# From Resource Exploitation to Nature Restoration: Unlocking the Potential of Agroforestry Systems as Feedstock Provisioners for Sustainable Composite Manufacturing

## An LCA study of bio-based carbon fibre precursors for aviation composites

*Iñigo Irache Cabello*
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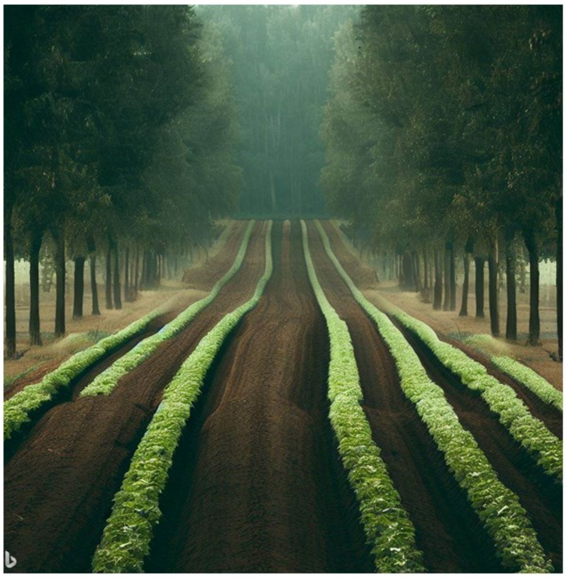

Academic supervisors:
*Lauran van Oers, Department of Industrial Ecology, Leiden University*
*Maarten Schrama, Department of Environmental Biology, Leiden University*
Case holder supervisor:
Uwe Beier, Airbus

Universiteit Leiden
TU Delft
AIRBUS

# Abstract

This research investigates alternative biomass feedstocks for environmentally improved composites in the aviation industry. It addresses challenges and opportunities associated with biomass use and proposes a sustainable biomass feedstock for bio-methanol production as a carbon fibre precursor for composites. The aim is to evaluate the environmental implications and practical considerations of utilizing this feedstock for sustainable bioeconomy models.

The study emphasizes the importance of lightweight carbon fibre composites in meeting emission reduction targets in aviation. It identifies biomass feedstocks for methanol production as a viable strategy for manufacturing sustainable composites. However, the sustainability of this approach is highly dependent on the strategies for biomass sourcing. A need to move from bioeconomy models based on the extraction of resources towards restorative systems based on Ecosystem Service (ES) provisioning is identified as the solution to deal with the sustainability challenges of biomass use. Agroforestry systems, integrating energy crops in farmlands, and in particular short rotation silvoarable systems (crops and short rotation trees integration), are identified as promising strategies for sustainable biomass production while enhancing ES provisioning and agricultural lands' resilience.

The subsequent research questions explore Life Cycle Assessment (LCA) results comparing different alternatives for methanol production. Silvoarable systems show favourable climate change and fossil fuel depletion performance when compared to natural gas-based methanol, but other impact categories do not offer significant advantages due to higher electricity consumption. The use of forest residues for methanol production performed better than the silvoarable alternative in most of the impact categories, but when more productive silvoarable plantations are considered or non-local sourcing of forest residues is necessary, silvoarable systems are as good or better than these systems. The alternative of using marginal lands for short rotation production had a lower performance compared with the silvoarable system mainly due to the lower productivity of these systems, however, this could also be considered as good feedstock for methanol production particularly if these are grown in floodplains to improve the yields of the system. Considerations of the aviation industry's environmental impact and supply chain are briefly included. While bio-based composites offer carbon emissions savings, these reductions are minimal compared to the overall aviation emissions. Cost considerations pose challenges, with bio-methanol alternatives currently having higher production costs. Suggestions include $CO_2$ emissions taxes, subsidies, and optimized supply chain processes to bridge this gap.

In conclusion, this research provides valuable insights into the potential of short-rotation silvoarable systems as sustainable biomass feedstock providers for composite manufacturing. While the LCA results demonstrate promising environmental advantages, the results are limited to the narrow scope of this study. Therefore, further exploring and studying these systems is required if these systems are aimed to be considered future biomass providers.

The findings offer Airbus and other industries an opportunity to embrace sustainable bioeconomy models, contributing to environmental footprint mitigation and restoration of equilibrium with natural systems.

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# Glossary of terms

***Acrylonitrile (ACN):*** A chemical compound used as a raw material in the production of polyacrylonitrile (PAN), which is subsequently converted into carbon fibres.

***Bioeconomy:*** An economic system that relies on the sustainable production and utilization of biological resources, such as agriculture, forestry, fisheries, and their conversion into bio-based products, energy, and services.

***Carbon Fiber Reinforced Polymers (CFRPs):*** Composite materials made by combining carbon fibers with a polymer matrix, resulting in strong and lightweight structures with high stiffness and resistance to corrosion.

***Carbon Fibers (CFs):*** Strong, lightweight fibers composed mostly of carbon atoms, known for their high tensile strength and low weight. They are commonly used as reinforcement material in composite structures.

***Ecosystem Services (ES):*** The benefits and services provided by ecosystems to humans, including the provision of clean air and water, regulation of climate, pollination, and nutrient cycling, among others.

***End of life (EoL):*** It refers to the stage in the life cycle of a product when it reaches the end of its useful life and is either disposed of, recycled, or reused.

***Land equivalent ratio (LER):*** A measure used in agroecology to compare the productivity of mixed crop systems to monocultures, taking into account the total land area required.

***Lignocellulosic biomass:*** Lignocellulosic biomass refers to plant material composed of cellulose, hemicellulose, and lignin. It is a non-food source derived from agricultural and forestry residues, energy crops, and other plant materials.

***Monocrop:*** Agricultural practices that involve cultivating a single crop species over a large land area.

***Polyacrylonitrile (PAN):*** A synthetic polymer used as a precursor material for producing carbon fibres through carbonization.

***Relative crop/tree yield (RCY):*** Yields of crops/trees in agroforestry systems when compared to monocrop plantations per area basis.

***Short Rotation Coppice (SRC):*** Specific forestry technique or system of growing trees that involves the regular and repeated harvesting of fast-growing tree species on a relatively short rotation cycle.

***Silvoarable***: An agroforestry system where trees are grown alongside arable crops, providing benefits such as improved microclimate, reduced soil erosion, and increased biodiversity.

***Silvopastoral***: An agroforestry system where trees are integrated into pastures or grazing areas, providing benefits such as shade for livestock, improved forage quality, and ecological functions support.

# Preface and acknowledgments

*There is a pressing need to rethink the way society interact with natural systems, we must move from resource extraction to nature restoration, and we must do it as soon as possible. The idea of this master thesis was born from the understating and the passion to explore the possibilities that the use of solutions that are based in natural system restoration could bring to address some of the sustainable challenges society faces today.*

*Multifunctional systems like agroforestry or silvoarable systems bring the opportunity to connect two big challenges: restore the natural balance of agricultural systems and provide a sustainable biomass feedstock for industrial purposes.*

*The role that these systems might play in the future of biomass production is still uncertain, however is today worth it to explore them to realize their full potential, and that is the main goal of this study.*

*I would like to thank all the people that have supported me during the writing of this thesis. Thank you, Lauran, for helping me to deal with the challenges that measuring these systems in LCA entail and overall, exponentially increase the quality of this work. Thank you, Maarten, for inspiring me in believing that there are new and better ways of agriculture that we should pursue. Thank you, Uwe, for all that great discussions and for inspiring me to give my best to trying to solve the sustainable challenges ahead of us.*

*Thank you to the friends which I wrote my thesis along, Amir for helping me understand that coffee breaks are not a waste but a gain of time, Mario for teaching me that is just better not to stress, Steph for reaffirm my idea that shorten library time for gym time is always worth it, Li for making me appreciate the quality of the law canteen food, Jacopo for teaching me that is never to late to arrive to the library and Will for make me value that day on the month when you just appear.*

*Last but not least I would like to thank my family for the great support you always give and in particular my father for encouraging me to do this master that has make me learn so much.*

# 1. Introduction

The aviation sector is responsible for approximately 2% of global $CO_2$ emissions and contributes to about 4% of human-induced global warming through the release of other greenhouse gases (Klöwer et al., 2021). Although flying is often associated with significant environmental burdens, it's important to consider that only a small portion of the world's population has access to air travel. When compared to other modes of public transportation, flying has a much higher average energy intensity greenhouse gas emissions, with approximately 144 $gCO_2$-eq/pkm, compared to non-urban buses (22 $gCO_2$-eq/pkm) or rail transport (14 $gCO_2$-eq/pkm) (IEA, 2019). To mitigate these emissions and promote sustainability in the aviation sector, the increase in use of lightweight composite materials is presented as a promising solution. Increasing the use of composites not only reduces fuel consumption in existing aircraft but also paves the way for the development of future sustainable models, where weight is a limiting factor. However, the current manufacturing of composites relies heavily on fossil fuel resources, necessitating the exploration of new production pathways that align with sustainable practices. In this context, bioeconomy models offer an opportunity to address these challenges by enabling the use of renewable materials for composite manufacturing and restoring a sustainable balance in resource utilization.

This research, driven by the collaborative effort with Airbus, aims to investigate the feasibility of implementing sustainable bioeconomy models for biomass provision in composite production for the aviation industry. Specifically, it focuses on the potential of short rotation silvoarable systems as biomass feedstock sources. A research area that has not yet being fully explored in literature and from which results the role of these systems as provisioners of biomass feedstock could be understood. The main research question that this study aims to address is: *What biomass source and conversion pathway offers the highest potential for sustainability in meeting the specific needs of carbon reinforcement in aviation composites?*

Building upon previous research of Airbus, which examined strategies including the use of biomass sources as precursors to reduce the environmental impact of composite manufacturing, this study seeks to address the need for sourcing this biomass feedstock in a more sustainable way and offer a comprehensive understanding of the challenges and solutions that this might imply. To provide a comprehensive perspective on the identified issues and proposed solutions, this research justifies the use of biomass, particularly within bioeconomy models, as a viable strategy for manufacturing sustainable composites. For that, it explores how the proposed feedstock aligns with sustainable biomass utilization approaches and conducts an environmental evaluation through a life cycle assessment (LCA) study to prove it.

The presented chapters delve into these topics, presenting a clear storyline to provide a reasoning of the selection and the environmental evaluation of the selected biomass feedstocks for composite manufacturing. This research endeavours to contribute to the ongoing efforts to advance sustainability in composite manufacturing and foster a harmonious coexistence between human progress and the preservation of our natural environment.

# 2. Methodology

The methodology employed in this study to address the main research question previously presented will be based on an inductive research approach. The research questions can be classified into two distinct stages:

1. *Stage 1: Identification of the most environmentally promising supply chain production pathways for carbon-reinforced composite for aviation use.*
2. *Stage 2: Environmental performance evaluation of the selected production pathways.*

The following paragraphs build up on the specific research questions, objectives, methodologies, and expected results for each of these stages.

## Stage 1: Identification of the most environmentally promising supply chain production pathways for carbon-reinforced composite for aviation use.

The first stage is based on the method of a literature review from scientific publications and available reports from the commissioner of the project, Airbus. The main outcome of this stage is the decision on what production pathways should be further environmentally evaluated based on their potential to achieve higher environmental performances than the current state of the art of composite manufacturing. Secondary outcomes are the reasoning of the relevance of this research, the contextualization of the selected pathway inside industry trends and the predicted technological availability of the selected production pathway. To deliver these outcomes stage 1 is divided into three research questions. These are presented in the following paragraphs. A graphical representation of the research design of Stage 1 is presented in Figure 1.

### RQ1: What is the currently explored most suitable composite manufacturing route for achieving more sustainable composites in aviation?

This question aims to acquire preliminary information about the composite manufacturing alternatives currently being explored and focus on one to be further studied in the subsequent RQs. For that the first RQ is divided into two sub-research questions:

1. How are composites currently used in aviation, and what are the key reasons for the industry's interest in improving their environmental performance?
2. What are the currently explored strategies to achieve more sustainable composites in aviation?

The first of these sub-research questions aims to provide a reasoning behind the conduct of this study addressing the relevance to improve the environmental performance of composites inside the climate targets of the aviation industry. The second aims to explore and decide on the production pathway to focus on in this research.

## RQ2: What are the environmental concerns related to biomass feedstock usage, and how can bioeconomy models based on Ecosystem service provisioning help mitigate them?

The second RQ of this study builds upon the result of the first RQ that concluded that the production of composites through the gasification of biomass is the one to further explore.

This question aims to provide an understanding of the environmental implications of the use of biomass as a feedstock, the gathered insights will serve to choose adequate feedstocks to compare. For that, a series of sub-research questions are derived from it:

1. What is the current and predicted demand for biomass for industrial purposes?
2. What are the main environmental concerns of biomass sourcing?
3. How can a Bioeconomy model based on the provisioning of ecosystem services can promote sustainable biomass use?

The first of these sub-questions aims to provide a context of the selected biomass gasification pathway inside the predicted use of biomass for industrial purposes to address the sustainability concerns that a great industry shifts towards biomass sources could entail.

The second provides a general understanding of the environmental concerns that are associated with the use of biomass as feedstocks to gather the required considerations to further decide on the biomass feedstocks to further evaluate. The third sub-research question provides a view on how certain Bioeconomy models can improve the overall sustainability of biomass feedstocks to provide further reasons regarding not only the type of feedstock but under which circumstances to source them to maximize its sustainability potential.

## RQ3: Which biomass feedstocks can be preferable to produce bio-methanol to maximize its sustainability potential?

This last research question of the 1st stage builds up on the more general results from RQ2 to decide on the feedstocks to further evaluate in the second stage of this research. For that, this question is also addressed with the use of three sub-research questions:

1. What are the most appropriate biomass feedstocks for biomass gasification considering the availability of conversion technologies?
2. What is the projected availability of these biomass feedstocks in the near future?
3. How can these biomass feedstocks be sourced to maximize their sustainability potential based on the provisioning of ecosystem services?

The goal of the first sub-rq is to identify both the availability of the technology for biomass gasification and the most suitable feedstocks from a technological point of view, the 2nd sub-rq explores the potential availability of these technically suitable feedstocks and the 3rd explores the potential for sustainability improvement of these feedstocks by land use alternatives that are based on ecosystem provisioning.

The research output of RQ3 and the main output of this first stage of the research is the decision of the feedstocks to further evaluate in the second stage of this research.

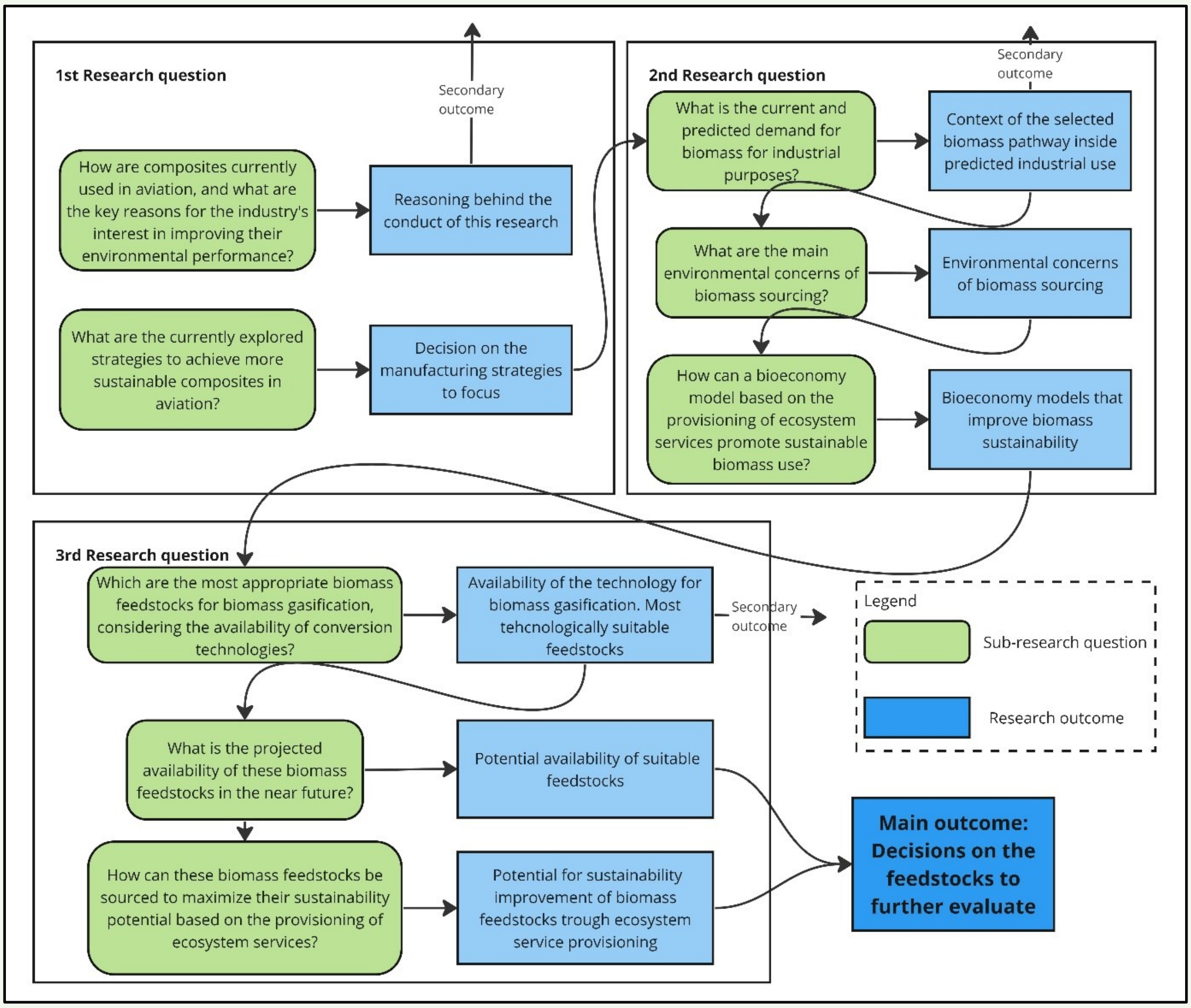


*Figure 1: Research design strategy for stage 1, including sub-research questions and expected research outcomes. Source: own.*

## Stage 2: Environmental and economic performance evaluation of the selected production pathways.

Stage 1 provided the selected production process to further evaluate in this study, gasification of biomass for bio-methanol production as the chemical feedstock for composite manufacturing, and the biomass feedstock/sourcing approach that is predicted to be environmentally advantageous, to be further evaluated against other considered alternatives. Therefore, the main RQ of this stage will be: *What could be the environmental consequences of sourcing biomass from the selected feedstocks when compared between each other and to a fossil alternative for methanol production?*

To answer this RQ a Life Cycle Assessment (LCA) study will be conducted. LCA is a quantitative methodology that aims to analyse the environmental associated impacts of product systems through all stages of their lifecycle (de Bruijn et al., 2002). The expected considerable degree of heterogeneity regarding the contribution of each lifecycle stage to the studied environmental impacts, as well as the variability in performance that is expected from the studied alternatives, justifies the use of LCA as the most suitable tool to answer this research question. Regarding the software used for the LCA modelling the free LCA software Activity Browser and the last available version (v3.9) of the Ecoinvent database are used in this study. The different phases of the LCA study that will be conducted: goal and scope definition, inventory analysis, impact assessment and interpretation will be adequately defined and addressed in Chapter 6.

As the final stage of this research, to connect the results of the study to some practical implications that the use of this pathway for composite manufacturing will imply regarding the reduction of GHG emissions and also provide a brief assessment of the practical feasibility of the selected biomass alternative, the final research question that will be addressed in this study will be: *What broader implications can be derived from the estimated CO2 savings and costs associated with the utilization of the selected biomass feedstock for methanol production in the context of composite manufacturing in the aviation industry?*

To answer this question approximate calculations will be conducted based on part of the results obtained from the LCA study and complemented with literature available data. These estimations will provide simplified results that could serve as a first insight on some of the practical implications of the proposed production pathway.

# 3. Composites for sustainable aviation

This chapter aims to answer the first RQ of this study: *Which are the production pathways that are being explored today to increase the environmental performance of composite manufacturing?* The following paragraphs elaborate on the sub-research questions and answers to address this first RQ.

## How are composites currently used in aviation, and what are the key reasons for the industry's interest in improving their environmental performance?

### An introduction to composites

Composite materials are the most promising materials for engineering applications that have been discovered this century due to the great amount of improvement in their properties compared to alternative engineered materials (Rajak et al., 2019).

Composites can be defined as an amalgamation of two or more materials that by combining the strength of the two bounded materials create a final product that compensates for the weaknesses of the singular materials (Park & Seo, 2011). This merge occurs through the combination of a matrix and its reinforcement, both of which could be formed from different materials such as polymers, metals, ceramics, and carbon, also the arrangement of the reinforcements can occur as continuous fibres, discontinuous fibres, whiskers (elongated single crystals), and particles (Zweben, 2015) .

Among these potential combinations, fibre-reinforced polymers (FRPs), through the integration of functional fillers into highly processable polymers, aim to create products with high strength and high elastic modulus (S, Prashanth et al., 2017). This synergetic combination brings significant advantages in mechanical properties such as high strength-to-weight ratio, durability, resistance to fire, corrosion and impact, and tailor-made behaviours among others (Rajak et al., 2019; S, Prashanth et al., 2017).

Three main types of fibres are usually distinguished for these composite types (S, Prashanth et al., 2017): Glass Fibres (GFs), the most used ones representing around 90% of FRPs production, different classes of GFs are commercially used providing a great variety of physical properties which are also dependent on the orientation they are placed, Carbon Fibres (CFs) are the ones that provide the highest specific modulus and strength, they are also chemically inert, electrically conductive and infusible, the last type Kevlar fibres which are a specific type of aramid fibre, provide high strength and low weight together with a high impact resistance, however, they present low compression strength (S, Prashanth et al., 2017). A comparison between the properties in which each fibre performs better is included in Table 1.

*Table 1: Properties comparison between different FRPs fibres modified from (S, Prashanth et al., 2017).*

| | **Fibre types** | | |
|---|---|---|---|
| **Property** | **Carbon** | **Glass** | **Kevlar** |
| Density | ☑ | | ☑ |
| Tensile strength | ☑ | ☑ | ☑ |
| Tensile modulus | ☑ | | |
| Electrical conductivity | ☑ | | |
| Fatigue resistance | | | ☑ |
| Abrasion resistance | | | ☑ |
| Chemical resistance | ☑ | | |

These previously mentioned properties and the possibility of a variety of combinations between matrix and fibres types open a window of opportunity for these materials to be used in high-performance systems in industry sectors such as construction, electronics, sports and leisure, and transportation (S, Prashanth et al., 2017).

Despite all these benefits regarding material performance, the use of these composites comes with considerable associated environmental and economic costs, the high energy-intensive manufacturing of these materials, their use of fossil fuel feedstocks that increase GHG emissions during production, and the fact that they are hardly recyclable claims for improvements to target their economic and environmental performance while still maintaining their excellent properties (Bachmann et al., 2021; Maiti et al., 2022).

## Composites use in aviation

The high strength-weight ratio and excellent fatigue resistance define fibre-reinforced polymers as ideal candidates to meet aerospace-demanding applications (S, Prashanth et al., 2017). The desire of plane manufacturers to reduce operational costs through fuel consumption savings converges also with the need of the aviation industry to achieve GHG emission reduction goals. This is owing to the almost near unique contribution of the use phase of the plane lifecycle environmental footprint, which for the climate change impact category is close to representing 99% of the total (Rahn et al., 2022). Therefore, despite the higher environmental impacts associated with their manufacturing phase, due to the resulting weight reduction, GHG emission savings of more than 20% compared to aluminium alloy structures can be achieved (Timmis et al., 2015). What is more, the successful development of future plane models to decarbonise aviation such as the hybrid or regional electric models is dependent on reducing the operating empty weight, for which extensive use of composite materials will be a requirement (Mukhopadhaya & Graver, 2022).

Similarly, regarding the economic costs associated with using advanced carbon fibre composites which imply higher manufacturing costs over metallic structures (Shama Rao N et al., 2018), these are overcompensated by the operational cost reduction through fuel savings (Lambert, 2011). Consequently, an increasing trend in the application of composite materials in the plane industry has been recognised in recent years (Bachmann et al., 2017), a trend that is less accentuated in other transport industries in which the high costs of these materials are not so strongly outweighed by their use phase benefits (Bachmann et al., 2021). This growth in composite use is ratified in the case of Airbus, in which the use of composites represented only 10% of the weight of the A320 model (manufactured between 1987 to 2005) a number that has raised up to 53% in the A350 model (manufactured from 2005 until today) (Chatterjee & Bhowmik, 2019).

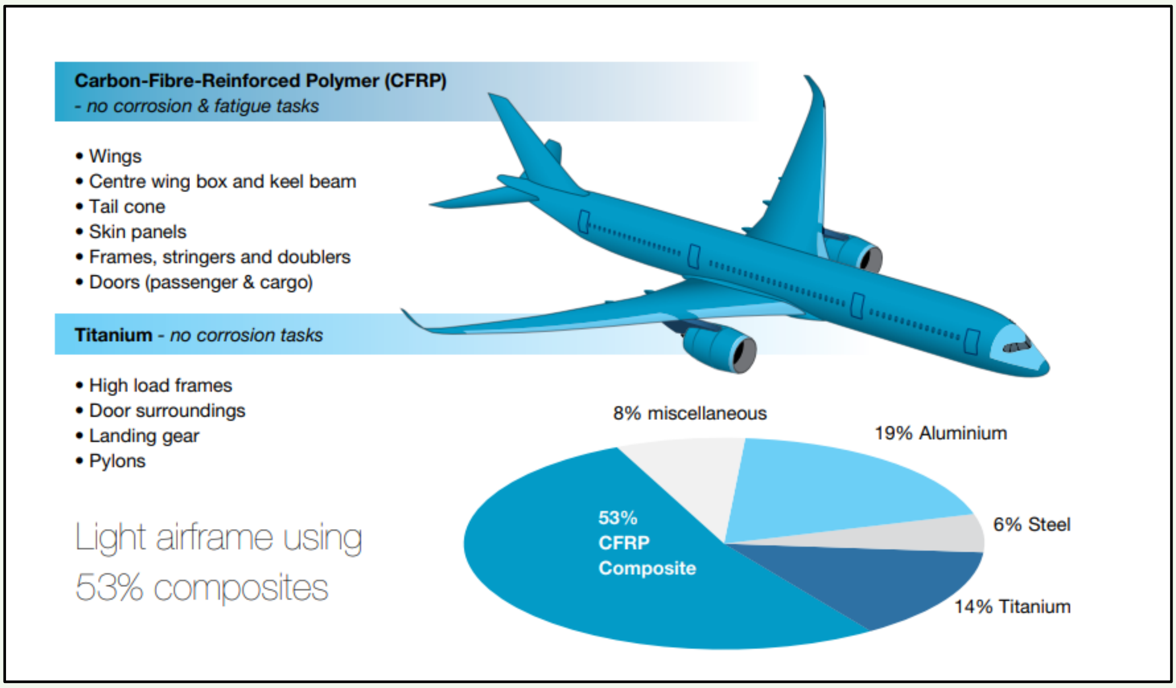


*Figure 2:Material composition Airbus Aircraft A350 XWB. source :(FAST Magazine Articles | Airbus Aircraft A350 XWB, 2013)*

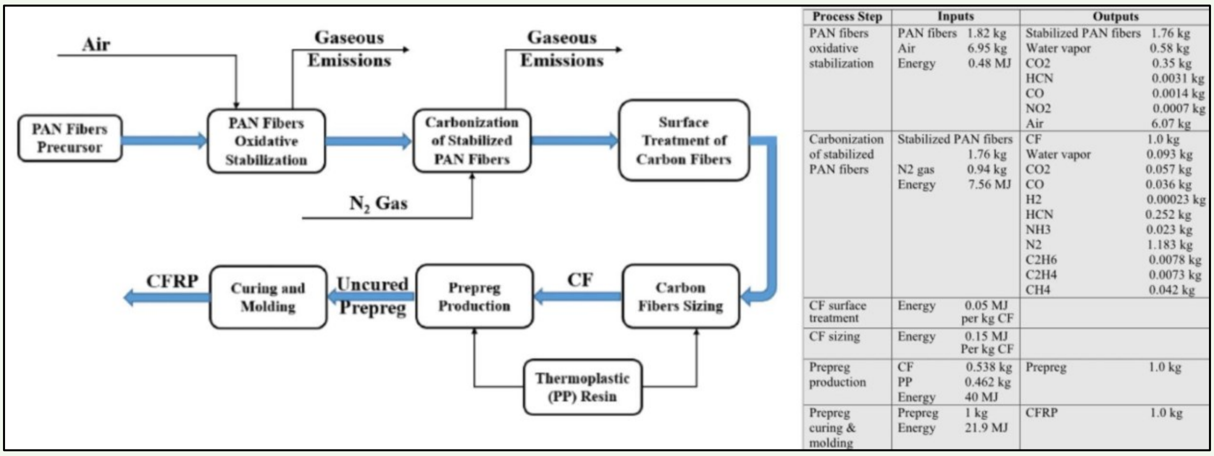
The composites used for aviation can be rated as the top-grade class of these materials due to their high-requirement applications (Bachmann et al., 2017). The main types of fibres and resin combinations that can be found in plane structures today according to (Bachmann et al., 2017) are the following: (1) CF and epoxy resins for structural applications, (2) CF and thermoplastics only used for special applications in structural parts,(3) GF or CF with phenolic resins for interior parts to deal with health hazard due to fire risk, (4) sandwich panels of GF/CF in combination with phenolic resins and (5) glass reinforced aluminium for certain sections of the fuselage.

## Environmental impact of conventional CFRP production

Carbon Fibre Reinforced Polymers (CFRPs), due to their presence in the main structures of planes could be categorised as the most relevant composite type used in modern aircraft composites. When comparing CFRPs, with Glass Fibre Reinforced Polymers (GFRPs), an LCA

study concluded that despite the higher manufacturing environmental impact of CFRPs, an overall better environmental potential for CFRPs over GFRPs was identified for their use in plane structures (Hermansson et al., 2022). This higher potential is due to their ability to use more sustainable feedstocks and better integrate recycling routes, on top of the achievement of more lightweight structures (Hermansson et al., 2022).
The manufacturing process of CFRPs starts with carbon fibre production from a precursor this process is further explained later in this chapter, the finished CF is then integrated into the matrix resin into pre-impregnated fibres (prepreg) that are then cured and moulded into the final product (Khalil, 2017). A graphical representation of the production process of CFRPs along with their mass and energy balance is included in Figure 3.

Regarding the environmental performance of CFRPs, a recent LCA study compared two different matrix types for the manufacturing of composite panels (thermoset and thermoplastic)(Ogugua et al., 2022). This study concluded that for the case of the thermoset composite (the one currently used in plane structures), when comparing the different lifecycle phase contributions to a total single score environmental impact (cumulative energy demand), the raw material production of the panel contributed to 58% of the total, out of which the CF production represents 60% and the epoxy resin 15%. The rest of the total lifecycle impact was associated almost entirely with the manufacturing process, as the EoL incineration of the panel had almost negligible contribution (Ogugua et al., 2022). The impact associated with the manufacturing stage of the curing of the panel is mainly represented by the electricity of the autoclave, which accounts for an impact of around 70% of this stage (Ogugua et al., 2022).



| Process Step | Inputs | Outputs |
|---|---|---|
| PAN fibers oxidative stabilization | PAN fibers 1.82 kg<br>Air 6.95 kg<br>Energy 0.48 MJ | Stabilized PAN fibers 1.76 kg<br>Water vapor 0.58 kg<br>CO2 0.35 kg<br>HCN 0.0031 kg<br>CO 0.0014 kg<br>NO2 0.0007 kg<br>Air 6.07 kg |
| Carbonization of stabilized PAN fibers | Stabilized PAN fibers 1.76 kg<br>N2 gas 0.94 kg<br>Energy 7.56 MJ | CF 1.0 kg<br>Water vapor 0.093 kg<br>CO2 0.057 kg<br>CO 0.036 kg<br>H2 0.00023 kg<br>HCN 0.252 kg<br>NH3 0.023 kg<br>N2 1.183 kg<br>C2H6 0.0078 kg<br>C2H4 0.0073 kg<br>CH4 0.042 kg |
| CF surface treatment | Energy 0.05 MJ per kg CF | |
| CF sizing | Energy 0.15 MJ Per kg CF | |
| Prepreg production | CF 0.538 kg<br>PP 0.462 kg<br>Energy 40 MJ | Prepreg 1.0 kg |
| Prepreg curing & molding | Prepreg 1 kg<br>Energy 21.9 MJ | CFRP 1.0 kg |

*Figure 3: Process steps and mass balance of PAN-based CFRP production process. Modified from (Khalil, 2017)*

The manufacture of carbon fibre today is mostly based (around 90% of production in 2016) on the use of polyacrylonitrile (PAN) as a precursor, which also accounts for 51% of the manufacturing cost of CFs (Milbrandt & Booth, 2016). For the particular case of aviation PAN-based are the only used precursor, alternatives like coal pitch or lignin-based are not used today (Bachmann et al., 2017). The manufacture of carbon fibre from the PAN precursor could be divided into two main phases: the precursor fibre preparation and the CF production. The first one starts with Acrylonitrile (derived from chemicals propylene and ammonia), as the starting material and after a polymerization chemical process ends with the obtention of PAN fibres, the second phase starts with PAN fibres and after a series of transformations involving oxidation, carbonization and surface treatment and sizing, the process ends up in the CF final product (Sakamoto et al., 2022). Regarding the GHG emissions associated with this production process contribution of around a third of the total emissions are attributed to the precursor fibre preparation, from the remaining emission associated with the CF production, around 75% of them comes from the gas-phase stabilization and the low and high-temperature carbonisation (Sakamoto et al., 2022).

## The challenges of carbon reinforced composites' end of life

In today's market, landfill and incineration are the main waste management strategies for CFRPs at their End of life, furthermore, the manufacturing of these products can also generate a lot of scraps (up to 40% of the initial input material) (Abbate et al., 2022). Consequently, around 62,000 tons of waste are accumulated each year in landfills, being the aeronautic and the wind energy sector the biggest contributors, due to the expected increase in their use if no further improvements regarding waste management strategies are applied, 23.600 and 483.000 tonnes respectively from the aviation and wind energy sector are expected to be accumulated for the year 2035 (Isa et al., 2022).

On top of this, the fact that landfilling imposes a cost on European manufacturers a shift towards incineration is being recognised, a strategy that can lower the cost of the EoL treatment but comes with higher associated environmental burdens (Bachmann et al., 2017).

The high degree of complexity associated with the recycling of composite parts allows only for a downcycling approach, as closed-loop recycling is today far from being economically viable (Bachmann et al., 2021). Recycling thermosetting CFRPs is challenging due to the difficulties of extracting the fibres once the composite is cured, furthermore, when the CFs are recovered these are of lower quality than virgin ones (Abbate et al., 2022). The pyrolysis process is identified as the most viable and sustainable recycling process commercially available today, this process is able to conserve similar mechanical properties of the fibres but limits the designer to constraints regarding fibre length and difficulties of processing (Naqvi et al., 2018).

Despite these limitations, recycled carbon fibres can still find their place in less demanding applications, still allowing for weight reduction accompanied by cost savings (Naqvi et al., 2018). In this respect, a recent LCA study that compared the use of carbon fibre composites with virgin and recycled CFs in the aviation sector, concluded that despite the environmental savings of using recycled fibres from a manufacturing perspective, the greater weight savings provided by virgin CFs favoured their environmental performance (Markatos & Pantelakis, 2022). These results are however not transferable to other composite applications like the automotive sector, where the use phase has less relevance in the overall lifecycle impact (Markatos & Pantelakis, 2022).

Therefore, is identified as highly important to create a network for the use of recycled composites in secondary applications that allow the achievement of environmental benefits from this downcycling process (Bachmann et al., 2017).

## What are the currently explored strategies to achieve more sustainable composites in aviation?

Previously the role of composites was described regarding their main features and applications for their use in the aviation industry. Their ability to reduce the environmental impact of flying through fuel reduction sets these materials in an advantageous position over alternative options for current and future scenarios to achieve emissions reduction targets. However, the need to reduce the environmental impact associated with the lifecycle of these materials is identified as one of the main issues to address for their future use (Bachmann et al., 2021). There are several challenges that need to be addressed from different perspectives when considering alternative feedstock and materials for both composite matrixes and reinforcements, as well as their potential benefits in reducing manufacturing-related emissions or end-of-life treatment scenarios.

The manufacturing emission reduction strategies and the use of alternative composite matrixes is briefly presented in the following paragraphs, as considered relevant for an overall achievement of more sustainable composite use, however the focus of this study will be in the available strategies for substituting fossil based by biomass based composite reinforcement. These were identified previously as the main area of concerns of the environmental performance of composites.

The use of biomass for composite fibre production can happen trough two main different routes, the first one, directly substituting CFs by natural fibres extracted from biomass, this approach is however not assumed to provide the required properties for composites as it will be explained later in this chapter. The second is to manufacture carbon fibre from biomass precursors, this approach aims to create CFs with similar properties to the fossil derived ones. In this strategy two different production pathways can be distinguished depending on the point where the fossil source is substituted by biomass, these are presented later in this chapter. These different pathways are graphically represented in Figure 4.

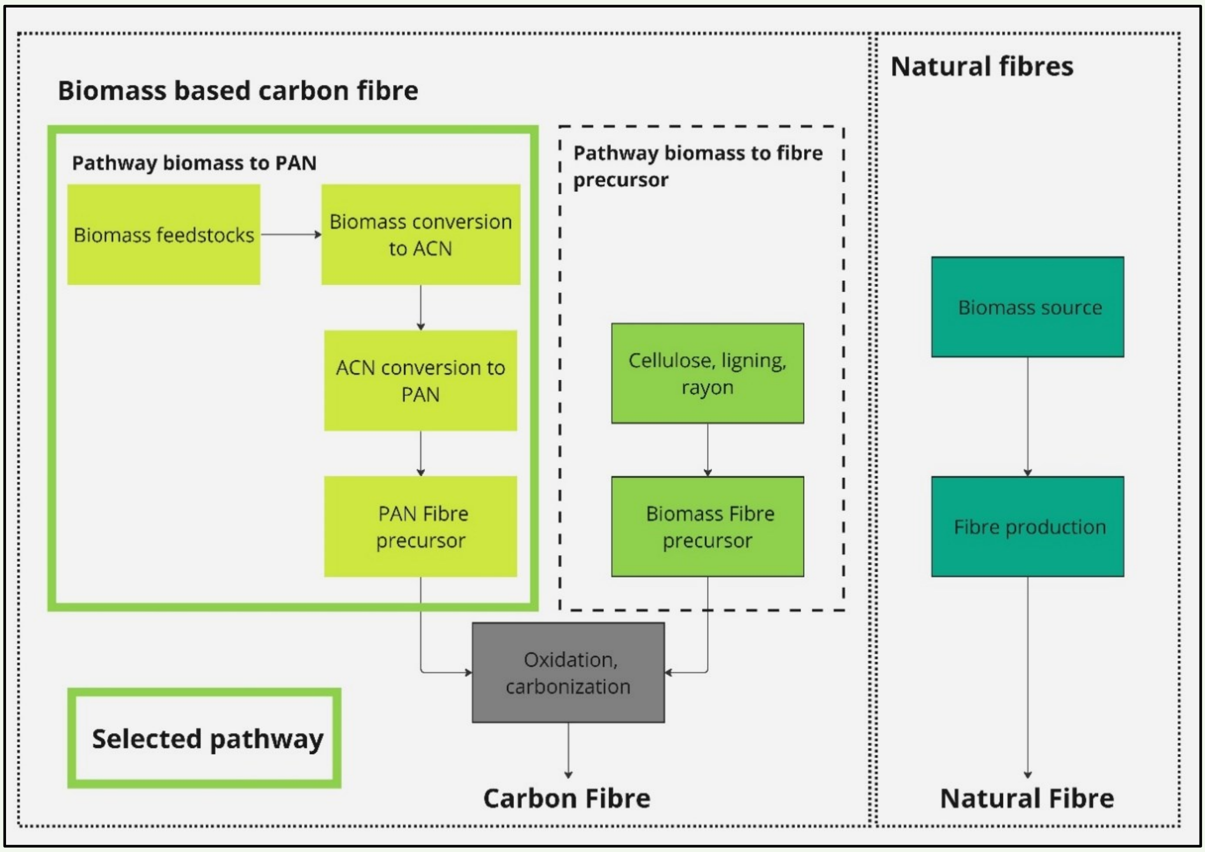


*Figure 4: Strategies for the integration of biomass feedstocks for composite fibre production. Source: own*

## Natural and recycled fibres

The ECO-COMPASS project, a collaboration between European and Chinese scientists starting in 2016 under the European Union research and innovation program Horizon 2020, aimed to preliminarily assess and develop ecologically improved composites for their use in the aviation industry, this study explored strategies to reduce the environmental impact of both the reinforcement component, with natural and recycled fibres, and the resins with the inclusion of bio-based materials (Bachmann et al., 2021). The initial phase of the project aimed to assess the potential use of these materials in current aviation structures, regarding natural fibres, like flax and ramie, their assessment confirmed that on top of providing a reduction of environmental impact over CFs, they also offer very good specific properties (Bachmann et al., 2017). However, due to their limitations regarding matrix adhesion, natural damage and moisture sensitivity, their initial assessment concluded that these fibres will be limited to interior and secondary structures (Bachmann et al., 2017). Similarly, and as previously stated in this work, the use of recycled CFRPs will also be limited to downcycled uses in less demanding applications (Bachmann et al., 2017). Finally, a later publication of the project concluded that the possible application of bio-based resins for aviation structures is also still limited to interior and secondary structures, for which further research is required (Ramon et al., 2018).

The final publication of this project provides an overview of the main findings regarding the challenges and opportunities identified for the use of “eco-composites” in the aviation sector (Bachmann et al., 2021):

- There is a need to further improve the main challenges presented by eco-composites such as moisture ingress, fire ignition or creep properties.

- Additional efforts should also be devoted to improving manufacturing costs and effectiveness.
- The implementation of these materials should also be proved for future aircraft designs. Hybrid solutions that combine natural with virgin or recycled CFs are identified as one the most viable solutions to explore.

From the ECO-COMPASS project, it can be concluded that the use of CFRPs for plane manufacturing is still mostly limited to the use of virgin CFs, furthermore, as previously explained the recycling of CFRPs is far from being a reality today. Therefore, strategies to improve the environmental performance of CFRPs should now address the challenges of reducing the environmental impact of carbon fibre production.

## CFRPs efficient manufacturing

As mentioned earlier in this text, apart from the feedstock-associated emissions (carbon emissions along its entire lifecycle) the energy use in the manufacturing stage is another significant factor that influences the life cycle impact of CFRPs. In this regard MAI carbon a Leading-Edge Cluster in CFRP manufacturing quantified and studied potential technology improvements that could reduce the cost and environmental impacts of CFRP manufacturing (Hohmann et al., 2017). This report concludes that for the best-case scenario of combining “green electricity” in both CF production and CFRP production on top of technological optimizations (low-energy use in CF production, reduction of cut-offs, reduction of curing time and recycling of cut-offs), a reduction of almost 70% of the GWP compared to the baseline scenario could be achieved (Hohmann et al., 2017). The report also stresses the considerable environmental saving potential that could be achieved through an optimization of the design of composite components (Hohmann et al., 2017).

## Biomass-based carbon fibres

Another main strategy to reduce the environmental impact of CFRPs is the use of carbon fibre precursors from biomass sources, these are assumed to obtain reinforcement fibres with a lower environmental impact due to the substitution of fossil fuel by a renewable source of carbon, but with similar properties to the ones sourced from conventional synthetic precursors (Milbrandt & Booth, 2016). Two different main pathways can be distinguished regarding where in the CF production process the integration of the biomass source occurs ACN (Milbrandt & Booth, 2016):

1. Substitution of PAN-derived fibres by biomass-derived fibres
2. Substitution of synthetic-based acrylonitrile (ACN) by biomass-based ACN

In the first approach two main types of precursors can be distinguished: cellulosic and lignin (Milbrandt & Booth, 2016). Both types of fibres present lower carbon yields than conventional CFs and require longer stabilization times making them impractical for high-demand industrial applications(Le et al., 2020). Despite ongoing research with the aim to deal with these limitations, in the case of Lignin precursors, the mechanical properties obtained are still inferior to PAN-based derived ones (Le et al., 2020).

Regarding the second approach different possible routes have been explored today for the obtention of ACN from biomass feedstock (Milbrandt & Booth, 2016)

In this regard, Airbus is researching possible different routes to manufacture bio-based ACN which is assumed to have identical properties to the conventional synthetic ACN. An internal study evaluated the environmental performance and technology readiness level of some of these possible alternatives to obtain ACN including the following precursors: bio-naphtha, methanol (conventional, bio-methanol, and e-methanol ), glycerol and lignocellulosic sugars.

A life cycle assessment between these alternatives that also compared to the fossil-based production route was performed in this internal study including also different future scenarios regarding renewable energy penetration. The obtained results showed that all these alternative routes for bio-based ACN production could reduce the GWP of CFRPs composite considerably from a 30% to more than 100% reduction (negative emissions[1]) when compared to the conventional crude-oil-based route.

Among these studied alternatives, due to the favourable results of this study and after conversations with Airbus, the decision to further explore the route of bio-based methanol from the gasification biomass was considered.

Bio-methanol production from the gasification of biomass feedstocks is a process that is based on a similar well-known technological process of gasification of fossil feedstocks for the obtention of syngas, however significant differences occur in the first steps of the gasification process (IRENA & Methanol Institute, 2021). Currently, there are no long term operational experience of these type of plants, however, several projects are close to being deployed for full commercial operation (IRENA & Methanol Institute, 2021).

A variety of biomass feedstocks could be considered feasible for the production of bio-methanol through the gasification process including forestry and agricultural waste, municipal solid waste or black liquor from the pulp industry among others, the use of these different biomass sources will have different implications regarding final reductions in CO2 emissions compared to fossil-based methanol (IRENA & Methanol Institute, 2021).

The following chapters will therefore explore and evaluate different biomass sources for the use in the selected conversion pathway for CF production: **bio-methanol production from biomass gasification for ACN conversion.**

***This chapter has outlined the primary challenges and opportunities associated with the use of composites to reduce the environmental impact of the aviation sector. It is crucial to maintain and increase the presence of these materials to meet the industry's emissions reduction objectives, but it is equally important to eliminate fossil fuel usage in their manufacturing to ensure a more sustainable use of these materials. To achieve this, the use of biomass sources as feedstocks to produce chemical precursors appears today to be the most effective strategy to reduce the environmental impact of composite manufacturing while***

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[1] negative emissions occur for the case of methanol from captured carbon due to the carbon absorption for methanol production and the absence of later lifecycle emissions where this carbon will be released

***preserving their technical properties. In particular, the gasification of biomass to produce bio-methanol as ACN precursor is identified as one of the most promising routes and will therefore be further evaluated in this research. However, the selection of the biomass feedstocks must be carefully evaluated to determine the sustainability implications of these pathways beyond carbon emissions. The following chapter will analyze what are the main environmental impacts that can be associated with the use of biomass sources and which bioeconomy models could offer solutions to minimize this impact.***

# 4. New Bioeconomy models for a sustainable use of biomass

This chapter aims to answer the second RQ of this study: *Which are the main environmental concerns associated with the use of biomass feedstocks and how can bioeconomy models based on Ecosystem service provisioning help to address them?*. The following paragraphs elaborate on the sub-research questions and answers to address this second RQ.

## What is the current and predicted demand for biomass industrial purposes?

The use of natural resources from biomass as an alternative to fossil resources could be in a broader sense defined with the term "Bioeconomy", a concept that is currently being promoted at a policy and industry level as the promise to reconcile sustainability development goals with economic growth (D'Amato et al., 2020).
An increase in the current use of biomass feedstock has an associated problem-shifting risk, as today's bioeconomy has mainly focused on the extraction of natural resources at the expense of further sustainable considerations (Bastos Lima & Palme, 2022) . Therefore, if the shift from fossil fuels towards bioeconomy aims to achieve a sustainable transformation, Bioeconomy models that enable green growth through the use and protection of natural resources, and at the same time, enable to meet Sustainable Development Goals (SDGs) should be promoted (Kuosmanen et al., 2020).

An analysis of the current supply and demand of these feedstocks is relevant to evaluate what this increase might imply, also a closer look at the predicted changes in the flows of biomass for energy and material purposes is relevant to address the magnitude of the future Bioeconomy. This analysis is included in Appendix 1-Analysis of the current and predicted demand for biomass for the industry sector, out of which the following main conclusions can be drawn:

1. Today the total demand of biomass makes use of close to a third of the total available land for biomass production purposes (Intergovernmental Panel on Climate Change, 2022). The demand is currently dominated by food purposes which are predicted to considerably expand in the coming years. A further expansion of biomass sourcing for industrial purposes will therefore need to happen in a sustainable way to limit the risk of posing greater environmental risks to the planet (Bastos Lima & Palme, 2022).
2. Despite the predicted exponential deployment of solar and wind energy, the use of biomass for bioenergy purposes is predicted to increase particularly for its use as heat and biofuels for transport, accounting for 18.7% of the global share of energy supply in 2050 increasing from approximately 60 EJ in 2020 to a final 100 EJ in 2050 (IEA, 2021).
3. Despite the predicted increase in the energy demand, the demand for carbon feedstocks for the energy sector is expected to be reduced by up to 50% due to the predicted increase of electricity, hydrogen and solar heat, the demand for the mobility sector could be reduced by up to 90% through electrification and hydrogen use. On the other hand,

the increase in the demand for the use of carbon in materials will double its current levels due to an increase in the sector demand that is not detachable from carbon sources (Kähler, F et al., 2023).

4. This demand for carbon feedstock for the materials and chemical sectors in a fully decarbonised scenario will imply the share of recycled carbon, and biomass-based carbon as the main sources accompanied by a smaller contribution from captured carbon (Kähler, F et al., 2023). Biomass sources for carbon embedded in materials will increase from the current use of 40 MT to 370 MT of carbon for the year 2050 (Kähler, F et al., 2023).

This predicted increase in biomass use entails both potential carbon emissions and mitigation as well as co-benefits and trade-offs with respect to land degradation, biodiversity and other sustainability aspects that will be mainly dependent on the land use and management regime of the expansion of these new biomass supply chains (Calvin et al., 2021). Therefore, the degree of sustainability that bioeconomy models could achieve will depend on multiple factors and entails a great degree of complexity (Paul Bennett & Pearse Buckley, 2021) .

To address some of these potential benefits and trade-offs, in the following paragraphs, the main environmental challenges and benefits that are associated with the sourcing of biomass feedstocks derived from agricultural or forestry practices are described. Nevertheless, despite not being included in this analysis, other environmental issues can occur later in the supply chain regarding the transport and processing of biomass sources as well as the indirect energy source that is intended to displace (Paul Bennett & Pearse Buckley, 2021). This analysis does not include other relevant economic and social factors that should also be considered for a total sustainability assessment of bioeconomy models.

# What are the main environmental concerns of biomass sourcing?

## Land use change and carbon balance

The environmental impacts associated with land use change are one of the biggest issues determining the sustainable use of biomass (Calvin et al., 2021; Fritsche et al., 2020; Paul Bennett & Pearse Buckley, 2021). These associated impacts can occur in two different manners: Direct and Indirect Land Use Change (Paul Bennett & Pearse Buckley, 2021). The first one accounts for the environmental burdens that might occur when a certain land area is transformed from previous use to an established energy crop production, the latter is related to the land uses that can indirectly be displaced by the energy crop production, causing land use change somewhere else (Paul Bennett & Pearse Buckley, 2021).

The importance of Indirect Land Use Change (ILUC) has been addressed in a recent EU policy, the EU's Renewable Energy Directive II (RED II), which from 2023 will ban the use of what is considered as "high ILUC-risk" biofuels that use as feedstocks biomass that can induce food or feed crop displacement (Panoutsou et al., 2022).

The use of bio-based/biogenic carbon is categorised as a climate change mitigation strategy and is even sometimes defined as a carbon-neutral energy source which does not contribute to the net increase in carbon in the atmosphere (Paul Bennett & Pearse Buckley, 2021). The reason behind this assumed neutrality is that CO2 emissions occurring in the combustion of biomass, contrary to the ones coming from fossil fuels (which increment the carbon content in the atmosphere), is balanced by the carbon absorption of the biomass, therefore the carbon being emitted equals the carbon being captured ending up in a neutral balance (EIA, 2022). Nevertheless, assuming this carbon neutrality can be somehow misleading as the whole lifecycle of biomass use also accounts for GHG emissions along its supply chain (fertiliser use, machinery use, transport or processing), induced changes in natural carbon stocks or even modifications in albedo effect (Paul Bennett & Pearse Buckley, 2021). Therefore, the analysis of carbon emissions should always be studied from a lifecycle perspective that includes all GHG emissions associated with biomass use and not only the ones related to its combustion, a graphical representation of how these flows of carbon can along the lifecycle of a biobased product is represented in Figure 5. However is worth mentioning that these represented flows do not account for the carbon fluxes that occur due to the changes in soil organic carbon, which are assumed to have a major impact on overall greenhouse gas lifecycle emissions but are not usually accounted for in biomass LCA studies (Schmer et al., 2015).

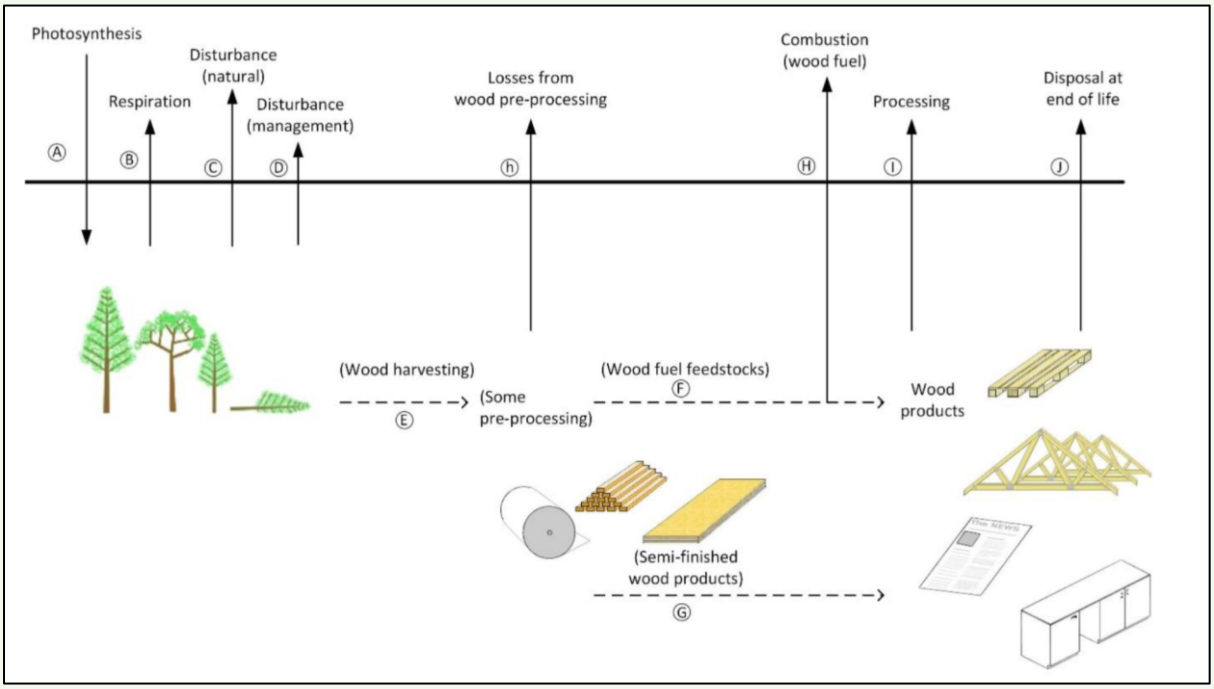

*Figure 5: Lifecycle carbon flows from wood products. Source: (Fritsche et al., 2020).*

Changes in land use influence land carbon stocks both above and below ground, soils are sources and sinks of GHGs and these fluxes can be affected by land transformations and management practices (Calvin et al., 2021). In fact, detrimental land use practices are estimated to have contributed to 23% of anthropogenic GHG emissions between the years 2007-2016 (Intergovernmental Panel on Climate Change, 2022).

Nevertheless, not all of these changes to land are associated with an increase in emissions, the conversion of croplands to perennial grasses and woody crops is assumed to increase both above-ground and belowground biomass levels (Calvin et al., 2021). This is increase in biomass is however assumed to be better for woody than C4-grass energy crops (switchgrass and miscanthus) (Schrama et al., 2016).

Land management practices such as tillage, fertilization, residue management or cover crops, can also modify these balances, for example, the change from conventional to conservation tillage can shift land from being a source to a sink of GHG (Calvin et al., 2021).

## Soil, water, and biodiversity

Changes in land use have not only an effect on carbon stocks and GHG fluxes, but soils also provide a variety of functions that are relevant both for the ecosystems that they are in and the productivity of the land (Paul Bennett & Pearse Buckley, 2021). As before the land transformation and management practices associated with biomass cultivation can positively or negatively influence the quality of the soil, the water quality and availability and the biodiversity of the habitat (Calvin et al., 2021; Paul Bennett & Pearse Buckley, 2021). Regarding soil quality management practices that imply high residue harvest can have a negative influence on soil fertility and erosion risk (Calvin et al., 2021). On the other hand, the planting of perennial trees can have positive effects on reversing land degradation, improving soil fertility, reducing soil contaminants and increasing water infiltration (Virano Riquelme et al., 2021) (Calvin et al., 2021).
Agriculture is responsible for over 70% of global freshwater use and cropped lands strongly influence the alteration of the water balances of local basins and therefore its availability (Paul Bennett & Pearse Buckley, 2021). Furthermore, water quality can be affected due to the pollution from agricultural fields, in high-income countries agricultural pollution is the main responsible for the degradation of inland and coastal water, and in Europe, 38% of water bodies are considered to be under pressure due to agricultural contaminants (mainly due to nitrate leaching) (FAO, 2017). On the other hand cultivation of short-rotation tree plantations for bioenergy as riparian buffers have a considerable positive environmental effect on water purification (Styles et al., 2016).

Biodiversity loss is also one of the biggest concerns surrounding the sustainability of biomass use, land transformation through the conversion of natural vegetation to agricultural land, pollution associated with agricultural intensification, or inclusion of non-native species are some of the main threats to biodiversity conservation (Paul Bennett & Pearse Buckley, 2021). Limiting biomass production for material/energy purposes to degraded lands would have negligible effects on biodiversity loss and land degradation (Intergovernmental Panel on Climate Change, 2022), perennial crops can even support the restoration of this degraded land by providing habitat and increasing the connectivity of species (Paul Bennett & Pearse Buckley, 2021).

On top of these environmental concerns associated with biomass feedstock sourcing, a great range of socioeconomic impacts can be affected by the implementation of Bioeconomy strategies (Paul Bennett & Pearse Buckley, 2021). The positive or negative extent of this effect in the long term is greatly dependent on the conservation of natural wealth, therefore moving towards a bioeconomy that is rooted in the restoration of ecosystem health and prevention of biodiversity loss is critical to achieving a complete sustainable paradigm for bioeconomy systems (Sharma & Malaviya, 2023).

The following paragraphs present bioeconomy systems models that can improve the sustainability of biomass use, these will serve later in this research to further define the type of biomass feedstocks sourcing for bio-methanol production.

# How can a Bioeconomy model based on the provisioning of ecosystem services can promote sustainable biomass use?

## A new model of bioeconomy based on ecosystem services.

From this understanding of the possible negative effects that bioeconomy models might exert in certain sustainability aspects, what is defined as a "new bioeconomy" based on maintaining ecosystems and building up on the sociocultural and ecological values is being framed as the bioeconomy best strategy for the environment (Bastos Lima & Palme, 2022).

In this regard, the concept of Ecosystem Services (ES) is identified as of great importance towards connecting the bioeconomy models to SDGs, ESs can be simply defined as the processes by which natural ecosystems provide support and feed the needs of society (Sharma & Malaviya, 2023). These services classified as provisioning, regulatory, cultural and supporting include not only the provision of resources like food, genetic resources or freshwater but also include regulating services like carbon sequestration or pollution remediation, and cultural services like a sense of place or aesthetic values see Figure 6 (Sharma & Malaviya, 2023). Sustainable management of ESs through an adequate bioeconomy vision will allow for a strengthening of the connection between human needs and the biosphere's capacity to maintain ecological functions (Sharma & Malaviya, 2023), shifting from a resource-oriented perspective towards one that envisions economy and society embedded within planetary boundaries (D'Amato et al., 2020).

A more ambitious vision for the Bioeconomy will go beyond maintaining the value of the natural systems and thrives on contributing to the expansion and restoration of it, is defined as a "Restorative Bioeconomy", this vision could regenerate lost vegetation and recover degraded ecosystems reversing the damages already done to natural systems (Bastos Lima & Palme, 2022). A shift in focus from natural resource extraction to the achievement of human well-being through the provision of ecosystem services will be an important element for the further positive advancement of the Bioeconomy, researchers and professionals when evaluating Bioeconomy strategies should consider their impacts in multiple ESs to contribute to the legitimacy and acceptability of many sustainability issues (D'Amato et al., 2020).

*Figure 6: Ecosystem service classification. Source: (James Karimi, 2017)*

## EU Bioeconomy plan

In line with the previously defined new strategies for further development of the sustainability of Bioeconomy strategies. The European Union adopted in 2018 a strategy to develop what is defined as the "new Bioeconomy", rooted in the strengthening of the connection between economy, society and environment (Fritsche et al., 2020). This new strategy aims to move away from the business as a usual vision of a Bioeconomy in which the benchmark is only defined by decarbonisation and embraces this new system as key for sustainable growth, that is bounded by planetary boundaries and socioeconomic constraints, with a particular focus on food security (Fritsche et al., 2020).

For this Bioeconomy to be able to grow sustainably, circular use of its natural resources should also take place, nevertheless, circularity should not be its only goal and the potential of a circular Bioeconomy to grow sustainably according to (Fritsche et al., 2020) should guarantee:

- An overall increase in the efficiency of the system
- Reduction of environmental impact and enhancement of ecosystem services
- Geographical redistribution of employment and economic growth
- Diversification of rural economies
- At least partially compensate for the decline of the fossil fuel economy

This vision of a sustainable bioeconomy in Europe will depend on achieving a maximum sustainable supply deployment of available feedstock sources, these will consider not only purposely cultivated biomass but also residues from the agricultural and other industries as well as organic municipal waste (Lange et al., 2021). These resources will be valorised in bioenergy systems, which despite the expected huge solar and wind electricity deployment, will still play a role in providing grid balancing services and being a complementary energy source in future scenarios (Fritsche et al., 2020). A bigger transformation will take place regarding biomaterials and ecosystem services that will strengthen the competitiveness and employment rates around the use of bio feedstocks for construction materials, food and feed, textiles and especially for the chemical industry (Fritsche et al., 2020). In this context, biorefineries, defined as processing facilities that transform biomass feedstocks into marketable bio-based products (European Commission et al., 2021), through their innovative processing routes will provide improved valorization of biological resources and a wide range of value-added products (Lange et al., 2021).

***In this chapter, the predicted increase in biomass use for industrial purposes is presented, an increase that could have detrimental environmental effects if biomass supply chains are based on natural resource extraction without further sustainability considerations. The main environmental concerns of biomass sourcing have been presented, these are greatly dependent on land use and management practices, which provide opportunities for environmentally improved design of biomass supply chains. In this regard, a vision for a bioeconomy that can restore natural systems has been presented as a key strategy to reconcile economic growth with sustainable development, a vision that is already being promoted by the European Union. From this understanding of the challenges and opportunities of bioeconomy models, and with the premise of exploring biomass feedstock that fit into the vision of a Bioeconomy based on ES provisioning, the following chapter will explore possible biomass feedstocks that can be suitable for bio-methanol and at the same time able to promote these sustainable bioeconomy models.***

# 5. Short rotation silvoarable systems as biomass provisioners

This chapter aims to answer the third RQ of this study: *Which biomass feedstocks can be preferable for the production of bio-methanol to maximize its sustainability potential?* The following paragraphs elaborate on the sub-research questions and answers to address this RQ.

## What are the most appropriate biomass feedstocks for biomass gasification considering the availability of conversion technologies?

Two main requirements to produce bio-methanol are the availability of both technology and feedstock for its production. Biorefineries provide this required technology to produce bio-methanol from biomass feedstocks. The development of biorefineries in Europe is recognised as one of the key drivers to unlocking the full sustainable potential of the bioeconomy and achieving a climate-neutral economy in the EU (Fritsche et al., 2020; Lange et al., 2021). Biorefineries will allow for the substitution of fossil feedstocks for bio-material manufacturing at the same time they co-generate biofuels and bioenergy flows (Fritsche et al., 2020), furthermore when developed close to biomass production could become strong sources of income and job creation for the development of rural areas, acting as political solid drivers for the Bioeconomy (Lange et al., 2021).

The sustainability of the biomass conversion pathways is therefore dependent on the geographical location of its production process and consequently on the availability of local biomass feedstock supply. Addressing the first matter regarding the potential development of biorefineries at a European level, a brief overview of the current and potential development of biorefineries for the production of high-value biobased products in Europe and in particular for the case of bio-methanol from biomass gasification are included in Appendix 2-Analysis of biorefineries in Europe and bio-methanol suitable feedstocks, and summarized in the following key points:

1. EU biorefineries are today dominated by facilities that operate on food and feed crop feedstocks representing 56% of the total, the supply from biorefineries is predicted to almost double to meet the future demand for bio-chemicals, and this expansion will be dominated by the use of non-food feedstocks (European Commission et al., 2021).
2. The selected biorefinery pathway for this study (lignocellulosic biomass gasification for bio-methanol production) is predicted to have a considerable expansion with the development of 4 new facilities for the year 2030, despite the possibility of using agricultural residues and wood, the deployment of this pathway could only achieve its full deployment potential with the use of non-food crops (European Commission et al., 2021).
3. Short-rotation coppice and forestry residues are assumed to have greater suitability than agricultural waste and grass energy crops for gasification technologies which are defined as much harder to process (BEIS, 2021).

## What is the projected availability of these biomass feedstocks in the near future?

From the previous analysis, it can be concluded that the deployment of biorefinery facilities in Europe to produce bio-methanol from biomass gasification is expected to happen in the near future and for that, the use of Short Rotation Coppice and wood residues feedstocks could be one of the preferable options to do so. The next question would be then whether these feedstocks will be available at a European level to meet this demand.

For the case of forestry residues, a predicted low availability of this feedstock in the near future in Europe, on top of that as a waste stream its provision of additional ESs can be assumed to be lower than other systems that can promote the restoration of natural and therefore can be as less ideal for the achievement of regenerative bioeconomy supply chains.

On the other hand, energy crops are surrounded with great uncertainty regarding their supply potential, this uncertainty is dependent on the availability of land to grow these crops, which provides also an opportunity to cultivate these crops to maximize their ES provisioning and create restorative supply chains (Based on information from Appendix 3-Biomass feedstock supply in Europe).

These findings suggest the exploration of alternative land use management practices that could maximize the provision of ecosystem services and at the same time maximize the productivity of SRCs. The following chapters elaborate on this possibility by exploring the potential of SRCs to maximise the overall sustainability of bio-methanol production.

## How can these biomass feedstocks be sourced to maximize their sustainability potential based on the provisioning of ecosystem services?

### Short rotation coppice plantations and Ecosystem services

SRC plantations are commonly defined by dense planting schemes of a few fast-growing tree species that quickly resprouts back after being cut, these are normally harvested in short rotation of 2 to 5 years but longer rotations of 8 to10 years can also be employed depending on growth conditions management practices, and the final intended uses of the sourced wood (Desair et al., 2022). After 20 to 25 years the plantation stumps are exhausted and removed or ploughed into the soil (Desair et al., 2022). Poplar and willow are two of the most commonly grown species as short rotation coppice, these have been used for thousands of years as provisioners of multiple products and services, their great phytoremediation potential, high biomass production, and high planting density tolerance make them ideal to conform systems that provide multiple ecosystem services (Townsend et al., 2018).

Conventional plantations are characterized by low input requirements during their cultivation, and their ability to recycle and store nutrients over winter, particularly for nitrogen, which reduces their need for fertilisation (Lewandowski, 2016). Cultivation does not require annual ploughing which can be associated with higher fertility of the soils, increase carbon sequestration and greater presence of biodiversity in the soils (Lewandowski, 2016). Due to the long harvest period, SRCs are able to provide shelter for mammals and birds as these are not harvested over the breeding seasons (Lewandowski, 2016). SRCs are also stress-tolerant and can be planted in marginal sites due to their deeper rooting system, having the ability to deal with droughts, salinity, cold and soil contamination (Lewandowski, 2016).

On top of conventional plantations, SRCs can be established in systems that are able to restore contaminated land, as riparian buffers to reduce nutrient leaching, as a treatment for wastewater, or as a windbreak or floodplain protection measures, on top of these remediation measures, when included in urban areas these trees can help to reduce the urban heat island effects or provide natural recreation areas when grown on longer rotations (Townsend et al., 2018).

An analysis of the main ESs (excluding cultural services) that can be provided by SRCs is addressed by (Desair et al., 2022) these are summarized in Table 2 excluding the ESs to agricultural systems as this will be discussed later in this chapter and the ESs related to their integration in the living environment which are considered less relevant for the goal of this study.

*Table 2: Ecosystem services provided by SRC plantations. Modified from: (Desair et al., 2022).*

| Category | Ecosystem service | Contribution | Comment |
|---|---|---|---|
| **Soil quality**<br>*An SRC system has multi-year rotations, little or no fertilisation or phytosanitary products are used, and soil cultivation is only carried out at the start and after the final harvest of the plantation. Therefore, planting SRC on a former agricultural field generally has a positive effect on soil quality. Compared to arable farming, an SRC can improve the soil structure* | Erosion control | Positive | Due to the extensive root system, absence of soil tillage, constant soil cover and high interception |
| | Support good soil structure | Positive | |
| | Support soil biodiversity | Positive | |
| | Manage nutrient leaching | Positive | Leaf fall and decomposition enrich the topsoil layer and the deep and fine rooting ensures good nutrient recycling and reduced leaching |
| | Phytoremediation of polluted soils | Positive | Willows and poplars have high resistance to levels of metal pollution in the soil and their ability to absorb and fix these metals in their biomass gives them the possibility to remediate polluted soils. However, this is only possible for moderately contaminated soils. |
| | Soil compaction during harvesting | Negative | SRC plantation harvest is generally mechanised, with heavy agricultural machinery or modified corn harvesters. If this happens when the ground is firmly frozen or dry, this does not pose a problem, but this is often not the case. As a result, soil compaction can occur. |
| | Damage to soils during uprooting | Negative | |

| | | | |
|---|---|---|---|
| **Above-ground biodiversity**<br>*Because SRC evolves from a bare plain to a young forest during each rotation, it can provide (partially and temporarily) a good habitat for many different species over time and space.*<br>*The biodiversity value can be increased by management measures, such as creating heterogeneity in time and space, using different varieties and planting flower borders or cover crops.* | Support insect diversity | Positive | The biodiversity of plants, insects and soil organisms is also higher under SRC than under annual agriculture. Yet it is often mainly generalists that do well in an SRC, and they contribute little to the conservation of endangered or rare species |
| | Support plant diversity | Positive | |
| | Conservation of native genetic material | Positive | |
| | Support vertebrate animal diversity | Positive | For large and medium mammals and birds, an SRC system is not sufficient as a habitat but it can be an important landscape element. Plantations can play a role as an ecological corridor between fractured pieces of nature. Smaller animals do find a habitat in an SRC that meets all their requirements. |
| | Indirect biodiversity loss because of indirect land use change | Negative | SRC plantation could occupy a field that was being used for food production, thus causing another piece of land, possibly with a high biodiversity value to be taken into production elsewhere for growing food (indirect land use change or ILUC). Also, an increased demand for biomass could cause forests to be replaced by SRC, which would lead to a loss of biodiversity. |
| **Water cycle** | Water purification | Positive | Due to its extensive root network and strong nitrogen and phosphorus absorption, SRC is excellently suited to purify wastewater. It can also serve as a buffer to catch the runoff and leaching of fertilisers to prevent it from ending up in the watercourses |
| | Increased water use | Neutral | SRC has a high-water consumption, in some cases, evapotranspiration is as high or higher than conventional agricultural crops, however, SRC can cause lower groundwater recharge compared to agricultural land. due to its dense network of roots and higher water retention. SRC from willow (and to a lesser extent poplar) can be very interesting in wet areas where agriculture is not possible. |

## Where should SRCs plantations be established?

As mentioned in Chapter 4 one of the main concerns of using biomass feedstocks for energy/material purposes is the potential competition with food provisioning that this can entail. SRCs contrary to other biomass feedstocks (1st generation) do not directly compete with food as they are not food/feed crops, nevertheless, they can indirectly compete with food production through land use competition.

In order to address this issue regarding land use competition, the cultivation of biomass can make use of two different strategies according to (Panoutsou et al., 2022):

1. Cultivation in land with biophysical constraints is usually defined as marginal land.
2. Cultivation under sustainable agricultural practices such as intercropping, cover cropping, rotational cropping or agroforestry.

Regarding the first option, energy crop cultivation under marginal conditions might come with certain challenges that can hinder the establishment of these plantations. In order to restore land with biophysical constraints to be productive, significant effort and material input is required, on top of that, cultivation in land with high contamination may result in environmental risks (Panoutsou et al., 2022). As previously presented SRCs are able to perform adequately and improve the quality of degraded and contaminated soils, however, the yields are always expected to be lower than in productive agricultural land (Liu et al., 2021). Other challenges that can be associated with their cultivation on degraded land are the potential increase in field operations due to possible irregular shapes or the possible longer transportation distances to less accessible marginal lands (Liu et al., 2011).
Higher investment and production costs are therefore expected for these systems when compared to normal agricultural land, making them less economically attractive and hindering their expansion (Liu et al., 2011).
A particular type of marginal lands, river floodplains or areas prone to flooding do however not share limitations regarding the expected yields of SRC, as these areas are assumed to have high nutrient availability and the water tolerance of SRC make them ideal for these land use types (Bardhan & Jose, 2012). On top of that the integration of SRCs in floodplains can enhance the restoration of these areas that support biodiversity, restores soil health and fertility and act as flood control mechanisms (Bardhan & Jose, 2012). Despite the interesting potential that these systems provide for the cultivation of SRCs, these were discarded for the further analysis of this study due to the lack of available data and the assumed difficulty to capture the benefits of the ESs that these systems can provide, however it will be of great interest to further evaluate these systems from an environmental perspective as an alternative for SRC cultivation.

*Figure 7: Short rotation silvoarable system. Source: (Krzyżaniak et al., 2019)*

The second option of implementing these crops as part of sustainable agricultural practices deals with some of the previously mentioned challenges. Through multifunctional biomass production systems (biomass systems aimed to provide multiple benefits and services on top of the biomass), energy crops could provide a reduction of environmental impacts from agricultural land at the same time providing biomass feedstocks (Englund et al., 2021). For the particular case of SRCs, this integration of trees in the agricultural systems, what is understood as agroforestry systems, could happen in different ways, including silvoarable systems as the combination of annual crops and tree strips in arable land, silvopastoral as the combination of trees and pasture lands, and windbreaks or buffer strips, integration of trees in the arable field hedges to reduce wind erosion and contamination protection of water bodies respectively (Beetz, 2002).

Short-rotation coppice in agroforestry systems combined with crop production is assumed to be able to have high wood biomass yields, without sacrificing food production and at the same time potentially increase water quality, sequester carbon, increase biodiversity and improve the aesthetics of agricultural fields (Holzmueller & Jose, 2012). Silvopastoral systems lack these interactions with crops, however, they can be provisioners of shade in summer and cold protection in winter improving the overall living conditions for livestock (Desair et al., 2022). The integration of SRCs in agricultural land as fields borders or alleys is defined as the best strategy to maximize the sustainability potential of these energy crops (Desair et al., 2022).

Silvoarable systems when compared with hedgerows can be assumed to have a higher degree of interaction with annual crops due to a larger amount of tree areas and closer distances to the crops, also when compared to silvopastoral systems, it can be assumed that these systems provide greater amount of ESs and also have an overall higher potential for biomass production as the amount of arable land almost doubles the amount of livestock grazing land in Europe (European Commission, 2018). Therefore, due to this greater potential for biomass production and more assumed positive interactions with the arable fields, short rotation silvoarable systems are further explored in the following paragraphs regarding their productivity to provide both crop and wood feedstock and as provisioners of ecosystem services to the agricultural fields.

## Productivity of trees and crops in Silvoarable systems

The main concern to address regarding the implementation of silvoarable systems is their performance regarding the yields of both the annual crops and the trees. A metric commonly used to evaluate this performance is the Land equivalent ratio (LER), this metric compares the yields from growing two or more crops together with the yields obtained from the same plants grown in monoculture (Tsonkova et al., 2012). See equation 1.

*Equation 1: Land equivalent ratio (LER) calculation formula. Source: (Lehmann et al., 2020).*

$$LER = \frac{crop\ yield\ in\ agroforestry}{crop\ yield\ in\ monoculture} + \frac{tree\ yield\ in\ agroforestry}{tree\ yield\ in\ monoculture}$$

Values of LER > 1 represent a productive combination of the system, as the overall production is higher for the combined system than when grown separately. The obtention of LER values implies providing a comparison between two systems that are similar regarding soil and climate conditions, due to the low presence of silvoarable systems in Europe this information is not highly accessible, for the case of short rotation silvoarable systems. For silvoarable systems in general, LER values between 1.0 and 1.4 for the European climatic regions are predicted (Tsonkova et al., 2012).

A literature search for available data regarding short rotation silvoarable plantations identified first a low amount of studies for these types of plantations, some of the main findings regarding the productivity of these systems are presented in this paragraph. (Burgess et al., 2005) studied three different silvoarable poplar plantations in the UK, for which a reduced yield of the trees of 10% and of crops of 4% of monocrop systems were obtained suggesting an overall lower productivity of these systems when compared to monocrop plantations (LER < 1). In contrast, (Lehmann et al., 2020) studied two willow silvoarable systems in the UK and Denmark that obtained LER values of 1,4 and 1.36 respectively. In Germany (Seserman et al., 2019) studied two poplar silvoarable plantations for which the LER values were 1,3 and 0,9, for these plantations the relative tree yield (yields of trees when compared to monocrop plantations) ranged from 1,1 to 1,6 and the relative crop yields (yields of crops when compared to monocrop plantations) ranged from 0,6 to 1,6 in the different studied plots of the plantations, suggesting that the yields of the trees were always higher than in the monocrop fields and the crop yields will be more dependent on the studied plot.

The available data suggest a considerable difference between the productivity performance of the presented plantations, but with a slightly beneficial tendency when compared to monocrop fields. If silvoarable systems are meant to be provisioners of biomass feedstock for industry, a further understanding of which could be the underlying reasons behind these differences in performances should be addressed. The following paragraphs provide a brief explanation of the main interactions that occur between trees and crops in silvoarable systems to provide an understanding of some of the underlying reasons affecting their productivity and how these could be better managed.

## Trees and crop interactions

In the transition zone between the trees and crops, the provision of shade from trees can be assumed to cause a reduction in the yield and quality of the crops, however during stress periods of heat and drought the shade can provide reduced soil evaporation and crop transpiration reducing temperature-related detrimental effects on the crops (Tsonkova et al., 2012). The planting of shade-tolerant crops in the shaded area and the reduction of tree height with more frequent harvesting to reduce the amount of shaded area will favour an increase in the yield in the transition zone (Seserman et al., 2019)

Wind protection due to the physical structure of the tree rows is one of the main benefits that poplar trees were able to provide to annual crops in an SRC silvoarable plantation in which reductions of up to 80% of wind speed were reported in (Veldkamp et al., 2023). This reduction of wind speed is able to decrease the mechanical stress and damage to the surface of the crops from exposure to wind, on top of avoiding the soil erosion caused by wind (Jacobs et al., 2022).

The integration of trees in the arable fields is also assumed to have a considerable influence on the water balance of the system see Figure 8. Trees have an effect on the partitioning of the precipitation between the vegetation and soil surface, below the tree canopy only water passing through or not stored in the canopy is assumed to reach the crops and the soil, the choice of the tree and the pruning frequency will therefore be determinant of the water availability for the crops (Jacobs et al., 2022). On the other hand, the raindrop interception of trees in addition to the soil litter deposition and water infiltration could benefit the reduction of soil erosion by rainwater (Jacobs et al., 2022).

The competition for water resources between the crops and trees can also happen through their routes systems, the extent to which the tree roots enter the crop field is a determinant factor in this aspect, adequate distances between the trees and crops are therefore assumed crucial for the success of agroforestry systems (Jacobs et al., 2022). Overall the spatial differences in the water uses of trees and crops on top of the microclimatic factors like wind speed reduction and shading will have a considerable effect on soil moisture and water availability for both crops and trees, an adequate plantation design that combines trees and crops in different development stages of their seasonal growth will reduce the overall competition for water and nutrients (Jacobs et al., 2022). Regarding water infiltration and groundwater recharge studies have reported higher recharge after precipitation events, however a lower groundwater recharge can also be predicted due to the enhanced water use and interception of tree rows, is therefore essential to better understand these mechanisms, particularly for future scenarios were longer summer droughts are expected (Jacobs et al., 2022).

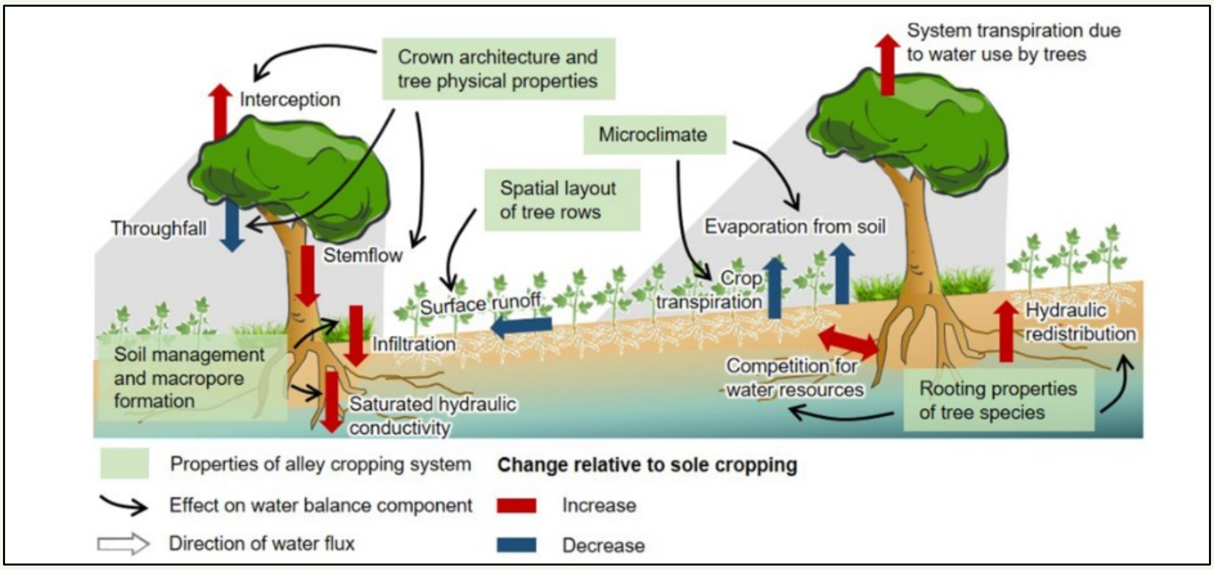

*Figure 8: Effects of alley cropping on components of the water balance (Jacobs et al., 2022)*

Regarding insect biodiversity, agroforestry offers opportunities to support the provision of crop pollination and biological pest management in temperate regions by providing habitat and enhancing its connectivity and mitigating pesticide exposure to beneficial insects, designs of agroforestry systems that benefit pollinators such as plant combinations for foraging resources or spatial distributions ta favour habitat connectivity could enhance the productivity of these systems (Bentrup et al., 2019).

A study on nutrient cycles found that in the transition zone between poplar trees and wheat crops, the negative effects of reduced light for seedlings and nutrient competition from poplar roots outweighed the potential benefits of additional nutrients and organic matter from poplar litter (Swieter et al., 2022). On the other hand in the case of tree growth, the availability of more light and the higher nutrient uptake from the fertilized crop increased the overall yield of the trees (Swieter et al., 2022). Regarding nutrient competition, (Veldkamp et al., 2023) stressed the fact that the full potential of short rotation silvoarable systems could only be achieved if the nutrient management practices are optimized, a reduction of fertilizer application in arable fields is assumed to improve the functions of soil nutrient cycling, soil GHG abatement potential and water regulation with only marginal yield losses.

Overall, it is assumed that for an optimal establishment of short-rotation agroforestry systems the choice of annual crops, the rotation periods and the layout of the plantation should be consciously designed to maximize the productivity of these systems (Swieter et al., 2022)
Furthermore, the microclimatic conditions and water balance components in agroforestry it is yet not fully understood today due to the large variations between the studied systems and the complexities that surround the interactions and feedbacks loops that occur in the microclimatic variables (Jacobs et al., 2022).
It is therefore of high importance that a better understanding of short rotation silvoarable is gathered through research and practical experience, under long term studies considering different locations, and design strategies, to gather insights for the design of these systems in a way that maximizes their sustainability potential for being providers of both food and biomass feedstock for industry.

***This chapter has identified a predicted increase in the expansion of biorefineries based on the gasification of lignocellulosic biomass in Europe. Short rotation coppice and forestry residues are defined as the most suitable feedstocks for this conversion pathway. The availability of these feedstocks is expected to be low for wood residues, but for the case of SRC, is dependent on the uncertainty of where to grow it. SRC can provide multiple ecosystem services mainly dependent on how is cultivated, today these plantations are planned to be established on marginal land to avoid food competition, nevertheless this approach is susceptible to failure due to the economic challenges that entail the use of unproductive lands for energy crop cultivation, an exception will be the grow of SRC in floodplains due to an assumed higher productivity and the ability to provide multiple ESs. The other proposed alternative to tackle some of the challenges of SRC cultivation is their integration in agricultural land as agroforestry systems, this approach is assumed to be beneficial for the yields of the trees and the same time provide ESs to the farmland. Nevertheless, in the case of silvoarable systems, their design is what will be crucial for the achievement of beneficial synergies between the trees and the crops that could make these systems profitable. From this chapter the decision to further evaluate the environmental consequences of using wood from short rotation silvoarable systems as a feedstock for bio-methanol production is derived. This evaluation will be performed through an***

***LCA study in which this feedstock will be compared to the conventional considered alternative of growing SRCs in marginal lands, the other identified alternative suitable feedstock for gasification, forest residues wood chips and the alternative fossil-based feedstock for methanol production.***

# 6. Comparative Life Cycle Assessment methanol production

## Goal definition

The main goal of this LCA is to perform a hotspot analysis and a comparative assessment between the production of methanol in a bio-refinery in Germany from wood chips from a German silvoarable system, and other alternatives of bio-methanol and fossil fuel-based methanol. This study is representative of a cradle-to-gate approach for which all relevant activities associated with the sourcing of biomass until the processing of the wood into the bio-methanol product are included. Ideally the LCA should cover all lifecycle stages to evaluate the total environmental impact of the studied product systems. However as referred in Chapter 3, this research builds up on an existing study from the commissioner of this project Airbus, in which first the manufacturing of CFs was identified as the main environmental concern of CFRPs and the use of bio-methanol pathway for ACN production was identified as one of the most advantageous from an environmental perspective. With that premise, this study will only focus on the evaluation of the methanol production alternatives from the different considered feedstocks to provide an answer to which is the biomass feedstock to integrate in this production pathway to maximize its environmental performance. Nevertheless, full cradle to cradle LCA study of CFRPs with this production pathway should be performed to evaluate the full environmental impact of this strategy.

The research question that this LCA study aims to address is the following: *What could be the environmental consequences of sourcing biomass from short-rotation silvoarable systems when compared to marginal plantations, forest residues and natural gas feedstocks for methanol production in Germany? And which are the main environmental hotspots of these production pathways?*

## Alternatives selection

The reasoning behind the biomass feedstocks alternatives to compare within the study is provided in Chapter 5. Marginal land poplar plantations as the currently defined alternative for SRC sourcing, and forest residues feedstock is defined as a feedstock with similar performance than SRC for the biomass gasification pathway.

As the last alternative to compare with, the use of natural gas as feedstock for methanol production is selected, this is considered the fossil-based alternative which is assumed to have a lower environmental impact when compared to coal-based methanol (Hamelinck & Bunse, 2022), and in the internal Airbus study was also considered as a pathway for CF production that also achieved an environmental reduction when compared with the oil based conventional route.

## Scope definition

The modelling approach evaluates the impact of the current demand as it is, what is usually referred to as Attributional LCA (ALCA). This differs from the Consequential LCA (CLCA) which measures the environmental burdens that occur from a change in the demand for the studied product (UNEP, 2011).

The geographical coverage of the study is delimited to the production of methanol in the country of Germany making use of feedstock sourced in this country (except for natural gas). The reasoning behind the selection of this geography is the availability of data for the modelling of the plantations and the existence of an Airbus manufacturing facility in Hamburg which could be representative of the destination of the manufactured composites. This geographical scope also defines the type of climate and soil characteristics of the studied plantations and therefore limits the results to these specific soil/climate characteristics.

The temporal coverage of the study in line with the research question, aims to be representative of the technologies that are being employed currently or will be available soon in the market, therefore it will use the most recent accessible data. To account for the total environmental burdens associated with the source of biomass from the different plantations under study, a full rotation of the plantations including their removal will be included.

The coverage of economic processes is consistent with the study's goal and includes all relevant processes that model a product system in which the inputs/outputs in its boundary are environmental interventions. All the relevant elementary flows and impact categories for the goal of the study would be included, these will be consistent with the selected impact assessment families for the study.

### Function, functional unit, alternatives, reference flows

The function to be addressed by the studied alternatives is the production of methanol in Germany. The functional unit will be to produce 1 ton of methanol in Germany.

The alternatives to compare are bio-methanol from poplar wood from a silvoarable plantation, bio-methanol from poplar wood from a poplar plantation in marginal land, bio-methanol from wood chips from spruce forest residues, and methanol from natural gas. For all alternatives the methanol production occurs in Germany and the biomass feedstock are also sourced in Germany Therefore, the 4 studied reference flows are:

A. Provide 1 ton of bio-methanol from a biorefinery located in Germany:
    a. from wood chips from a poplar silvoarable plantation in Germany.
    b. from poplar plantation in marginal land in Germany.
    c. from wood chips from spruce forest residues from a German forest.
B. Provide 1 ton of methanol from a refinery located in Germany from natural gas.

## Inventory Analysis

This section elaborates on the definition of the product systems under study. This definition is composed of the following parts: the system boundaries including the relevant cut-offs, the flow diagrams that are representative of the interrelation between the different unit processes, the data collection process required for the definition of these unit processes, and the performed allocations to solve the multifunctionalities. Finally, the inventory results are presented.

## Modelled plantations

For the first two alternatives based on biomass sourcing from Poplar Short Rotation Coppice, the modelling will be based on data from real/experimental plantations. The process regarding the decision to choose which plantations to model was based on the aim to address the goal and scope of the study and the accessibility to sufficient real data measurements. The approximate locations of these plantations are included in Figure 9

*Figure 9: Approximate location of modelled plantations. Source: own*

The silvoarable modelled plantations are based on the study of (Veldkamp et al., 2023). In this study data from three different short rotation silvoarable systems with similar design characteristics located in Germany are considered. These plantations are characterized by tree alleys of 12 m with Populus nigra x P. maximowiczii species and arable strips of 48 m width with different yearly crop rotations, more information regarding the soil types and climate of these plantations can be found in the supplementary material (Veldkamp et al., 2023). For the marginal land SRC plantation, the data is gathered from the experimental site described in (Schweier et al., 2017), a plantation of two commercial hybrid poplar clones (Populus maximowiczii A. Henry 9 P. nigra L. and P. 9 generosa A. Henry 9 P. nigra L.) established in a terrain with a soil quality index of 37 (representative of an average marginal land in Germany) (Schweier et al., 2017).

The data from the third and fourth alternatives will be based on existing Ecoinvent background processes with additional considerations adapted to the goal and scope of the study, these are explained later in this chapter.

## System boundaries and cut-offs

The economy-environment system boundary in accordance with (de Bruijn et al., 2002) is defined as the limit in which, economic inputs and outputs are converted into environmental interventions/extensions. These are not only defined as flows of emissions to air or water but also include measurements like land use change or raw material extraction, flows from/to the environment that undergoes no further human intervention (de Bruijn et al., 2002). For the case under the study of agricultural systems, the definition of what is considered an economic input and what an emission could be sometimes misleading, for example, manure fertilizer could be defined as an emission or an economic input. This is solved by attributing economic values to the flows, it will therefore be assumed that all flows with a monetary value are defined as economic inputs. The flows with assigned values are in accordance with the Agrifootprint LCI database (Hans Blonk et al., 2022).
In accordance with the previous definition, all inflows/outflows connected to the unit processes can be traced back until they are connected to environmental extensions[2].

Due to the lack of certain data, certain cut-offs are included to define product systems:

- Herbicide application emissions
- Methane and heavy metal field emissions
- Membrane production for bio-methanol production process

A graphical representation of the system boundaries of the considered alternatives are included in the flowchart provided in Figure 10. In this flowchart the focus is given to the agricultural activities related to the biomass sourcing which is the main focus of this study. The modelling of the bio-methanol production process is strictly based in the publication from (Galusnyak et al., 2023) and we refer the reader to this publication for further information on the LCI modelling of this process.

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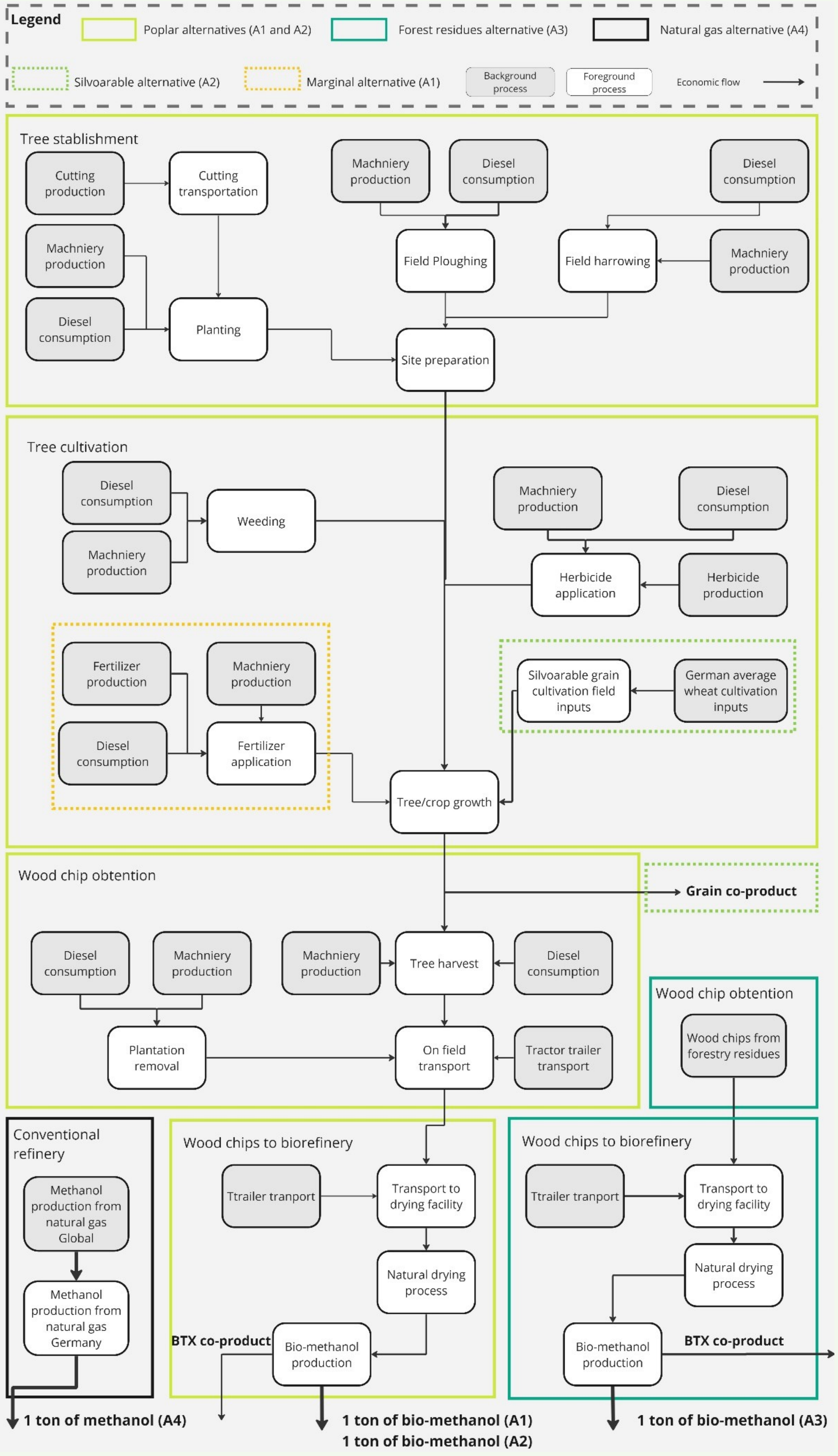


*Figure 10: Flowchart studied alternatives. Source: own*

# Unit process descriptions

For the aim of increasing the readability of this report a description of the main unit processes of the different alternatives under consideration is provided in Appendix 4-Unit process description. In the following paragraphs some of the main assumptions for the different alternatives are included.

## Alternative 1- Marginal land poplar plantation

The Lifecycle inventory for the modelling of this plantation is based on the LCI data of the LCA study (Schweier et al., 2017) This LCI data is adjusted and completed to be modelled for the goal of the study. The following main modifications include:

*Land use- Soil quality*

In order to define the impact related to land use change for the category of soil quality and in accordance with the methodology presented in Appendix 4-Unit process description, the need to evaluate the change in soil quality is addressed with the modelling of typical land uses provided in the LCA databases to evaluate this change without the need of including specific soil parameter characteristics in the plantation. The inclusion of the SRC plantation in degraded land is assumed to have a positive restorative effect on the managed land. The degree of this positive effect is assumed to be represented by the change from a “worst” to a “better” land use type in accordance with the available land uses. The land use type that is associated with the SRC plantation will be “permanent crop non-irrigated intensive” as defined in the Ecoinvent database for a willow plantation. For the case of the plantation in degraded land, the type of area selected to represent the marginal land will be “bare area”, despite this type of area could be defined as the worst case for the marginal land, it can also be defined as marginal (Csikós & Tóth, 2023), and is the closest available in the land use types of the Ecoinvent database. Therefore, the transformation of land will be from “bare area” to “permanent crop non-irrigated intensive” and the occupation will be for 21 years before the removal of the plantation.

*Land use- Climate change*

The field emissions included in (Schweier et al., 2017) are the Photosynthesis rate, Ecosystem respiration, $N_2O$ emissions and $NO_3$ leaching. The emissions of $N_2O$ are assumed to represent both the indirect emissions from fertilizer application as well as other sources of emissions like the mineralization from soil organic matter or the nitrogen present in wood/crop residues (Hans Blonk et al., 2022).

The information regarding the Photosynthesis rate and ecosystem respiration represents the balance of $CO_2$ emissions from the field, this information is not available in the rest of the alternatives and therefore a proposed alternative to account for the balance of carbon emissions that can be used for all the studied alternatives is proposed.

The assumption made is that the carbon dioxide balance of the field defined by the difference between the Photosynthesis rate and the Ecosystem respiration can be approximated by the carbon sequestration in biomass as the net primary productivity of biomass, which is information available for the rest of the alternatives. This is measured in dry matter content and is converted into captured $CO_2$ assuming a 49% carbon content in accordance with (Singh &

Lodhiyal, 2009). The validity of this assumption has been proven using certain calculations included in Appendix 4-Unit process description

The build-up of Soil Organic Content due to land use is not considered due to the absence of information but note that this rate of carbon capture could be considered relevant for both the marginal and the silvoarable plantations alternatives. Soil Organic Content is assumed to be increased by a change from normal cropland to agroforestry systems (similarly will occur from marginal land to a SRC plantation), as a graphical simplification of this process Figure 11 shows how a system that favours higher degrees of carbon sequestration like agroforestry systems provides higher steady state SOC stock than the current cropland, and also how a lower C-sequestration land use like deforestation will lead to a net loss of carbon, also it can be observed that for all three scenarios the initial change in land use will always imply a loss of carbon (Tsonkova et al., 2012).

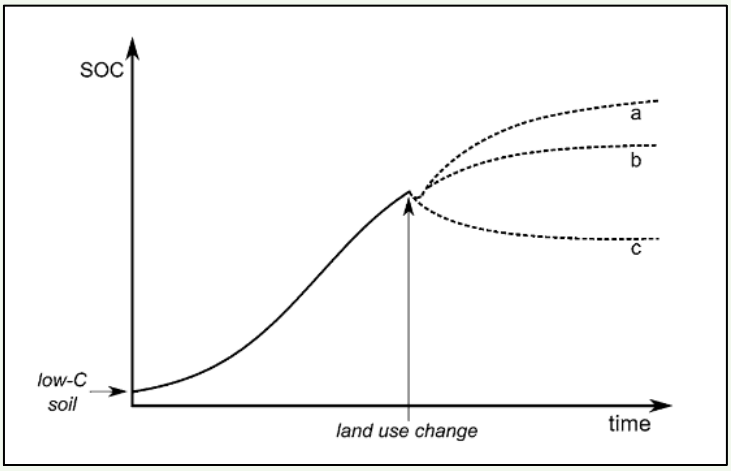


*Figure 11: Hypothetical influence of land use change in Soil Organic Content for different land use changes. (a) agroforestry, (b)cropland and (c)deforestation. Source: (Tsonkova et al., 2012)*

The emissions occurring during the removal of the plantation are however included in this analysis as they were presented in (Schweier et al., 2017), this however is assumed to be not correct as if these emissions are considered, the captured carbon in the soils should also be considered. The contribution of these emissions to the results of the study are later considered in the consistency check of the study.

## Alternative 2-Silvoarable plantation

The publication from which the silvoarable plantation is modelled (Veldkamp et al., 2023) provides information for the three different locations of the study about the yields of both the trees and the crops of the system for the silvoarable systems as well as for the control fields of monocrop (of annual crops) systems to compare with. This publication also provides data regarding field emissions for both the silvoarable and the control system, however, this information is only provided as an average of the three different locations.

Therefore, the decision is to model a unique plantation considering the average of the yields of the three locations. Despite the yields of the trees having similar results the yields of the crops,

when compared to their respective monocrop control plots differ considerably, and therefore the different results for the three locations will be included later in a sensitivity analysis.
Most of the required LCI data is absent in (Veldkamp et al., 2023) for the modelling of the silvoarable system, the general approach that will be followed to complement the absent data is the following:

- The modelling of the required operation for the trees will be based on the processes included in the LCA study for alternative 1 of the marginal plantation based on (Schweier et al., 2017). This is based in the assumption that the related tree operations will be similar and this will also allow to provide results between these two alternatives that are more comparable.
- The modelling of the crop operations will be based on Ecoinvent data for the region and the selected crop.
- The data in (Veldkamp et al., 2023) regarding field emissions and yields of trees and crops will be included in the previous modelled processes.
- Regarding the land use quality and the land use emissions, the same assumptions as in the marginal land alternative are included, considering predefined land use types for the soil quality impact category, and including the emissions of N2O, carbon sequestration above ground, and plantation removal emissions, but not the carbon sequestration below ground.

A more detailed explanation of the LCI inventory for the silvoarable system is provided in Appendix 4-Unit process description. The main assumptions used are included in the following paragraphs.

### Activities involving transport

The transport activities including on-field transport and transport of the wood chips to the biorefinery will be assumed to be the same as in the case of the marginal plantation, however, for the case of the silvoarable system it is assumed that the lower productions per system area compared to the marginal plantation (despite higher productivity per area of tree strip the system produces less wood per ha than the marginal land) will imply higher transportation distances. Therefore a 50% increase in transport distances compared to the marginal plantation is assumed.

### Arable field inputs

To define the arable field inputs and related emissions the Ecoinvent process of wheat grain production in Germany is used. Wheat production was selected as the grain production of the systems as it was grown in each modelled field at least in one rotation year (Veldkamp et al., 2023). Furthermore, for the modelled average plantation the value of the relative crop yield is close to 1, meaning that the crop yield in the arable fields of the silvoarable and monocrop systems are the same per area basis, therefore the type of selected crop is assumed to have very small influence on the results.

To define the arable field inputs for the silvoarable system the following steps are performed: first, with the calculated grain yield of the monocrop control system (average of the three plantations) and the assumed yield of the Ecoinvent process the emissions per hectare of the arable field are proportionally calculated as seen in Table 3. The assumption used is that a lower yield of the studied system will imply a higher input from the background Ecoinvent process, this assumption implies allocating more environmental burdens to the arable field due to a lower production with the premise that in order to match the amount of grain that the background process is providing the amount of inputs will have to increase proportionally. The contrary could also be possible as if the field has less grain output could mean that less inputs are required, the first approach was selected as a conservative estimate.

*Table 3: Calculation of proportional inputs for grain production. Source: own.*

| **System** | **Yield (kg/ha)** | **Proportional inputs** |
|---|---|---|
| **Monocrop average** | 6555 | 1.15 |
| **Ecoinvent** | 7567 | 1 |

Second, the emission of nutrient leaching and N2O are modified with the primary data of (Veldkamp et al., 2023), also the carbon captured by the growth of the crop is not included as it is assumed that the EoL of the crop will release this captured carbon.

Lastly, regarding the machinery operation in the silvoarable plantation, a study that evaluated the energy balance of an agroforestry system (Kanzler et al., 2021) assumed that the reduction in the size of the arable fields could imply a higher turning frequency of the machines in the cropped area, therefore an assumption of a 5% increase in arable field operations compared to the conventional area of arable land is included.

## Alternative 3-Wood chips from Beech forestry residues

The obtention of wood chips from forestry residues is modelled using the available Ecoinvent process “hardwood forestry, beech, sustainable forest management DE”. This process represents the sourcing of wood chips from forestry residues of a beech plantation in Germany under a sustainable management regime. The process includes all operations from the site preparation until wood chipping for a final chips obtention at the forest road. In forests contrary to the SRC plantations can be assumed that there is no removal of the plantation. The selection of beech as the wood source was based on the fact that according to the Ecoinvent data, it was the most significant source of wood chips in Germany (Werner, 2017). The wood chips from forest residues similarly to the marginal plantation alternative to have 50 km transportation distance until the biorefinery.

Regarding the land use induced impacts, the Ecoinvent process includes predefined land use type for the soil quality impact category. For the land use induced climate change the background process only accounts for the carbon emissions sequestered in the above ground biomass. When compared to the other alternatives, despite the assumption that in the lifetime of the study no plantation removal is assumed, the emissions of N2O are lacking and therefore the system will not fully comparable with the previous alternatives. In fact, according to (Audet et al., 2020), despite today great focus is given of the N2O from agricultural lands due to nitrogen application, forests are increasingly being recognise as great contributors to the global stream of this gas. The contribution of the N2O emissions to the overall results will therefore be included later in the consistency check of this study.

## Natural drying process of wood chips

The wood chips from Beech forestry residues and the two poplar plantations are assumed to have differences regarding water content (WC) and energy content when received in the biorefinery. These are included in Table 4.

*Table 4: Properties of modelled wood chips. Source: own*

| Received feedstock | WC (%) | Energy content (GJ/Mg dm) | Source |
|---|---|---|---|
| **Poplar wood chips** | 55 | 11,84 | (Schweier et al., 2017a) |
| **Beech residues wood chips** | 44 | 10,2 | (Werner, 2017) |

Regarding the energy content the difference is not significant, and it will be assumed that the performance of both wood types will be similar. According to the bio-methanol production study of (Galusnyak et al., 2023) the wood chips are assumed to enter the process of bio-methanol production with a 35% WC.

The natural drying process included in (Schweier et al., 2017) is assumed to bring down the WC to 30% with a respective loss of 17% of the dry matter content of the wood chips, this degradation implies carbon dioxide emissions. Therefore, for both poplar and beech wood chips, a proportional loss of carbon is assumed regarding the reduction of WC. This proportional loss of dry matter content and respective carbon dioxide emissions are included in the three alternatives (A1, A2 and A3). The calculations are included in external Appendix1 LCA._modelling

## Bio-methanol production

The bio-methanol production process is modelled in accordance with (Galusnyak et al., 2023), this publication provides the LCI of two improved methanol production processes from wood chips compared to what is defined as the “base case” scenario. The methanol conversion process selected from this publication is “Case 1” for being the one with the best environmental performance of the compared ones (Galusnyak et al., 2023).

The bio-methanol production process is modelled according to the data provided by (Galusnyak et al., 2023), with the use of the following assumptions:

- The membrane production needed for the reactor is not included in the modelling due to the inability to access data, the results showed that this process has no relevant influence on the results.
- The infrastructure of the reactor is assumed to be the same as the one included in the bio-methanol production of the Ecoinvent process.

- The electricity consumption is assumed to come from the Germany electricity production mix.
- The heat for drying the biomass is assumed to come from waste heat from the gasification process as it is included in the bio-methanol production of the Ecoinvent process.
- The ash treatment is modelled from the Ecoinvent process of treatment of ash from the combustion of straw.

### Alternative 4- Natural gas methanol production

For the methanol production from natural gas the Ecoinvent available process is selected, this process is defined as a generic global geography using global markets. This process is modelled for the generation of methanol in Germany by changing the origin of the main raw materials and energy flows from a global location to a German or if not possible European location.

## Multi-functionality and allocation

Multifunctionality can be defined in the context of an LCA study as the provision of more than one function or valuable product or service for the product system under study, for these cases an allocation procedure is required in which the economic flows and environmental interventions are allocated to the functional unit that is considered in the study (de Bruijn et al., 2002).

Two multi-functional processes occur in the product systems under study:

- Co-production of grain and wood in the silvoarable system
- Co-production of bio-methanol and BTX aromatics in the bio-methanol production system.

The European standard norm EUR 24708 EN for conducting an LCA study (Joint Research Centre. Institute for Environment and Sustainability., 2010), presents a hierarchy to deal with the multifunctional problem. The particular case of the modelling of agroforestry systems in LCA presents a challenge regarding the multifunctionality of these systems, furthermore no studies have been found in which the production of wood from agroforestry systems as the functional unit of these systems was evaluated in an LCA. Therefore and in order to provide a clear reasoning for the allocation of this process. In the following paragraphs the applications of these allocation strategies are presented for the case of the co-production of grain and wood product in the silvoarable system. This can provide an understanding of the relevant multifunctionality issue to consider when using LCA studies for silvoarable systems.

### 1st Approach sub-division of the multifunctional process

In this approach, the multi-functional process is divided into two mono-functional processes avoiding the need for allocation. For the silvoarable systems, the inputs might be divisible between the two sub-systems, as the field operations that occur for both sub-systems can be differentiated (Kanzler et al., 2021). However, using this approach will overlook the fact that both sub-systems interact with each other and consequently affect their required inputs and outputs. Therefore, in this case a need to further allocate these interactions between the systems will be needed.

## 2nd Approach system expansion

The second approach in the hierarchy is what is referred to as system expansion. This approach can be performed in two different ways according to (de Bruijn et al., 2002):

1. System expansion: in which allocation is avoided by including an extra function to the functional unit of the system to compare and adding the missing functions to the respective mono-functional processes to compare with by expanding their system boundaries.
2. System substitution: implies expanding the system boundaries and substituting the not required function with an alternative way of providing it and subtracting the impact of this alternative from the studied process.

For the system under study, the system substitution approach could provide a solution to the allocation of the interactions between the sub-systems. By modelling an adjacent mono-crop system with similar management practices as the arable field of the silvoarable system, the substitution of the environmental burdens of the monocrop system from the silvoarable system will provide an accurate approximation of the environmental impacts associated with the sourced wood. This approach is graphically represented in Figure 12.

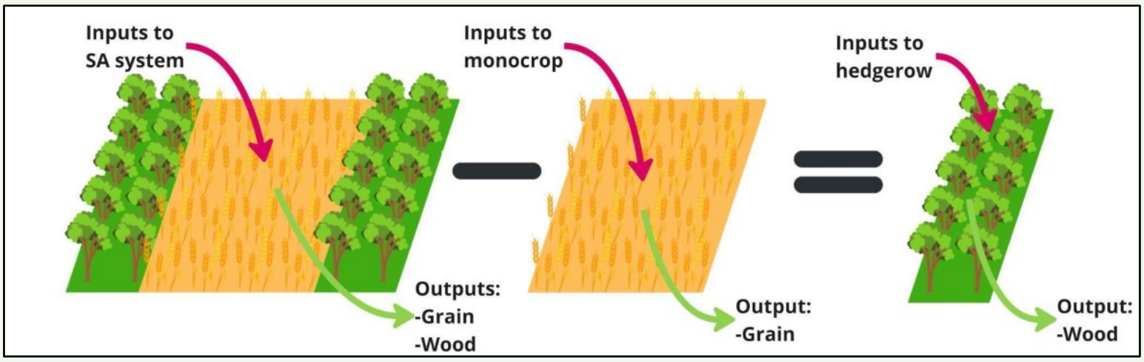


*Figure 12: System substitution approach for silvoarable systems. Source:own*

## 3rd Approach partitioning method

The third and last approach in the hierarchy will be to apply the partitioning method. This implies allocating the inputs and outputs of the multifunctional system according to a defined criterion property of the co-functions mass, energy yield (energy content *yielded mass), revenue (price * yielded mass)… A graphical representation of a simplified economic based partitioning for the GWP impact category is included in Figure 13

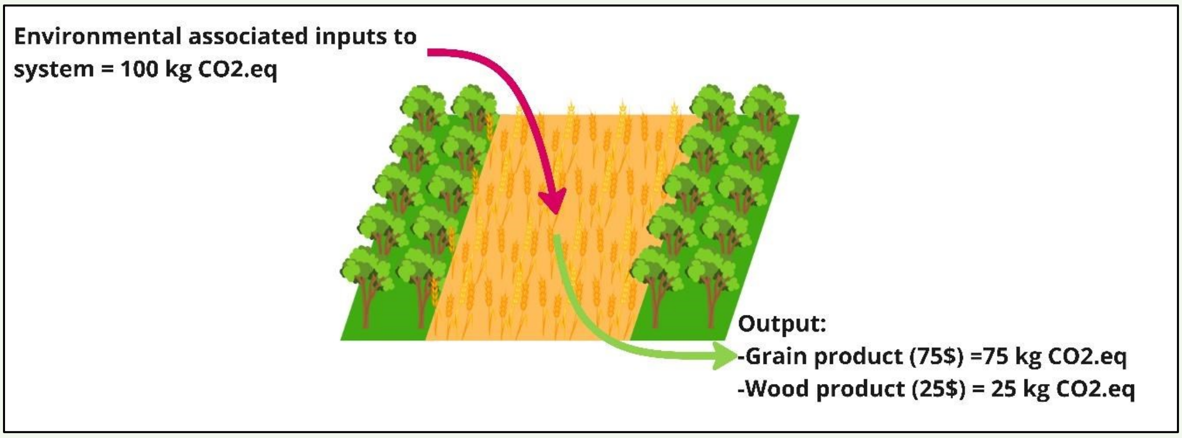


*Figure 13: Simplified example of an economic based allocation for a silvoarable system. Source: own*

Before deciding on which is the best method to apply for the case of this study, first, an overview of existing literature that deals with similar allocation problems has been explored and is summarized in the following paragraphs.

## Literature on allocation for multi-fuctional agricultural systems

Two methodological reviews that addressed the issue of allocation of environmental burdens in multi-functional agricultural systems were found: (Bessou et al., 2013; Goglio et al., 2018).

In (Goglio et al., 2018) first a clear distinction between the methodological choices depending on two different types of LCA study: system LCA and product LCA. The latter aims to assess the environmental burdens associated with a good produced in an agricultural system (Goglio et al., 2018), which matches the goal of this study.
For this type of LCA, (Goglio et al., 2018), address the difficulties of allocation procedures for silvoarable systems. Despite not providing specific guidelines for these systems, it provides general guidelines for multifunctional cropping systems, which for the system under study could be summarised as follows:

1. When possible, the environmental burdens of certain practices should be fully attributed to the corresponding crop associated with this practice.
2. If the previous is not possible, an allocation approach with generic attributing criteria should be applied.

This previous approach does not differ from the hierarchy of allocation processes defined previously.

Addressing the problem of the interactions between the sub-systems, which also relates to the identification and quantification of the ecosystem services of an alley cropping system, (Bessou et al., 2013) proposes an approach to be applied in simply structured alley cropping systems (sequential rows of trees and arable lands):

1. Performances and impacts should be quantified for each crop individually based on the performance of corresponding single-crop systems.

2. The inputs and outputs of these mono-crop systems will be multiplied by the inverse of the Land Equivalent Ratio (LER) see Chapter 5: Productivity of trees and crops in Silvoarable systems of the system.

This approach takes into account the interactions that can occur in silvoarable mixed systems. However, is based on a simplification that might underestimate certain benefits or tradeoffs of these systems. This approach implies the assumption that the impacts associated with the trees and crop production are of similar magnitude, as for a case in which a reduction in crop growth is overcompensated by a higher increase in tree production. This can be observed with a simplified example using information from one of the silvoarable plantation (Seserman et al., 2019). See Table 5.

*Table 5: Example table for allocation of multifunctional agricultural systems according to: (Bessou et al., 2013) Source: own.*

| | **Yield (Mg Dm/ha)** | **N fertilizer input (kg/ha)** | **Relative yield (tree-crop)*** | **LER**** |
|---|---|---|---|---|
| **Monocrop Tress** | 9.4 | - | - | |
| **Monocrop Wheat** | 7.6 | 162 | - | |
| **Silvoarable (tree-wheat)** | 14 -6.8 | 0-162 | 1.48-0.89 | 1 |

*Relative yield = Monocrop yield (tree-crop)/Silvoarable yield (tree-crop)

**LER = Silvoarable yield tree/Monocrop yield tree + Silvoarable yield crop/Monocrop yield crop

If the only environmental burdens associated with the production of wheat are associated with fertilizer use, it can be observed that producing wheat in the mono-crop system will imply a ratio of 162 kg N/ha /7.6 Mg DM/ha = 21,31 kg of N per Mg of DM, while for the case of the silvoarable plantation 162 kg N/ha /6.8 Mg DM/ha = 23,82 kg of N per Mg of DM. This implies that the inputs required to grow wheat are higher in the silvoarable system than in the mono-crop system, a result that will differ from the application of (Bessou et al., 2013) method in which the fertilizer application is assumed to be the same for both systems as the LER = 1.

From the studied literature, it can be concluded that the modelling of the silvoarable systems as producers of biomass is not yet fully addressed today in the literature, and therefore a need for methodological assumptions that better capture the environmental burden of these systems is required.

## Selected allocation process for the case study

From the above-mentioned approaches and following the presented hierarchy the decision will be to solve the multifunctionality by using the substitution approach. For that, the data of the monocrop control systems of (Veldkamp et al., 2023) will be used as the system to subtract from the model silvoarable plantation. Similarly to the arable field of the silvoarable system, the monocrop system is modelled by including the available emissions of (Veldkamp et al., 2023) and the rest of the inputs and emissions will be coming from the previously modelled process from Ecoinvent that is assumed to be the same for both the monocrop and the silvoarable systems.

To make the substitution approach the output of the grain of both the silvoarable and the monocrop systems needs to be the same, therefore the required hectares of the monocrop system will be adjusted accordingly, this is graphically presented in Figure 14.

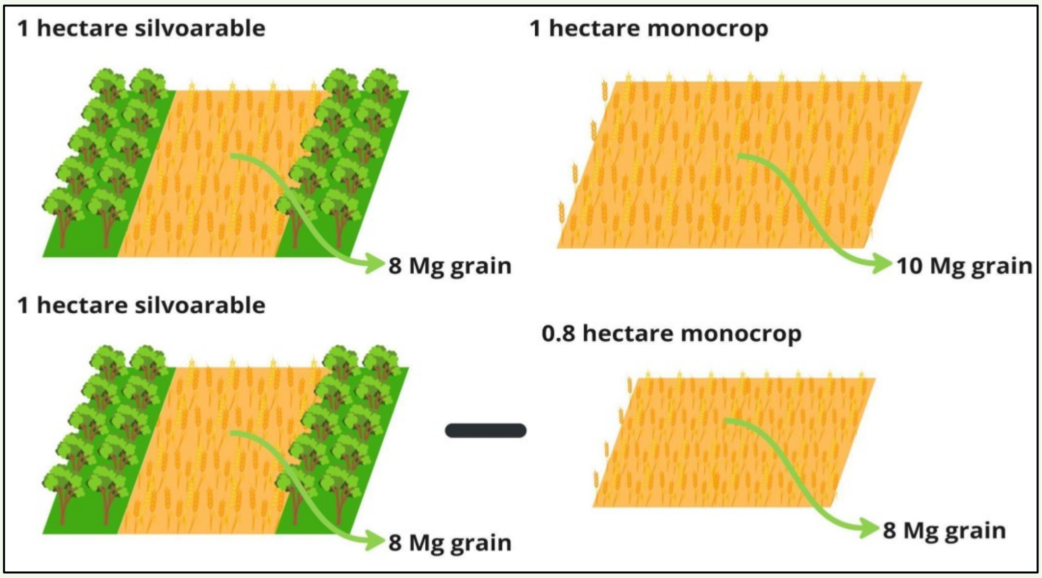


*Figure 14: Proportional adjustment of monocrop area for system substitution. Source:own*

For the allocation of the BTX co-production in the bio-methanol production process an economic based partitioning is applied. This allocation method is justified due as it is advised as baseline method for most allocation situations (de Bruijn et al., 2002) and the assumed difficulty that will imply the use of other allocation methods. Ideally, in LCA studies, the same allocation method should be consistently applied to all modelled processes. However, in this specific study, it is deemed important to explore the impact of different allocation methods on the modelling of agroforestry systems. Therefore, a sensitivity analysis will be conducted to isolate the influence of allocation processes solely on the silvoarable systems. This sensitivity will not modify the allocation method used in the remaining multifunctional processes, which will also influence the overall results.

## Results of inventory analysis

The inventory results for the four alternatives at the process and emission level are included in external Appendix2 LCA_results. Some relevant results extracted from the inventory results are:

- At the process level it can be observed that to produce 1 ton of bio-methanol 0,017 and 0,047 hectares of marginal and silvoarable plantations respectively will be needed.
- The Production of 1 ton of bio-methanol makes use of approximately 68 kWh while the natural gas-based methanol only uses 2,6 kWh
- Despite the higher associated field operations to the silvoarable systems the diesel burned in the agricultural machine is slightly lower than the marginal plantation due to the higher productivity of the silvoarable trees

## Impact assessment

The lifecycle impact assessment (LCIA) is the section of the LCA study in which the results of the inventory analysis are connected to certain environmental impacts with the use of impact assessment methods that in the defined characterisation step convert the inventory results in impact category results (de Bruijn et al., 2002).

The impact assessment method selected is the most recent version of the Environmental Footprint (EFv3.1 EN15804) methodology recommended by the European Commission and adapted to the EN 15804 standard (European Commission, 2023). This methodology includes a set of 18 impact categories see Table 6. To be able to give more level of detail to the results the number of categories to be evaluated is reduced. For that first the global warming aggregated impact category is selected discarding the rest three disaggregated ones (biogenic, fossil and land use climate change), water use is discarded due to the absence of collected data for the plantations under study and the assumed difficulty to express the environmental concerns of this category. For the remaining categories a normalization of the average results of the four alternatives for which normalization factors are available is performed according to the global normalization factors from (Crenna et al., 2019), built from data from emissions and resource use at a global scale for the year 2010. This procedure to discard impact categories was defined as valid, however expert validation of the results will be needed to identify any potential issue regarding the environmental evaluations of the systems under study.

*Table 6: Normalized inventory results for selected impact categories from the average results of the four considered alternatives*

| **Impact category** | **Global NFs (Crenna et al., 2019))** | **Normalized results** |
|---|---|---|
| EF v3.1 EN15804 \| acidification \| accumulated exceedance (AE) | 3,83E+11 | 8,54128E-12 |
| EF v3.1 EN15804 \| climate change \| global warming potential (GWP100) | 5,53E+13 | 1,0834E-11 |
| EF v3.1 EN15804 \| climate change: biogenic \| global warming potential (GWP100) | - | - |
| EF v3.1 EN15804 \| climate change: fossil \| global warming potential (GWP100) | - | - |
| EF v3.1 EN15804 \| climate change: land use and land use change \| global warming potential (GWP100) | - | - |
| EF v3.1 EN15804 \| ecotoxicity: freshwater \| comparative toxic unit for ecosystems (CTUe) | 2,94E+14 | 1,01289E-11 |
| EF v3.1 EN15804 \| energy resources: non-renewable \| abiotic depletion potential (ADP): fossil fuels | 4,48E+14 | 4,65282E-11 |
| EF v3.1 EN15804 \| eutrophication: freshwater \| fraction of nutrients reaching freshwater end compartment (P) | 1,11E+10 | 1,01326E-10 |
| EF v3.1 EN15804 \| eutrophication: marine \| fraction of nutrients reaching marine end compartment (N) | 1,35E+11 | 2,29995E-11 |
| EF v3.1 EN15804 \| eutrophication: terrestrial \| accumulated exceedance (AE) | 1,35E+11 | 7,83806E-11 |

| | | |
|---|---|---|
| EF v3.1 EN15804 \| human toxicity: carcinogenic \| comparative toxic unit for human (CTUh) | 1,28E+05 | 3,52402E-12 |
| EF v3.1 EN15804 \| human toxicity: non-carcinogenic \| comparative toxic unit for human (CTUh) | 1,59E+06 | 6,05069E-12 |
| EF v3.1 EN15804 \| ionising radiation: human health \| human exposure efficiency relative to u235 | 9,54E+11 | 1,87466E-10 |
| EF v3.1 EN15804 \| land use \| soil quality index | | - |
| EF v3.1 EN15804 \| material resources: metals/minerals \| abiotic depletion potential (ADP): elements (ultimate reserves) | 4,39E+08 | 6,1481E-12 |
| EF v3.1 EN15804 \| ozone depletion \| ozone depletion potential (ODP) | 3,33E+08 | 9,36795E-14 |
| EF v3.1 EN15804 \| particulate matter formation \| impact on human health | 1,24E+07 | 1,68782E-12 |
| EF v3.1 EN15804 \| photochemical oxidant formation: human health \| tropospheric ozone concentration increase | 2,80E+12 | 1,18307E-12 |

From these normalized results included in Table 6 the seven categories with the highest impacts will be included. Marine eutrophication won't be included as there are already two categories addressing the issue of eutrophication. Additionally, the category of the land use soil quality index is selected due to the relevance of the land use impact that has been addressed in this study (an explanation of this impact category is presented in Appendix 4). A total of 7 categories will therefore be studied. Table 7 includes the impact categories included in this study along with a simplified name of the category for readability purposes and a brief description of the category.

*Table 7: Selected impact categories for the study*

| Full name impact category | Simplified name category | Category description |
|---|---|---|
| EF v3.1 EN15804 \| acidification \| accumulated exceedance (AE) | acidification | Measures the potential release of acidic substances and cumulative impact on ecosystems |
| EF v3.1 EN15804 \| climate change \| global warming potential (GWP100) | climate change | Assesses contribution to long-term climate change in terms of greenhouse gas emissions. |
| EF v3.1 EN15804 \| ecotoxicity: freshwater \| comparative toxic unit for ecosystems (CTUe) | ecotoxicity: freshwater | Evaluates potential harm to aquatic ecosystems based on relative toxicity. |
| EF v3.1 EN15804 \| energy resources: non-renewable \| abiotic depletion potential (ADP): fossil fuels | abiotic depletion fossil fuels | Quantifies impact of depleting non-renewable energy resources, specifically fossil fuels. |
| EF v3.1 EN15804 \| eutrophication: freshwater \| fraction of nutrients reaching | eutrophication: freshwater | Measures excessive nutrient enrichment in freshwater ecosystems |

|  |  |  |
|---|---|---|
| freshwater end compartment (P) |  |  |
| EF v3.1 EN15804 \| eutrophication: terrestrial \| accumulated exceedance (AE) | eutrophication: terrestrial | Assesses excessive nutrient enrichment and cumulative impact on terrestrial ecosystems |
| EF v3.1 EN15804 \| land use \| soil quality index | Land use quality | Measures impact on land resources and soil quality potential degradation |

# Classification

The classification of the inventory results is provided by the selected impact assessment methodologies that as mentioned previously classify and characterize each of the inventory results accordingly to the different characterization methods recommended.

## Characterization results and discussion

Table 7 presents the characterization results for the 7 selected impact categories for the four alternatives under study:

- A1 : Bio-methanol from marginal poplar plantation
- A2: Bio-methanol from silvoarable plantation
- A3: Bio-methanol from forest residues
- A4: Methanol from natural gas

Additionally, the characterized results for the rest of the 18 impact categories of the PEF v3.1 methodology are included in external Appendix2 LCA_results.

*Table 8: Characterization results for selected impact categories for the 4 considered alternatives for the production of 1 ton of methanol from*

| **Impact category** | **A1-Marginal** | **A2-Silvoarable** | **A3-Forest residues** | **A4-Natural gas** | **Unit** |
|---|---|---|---|---|---|
| acidification | 4,85 | 4,43 | 2,83 | 0,98 | mol H+ eq |
| climate change | -615,46 | -816,89 | -995,55 | 599,12 | kg CO2 eq |
| ecotoxicity: freshwater | 3092,61 | 4423,17 | 3147,98 | 1247,78 | CTUe |
| abiotic depletion: fossil fuels | 17468,34 | 18909,77 | 17250,21 | 29750,24 | MJ |
| eutrophication: freshwater | 1,57 | 1,41 | 1,43 | 0,09 | kg P eq |
| eutrophication: terrestrial | 16,62 | 14,52 | 7,80 | 3,39 | mol N eq |
| land use soil quality index | -33661 | 106266 | 245179 | 554 | Dimensionless |

The analysis of the results indicates that the alternatives based on bio-methanol performed better only in the categories of climate change, abiotic depletion: fossil fuels and land use (only for the A1) when compared to the methanol from natural gas.
Regarding the comparison between the bio-methanol alternatives, the bio-methanol from wood residues (A3) performed similar or better in all the categories except for land use.
For the comparison between the two alternatives of poplar wood plantations, the silvoarable plantation (A2) performed better in four (acidification, global warming, terrestrial and freshwater eutrophication) out of the seven considered categories.

To see the relative differences between the alternatives the results for the selected impact categories for the 4 alternatives is normalized to the maximum value between the alternatives Figure 15. The global warming and land use impact categories are discussed later due to the particularity of their results.

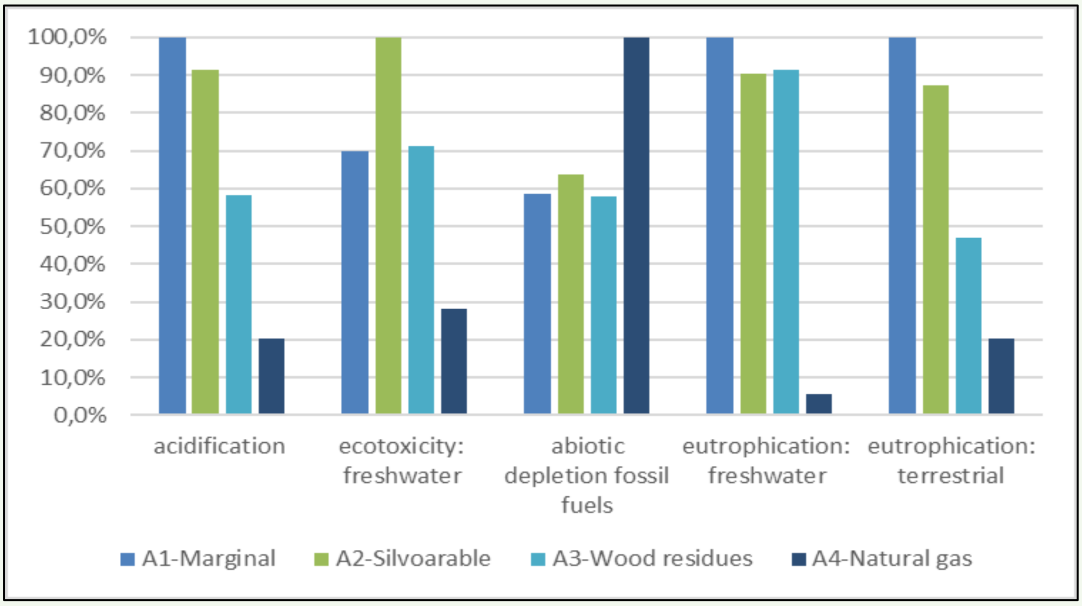


*Figure 15: Selected impact categories results normalized to the highest value of the 4 considered alternatives (excluding climate change and land use) for the production of 1 ton of methanol*

In Figure 15 it can be observed that when comparing the bio-methanol with the conventional methanol, the differences were considerable for the four categories in which the biobased alternatives performed worse, when compared to the maximum value the impact from the natural gas ranged from a minimum of 5,5% (freshwater eutrophication) to a maximum of 28,2% (ecotoxicity freshwater). Furthermore, for the only category with worse performance (fossil fuel abiotic depletion), the impact was less than double when compared to the bio-methanol alternatives.

The three bio-methanol alternatives performed similarly between them in the categories of freshwater eutrophication and fossil fuel depletion potential. The wood residues alternative (A3) supposes a considerable advantage regarding the terrestrial eutrophication and acidification when compared to the poplar wood chips alternatives with reductions of 42% and 60% respectively when compared to the maximum values of these categories addressed to the marginal poplar plantation (A1).

Regarding the comparison between the two poplar alternatives(A1, A2), not significant differences between their results were observed (5% to 12%), the exception will be the freshwater ecotoxicity for which the marginal plantation (A1) had a 30% less impact compared to the silvoarable one (A2).

For the category of climate change a big difference can be observed between all the considered alternatives. All three bio-methanol alternatives accounted for negative values; these "negative emissions" are due to the consideration of the carbon absorbed by the biomass that is assumed to be "stored" in the final product of bio-methanol. A full cradle-to-cradle (including the EoL emissions of the product) assessment will imply that these emissions will be released during the subsequent steps of the lifecycle of the product balancing these negative emissions and obtaining a positive result. Furthermore, the use of allocation can also cause a negative balance due to the subtraction of an impact that is higher than the considered one.

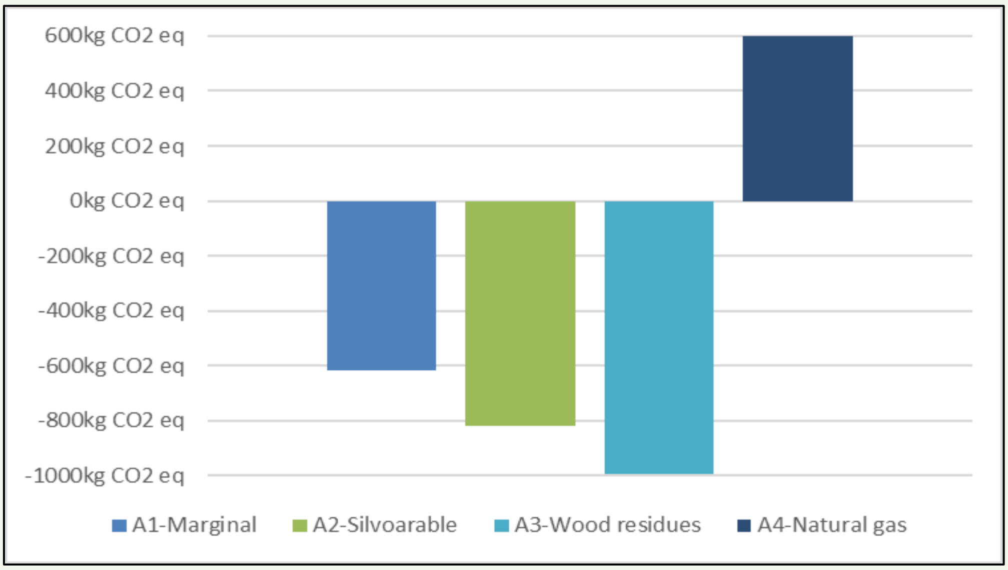


*Figure 16: Climate change impact category results in kg CO2.eq for all studied categories*

As observed in Figure 16, the negative values of the category ranged from -995,5 kg CO2.eq for the bio-methanol from wood residues (A3), to -615,46 kg CO2.eq for the marginal poplar alternative (A1), for the silvoarable alternative (A2) the result lies in between with a value of -816,89 kg CO2.eq per ton of bio-methanol. This implies that A2 and A3 performed 1.3 and 1.6 times better than A1.

Finally, for the land use category measured as the soil quality index see Table 8, A1 presents a negative value, which implies that the production of bio-methanol from poplar wood chips from marginal land is assumed to increase the quality of the soil. A3 presents the highest score (245179) 2.3 times higher than A2 (106266) and 442 times higher than the natural gas-based alternative (554). The results of this impact category could be somehow misleading as these are based on pre-defined land uses that are not fully representative of reality see Appendix 4. The sourcing of wood residues from the forest is assumed to have a detrimental impact on the soil quality index, this however will be the case only if the wood residues are extracted at high rates (Lal, 2009). Nevertheless, it can be assumed that the use of marginal land for growing wood feedstock (A1) is regarding the parameters considered for the soil quality index the best alternative from the studied ones as it is able to restore a marginal into productive land, to a less extend this should be also the case for the silvoarable plantation, but in this case, the assumed land use flows are not able to capture this reality. Due to the previous uncertainty regarding the reliability of this impact category results for this impact category won't be considered in the further analysis of this study.

# Interpretation

## Consistency check

The consistency check determines if the given assumptions are consistent with the goal and scope of the study. In this case, the consistency check will be applied by comparing the obtained results with the results from the LCA of bio-methanol production from wood chips (Galusnyak et al., 2023), this is the study used for the modelling of the bio-methanol production of this study. For the simplicity of this check, the results from the category of GWP potential of the ReciPe methodology used in (Galusnyak et al., 2023) are evaluated, the results for the forest wood chips of this study (A3) and the case study of (Galusnyak et al., 2023) are presented in Table 9.

*Table 9: Results for the GWP impact category (kg CO2. Eq ReciPe) per ton of bio-methnanol excluding captured carbon in biomass for the modelled forest residue alternative and the results Galusnyak case study*

| | **Alternative 3- forest residues** | **Results from (Galusnyak et al., 2023)** |
|---|---|---|
| **Total** | 2821 | 1436 |
| **Electricity** | 969.4 | 57.4 |
| **MILENA, methanol production** | 732 | 718 |
| **SER, methanol production** | 661 | 544 |
| **Wood chips drying** | 234 | Not included |

The results show a considerable difference between the two modelled systems, the difference in the electricity impact is attributed to the fact that in (Galusnyak et al., 2023) the methanol production makes use of the Sweeden electricity mix which is mainly dominated by renewable electricity, contrary to the German electricity mix used in this study. The smaller differences in the emissions coming from the MILENA, and SER production process steps can be a consequence of the allocation process used in the model of this study for the BTX production which can slightly differ from the one used in (Galusnyak et al., 2023). Finally, the emissions coming from the drying of the wood chips were not included in (Galusnyak et al., 2023).

If the impact of the electricity is changed to the Sweeden mix and the drying emissions are not accounted the final GWP result for the modelled alternative will be 1675 kg CO2.eq which is 16% higher than the value of (Galusnyak et al., 2023), and could be assumed as consistent assuming the rest of the differences could come from the wood chips supply chain modelling decisions and the allocation process of the BTX co-product.

Furthermore, (Galusnyak et al., 2023) despite not considering the absorbed carbon emissions in the biomass in the LCA results, addressed that if included the GWP value per ton of bio-methanol will be -1658 kg CO2.eq which compared to the obtained value of -995,5 kg CO2.eq for A3 and considering the higher impact from the electricity mix will derive similar results.

Also as presented in the unit process description section, for the case of the forest residue alternative (A3) no emissions from N2O were include contrary to the marginal (A1) and silvoarable (A2) alternatives. To check the influence of this parameter in the results contribution analysis from the emission flow of N2O to the climate change impact category is performed, the results showed that the contribution of this gas to the climate change impact category (excluding the carbon captured in the biomass) is of 6,8% for A1, 4,7% for A2 see external Appendix2-LCA_results. These results entail that the inclusion of the N2O emissions have non-negligible influence on the results.
Similarly the inconsistency of including the emissions due to the removal of the plantation without considering the emissions captured is studied a contribution of this process to the climate change impact category, which provided results of 3,5% and 1,4% for A1 and A2 respectively. Therefore, despite the assumption can be made that these inconsistencies have no great influence in the results, the correction of these inconsistencies will be required to correctly evaluate the environmental impact of these systems.

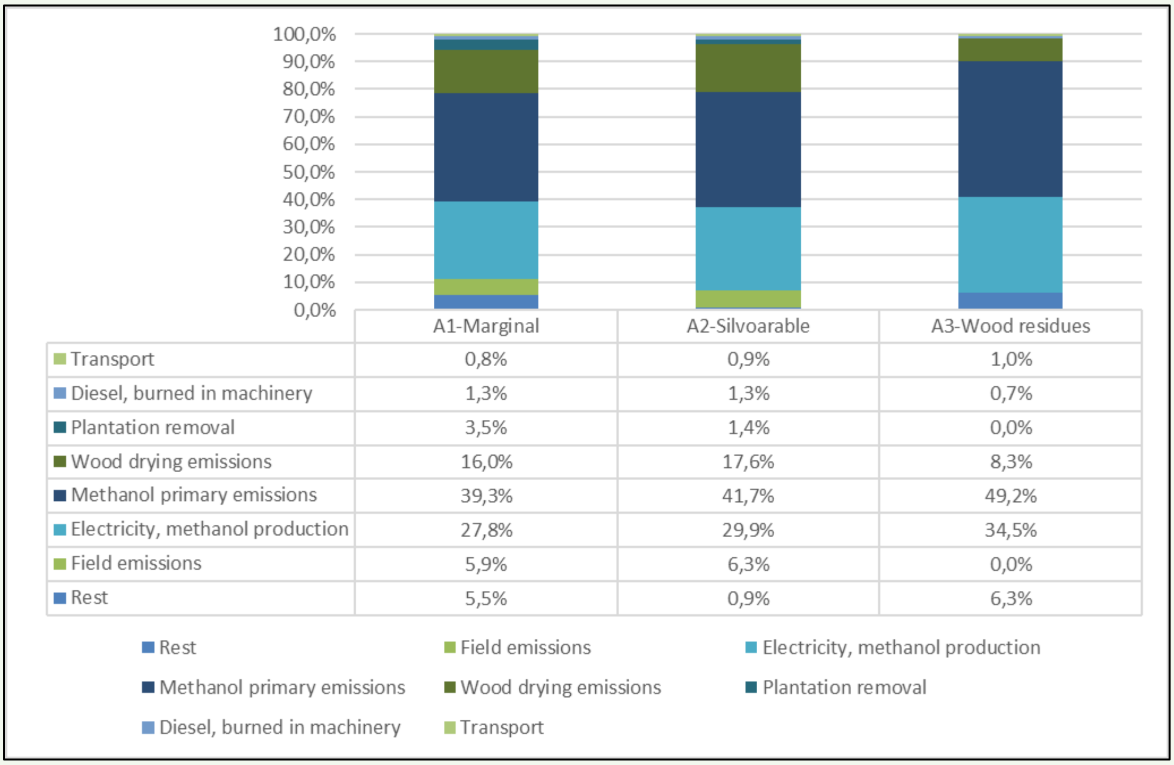
## Completeness check

The completeness is assumed to be satisfied as the level of detail and coverage of processes for the considered 4 alternatives is highly comparable, nevertheless, more detailed inventory data was included in the first two alternatives due to the use of real data measurements that included for example field emissions which were not considered in A3. These are however assumed to be less relevant for the wood chip residues alternative due to the absence of fertilization in the forest fields and way longer time for the removal of the plantation if removed. The completeness regarding the methanol production process is also assumed to be justified as both the bio-methanol and natural gas methanol include similar system boundaries.
Regarding the differences between environmental extensions not captured by characterization factors, no difference was found between the alternatives.

## Contribution analysis

Several contribution analyses are performed at different levels to provide a better understanding of the environmental impact of the different alternatives.

The first contribution is performed for the climate change impact category for the bio-methanol alternatives at the level of process contribution. Results are presented in Figure 17. For the bio-methanol alternatives the process with the main contribution to this category is the captured carbon in the biomass, for a better analysis of the rest of the lifecycle processes, the captured carbon is not included in the analysis.

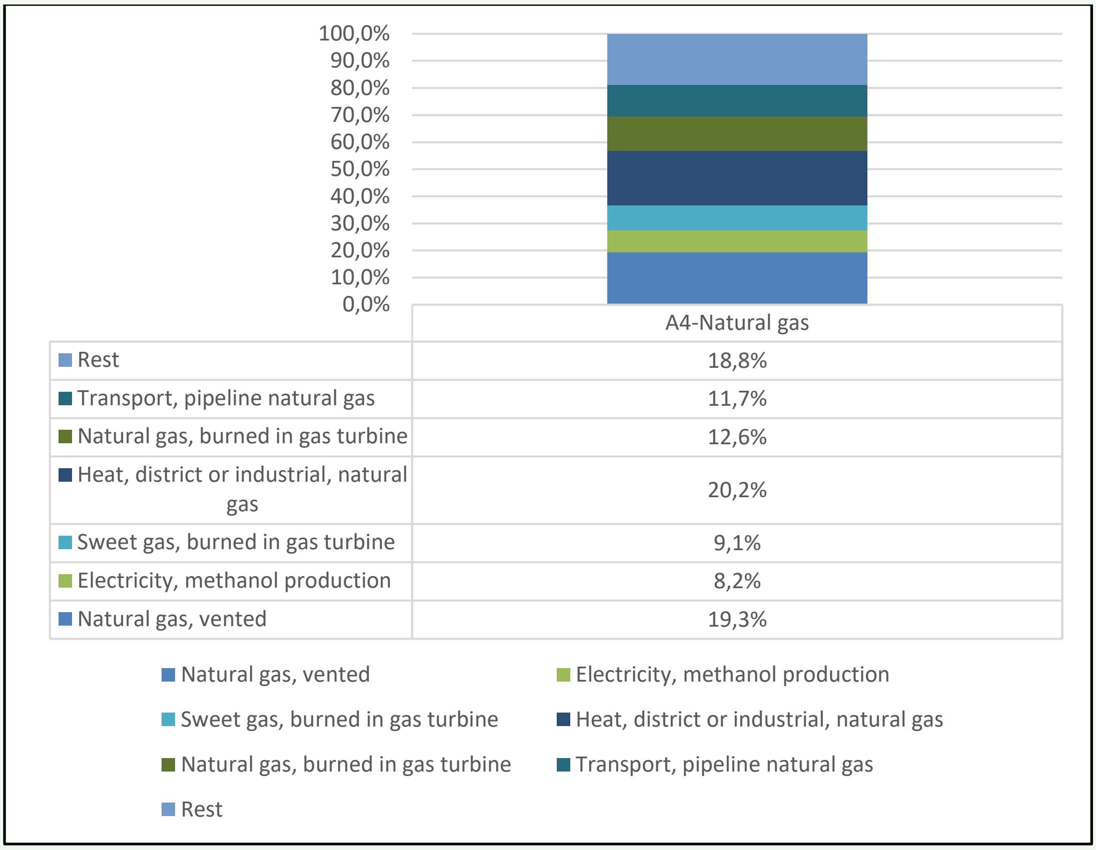


| | A1-Marginal | A2-Silvoarable | A3-Wood residues |
|---|---|---|---|
| ■ Transport | 0,8% | 0,9% | 1,0% |
| ■ Diesel, burned in machinery | 1,3% | 1,3% | 0,7% |
| ■ Plantation removal | 3,5% | 1,4% | 0,0% |
| ■ Wood drying emissions | 16,0% | 17,6% | 8,3% |
| ■ Methanol primary emissions | 39,3% | 41,7% | 49,2% |
| ■ Electricity, methanol production | 27,8% | 29,9% | 34,5% |
| ■ Field emissions | 5,9% | 6,3% | 0,0% |
| ■ Rest | 5,5% | 0,9% | 6,3% |

*Figure 17: Process level contribution analysis results to the climate change impact category (excluding biomass captured carbon) for the three bio-methanol alternatives*

The main contribution to this impact category occurs in the methanol production process, both from the primary emissions in the methanol conversion process (39% to 49%) and the electricity consumption in the biorefinery (28% to 35%). Regarding the emissions of the biomass supply chain, for all three alternatives, the main contributor to this category are the emissions occurring in the natural drying of the wood chips due to biomass degradation. The other two main contributors of the biomass supply chain emissions for alternatives 1 and 2 are the field emissions and the plantation removal. The transportation phase for all three alternatives only accounts for around 1% of the impact also due to the assumed local sourcing of the feedstocks (50 km transport).

Regarding the contribution of the natural gas-based methanol alternative to the climate change impact category as seen in Figure 18, the impact of electricity consumption only accounts for 8% of the total impact. The main rest of the emissions apart from the heat generation in the burning of the natural gas will come from the downstream operations for the obtention of the natural gas.



| | A4-Natural gas |
|---|---|
| Rest | 18,8% |
| Transport, pipeline natural gas | 11,7% |
| Natural gas, burned in gas turbine | 12,6% |
| Heat, district or industrial, natural gas | 20,2% |
| Sweet gas, burned in gas turbine | 9,1% |
| Electricity, methanol production | 8,2% |
| Natural gas, vented | 19,3% |

*Figure 18: Process level contribution analysis results to the climate change impact category for the natural gas based alternative*

For the categories of acidification and eutrophication both freshwater and terrestrial, a contribution analysis at a process level is performed for the marginal plantation alternative (A1) which had the worst performance in these impact categories.

For these three categories the impacts come from two main lifecycle processes as it can be observed in Figure 19 . The high contribution of electricity is mainly due to the impact associated with the electricity production from lignite which accounts for 15.7% and 74.5% of the total impact of the acidification and freshwater eutrophication respectively. The fertilization associated emissions of the marginal plantation had great influence in the categories of terrestrial eutrophication (46%) and acidification (36%) and less relevant to the category of freshwater eutrophication (11%).

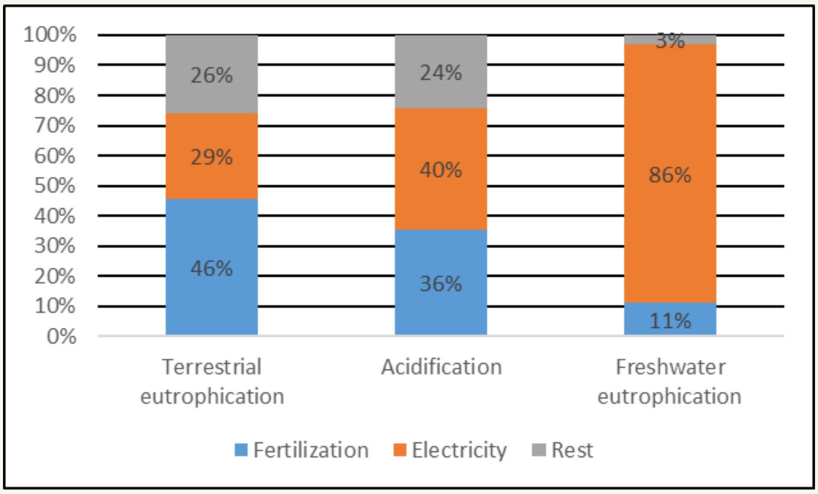


*Figure 19: process level contribution analysis for the impact categories of terrestrial and freshwater eutrophication and acidification for the marginal poplar plantation alternative (A1)*

A2 and A3 as seen previously in Figure 15 have slightly lower impact of the freshwater eutrophication than A1 and this is attributed to the absence of fertilization.

For acidification and terrestrial eutrophication, the absence of fertilization reduces the impact on these categories for the other bio-methanol alternatives (A2 and A3), however, for the case of the silvoarable plantation (A2) the associated impacts from wheat grain production compensate for part of this reduction.

For the category of freshwater ecotoxicity the higher impact is the one of the silvoarable alternative (A2), this can also be associated to the impacts of the wheat grain associated emissions (32%), the rest of the impact of this category comes from several sources including the transportation (7,12%), diesel burned in machinery (7,77%), the extraction of the olivine for the methanol production process (10,9%) or the electricity consumption (24.7%). This analysis is included in external Appendix2-LCA_results.

## Sensitivity analysis

For the sensitivity analysis five different types of analysis are performed based on the previous contribution analysis and other considerations that are perceived as relevant in the context of this study.

### Change in allocation method for the silvoarable plantation

As previously presented the method use for dealing with the multifunctionality of the silvoarable product system (A2) is the application of the substitution method. In this section, it is evaluated how the use of economic partitioning will influence the overall impact category results of the product system. Economic allocation was selected as the partitioning method for the sensitivity analysis with the assumption that the function of the grain and wood product of the system is not easily comparable in a physical metric (energy or mass), furthermore, economic value is many times the main reason behind growing a certain product in agricultural lands. The assigned economic values and partitioning of the flows are included in external Appendix 1-LCA_modelling.

Figure 20 presents the comparison between the results of the substitution and economic allocation normalized to the highest value for each impact category.

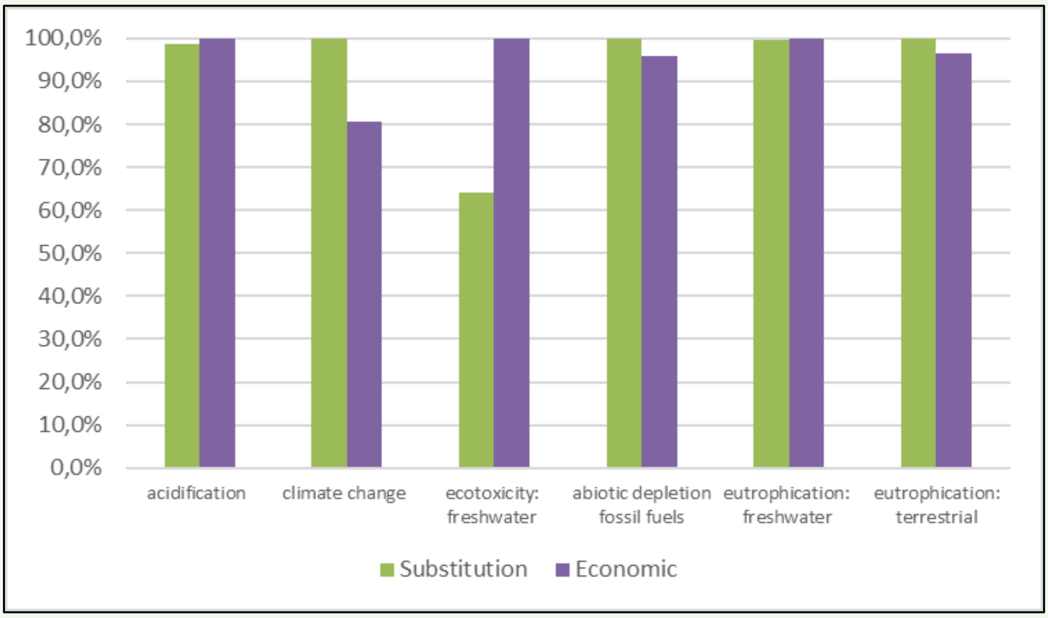


*Figure 20: Allocation sensitivity analysis results normalized to the highest value for the substitution and economic methods for the silvoarable alternative (A3)*

The differences between the results are not relevant for 4 out of the 6 categories, this is mainly because these categories are more influenced by other stages of the supply chain rather than the agricultural souring processes. The two categories mainly influenced by agricultural processes presented though significant and contradictory differences of around 20% (climate change) and 40% (ecotoxicity). The economic allocation reduces the impact of the climate change category, this is mainly due to the lower attribution to the wood chips of the N2O emissions that occur in the field, which for the substitution approach were fully attributed to the wood chips. The N2O emissions were considerably higher in the silvoarable plot when compared to the monocrop field used for the substitution, therefore this difference is fully attributed to the sourced wood in the substitution approach, and for the economic allocation these impact will be more distributed between wood and grain co-product.

The higher Ecotoxicity value in the economic allocation is due to a higher attribution of the wheat grain emissions to the wood chips, that were almost neglected in the substitution approach as the yields between the silvoarable and the monocrop systems were very similar and therefore the subtraction resulted in a low amount of grain production impact attributed to the wood chips.

It can be concluded that the allocation approaches did not imply significant differences in the results, the possibility of including the economic allocation in particular for systems in which data from control monocrops plots are not available, can therefore be defined also as a valid approach to solve the multifunctionality issue of silvoarable systems.

### Influence of silvoarable crop yields in results

The modelled silvoarable plantation is based on the average results of the three studied plantations in (Veldkamp et al., 2023), for this average plantation the yield of the crops per hectare basis of the silvoarable plantation and the control monocrop field are almost the same (RCY=0,99 see External Appendix 1-LCA_modelling) and as previously explained, with the substitution approach this implies that the influence on the grain production in the overall impact of the wood chips is almost negligible. However, when studied separately this is not the case anymore. The three plantations accounted for significant differences regarding their relative crop yield values: Forst (RCY=1,36), Wendhausen (RCY=0,75) and Dornburg (RCY=0,88). To analyze the influence on the value of the RCY on the LCA results, the best (A2-Forst) and worst (A2-Wendhausen) performing plantations are modelled and compared to the average silvoarable plantation (A2-average) and the forest residues wood chips (A3).

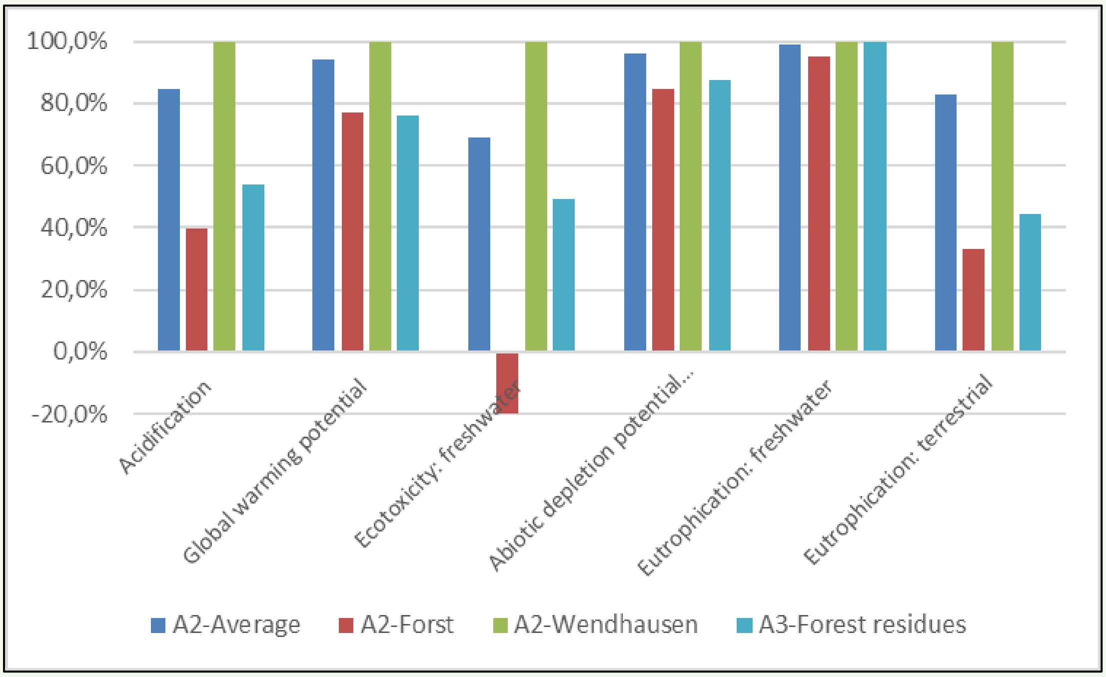


*Figure 21: Influence of relative crop yield sensitivity analysis results normalized to the highest value for the average silvoarable (A2), the best (A2-Forst), and worst (A2-Wendahsuen) plantations and the forest residue alternative (A3)*

In Figure 21 it can be observed that for the worst-performing silvoarable plantation (A2-Wendahausen) the impacts for 3 of the categories (GWP, ADP and freshwater eutrophication) did not imply a high increase when compared to the average (A2-Average), as previously explained these categories are more influenced by later stages of the supply chain. The biggest increase occurred in the ecotoxicity category (around 35%) a category more influenced by the wheat grain associated environmental impacts.

For the best performing silvoarable case (A2-Forst) the reduction of impacts when compared to the average scenarios is as significant to the point of performing as good and better than the forest residues alternative (A3) in all the presented impact categories. The subtraction of the wheat crop impacts reduces considerably the environmental impact from the wood chips due to the highest co-production of grain per arable hectare basis when compared to monocrop systems.

It can be concluded therefore that the grain yields of the silvoarable plantations is of high importance when evaluating the environmental impact of the bio-methanol obtained from these systems. Nonetheless, it should also be taken in consideration that the modelled environmental impacts on the grain production of these systems was based on secondary data that is also based on average inputs and outputs from geographical averages and this is not able to reflect the full reality of the arable plantations.

## Change in the electricity generation source

The previously presented contribution analysis has showcased that the electricity consumed in the bio-methanol production process is a great contributor to most of the impact categories. The impact associated with electricity (particularly from the influence of the use of brown coal for the German electricity generation mix) reduces part of the benefits of bio-methanol production, electricity consumption in the bio-methanol production is around 20 times higher than in the natural gas methanol production, this implies that a reduction of the electricity environmental impact will certainly increase in the environmental benefits of the bio-methanol alternatives. To prove this hypothesis and evaluate the influence of the use of renewable electricity in the overall environmental performance of the bio-methanol production process, the production of bio-methanol from silvoarable systems using wind-generated electricity (A2-wind) is modelled as an alternative product system.

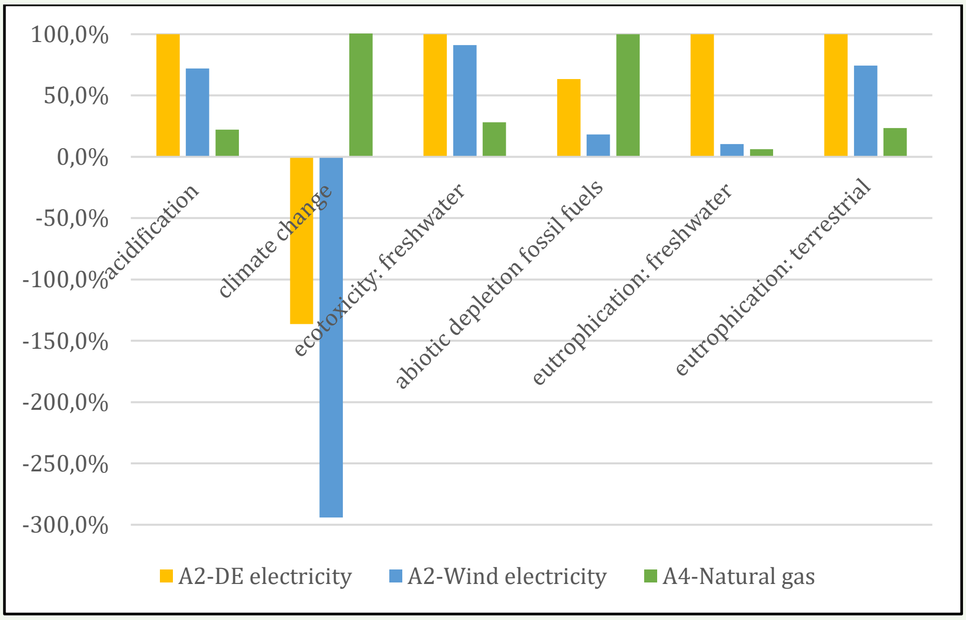


*Figure 22: Renewable electricity sensitivity analysis results normalized to the highest impact for the silvoarable alternative with German electricity mix (A2-DE) and wind electricity (A2-Wind) and the natural gas alternative (A4)*

As can be observed in Figure 22, the use of wind-based electricity to produce bio-methanol provides significant benefits in all the studied impact categories. The climate change category is improved around 2 times until a value of -1762 kg $CO_2$.eq which implies that the methanol product could be defined as carbon negative as the maximum emissions from burning the bio-methanol product will be of 1373 kg $CO_2$.eq. This negativity is achieved due to the fact that the existing allocation processes are able to reduce the associated the carbon emissions of the final product.

For the categories of acidification and terrestrial eutrophication considerable reductions are achieved (around 30% reduction), but still the performance of the bio-methanol from renewables performs around three times worse than the natural gas alternative. As previously mentioned, these categories and ecotoxicity (which presented almost no benefit from the renewable use) are mainly influenced by the biomass feedstock supply chain.

Freshwater eutrophication is reduced by around 90% to a level comparable to the natural gas alternative and fossil fuel depletion is further reduced to a third of the A2 using the German electricity mix.

The increase in renewable electricity, will however cause a trade-off regarding material use and mineral depletion, despite not being included in this analysis, the category of material resource depletion was analysed separately from which an increase of 2,57 times of the impact category result from the original use of electricity compared to the renewable scenario for the silvoarable alternative (A2) was obtained (See External Appendix 1-LCA_results). Highlighting the importance of further evaluate the relevance of the results of this impact category for future scenarios with higher renewable penetration.

Overall, it can be concluded that the use of renewable electricity (as wind) has a significant influence on the results to the point where bio-methanol production is able to compensate for some of the environmental impacts that had the highest globally normalized impact results (ecotoxicity, abiotic depletion and freshwater eutrophication). This suggests that the use of bio-methanol from silvoarable plantations with renewable electricity is overall a environmentally better alternative than the use of natural gas methanol.

### Import wood residues

As previously presented the overall performance of the bio-methanol from forest residues wood chips (A3) was better than the ones coming from both poplar wood chips alternative (A1, A2). Nevertheless, as presented in Chapter 4 the availability of this feedstock at a European level is predicted to be low to meet the increase in its demand. In this situation, a possible import of this feedstock could occur to compensate this lack of supply. The main implications of this regarding the overall impact of the feedstock will be the increase in transportation distances due to the associated transport emissions. To evaluate how these changes could affect the overall environmental performance of the product system, different scenarios of transport were modelled to represent possible import routes for the forest residues wood chips. The selection of the countries from which the wood chips are assumed to be imported are based on average data of the countries with the highest exports of wood both from Europe (Sweden) and outside Europe (Canada), the distances are calculated with an average freight distance transportation tool. These scenarios are graphically presented in Figure 23.

*Figure 23: Modelled scenarios for import of forest wood chips. Source: own.*

The obtained results are presented in Figure 24 as the normalized values to the highest impact for the modelled alternatives, (freshwater eutrophication is not included as is not influenced by the transport emissions), the results indicate that for both Sweden and Canada import scenarios, the overall better performance of the local forest residues wood chips (A3-Germany) over the silvoarable alternative (A2) are lost. Regarding climate change the bio-methanol from wood chips from the German silvoarable systems (A2) will have 3 times and 2 times better than the bio-methanol from wood residues imported from Sweden and Canada respectively. Also, despite higher transport distance from Canada the use of sea freight transport has a lower contribution to the climate change, freshwater ecotoxicity and fossil fuel depletion, but a higher contribution to acidification and terrestrial eutrophication impact categories.

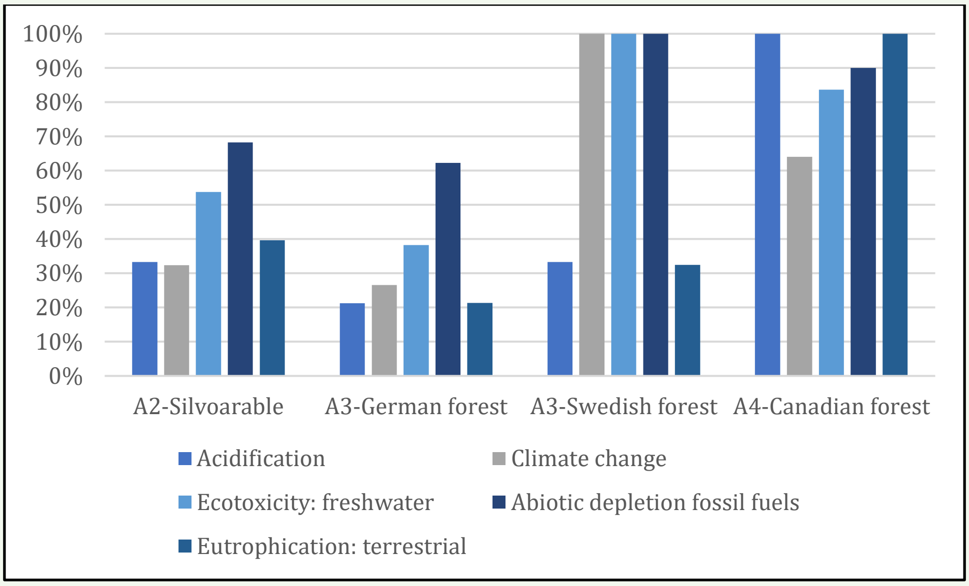


*Figure 24: Import forest residues sensitivity analysis results normalized to the highest impact for the silvoarable alternative (A2) and the forest residues sourced in Germany (A3-German), Sweden (A3-Swedish) and Canada (A3-Canadian)*

Therefore, it can be concluded that all the environmental benefits associated with the bio-methanol from forestry residues systems could be lost if the wood residues need to be imported from foreign countries. The possibility of importing the final product instead of the biomass feedstock could also be a better alternative than the import of the feedstock but this will also be dependent on the transportation distances of the final product or the impact of the electricity mix used in the respective among other factors. This highlight the overall importance of the local supply chain of the feedstocks for bio-methanol production regarding their environmental impact and how the transportation should be clearly defined if the conclusions need to be drawn regarding which is the most relevant feedstock to consider for bio-methanol production.

### A best-case scenario for silvoarable plantations

To see how a best-case scenario for silvoarable plantations will perform against the natural gas alternative the use of renewable electricity for the case of the best performing plantation (Forst) is modelled and compared to the natural gas methanol alternative. Results are presented in Table 10.

*Table 10: Best case scenario sensitivity results for selected impact categories for the production of 1 ton of methanol from the best case silvoarable alternative and the natural gas methanol alternative (A4-Natural gas)*

| **Category** | **Silvoarable (best case)** | **A4-Natural gas** | **% Difference** |
|---|---|---|---|
| acidification | 0,84 | 0,98 | -14% |
| climate change | -1931,65 | 599,12 | -422% |
| ecotoxicity: freshwater | -1656,81 | 1247,78 | -233% |
| abiotic depletion fossil fuels | 3155,86 | 29750,24 | -89% |
| eutrophication: freshwater | 0,09 | 0,09 | 9% |
| eutrophication: terrestrial | 2,05 | 3,39 | -40% |

The results reflect that for this best case the performance of the silvoarable plantation is better than the natural gas alternative in almost all the categories particularly for climate change, ecotoxicity and fossil fuel depletion. And for the only category that the performance is worse (freshwater eutrophication) the difference is not as relevant. These results present of course the best of the scenarios regarding the use of wood chips from silvoarable plantations, but also serve as way to evaluate their great environmental reduction potential for longer term future scenarios, in which the degree of renewable electricity is increased and the use of productive plantations is considered.

***This chapter presented the results of the LCA study of different alternatives for methanol production for the production of composites. These results have shown that despite bio-methanol alternatives have a much better performance regarding the category of climate change and fossil fuel depletion, for the rest of the studied impact categories the bio-methanol did not provided an advantage over the natural gas alternative. One of the main reasons behind a lower performance in some of these categories is the 30 times higher electricity consumption in the bio-methanol production which is based on the use of a German electricity mix in which lignite power generation is considerably present. Despite a change to renewables could reverse these impacts, trade-offs in mineral resource depletion should be further evaluated. When comparing the different bio-methanol production routes the use of forest residues performed better than the silvoarable and the marginal plantations except for the land use category, an impact category for which the results might not be able to capture the full reality of this environmental impact. Silvoarable plantations can be considered a better***

***environmental alternative than marginal plantation, however this is highly dependent on the crop yields they are able to obtain, this factor is relevant to the point that for the most favourable silvoarable plantation, the results are better than the ones from the wood chip residues. Furthermore, when forest residues need to be imported, their environmental advantages are lost over the silvoarable plantations.***

***The limitations of the LCA study are not able to capture some of the additional environmental benefits that are brought by silvoarable systems including biodiversity increase, increase on soil health or build of soil organic carbon among others, nevertheless, the sensitivity results of the LCA showed that for plantations with favourable crop yields, and if renewable electricity sources are employed the bio-methanol production from silvoarable systems is overall a good potential feedstock to substitute fossil fuels for methanol production and consequently for CFRPs manufacturing.***

# 7. Aviation industry implications for the use of silvoarable systems for composite manufacturing

This chapter aims to answer the last research question of the study: *What broader implications can be derived from the estimated CO2 savings and costs associated with the utilization of wood chips sourced from silvoarable plantations as feedstock for methanol in the context of composite manufacturing in the aviation industry?*

This RQ will be based on the comparison with the natural gas-based methanol as the alternative to compare with.

For providing the estimation of the achievable CO2 emissions, first, the estimated amount of methanol required for the manufacturing of carbon fibre-reinforced composites is calculated from available literature sources. This calculation is presented in Table 11.

*Table 11: Calculation of required methanol product for CFRP manufacturing.*

| **Process** | **Input** | **Output** | **Source** |
|---|---|---|---|
| Methanol to propylene | 3,45 ton Methanol | 1 ton of propylene | Airbus (state-of-the-art Lurgi-MTPTM) |
| Propylene to ACN | 0,883 ton propylene | 1 ton ACN | Ecoinvent ("Sohio propylene ammoxidation.") |
| ACN to PAN fibres | 2,25 ton ACN | 2,36 ton of PAN fibre | (Das, 2011) |
| PAN fibres in CFRP | 1,82 ton PAN fibre | 1 ton CFRP | (Khalil, 2017) |
| **Final balance** | **5,29 ton Methanol** | **1 ton CFRP** | |

According to the previously presented LCA results on the climate change impact category, 1 ton bio-methanol from silvoarable plantation (A2) accounted for a negative impact of -816,9 kg CO2.eq, for the case of the natural gas (A4) the impact is of 599,1 kg CO2.eq per ton of methanol. Therefore, the savings per ton of methanol will be of 1416 kg CO2.eq per ton of methanol and of 7490 kg CO2.eq per ton of CFRP, assuming that the emissions for the methanol conversion to the CFRP are the same for both conventional and bio-methanol, these numbers could raise up to 2530 kg CO2.eq savings per ton of methanol for the previously defined best-case scenario.

To put this number in perspective the Airbus model A350 XWB, weights around 140 tons and approximately 53% of that weight is coming from the carbon fibre composites of its structure(Airbus, 2021). This implies that the inclusions of CFRPs from silvoarable wood bio-methanol (assuming 1416 kg CO2.eq saved per ton of methanol) could save up to 555,76 tons of CO2.eq per plane when compared with the natural gas methanol CFRP. This saving could be doubled with the use of renewable energy use in electricity generation as presented in the sensitivity analysis.

According to industry data the number of planes that are predicted to be manufactured until the year 2027 are around 9400 (McKinsey, 2023) . Based on the previous assumptions this will imply a demand of around 3.69 million tons of methanol to produce the required composites. With the assumption that all this demand is covered using bio-methanol from silvoarable systems this will imply that the amount of savings that could be achieved when compared with natural gas-based methanol will be of 5,22 million tons of CO2. eq in 5 years or 1,04 million tons of CO2.eq per year. A number that is equivalent to the average yearly emissions of 153.529 European citizens in 2019 (EUROSTAT, 2022)but still quite low when compared to the total aviation industry GHG emissions of 720 million tons for the year 2021 (IEA, 2022)

Regarding the required land availability to meet this demand, as previously presented for the obtention of 1 ton of bio-methanol from a silvoarable plantation 0,047 hectares will be needed, therefore assuming that a third of the global demand for CFRP aircraft manufacturing is met by the use of bio-methanol (1,23 million tons) from German silvoarable systems, this will imply a total land transformation of around 57810 hectares, which represents 0,5% of the total arable land in Germany (11.7 million hectares (EUROSTAT, 2023) ).

Regarding the economic costs for the silvoarable plantations available data for the costs of conventional poplar plantations are extracted from (Desair et al., 2022), these costs are modified by certain correction factors based on assumptions to calculate the costs of the wood chips from the silvoarable plantations, no subsidies for agroforestry systems were included. The calculations are included in External Appendix 1- LCA_modelling.
The calculated costs of the wood chips sourcing from the silvoarable system are of 3,97- 4,53 EUR/GJ which assuming a 30% increase over the cost as the final price will be of between 5.1 to 5,9 EUR/GJ which lies among the low cost biomass feedstock and average prices of woody biomass in Europe (3 to 6 EUR/GJ) and will imply values of methanol cost from 227 to 543 USD/ton of methanol according to (IRENA & Methanol Institute, 2021).

According to the prices of today's natural gas based methanol range from 100 to 200 USD per ton (IRENA & Methanol Institute, 2021). Assuming the low-cost end of both natural gas and silvoarable based methanol this will imply that an extra of 127 USD/ per ton of methanol will be paid this will require around 90 EUR/per ton of CO2 taxes (assuming 1416 kg CO2.eq saved per ton of methanol) to compensate this extra cost, a number that is still higher than predicted taxes in the near future for Germany that for the year 2030 could range between 35 to 60 EUR per ton of CO2 (Benjamin Wehrmann, 2019).

***This chapter has provided estimated calculations regarding CO2 emissions that could occur if the bio-methanol from silvoarable system feedstock is used for composite production. This reduction will imply considerable reductions for the aviation sector, however, these reductions are far from being comparable to the total emissions associated with in-flight emissions. Land availability will not pose a barrier to the use of this feedstock, however, today the predicted costs of the use of this biomass feedstock for methanol production are considerably higher than the fossil fuel alternatives. An increase in CO2 emissions taxes will***

***be required to compensate for these higher costs, furthermore, subsidies in the establishment of these systems on top of costs reduction on the biomass feedstock supply chain and bio-methanol production process could also reduce further this cost gap.***

# 8. Discussion and conclusion

## Discussion of results

This research started with the idea to explore alternative material feedstocks to manufacture environmentally improved composites for the aviation industry. This initial exploration was performed with 3 RQs that brought to the decision of which feedstock to further evaluate in an LCA study from which results two more RQs were answered regarding the environmental and practical implications of the use of the proposed feedstocks. At the end of each chapter discussions and main findings were provided for each of the RQs, the following paragraphs provide a more general discussion addressing the main outcomes of the study.

**Agroforestry systems as provisioners of biomass feedstocks**

This study identified an increasing need for biomass feedstock for industrial purposes. This need however will required to be met through Bioeconomy models based in ecosystem service provisioning to achieve a sustainable use of biomass. For that agroforestry systems that integrate energy crops in farmlands could be one of the main strategies to not only provide a sustainable source of biomass, but also increase the resiliency and overall sustainability of agricultural lands. Despite the identified benefits for these systems, the consequences of expanding these systems as biomass provisioners should be however further evaluated regarding possible tradeoffs, as for example a high transformation to these systems particularly for the case of systems with low relative crop yield could cause land use competition with food production.

This study despite being framed for the case of bio-methanol production for composite manufacturing, has presented valuable insights and addressed the exiting literature gap of performing a Life Cycle Assessment for these systems as provisioners of biomass industrial feedstocks, proving not only results for the LCA but also proving how different allocation methods could be used to deal with the multifunctionally issue of these system.

**LCA results in perspective**

This study presents the results of an LCA study as form of evaluation of the environmental benefits that sourcing feedstock from silvoarable systems for bio-methanol production can entail. According to the obtained results this alternative could partially achieve this goal today, as not all of the studied impact categories favoured the silvoarable over the natural gas alternative, and therefore a further analysis of the relevance of these categories should be performed in order to provide a more conclusive answer. Nevertheless, assuming that the production of bio-methanol takes place in future scenario where the renewable electricity use is dominant and if the silvoarable systems are better designed to achieve higher yields of both crops and trees, the use of these systems for composite production will be overall a much environmentally better strategy than the fossil fuel-based composites (see Sensitivity). However, as previously introduced the category of mineral resource depletion is predicted to increase with the increase in the use of renewables, so this category and the rest not considered in this study should be further evaluated and their results consulted with experts to provide a definite answer on how better overall is the use of bio-methanol from silvoarable systems when compared to natural gas, and which are the main environmental areas of concern of this strategy.

When compared to the marginal land plantation overall the performance of the silvoarable systems could be considered better, this is mainly due to the higher productivity of these systems, however marginal plantations can also be considered as a good alternative for bio-methanol production, particularly as presented in Chapter 5 when they are included in marginal lands that are productive like river floodplains. The degree of sustainable benefits that both marginal and silvoarable plantations could provide will be dependent on the particular cultivation strategies but overall when designed for maximizing ecosystem service provisioning both could be defined as sustainable sources of biomass.

When compared to the use of forest residues for bio-methanol production, this alternative overall performed better than the average silvoarable system. This result contradicts the presented hypothesis in Chapter 4 that ecosystem service-based Bioeconomy models (for which silvoarable feedstocks are assumed to compile better than forest residues) are the most sustainable systems for biomass sourcing. This, however, could be explained by two main reasons several reasons: the first is that a silvoarable system that complies with this model of Bioeconomy should be able to improve the yields of arable crops, for that case, this research has confirmed this hypothesis as for the modelled plantation that improved the yields of arable crops, the environmental performance was superior to the forestry residues.

The second is regarding the limitations of this LCA study to capture the ES provisioning of these systems, to understand this limitation Table 12 includes an overview of the ESs of silvoarable systems (the ones included in (Desair et al., 2022) plus additional ones considered in this study), how these can be captured in LCA with the PEF methodology and if they were captured in this particular study.

*Table 12: Ecosystem services measurable with PEF methodology and captured in this study. Source: own*

| **Ecosystem service** | **Measurable in LCA (PEF)** | **Required data** | **Captured in this study** | **Comment** |
|---|---|---|---|---|
| Erosion control | With soil quality index indicator: Erosion resistance | kg of soil loss | Partially trough average land uses | This ES will be captured by the reduction of the soil loss reducing the impact in the soil quality index category |
| Support good soil structure | With soil quality index indicator: Biotic production | kg biotic production | Partially trough average land uses | These ESs will be captured by the increase in soil biotic production reducing the impact in the soil quality index category |
| Support soil biodiversity | With soil quality index indicator: Biotic production | kg biotic production | Partially trough average land uses | |
| Manage nutrient leaching | Environmental extensions measuring | kg of nutrient leaching | Yes | A substitution approach with the silvoarable and monocrop emissions measurements capture this |

| | | | | |
|---|---|---|---|---|
| | leaching nutrients | | | ES. Reducing the affected impact categories |
| Phytoremediation of polluted soils | Environmental extensions measuring soil contamination | kg of soil contaminants | No | A flow of negative emissions of soil contaminants or a substitution with soil remediation process will capture this ES reducing the affected impact categories |
| Soil compaction during harvesting | With soil quality index indicator: Erosion resistance | kg soil loss | No | This should be captured in the overall lifetime kg of soil loss metric |
| Damage to soils during uprooting | With soil quality index indicator: Erosion resistance | kg soil loss | No | |
| Support insect diversity | No | - | No | A need for a metric to capture biodiversity impacts will be required. |
| Support plant diversity | No | - | No | |
| Conservation of native genetic material | No | | No | |
| Support vertebrate animal diversity | No | | No | |
| Indirect biodiversity loss because of indirect land use change | No | - | No | |
| Water purification | Environmental extensions measuring water contamination | kg of water contaminants | No | A flow of negative emissions of water contaminants or a substitution with water purification process will capture this ES reducing the affected impact categories |
| Water cycle/balance | Environmental extensions measuring water consumption | kg of water use | No | These ESs will be captured by the reduction of the water use category |
| Groundwater recharge | With soil quality index indicator: | m3 groundwater | No | This ES will be captured by the reducing the impact in the soil quality index category |

| | | | | |
|---|---|---|---|---|
| | groundwater regeneration | | | |
| Increase in crop yields | Quantification of co-production crop | kg of crop grain | Yes | The higher the co-production of grain crops the lower the associated environmental impact of the silvoarable system |
| Reduced fertilization | Quantification of fertilization use | kg of fertilizer use | No | These ESs will be captured by a reduction of the applied products when compared to monocrop systems. For this study same application rates were considered. |
| Biological pest management | Quantification of pesticide use | kg of pesticide use | No | |

### Aviation industry environmental impact and supply chain considerations

Despite the considerable carbon emissions savings that the presented bio-based composites could provide when compared with fossil-based alternatives, these savings still represent a minor portion of aviation industry emissions which are totally dominated by in-flight emissions. Even though composites can reduce fuel use and therefore fuel associated emissions, if these reductions in fuel consumption promote higher rates of flying, all the benefits of reducing the environmental impact of composites will be pointless. Is therefore of high importance to first have adequate discussions regarding the role of the aviation sector in a future sustainable society and then aim to reduce its different environmental impacts like in this study for plane manufacturing.

This study has presented a simplified estimation regarding land availability and estimated costs of production that could be associated with the use of silvoarable systems for bio-methanol production. Land availability is far from being a barrier to meet the demand of bio-methanol for composite manufacturing, furthermore, the promotion from the aviation industry to source biomass from silvoarable systems could also create the opportunity to use this feedstock for sustainable aviation fuel (SAF) production.

The estimated costs are however still considerably higher for the bio-methanol alternatives when compared to fossil-based methanol for composite manufacturing, nevertheless, on top of optimizations of the conversion pathways, if subsidies for agroforestry systems are implemented, payments for ecosystem service or higher carbon taxes are implemented, the cost of the feedstock will be further reduced.

## Conclusions

This study provides an answer to the formulated research questions that aimed to explore alternatives feedstock for the manufacturing of composites for aviation. This study can conclude that Short-rotation silvoarable systems can be considered a sustainable feedstock provisioners for composite manufacturing, both from the perspective of the obtained LCA results and for the compliance of these systems with the vision of a sustainable Bioeconomy. However, as complex natural systems, their performance is dependent on multiple factors such as climate conditions, plantation design or supply chain considerations. Therefore, when considering these systems as biomass suppliers these will need to be understood and evaluated under the circumstances that they are considered as this will define their degree of sustainability over other alternatives. Therefore, from this research, it can also be concluded that there is a need to further explore the role of multifunctional agricultural systems inside Bioeconomy models to evaluate their potential as biomass feedstock producers for future sustainable scenarios.

The findings of this study offer Airbus and other industries an opening to explore the adoption of sustainable Bioeconomy models into their sustainability strategies. Such models will not only contribute to mitigating their environmental footprint but also promote the restoration of equilibrium with natural systems. By embracing these environmentally conscious practices, industries can attain a sustainable utilization of resources while help reduce the current pressures on Earth's systems.

# 9. Limitations and recommendations

In this chapter the limitations of the study and the consequent recommendations for further research on this topic are provided. Additionally, specific recommendations are also provided for the commissioner of this project for the use of the results of this study.

**Environmental assessment limitations**

*Limitation: lack of studies and system design strategies for short rotation silvoarable systems*

*Recommendation: Increase experimental and computer simulation studies with different system designs for different climates, soils, and hydrology conditions, LCI inventory data (fertilizer use, yields, operations, emissions…) is monitored over long-term studies*

Different combinations of trees and crops, plantation layouts and under different climate and soil conditions will provide a better understanding of the design these systems in a way that maximizes their sustainability and productive potential as providers of both food and biomass feedstock.

LCI data gathering for the modelling of these systems under different conditions will allow for better LCA modelling studies and drawing more relevant conclusions regarding the environmental benefits of these systems.

*Limitation: environmental aspects not fully captured by LCA impact categories*

Biodiversity protection, soil organic carbon increase, increase in soil quality or water balance improvements are some of the environmental benefits that are predicted to be benefited by the use of silvoarable systems, but however they are assumed to not be totally captured by the available impact categories of this study due to lack of available data for their modelling or lack of appropriate impact categories to measure them.

*Recommendation: Review of impact categories and include other environmental assesment tools.*

The methodologies behind the LCA impact categories should be reviewed in order to explore to what extent they are able to capture the environmental benefits of silvoarable systems and if required additional environmental assessment tools to evaluate the environmental benefits of these categories.

*Limitation: scope of the LCA study limited to composite precursor manufacturing*

The study does not represent a full LCA study and therefore the conclusions of the of the strategies to manufacture environmentally better composites are limited by the scope of the study.

*Recommendation: Include a full lifecycle assessment that also considers composite EoL.*

This will allow to better understand the full environmental perspective of the presented production pathways and particularly how different EoL scenarios will influence the results.

**Social and economic dimensions for a full sustainability assessment**

This study did not focus on the social and economic dimensions when evaluating the biomass feedstocks. This is however relevant to capture the full sustainability aspect of them. Some of the considered relevant economic and social dimensions that could be explored are to address this limitation of the study are presented here.

*Limitation: absence of an in depth economic impact assessment of silvoarable systems*
*Recommendation: Life Cycle Cost assessment and Cost-benefit analysis.*
The use of a Life Cycle Cost assessment will provide information on which are the lifecycle phases which represent the highest cost of pathway for composite manufacturing, this could help to derive strategies to reduce the overall costs and make them more competitive with fossil fuel alternatives.

A cost benefit analysis at the level of the silvoarable plantation will provide valuable information regarding the economic incentives for farmers to consider these systems, this could also serve for policymakers to evaluate the economic implications of including payments for ecosystem service provisioning.

*Limitation: Lack of understating of the social barriers and opportunities for the expansion of short rotation silvoarable systems as biomass feedstock provisioners*
*Recommendation: Application of socio-technical innovation frameworks*
The application of socio-technical methodologies such as the multi-level perspective framework will provide an understanding of the barriers and opportunities for the transition addressing social components like agricultural policies, cultural norms of farmers or markets and business models involved in this transition and provide strategies to accelerate the deployment of these systems.

**Recommendations for Airbus**

The previous recommendations regarding the need for research could also be applied to the research requirements of Airbus to further understand the implications of using this feedstock for composite manufacturing. Regarding more particularities for the case of Airbus as a user of this feedstock, first a more in-depth study of the costs that can be associated to the use of this feedstock should be performed, including predicted costs reduction regarding optimization of the supply chain, possible agricultural subsidies, on top of predicted increase in fossil fuel prices and carbon taxes. From this analysis the willingness to pay for what is considered a sustainable better alternative should be internally evaluated. The use of silvoarable systems as biomass feedstock producers might take some time to be expanded and optimized, however the use of wood forest residues bio-methanol is considered as a good in between alternative while this transition is further developed.

Then the promotion of a locally based supply chain that guarantees both reliability and sustainability of the sourced feedstock could be implemented. Initial investments to promote these systems will encourage farmers to adopt these systems and increase the supply availability, a further investment on these practices could even provide the possibility of also using these feedstocks for biofuel production, here however the land availability requirements should be further evaluated. Furthermore, the promotion of these practices could improve the social image of the aviation industry as promotors of sustainable local development.

Additionally, to address the full sustainability perspective of this pathway for composite manufacturing research efforts should also be included regarding the EoL considerations of the composite use to maximize the circularity in their use.

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# Appendices

## Appendix 1-Analysis of the current and predicted demand for biomass for the industry sector

This section provides a brief analysis at the world level of the current and predicted flows of biomass in the economy and in particular for industry as source of bioenergy or to be used as a feedstock for materials.

The quantification of biomass flows can be done with the use of the metric of carbon content as it is done in (Kähler, F et al., 2023), the bio-based carbon demand is clearly dominated by the food industry's needs, for which livestock and food represent 61% and 15% respectively of the total demand. The rest of the demand is shared by energy purposes from bioenergy (16%) and biofuels (1%) and carbon embedded in materials (7%).
As a consequence of this current use of bio-based carbon, according to the IPCC reports humanity makes use of close to a third of the total available land production to meet these demands (Intergovernmental Panel on Climate Change, 2022), therefore, on top of a predicted increase in global food demand, expected to rise between 35% to 56% from the year 2010 until 2050 (van Dijk et al., 2021), an increase in demand for the energy and materials sectors might pose a greater risk to the world capacity to source biomass among sustainability parameters.

### Biomass for energy

The use of biomass for energy represents the major source of renewable energy use today in the world, what is also defined as bioenergy will also play an important role in the achievement of the net zero targets for 2050 in particular for the hard-to-decarbonise industries (Paul Bennett & Pearse Buckley, 2021). The energetic uses which biomass use is expected to considerably expand in the coming years according to the International Energy Agency (IEA) are electricity generation, heat generation, and transport fuels (IEA, 2021a).

Renewable electricity penetration is expected to be dominated by solar PV and wind energy generation, an expansion that will not be as significant for the case of electricity from bioenergy (IEA, 2021a). Nevertheless, an annual increase of 7% from its current capacity will still be required to meet net-zero targets (Paul Bennett & Pearse Buckley, 2021).

Heat generation represents the world's largest energy use with almost half of the total energy consumption for the year 2021 (IEA, 2021a). The use of modern bioenergy contributed only 11% to the heat demand of 2020 up from 10% in 2015, a need to increase this trend of use of bioenergy heat at a rate 2.5 faster than the current one will be required to achieve net zero targets (IEA, 2021a).

Global demand for transport biofuels is predicted to grow 28% in the period 2021-2026, this demand, however, would need to be doubled to achieve the net zero target goals, the increase in the use of biofuels will mainly target the reduction of road transport emissions and to a lesser extent the air and maritime transport (IEA, 2021a).

In these net zero scenarios proposed by the IEA, a sustainable supply of biomass is considered in which a complete phase-out of traditional biomass[3] occurs and biofuels from 1st generation biomass[4] are also significantly reduced (IEA, 2021b). The overall role of bioenergy in these scenarios for the year 2050 will account for 18.7% of the global share of energy supply increasing from approximately 60 EJ in 2020 to a final 100 EJ in 2050 (IEA, 2021b).

**Biomass embedded in materials**

To meet climate change reduction targets the achievement of a decarbonised energy system is a crucial and urgent goal, however, not only energy-related systems are a source of carbon emissions, and in order to fully decarbonise the future world economy fossil fuel feedstocks should be replaced by recycled carbon, biomass carbon or captured carbon from the atmosphere (Kähler, F et al., 2023).

In this regard, the Renewable Carbon Initiative (RCI) provides a comprehensive database that accounts for the carbon flows both fossil and biogenic to the world's economic sectors (Kähler, F et al., 2023).

The global demand for carbon embedded in materials accounts for 1200 MT of Carbon per year, out of which more than half is currently coming from fossil sources (Kähler, F et al., 2023). As seen in Figure 25 the main global demand for fossil-embedded carbon takes place in the chemical industry including chemical-derived materials and heavy oil fraction. A global share of fossil carbon use that does not differ from the one occurring in Europe in which around 93% of the chemical industry is dependent on fossil-embedded carbon (Kähler, F et al., 2023).

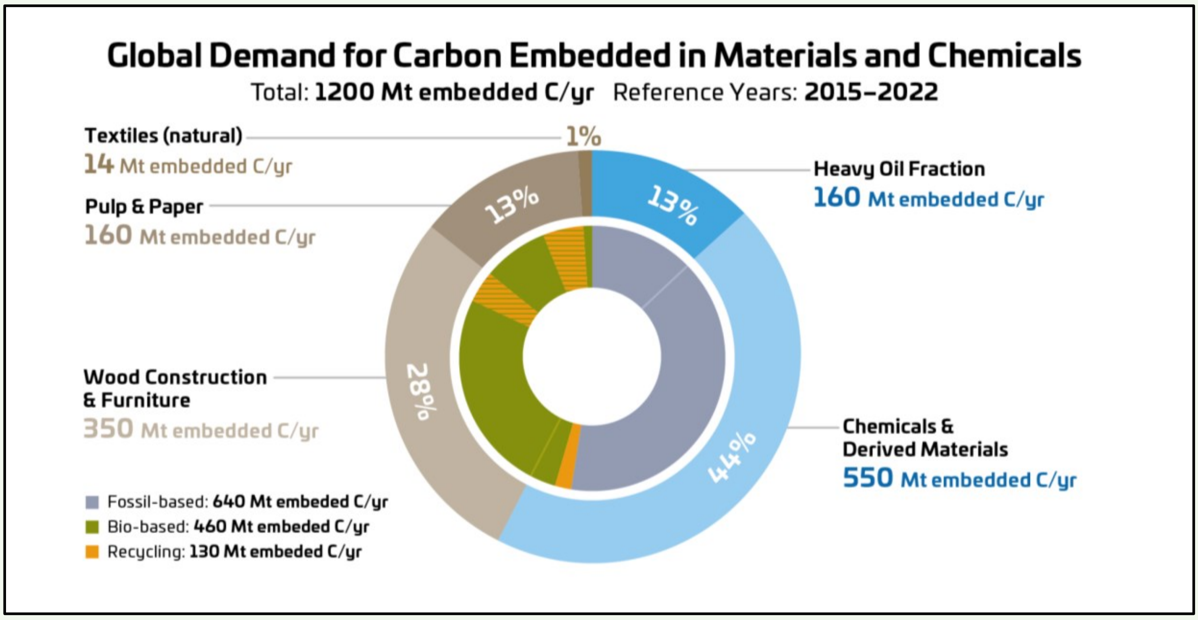

*Figure 25: Global carbon demand embedded in materials. Source: (Kähler, F et al., 2023)*

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[3] Definition of traditional biomass: Woodfuels, agricultural by-products and dung burned for cooking and heating purposes. In developing countries, traditional biomass is still widely harvested and used in an unsustainable and unsafe way. It is mostly traded informally and non-commercially.

[4] First-generation biofuels are those that are produced from edible energy crops such as sugar-based crops (sugarcane, sugar beet, and sorghum), starch-based crops (corn, wheat, and barley) or oil-based crops (rapeseed, sunflower, and canola).

The global chemical industry is assumed to increase its demand for carbon at a rate of 2.5% yearly, if this increase in carbon demand needs to be coped with a full decarbonisation of industry in 2050 alternative carbon sources coming from recycling processes, bio-based carbon and carbon captured from the atmosphere will be required (Kähler, F et al., 2023) Assuming a sustainable use of these sources which considered the inclusion of maximum recycling potentials and limitations regarding the availability of biomass supply according to t to sustainability parameters, (Kähler, F et al., 2023) draws a future scenario for the chemical and derived materials in which 55% of the carbon will come from recycling processes and 20% from bio-based carbon, in the case of the heavy-oil fraction a similar share of 40% of bio-based and recycled carbon will occur, for both sectors the rest of the demand is assumed to be covered by the utilisation of carbon from CO2 (Kähler, F et al., 2023). Overall this will imply an increase in biomass demand for materials from 40 MT to 370 MT of carbon for the year 2050 (Kähler, F et al., 2023).

Decarbonisation of the energy sector through electrification, the use of hydrogen and solar heat will imply a reduction of 50% of the carbon demand, for the case of mobility the demand for carbon could be reduced up to 90% through electrification and hydrogen use (Kähler, F et al., 2023). On the other hand, the use of carbon in materials will double its current levels due to an increase in the sector demand that is not detachable from carbon sources (Kähler, F et al., 2023). This predicted change in the use of embedded carbon is graphically represented in Figure 26
Even in a future "decarbonized" scenario the role of carbon will still be of great importance, the use of biomass for both energy-related uses and embedded carbon in materials needs to considerably increase according to the predicted scenarios of both the IEA and the RCI to reach full decarbonization in 2050 see Figure 26. The demand for bio-based feedstock for the chemical industry according to the IEA and the EC scenarios could represent up to 50% of the global available sustainable biomass for industrial purposes in the year 2050 (Fritsche et al., 2020).

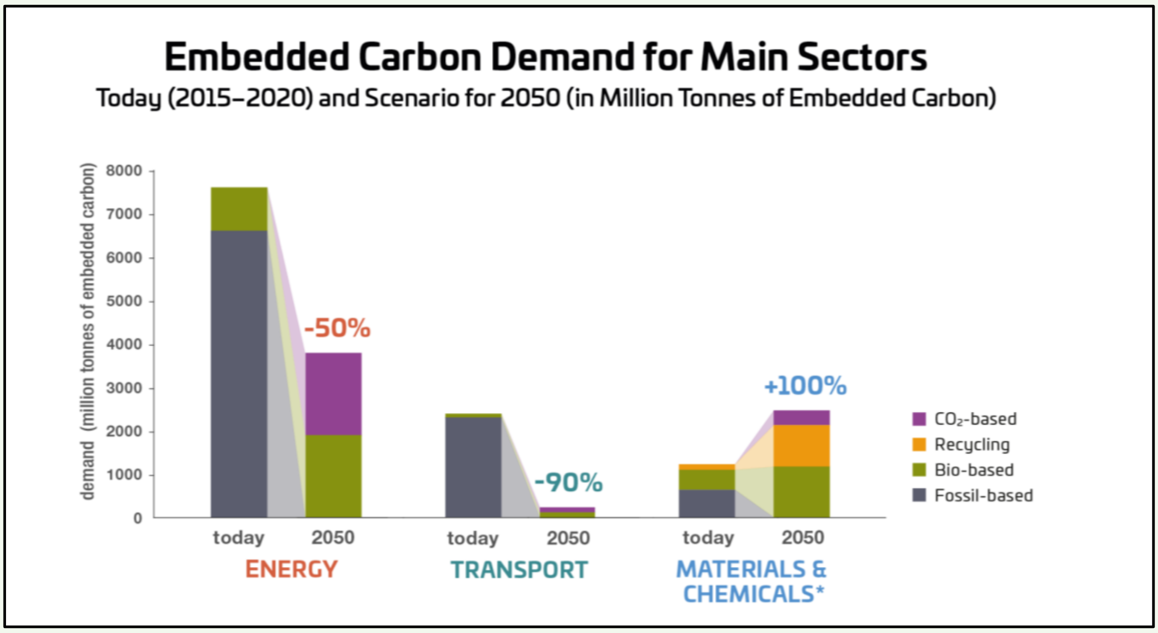

*Figure 26: Predicted embedded carbon demand in industrial sectors. Source: (Kähler, F et al., 2023)*

This predicted increase in the use of biomass has an associated problem-shifting risk, as today's bioeconomy has mainly focused on the extraction of natural resources at the expense of further sustainable considerations (Bastos Lima & Palme, 2022). Therefore if the shift from fossil fuels towards bioeconomy aims to achieve a sustainable transformation, Bioeconomy models that enable green growth through the use and protection of natural resources, and at the same time, enable to meet Sustainable Development Goals (SDGs) should be promoted (Kuosmanen et al., 2020).

# Appendix 2-Analysis of biorefineries in Europe and bio-methanol suitable feedstocks

For predicted demand scenarios of bio-based chemicals and materials for the year 2030, the supply from EU refineries could increase by an additional 3.1 million tones of material from the current 4.6 million ton supply for which still 9,3 million tonnes will still need to be imported to meet the high demand scenario of 17 million tonnes.
The chemicals products that have a higher predicted growth rate are the building blocks, solvents, and resins (European Commission et al., 2021), this is representative of the strategy of the approach of industrial actors for which drop-in solutions that allow for achieving properties comparable properties to fossil-based components will allow them to obtain products that are almost identical to the currently existing ones.

Biofuels and biochemicals can be produced in single-unit processes, however, in analogy with oil refineries, more efficient production is achieved when bio-based products are produced along with energy carriers like fuels, power or heat (European Commission et al., 2021). Therefore policies that promote the production of advanced biofuels for the transportation industry could come as a boost for the biorefinery expansion plans as they will also reduce the perceived investment risk due to a widening of the markets that they can address (European Commission et al., 2021). This is in particular a great opportunity for the aviation sector that could further reduce its environmental footprint by promoting both the use of biomaterials and biofuels for its sustainable transition strategies.

Biorefineries are classified according to their pathway of the type of feedstock, conversion process and end-products see table 13 (European Commission et al., 2021). The current status of biorefineries today in Europe is dominated by facilities that operate on food and feed crop feedstocks (A, B and C) representing 56% of the total, facilities that operate on wood feedstock (D), including residues represent 20%, the remaining is shared by sugar and lignin (E) and natural fibres an oil (H) feedstock based refineries, pathways A-D are defined as commercially established and E-K are still considered in a phase of development (European Commission et al., 2021).

*Table 13:Biorefinery pathway classification Source: (European Commission et al., 2021)*

| | Name | Feedstocks | Products |
|---|---|---|---|
| A | One platform (C6 sugars) biorefinery using sugar crops | Sugar crops | Chemicals, polymers, food, animal feed, ethanol (building block or fuel), Co2, power and heat |
| B | One platform (starch) biorefinery using starch crops | Starch crops | Chemicals, (modified) starches, polymers, food, animal feed, ethanol (building block or fuel) and Co2 |
| C | One platform (oil) biorefinery using oil crops, wastes and residues | Oil crops, waste/residue fats, oil and greasesa | Chemicals (fatty acids, fatty alcohols, glycerol), food, animal feed, fuels (biodiesel and renewable diesel) |
| D | Two-platform (pulp and spent liquor) biorefinery using wood | Lignocellulosic crop, wood/forestry, residues from agriculture and forestry | Materials (pulp and paper, specialty fibres), chemicals (turpentine, tall oil, acetic acid, furfural, ethanol, methanol, vanillin), lignin, power and heat |
| E | Three platform (C5 sugars, C6 sugars and lignin) biorefinery using lignocellulosic biomass | Green biomass | Chemicals, lignin products (materials, aromatics, pyrolytic liquid, syngas), ethanol (building block or fuel), power and heat |
| F | Two-platform (organic fibres and organic juice) biorefinery using green biomass | Aquatic biomass | Materials, chemicals (lactic acid, amino acid), animal feed, organic fertilizer, fuels (biomethane, ethanol), power and heat |
| G | Two-platform (oil and biogas) biorefinery using aquatic biomass | Natural fibres (e.g. hemp, flaxy | Chemicals (fatty acids, fatty alcohols, glycerol), nutraceuticals, food, organic fertilizer, biodiesel, power and heat |
| H | Two-platform (organic fibres and oil) biorefinery using natural fibres | Lignocellulosic biomass, MSW | Materials, chemicals (fatty acids, fatty alcohols, glycerol, nutraceuticals, cannabinoids, food and biodiesel |
| I | One platform (syngas) biorefinery using lignocellulosic biomass and municipal solid waste | Lignocellulosic biomass | Chemicals (methanol, hydrogen, olefins), waxes and fuels (F-T biofuels, gasoline, LNG, mixed alcohols) |
| J | Two-platform (pyrolytic liquid and biochar) biorefinery using lignocellulosic biomass | Lignocellulosic biomass, organic residues, aquatic biomass | Pyrolysis oil (for materials, chemicals, food flavourings, syngas, biofuels), biochar, power and heat |
| K | One platform (bio-crude) biorefinery using lignocellulosic, aquatic biomass, organic residues | Lignocellulosic crop, wood/forestry, residues from agriculture and forestry | Chemicals and fuels |

The predicted expansions of refineries pathways will be based on the promotion of non-food-based feedstocks, and an increase of up to 42 new biorefineries including demonstration scale plants could be operational for the year 2030 (European Commission et al., 2021). This increase will be dominated by the refineries pathways D and E with a predicted expansion of 12 and 19 new facilities respectively, the biorefinery pathway type I based on the gasification of biomass, which has previously been defined as the pathway to explore for this study will represent the

3rd pathway with the greatest expansion with 4 new predicted facilities for the year 2030 (European Commission et al., 2021).

Both pathways E and I are mainly dependent on the use of lignocellulosic feedstocks, one main barrier identified that could slow down the expansion of these pathways, is that despite their ability to use other feedstocks like agricultural residues and wood their full deployment potential will be achieved with the use of non-food crops (willow, poplar or miscanthus), a biomass feedstock that is under great uncertainty regarding the potential it can provide due to land use concerns and lack of current supply chains for these materials (European Commission et al., 2021). Actions that could provide a solution to these challenges can come from the R&D to improve the performance of this cropped biomass in marginal land, the identification of land suitable for the expansions of these feedstocks and the support for projects to expand and create new supply chains for these materials (European Commission et al., 2021).

The United Kingdom Department for Business, Energy and Industrial Strategy (BEIS) also recognises the relevance of the development of advanced gasification technologies for biomass as a key technology to achieve a net zero carbon economy (BEIS, 2021). In a report that aims to address its development status, the suitability of different biomass feedstocks for this technology was addressed regarding their technical suitability or the treatment requirements among other criteria, for which energy crops in the form of short rotation trees along with other wood products were defined as the most suitable feedstocks for the gasification process, in contrast with energy crops grasses and straw that are much harder to process, or waste wood which is hardly available in the low contaminated required standards (BEIS, 2021). The technical criteria excluding economic and environmental considerations for biomass feedstocks considered are included in the following table.

| Fuel Type | Suitability for | Difficulty |
|---|---|---|
| Clean Wood/forest residues | Generally good, | Low |
| Wood pellets | Generally good, | Low |
| Energy crops SRC | Generally good, | Low |
| Energy crops grasses | Poor, requiring | High |
| Waste wood | Generally good, | Medium |
| Straw | Specialist | High |

# Appendix 3-Biomass feedstock supply in Europe

Overall the biomass feedstocks sourced in Europe are predicted to fall short of meeting their future expected demand, today 70% of the supply of biomass for materials and energy is coming from woody biomass, however, an increase in the supply of this biomass will be limited due to sustainability concerns (Material Economics, 2021). Lignocellulosic biomass in the form of energy crops and agricultural waste are the biomass sources with the highest predicted growth, the contribution to the future supply from energy crops is the one that has the most uncertainty regarding its possible range of values, this uncertainty is dependent on the availability of land to grow these crops sustainably, nevertheless, the higher estimates establish a sustainable growth potential that could overpass all of the other biomass sources, moving from a current supply of 0.8 EJ to 5.6 EJ for the year 2050 (Material Economics, 2021). For the case of forest residues, the availability of this feedstock is assumed that could be increased with the highest removal rates from forests, nevertheless, high removal rates could create adverse impacts regarding alteration of the carbon cycles or biodiversity loss among others.

The European Union-funded project S2Biom established a vision for the use of lignocellulosic biomass in Europe, regarding cropped biomass (energy crops) the estimates of biomass availability under the sustainability regulations established by the Renewable Energy Directive, predicts an expansion from almost negligible supply to 152,000 tonnes/year for the year 2050 as seen in the total potential baseline scenario in Figure 27.

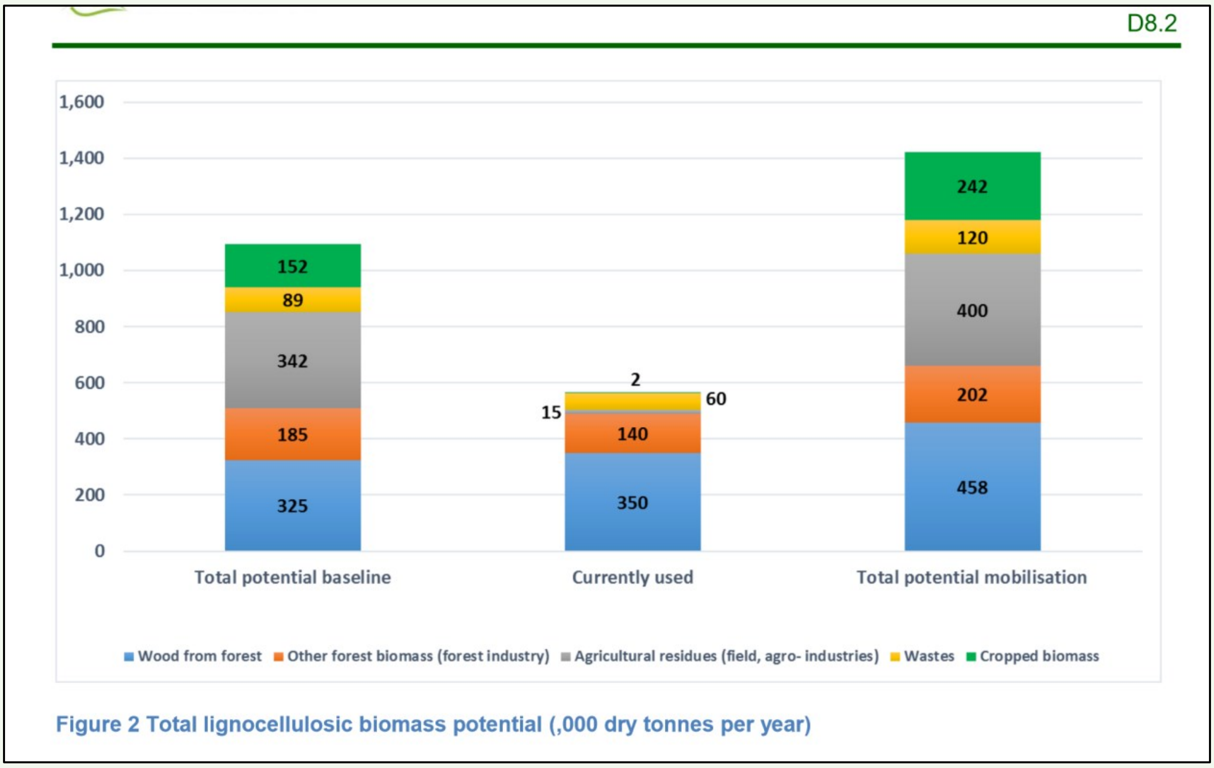

Figure 2 Total lignocellulosic biomass potential (,000 dry tonnes per year)

*Figure 27: Lignocellusic biomass supply potential in Europe for a sustainable and maximum scenario. Source: (S2Biom, 2016)*

The availability of the cropped biomass under these sustainable regulations will be dependent on its production on unused land, which refers to land difficult to access or with poor soil or climatic conditions, or previously farmed land that has been abandoned due to a decrease in economic margins (S2Biom, 2016). Despite the existence of a considerable amount of unused land in Europe that could be defined as suitable for the growth of these crops (Gerwin et al., 2018), using this land for biomass production for 2030 is identified as a significant challenge not only due to sustainability issues but also due to profitability and economic concerns related to cropping practices in different countries (S2Biom, 2016).

On top of that plantations on marginal lands are assumed to have lower yields which can result in low-margin profit productions, and overall the growth of these crops in marginal conditions will imply greater challenges than on good agricultural land (Lewandowski, 2016).

# Appendix 4-Unit process description

## Land use impact categories

Regarding the land use-related impact categories, several considerations are addressed. According to (Perdomo E. et al., 2021), the impact categories related to land use are frequently not included in LCA studies of SRC plantations, the main reason behind this is the low degree of maturity that can be associated with the methodology to account for the environmental related impact categories, particularly for the accounting methods of carbon stocks which are highly debated in the literature. In the case of the publication defining the SRC plantation under study, the LU considerations were not included also due to its complexity (Schweier et al., 2017b). Nevertheless, it is considered in this work that the impacts related to LU are highly relevant for this study; therefore, an approach to include them as reliably as possible is considered.

For the family of impact categories of the PEF methodology, two impact categories are: land use-induced climate change and land use change. The first one accounting for the GHG emissions related to soil pool changes is assumed to be included to a certain degree. For the case of the latter, an explanation of how this category will be included is provided in the following paragraphs according to the methodology of the PEF category based on (Bos et al., 2016).

The methodology presented by (Bos et al., 2016) accounts for the land use impact based on two parameters the transformation and the occupation occurring in the land, occupation referring to the static use of the land and its effect on the quality and transformation referring to the change in quality from the initial to the final state of the land. This methodology accounted for the influence of land use in erosion resistance, mechanical filtration, groundwater regeneration and biotic production, which are aggregated in a single score of a quality index for the PEF methodology according to the methodology of (De Laurentiis et al., 2019).

## Alternative 1- Marginal land poplar plantation

### Cuttings production and transport

The LCI data for the nursery production of the cutting is extracted from the Ecoinvent process of willow stem cutting production in Germany. No other LCI data were found regarding the production of poplar cuttings. The use of this data is considered valid as the assumption made is that the influence of the model of this process will be low compared to the rest of lifecycle operations and the growth of willow cuttings could be similar to the growth of poplar cuttings.

For the transportation distance of the cuttings to the agroforestry plantation a distance of 30 km is defined, this distance is assumed on the basis of possible close locations of nursery facilities. The selected process for the transportation will be the Ecoinvent process agricultural transport including trailer and tractor transport which is assumed to be representative of the mode of transport affecting this operation.

### Trees establishment operations

The operations for the tree establishment are in accordance with (Schweier et al., 2017b), which include the operations of Ploughing, Harrowing and Planting. The diesel consumption for each operation is provided in kg of diesel and the amount of kgs of machinery is also provided per operation (Schweier et al., 2017b). The kgs of diesel consumed are converted into MJ for their modelling in the Ecoinvent process of diesel burn in agricultural machinery according to the conversion factor of the process. These are included in the external Appendix1-LCA_modelling.

### Land use emissions

For the case of the land use associated emissions these are assumed to be included in the measured data of field GHG emissions of (Schweier et al., 2017b). The changes in SOC are not included due to the lack of available data.

### Fertilizer application

For the fertilisation process, the selected product is in accordance with (Schweier et al., 2017b), for which it was modelled the application of Ammonium nitrate ($NH_4NO_3$) fertiliser, the rate of application is in accordance with the selected scenario of (Schweier et al., 2017b), the conversion from kgs of N to kgs of fertiliser is made with the information from the Ecoinvent process. The machinery used including the burned diesel is also included in this process according to (Schweier et al., 2017b).
According to (Hans Blonk et al., 2022) two different types of Nitrous oxide emissions occur from fertilizer application: direct and indirect emissions. The direct emissions are calculated using the formula provided by (Hans Blonk et al., 2022) which approximates the emissions with the kgs of N contained in the fertilizer and an emission factor, this calculation is included in external Appendix 1-LCA_modelling. The indirect emissions from fertilizer application are included in the field emissions process.

Similarly, the ammonia emissions from fertilizer application are approximated with an equation from (Hans Blonk et al., 2022) and included in the external Appendix1 LCA_modelling
For the phosphorus emissions despite the modelled field emissions being based on the application of Ammonium nitrate, the real plantation used NPK fertilisation (Wuxan 5% N), therefore an assumption of the P emissions is included. First, an equivalent between the rate of application of NPK and Ammonium nitrate application is provided, and the emission factor of 0.1 kg of P emission per kg of fertilizer is used from (Hans Blonk et al., 2022).

### Field emissions

The comprobation of the validity of the assumption of the captured carbon in biomass is done with the following calculations:

$$\begin{aligned} &\mathit{CO2\ captured}(\mathit{Mg\ CO2eq/\ ha}) \\ &\quad = \mathit{Photosynthesis\ rate}\ (\mathit{Mg\ CO2eq/\ ha}) - \mathit{Ecosystem\ respiration}(\mathit{Mg\ CO2eq/\ ha}) \end{aligned}$$

$$\mathit{CO2\ captured} = 557.45 - 378.3 = 179.15\ \mathit{Mg\ CO2eq/\ ha}$$

$$\mathit{CO2\ captured}(\mathit{Mg\ CO2eq/\ ha}) = \mathit{Aboveground\ biomass}\ (\mathit{Mgdm/\ ha}) * \mathit{Carbon\ Content}\ * 44/12$$

$$\mathit{CO2\ captured} = 116.9 * 0.45\ * 44/12\ = 192\ \mathit{Mg\ CO2eq/\ ha}$$

The results show that the amount of captured carbon is considerably similar for both alternatives and therefore the approach is considered as valid.

Methane uptake is not considered due to the absence of data for the plantation and the assumption that will have small relevance in the results.

### Harvesting and on-field transport

The process of harvesting is also defined with the information provided in (Schweier et al., 2017b) this process includes the use of the harvester machine and the accompanying tractor-trailer that transports the chipped wood to the storage at a 2km distance.
The forager and biomass header are represented by the available Ecoinvent process representative of a harvester assumed as the most representative. A 5% loss of DM of biomass is assumed in the harvest process (Schweier et al., 2016).

### Transport to biorefinery

The transport distance to the biorefinery is assumed to be 50km and covered by a lorry truck. This distance is defined with the assumption that the marginal plantation will be closely located to the biorefinery, similar assumptions regarding transport distance will be employed for the rest of the alternatives.

### Removed plantation

The field operations required for the removal of the plantations as well as the CO2 and N2O emissions are in accordance with (Schweier et al., 2017b).

## Alternative 2-Silvoarable plantation

### Cuttings production and transport

The type of cutting used will be the same as the ones provided in alternative 1, the number of cuttings of the tree studies under the plantation have different amounts of cuttings ranging from 2500 to 10000. To better associate the rest of the tree operations to the number of cuttings the assumption made will be that the silvoarable plantation will also employ 6500 cuttings.
Regarding the transport of the cuttings, the assumption made is that the distance will increase from 30km to 50km, assuming a higher transport distance due to the lower production per total hectare of the system.

### Tree establishment operations

The tree establishment operations are assumed to be the same per hectare basis as alternative 1. The assumption made is that the field preparation should not differ in both cases and as previously defined the number of cuttings to plant is assumed to be the same. However, in this case, the field operations will be the ones defined in (Schweier et al., 2017b) for the case of the 3-year rotation plantation as the silvoarable systems are harvested in rotations of 3 to 8 years, the use of the 3-year rotation is assumed to have a slightly higher impact than the ones of the 7-year rotation according to (Schweier et al., 2017b), which is in line with the assumption that in general silvoarable systems will imply higher impacts regarding field operations.

### Land use

The assumption of the silvoarable system regarding the land transformation is in accordance with the previously defined methodology for the marginal plantation alternative. In this case, the tree strips of the agroforestry systems, will transform an area of annual crop non-irrigated intensive, and to permanent crop non-irrigated intensive. Furthermore, in accordance with (Veldkamp et al., 2023), silvoarable systems are able to increase the quality of the soils not only in the tree area but in the whole system area when compared to monocrop systems.
Therefore the flow of transformation will be assumed to occur for the whole plantation including the arable strip. The flow of land occupation however will be for the arable strip as “annual crop non-irrigated intensive” and for the tree strip area as “permanent crop non-irrigated intensive”.

### Trees herbicide application and weed control

Similarly to the tree establishment operations the applied herbicides and the machinery operation for their application and the machinery operation for weed control are also assumed to be the same as the marginal plantation and also in this case for the case of the 3-year rotation plantation.

### Trees fertilizer application

The trees are assumed to not receive any fertilizer application according to (Veldkamp et al., 2023).

### Field emissions

The emissions of N2O and nutrient leaching are taken from (Veldkamp et al., 2023).
The carbon flux will be calculated with the aboveground net primary production with the same procedure as the marginal plantation.

### Tree harvesting and on-field transport

To include the harvest operation consumption for the silvoarable system the following assumptions are made. An average ratio of harvest operation inputs and the amount of biomass production is calculated between the different production chains (Schweier et al., 2017b). With this average ratio and the biomass production of the silvoarable system, the rate of harvest inputs is included. Similarly to the marginal plantation, 5% yield losses are assumed for the harvest process (Schweier et al., 2016).
Similarly, the average amount of tractor-trailer units is calculated for the different production chains and then based on the amount of biomass production of the AF the transport requirements are calculated. The assumed distance of 2km to the intermediate storage in the marginal plantation is increased to 3km for the case of the AF system as it is assumed that the lower productions per system area compared to the marginal plantation will imply higher transportation distances.

### Transport wood chips to biorefinery

The transport process will be assumed to be the same as in the case of the marginal plantation but also for this case in line with the previous assumptions regarding productivity per ha, a 50% increase in transport will be included assuming more transport distance for the silvoarable plantation.

### Removed tree plantation

No information about the removal emissions of the silvorarable systems is available, therefore plantation removal emissions are in accordance with (Schweier et al., 2017b), and the scenario of no fertilization is selected in this case.

### Herbicide application and weed control

The applied herbicides and the machinery operation for their application and the machinery operation for weed control are in accordance with (Schweier et al., 2017b). The Dicamba weed control product is substituted by an available Ecoinvent similar herbicide product “benzoic compound pesticide” which is assumed to have similar characteristics.
Herbicide emissions not included