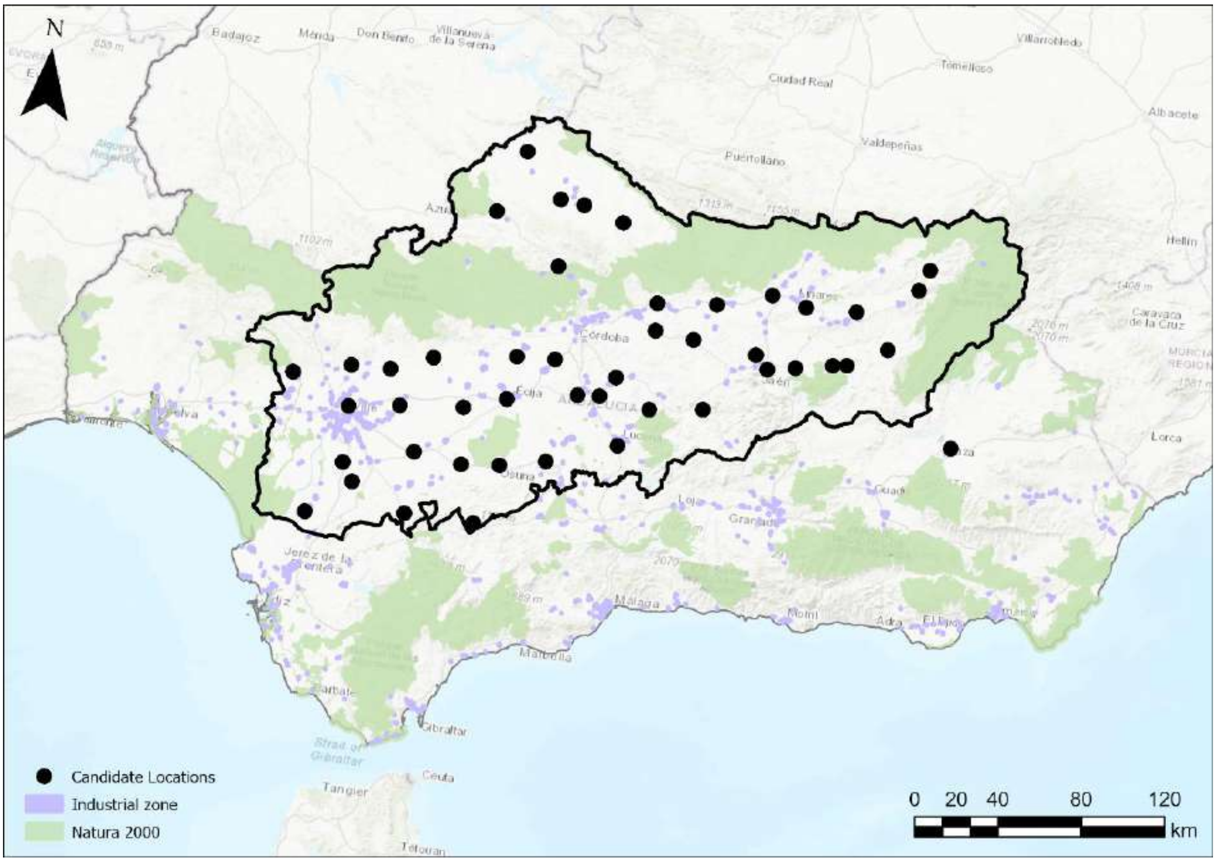



*Figure 29: Pruning in Andalusia – Biorefinery candidate locations.*

### *Bioplastic clients*

Potential clients for the produced bioplastics are not included in the current logistics assessment due to the unavailability of concrete data at the time of analysis. However, as a hypothetical ideation developed in consultation with Andaltec, several illustrative client locations can be envisioned (Figure 30):

- A processing plant within Andalusia, located in the olive cultivation zone and within 100 km of the biorefinery;
- A facility in northern Spain, such as Catalonia;
- A client site in Nantes, France;
- An industrial plant in Aachen, Germany;
- A potential customer based in Turkey.

These hypothetical locations offer a starting point for future extensions of the supply chain model, particularly in assessing downstream logistics and evaluating market accessibility at regional and international levels.

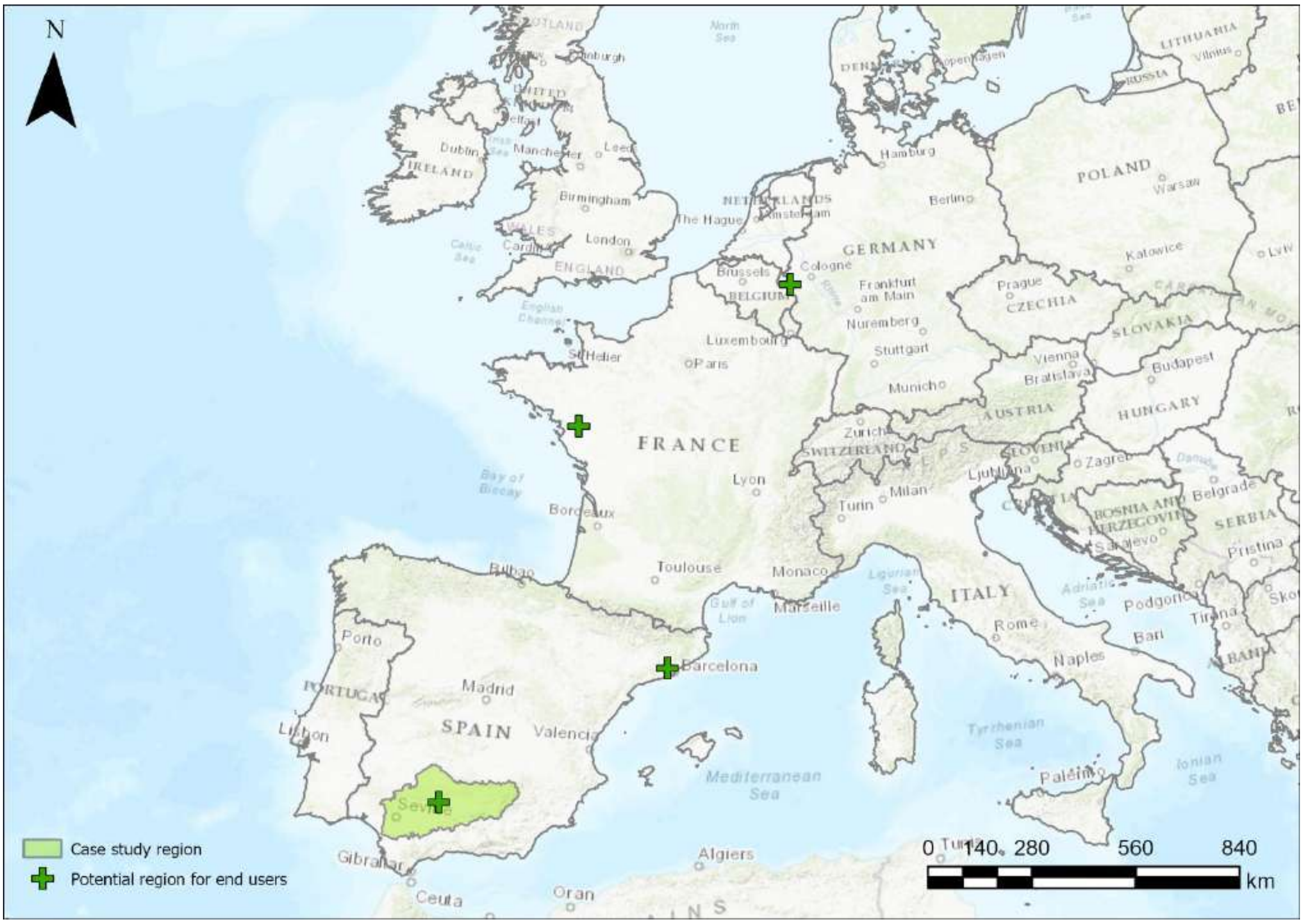



*Figure 30: Pruning in Andalusia – Bioplastic clients (hypothetical).*

### Transport

The first transport step involves moving the mobile chipper to and between the fields. This transport is assumed to start from a farm or regional garage and covers the fields within a 30 km road distance. Since the exact locations are unknown, a 60 km × 60 km raster grid is defined for the study area, with the centroid of each grid cell representing a potential starting point for the chipper.

A chipper can typically process 1 hectare per hour (Table 4), meaning it can serve multiple fields in a single day (i.e., a first-mile route). To calculate the travel distance for the chippers, the Continuous Multiscale Approach (Section 3.3.1) is used to determine the total travel distance from the various starting points (based on the 60 km × 60 km grid) towards the fields within their 30 km radius.

In a first step, the CMA defines the different districts, i.e. combining different fields to maximize the chipper's daily capacity. For each district the (first mile) travel distance is then calculated from the nearest starting point for chippers. As a result, each district is characterised by a travel distance for the chipper (km) and the total olive field area in the district (ha). Finally, the districts (and linked data) are aggregated to the 10km x 10 km grid defining the olive field area (Figure 26), summing the travel distance and summing the area of the olive fields. This results in the average travel distance for a chipper, defined in km per ha, for each point from where the truck can start the journey towards the storage site of the refinery (Figure 31).

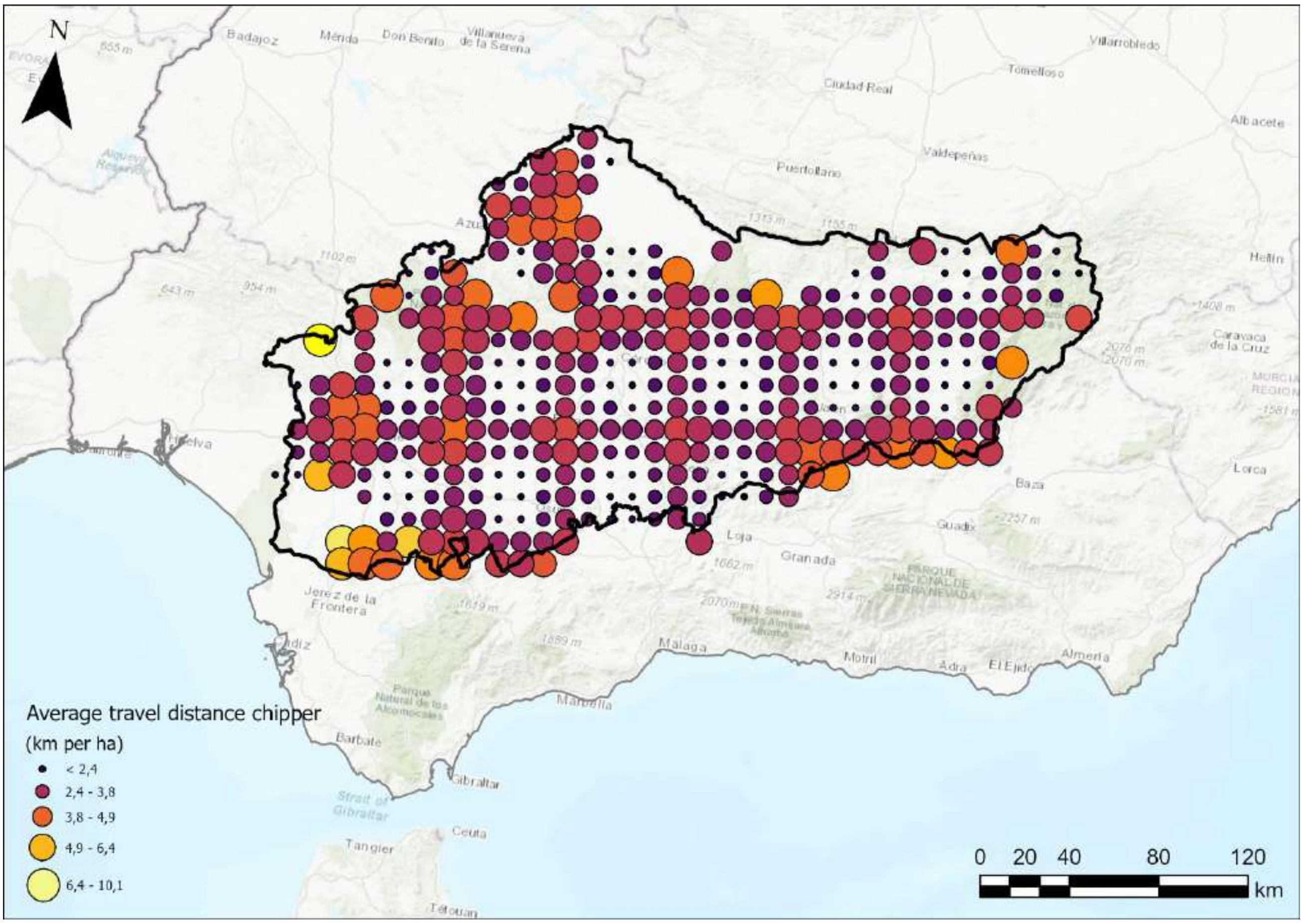



*Figure 31: Pruning in Andalusia – Average travel distance of the chipper.*

In the analysis, fresh chips are transported from the aggregated fields (represented by the points on the aggregated 10 km × 10 km grid) by truck, equipped with a container with a 25 m³ capacity. The chips are delivered either to the biorefinery (in the case of on-site storage) or to an intermediate storage facility (in the case of off-site storage). After the chips are stored and naturally dried off-site, they are transported to the biorefinery using a walking-floor trailer (Figure 23).

Within the objective function, the transport encompasses the costs related to the travelled distance, the costs related to the travelled time as well as the time needed for loading and unloading the trucks. The transport cost includes fixed costs (such as depreciations, vehicle excise duty, eurovignet, interest on capital assets, insurance costs, miscellaneous vehicle costs, costs for auxiliary hauled assets), variable costs (such as fuel costs, depreciation of capital assets, tyres, maintenance and repairs) and staff costs (such as wages, accommodation, miscellaneous) [20].

To determine the required number of trucks, the MOOV model takes into account limitations on the maximum volume as well as limitations on the maximum weight (Table 9) (Section 2.3.2). Since the functional unit of the MOOV model is 'ton', the bulk density of the different types of chips is used to calculate the respective volume (Table 10) [Martin et al. (2020)].

[20] https://www.kimnet.nl/publicaties/notities/2023/03/30/kostenkengetallen-voor-het-goederenvervoer

*Table 9: Pruning in Andalusia – Transport types, parameters and characteristics [21]*

| Transport type | Capacity (ton) | Capacity ($m^3$) | Distance cost (€/km) | Hour cost (€/h) | Load + Unload (minutes) |
|---|---|---|---|---|---|
| Chipper | - | - | 1,52 | - | - |
| Container truck (Field to storage) | 20 | 25 | 2,70 | 40 | 30 + 5 |
| Walking floor trailer (Storage to biorefinery) | 26 | 85 | 2,90 | 46 | 45 + 20 |

*Table 10: Pruning in Andalusia – Product characteristics*

| Product type | Bulk density (range) (ton/$m^3$) | Bulk density (in model) (ton/$m^3$) |
|---|---|---|
| OTP chips (50% MC) | 0,272 – 0,348 | 0,31 |
| OTP dried chips (10% MC)) | 0,15 – 0,165 | 0,16 |

### 2.2.2 Network flow diagram

The complete process chain—from feedstock collection to end-processing is not confined to a single location. Following on-field chipping of pruning into woodchips, the fresh material is transported by truck to a storage site, which may be either on-site or off-site. If stored off-site, the dry woodchips are subsequently delivered by truck to the end-processing facility after a limited storage period. The corresponding network flow diagram captures these activities and corresponding flows between activities and locations and serves as the foundation for the Biotransform MOOV model. (Figure 32).

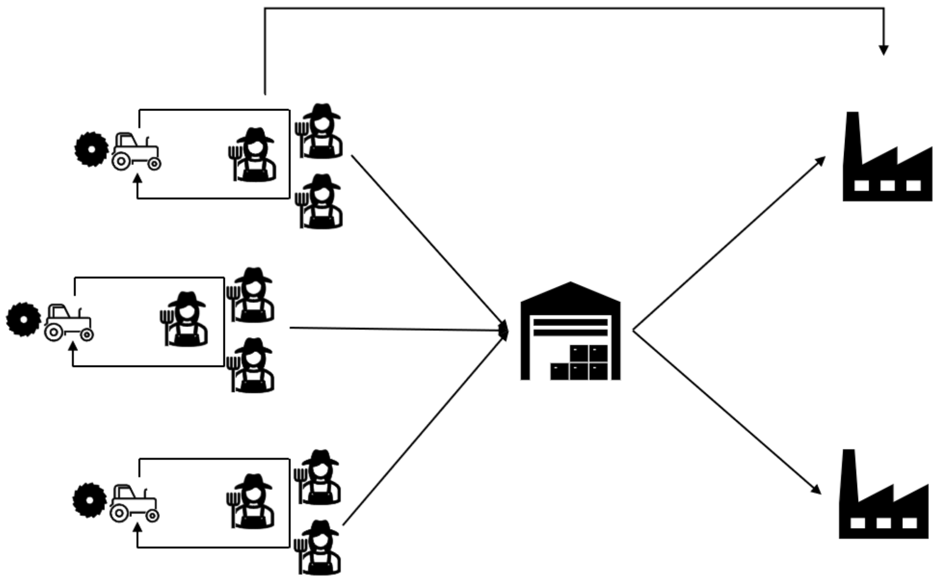


*Figure 32: Pruning in Andalusia - Network flow diagram*

[21] https://www.kimnet.nl/publicaties/notities/2023/03/30/kostenkengetallen-voor-het-goederenvervoer

## 2.3 Design – the MOOV Biotransform Andalusian model

To reflect the unique characteristics of the Andalusian case, a shell is modelled embedding case-specific requirements, constraints, and contextual details derived from user inputs. This modular structure enhances the model's adaptability: individual parameters, processes, or constraints can be added, modified, or removed without impacting the underlying core logic (section **Error! Reference source not found.**). As a result, multiple scenario analyses can be conducted using a consistent modelling framework, thereby enabling robust comparability between scenarios.

The Biotransform-shell of the Andalusian case includes the definition of the objective function (Section 2.3.1), the addition of several specific constraints (Section 2.3.2) and the connection of the MOOV-core to the CMA (Section 2.3.3).

### 2.3.1 Objective function

In mathematical modelling, especially in optimisation problems, the objective function is a mathematical expression that defines the goal of the model—what you want to maximise or minimise. Within the Andalusian case, the current focus is on **the minimisation of the mobilisation costs related to the transport of woody biomass from olive fields up to the gate of the biorefinery.** However, regional stakeholders have expressed interest in broadening the scope of the optimisation in future iterations such as extending the supply chain towards bioplastics clients (Section2.2.1) or enhancing circularity and reducing environmental impacts by aligning the supply chain with broader sustainability objectives.

The total mobilisation cost is composed of the following key cost elements, each representing a specific activity in the biomass supply chain (Figure 33).

1) Chipper transport: This includes the cost associated with the movement of the chipper to the olive tree pruning (OTP) fields and between individual field locations.
2) Feedstock: This refers to the cost of chipping the OTP into woodchips at the field site.
3) Storage: These costs encompass capital expenditure (CAPEX) and operational expenditure (OPEX) related to storage activities. Based on Tschulkow et al. (2020), OPEX is assumed to be marginal, while CAPEX is only considered in scenarios where new storage infrastructure is required.
4) Transport: This includes the cost of moving feedstock and processed material between locations, as well as costs related to transshipment activities, such as loading and unloading. Specific transport flows considered are:
    a. transport from field to the storage
    b. transport from storage to end-processing
    c. transport from field to biorefinery (direct transport in case no storage sites are used)

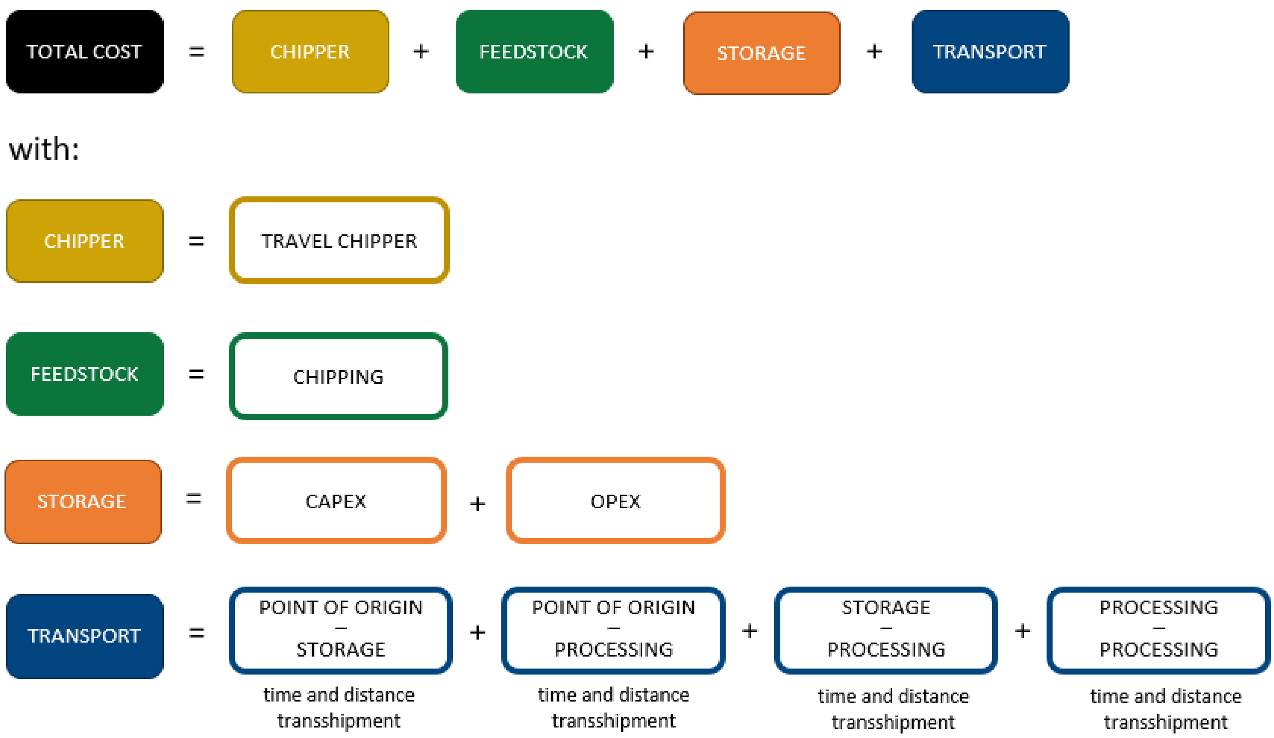



*Figure 33: Pruning in Andalusia - Components of the total mobilisation cost included in the MOOV model.*

In addition to the total mobilisation cost (€), the total transport distance (km) and the number of vehicle movements (#) are assessed for each scenario.

### 2.3.2 Constraints

In addition to the objective function, which defines the goal of the optimisation (i.e. minimising costs), a set of constraints is implemented to reflect the limitations and operational conditions under which the supply chain must function. These constraints ensure that the solutions generated by the model are both feasible and realistic within the context of the Andalusian case:

- The availability of OTP is characterised by distinct seasonal peaks that differ between the 3 regions (Table 6). To include this spatio-temporal availability of OTP, 2 constraints are added. A first constraint to calculate the quantity of OTP used in a specific region in a specific month and a second constraint to limit this calculated quantity to the available amount at that time in that region (considering the percentages defined in Table 6).
- The transport can be limited by the weight of the container or by its volume. Therefore, transport constraints are added defining the number of trucks required to transport the fresh or dried woodchips, based on the maximum allowed volume versus the maximum allowed weight. The maximum of both constraints is considered in the transport cost function.

### 2.3.3 Continuous Multi-scale Approach

The Continuous Multi-Scale Approach (CMA) is an innovative framework developed to model the challenges of last-mile distribution at a strategic level [Arevalo-Ascanio et al. (2024)]. It integrates spatial demand patterns and estimates of distribution route lengths. The CMA framework combines two key theories: Continuous Approximations (CA) and the Districting Problem (DP), in order to support multi-scenario, long-term decisions in supply chain design.

**Districting Problem (DP):** The CMA framework begins with a multi-scale district configuration. The service area is divided into smaller, congruent districts, primarily using hexagonal tiles for optimal compactness and contiguity. Hexagons are chosen due to their geometric efficiency in covering areas without overlap and with a minimal perimeter-to-area ratio, resulting in more efficient route planning. The size of the districts varies depending on demand density, with areas of higher demand having smaller, more concentrated districts, while sparsely populated regions have larger districts. Figure 34 gives an overview of the districting result for the whole region (L) and a zoom into a specific region (R).

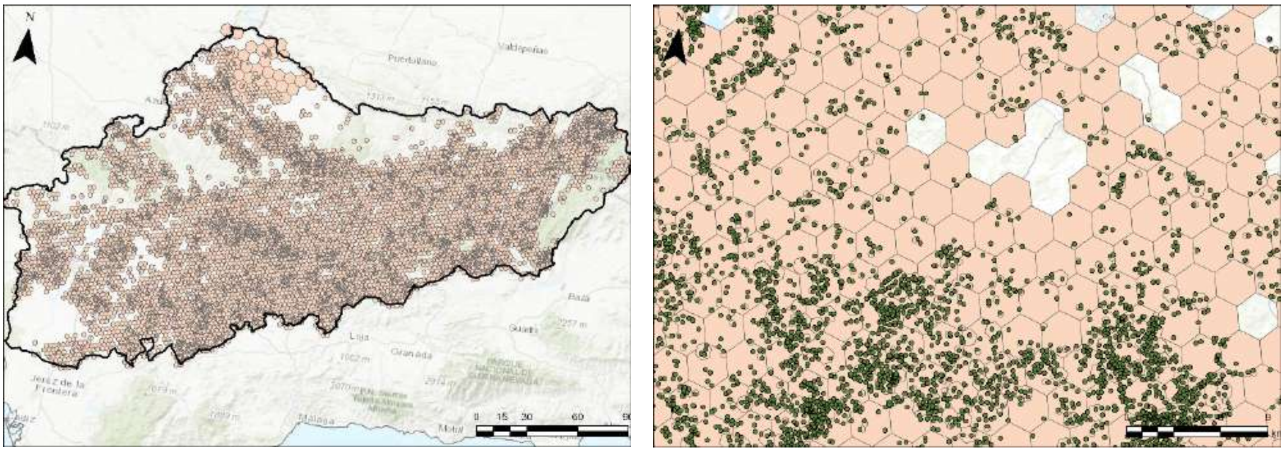


*Figure 34 Pruning in Andalusia – Result of the Continuous Multiscale Approach (Districting step).*

**Continuous Approximations (CA):** Within each district, continuous approximation techniques are applied to estimate the length of potential delivery routes. The CA method generalizes the Traveling Salesman Problem (TSP) by using minimal informational requirements, such as the area and the number of delivery points, to estimate travel distances without detailed routing information. This estimation is done using the Beardwood-Halton-Hammersley (BHH) theorem, which provides a formula to approximate the distance required to visit a set of randomly distributed points in an area.

The output of the CMA approach is the travel distance for the chipper (km) as well as the total olive field area (ha) in each district, representing the fields addressed in 1 working day of a chipper. Finally, the districts (and linked data) are aggregated to the 10km x 10 km grid defining the olive field area (Figure 26), summing the travel distance and summing the area of the olive fields. This results in the average travel distance for a chipper, defined in km per ha, for each point from where the truck can start the journey towards the storage site of the refinery (Figure 31).

## 2.4 Deliver

### 2.4.1 Overview

*Scenario overview*

The goal of the MOOV analysis is to explore the collection and transportation scenarios of OTP from the olive fields to biorefineries in the Andalusian region. The scenarios to be investigated have been defined in close collaboration with the regional stakeholder Andaltec, with additional support from the University of Jaén and the technological innovation cluster CTA (Corporación Tecnológica de Andalucía).

A concise summary of the investigated scenarios is presented below and further elaborated upon in the subsequent subchapters. The primary differentiating factors between scenarios are shown in Table 11 and can be used as a reader's guide.

- **Scenario 1:** One biorefinery with a 32 kton capacity
- **Scenario 2:** One biorefinery with a 150 kton capacity
    - **Sensitivity 2A:** Impact of additional biorefineries
    - **Sensitivity 2B:** Impact of additional storage facilities
- **Scenario 3:** One biorefinery with a 700 kton capacity
    - **Sensitivity 3A:** Impact of additional biorefineries

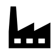
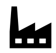
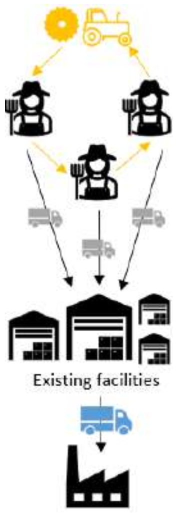
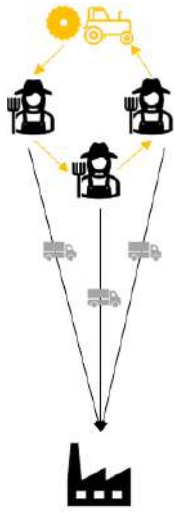
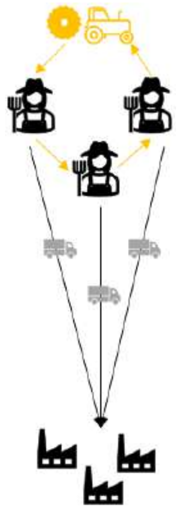
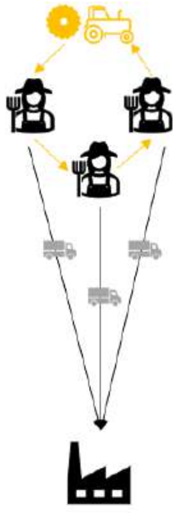
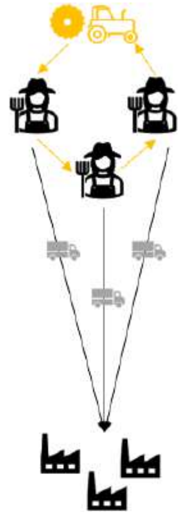
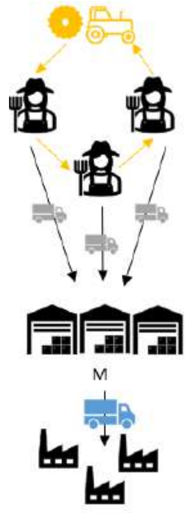
*Key performance indicators*

The KPIs in the sections below are 'cost' and 'mileage', which can be found in the result tables. The indicators are to be interpreted as follows:

- **Cost:** expresses the logistics cost per ton dry OTP - including cost for collection, chipping, storage and transport movements.
- **Mileage:** expresses the transport distance per ton dry OTP delivered at the gate of the biorefinery. The mileage includes
    - transport from field to the storage
    - transport from storage to end-processing
    - transport from field to biorefinery (direct transport in case no storage sites are used)

As a reminder, the objective of each scenario is to **minimise the mobilisation cost** (see section 2.3.1)). The main degrees of freedom to obtain this include the **optimal selection of field locations for biomass sourcing**, as well as the optimal locations for **placement of storage sites and biorefineries**.

*Table 11: Pruning in Andalusia – Visualisation of the scenarios*

| | | SCENARIOGROUP 2 | | | SCENARIOGROUP 3 | | |
|---|---|---|---|---|---|---|---|
| | Scenario 1 | Base scenario 2 | Sensitivity 2A | Sensitivity 2B | Base scenario 3 | Sensitivity 3A | Sensitivity 3B |
| Biomass production | 1,5 ton/ha | 1,5 ton/ha | 1,5 ton/ha | 1,5 ton/ha | 1,5 ton/ha | 1,5 ton/ha | 1,5 ton/ha |
| Storage location |  |  |  |  |  |  |  |
| Storage capacity | Existing | XL | XL | XXS → XL | > XL | > XL → M | M |
| Number of biorefineries | 1 | 1 | 1, 2, 4 | 1, 2, 4 | 1 | 1, 2, 5, 10 | 1, 2, 5, 10 |
| Biorefinery capacity | 32 kton/y | 150 kton/y/BR | 150 kton/y/BR | 150 kton/y/BR | 698 kton/y | 698 – 349 – 140 - 70 kton/y/BR | 698 – 349 – 140 - 70 kton/y/BR |
| Flow chart |  |  |  |  |  |  |  |

### 2.4.2 Scenario 1: One biorefinery (32 kton capacity) – using existing off-site storage

Since the pruning campaign is limited to six months of the year, biorefineries—which typically require a continuous, year-round supply of woodchips—must rely on storage to ensure feedstock availability. This scenario assumes that existing roofed storage infrastructure at processing sites, such as olive extraction and drying facilities, is about 21.000 m² and can be used as off-site storage for OTP (Figure 28) [22,23,24].

With a storage density of approximately 700 kg/m², this infrastructure offers a total storage capacity of about 15 kton. When utilised to its full extent, this capacity is sufficient to support a biorefinery with an annual input requirement of 32 kton OTP.

In this scenario, storage site locations are fixed, as they rely on existing infrastructure. Therefore, optimisation focuses on the selection of optimal sourcing fields and the ideal biorefinery location. Results from the optimisation analysis indicate that the Jaén region emerges as the most favourable location for the biorefinery (Figure 35). This choice is primarily driven by the higher concentration of large storage facilities in the area (Figure 28).

The selected fields supplying fresh woodchips are located in proximity to the storage sites. However, it is noteworthy that not all selected fields are the closest ones to the storage. This outcome highlights the trade-off between chipper transport costs and the transport costs from field to storage.

[22] Notably, these facilities typically conclude their operations after the olive season (September–March), which coincides with the olive pruning campaign. This temporal alignment makes them particularly suitable for temporary biomass storage during the critical period of OTP collection.

[23] Source: Andaltec and the University of Jaen.

[24] Notably, these facilities typically conclude their operations after the olive season (September–March), which coincides with the olive pruning campaign. This temporal alignment makes them particularly suitable for temporary biomass storage during the critical period of OTP collection.

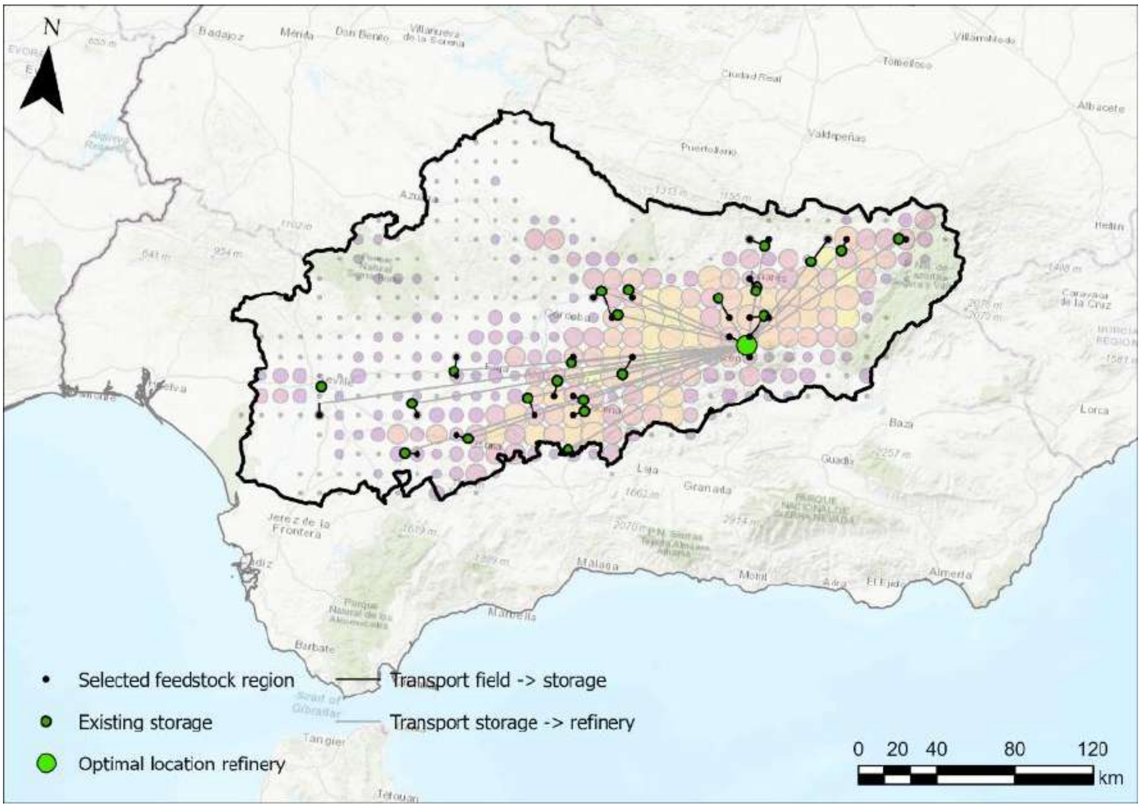



*Figure 35: Pruning in Andalusia – Scenario 1: one biorefinery with a 32 kton capacity.*

When the optimal field locations and biorefinery site are selected—while fully utilising the available storage capacity—the mobilisation cost is estimated at 122 € per ton of OTP delivered to the gate of the biorefinery. This corresponds to an average travel distance of 18 km per ton of woodchips (Figure 36).

Within this cost structure, chipping represents the largest cost component, accounting for 48% of the total. The feedstock collection cost, defined as 30–40 € per hectare (

Table 7), translates to an average of approximately 58 € per dry ton of OTP. Storage costs are considered negligible, as operations utilise existing infrastructure with marginal operating expenses (OPEX) and investments are assumed to be fully depreciated (CAPEX) (Table 8).

Along the supply chain, transporting fresh woodchips from the field to the storage facilities accounts for approximately 15% of the total mobilisation cost, equivalent to 18 € per ton of dry woodchips. As previously noted, the transport of the chipper between fields represents 12% of the cost, or 15 € per ton. These two transport components are carefully balanced by optimising field selection and logistics. This balance is also evident in the respective travel distances: the chipper covers an average of 4 km per ton of dry woodchips, while the truck transport from field to storage spans an average of 5 km per ton.

For the final leg of the supply chain, the transport distance from the storage facilities to the biorefinery averages 9 km per ton of dry woodchips, with an associated cost of 31 € per ton. This represents approximately 26% of the total mobilisation cost. Given that both the storage locations and feedstock collection costs are fixed in this scenario, the transport cost from storage to the biorefinery becomes the primary variable available for cost optimisation.

Consequently, this segment of the logistics chain plays a decisive role in the selection of the biorefinery site. The Jaén region emerges as the optimal location, primarily due to its concentration of suitable storage infrastructure and the presence of efficient transport corridors, notably along the A316. These favourable conditions enable a significant reduction in total mobilisation costs, reinforcing the strategic importance of location in the supply chain configuration (Figure 35).

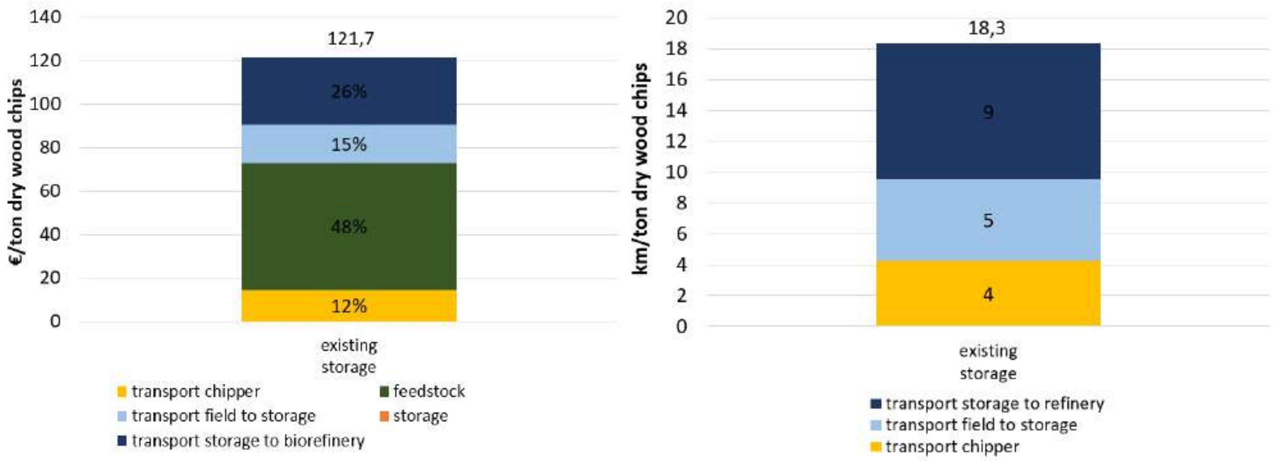



*Figure 36: Pruning in Andalusia – Scenario 1: mobilisation cost (€/ton) (L) and transport distance (km/ton) (R)*

### 2.4.3 Scenario 2: One biorefinery (150 kton capacity) – no off-site storage

While the previous scenario shows that using the current storage capacity to its maximum, allows for a biorefinery of 32 kton per year.

However, Tschulkow et al (2020) focused on the techno-economic assessment of a woody biomass-based biorefinery and highlighted the significant positive impact of scale on economic feasibility. Through a techno-economic assessment, the study identified that a processing scale of approximately 150 kton per year yielded the most favourable performance in terms of cost-effectiveness and total viability[25].

Building on these insights, scenario 2 explores the establishment of a biorefinery with a processing capacity of 150 kton per year. As a first step, a base case is assessed in which no off-site storage infrastructure is used—meaning that fresh OTP woodchips are transported directly from the field to the biorefinery.

In addition, two sensitivity scenarios are evaluated:

- Sensitivity Scenario 2A examines the impact of deploying multiple biorefineries within the system.
- Sensitivity Scenario 2B investigates the effect of integrating off-site storage facilities into the supply chain.

The results of the 150 kton base scenario (Scenario 2) serve as the benchmark against which the outcomes of these sensitivity analyses are compared. This approach enables a clear assessment of how various design and logistical decisions influence the total mobilisation cost.

---

[25] The study addressed different capacity levels:20, 75, 150 kt/y

Results of scenario 2 show that the optimal biorefinery location is located in Porcuna, near the border between Córdoba and Jaén along the A306. The location's favourable conditions, including a high olive area density (Figure 26), a low average transport distance for the chipper (Figure 31) and efficient transport links (along A306), make it the optimal choice (Figure 37) for this base scenario.

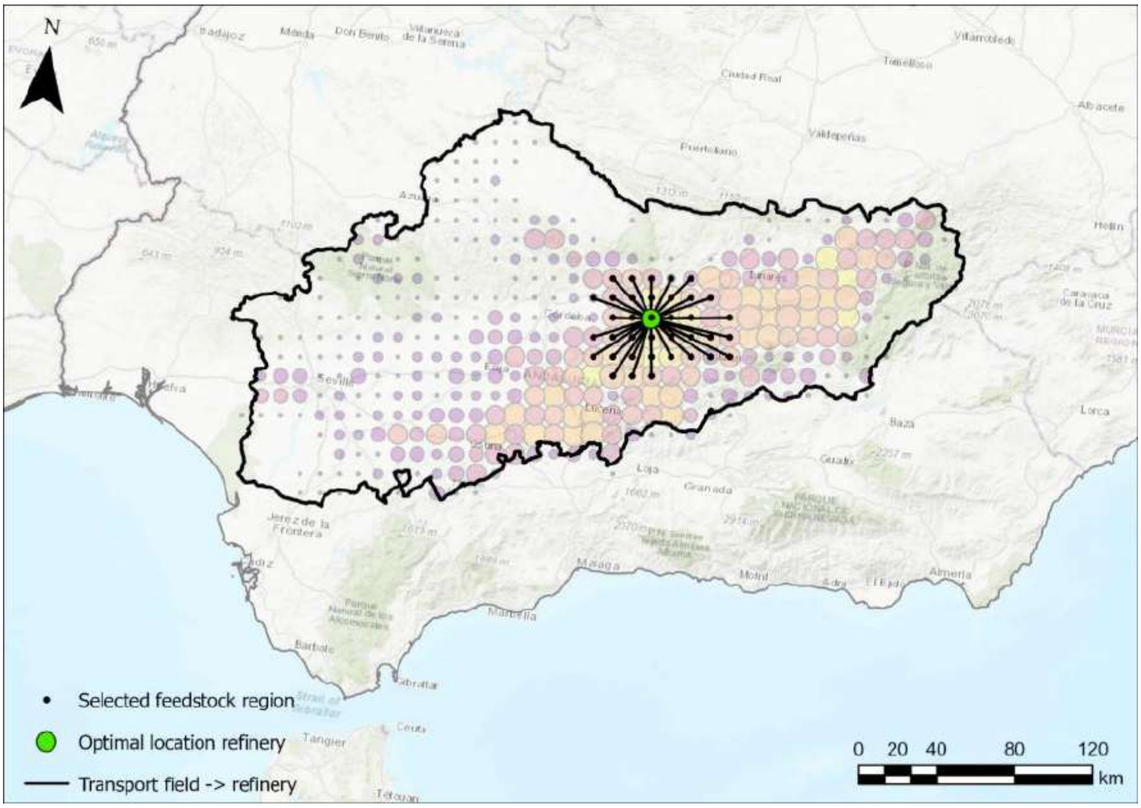



*Figure 37: Pruning in Andalusia – Scenario 2: One biorefinery with a 150 kton capacity*

The total mobilisation cost amounts to 143 € per dry ton of OTP. The chipping cost represents the largest share of this cost, accounting for 41%.

The results indicate that, for a biorefinery operating at a scale of 150 kton per year, an on-site storage capacity of approximately 5 million m³ is sufficient to ensure uninterrupted feedstock availability. This requirement corresponds to an estimated capital expenditure (CAPEX) of around 2 million euros per year (Table 8). When allocated over the annual throughput, this translates to a storage cost of approximately 13 € per ton of dry OTP, representing about 9% of the total mobilisation cost.

With on-site storage in place, woodchips are transported fresh directly from the fields to the biorefinery. This transport operation results in a cost of 46 € per ton of dry OTP[26], accounting for approximately 32% of the total mobilisation cost.

The selection of the optimal biorefinery location is driven by a trade-off between chipper transport costs and the transport cost of moving fresh woodchips to the on-site storage facility at the biorefinery. Given the higher moisture content of fresh woodchips and the reduced volume-based payload

[26] Although the woodchips in this scenario are transported in a fresh state, the results have been recalculated on a dry basis to enable consistent comparison across scenarios.

capacity of container trucks[27], the cost of field-to-biorefinery transport becomes a more influential factor in total cost optimisation.

The total transport distance amounts to 21 km per ton of dry OTP (Figure 37). While the fields are selected in the vicinity of the biorefinery, the average travel distance from field-to-storage[28] amounts to 16 km, accounting for 73% of the total transport distance (Figure 38).

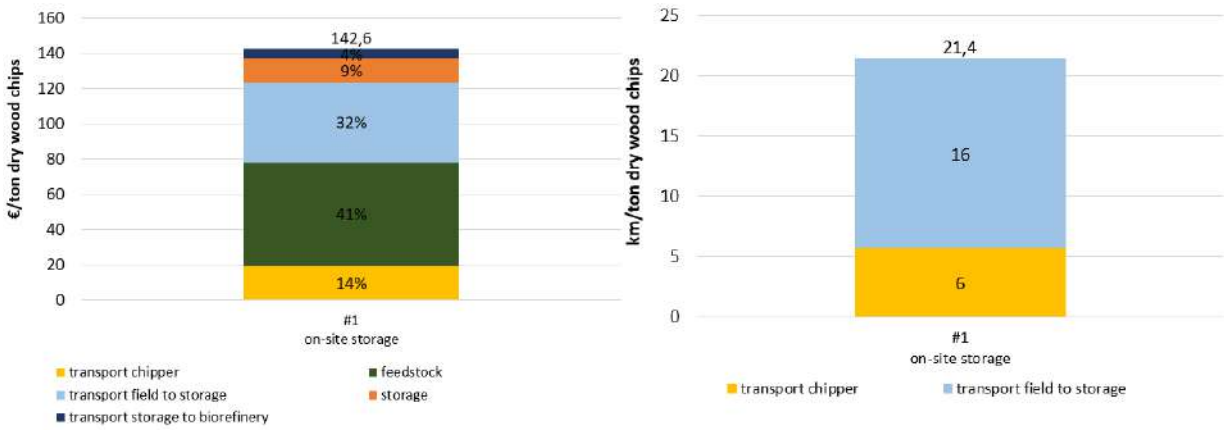



*Figure 38: Pruning in Andalusia – Scenario 2 – Mobilisation cost (€/ton) (L) and transport distance (km/ton) (R).*

## 2.4.3.1Sensitivity 2A: Impact of multiple biorefineries

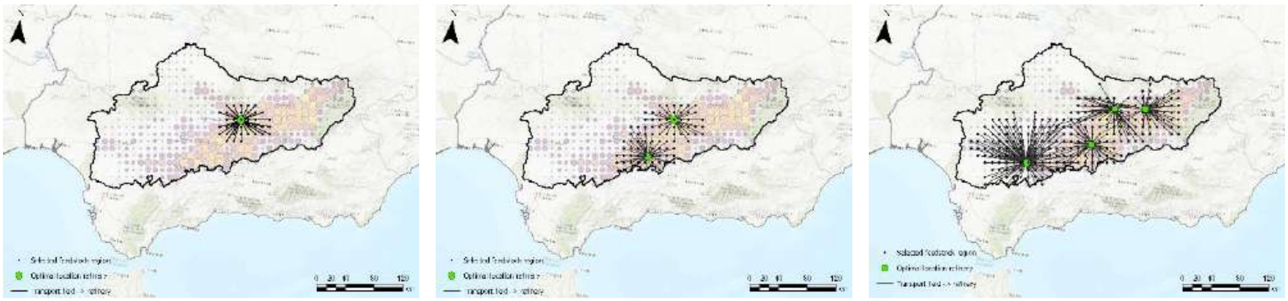
Scenario 2 focused on the establishment of a single biorefinery. However, the availability of additional feedstock in the region indicates the potential to support multiple facilities. Sensitivity Analysis 2A explores the impact of deploying additional biorefineries, each with a processing capacity of 150 kton of dry OTP per year.

The estimated regional feedstock potential amounts to approximately 770 kton of dry OTP annually. While this would theoretically support up to five biorefineries of this scale, a more conservative and realistic assumption limits the maximum to four. Based on this, two alternative configurations are assessed: one scenario with two biorefineries and another with four.

Each scenario is analysed independently, with biorefinery locations determined anew for each case. This approach ensures that the site selection process remains responsive to the specific supply chain configuration of each scenario, rather than being constrained by prior location choices.

While the optimal location for one refinery is located in Porcuna (Figure 39 - left), for 2 biorefineries, the location in Porcuna is retained and an extra refinery is opened in Lucena, in the south of Córdoba (Figure 39 - middle). In case of opening 4 biorefineries, 4 new locations are selected near Linares, Andujar, Dona Mencia and Cazalla (Figure 39 - right).

[27] See Table 9 – container truck (25 m³) vs. walking floor trailer (85 m³)
[28] In this case, storage refers to on-site storage at the biorefinery.



1 biorefinery of 150 kton with on-site storage | 2 biorefineries of 150 kton with on-site storage | 4 biorefineries of 150 kton with on-site storage

*Figure 39: Pruning in Andalusia – Sensitivity 2A – Impact of additional biorefineries*

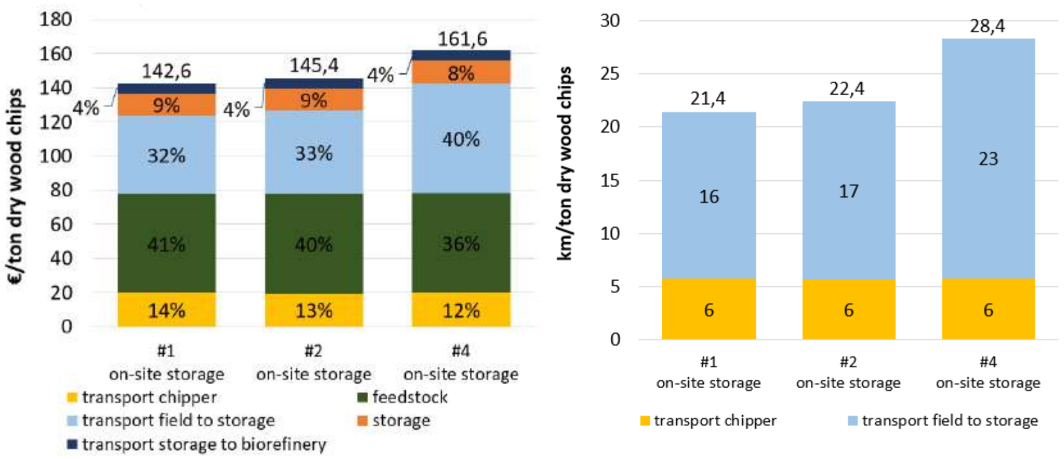
With increasing biorefineries, logically the mobilisation costs increase, as more feedstock is required. With 2 refineries the mobilisation cost rises only slightly by 2%, to 145 € per ton of dry OTP. A scenario with 4 refineries shows a more substantial increase by 13%, to 162 € per ton of dry OTP. The increase in total mobilisation cost is primarily due to increase in field-to-storage[29] transport cost (Figure 40 - L).

This trend is also evident in the transport distances, which increase by approximately 5% in the case of two biorefineries and by 33% when four are established (Figure 40 – R). The rise in field-to-storage transport distances is primarily attributed to the increased feedstock demand associated with a higher number of biorefineries. To meet this demand, sourcing fields are located further from the selected biorefinery locations, thereby extending the average transport distance.

Note that the feedstock cost—representing the cost for chipping—is assumed to remain constant at 58 €/ton across all scenarios. This value is fixed, as it is derived from a field-level cost estimate of 30–40 €/ha (

Table 7).

However, the relative contribution of feedstock cost to the total mobilisation cost decreases as the number of biorefineries increases from 41% in the scenario with a single biorefinery to 36% when four biorefineries are deployed. This is because, while feedstock costs remain unchanged, the total mobilisation cost increases with the addition of more facilities. As a result, the feedstock cost constitutes a smaller share of the total cost in scenarios with a greater number of biorefineries.

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[29] In this case, storage refers to on-site storage at the biorefinery.

*Figure 40: Pruning in Andalusia – Sensitivity 2A – Impact of additional biorefineries: Mobilisation cost (L) and transport distance (R)*

The transport distance for the chipper remains relatively stable at approximately 6 km per ton, even as additional biorefineries are introduced. This indicates that, despite the need to mobilise around 80% of the regional feedstock potential in the scenario with four biorefineries, it is still feasible to select sourcing fields that maintain a limited average travel distance for the chipper (Figure 31).

This outcome is largely attributed to the high concentration of olive fields in the south-eastern part of the region (Figure 26), where the field distribution is relatively even. This spatial distribution enables efficient sourcing and helps meet the required 80% feedstock supply without significantly increasing chipper transport distances.

The storage cost is estimated at 13 € per ton of dry OTP, accounting for approximately 8–9% of the total mobilisation cost. This relative share remains constant across scenarios with additional biorefineries, as each facility is assumed to have its own dedicated on-site storage. Each biorefinery receives a similar volume of fresh woodchips and thus incurs equivalent storage costs. As a result, the relative contribution of storage to the total mobilisation cost does not change when more biorefineries are added.

### 2.4.3.2Sensitivity 2B: Impact of off-site storage

In Scenario 2, fresh woodchips are stored on-site at the biorefinery, with transport from the field to the biorefinery carried out using smaller container trucks.

Sensitivity Scenario 2B explores the impact of introducing off-site storage facilities that serve as intermediate hubs between the sourcing fields and the biorefinery. This scenario is evaluated for the delivery of woodchips to a single biorefinery with a processing capacity of 150 kton per year.

At these off-site storage sites, natural drying is assumed to occur fresh woodchips are delivered using smaller container trucks, and after the drying phase, the dry woodchips are transported to the biorefinery using larger walking floor trailers. This setup enables improved transport efficiency in the final leg of the supply chain.

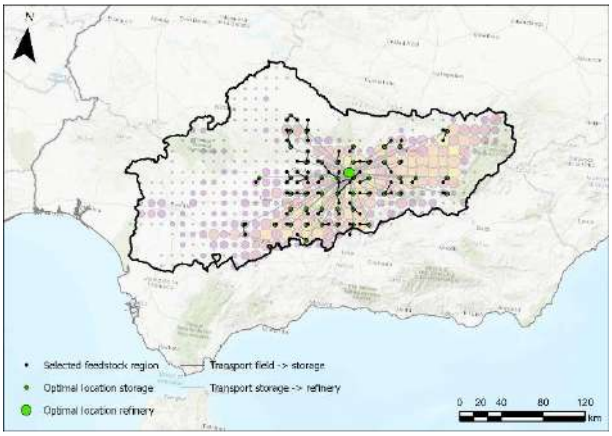
Candidate locations for these off-site storage sites are identified based on a spatial grid analysis using a 15 km by 15 km raster, allowing for systematic evaluation of off-site storage integration across the region (Figure 28 b).

To assess the impact of off-site storage facilities, different storage capacities are tested, ranging from extra-small (XXS) to extra-large (XL), as defined in Table 8.

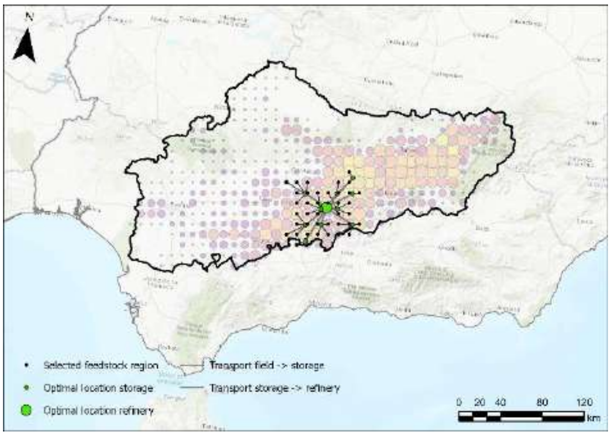
The storage types are structured such that the XL storage unit can accommodate the entire volume of OTP on its own, requiring only one storage site. In contrast, the XXS storage unit represents the smallest feasible capacity per site that still allows for a viable logistical configuration.

In the XXS scenario, a total of 48 storage sites are required, while the optimal biorefinery location remains unchanged from Scenario 2 (Figure 41 a). For configurations with larger off-site storage capacities, the optimal refinery location shifts toward the Doña Mencía region (Figure 41 b to f). In the XS scenario, 10 storage sites are needed. As the storage size increases from S to XL, the selected storage sites are progressively located closer to the biorefinery.

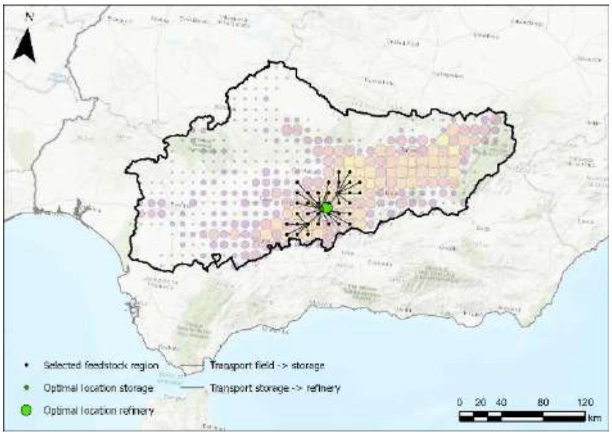
In the S scenario, 3 storage facilities are required. Both the M and L scenarios require only 2 sites, suggesting that within this capacity range, the specific storage volume does not substantially alter the total supply chain layout. Finally, in the XL scenario, only a single storage facility is needed, resulting in a configuration that logically closely resembles the base case with on-site storage at the biorefinery.



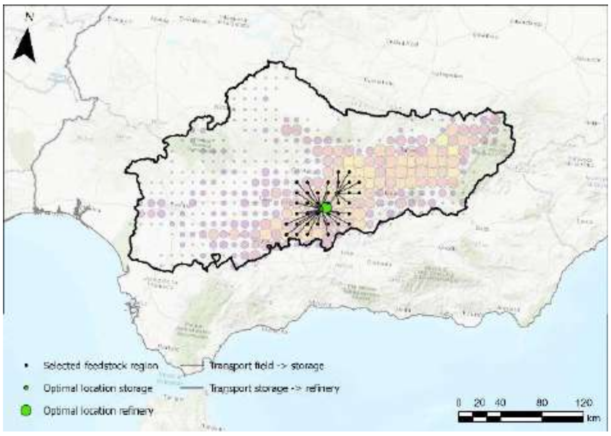

**(a)** 1 biorefinery of 150 kton with XXS off-site storage



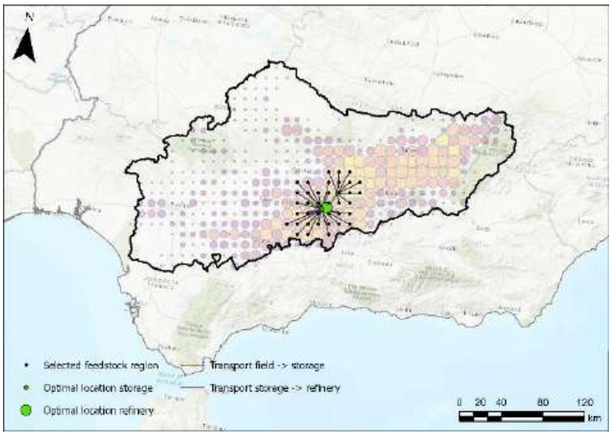

**(b)** 1 biorefinery of 150 kton with XS off-site storage



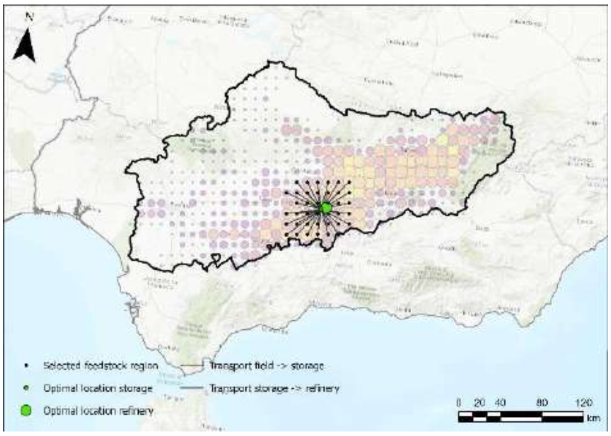

**(c)** 1 biorefinery of 150 kton with S off-site storage




**(d)** 1 biorefinery of 150 kton with M off-site storage




**(e)** 1 biorefinery of 150 kton with L off-site storage




**(f)** 1 biorefinery of 150 kton with XL off-site storage

*Figure 41: Pruning in Andalusia – Sensitivity 2B – Impact of off-site storage – Storage locations*

The total mobilisation cost associated with off-site storage ranges from 134 € per ton of dry OTP in the XXS scenario to 145 € per ton in the XL scenario, with the lowest cost observed in the XS scenario at 124 € per ton (Figure 42). The XS scenario shows a 13% cost reduction compared to Scenario 2 with on-site storage.

The cost-effectiveness of decentralised storage is driven by trade-offs between field-to-storage and storage-to-refinery transport distances, as well as the number of required storage facilities. These factors influence both transport costs and capital expenditures (CAPEX). Notably, CAPEX is affected by economies of scale—larger storage units typically reduce per-unit costs but may increase transport distances, while smaller units offer logistical flexibility but result in higher cumulative infrastructure costs.

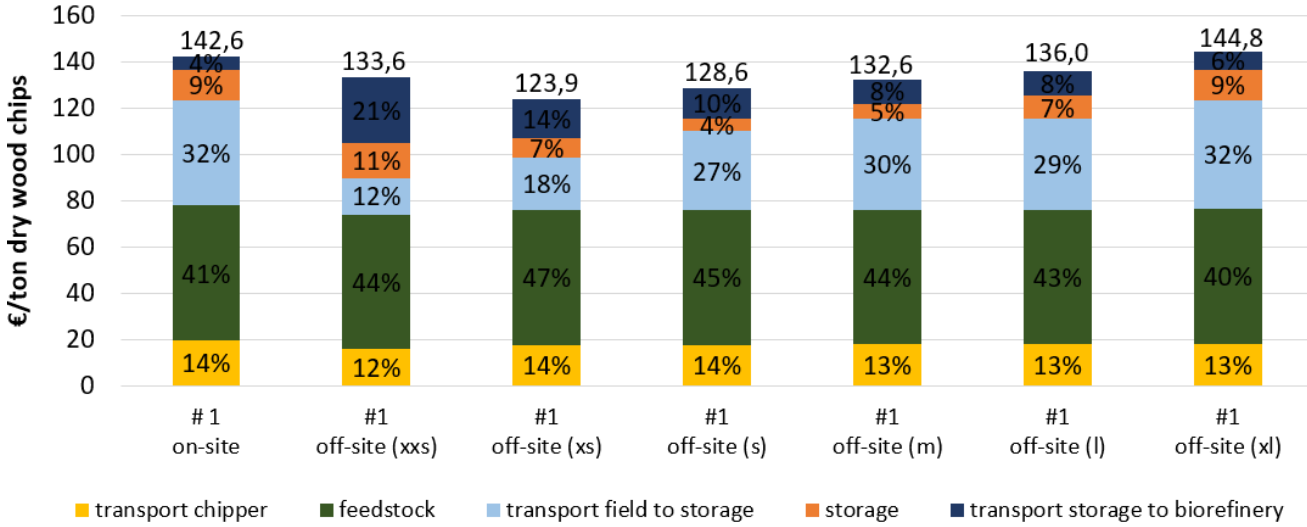



*Figure 42: Pruning in Andalusia – Sensitivity 2B – Impact of off-site storage: Total mobilisation cost.*

A more detailed analysis of the transport cost components within the total mobilisation cost reveals a significant reduction in the field-to-refinery transport cost in the XS scenario. Specifically, the cost decreases by approximately 23%—from 52 € per ton of dry woodchips in Scenario 2 to 40 € per ton in the XS scenario.

This cost reduction is primarily attributed to a 25% decrease in the field-to-storage transport leg. In the XS configuration, the average travel distance for this segment is approximately 7 km per ton, compared to 16 km per ton in Scenario 2 (Figure 43).

Although the inclusion of off-site storage introduces an additional transport leg—from storage to refinery—this segment adds only a limited distance of about 4 km. This is largely due to the use of walking floor trailers, which offer higher volume payloads and transport dry OTP, making this leg more efficient despite the added logistical step.

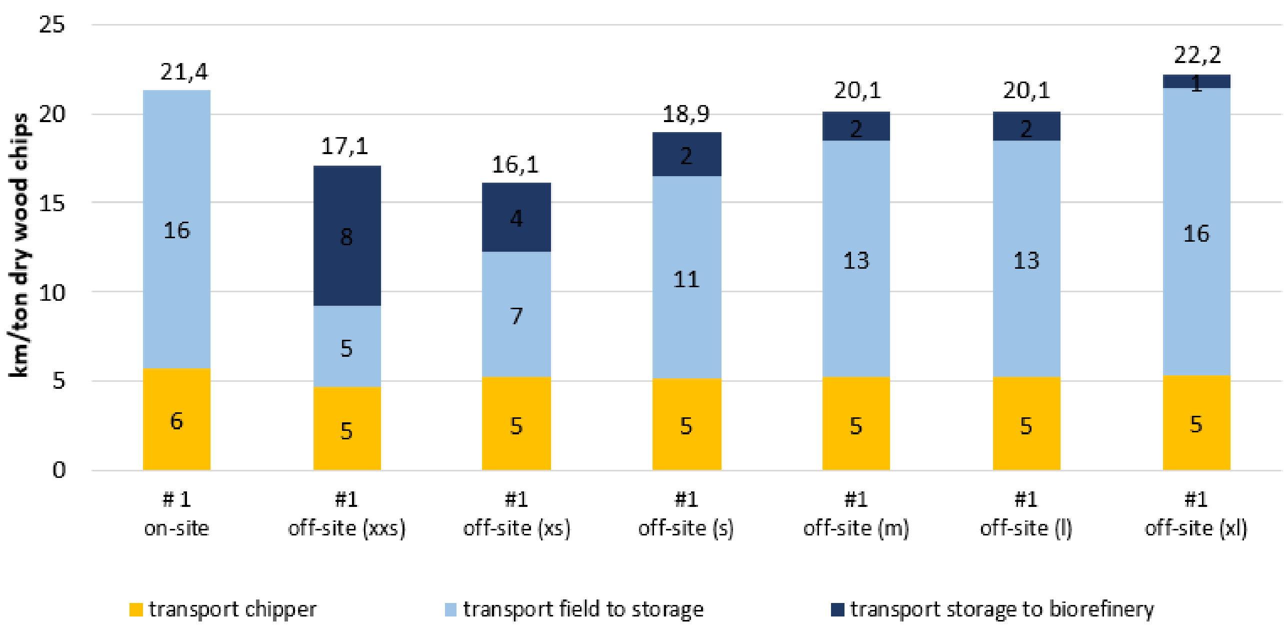



*Figure 43: Pruning in Andalusia – Sensitivity 2B – Impact of off-site storage: Total transport distance*

Based on total transport distance (Figure 27), the XXS scenario is the second-best in terms of logistics, with only a 6% increase compared to the XS scenario. Proximity of storage sites to aggregated fields limits the field-to-storage transport to 5 km per ton, but the storage-to-refinery leg doubles, raising total transport distance to 17 km per ton.

Despite the logistical efficiency, with a mobilisation cost of 134 € per ton the XXS scenario shows a modest decrease of 7% over Scenario 2. This is mainly due to the need for 48 storage sites (versus 10 in XS) and consequently the increased CAPEX.

From the S-scenario onward, both the total mobilisation cost and transport distance increase, approaching the levels observed in Scenario 2. This rise is primarily driven by longer and more costly field-to-storage transport. The findings suggest it is more cost-effective to minimise the transport of fresh woodchips and instead prioritise transporting dried woodchips using walking floor trailers, which offer greater efficiency. Nevertheless, the sensitivity analysis highlights the importance of balancing both cost components—field-to-storage and storage-to-refinery—resulting in the XS scenario being identified as the most optimal configuration.

The M and L scenarios yield identical supply chain configurations, with a transport distance of 20 km per ton of dry woodchips. However, the mobilisation cost is slightly higher in the L scenario (136 €/ton) compared to the M scenario (133 €/ton), due to increased storage costs. As the storage volume remains constant, this indicates underutilisation of the larger L-sized storage capacity, reducing its cost efficiency.

The XL scenario closely mirrors the base case in configuration and cost structure. However, total mobilisation cost and transport distance are higher due to the additional transport leg between storage and the biorefinery—absent in the base scenario with on-site storage.

A parallel sensitivity analysis was conducted for configurations with two and four biorefineries. Since the outcomes aligned with the conclusions discussed above, these results are not elaborated further.

### 2.4.4 Scenario 3: One biorefinery (700 kton capacity) – no off-site storage

Scenario 3 explores a more hypothetical case in which a single biorefinery with a capacity of 700 kton is established to process nearly the entire available OTP potential in the study region (770 kton), with all woodchips stored on-site. This scenario serves primarily as a "what-if" thought experiment, rather than a realistic short-term implementation.

The optimal refinery location is identified near Porcuna, situated at the border of Córdoba and Jaén provinces along the A306 corridor (Figure 44). This site offers several strategic advantages, including a central position within the region, proximity to the main olive-producing areas (Figure 25), and access to efficient transport infrastructure via the A306.

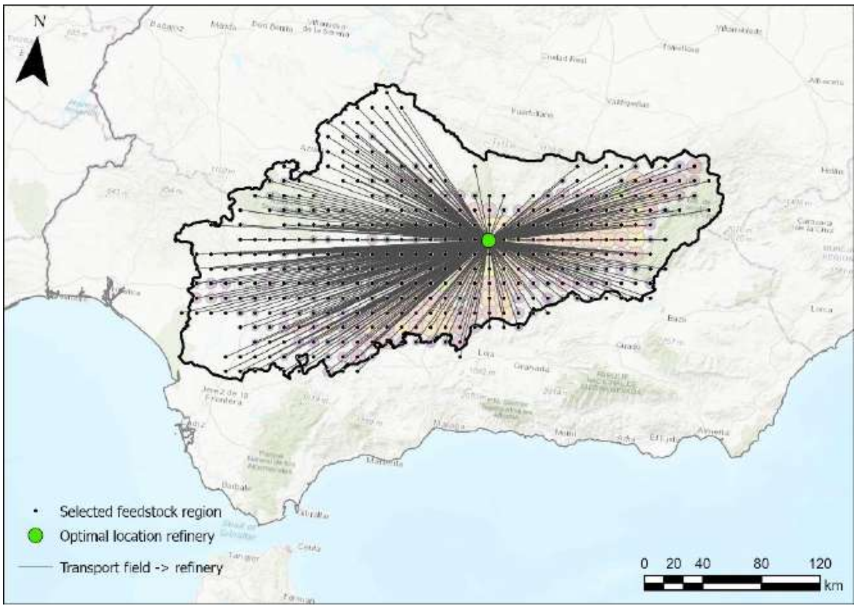



*Figure 44: Pruning in Andalusia – Scenario 3 – Optimal location of one biorefinery with a 700 kton capacity*

The total mobilisation cost for Scenario 3 is estimated at 219 € per ton of dry OTP, significantly higher than the 143 € per ton observed in Scenario 2, which is based on a 150 kton biorefinery.

When isolating the transport component, Scenario 3 incurs a transport cost of 132 € per ton of dry OTP, representing approximately 61% of the total mobilisation cost. This substantial cost increase is driven by the requirement to mobilise nearly all available OTP in the region. As a result, the average transport distance from field to storage triples—from 16 km in Scenario 2 to 48 km per ton in Scenario 3 (Figure 45).

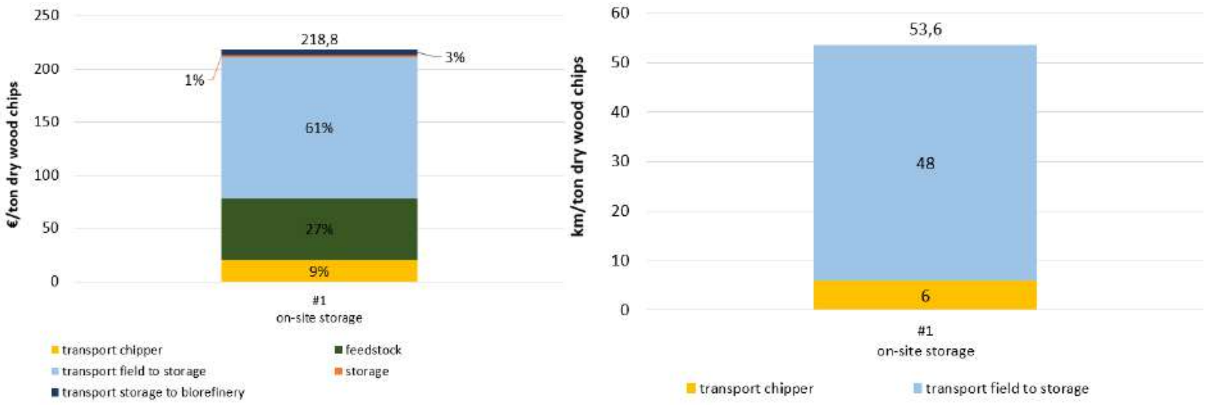



*Figure 45: Pruning in Andalusia – Scenario 3 – Mobilisation cost (L) and transport distance (R) - one biorefinery to process all available OTP.*

Finally, as previously noted, the feedstock cost—representing the chipping cost—remains constant at 58 €/ton across all scenarios (

Table 7). However, in Scenario 3, the relative share of feedstock cost in the total mobilisation cost decreases compared to Scenario 2, as the overall mobilisation cost increases by approximately 50%.

### 2.4.4.1Sensitivity 3A: Impact of multiple biorefineries

In Scenario 3, the analysis was limited to the establishment of a single biorefinery. This sensitivity analysis investigates the impact of opening multiple biorefineries to jointly process the total available woodchip volume in the region, estimated at 770 kton dry OTP. The analysis considers configurations with 2, 5, and 10 biorefineries. In each case, the total OTP volume is evenly distributed across the refineries, resulting in equal processing capacities per facility.

The objective of this analysis is to explore the implications of decentralising biorefinery infrastructure within the region. Each configuration is evaluated independently, with optimal biorefinery locations determined specifically for the given number of facilities (2, 5, or 10). This approach ensures that location selection remains responsive to the unique logistical and spatial requirements of each scenario, rather than being influenced by outcomes from previous configurations.

Scenario 3 identified the optimal location for a single biorefinery near Porcuna (Figure 46- top left). When two biorefineries are considered, the optimal sites are located in Bailén and Montilla (Figure 46- top right). Both locations offer strong connectivity within the regional transport network and are centrally positioned within the main olive-growing zone.

In scenarios with 5 and 10 biorefineries, the facilities are more widely distributed across the region, extending into less densely populated areas to ensure proximity to available feedstock sources (Figure 46- bottom). This spatial distribution reflects the need to optimise transport distances and decentralise processing operations as the number of biorefineries increases.

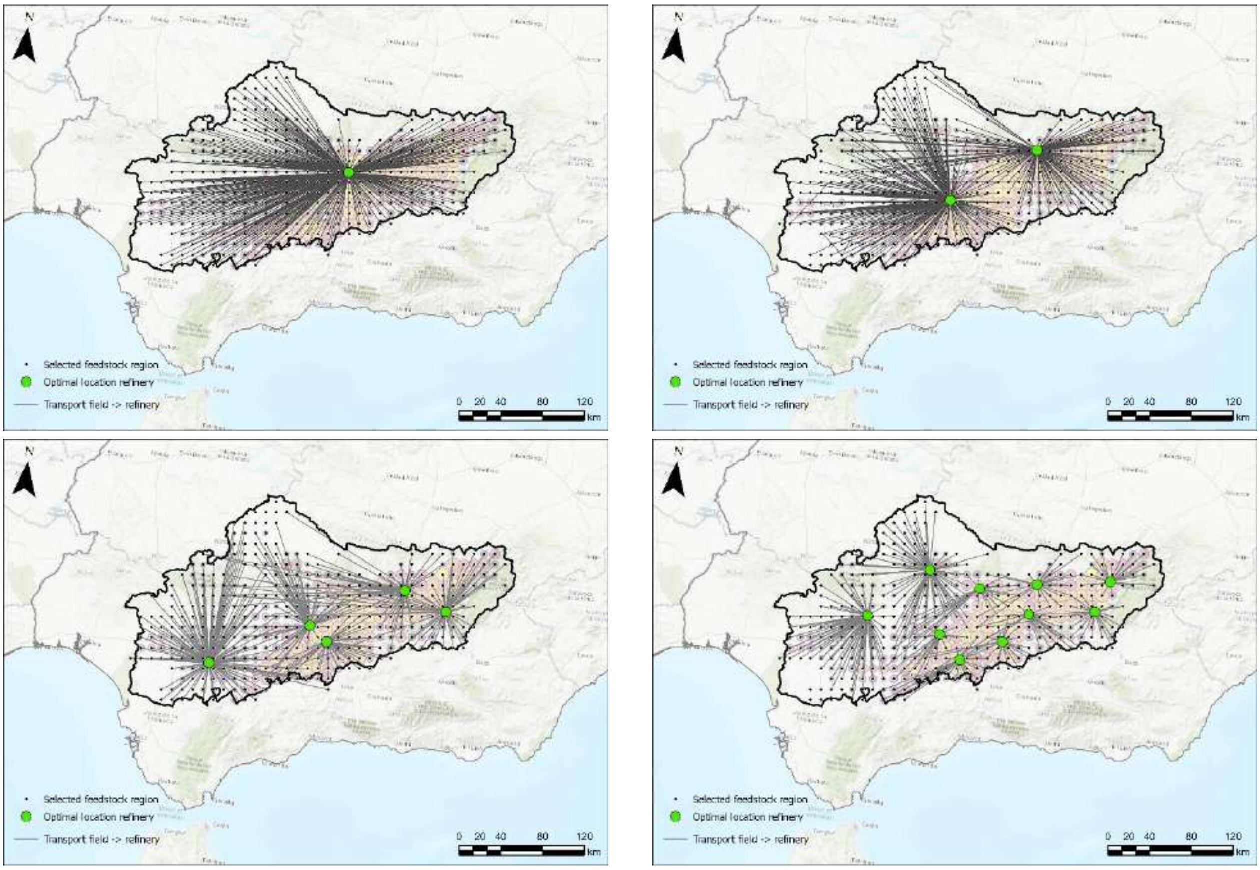



*Figure 46: Pruning in Andalusia – Sensitivity 3A – Impact of multiple biorefineries – processing all available OTP - Optimal biorefinery locations.*

Both the total mobilisation costs and transport distance decrease as more biorefineries are introduced (Figure 47). Specifically, the mobilisation cost decreases by 20%, to 180 € per ton of dry OTP when two biorefineries are introduced, by 26%, to 161 € per ton when five biorefineries are added, and by 33%, to 147 € per ton when ten biorefineries are introduced.

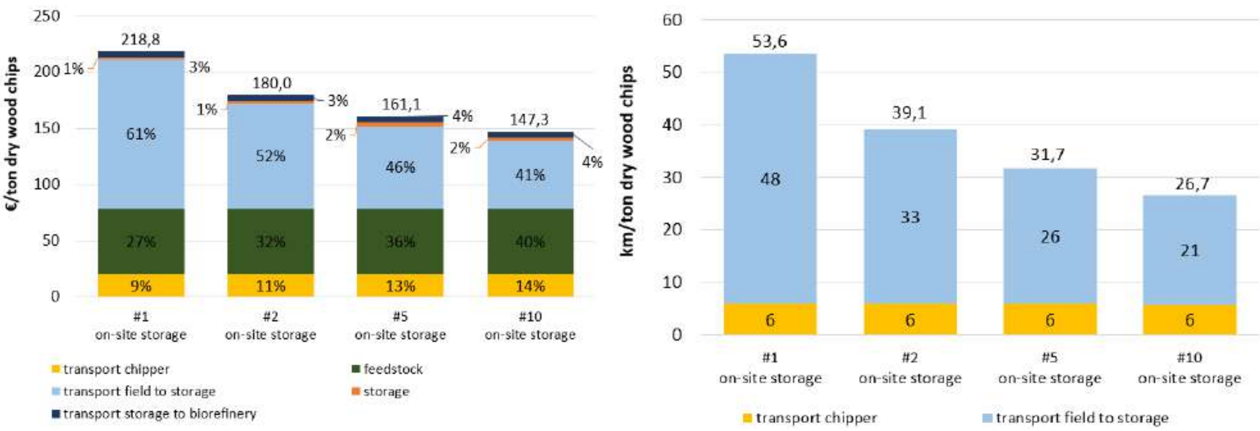



*Figure 47: Pruning in Andalusia –Sensitivity 3A – Impact of multiple biorefineries - processing all available OTP: Mobilisation cost (L) and transport distance (R)*

The reduction in total mobilisation cost is primarily due to the significant decrease in field-to-storage[30] transport costs (Figure 47 – L - light blue bar), which decrease by 30% when two biorefineries are introduced, 45% when five biorefineries are added, and 55% when 10 biorefineries are introduced.

This trend is also evident in the transport distances, which decrease by 31% with two biorefineries, 46% with five, and 56% with ten (Figure 47 – R). The reduction in field-to-storage transport distance is primarily due to the increased spatial distribution of biorefineries, allowing them to be located closer to the aggregated feedstock fields. This decentralisation improves logistical efficiency by shortening average transport routes.

Finally, it is important to note that the costs of installing additional biorefineries (CAPEX) are not considered in this analysis. It is however recommended that these costs are considered in conjunction with the reported reductions in mobilisation costs and transport distances.

#### *2.4.4.2Sensitivity 3B: Impact of off-site storage*

In Scenario 3, the analysis was limited to the establishment of a single biorefinery without the use of off-site storage facilities. As a result, fresh woodchips must be transported directly from the field to the biorefinery using container trucks, where natural drying is assumed to take place on-site.

This sensitivity analysis examines the impact of introducing off-site storage facilities that serve as intermediate hubs between the olive fields and the biorefinery. At these sites, natural drying takes place, after which the dry woodchips are transported to the biorefinery using walking floor trailers.

For this analysis, a medium (M) capacity off-site storage facility has been considered, as defined in Table 8. Additionally, to capture how the impact of off-site storage may vary with different levels of infrastructure, the number of biorefineries has been varied across the scenarios, with configurations including 1, 2, 5, and 10 biorefineries.

[30] In this case, storage refers to on-site storage at the biorefinery.

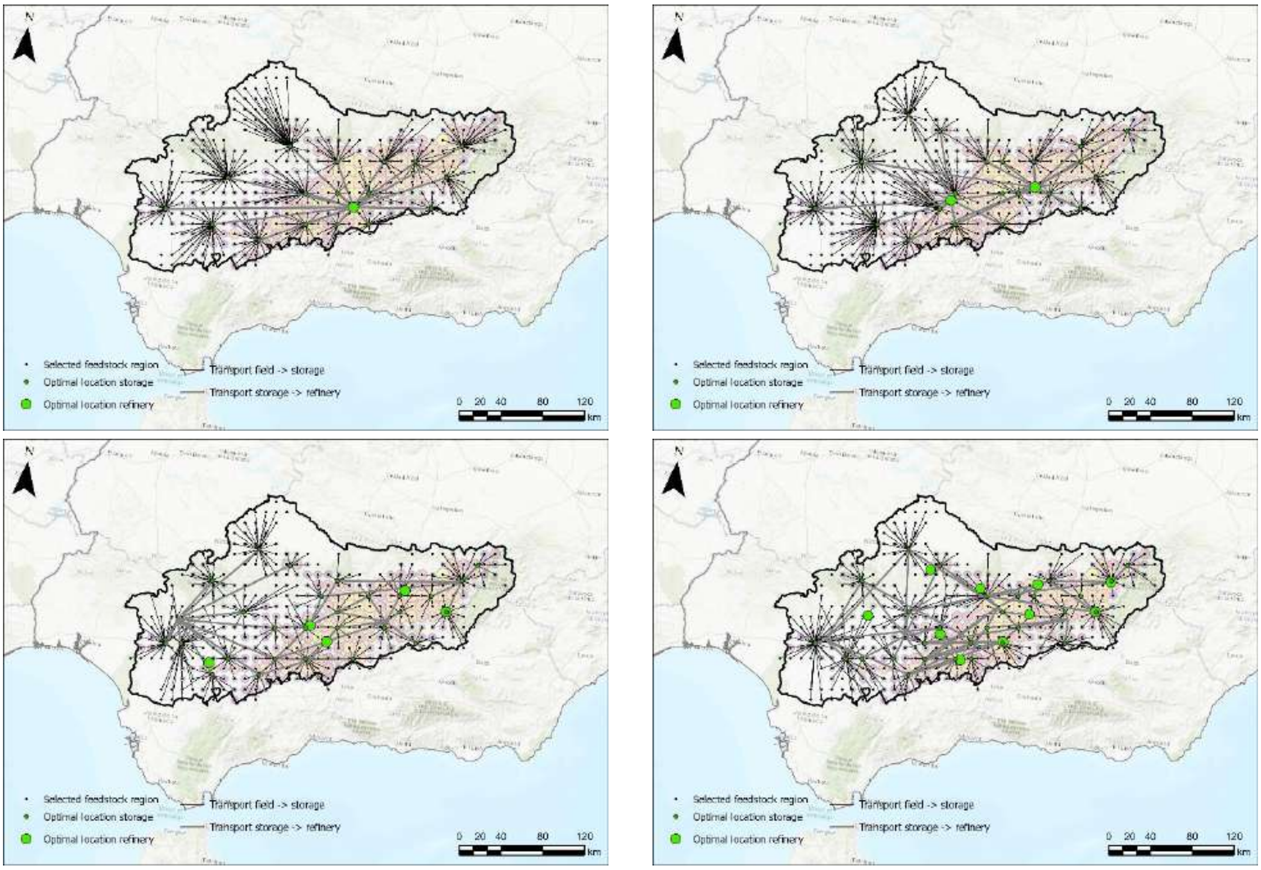



*Figure 48: Pruning in Andalusia – Sensitivity 3B – Impact of off-site storage - processing all available OTP: Optimal biorefinery and storage locations.*

When introducing medium-sized off-site storage in the scenario with one biorefinery, the total mobilisation cost is reduced by 21% compared to Scenario 3, amounting to 172 € per ton of dry OTP (Figure 48 – top left). In this configuration, 17 storage facilities are required to store and dry the full volume of available biomass. These facilities are distributed across the region, enabling a 70% reduction in field-to-storage transport costs.

However, this widespread distribution also increases the distance from storage sites to the biorefinery, resulting in a transport cost of 42 € per ton of dry OTP. This segment accounts for approximately 25% of the total mobilisation cost (Figure 49 - #1 off-site (m)).

With regard to storage, the use of off-site facilities leads to higher capital costs per ton, resulting in a storage cost of 12 € per ton of dry OTP—significantly higher than the 2 € per ton associated with on-site storage (Figure 49 - #1 off-site (m) – orange bar segment).

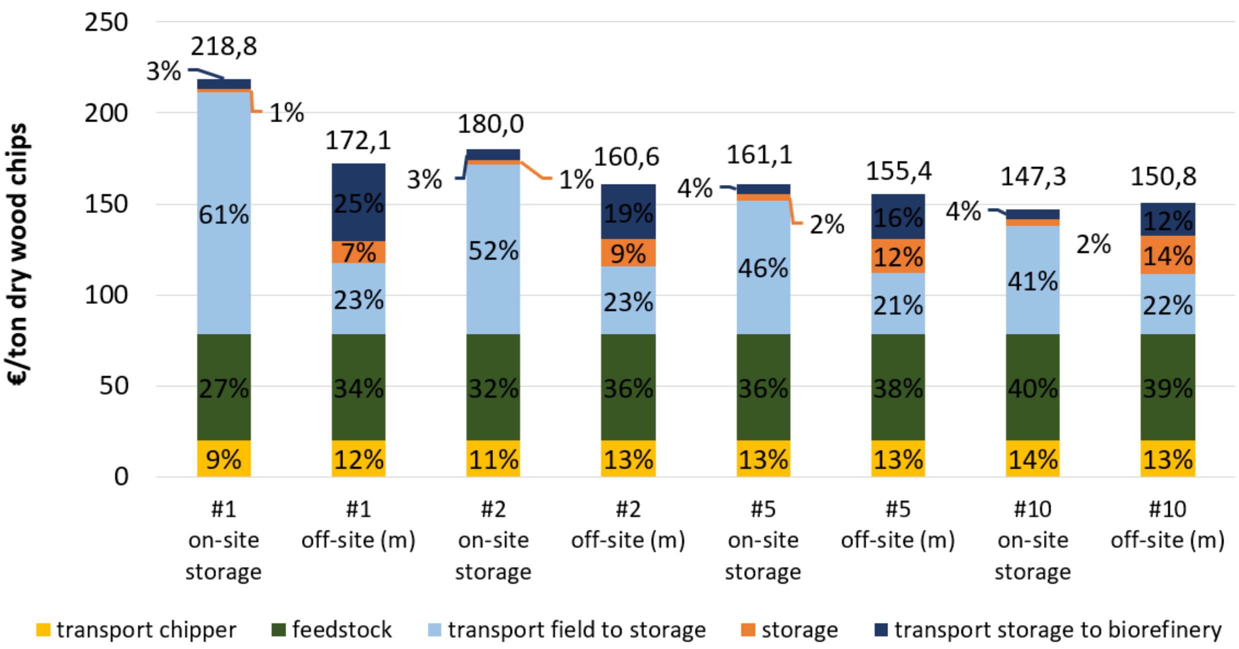



*Figure 49: Pruning in Andalusia – Sensitivity 3B – Impact of off-site storage – processing all available OTP: Total mobilisation cost.*

In addition to the reduction in mobilisation cost, the total transport distance decreases by 40%, reaching 32 km per ton of dry OTP. This distance is approximately evenly split between the field-to-storage and storage-to-refinery transport legs (Figure 50 - #1 off-site (m)).

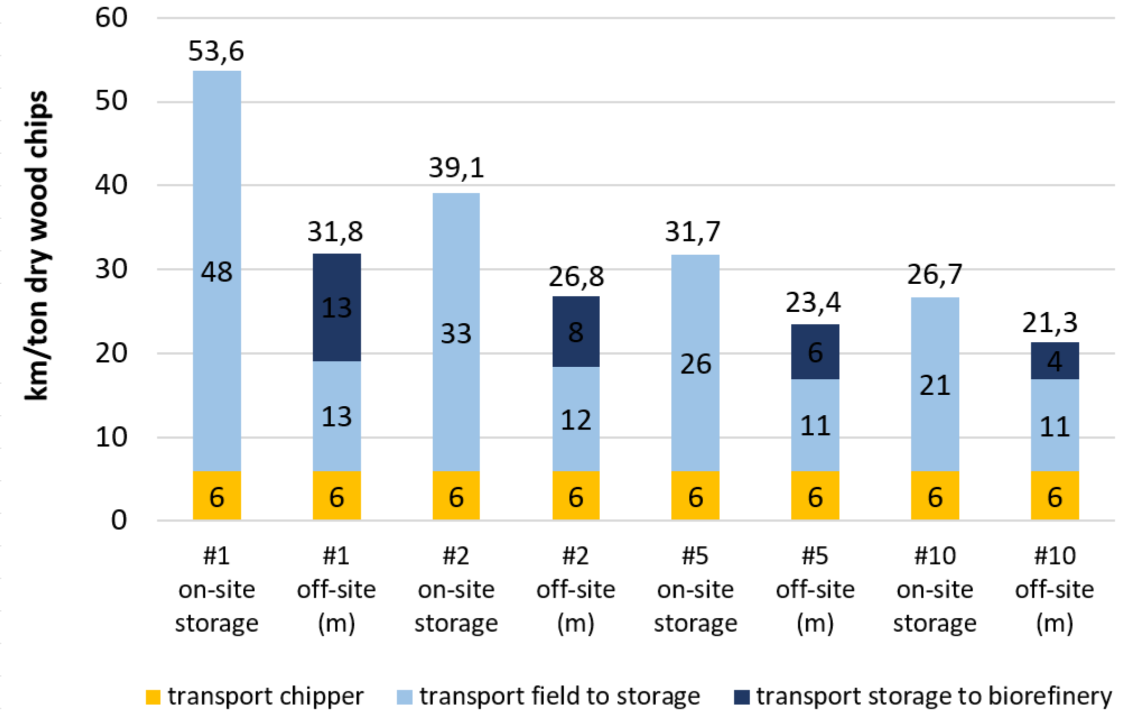



*Figure 50: Pruning in Andalusia – Sensitivity 3B – Impact of off-site storage – processing all available OTP: Transport distance*

As a final elaboration on this scenario, the number of biorefineries has been varied to 2, 5, and 10 biorefineries. This analysis shows that the added value of off-site storage (with medium capacity) decreases as the decentralisation of the biorefineries increases (Figure 35).

In the case of two biorefineries, the introduction of medium-sized off-site storage reduces the mobilisation cost by 11%, from 180 € to 161 € per ton of dry OTP, compared to the configuration with on-site storage. For five biorefineries, off-site storage only reduces the mobilisation cost by 5%, and with 10 biorefineries, the mobilisation cost even increases 3%.

Overall, the results show that while travel distances decrease with the introduction of off-site storage, this benefit is offset by the associated increase in storage costs. In scenarios with 5 and 10 biorefineries using on-site storage, the decentralisation of refinery locations alone already achieves significant logistical efficiency. As a result, the added value of implementing off-site storage in these cases is limited.

## 2.5 Conclusions

This study investigates the logistical feasibility of valorising olive tree pruning (OTP) from Andalusia's extensive olive fields as a feedstock for bioplastic production. The region, with over 1,16 million hectares of olive cultivation, generates large volumes of woody biomass that are often underutilised or burned. However, the seasonal nature of pruning, fragmented field distribution, high moisture content of fresh OTP, and lack of suitable infrastructure pose significant logistical challenges. Efficient collection, storage, and transport in combination with optimal siting strategies are essential to enable the year-round operation of biorefineries and to unlock the economic potential of this biomass stream.

To address the supply chain challenges, MOOV investigated a range of OTP collection, storage and transportation scenarios in the Andalusian region.

The scenarios differ in terms of the number, size, and location of storage facilities and biorefineries, as well as the impact of decentralised storage and processing.

- **Scenario 1:** One biorefinery (32 kton capacity) – using existing off-site storage
- **Scenario 2:** One biorefinery (kton capacity) – no off-site storage
    - **Sensitivity 2A:** Impact of multiple biorefineries
    - **Sensitivity 2B:** Impact of multiple off-site storage
- **Scenario 3:** One biorefinery (700 kton capacity) – no off-site storage
    - **Sensitivity 3A:** Impact of multiple biorefineries
    - **Sensitivity 3B:** Impact off-site storage

The summary results demonstrate the impact of introducing alternative logistics scenarios on the performance indicators: **mobilisation cost** (Figure 51) and **transport distance** (Figure 52). Mobilisation cost is defined as the sum of the costs for chipping, chipper transport, storage, and all transport between the field, storage facilities, and biorefinery.

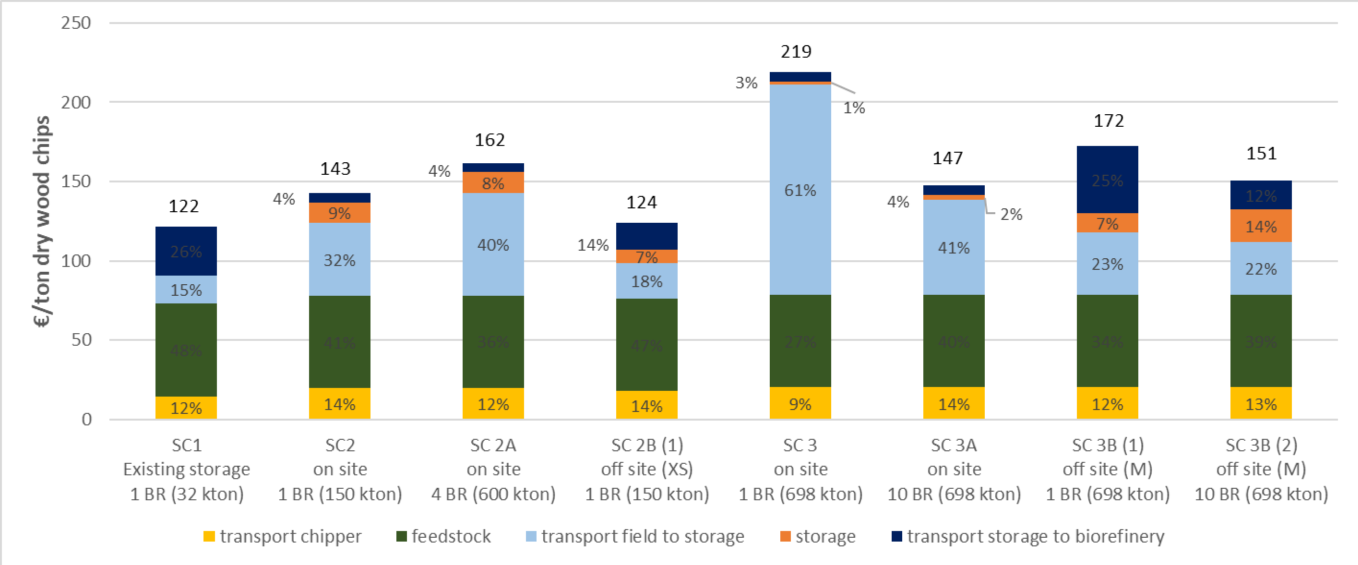



*Figure 51: Mobilisation cost (€ per ton dry OTP)*

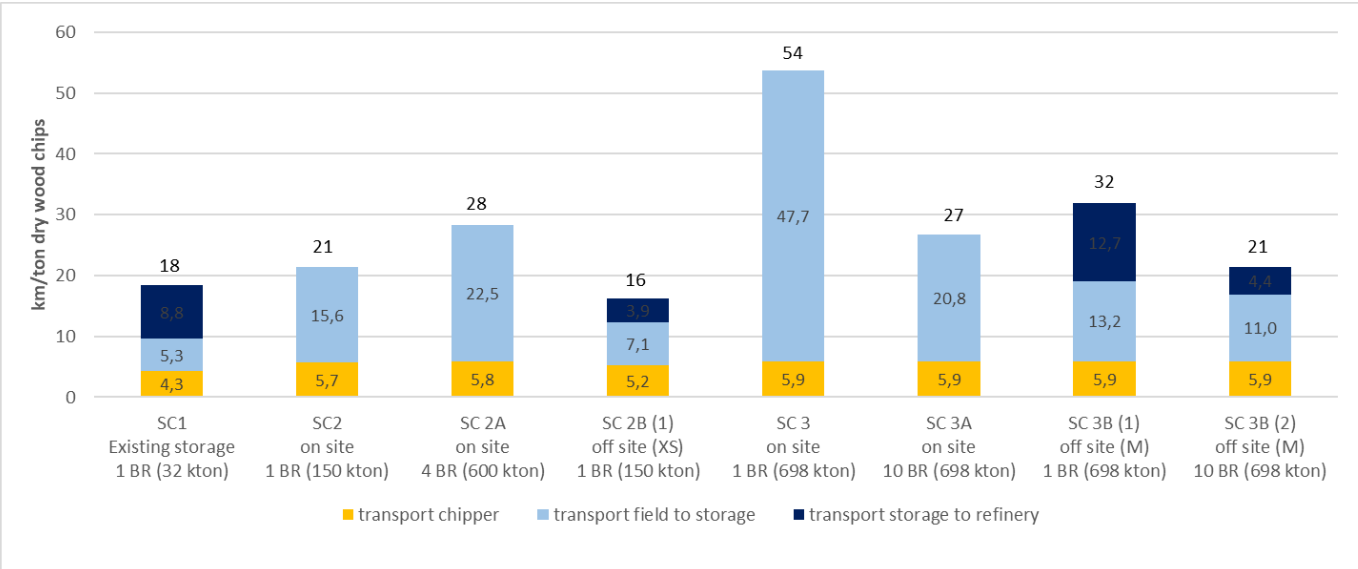



*Figure 52: Transport distance (km per ton dry woodchips)*

The key conclusions drawn from the analysis and its results are:

- Decentralised systems are consistently more cost-effective.
  Scenarios involving multiple localised facilities — whether in the form of off-site storage near production zones or distributed biorefineries — outperform centralised configurations by significantly reducing transport distances and leveraging regional OTP availability. The XS off-site storage scenario (124 €/ton) and 10-refinery setup (147 €/ton) proved to be the most economically viable strategies, demonstrating that a decentralised network better matches the spatial reality of the OTP supply base. The benefits of decentralization are determined by balancing field-to-storage transport costs and storage-to-refinery transport costs, as well as balancing the number of required storage facilities and related CAPEX, which is influenced by economies of scale.

- Transport of fresh chips from the field to the storage is the dominant cost driver, especially at larger scales.

OTP has a high moisture content and low bulk density, resulting in high transport volumes and costs per ton when moved in fresh form. In centralised configurations, transport alone accounted for 30% (SC2) up to 60% (SC3) of total mobilisation cost. This makes minimising the fresh transport leg critical for cost control—whether by drying near the source decentralising storage capacity or by decentralising processing capacity.

- Feedstock cost is fixed, but its weight in total cost shifts with scale.

The cost of chipping OTP remains constant at 58.3 € per ton of dry woodchips, based on the pre-defined cost of 30–40 € per ha. However, its share of total mobilisation cost varies—from ~48% in low-cost scenarios to ~27% in high-cost setups with increased transport and infrastructure costs.

- Optimal design balances minimal field-to-storage transport with efficient storage sizing.

Smaller, local storage hubs can reduce the distance that fresh chips must travel, but excess storage decentralisation comes at the expense of capital investment. The XXS scenario, for instance, achieved low transport distances (~17 km/ton) but required 48 facilities, driving up CAPEX and pushing the total cost to 134 €/ton. In contrast, the XS configuration (10 hubs) struck a better balance between logistics efficiency and infrastructure investment.

- XS off-site storage with a biorefinery of 150 kton of dry woodchips per year is the most effective logistics configuration.

The XS scenario emerged as the lowest-cost configuration across all scenarios (123 € per ton of dry woodchips). It efficiently matched storage capacity to the spatial density of olive fields, kept field-to-storage transport to 7 km/ton, and allowed for natural drying before transporting the lighter, drier chips to the refinery (4 km per ton of dry woodchips). Its modular, scalable design makes it especially suitable for incremental rollout and adaptation to future demand or processing expansion.

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