Circular bioeconomy transformation for regions by enabling resource and governance networks

D2.2.1 Supply chain optimisation and logistic network design

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Executive Summary

MOOV tackling logistic challenges in transforming toward a circular bioeconomy

BIOTRANSFORM brings together six EU regions committed to accelerating their **transformation toward a circular bioeconomy**. Each region faces unique challenges and priorities in achieving this transformation.

Within BIOTRANSFORM, **MOOV offers decision support for supply chain and logistics network design and optimisation** (more info). MOOV is developed by a dedicated research team within VITO and:

- Finds the optimal supply chain configuration
    - From an economic, environmental or social viewpoint
    - Customise for specific client needs, conditions and goals
    - Applicable to existing, changing or new supply chains
    - Focus on sustainable, circular and biobased strategies
    - Considers all key conditions - including location, costs, quantity, quality, and planning
    - Considers all key activities - including resource collection, treatment, storage, processing and transport – in an integrated manner (Figure 1).
- Provides decision support and impact assessment
    - Comparative assessment of multiple supply chain scenarios, encompassing both current setups and potential future configurations.
    - The impact of each scenario is evaluated against a consistent set of Key Logistic Performance Indicators such as logistic costs/benefits, transport distances, loading rates and efficiencies, number of vehicle movements…
    - Clear customised decision support is provided to clients on the optimal supply chain design for their specific case and needs

Investigated scenarios include, for example:

- Identifying optimal locations for new infrastructure or activities,
- Integrating innovative processes or products into existing supply chains,
- Selecting suitable transport modalities and determining fleet composition,
- Evaluating new planning strategies for optimizing feedstock delivery and storage capacity.

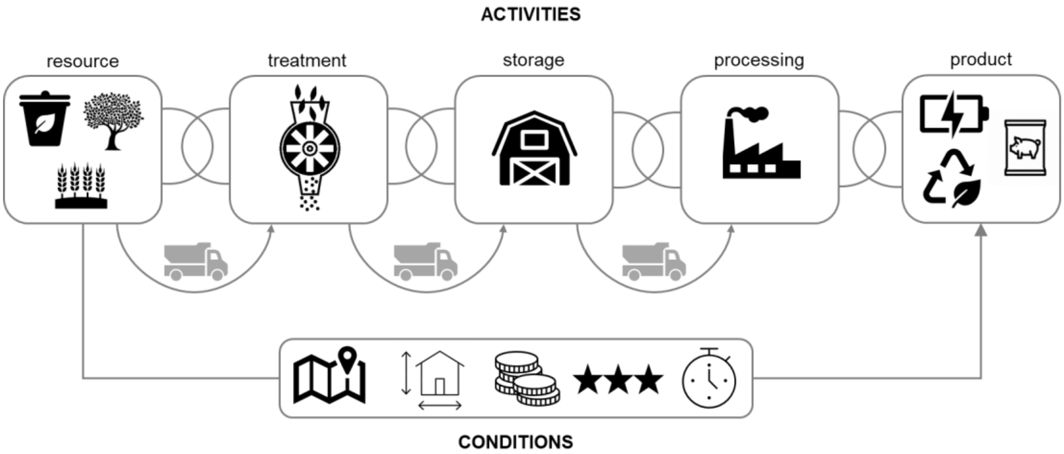


Figure 1: MOOV – supply chain concept

The MOOV team initiated a screening of logistic challenges in collaboration with representatives from all six **BIOTRANSFORM regions**, aiming to identify those regions **requiring support in tackling logistic challenges in transforming toward a circular bioeconomy**. This process led to the selection of two BIOTRANSFORM regions, whose logistic cases are discussed in the sections below:

- Spain (Andalusia): valorisation of pruning from olive groves (Section 2)
- Czechia (Karlovy Vary): valorisation of food waste (Section 3)

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 2).

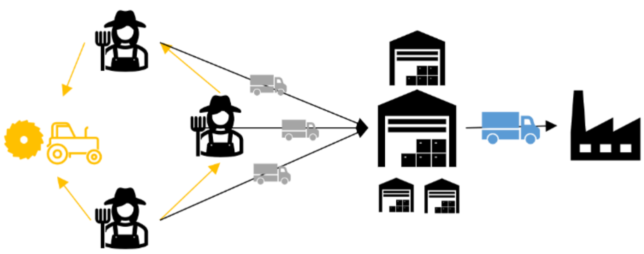


Figure 2: Network flow diagram.

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 3) and **transport distance** (Figure 4).

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.

Scenario results

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.

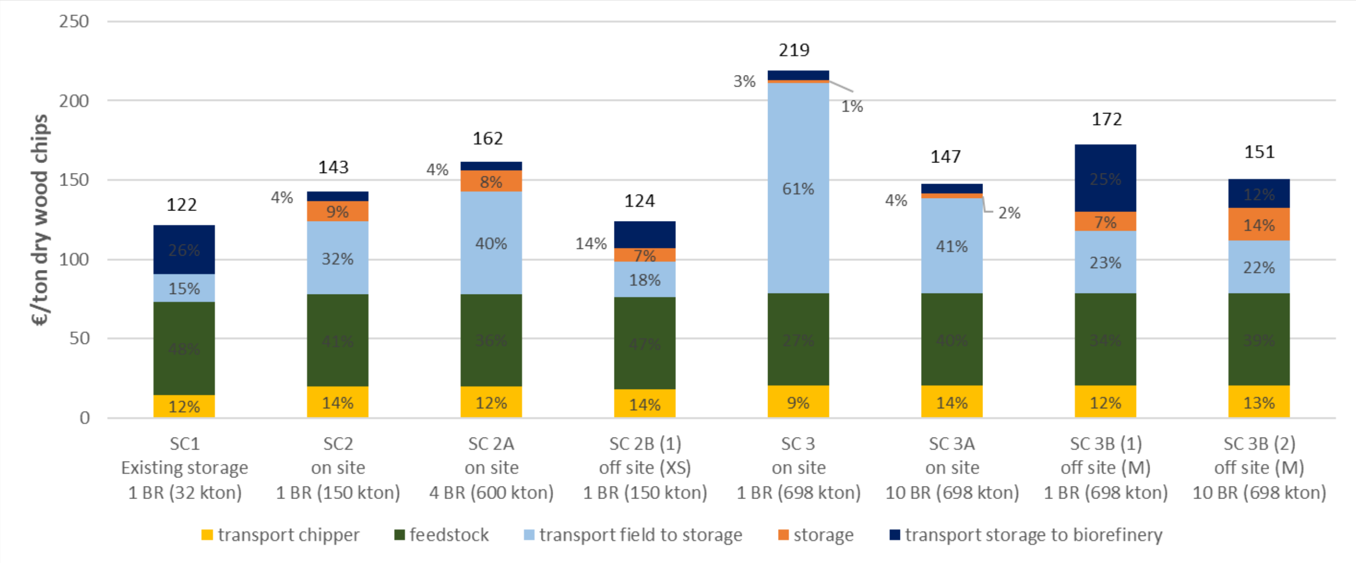


Figure 3: Olive tree pruning in Andalusia - Mobilisation cost [€/ton dry OTP]

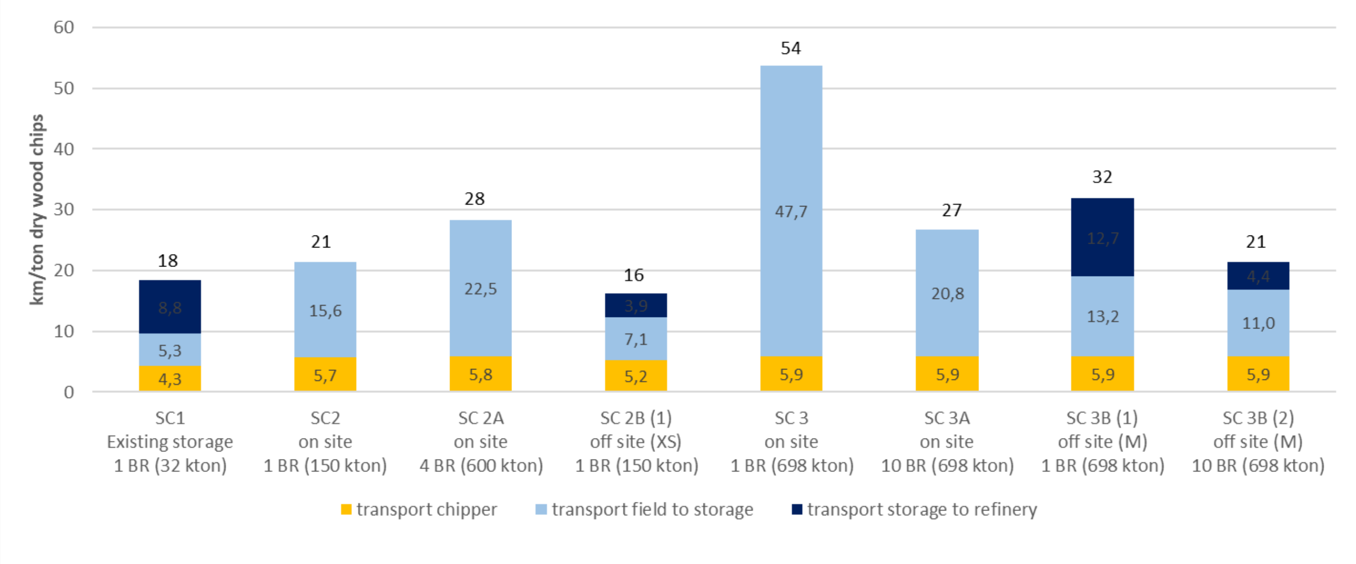


Figure 4: Olive tree pruning in Andalusia - Transport distance [km/ton dry OTP]

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.

Food waste in Karlovy Vary

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.

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.

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 5).

This case study explores the **impact of introducing alternative logistic and processing scenarios** on the **transport distance** (Figure 6) and **mobilisation cost** (Figure 7).

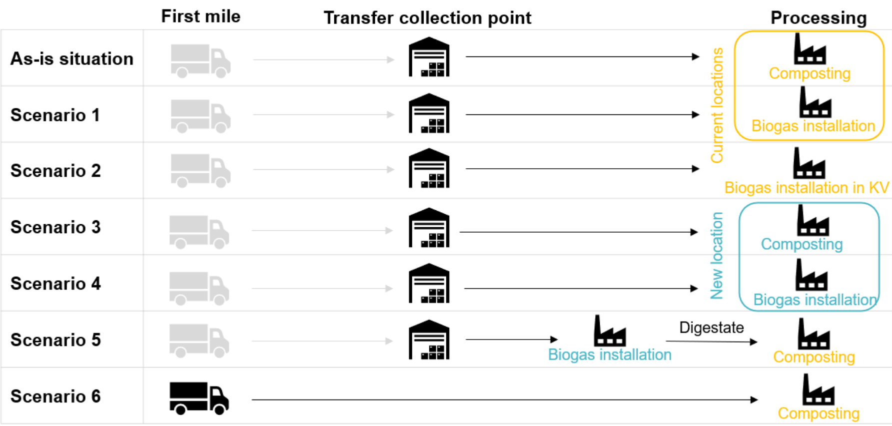


Figure 5: Food waste in Karlovy Vary - Scenario overview

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.

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

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%.

<u>**In conclusion**</u>

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

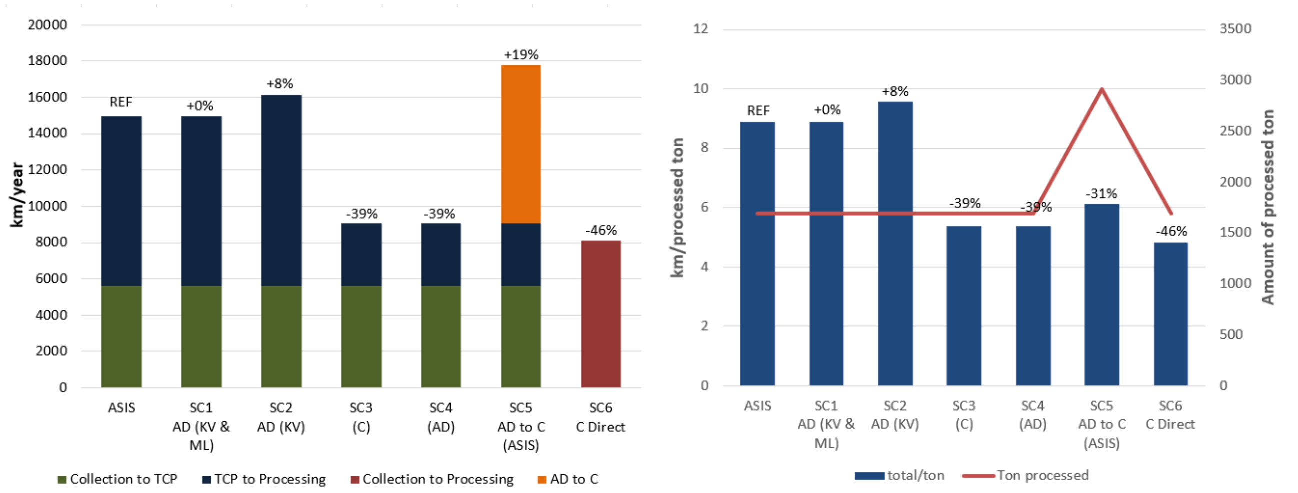


Figure 6: Food waste in Karlovy Vary - Transport distance [km/year (L) and €/ton (R)]

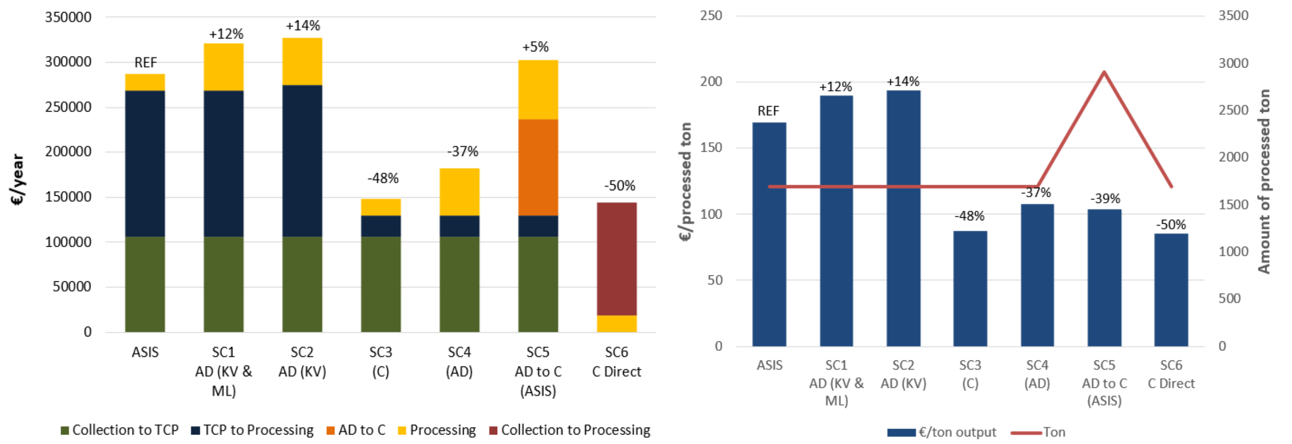


Figure 7: Food waste in Karlovy Vary - Mobilisation cost [€/year (L) and €/ton (R)]

1. Introduction

The BIOTRANSFORM project aims to support both **policymakers and industry stakeholders** in facilitating the transition from traditional **linear, fossil-based value chains** to more **sustainable, circular bio-based systems** across the European Union. Grounded in six representative case studies, the project seeks to generate actionable insights and strategies tailored to regional contexts.

This report focuses specifically on the **design of supply chains and logistics networks** within the BIOTRANSFORM framework, examining how they can be optimized to enable and accelerate the circular bioeconomy transition.

1.1 About MOOV & tackling logistic challenges

1.1.1 Application of the MOOV model

MooV - https://MooV.vito.be - is VITO's supply chain optimisation service dedicated to optimising logistics, supply chain design and mobilisation strategies. The service is developed by the MooV research and consultancy team at VITO and an integral part of the VITO technological research institute.

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.

Error! Reference source not found. 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.

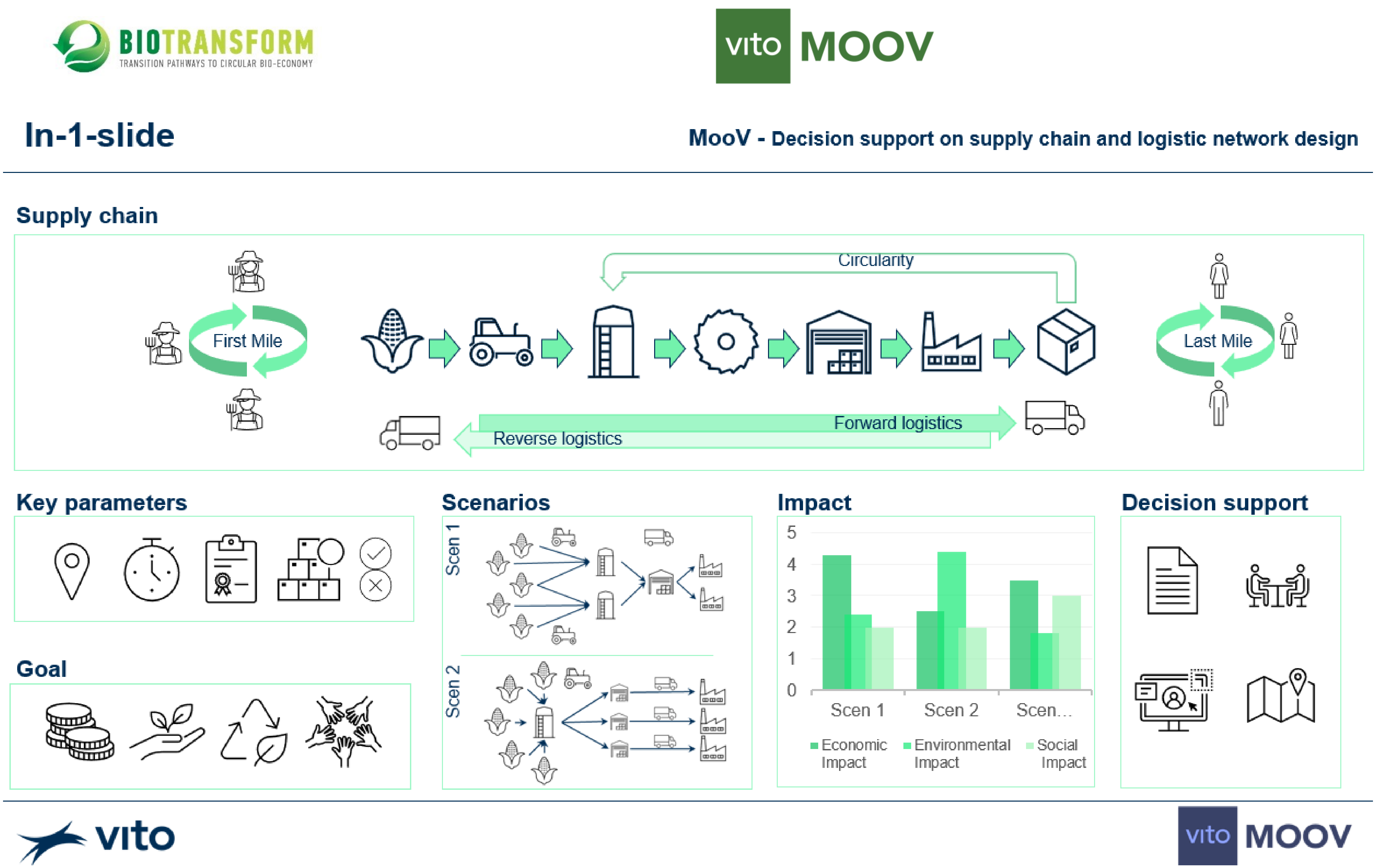


Figure 8: MooV explained in one slide

1.1.2 Scenario evaluation and key performance indicators

MOOV allows for the comparative assessment of multiple supply chain scenarios, encompassing both current setups and potential future configurations. Each scenario is evaluated against a consistent set of Key Performance Indicators (KPIs), which reflect the most relevant logistic parameters, including:

- Logistic and transport costs/benefits,
- Transport distances,
- Loading rates and efficiencies,
- Number of vehicle movements,
- Fleet emissions and environmental impacts.

These KPIs enable a data-driven approach to assess trade-offs and identify performance bottlenecks or improvement opportunities. Model results are communicated through user-friendly outputs — such as summary reports, geospatial maps, and graphical dashboards — ensuring accessibility and clarity even for stakeholders with limited technical backgrounds.

1.1.3 Goal-oriented and constraint-aware optimisation

The MOOV model supports goal-oriented supply chain optimisation within defined operational and strategic contexts. Users can specify objectives such as:

- Minimisation of total cost,
- Reduction of CO_2 and other emissions
- Minimisation of transport distances,
- Equitable resource distribution across the network.

The model is capable of handling complex constraints, including capacity limits, regional infrastructure availability, transport fleet characteristics, and processing capabilities. By simulating and analysing these scenarios, MOOV provides robust decision support for the development of efficient, flexible, and sustainable logistics solutions tailored to regional and sector-specific requirements.

1.1.4 Flexible architecture

MOOV translated the logistic problem into a deterministic, multi-period, multi-echelon, multi-product mixed integer linear programming (MILP) model (defined in Python and solved with Gurobi 9.0.). This implies that the model's objective(s) and constraints are defined as linear relationships with continuous and integer (and binary) decision variables that describe the material flow and decision stages. Gurobi 9.0. then solves the model, using heuristics and branch-and-bound methods, with the goal to find the optimal mobilisation strategy at least cost (the objective) while fulfilling case-specific requirements defining the degrees of freedom under which the objective function needs to be solved (the constraints).

The MOOV service combines a proprietary optimisation engine with expert-driven customisation. Its architecture consists of two main components: the core model and the shell model. These two layers are seamlessly integrated into a single operational model, allowing MOOV to remain both scalable and adaptable across a wide range of use cases and application domains.

The **core model** captures the universal logic and algorithms required for the general supply chain optimisation. It is used to analyse the impact of various supply chain configurations on total chain performance and logistics-related costs. The MOOV core model is specifically developed to address the complexity of modern supply chains. It is designed to assess the implications of strategic and operational decisions, as well as dynamic external factors, on key performance outcomes. The core model integrates the fundamental logic and structural principles that are common to all supply chains. Within the core model, 3 groups of constraints capture the universal supply chain logics:

- Constraints imposing physical and regulatory limitations on the combinations between products and activities and activities mutually and on the allowed activities at production locations, storage locations and conversion locations;
- Constraints ensuring the mass balance in the material flow in activities, between activities and between locations on the available (multi-modal) transportation network;
- Constraints ensuring that the demand for a certain end-product (i.e. primary product from the conversion process) or by-product (i.e. secondary product from the conversion process) are met.

Complementary to the core model, a case-specific shell is modelled that captures the unique characteristics of a case-study. The **shell model** embeds 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.

This approach allows for the **flexibility** to perform and compare a variety of scenario analyses and sensitivity analyses; or to swiftly use the same model to assess comparable cases in the future. This setup allows for adjustments of activities and related characteristics of the products, origin, storage, treatment, demand, and transport modes, without requiring changes to the model itself. Examples of such activities and their related characteristics along the supply chain include:

- Products: feedstock typology and potential, intermediate and end-products typology;
- Harvest: harvesting types, costs, capacities, cycles, effect on the quality;
- Treatment: treatment types, costs, capacities, effect on quality;
- Storage: storage types, costs, capacities, storage effects on quality;
- End-processing: processing types, required quality, capacities;
- Transport modes: type, capacity, cost, bulk densities.

As such, the MOOV model provides a robust and scalable framework for supply chain assessment across diverse regional and operational contexts.

1.1.5 Methodological framework

The MOOV methodology follows a structured, three-step process (Figure 3):

1. Define Phase: This initial phase focuses on jointly identifying case-specific needs, characteristics, and objectives with key stakeholders. It also involves the collection, processing, and validation of all necessary input data.

2. Design Phase: In this phase, the shell model is constructed based on the defined inputs. It is then programmed and integrated into the MOOV core model to form a complete, customised solution.

3. Deliver Phase: The final phase entails the application of the model, analysis and interpretation of the outcomes, and clear communication of results to relevant stakeholders.

This methodology is applied iteratively in Chapters 3 and 4, where it supports the analysis of the regional BIOTRANSFORM case studies introduced in Chapter 2.

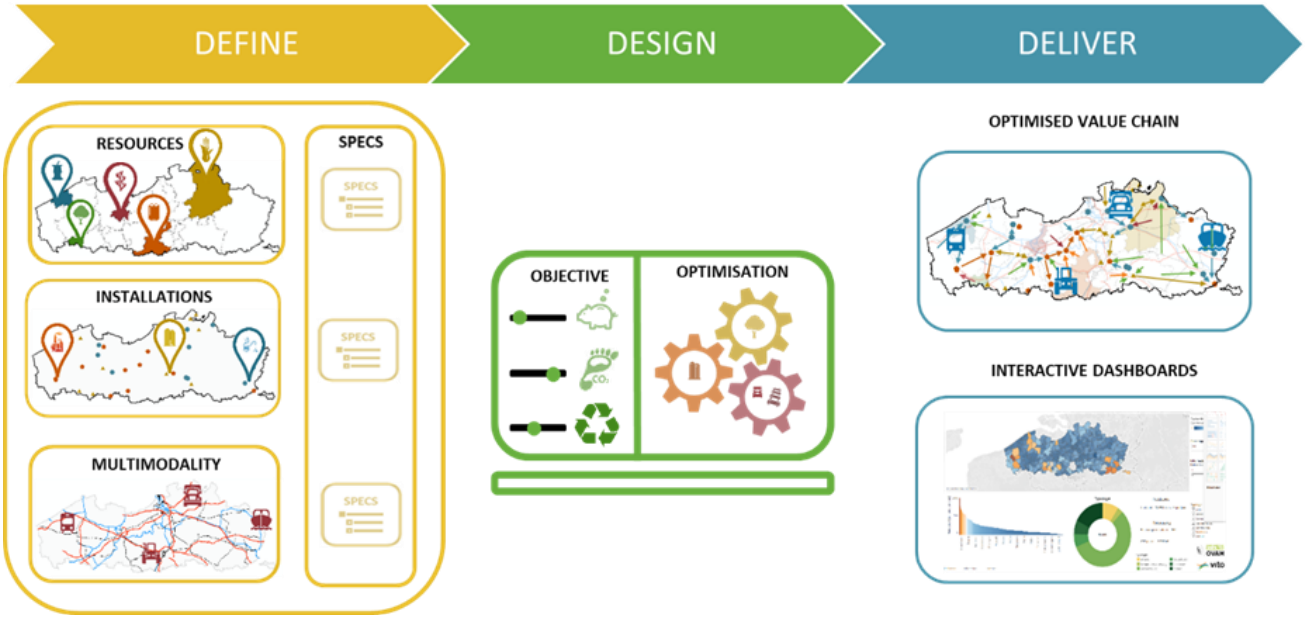


Figure 9: The MOOV methodology

Additionally,

Figure 10 outlines the practical implementation steps of the methodology described above. These steps are systematically applied and discussed for each case study individually in the following sections.

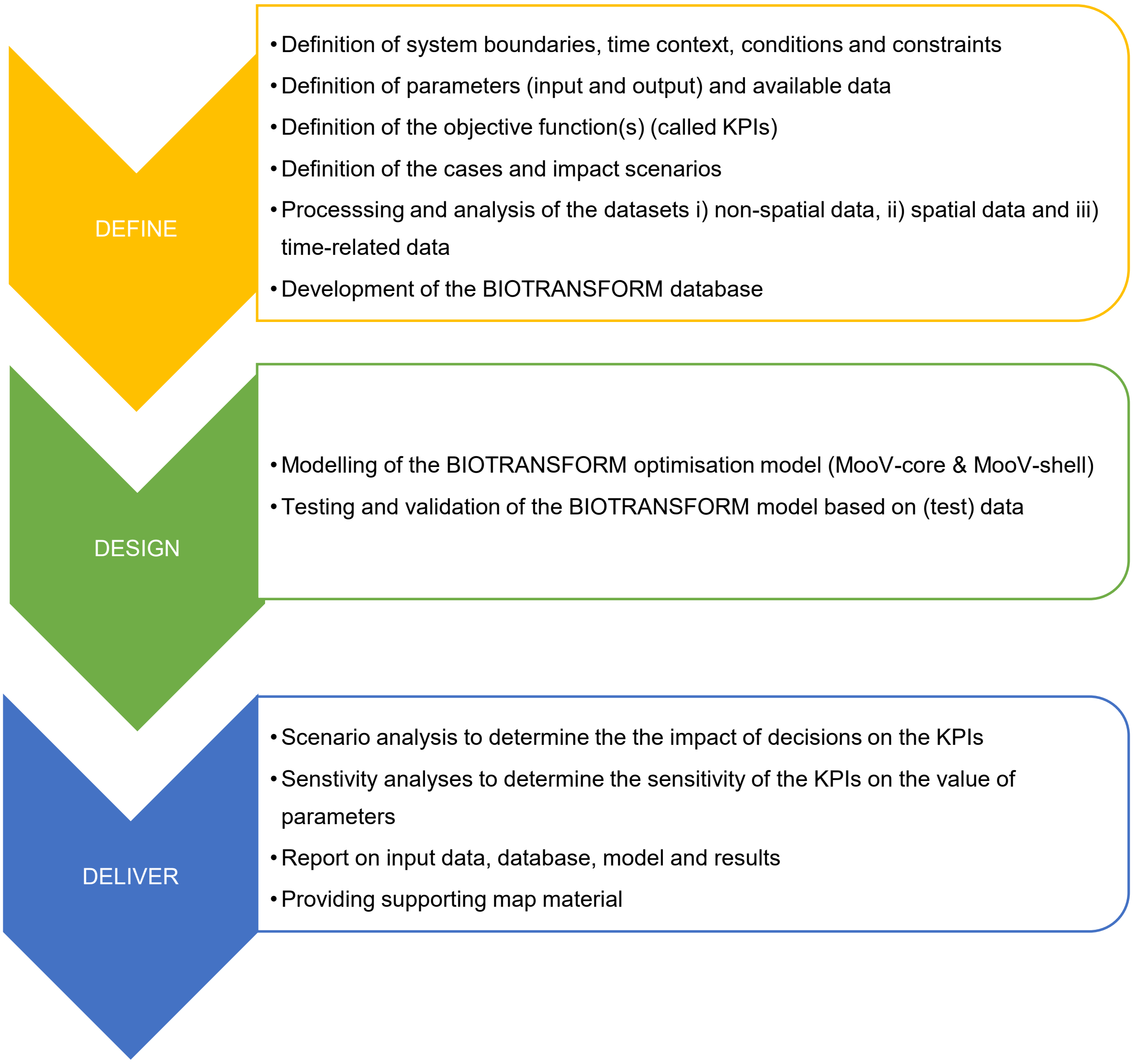


Figure 10: The MOOV plan of approach

1.1.6 Decision support and comparative scenario analysis

MOOV supports a structured evaluation of **logistic configurations and their resilience** under various conditions. By enabling side-by-side comparison of different supply chain setups, it helps to quantify the impact of design choices on KPIs such as logistics costs, transport distances, loading efficiencies, and emissions.

This evidence-based approach empowers stakeholders to make informed decisions that enhance supply chain robustness, cost-effectiveness, and sustainability.

1.2 About Biotransform & transitioning toward a circular bioeconomy

Due to the exploitation of crude oil and fossil-based resources for unsustainable linear business models, new challenges are arising along many industrial value chains and the possibility to shift the industry to a **circular bio-based economy** is under exploration. However, there is still a lot of unawareness about the benefits, possibilities, and whereabouts of this possible shift. The lack of knowledge around this transformation must be targeted through the fostering of suitable cooperation strategies and access to finance for these conversion technologies, to test and demonstrate their novelty through a first-hand approach, and in the end create interest and jobs. Many biomass residues are currently already used in different applications which are usually low value and don't necessarily feed other aspects of the bioeconomy. Furthermore, these biomass transfers are connected to an additional effort, and multi-stakeholder management.

In this context, the **BIOTRANSFORM** project provides European policymakers with an adequate assessment and policy development framework, knowledge base and expert support ecosystem, to accelerate the transition from linear fossil-based systems to circular bio-based systems, therefore operating at the interface between the circular economy and the bioeconomy transitions. In this way, this project equips policymakers with the tools to set informed priorities that serve environmental, economic, and social goals, being actionable, future-proof, and align with supply-and-demand trends in related industries and value chains. BIOTRANSFORM seeks to achieve the holistic transformation of biomass and caters to the whole range of bio-product portfolios. This includes cascading utilisation of secondary biomass streams to recover high added-value compounds, mid-range products and materials, and residues for bio-energy generation and soil amendments. All residues are used for something else through a rural-urban-industry symbiosis. The key is to implement process pathways for efficiently capturing and storing carbon in materials, commodities, and soil.

In order to shift from a fossil-based supply chain towards a sustainable bio-based economy, BIOTRANSFORM introduces an **assessment package** of three synergistic tools: the Impact Assessment Tool (IAT by LIST), the Resource Flow Analysis Tool (RFA from ALCN), and the Logistics Tool (MOOV provided by VITO). This package is used as a comprehensive approach to assess regional sustainability goals assessed with regional challenges. These pathways are rigorously compared, revealing disparities between conventional linear (fossil-based) and emerging circular bio-based value chains in social, environmental, economic, and circular aspects.

This framework is developed and tested based around six **regional cases**: Andalucía (Spain), Northern Burgenland (Austria), Western Macedonia (Greece), Finland, Karlovy Vary (Czech Republic) and North Rhine Westphalia (NRW-Germany). These regional case studies represent several industries and scenarios such as: forestry, agri-food, aquatic scenes, minerals and chemicals.

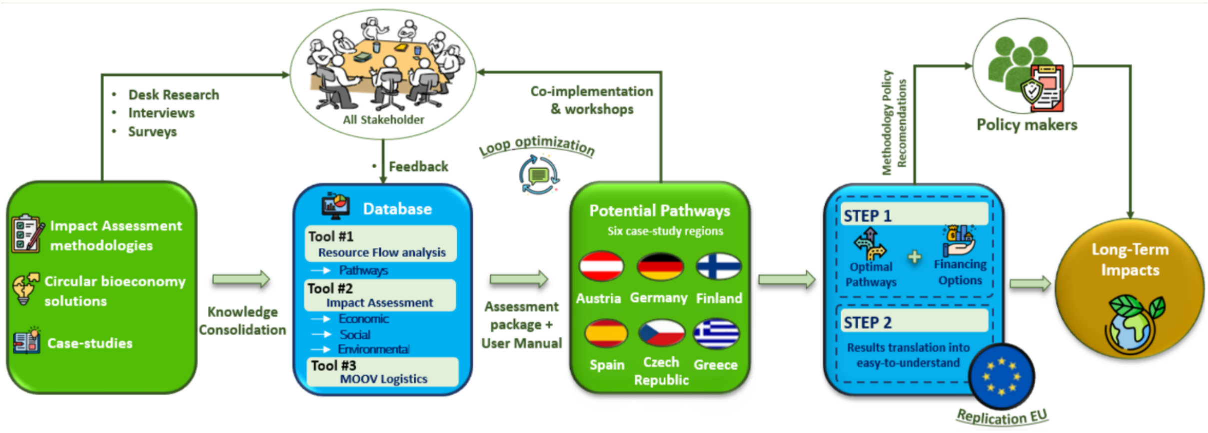


Figure 11: BIOTRANSFORM project concept

2. Biotransform case selection with logistic challenges

BIOTRANSFORM brings together six EU regions committed to accelerating their transition toward a circular bioeconomy. Each region faces unique challenges and priorities in achieving this transformation. Given that the MOOV service offers decision support for supply chain and logistics network design, an initial screening was conducted across all six regions to identify those most in need of support from the MOOV service.

MOOV experts engaged in iterative discussions with representatives from the six BIOTRANSFORM regions, resulting in the selection of two BIOTRANSFORM cases requiring the MOOV service;

- Czechia (Karlovy Vary): valorisation of food waste (section 4)
- Spain (Andalusia): valorisation of pruning from olive trees (section 3)

The selection process and the outcomes of these discussions are explained below and summarised in Table 1.

Table 1: Case selection - Summary

Country/Region	Regional Repr.	Define	Design	Deliver	Conclusion
Spain/Andalusia	CTA	✓	✓	✓	Biotransform case: Olive tree pruning (section 3)
Czechia/Karlovy Vary	BioEast HUB CZ	✓	✓	✓	Biotransform case: Food waste (section 4)
Greece/Western Macedonia	CLUBE	✓	✗	✗	No Biotransform case: despite logistical challenges, limited data and regional capacity hindered case development.
Finland	VTT	✗	✗	✗	No Biotransform case: no logistical challenges identified
Austria	CLUBE	✓	✗	✗	No Biotransform case: no logistical challenges identified
Germany	CLIB	✓	✗	✗	No Biotransform case: logistic challenges are covered outside the Biotransform project

The MOOV-service was introduced by VITO to CTA, the **Spanish** intermediate, and to local Andalusian stakeholders. This led to the identification of the interest of Andaltec, a research centre focused on (bio)plastic research. Andaltec is interested in the use of woody olive pruning as a feedstock for bioplastic production. However, the collection and mobilisation of these pruning pose a significant logistic challenge. Consequently, MOOV and Andaltec – complemented with collaborating partner the University of Jaén - had several bilateral meetings in order to define their case, challenges and the logistic questions. This case is elaborately explained in section 3.

To identify a potential logistics case in **Czechia**, several meetings were held between VITO and BIOEAST HUB, which acted as the representative of local stakeholders. These discussions facilitated the exchange of information and identification of logistic challenges. As a result, a logistics case was selected on the mobilisation of biowaste in West-Czechia (Karlovy Vary and Mariánské Lázně) as described in detail in section 4.

For the **Greek** case studies, three valorisation pathways were shortlisted: (1) sludge to hydrogen, (2) wood dust to wood panel production, and (3) wood dust to bioenergy. The sludge-to-hydrogen pathway is still in its early stages, and no logistical challenges have been identified at this point. In contrast, the two wood dust pathways have already encountered logistical issues, as highlighted by the Greek stakeholders. The ambition to increase production by 500% will significantly increase the volume of woody biomass to be transported. Combined with high transport costs, this makes these pathways particularly relevant for applying the MOOV service. These insights emerged from bilateral meetings between VITO and CLUBE, local facilitator, as well as a broader expert meeting. From these discussions, it was concluded that a collaboration with a leading Greek wood processing company would offer an interesting case. However, due to time constraints from the local facilitator and limited data availability, no MOOV analysis could be carried out.

During bilateral meetings, VITO provided a detailed explanation of the MOOV service, and discussions were held with VTT—the **Finnish** representative—to explore the definition of a lignin-related case. However, VTT confirmed that the logistics of the lignin case had already been comprehensively assessed. As a result, no further actions were undertaken regarding logistics assessment or optimisation for this case.

In the cases of **Austria**, the focus is primarily on choosing the technology and application pathways for straw material. Due to late identification of logistic integration and possible challenges by the local facilitator, no MOOV analysis could be carried out.

For the **German** region, two valorisation pathways were selected to assess in the BIOTRANSFORM project. The first case investigates the use of primary production/food industry for insect breeding. This new pathway entails a lot of logistic questions, but these questions will be analysed outside the BIOTRANSFORM project. In order to avoid duplication and centralises assets efficiently MOOV will not assess this pathway. The second pathway investigates the use of sugar beet pulp from the sugar industry as feedstock for polylactic acid (PLA) production. However, no logistic questions were raised concerning this pathway.

In summary, MOOV is applied on two cases within the BIOTRANSFORM project: a Spanish case on the mobilisation of olive tree pruning (section 3) and a Czech case on the mobilisation of food waste (section 4).

3. Olive tree pruning in Andalusia (Spain)

3.1 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[1].The EU-project SCALE-UP[2], 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[3,4].

Within Spain, olive production is concentrated in the Andalusia region in the south (Figure 12). 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 2 and Figure 12).

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

Table 2: Pruning in Andalusia – Area of olive production in Cordoba, Jaen and Sevilla[5]

	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

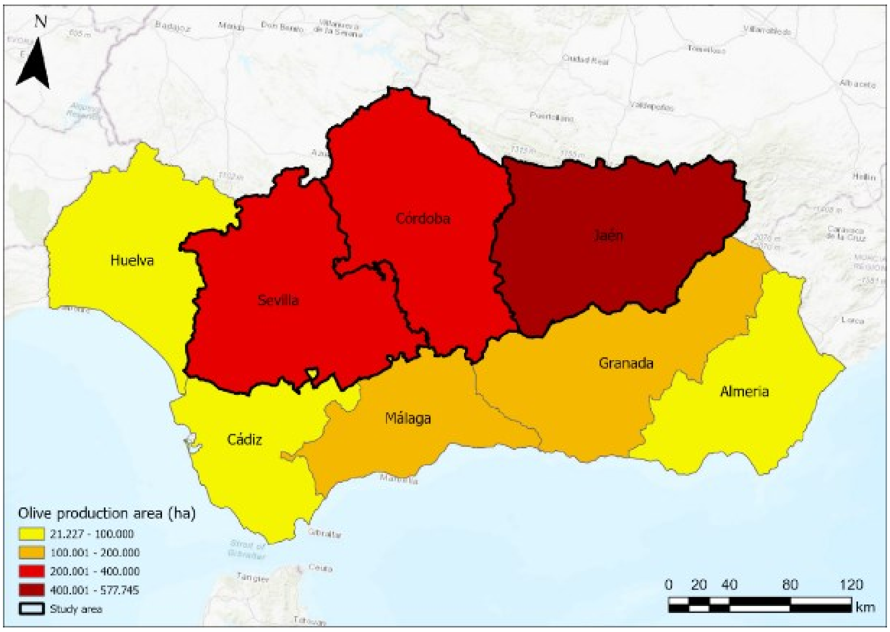


Figure 12: Pruning in Andalusia – Area of olive production (ha) in Andalusia by province[6]

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

[5] Source: Univ. of Jaén
[6] 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’[7] – 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.

3.2 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 13 - yellow)discharges the fesh woodchips into a medium-size transport vehicle (Figure 13 - 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.

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

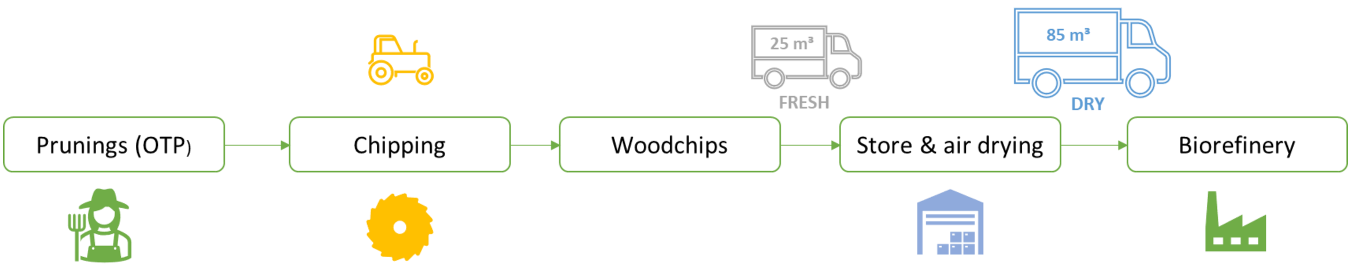


Figure 13: Pruning in Andalusia – logistics chain.

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.

3.2.1 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 3, 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 3: Pruning in Andalusia –Distribution of OTP availability per month and region [8].

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

[8] University of Jaén

carried out after the harvest season. As illustrated in Figure 14 (a), farmers typically collect the OTP at the edge of the field.


(a) (b) (c)

Figure 14: Pruning in Andalusia – Feedstock collection[9].

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[10] 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 4).

Based on a total surface area of 1.165.000 hectares (Table 2) 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.

[9] Images by Andaltec
[10] 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 4: Pruning in Andalusia – Feedstock collection, parameters and characteristics[11]

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

Figure 15 (L) displays the olive fields locations as mapped by Cardoza et al. (2021), which are then translated into a field density map (R).

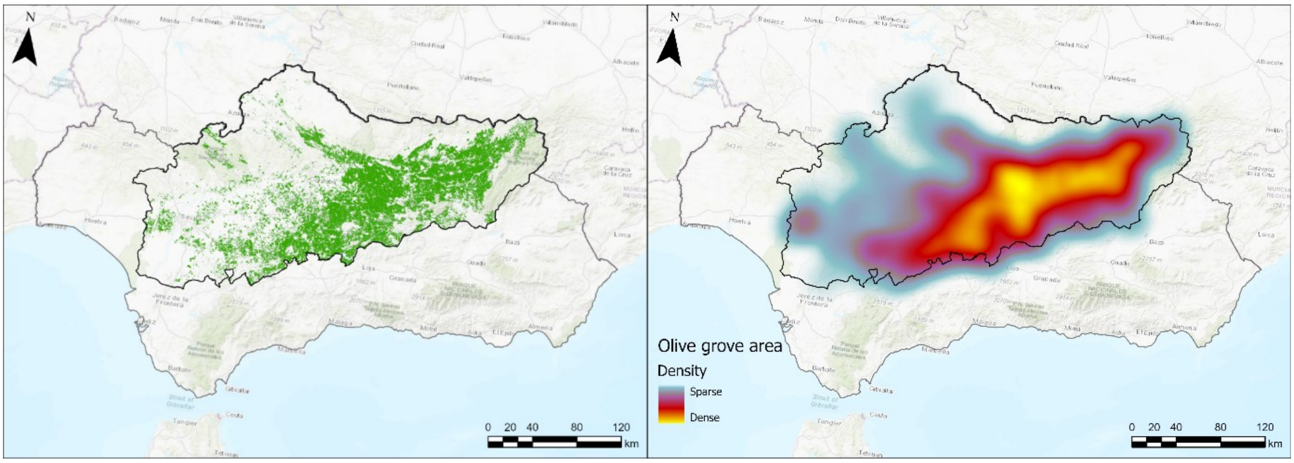


Figure 15: Pruning in Andalusia – Olive field locations and olive field density[12]

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 16). 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 16) matches the distribution of the olive field density in the area (Figure 15 – R). More densely regions, such as the Jaen region, provide more OTP in absolute numbers than for example in the northern region of Cordoba.

[11] Source: Andaltec
[12] Source: based on data received from Univ. of Jaén

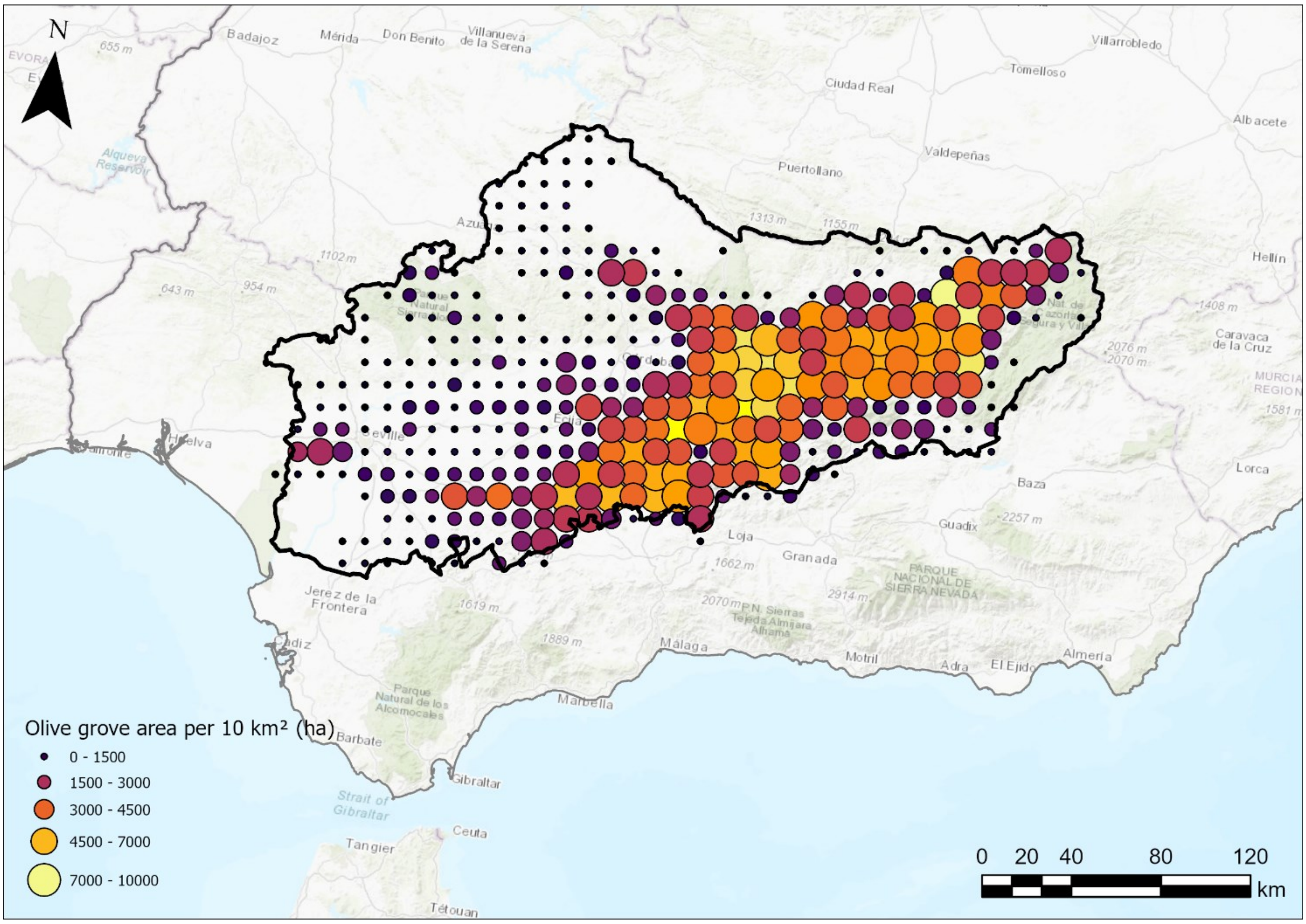


Figure 16: Pruning in Andalusia – Olive field area aggregated to a grid of 10 km x 10 km.

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 19). 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[13] - can be used as candidate locations for off-site storage (Figure 17)[14].

[13] 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.

[14] Andaltec and the University of Jaen.

Figure 17: Pruning in Andalusia – Example of roofed storage facilities

Figure 18A 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.

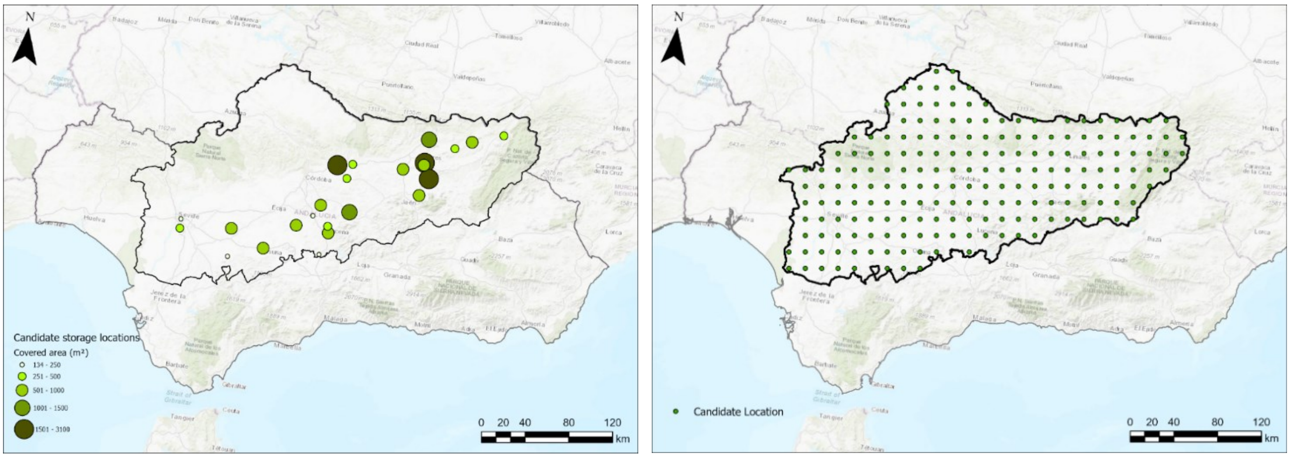


Figure 18: Pruning in Andalusia – Existing off-site storage locations with indication of roofed area (A) and candidate locations for potential new off-site storage (B).

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 3.4). Storage types are divided into five categories—extra-small, small, medium, large, and extra-large—with the corresponding capacities outlined in Table 5. 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 5: 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[15]. 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 3.4) 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 3.1. 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

[15] 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 19).

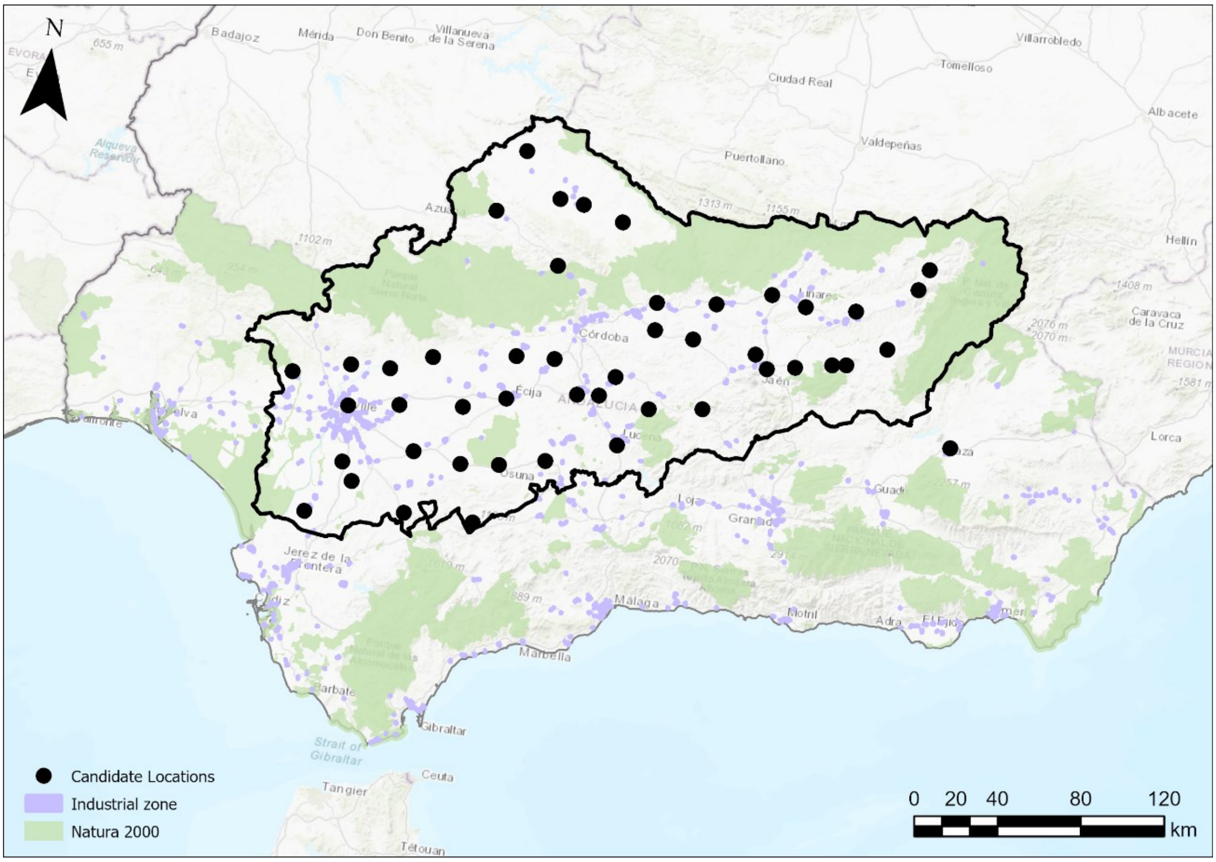


Figure 19: Pruning in Andalusia – Biorefinery candidate locations.

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 20):

- 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.

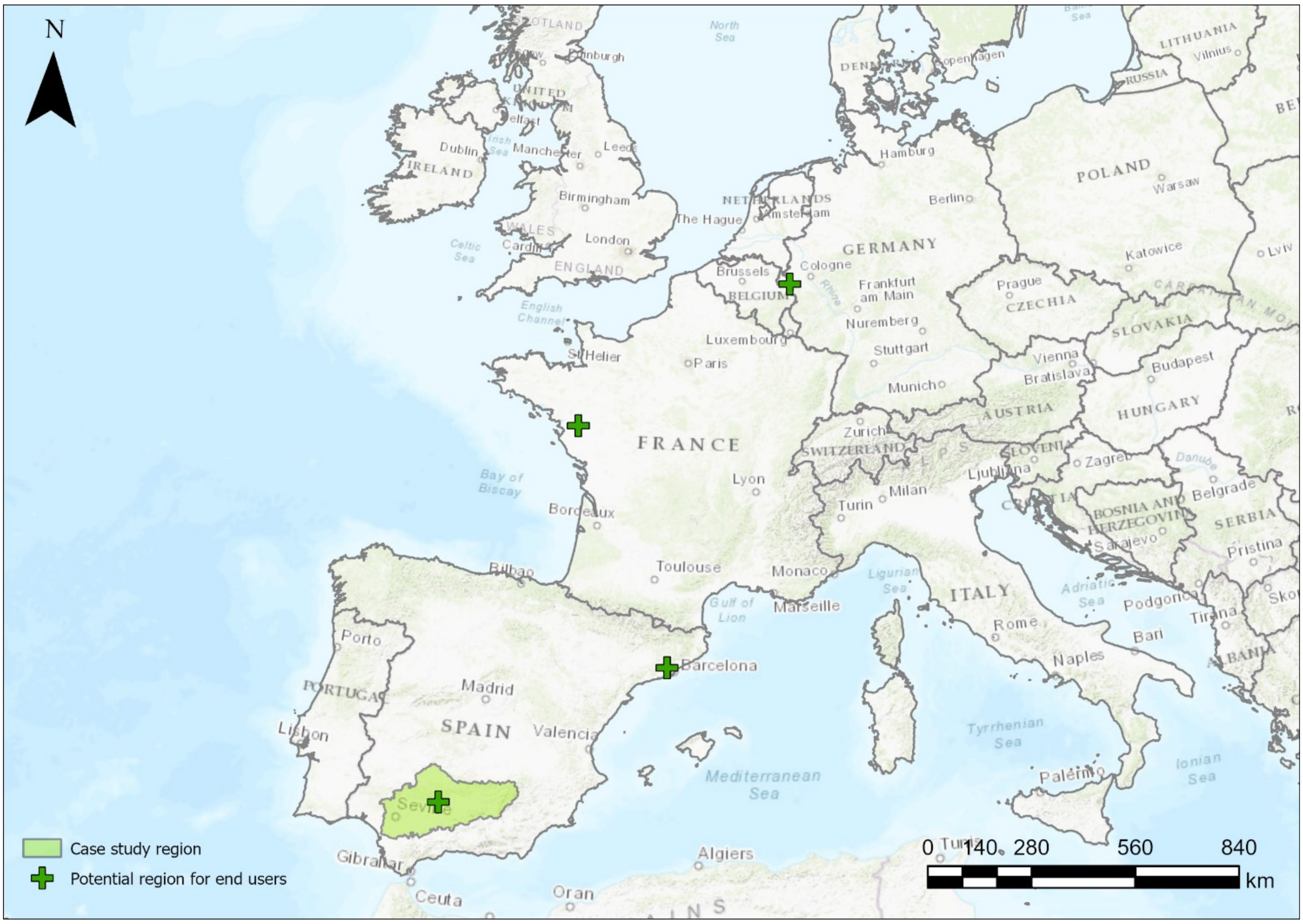


Figure 20: Pruning in Andalusia – Bioplastic clients (hypothetical).

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 16), 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 21).

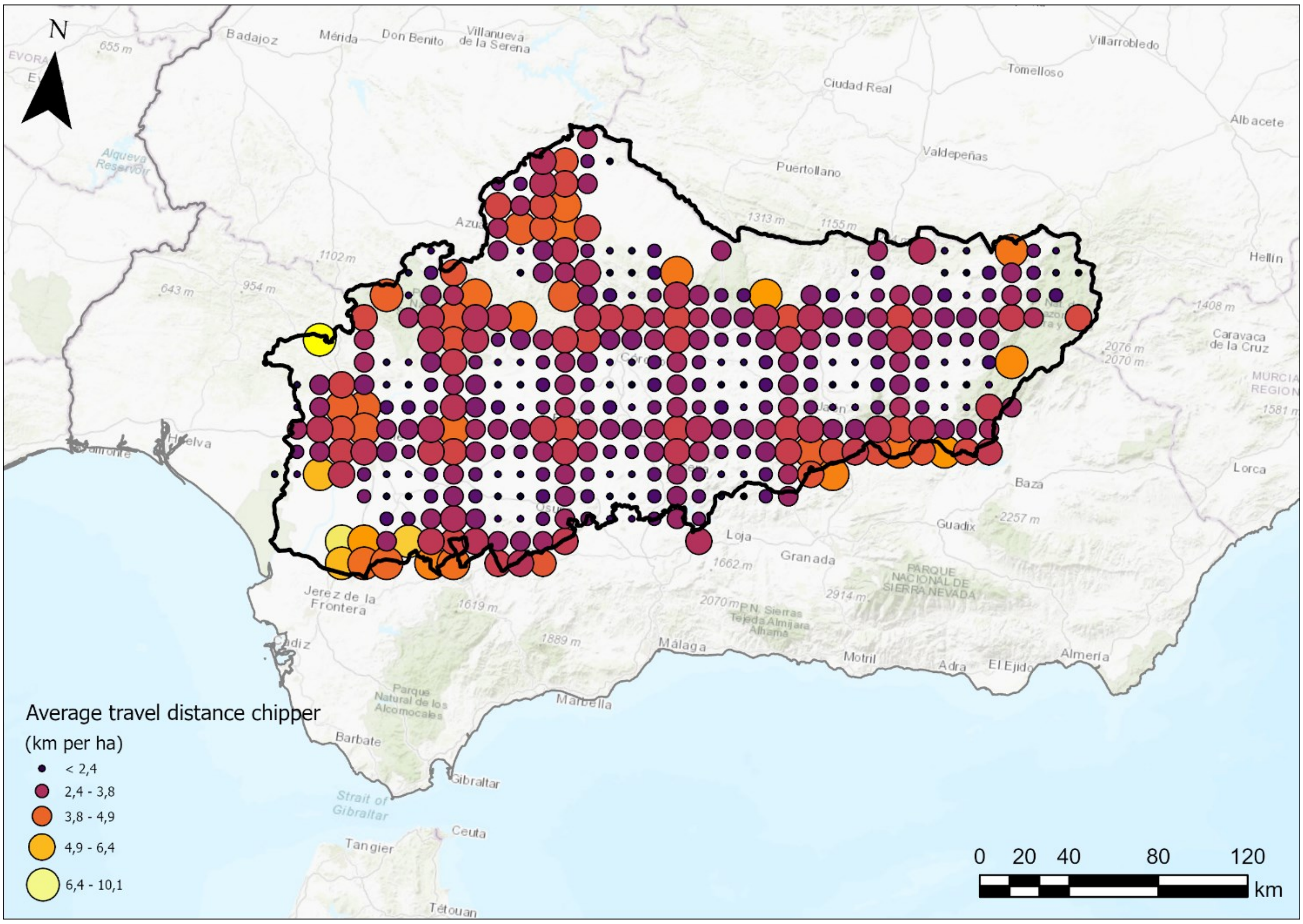


Figure 21: Pruning in Andalusia – Average travel distance of the chipper.

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 13).

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) [16].

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 6) (Section 3.3.2). 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 7) [Martin et al. (2020)].

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

Table 6: Pruning in Andalusia – Transport types, parameters and characteristics [17]

Transport type	Capacity (ton)	Capacity (m³)	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 7: Pruning in Andalusia – Product characteristics

Product type	Bulk density (range) (ton/m³)	Bulk density (in model) (ton/m³)
OTP chips (50% MC)	0,272 – 0,348	0,31
OTP dried chips (10% MC))	0,15 – 0,165	0,16

3.2.2 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 22).

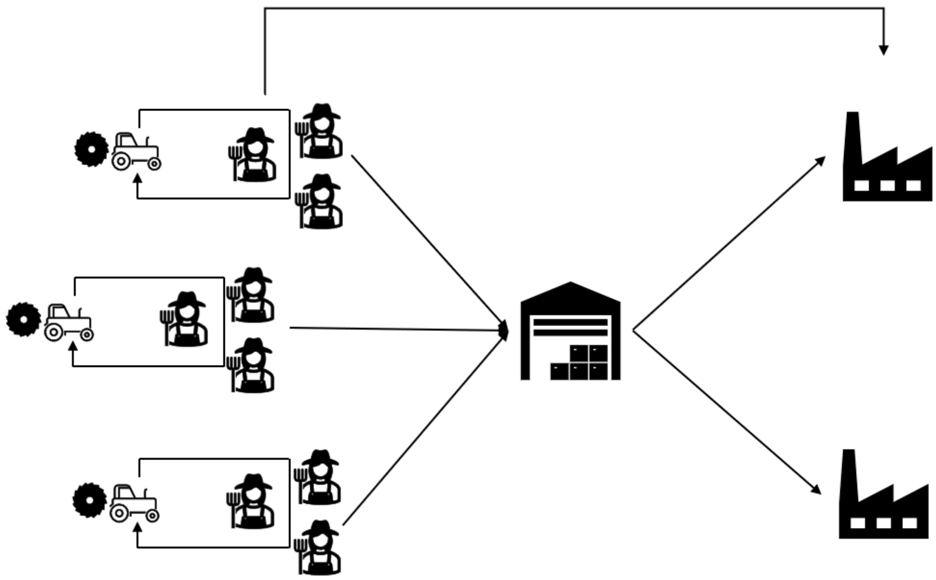


Figure 22: Pruning in Andalusia - Network flow diagram

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

3.3 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 1.1.4). 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 3.3.1), the addition of several specific constraints (Section 3.3.2) and the connection of the MOOV-core to the CMA (Section 3.3.3).

3.3.1 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 (Section3.2.1) 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 23).

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)

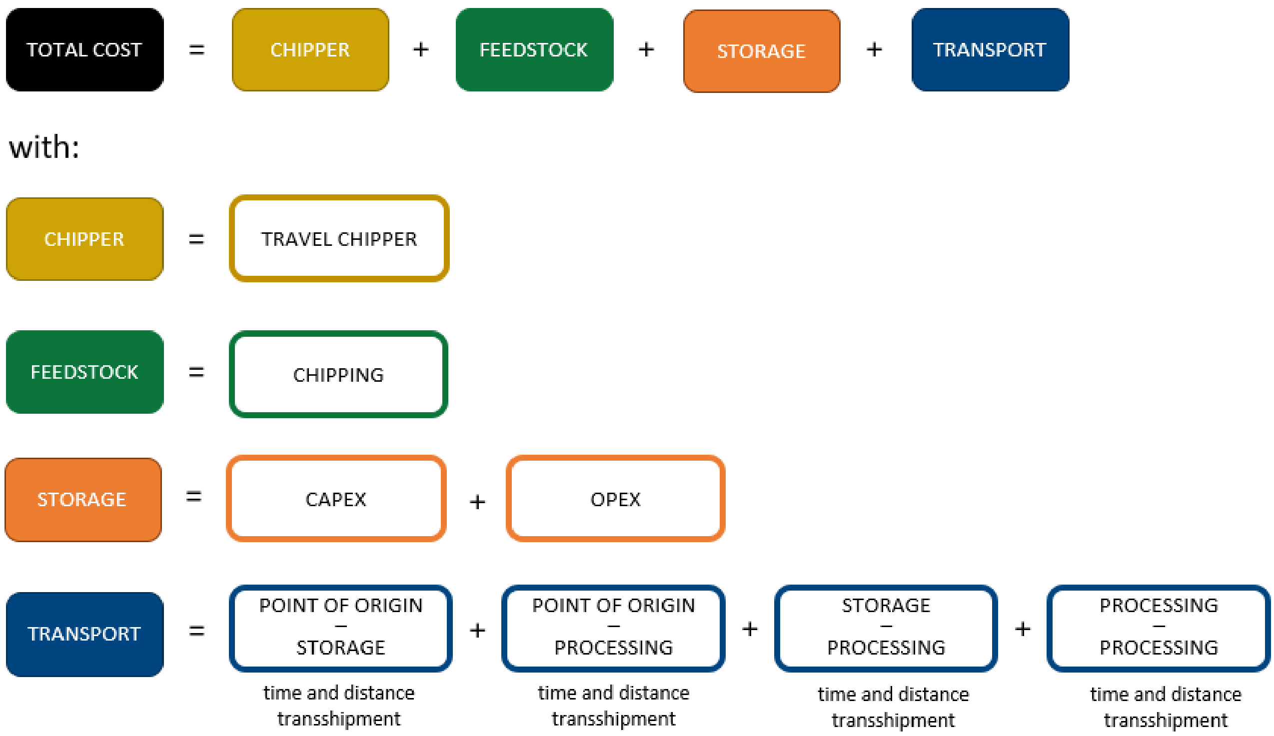


Figure 23: Pruning in Andalusia - Components of the total mobilisation cost included in the MOOV model.

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

3.3.2 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 3). 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 3).
- 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.

3.3.3 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 24 gives an overview of the districting result for the whole region (L) and a zoom into a specific region (R).

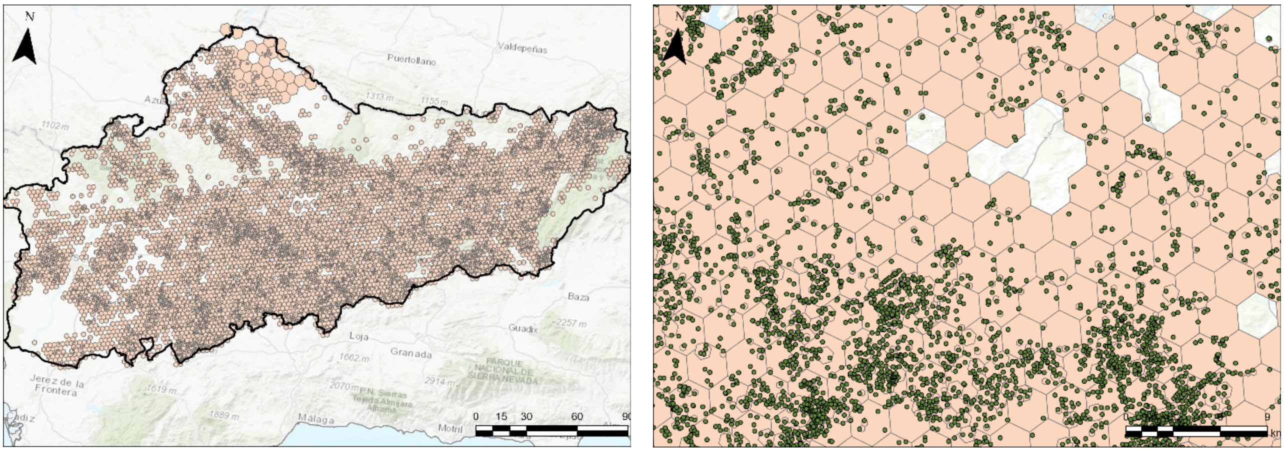


Figure 24 Pruning in Andalusia – Result of the Continuous Multiscale Approach (Districting step).

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 16), 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 21).

3.4 Deliver

3.4.1 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 8 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

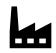
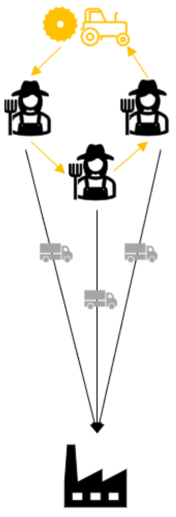
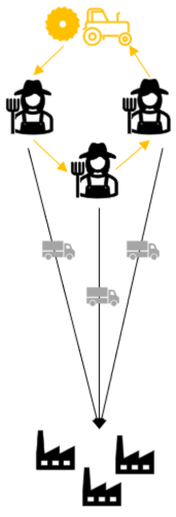
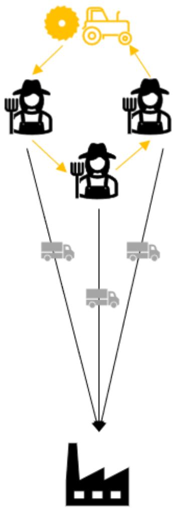
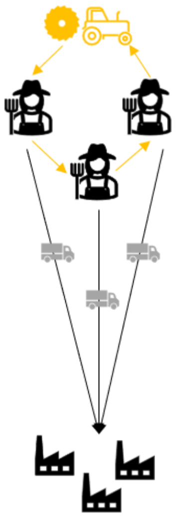
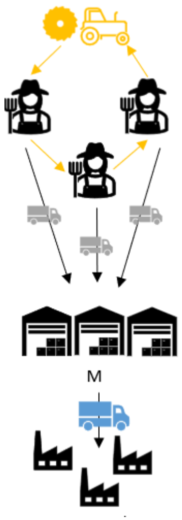
Key performance indicators

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 3.3.1)). 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 8: 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							

3.4.2 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 18) [18,19,20].

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 25). This choice is primarily driven by the higher concentration of large storage facilities in the area (Figure 18).

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.

[18] 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.
[19] Source: Andaltec and the University of Jaen.
[20] 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.

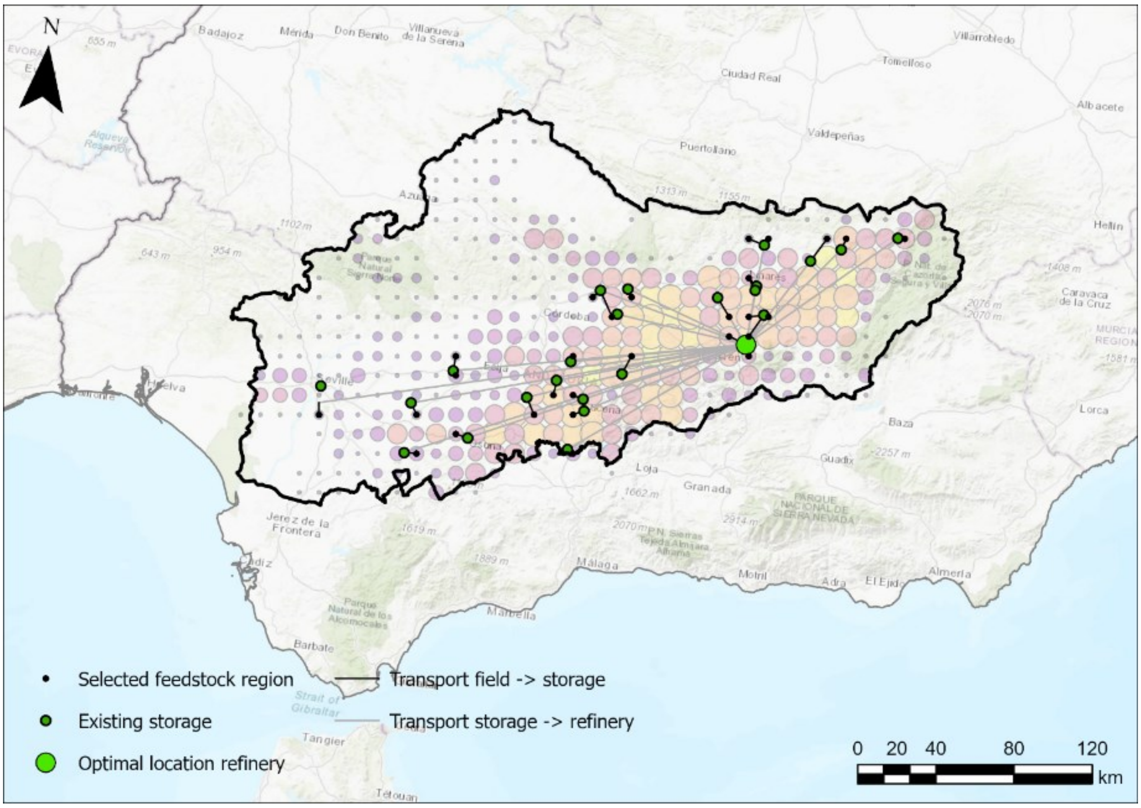


Figure 25: Pruning in Andalusia – Scenario 1: one biorefinery with a 32 kton capacity.

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 26).

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 4), 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 5).

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 25).

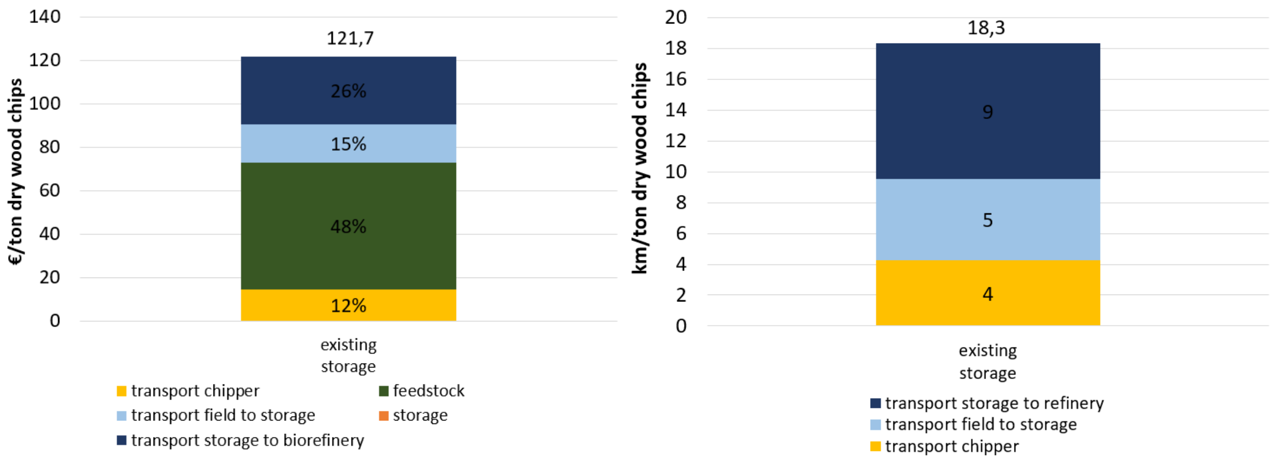


Figure 26: Pruning in Andalusia – Scenario 1: mobilisation cost (€/ton) (L) and transport distance (km/ton) (R)

3.4.3 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[21].

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.

[21] 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 16), a low average transport distance for the chipper (Figure 21) and efficient transport links (along A306), make it the optimal choice (Figure 27) for this base scenario.

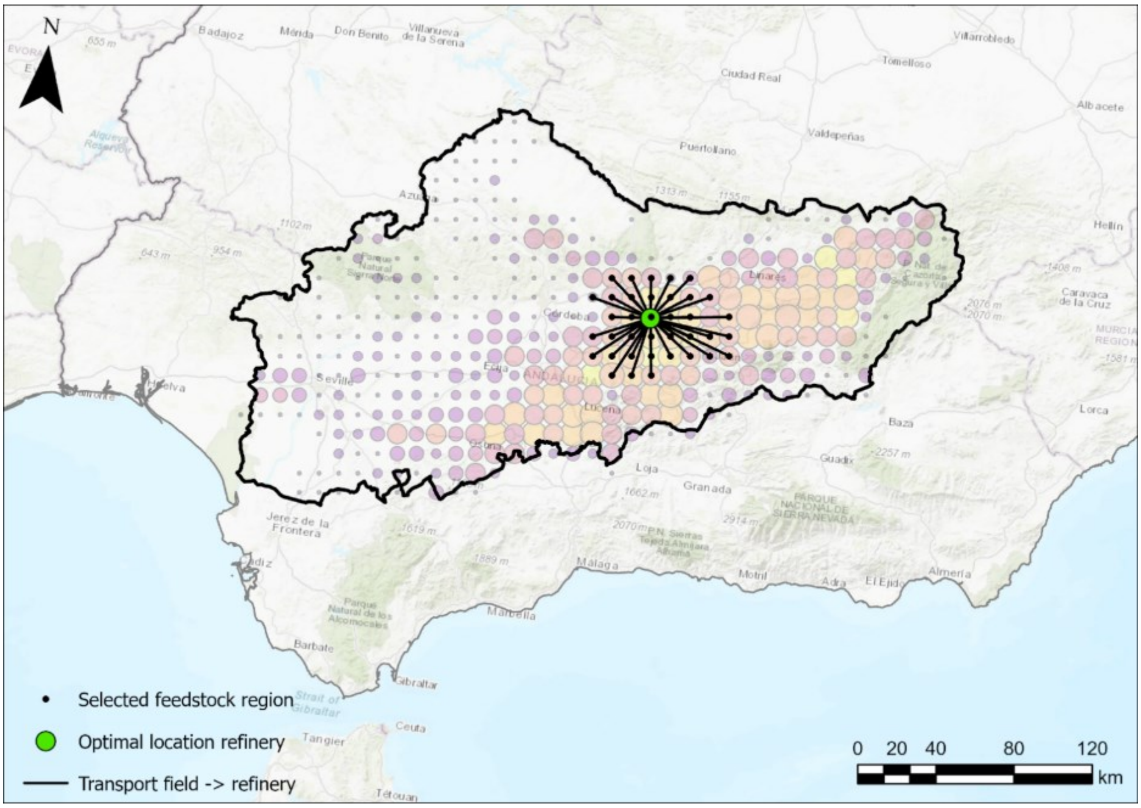


Figure 27: Pruning in Andalusia – Scenario 2: One biorefinery with a 150 kton capacity

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 5). 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.

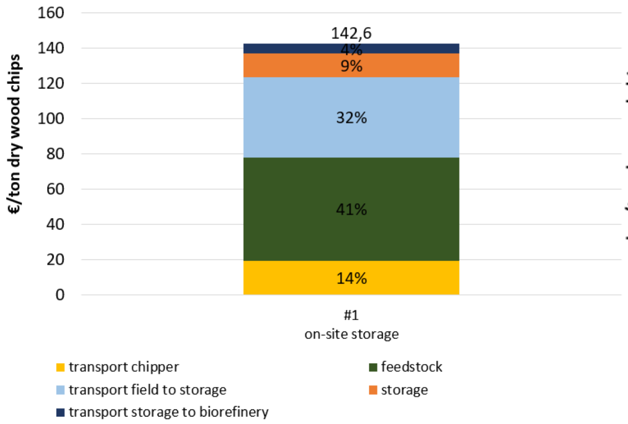
With on-site storage in place, woodchips are transported fresh directly from the fields to the biorefinery. This transport operation results in a cost of 46 € per ton of dry OTP[22], accounting for approximately 32% of the total mobilisation cost.

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

[22] 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[23], 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 27). While the fields are selected in the vicinity of the biorefinery, the average travel distance from field-to-storage[24] amounts to 16 km, accounting for 73% of the total transport distance (Figure 28).



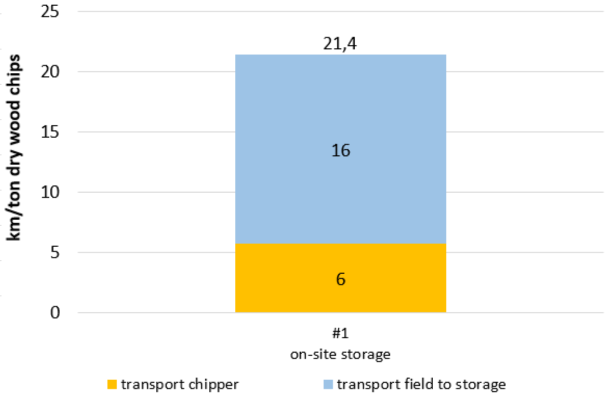


Figure 28: Pruning in Andalusia – Scenario 2 – Mobilisation cost (€/ton) (L) and transport distance (km/ton) (R).

3.4.3.1Sensitivity 2A: Impact of multiple biorefineries

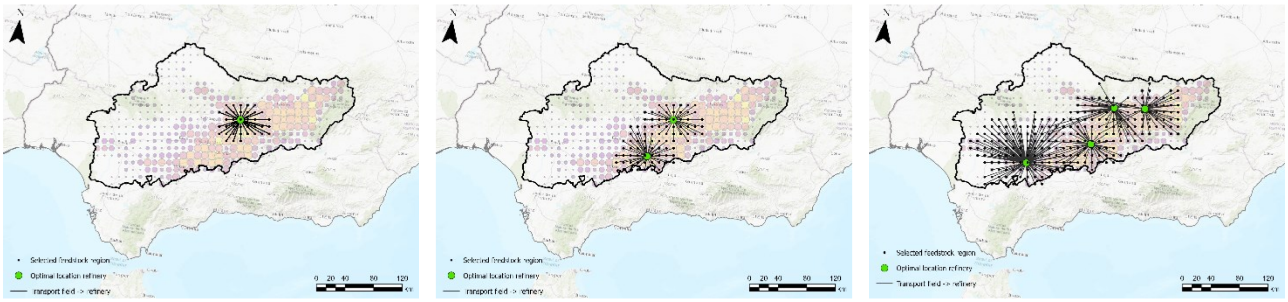
Scenario 2 focused on the establishment of a single biorefinery. However, the availability of additional feedstock in the region indicates the potential to support multiple facilities. Sensitivity Analysis 2A explores the impact of deploying additional biorefineries, each with a processing capacity of 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 29 - left), for 2 biorefineries, the location in Porcuna is retained and an extra refinery is opened in Lucena, in the south of Córdoba (Figure 29 - middle). In case of opening 4 biorefineries, 4 new locations are selected near Linares, Andujar, Dona Mencia and Cazalla (Figure 29 - right).

[23] See Table 6 – container truck (25 m³) vs. walking floor trailer (85 m³)
[24] 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 29: Pruning in Andalusia – Sensitivity 2A – Impact of additional biorefineries

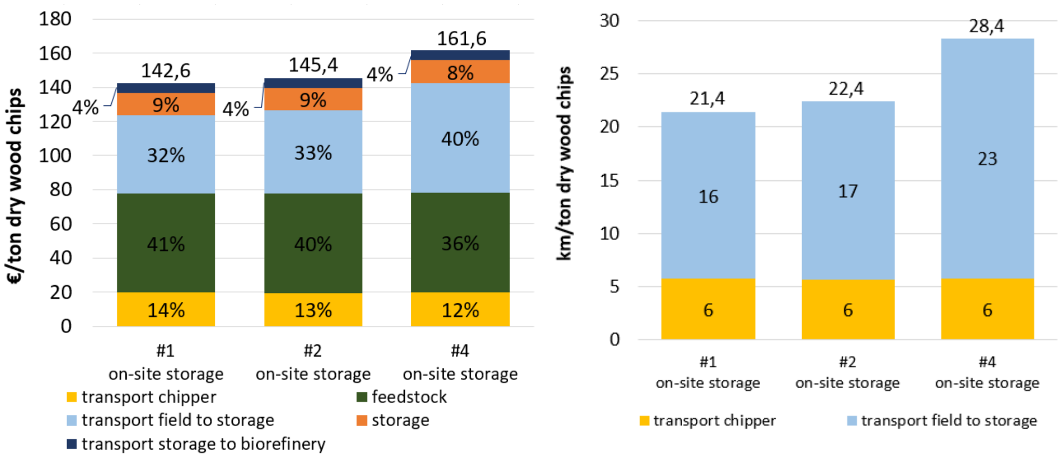
With increasing biorefineries, logically the mobilisation costs increase, as more feedstock is required. With 2 refineries the mobilisation cost rises only slightly by 2%, to 145 € per ton of dry OTP. A scenario with 4 refineries shows a more substantial increase by 13%, to 162 € per ton of dry OTP. The increase in total mobilisation cost is primarily due to increase in field-to-storage[25] transport cost (Figure 30 - 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 30 – 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 4).

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.



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

Figure 30: 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 21).

This outcome is largely attributed to the high concentration of olive fields in the south-eastern part of the region (Figure 16), 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.

3.4.3.2Sensitivity 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.

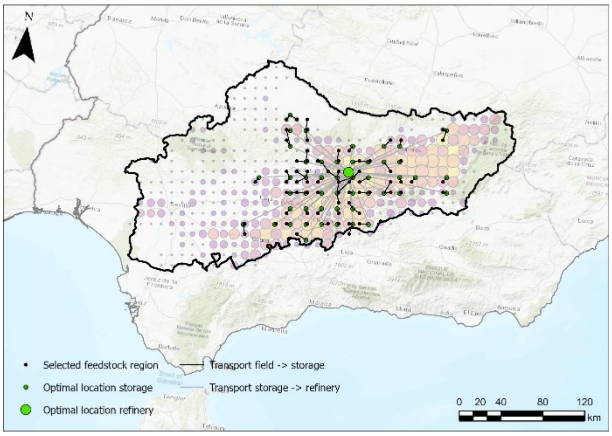
Candidate locations for these off-site storage sites are identified based on a spatial grid analysis using a 15 km by 15 km raster, allowing for systematic evaluation of off-site storage integration across the region (Figure 18 b).

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 5.

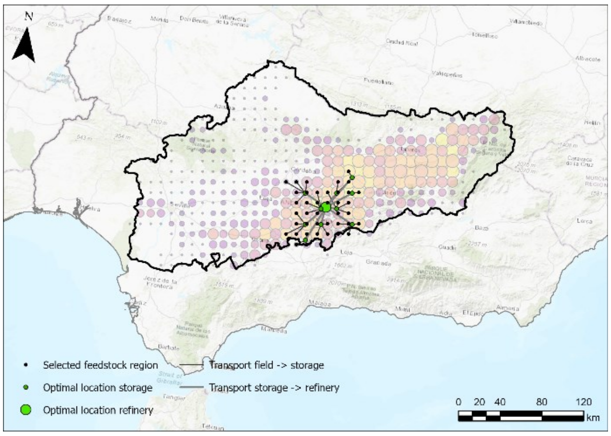
The storage types are structured such that the XL storage unit can accommodate the entire volume of OTP on its own, requiring only one storage site. In contrast, the XXS storage unit represents the smallest feasible capacity per site that still allows for a viable logistical configuration.

In the XXS scenario, a total of 48 storage sites are required, while the optimal biorefinery location remains unchanged from Scenario 2 (Figure 31 a). For configurations with larger off-site storage capacities, the optimal refinery location shifts toward the Doña Mencía region (Figure 31 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.

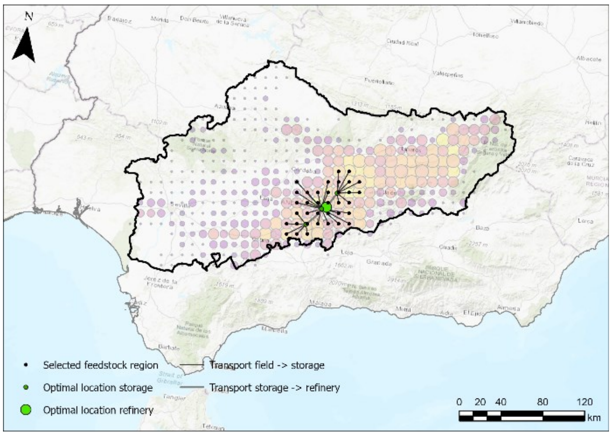
In the S scenario, 3 storage facilities are required. Both the M and L scenarios require only 2 sites, suggesting that within this capacity range, the specific storage volume does not substantially alter the total supply chain layout. Finally, in the XL scenario, only a single storage facility is needed,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



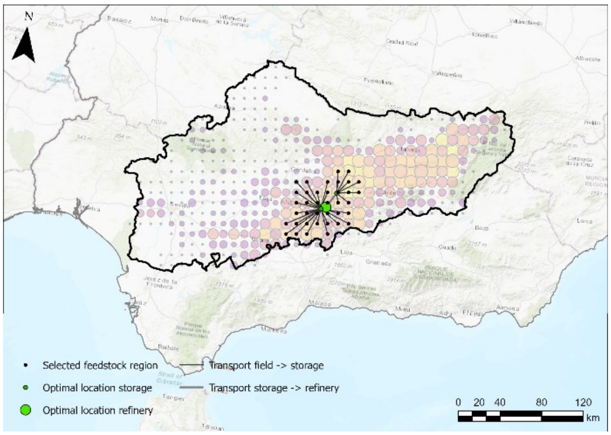
(a) 1 biorefinery of 150 kton with XXS off-site storage



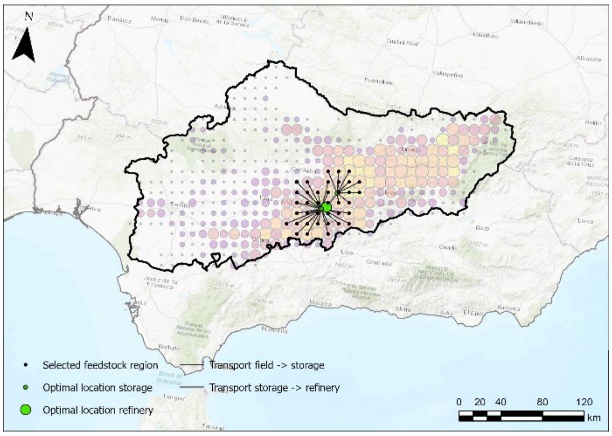
(b) 1 biorefinery of 150 kton with XS off-site storage



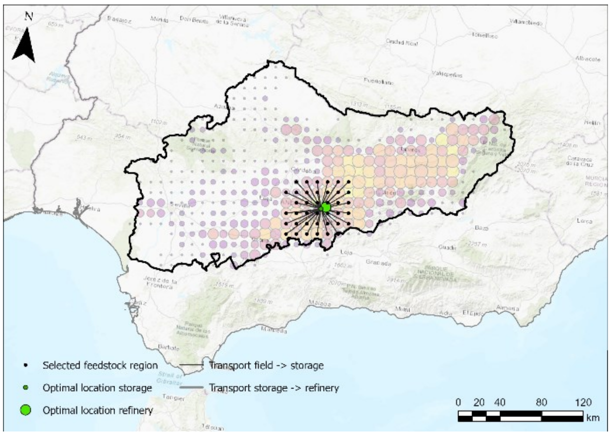
(c) 1 biorefinery of 150 kton with S off-site storage



(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 31: 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 32). 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.

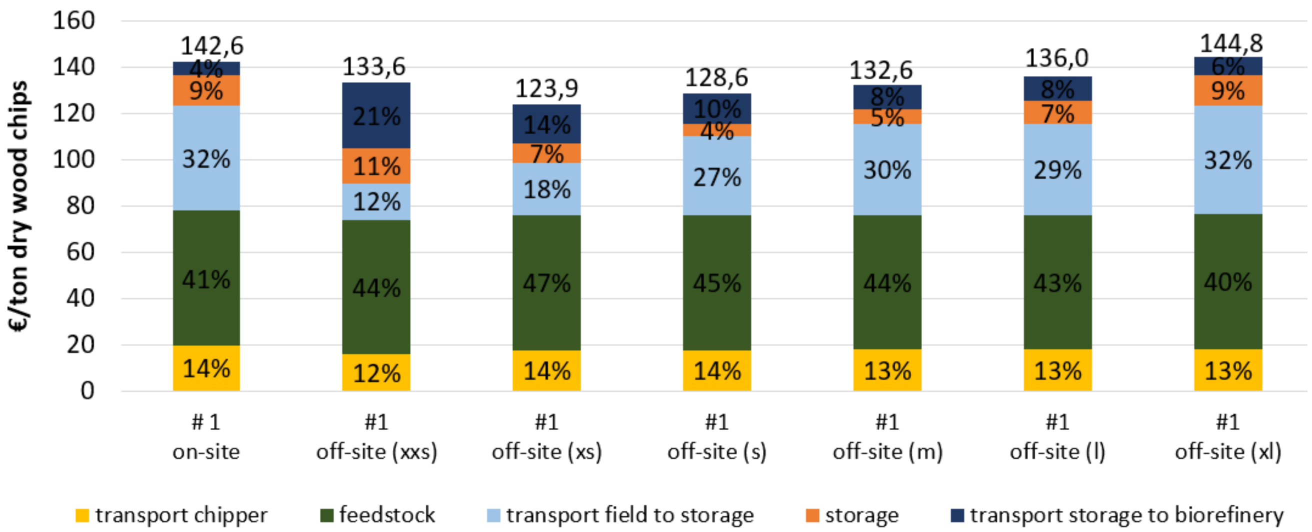


Figure 32: Pruning in Andalusia – Sensitivity 2B – Impact of off-site storage: Total mobilisation cost.

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 33).

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.

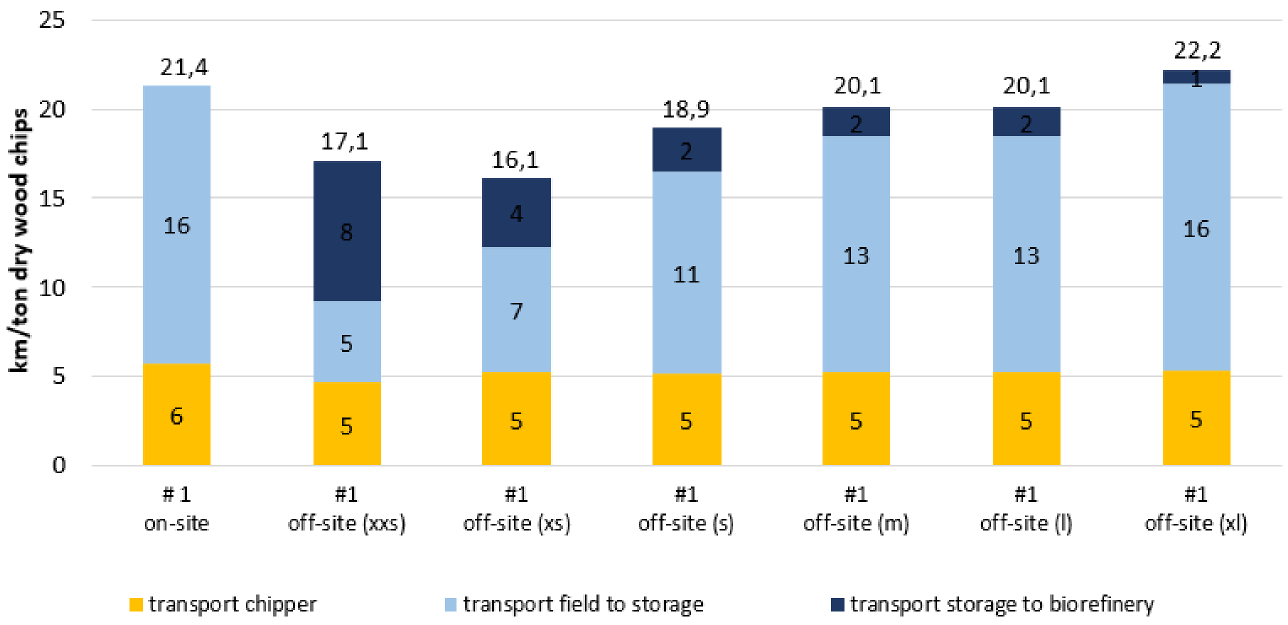


Figure 33: Pruning in Andalusia – Sensitivity 2B – Impact of off-site storage: Total transport distance

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.

3.4.4 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 34). This site offers several strategic advantages, including a central position within the region, proximity to the main olive-producing areas (Figure 15), and access to efficient transport infrastructure via the A306.

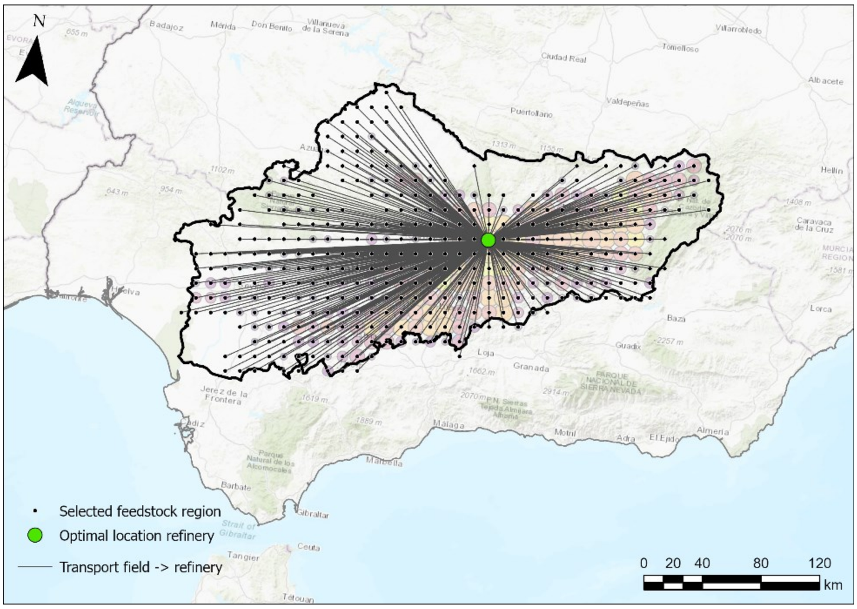


Figure 34: Pruning in Andalusia – Scenario 3 – Optimal location of one biorefinery with a 700 kton capacity

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 35).

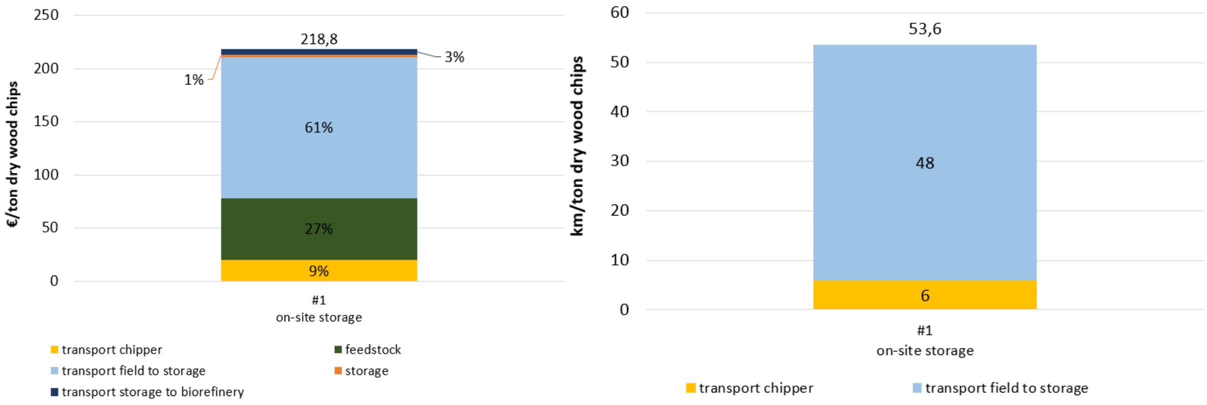


Figure 35: Pruning in Andalusia – Scenario 3 – Mobilisation cost (L) and transport distance (R) - one biorefinery to process all available OTP.

Finally, as previously noted, the feedstock cost—representing the chipping cost—remains constant at 58 €/ton across all scenarios (

Table 4). 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%.

3.4.4.1Sensitivity 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 36- top left). When two biorefineries are considered, the optimal sites are located in Bailén and Montilla (Figure 36- 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 36- bottom). This spatial distribution reflects the need to optimise transport distances and decentralise processing operations as the number of biorefineries increases.

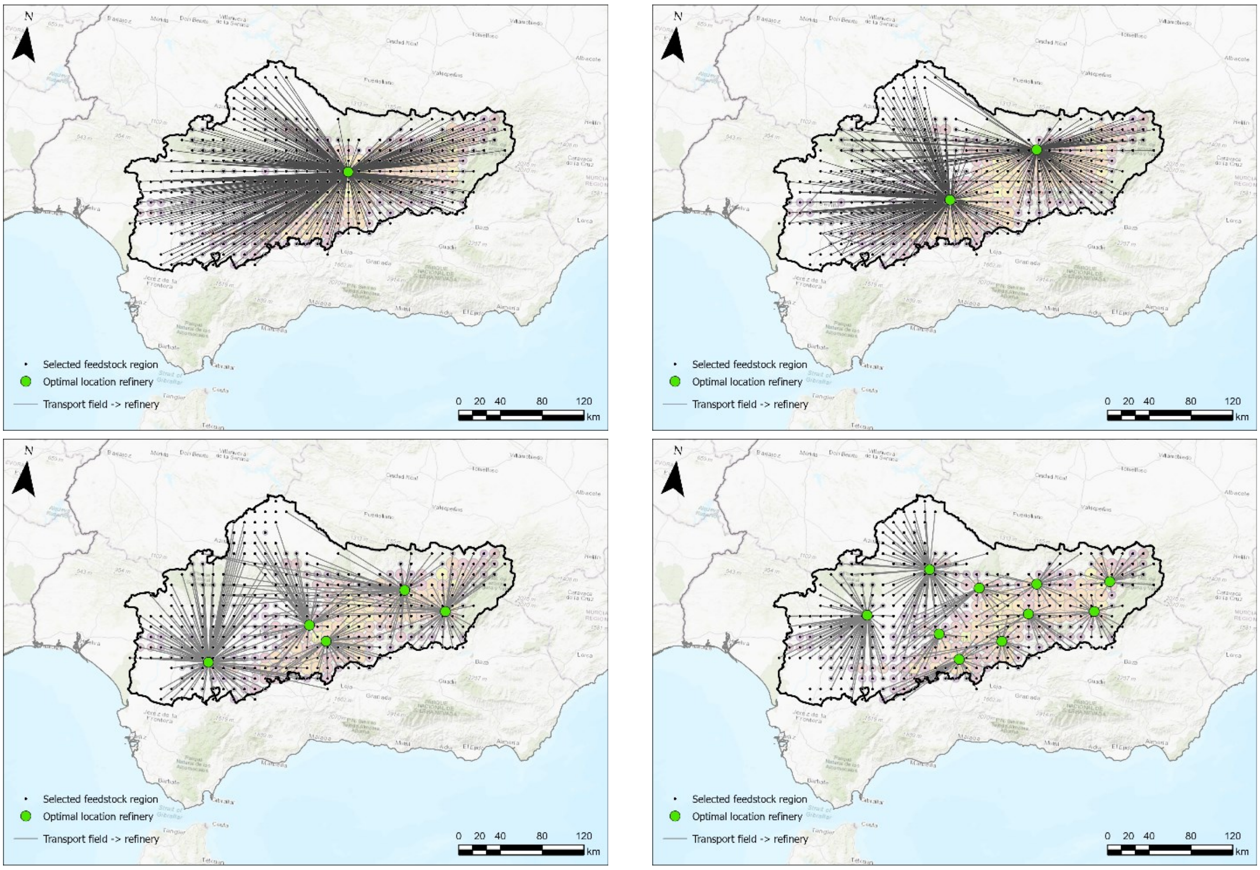


Figure 36: Pruning in Andalusia – Sensitivity 3A – Impact of multiple biorefineries – processing all available OTP - Optimal biorefinery locations.

Both the total mobilisation costs and transport distance decrease as more biorefineries are introduced (Figure 37). 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.

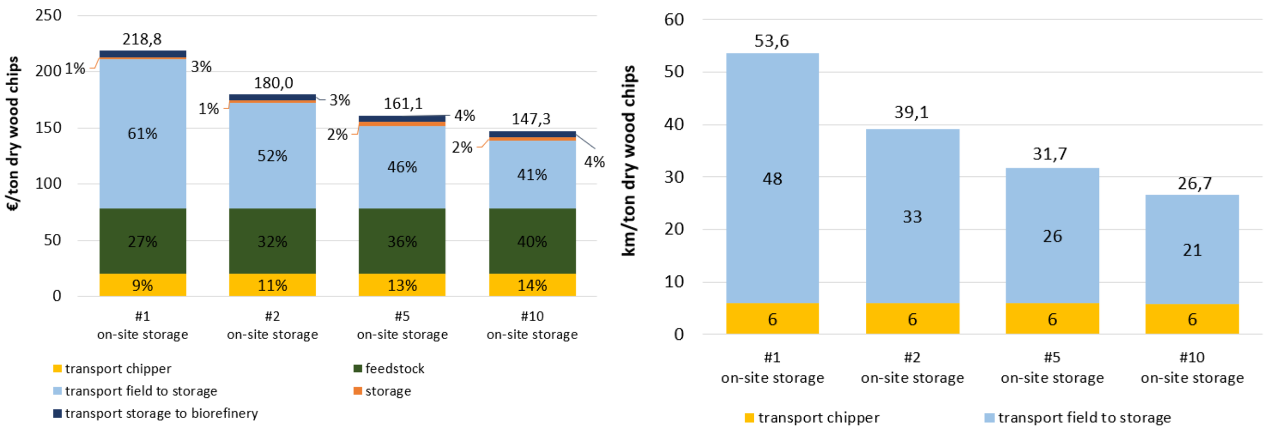


Figure 37: Pruning in Andalusia –Sensitivity 3A – Impact of multiple biorefineries - processing all available OTP: Mobilisation cost (L) and transport distance (R)

The reduction in total mobilisation cost is primarily due to the significant decrease in field-to-storage[26] transport costs (Figure 37 – 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 37 – 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.

3.4.4.2Sensitivity 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 5. 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.

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

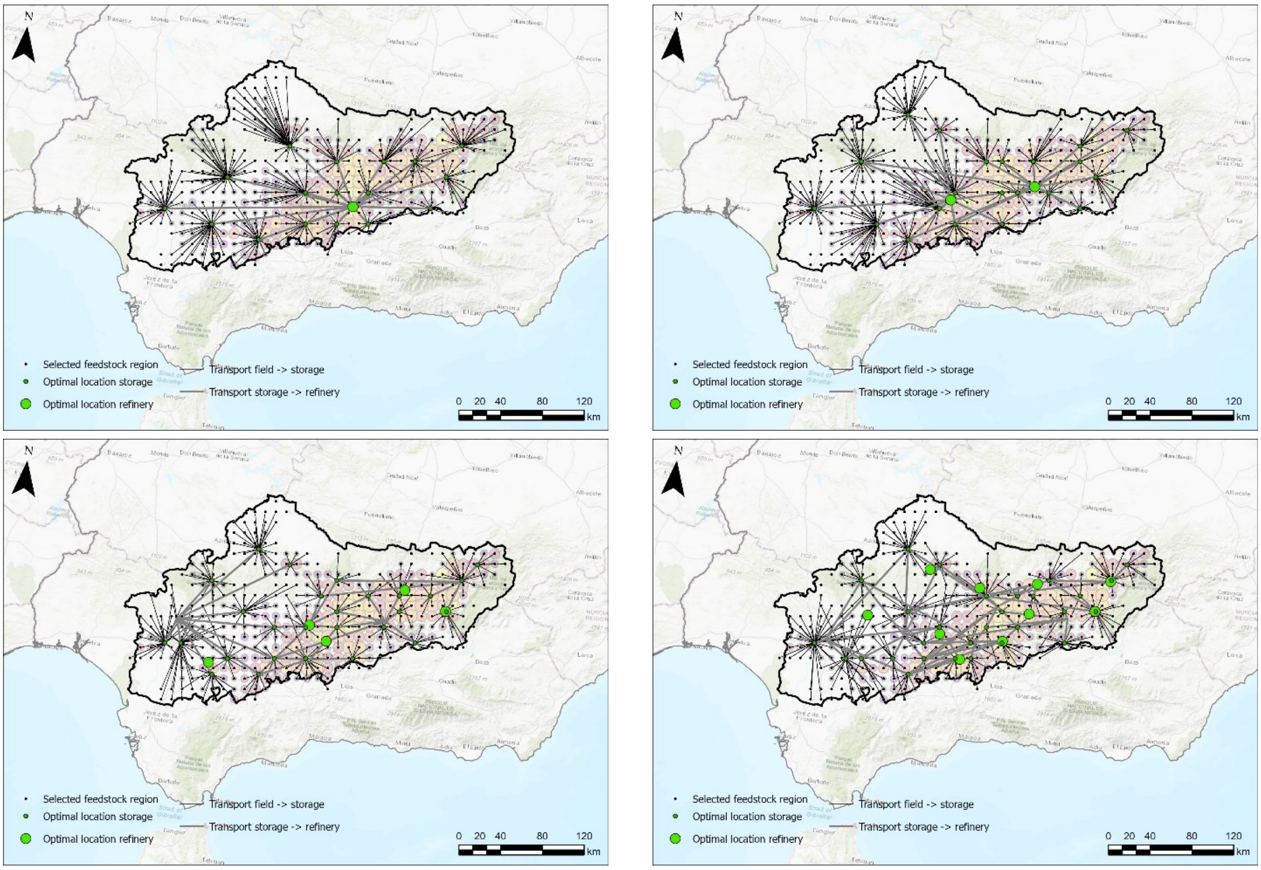


Figure 38: Pruning in Andalusia – Sensitivity 3B – Impact of off-site storage - processing all available OTP: Optimal biorefinery and storage locations.

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 38 – 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 39 - #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 39 - #1 off-site (m) – orange bar segment).

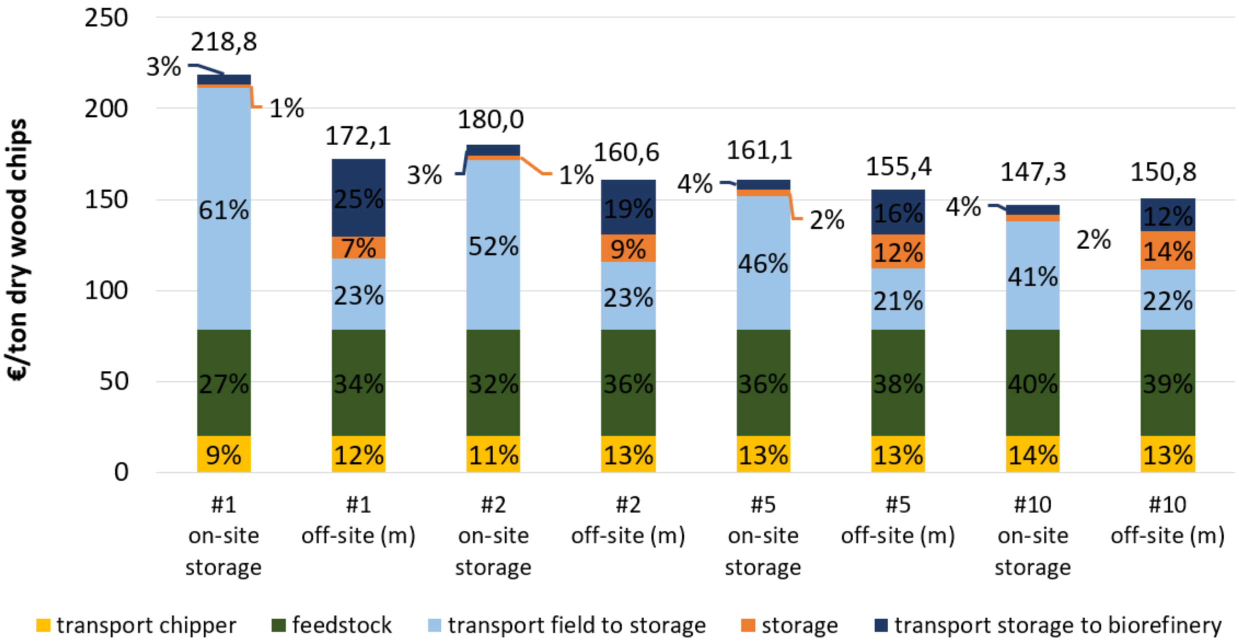


Figure 39: Pruning in Andalusia – Sensitivity 3B – Impact of off-site storage – processing all available OTP: Total mobilisation cost.

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 40 - #1 off-site (m)).

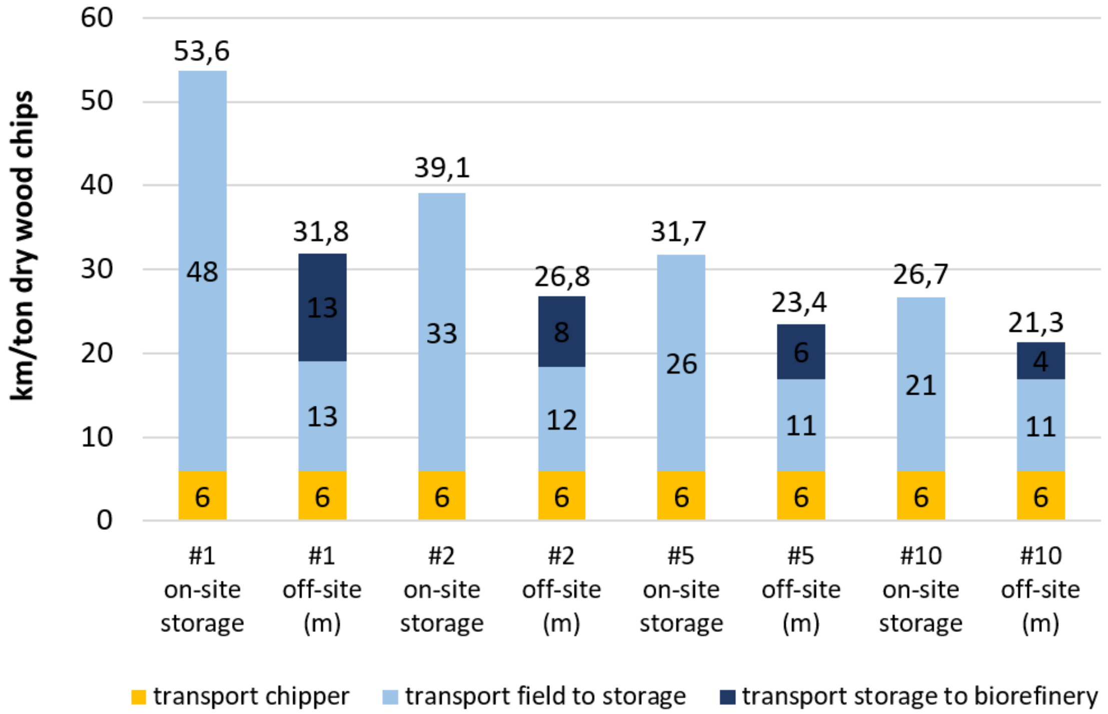


Figure 40: Pruning in Andalusia – Sensitivity 3B – Impact of off-site storage – processing all available OTP: Transport distance

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.

3.5 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 41) and **transport distance** (Figure 42). 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.

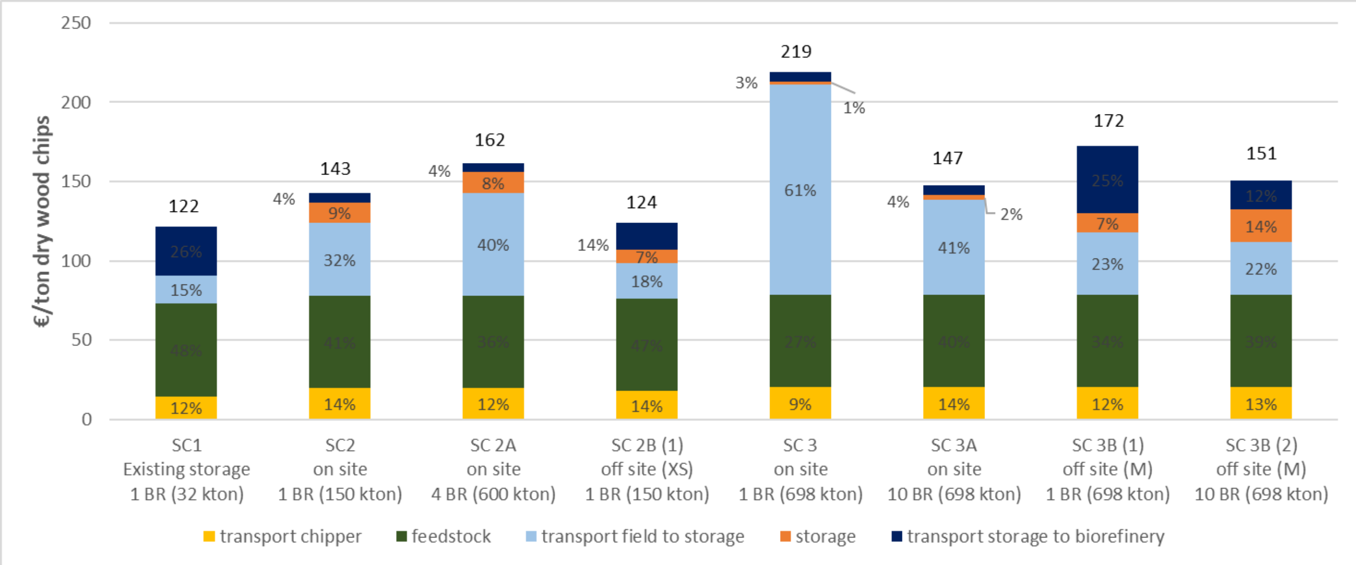


Figure 41: Mobilisation cost (€ per ton dry OTP)

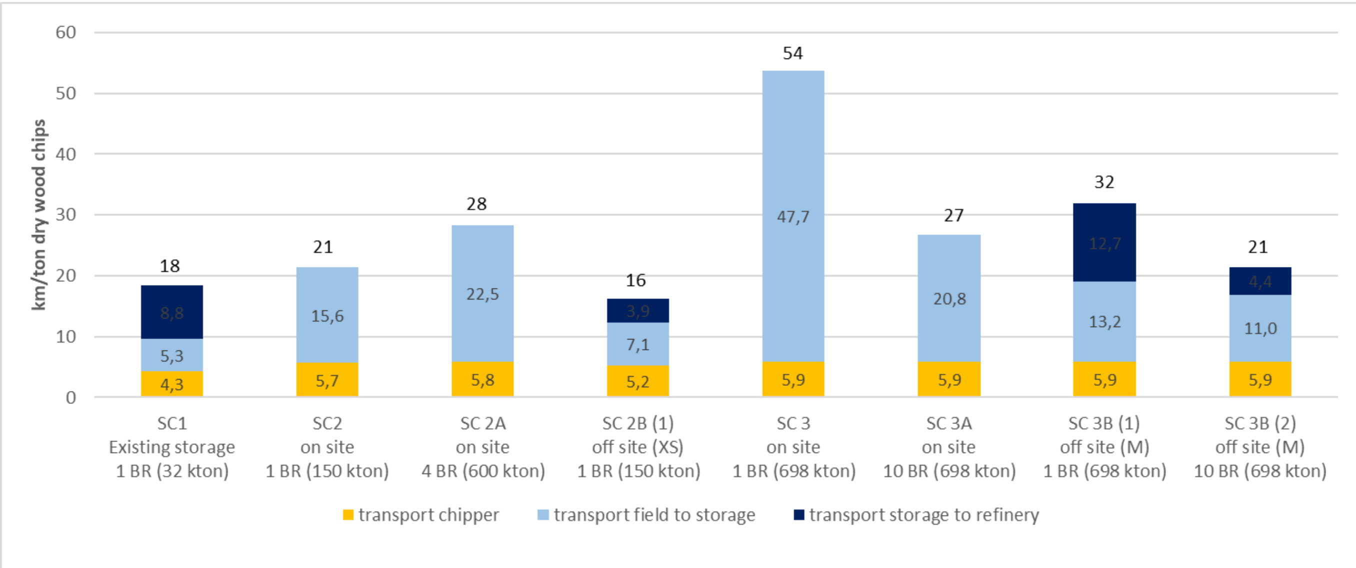


Figure 42: Transport distance (km per ton dry woodchips)

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.

4. Food waste in the Karlovy Vary (Czech Republic)

4.1 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 43) – 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.

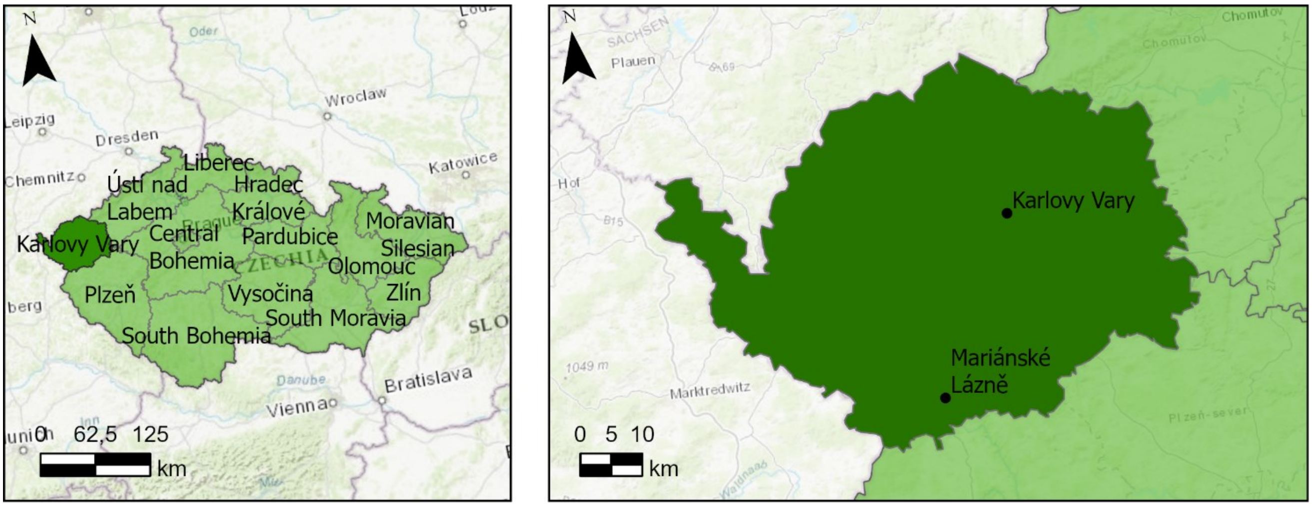


Figure 43: Food waste in Karlovy Vary - Region of focus (dark green)

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.

4.2 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 44).

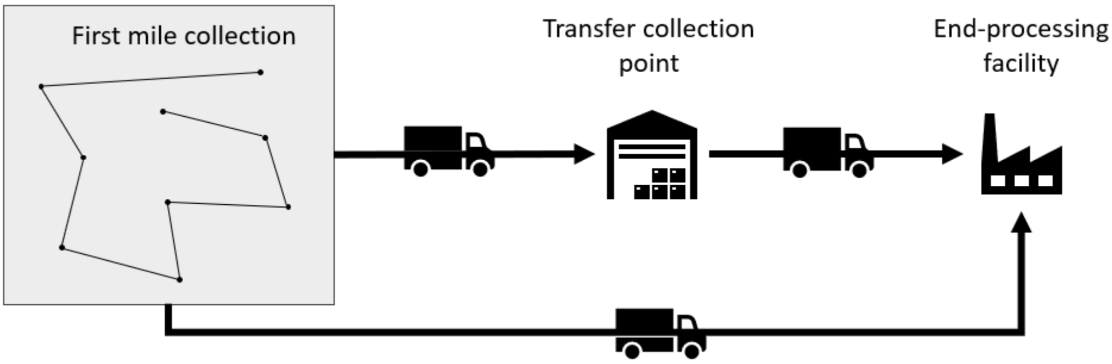


Figure 44: Food waste in Karlovy Vary region - Stages of focus of the pathway to valorise food waste.

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

4.2.1 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 45 and Table 9), 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 45 and Table 9).

Table 9: Food waste in Karlovy Vary – Resource collection: Parameters and characteristics required in the MOOV analysis (data 2023). With KV: Karlovy Vary and ML: Mariánské Lázně.

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

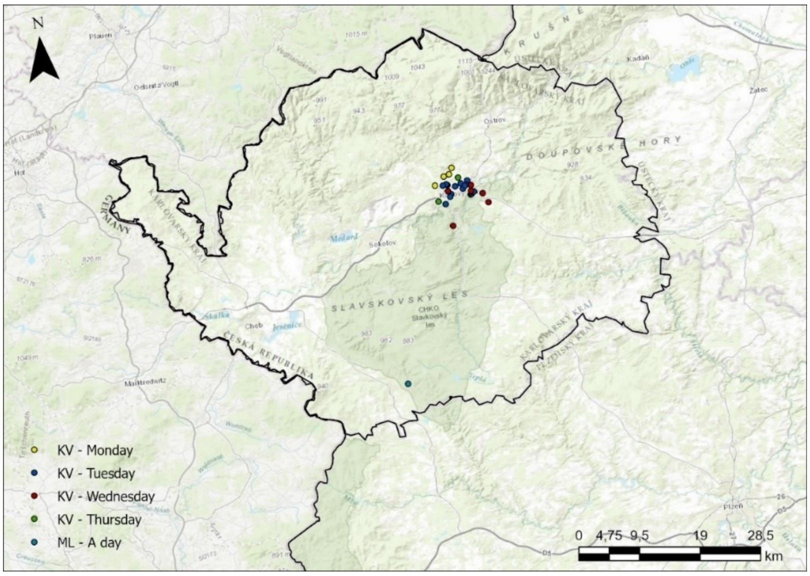


Figure 45: Food waste in Karlovy Vary – Resource collection: Sourcing locations

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 46). The maximum time that food waste can remain at this point typically is 48 hours at maximum.

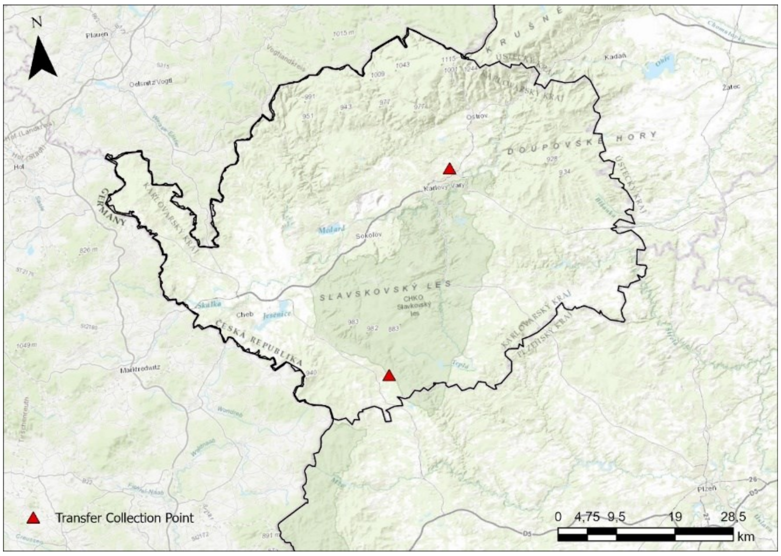


Figure 46: Food waste in Karlovy Vary – Transfer collection point locations.

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 47). 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 10.

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 10 (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 10: Food waste in Karlovy Vary – Processing types – Parameters and characteristics [27].

Processing type	Capacity (ton per year)	CAPEX[28] (€ 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 11 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 11: 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%

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

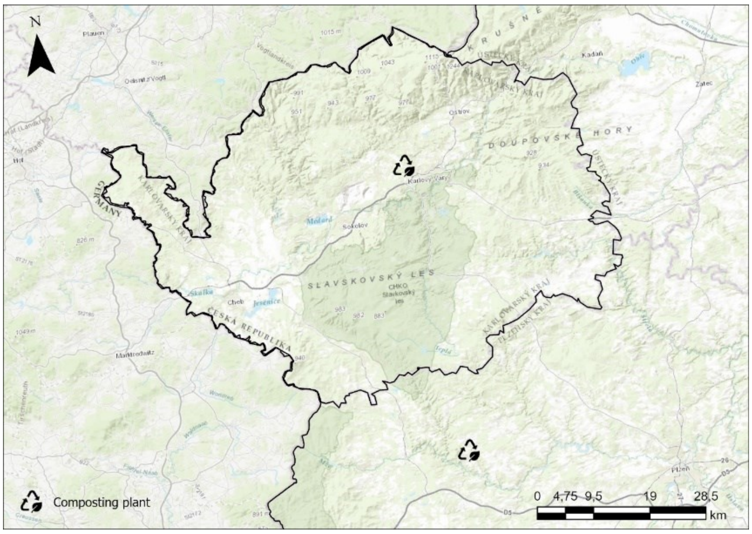


Figure 47: Food waste in Karlovy Vary region – Current composting locations (AS IS).

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 48):

- **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.

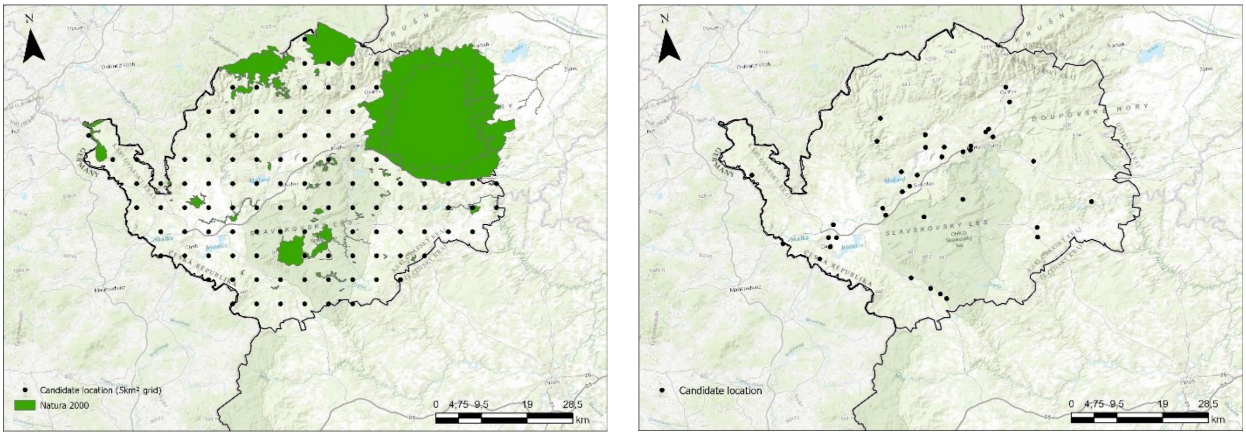


Figure 48: Food waste in Karlovy Vary – Candidate locations for end-processing based on the GF approach (L) and the multi-criteria analysis (R).

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 9, 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 12).

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 12: 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 49 shows the transportation network in the Karlovy Vary region. Only the main roads are provided on the image to increase readability.

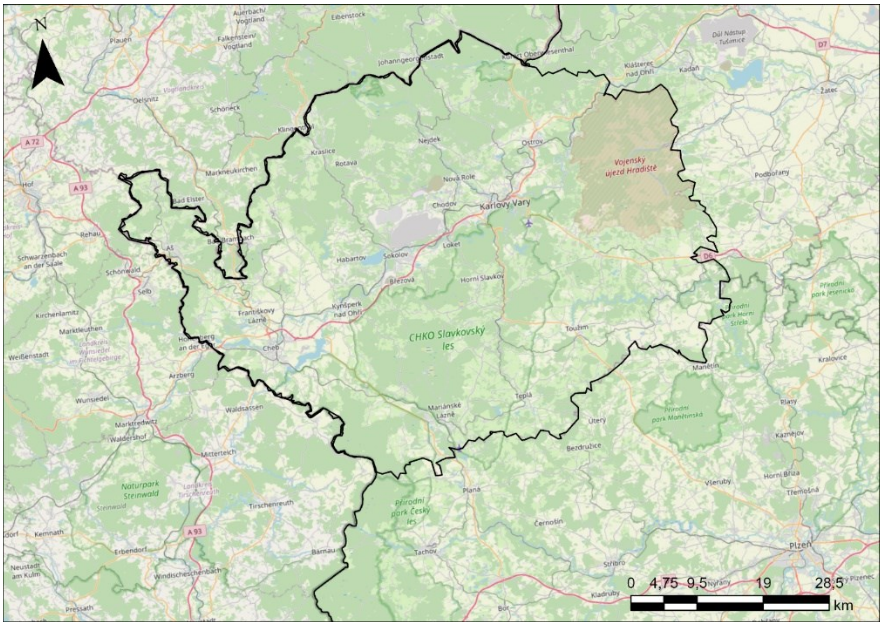


Figure 49: Food waste in Karlovy Vary – Transport network Network flow diagram[29]

[29] 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 50)

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.

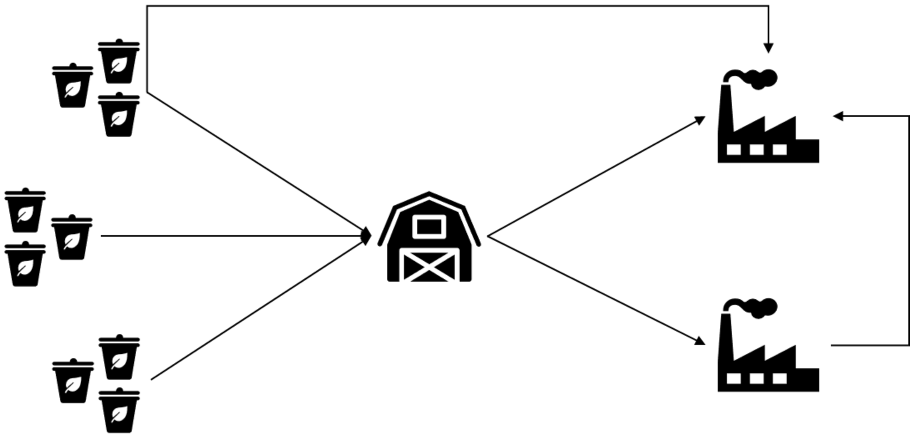


Figure 50: Food waste in Karlovy Vary – Network flow diagram as a generic representation of the potential resource flows.

4.3 Design –development of the optimisation model

The specifics defined in chapter 4.2 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.

4.3.1 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 51). 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 51):

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 50) 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.

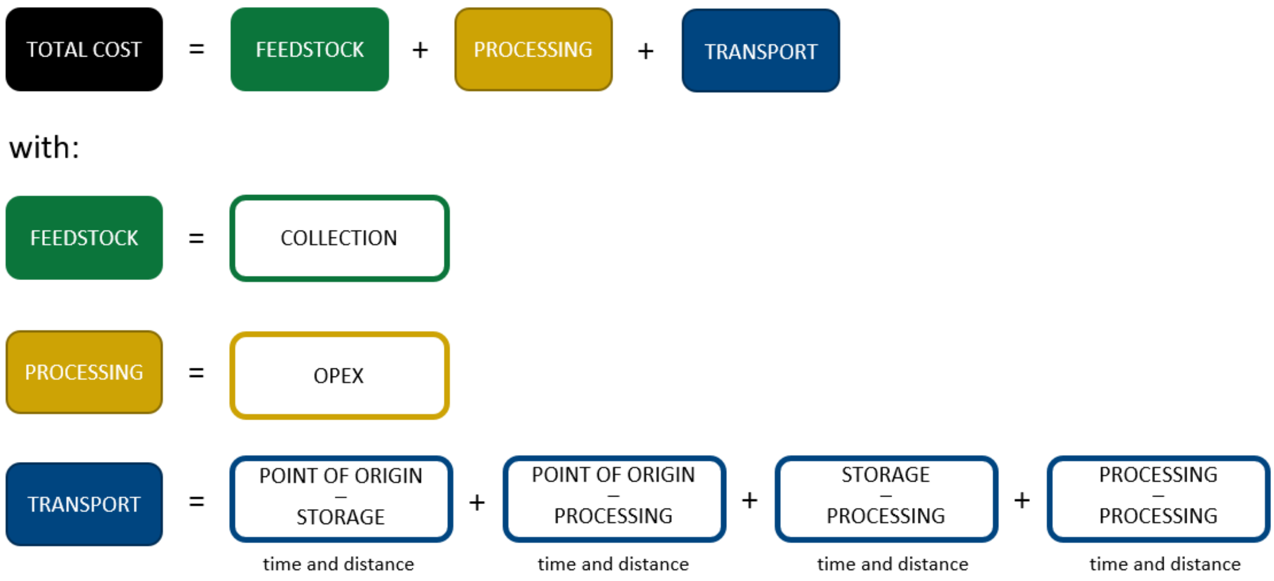


Figure 51: Food waste in Karlovy Vary – Components of the total mobilisation cost included in the MOOV model.

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.

4.3.2 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.

4.4 Deliver

4.4.1 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 52.

- **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.

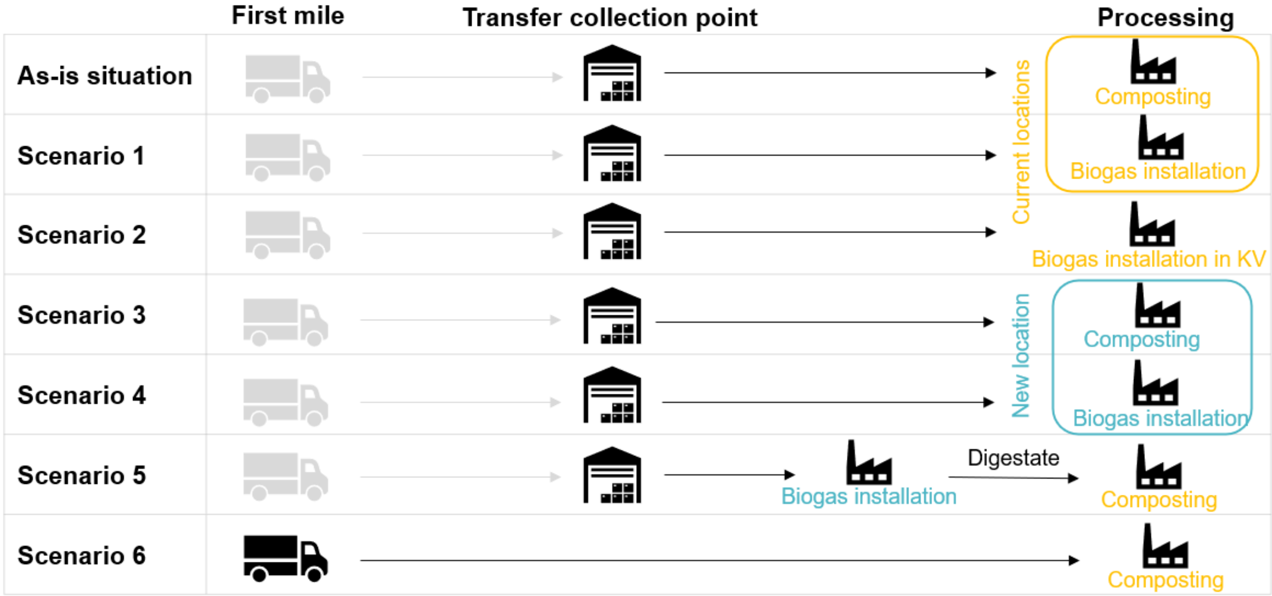


Figure 52: Food waste in Karlovy Vary - Visualisation of the AS IS situation and TO BE scenarios.

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.

4.4.1 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 53 the transport routes, the location of the TCP and the composting site are indicated for both Karlovy Vary (L) and Mariánské Lázne (R).

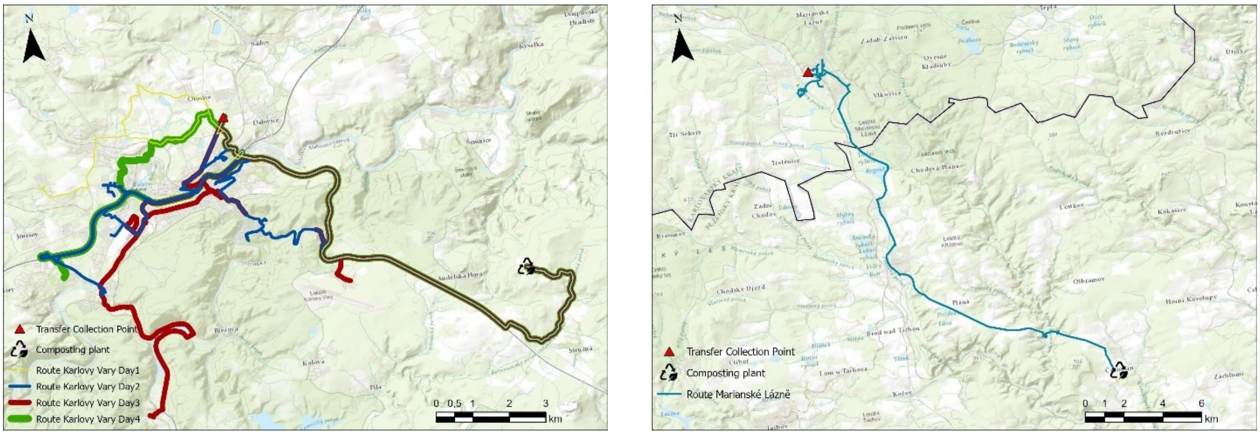


Figure 53: Food waste in Karlovy Vary – Map of resource flows in the current situation (AS IS) for Karlovy Vary (L) and Mariánské Lázne (R).

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 54).

The cost (286.726 €/year) implies the following elements (Figure 54):

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

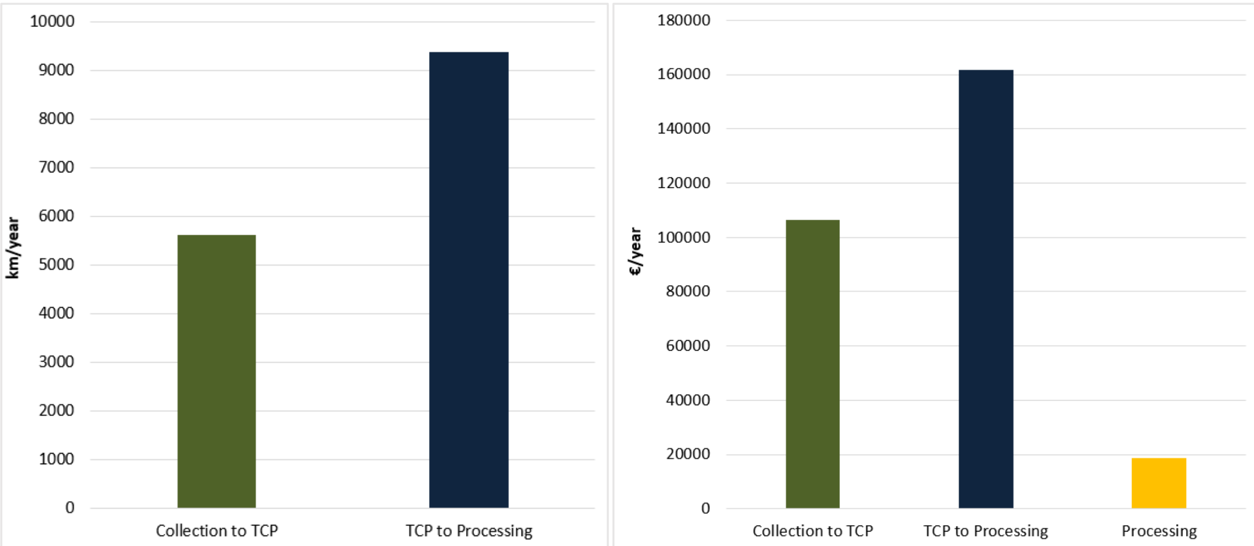


Figure 54: Food waste in Karlovy Vary region – transport distance (L) and cost (R) in the current situation (AS IS).

4.4.2 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 55).

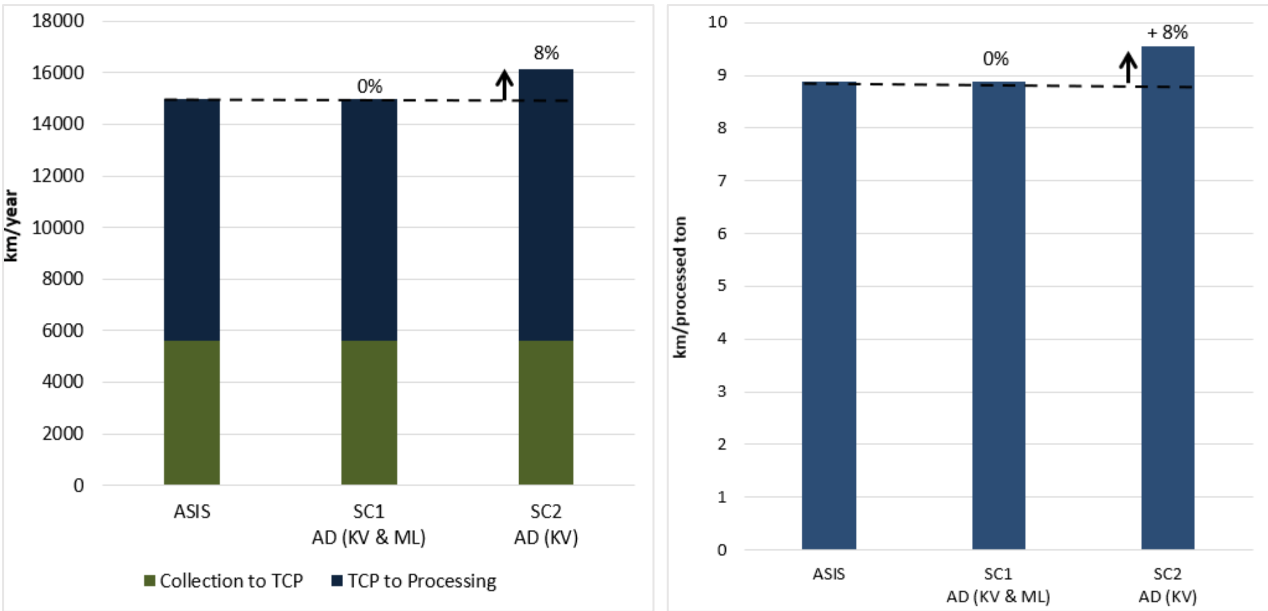


Figure 55: Food waste in Karlovy Vary region – Transport distance in km/year (L) and km/processed ton (R) of processing type (scenario 1 and scenario 2) in comparison to the current situation (AS IS)

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 10). This change corresponds to an approximate 12% rise in total costs (Figure 56).

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 55. Combined, both factors contribute to a total cost increase of ca. 14% compared to the AS IS situation (Figure 56).

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.

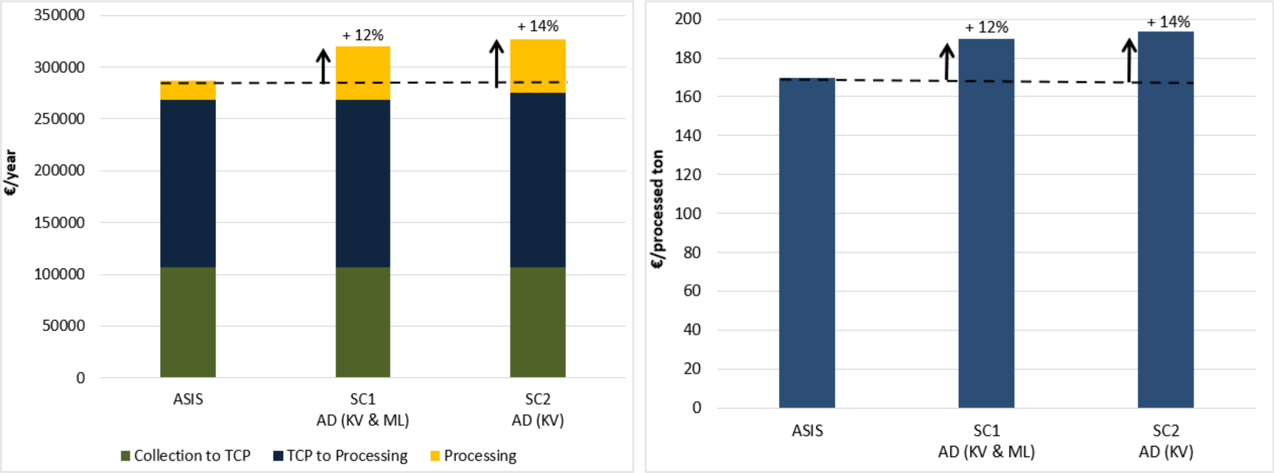


Figure 56: Food waste in Karlovy Vary region – Mobilisation cost in €/year (L) and €/processed ton (R) of processing type (scenario 1 and scenario 2) in comparison to the current situation (AS IS)

4.4.3 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 4.2.1 – 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 57. 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 9.

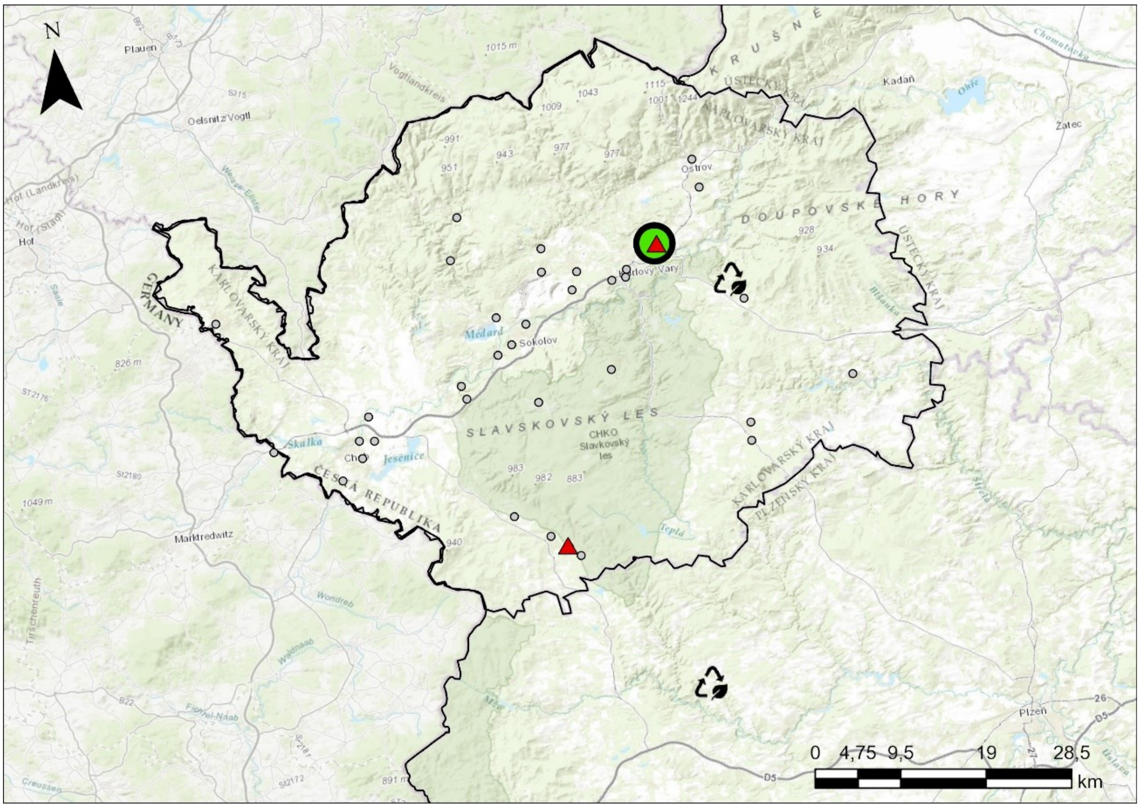


Figure 57: Food waste in Karlovy Vary – Optimal location for end-processing.

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 58).

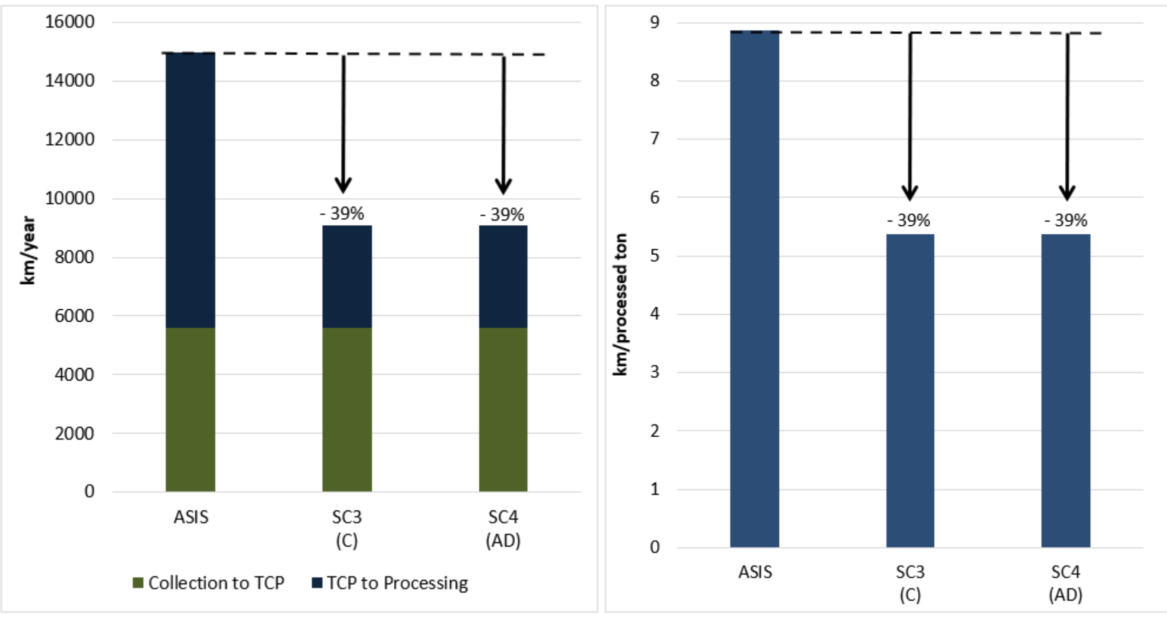


Figure 58: Food waste in Karlovy Vary region – Transport distance in km/year (L) and km/processed ton (R) of centralisation (scenario 3 and scenario 4) in comparison to the current situation (AS IS).

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 59).

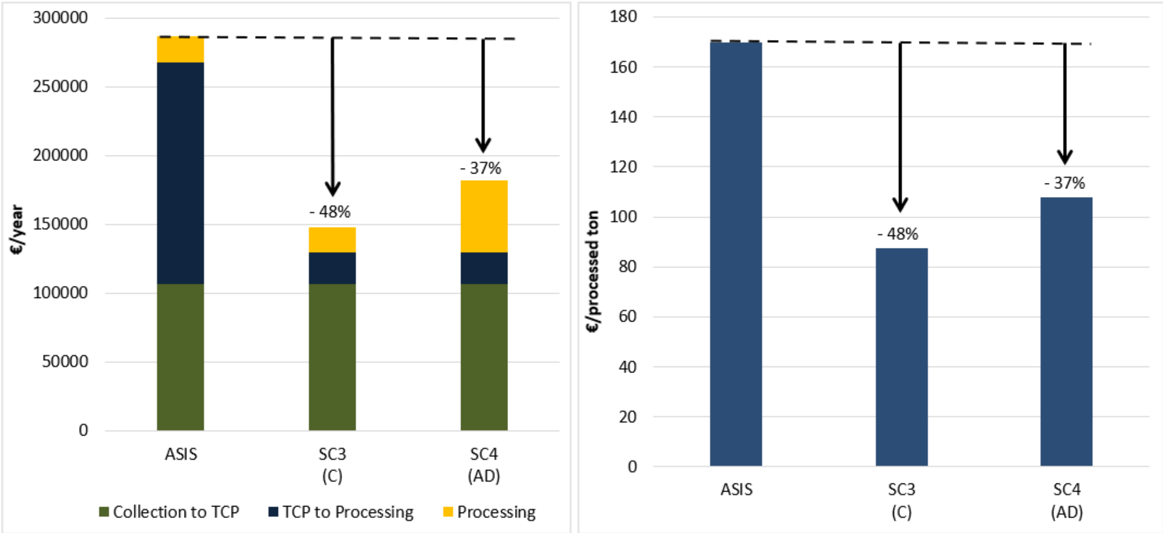


Figure 59: Food waste in Karlovy Vary region – Mobilisation cost in €/year (L) and €/processed ton (R) of centralisation (scenario 3 and scenario 4) in comparison to the current situation (AS IS).

4.4.1 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 57). 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 60 (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 60 (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 60 – 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 59).

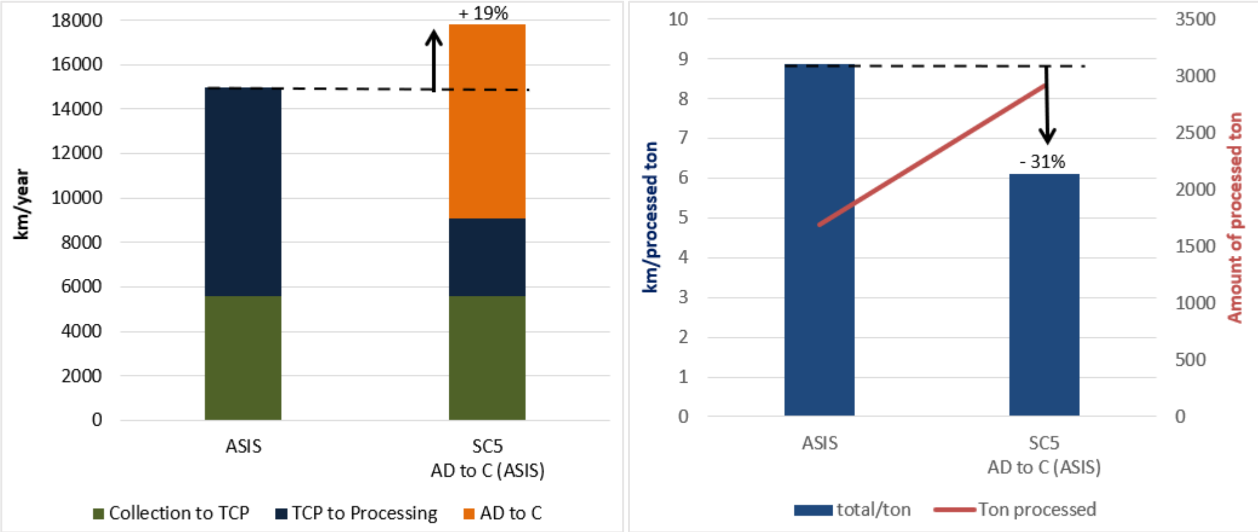


Figure 60: Food waste in Karlovy Vary – Transport distance in km/year (L) and km/processed ton in comparison to the total amount of processed ton (R) of end-processing combination (scenario 5) in comparison to the current situation (AS IS).

In terms of total costs, Figure 61 (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 61 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 12). As a result, the transport cost of this leg is reduced, which is reflected in the orange bar of Figure 61.

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 61– right).

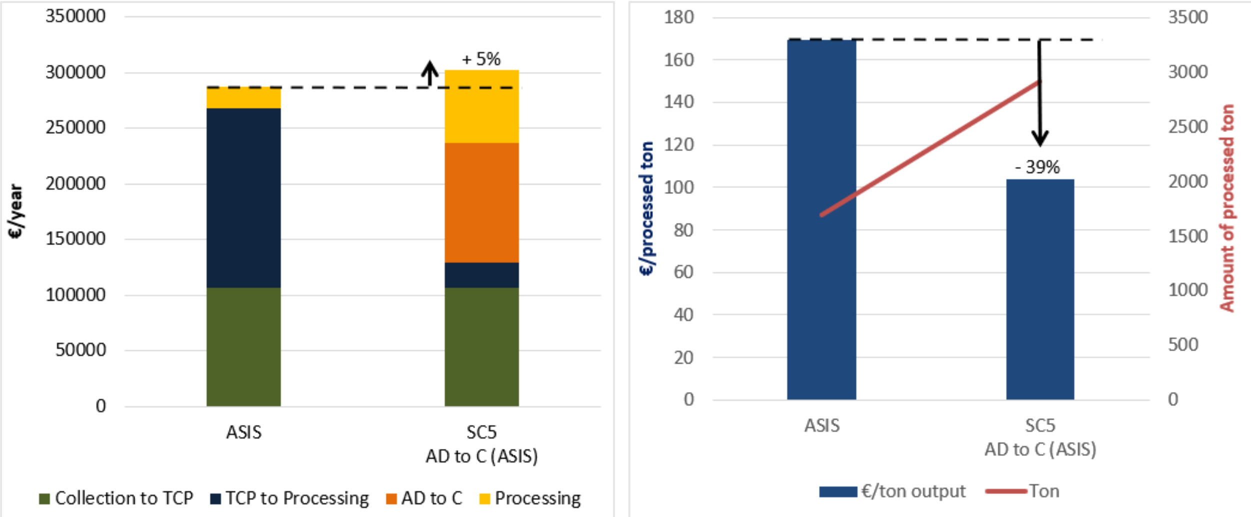


Figure 61: Food waste in Karlovy Vary – Mobilisation cost in €/year (L) and €/processed ton in comparison to the total amount of processed ton (R) of end-processing combination (scenario 5) in comparison to the current situation (AS IS).

4.4.2 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 62).[30]

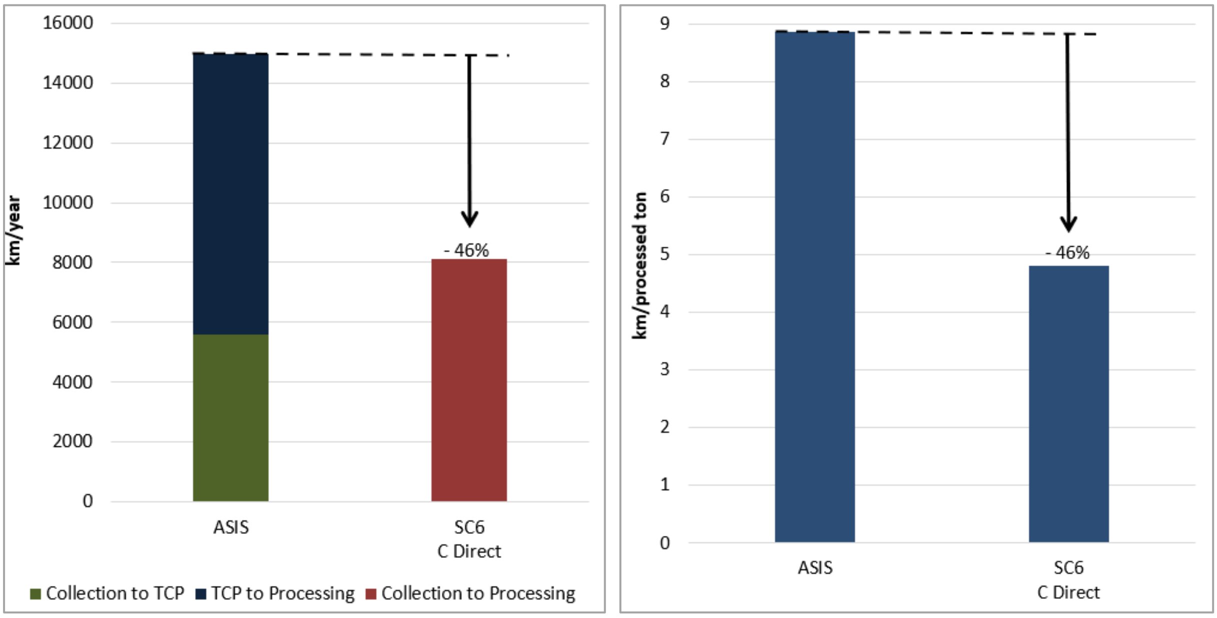


Figure 62: Food waste in Karlovy Vary – Transport distance in km/year (L) and km/processed ton (R) of decentralisation (scenario 6) in comparison to the current situation (AS IS) in km/year (L) and km/processed ton (R).

The end-processing cost remains unchanged at €18,581 per year, as the same 1.689 tons of food waste is composted (Figure 63, yellow bar section). However, the annual mobilisation cost drops

[30] 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 63).

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.

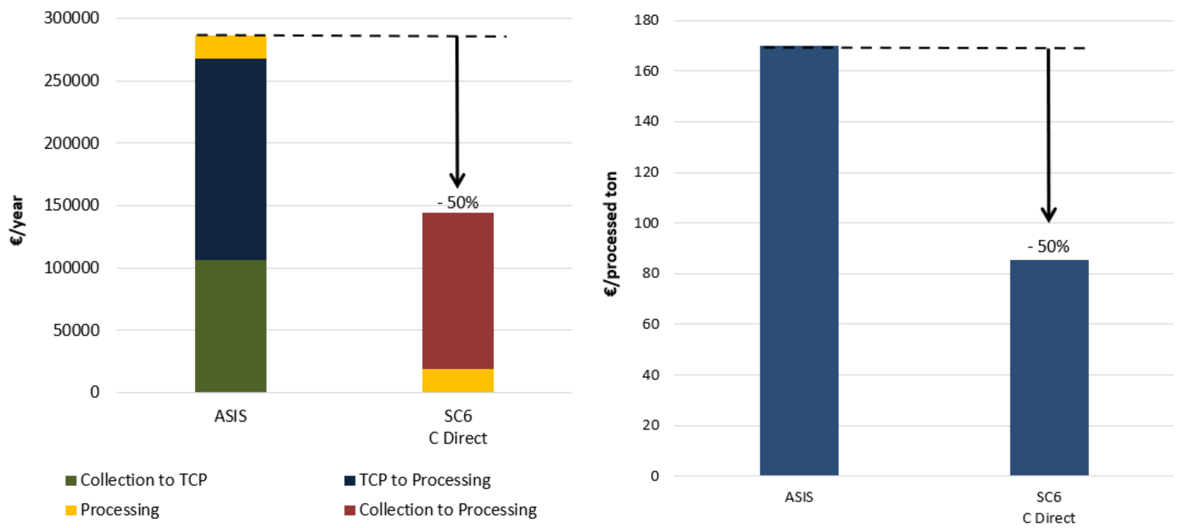


Figure 63: Food waste in Karlovy Vary – Mobilisation cost in €/year (L) and €/processed ton (R) of decentralisation (scenario 6) in comparison to the current situation (AS IS).

4.5 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.

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

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

5. References

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