Social implications of and biomass availability for an innovative lignocellulose biorefinery concept based on the acetone organosolv process

(Final report on social and SWOT assessment)

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Summary

Large quantities of lignocellulosic residues are generated in agriculture and forestry, which have so far mainly been used for energy provision, if at all. In order to strive for a higher-value use in the future, various processes have been developed to break down lignocellulose into its components and facilitate efficient conversion into chemicals and building materials. One of these is the so-called organosolv process, in which the lignocellulose is treated with organic solvents such as ethanol, formic acid or acetone. In order to investigate the technical feasibility and overall sustainability, the EU and the Bio Based Industries Consortium co-funded the project "UNRAVEL: A Unique Refinery Approach to Valorise European Lignocellulosics". It researches and develops acetone organosolv fractionation to boost delignification, recovery yields and purity of the main constituents from lignocellulosic biomass.

The project is accompanied by an integrated life cycle sustainability assessment covering environmental, economic and social sustainability aspects using a common set of scenarios based on mass and energy balances from detailed process models. The scenarios comprise several valorisations of the lignocellulose fractions lignin, C5 sugars from hemicellulose and C6 sugars from cellulose. They include polyols from lignin for PUR/PIR (poly–urethane/polyisocyanurate) insulation foams and fermentation of the sugar streams to chemicals (C5 to xylonate and C6 to acetone). This report covers the social assessment and an analysis on strengths, weaknesses, opportunities and threats, which has been contributed by IFEU.

This report analyses social risks and benefits of potential future biorefineries according to the concept under investigation as well as social and environmental aspects of sustainable biomass availability based on three analyses: (i) a social life cycle assessment (sLCA) using the social hotspot database, (ii) an analysis of strengths, weaknesses, opportunities and threats covering further positive and negative social impacts as well as (iii) a complementary analysis on the availability of lignocellulosic biomass that is environmentally and socially sustainable.

Social risks

The general level of social risks in the supply chain is comparable for potential biorefineries according to the UNRAVEL concept and their conventional competitors, which is largely independent of the analysed technical configuration. These **risks mostly arise from indirect**

suppliers outside of the EU and are in particular related to occupational health and safety, governance aspects including corruption, and procurement from high conflict zones. Actual social impacts are however no physical consequences of the examined supply chain processes but are very much dependent on their management. Therefore, a comparison of the generic risk levels between the options can only **guide process development** to avoid input materials, which are mostly produced under unacceptable conditions, which is not the case for any of the assessed scenarios. In particular, none of the analysed European **biomass feedstocks** brings about exceptionally high risks in the supply chain while imported biomass, which is not foreseen in the analysed concept, may be connected to substantial risks. Therefore, feedstock choice can concentrate on other selection criteria if competition is avoided that may otherwise indirectly lead to increased biomass imports into the EU.

Relevant social risks in the supply chain that have been identified in this study are no reason to refrain from implementation but rather entail obligations. They need to be **managed and monitored during implementation and operation** of a future biorefinery. Relevant social risks (social hot spots) associated with the assessed potential biorefinery supply chains are in particular:

- Biomass supply, in particular in Eastern European countries
- Provision of lignin modifiers and, to a lower extent, also of other input chemicals
- Energy and transportation (depending on process efficiency)

These social risks in the supply chain should be taken as starting points to design a strategy of monitoring and mitigating risks.

Work in the biorefinery itself and connected to the supply of high-end inputs and services is only connected to comparatively **low risks**, mainly related to occupational health and safety. This can and needs to be addressed using existing up to date concepts. Further **risks can arise from the emergence of a single powerful economic actor** in a rural environment such as operators of large biorefineries. This requires fair negotiations in particular about wages and biomass supply as well as strategies aiming at local employment and procurement.

Last but not least, this project seeks to contribute to a **transition from a fossil-based economy** with all its established networks, infrastructure and employment **to a bio-based economy**. This can only lead to the desired sustainability benefits if fossil-based processes are actually shut down, which is very likely to cause adverse social impacts on the stakeholders connected to processes that are to be phased out. This transition needs to be actively managed by politics to mitigate social impacts in particular on **employees in regions with a strong fossil-based industry**. Additionally, products could become more expensive for consumers at least in a transition phase especially because of high investment requirements. Impacts of **potentially increased inflation** on vulnerable societal groups need to be mitigated by politics by implementing suitable measures.

Social benefits

Besides mitigation of climate change, another main motivation behind support for a future bio-based economy is the **creation of jobs and prospering local economies** in rural areas. Large biorefineries using lignocellulosic residues as feedstock are expected to contribute to this goal in particular via creating a stable demand for biomass and thus income and jobs in agriculture and forestry. Moreover, tax revenues and revenues for state-owned forests are increased while the municipalities' costs for road maintenance are reduced if roadside grass is used. Additionally, high quality jobs are created in the biorefinery itself and at high-tech specialty suppliers.

The full realisation of these potential benefits however requires a **location in less privileged rural areas, equal employment opportunities** and a **local procurement** approach that should be a prerequisite for public support. Furthermore, **training programmes** and enhanced **health and safety measures** for local workforce may be needed to improve local employment instead of causing an influx of external workforce and/or bad working conditions that could create social friction.

Sustainable biomass availability

Feedstock supply can be a critical bottleneck for any biorefinery, with a significant impact on social and environmental sustainability. Through its focus on lignocellulosic residues and especially its flexibility to shift between and to mix feedstocks, the biorefinery concept under investigation is designed from the outset to avoid competition with food/feed production and to minimise competition with existing users of the same residues. Despite this general advantage, competition about biomass can still be a limiting factor. In contrast to genuine biomass residues, technically favourable **lower-grade stemwood** (pulpwood/energy wood) seems to be already largely used. Therefore, the **sustainable availability of lignocellulosic residues** has been analysed based on studies covering the EU-wide availability of the feedstocks cereal straw, forest residues and roadside grass, which are relevant for the biorefinery concept under investigation, taking into account sustainability restrictions and existing uses.

The most important lignocellulosic residues in the EU are cereal straw and forest residues. The sustainable, available potential for **cereal straw** is reported to be in the range of **around 30 million tonnes (dry matter content) per year** (Mt_{DM}/year). A current increase in biofuel production capacity from straw triggered by a dedicated mandate in the current renewable energy directive (RED II) may however already absorb substantial parts of this straw in the next years.

For **forest residues** it is debated if and at which locations this resource could be already **overused** or if on the contrary up to **35 Mt_{DM}/year** could still be sustainably available, depending on location-dependent sustainability restriction and current use. A small fraction is represented by tops and branches of birch trees, which were exemplarily researched in this project. An option to increase the amount of forest residues and also lower-grade stemwood available for material use would be to **replace other uses that do not require the carbon contained in the biomass** as such, i.e. primarily combustion for heat and power generation, by other renewable alternatives such as solar and wind power and by substantially decreasing the energy demand through better insulated buildings. However, if the use of wood by small businesses or for domestic heating was to be restricted, financial support would be required to balance socio-economic impacts, in particular on low-income households.

Roadside grass represents a so far largely unused sustainable resource that should be used as far as logistically possible. Its sustainable, available potential amounts to about **3 Mt_{DM}/year** and thus represents a small but nevertheless worthwhile expansion of the biorefinery's feedstock spectrum.

The sustainably available amounts of lignocellulose biomass feedstock are sufficient to feed several large-scale biorefineries. At the same time, they are very location-dependent and may vary annually. Therefore, it is important to ensure during the **site selection process** that sufficient biomass is available for all local users, including the biorefinery. A feedstock-flexible concept such as the one developed in this project can be crucial to avoid potential negative impacts on environmental and social sustainability.

Outlook

Biorefineries using lignocellulosic biomass residues as feedstock can contribute positively to a more sustainable society despite general limitations in feedstock availability provided that several important boundary conditions identified in this report are taken into account. This concerns in particular the choice of the biorefinery's location based on sustainable biomass availability and socio-economic criteria, aiming at a well-balanced integration into the local economy and managing social risks in the supply chain. A first implementation of this biorefinery concept is however expected to require support. If the investigated biorefinery concept can achieve advantages with regard to other sustainability dimensions, too, then politics should adopt supporting measures. These should be connected to suitable boundary conditions including those identified in this study to ensure that the potentials to contribute to a sustainable future are actually realised.

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1 Introduction

The UNRAVEL project aims for an efficient and feasible conversion of second generation biomass from forestry and/or agriculture into chemicals and building materials. Biomass streams will undergo Fabiola™ organosolv fractionation in order to boost delignification, recovery yields and purity of their main constituents. The product streams obtained from fractionation are lignin, C6 sugars and a C5 sugars stream. Various valorisations of the product streams are addressed such as lignin for PUR/PIR, and fermentation of the C5 and C6 sugar streams into chemicals, see Figure 1-1.

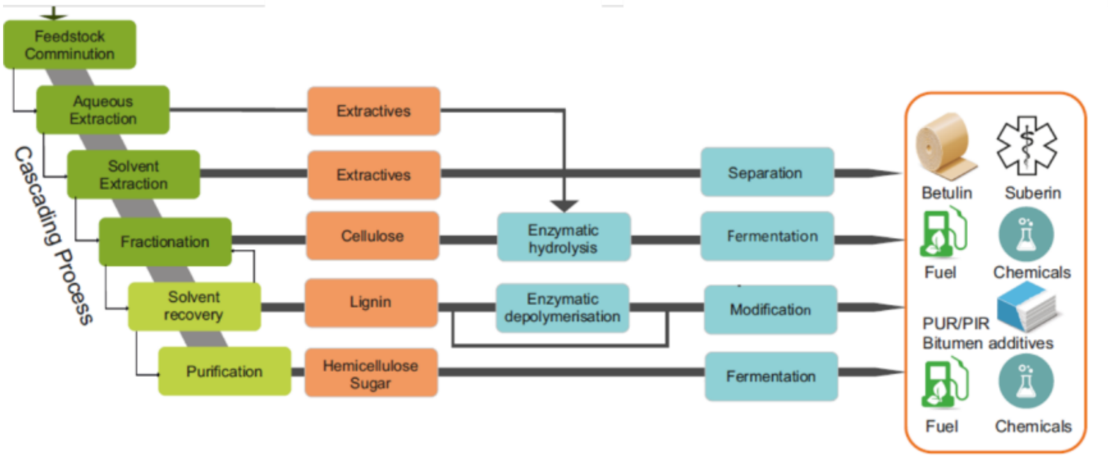

Figure 1-1: Overview of the UNRAVEL concept

One main motivation for the UNRAVEL project is to improve the technology, economics and further sustainability impacts of advanced pre-treatment, separation and conversion technologies for complex lignocellulosic biomass. The sustainability assessment within this project ensures that process and product improvements indeed lead to a more sustainable performance over the whole life cycle.

Work package 6 of the UNRAVEL project conducts an integrated life cycle sustainability assessment analysing the three main pillars of sustainability: environment, economy and society. This document contains:

- Social assessment using social life cycle assessment (sLCA) (results in chapter 4)
- A complementary SWOT assessment on strengths, weaknesses, opportunities and threats regarding social aspects (results in chapter 5)
- Biomass potentials analysis (results in chapter 6)

All parts cover the scenarios defined commonly for all parts of the integrated sustainability assessment based on mass and energy balances from Task 6.2 on process design [Dijkstra & Luzzi 2022].

2 Methodology

In order to achieve reliable and robust sustainability assessment results, it is inevitable that the principles of comprehensiveness and life cycle thinking (LCT) are applied. Life cycle thinking means that all life cycle stages for products are considered, i.e. the complete supply or value chains, from the production of biomass, through processing in the biorefinery and production of the end user products, to product use and end-of-life treatment / final disposal. Through such a systematic overview and perspective, the unintentional shifting of environmental burdens, economic benefits and social well-being between life cycle stages or individual processes can be identified and possibly avoided or at least minimised. The performance of each product and co-product is compared to alternative reference products.

This assessment is based on the methodology of Integrated Life Cycle Sustainability Assessment (ILCSA) [Keller et al. 2015]. The structure of WP 6 that implements this integrated life cycle sustainability assessment is depicted in Figure 2-1.

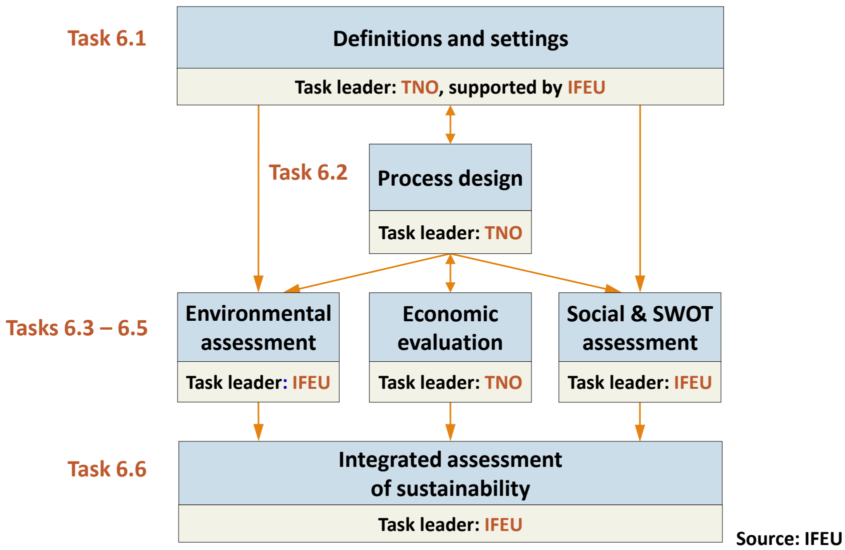

Figure 2-1: Structure of the work package on sustainability assessment in UNRAVEL

Common definitions and settings such as goal and scope of the assessment are described in section 2.1 and the specific methodologies and settings applied for the social assessment are described in section 2.2 for social life cycle assessment, section 2.3 for the SWOT analysis on social aspects and in section 2.4 for the complementary biomass potentials analysis.

2.1 Common definitions and settings

A well-founded sustainability assessment requires common definitions and settings on which the environmental, economic and social assessment will be based. They ensure consistent data and results for the integrated sustainability assessment. This chapter summarizes the settings for the sustainability assessment that were discussed and agreed upon with all partners on an internal workshop on definitions and settings on February 5th, 2019 in Limerick (Ireland) [Dijkstra et al. 2019]. It comprises the basis for the whole sustainability assessment in this work package.

2.1.1 Goal

The goal of this work is to assess the sustainability of the UNRAVEL value chains in a streamlined and comprehensive manner, covering the main aspects of sustainability: environment, economy and society.

Main purpose

- Decision support
- Support pilot case development

Addressees

Decision makers in:

- Policy
- Research
- Industry
- General public

Guiding questions

These guiding questions are the basis of the sustainability assessment. It is the goal of the final report at the end of the project to answer these questions.

Main question is formulated as follows:

How far and under which conditions can the UNRAVEL biorefinery concept contribute to a more sustainable supply of the targeted products?

Sub-questions:

- How does the studied biorefinery concept compare from a sustainability perspective to (a) conventional products and (b) to other use options of the same biomass, in particular other state-of-the-art biochemical biorefinery concepts?

Is the objective reached to reduce OPEX and carbon footprint of the pre-treatment by 30% and 15%, respectively?

How do specific results for the different perspectives on sustainability (such as environmental, economic, social) differ from each other?

To which extent do the pre-extractions impact sustainability compared to current practice without pre-extractions, and to which extent do the different options for lignin valorisation impact sustainability?

Which sections or unit operations therein determine the results significantly and what are the optimisation potentials?

What is the influence of feedstocks on this?

What is the influence of possible transitions in the economy (e.g. renewable energy, oil and feedstock price)?

- Which barriers (e.g. technological) and limitations may hinder the industrial-scale implementation of UNRAVEL or require changes to the concept that affect sustainability?

Is the objective reached to develop an economically viable process for purification of the hemicellulose hydrolysate for effective fermentation into chemical building blocks?

Is the objective reached to develop high value applications for lignin i.e. its application in PUR/PIR and as polymer fillers?

2.1.2 Scope

With the scope definition, the objective of the sustainability assessment (i.e. the exact product or other system(s) to be analysed) is identified and described. The scope should be sufficiently well defined to ensure that the comprehensiveness, depth and detail of the study are compatible and sufficient to address the stated goal. Resulting definitions and settings are used in the subsequent analyses (tasks) to guarantee the consistency between the different assessments of environmental, economic and social implications.

The comprehensiveness and depth of detail of the sustainability assessment can differ considerably depending on its goal.

System boundaries

Entire life cycles (value chains) are analysed from cradle to grave

- *I.e.* from production of inputs to the disposal of the products
- Applies to products and conventional reference products

The system boundaries include a part that is modelled in detail (foreground system, within battery limits) and a part for which data is supplemented from other sources.

Technical reference, timeframe

Mature technology at industrial scale ("nth plant") will be analysed. The reference year will be 2030 for a mature, full scale industrial production. The life cycle sustainability assessment evaluates scenarios depicting potential mature technology in 2030 based on available measured data and expert knowledge supplemented by literature sources where necessary.

Geographical scope

EU (no biomass from outside EU considered)

Where specific datasets have to be selected, the Netherlands are selected as primary example complemented by France, Hungary and Estonia for sensitivity analyses. These countries were selected for possible biomass logistics concepts.

2.2 Specific definitions and settings for social life cycle assessment (sLCA)

Social life cycle assessment (sLCA) is based on the life cycle thinking approach like environmental LCA. For that reason, many provisions from international environmental LCA standards [ISO 2006a; b] and the common definitions and settings described in section 2.1 can be and are applied to this sLCA study, too. The methodology of this sLCA study follows the guidelines for social life cycle assessment of products and organizations [Benoît Norris et al. 2020]. Several specific settings and methodological choices nevertheless have to be made for each individual study based on this methodology. In the following, these choices are detailed.

- Choice of assessment approach,
  The impact assessment method chosen is the Reference Scale Assessment (RS). This method classifies observed social risks of activities related to a product system e.g. as low, medium or high compared to a reference scale. This classification can be based on international standards, local laws or industry best practices – but also on other documented criteria [Benoît Norris et al. 2020]. In this study, the social risks observed in a specific industrial sector in a specific country are classified into the social risk levels ‘low’, ‘medium’, ‘high’ and ‘very high’ for each indicator using the criteria as described by [Benoît Norris, Bennema, et al. 2019]. This allows estimating the magnitude and significance of the potential social impacts associated with a product system. The alternative method Impact Pathway Assessment, which was not chosen for this study, uses causal or correlation/regression-based directional relationships between the product system/organizations activities and the resulting potential social impacts [Benoît Norris et al. 2020]. This approach is not as mature as the reference scale approach yet.
- Background database
  Background data on social risks are taken from the Social Hotspot Database (SHDB, version 2019 (V4) [Benoît Norris, Norris, et al. 2019]), which is based on the multiregional input/output (MRIO) model GTAP version V9 (reference year 2011).
- Activity variable
  Observed social risks, which were classified using the reference scale approach, are

related to an activity variable to allow a connection to a product system. As activity variable work-hours in the individual country-specific sector have been chosen following the approach of the SHDB. This reflects the labour intensity of a production activity. The activity variable is multiplied by a factor associated with the social risk levels of an indicator in a country-specific sector to calculate the medium risk work-hours equivalent. In this project, the factors proposed by [Benoît Norris et al. 2019] are used.

- Indicators, impact categories, weighting and aggregation
  The aim of sLCA is to depict potential social impacts, i.e. potential impacts on the well-being of stakeholders/affected persons. These impacts are estimated using the full set of 141 risk indicators grouped into 24 subcategories or 5 impact categories (‘labor rights and decent work’, ‘human rights’, ‘health and safety’, governance’ and ‘community’) provided by the SHDB [Benoît Norris, Bennema, et al. 2019 p. 11].
  Values of related indicators are averaged to yield an impact subcategory value. Aggregation of subcategory values to category values and/or of subcategory values into a single risk score using the unit “medium risk work-hours eq.” requires weighting factors. Weighting of largely independent social impacts is necessarily based on value-based choices. For social impacts this is even more difficult than for environmental impacts because each affected person has its individual set of preferences. Data for an alternative normalisation approach is not available. For the purpose of displaying all impact subcategories values in the same graph, they are weighted equally. This allows identifying social hot spots but no further conclusions on severity of potential impacts or on trade-offs like the reduction of one risk at the cost of increasing another one.

Choices specific for the assessed system:

- Data on background system:
  The mass and energy balance provided by Task 6.2 and the prices of the economic assessment (Task 6.4), where available, are used to calculate the costs required as inputs in the GTAP multiregional input/output model.
    - Conversion of prices.
      Current prices (2021) were provided in € by the economic assessment (Task 6.4). To convert to $ 2011, the reference of the GTAP input/output model, € 2021 is multiplied by 0.8. This factor is based on the mean exchange rate of € and $ in 2011 and the inflation between 2011 and 2020 in the euro zone.
    - Mapping of inputs to country-specific sectors to: see Table 2-1. The countries were chosen according to the specified geographical scope (section 2.1.2), i.e. the Netherlands for the basic scenario. For sensitivity analyses, France and Hungary are chosen to cover European differences.

– Approach to foreground system:
  The foreground system includes the social risks associated with the work performed in a potential future UNRAVEL plant. Data on social performance in such plants could not be collected because similar plants do not exist yet at relevant scale. For this purpose, the chemicals sector was taken as a proxy for risks associated with a biorefinery according to the UNRAVEL concept. Only risks directly related to work in the chemicals sector were taken into account, not indirect risks resulting from purchases from other sectors.

Table 2-1: Mapping of inputs to sectors. Unless otherwise specified, the country of the plant location was used to select a country-specific sector.

Item	Sector(s)
Acetone (solvent make-up, product)	Chemical, rubber, plastic products
Activated carbon / biochar (sorbent)	Petroleum, coal products
Ash (to landfill)	Public Administration, Defense, Education, Health
Biomass: beech wood chips without bark	Forestry
Biomass: birch&bark	Forestry
Biomass: roadside grass	Public Administration, Defense, Education, Health
Biomass: wheat straw	Wheat
Boiler feed water, demineralised	Water
$Ca(OH)_2$	Mineral products nec
Calcium sulphate (to landfill)	Mineral products nec
CaO	Mineral products nec
Cellulase	Chemical, rubber, plastic products
Cooling	Electricity
Corn steep liquor	Food products nec
Diammonium phosphate	Mineral products nec, Chemical, rubber, plastic products
DMP waste to chemical incinerator	Public Administration, Defense, Education, Health
Ethyl carbonate (EC)	Chemical, rubber, plastic products
EC modified lignin	Chemical, rubber, plastic products
Ethanol (solvent make up)	Chemical, rubber, plastic products
HCl	Chemical, rubber, plastic products
Heating	Gas manufacture and distribution
K_2CO_3	Mineral products nec
NaOH	Chemical, rubber, plastic products
Na-Xylonate (product)	Chemical, rubber, plastic products
Power	Electricity
Process water	Water
Stillage (treated, to field)	Mineral products nec, Chemical, rubber, plastic products
Sulphuric acid (H_2SO_4)	Chemical, rubber, plastic products
Tap water	Water

TMP modified lignin	Mineral products nec
TMP purge to chemical incinerator	Public Administration, Defense, Education, Health
Trimethyl phosphate (TMP)	Chemical, rubber, plastic products
Truck transport	Transport nec
Wastewater	Public Administration, Defense, Education, Health
Water purge to chemical incinerator	Public Administration, Defense, Education, Health
Direct Labor, Administration & Corporate, Sales Expense	Chemical, rubber, plastic products foreground
Indirect Labor	Business services nec

2.3 Specific definitions and settings for SWOT analysis

The social life cycle assessment, which constitutes the main methodology to assess social sustainability aspects in this study, predominantly covers social risks in the supply chain on a rather general level. This needs to be supplemented by analyses of social aspects specific to the analysed system itself and of social benefits. In projects like UNRAVEL, technologies are developed that are not yet implemented and, hence, possibilities for stakeholder engagement as a basis for such an analysis of social aspects are very limited. Therefore, an interactive SWOT workshop on **strengths, weaknesses, opportunities and threats regarding social aspects of the UNRAVEL systems** was conducted with all project partners because they are connected to current and future stakeholder groups of potential biorefineries according to the UNRAVEL concept.

A SWOT analysis is a tool that can be used to assess the performance of any venture, whether it is a project, a product or a company or specific aspects thereof. It originates from business management and is a strategic planning tool to identify and assess the Strengths (S), Weaknesses (W), Opportunities (O) and Threats (T) of the system under study. Strengths and weaknesses are defined as internal characteristics of the assessed system, while opportunities and threats are external factors, determining the success or failure of the venture. The results of a SWOT analysis are generally summarised in a SWOT matrix. The general structure of a SWOT matrix is shown in Table 2-2.

Table 2-2: Structure of a SWOT matrix.

	Helpful factors to achieving the objective	**Harmful** factors to achieving the objective
Internal (attributes of the organisation/product)	Strengths	Weaknesses
External (attributes of the environment)	Opportunities	Threats

The aim of SWOT analysis in UNRAVEL is to detect, and thus account for, positive and negative social aspects that are not fully covered by the social life cycle assessment (sLCA).

The function of the SWOT analysis within UNRAVEL is to make sure that no key social factors for success or failure are omitted in the integrated sustainability assessment.

Social impacts can be very diverse and depend very much on the affected stakeholders. Which stakeholders are affected in turn depends very much on the life cycle stage. Therefore, separate SWOT matrices were set up for each life cycle stage:

- Input provision (chapter 5.1)
- Biomass conversion (chapter 5.2)
- Use phase of products (chapter 5.3)

Regarding input provision, the focus was laid on biomass provision because the remainder of the supply chain is firstly already covered extensively by the sLCA and, secondly, the participants in this project and workshop are lacking specific information on this part. Therefore, sLCA and SWOT analysis complement each other very well.

Within each life cycle stage, variants of the process were defined that could make a difference in social aspects and were treated in separate matrices. Then affected stakeholder groups were identified. Within each matrix, all potential social impacts were collected by stakeholder group.

The SWOT analysis was conducted as an internal online workshop on 30th September 2020 supplemented with a further round of offline extension of the collected inputs by all partners and collation of all inputs. Based on the outcomes, joint SWOT matrices comprising the aligned statements of the participants were elaborated.

2.4 Specific definitions and settings for biomass potential analysis

The motivation to know the sustainable, available amount of residual biomass feedstocks in the EU is driven by the aim to get this biomass into usage. To estimate the biomass potentials for the Unravel feedstocks at EU level, we performed a literature review based on peer-reviewed scientific literature and scientific project reports.

2.4.1 Definition of terms: different biomass potentials

Usually, for biomass potential analysis, a theoretical potential is calculated, which includes the total biomass stock e.g. grown in a certain area. To account for technical limitations due to losses during harvest, transportation or storage, a technical potential is differentiated. To furthermore specify the biomass potential that can be extracted without harming the environment, e.g. by reducing soil quality, in some cases studies communicate a "sustainable potential" (alternative nomenclature: "base potential"). In a second step shares for competing usage, and sometimes usage "under-construction", are deduced to get a "sustainable, available potential" (alternative nomenclature: "user potential", "removable potential").

2.4.2 Approaching inconsistencies within the data basis

We focussed on the lignocellulosic biomass feedstocks relevant for UNRAVEL by looking at wheat straw and other wheat-straw-like material (barley, rye, oat and rice straw), here also called "other cereal straw". Furthermore, roadside grass biomass potentials have been assessed. Forestry biomass feedstock potentials were approached exemplary by looking at beech wood and forest residues with focus on small birch branches with bark.

We found several high-quality reports and peer-reviewed publication with focus on biomass potentials in the EU which where suitable for a comparison of biomass potentials. The studies differed in several boundary conditions which had to be addressed for reliable results.

General inconsistencies

Main differences were varying scales and scopes within the studies examined for example in terms of the number of European countries (EU-27, EU-28, geographically). The methods used to estimate current and future biomass potentials ranged from geospatial analysis to yield and harvest statistics.

Whereas some studies reported the biomass potentials on a country-wise level, others showed their results on an overall European basis. If not stated otherwise the focus has been on EU-28. The differences between EU-27 and EU-28 concerning the biomass potentials are small and can therefore be neglected for the purpose of this study.

In terms of conversion factors e.g. for calculation of dry matter amounts from wet matter, the respective factors mentioned in the studies were used if not stated otherwise. The standard for this study was metric tonnes of dry matter per year (tonnes_{DM}/year).

Inconsistencies related to forest biomass

The terminology of „forest residues" was used in different ways for multiple biomass potential studies and reports. Most count branch material of differing size and tree tops to this biomass fraction, whereas needle/leaves, stumps, undergrowth trees, early thinning and complementary felling have been included in some studies only.

The biomass potential for forest residues can be derived by application of different methods. Studies in this field for example went via the national forestry inventories, applied statistical approaches or spatially methods. Furthermore, analysis can be expanded and complemented by wood market data.

The sustainable potential can include several and different sustainability assumptions besides the technical feasibility and availability already included in the technical potential. Dependent on the aim and scope of a study, the following sustainability aspects can be exemplary included to account for sustainable utilization, leading to a sustainable potential: recovery rate of the forest, soil bearing capacity, biodiversity protection, water protection and others [Boeraeve 2012].

As no EU-standard exists for fine woody debris removal limits, the respective countries set their own recommendations for sustainable harvesting of forest biomass. While Finnish guidelines recommend to leave 30 % of forest residues in the forest, French guidelines suggest a rate of 10 % - 30 % dependent on soil sensitivity to mineral exports [Bessaad et al. 2021].

Inconsistencies related to straw biomass

The straw biomass potential can be obtained by several methods like for example via statistical yields and product/residue ratios but also via spatially explicit modelling. Only few studies reported the biomass potential on species level [García-Condado et al. 2019], whereas most publications and reports focused on more general boundaries like crop type (cereals, oil crops) or type of residue (dry – straw and stubbles, wet – manure) to define the biomass stocks observed. As no study showed the sustainable, available potential of wheat straw, we applied the ratio in the sustainable, available potential between wheat straw and other cereal straw based on scientific literature [García-Condado et al. 2019; EuroStat 2020] if the studies did not report this ratio. The ratio applied was: 65 % wheat straw and 35 % other cereal straw. García-Condado et al. [2019] did not report a sustainable potential or a sustainable, available potential.

Wheat/cereal straw has been accounted under multiple different terms, like: “straw and stubbles”, “agricultural waste”, “removable straw” or “cereal residues”. This also includes the question whether maize, sunflower and rapeseed straw has been addressed together with cereals. Additionally, the definition of “sustainable, available potential” varied widely as the term “sustainable” could be defined in various ways (e.g. due to different methods to calculate the soil carbon stock balance).

Furthermore, the projections and scenarios of biomass development within the future are also highly different. For example, in the S2Biom project [S2Biom-Project 2012; S2Biom et al. 2017] a decreasing development has been scheduled, while scenarios developed by Building Research Establishment (BRE) [BRE et al. 2015] reported an increase in biomass potentials for technical and sustainable technical biomass potentials in future.

Concerning differences in the definition of sustainable, available biomass potentials, BRE [2015] took a proportion of 33 % of the total technical potential for competing demands and another 33 % for sustainability constraints, while BiomassPolicies [2016] used a fixed removal rate of 40% for cereals. In BioCore [2012] the “removable straw” has been calculated with respect to competing usage and in order to maintain the soil carbon stock balance based on EUROSTAT data and with data derived from the European Office for Statistics. S2Biom [2017] applied the sustainable guidelines of the CAP (Common Agricultural Policy) and added restrictions for protected areas and restrictions as a result of RED (Renewable Energy Directive). However, no deduction for competing usage has been included as the “base potential” instead of the “user-defined potential” has been taken here. This leads to a slight overestimation, but offers the possibility to look at the shares of different feedstocks accordingly. Scarlat et al. [2010] used sustainable removal rates and accounted for different types of competing usage (e.g. animal bedding, mushroom production and mulching in horticulture). Scarlat et al. [2019] mainly focussed on soil organic content as sustainability constrain, using spatially explicit modelling approaches. This study is an update of Scarlat et al. [2010].

Inconsistencies related to roadside grass biomass

In general, the roadside grass biomass potential can be calculated for example via street registers/cadastre or by aerial photographs [Hamelin et al. 2019]. However, the methods applied where unfortunately rarely described in the studies.

The studies differed in terms of the type of potential specified (technical vs. theoretical potential) and the type of infrastructure included as Hamelin et al. [2019] focussed on the theoretical potential, including the railway network besides motor ways, primary ways and trunk ways. Furthermore, shrub cuttings and leaves where included also. Additionally, the reported value has been specified for wet matter. For better comparability, we took the ratio of grassy to woody biomass described the scientific literature [BioRest 2019] and estimated a moisture content of 40% for the grassy feedstock component and 20% for the woody feedstock part for this study. The other two studies [BiomassPolicies et al. 2016; S2Biom et al. 2017], however, showed the technical biomass potential for road side grass.

Different assumptions about the future development of this feedstock component were taken into account. While S2Biom [2017] accounted for a small increase of the road network, BiomassPolicies [2016] set a constant roadside biomass potential.

In summary, the main differing boundary conditions where: number of countries, different methods to estimate the biomass potentials as well as different assumptions to set a sustainable potential, different set of included biomasses, different assumptions on the future increase or decrease in crop yield and cultivation area or of the development of road construction. Beside few different assumptions and slightly differing boundary condition, the different studies could be included to show the range of biomass potentials and to subsequently conclude on available biomass stocks in the EU.

3 System description

3.1 Overview of the UNRAVEL concept

An overview of the UNRAVEL concept is depicted in Figure 2. The feedstocks and products for the sustainability analysis are indicated in blue text.

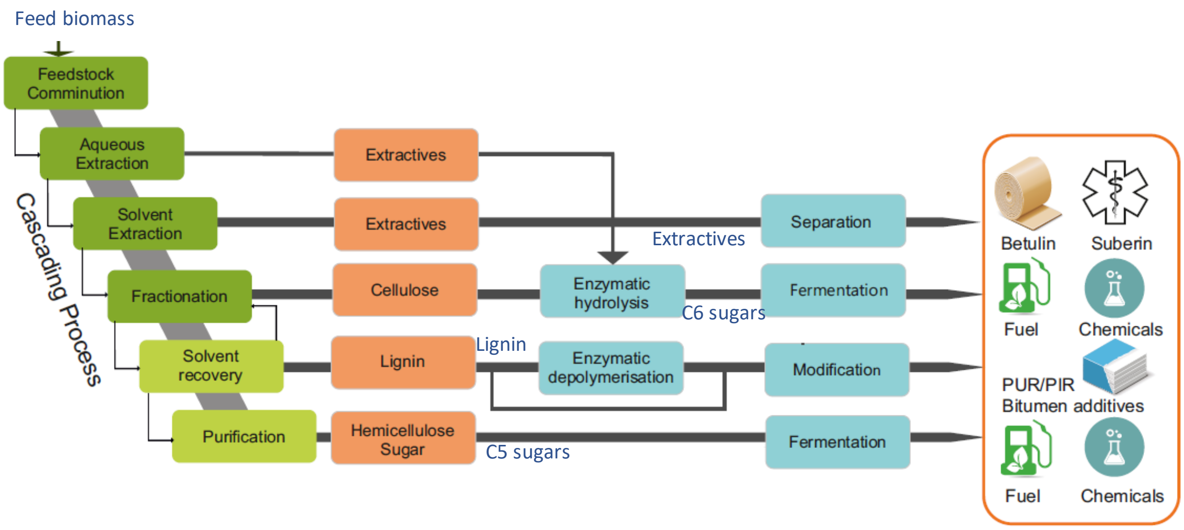

Figure 2: Overview of all sections and main products in the UNRAVEL concept. Feedstocks and products for the sustainability analysis are indicated in the blue text outside of the boxes.

Feedstock biomass is comminuted to the required particle size. Extraction by an aqueous medium and/or a solvent (biomass pre-extraction) is done to improve in particular downstream processing, lignin purity, C5 sugar yield and offers the possibility of extractives valorisation. The comminution and pre-extraction steps are both optional and may depend on feedstock type and composition.

The main step is then fractionation by the organosolv process. The key technology evaluated is the aqueous acetone fractionation, known as the Fabiola™ process. This involves treatment in a mixture of acetone, water with acid added in order to separate the biomass into the three main fractions: lignin, cellulose and hemicellulosic sugars. Lignin application in PUR/PIR foams or as a filler in polymers is being studied. The cellulose is sent to enzymatic hydrolysis after which the resulting C6 sugars are used for fermentation towards chemicals. Specifically, fermentation towards acetone is considered in the analysed scenarios. The (detoxified) C5 sugars are also fermented towards fuels or chemicals. Specifically, fermentation towards xylonate (i.e. sodium xylonate, the sodium salt of xylonic acid) is depicted in the scenarios.

3.2 Scenarios

This section describes the analysed UNRAVEL scenarios. The scenarios analysed within the environmental assessment are summarised in Table 3. More information on the particular scenarios is described in sections 3.2.1 - 3.2.12. While in section 3.2.1 the basic scenario is described in detail, sections 3.2.2 - 3.2.12 highlight the differences compared to the basic scenario. All analysed scenarios are based on mass and energy balances from detailed process modelling, which is described in detail in D6.3 on process design [Dijkstra & Luzzi 2022].

Table 3: Final selection of scenarios analysed within the environmental assessment.

Scenario	Description	Section
Beech wood		
Basic scenario (beech)	Feedstock: beech stemwood, C5 fraction used for production of xylonate, C6 fraction used for production of acetone, lignin used for production of polyols for PUR/PIR via EC modification; residues to CHP.	3.2.1
Lignin to fillers	Difference to basic scenario: lignin used for production of light weight fillers via TMP modification.	3.2.2
Residues to heat only	Difference to basic scenario: heat plant instead of CHP.	3.2.3
Lignin combustion	Difference to basic scenario: lignin exported for combustion as benchmark.	3.2.4
Reference	Difference to basic scenario: fractionation via ethanol organsolv instead of Fabiola™ fractionation process.	3.2.5
Herbaceous biomass		
Wheat straw	Difference to basic scenario: feedstock: wheat straw instead of beech stemwood.	3.2.6
Wheat straw, pre-extraction	As wheat straw, pre-extraction process before fractionation.	3.2.7
Roadside grass, pre-extraction	Difference to basic scenario: feedstock: roadside grass instead of beech stemwood, pre-extraction process before fractionation.	3.2.8
Hardwood branches incl. bark		
Birch & bark	Difference to basic scenario: feedstock: birch branches including bark instead of beech stemwood.	3.2.9
Birch & bark, pre-extraction	As birch & bark, pre-extraction process before fractionation.	3.2.10
Mixed feedstock (birch & bark + wheat straw)		
Mixed feedstock, alternating	Alternating feedstock campaigns (based on wheat straw, pre-extraction and birch & bark, pre-extraction).	3.2.11
Physically mixed feedstock	Physically mixed feedstock (based on wheat straw, pre-extraction and birch & bark, pre-extraction).	3.2.12

3.2.1 Basic scenario (beech)

In this section, the basic scenario is described. In the basic scenario beech wood is used as biomass and lignin is used to produce polyols for PUR/PIR foams via EC (ethylene carbonate) modification (Figure 3).

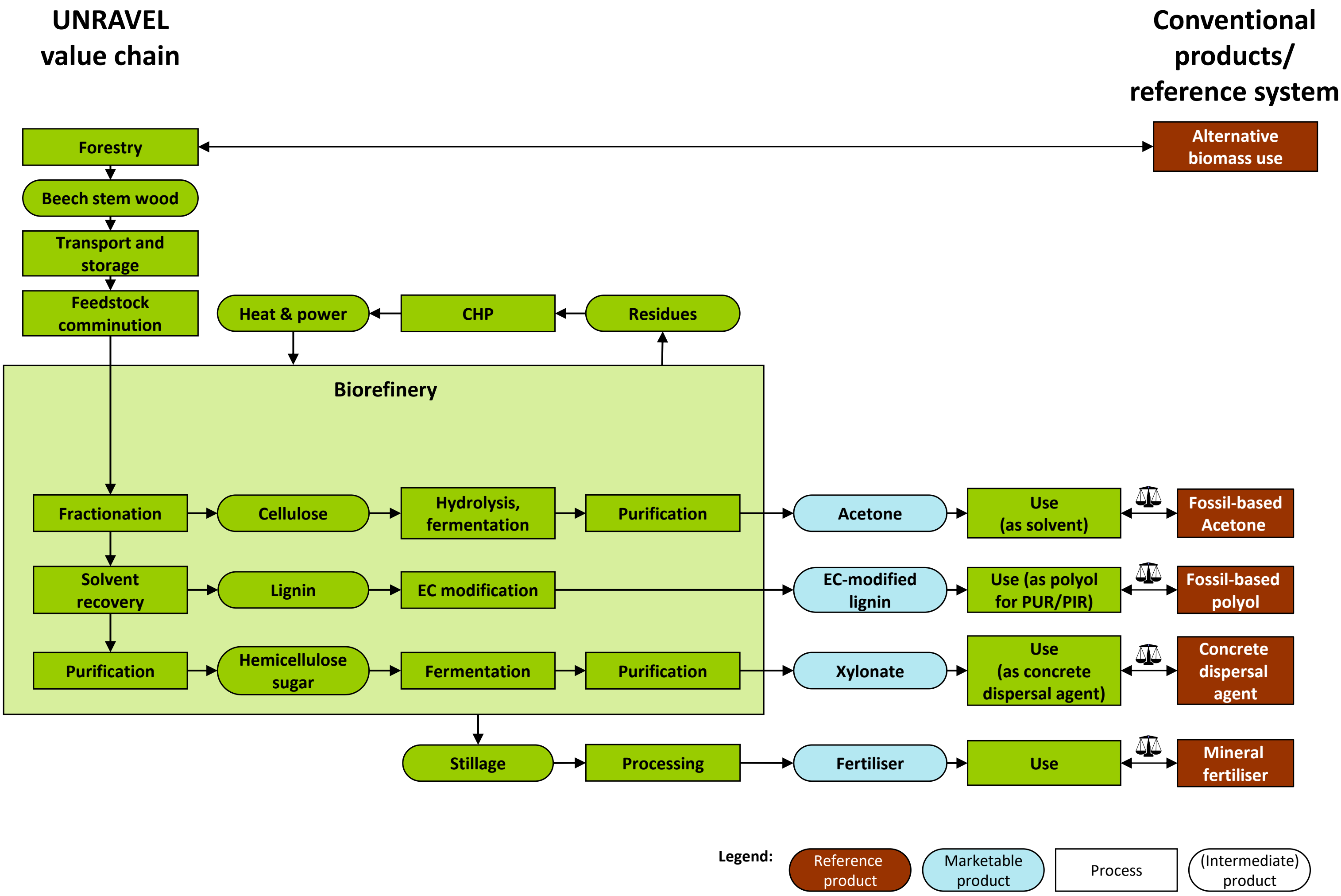

Figure 3: Life cycle scheme of the basic scenario (beech).

This scenario uses beech stemwood in pulp wood / energy wood quality such as obtained from forest thinnings. After harvesting the beech stemwood, it is *transported*, *stored* and again transported to the biorefinery. The plant is assumed to be a greenfield plant with a capacity of processing 300 000 t biomass (dry matter) per year. In *feedstock comminution* the beech stemwood is chipped.

Afterwards, the sized feedstock is *fractionated* within the Fabiola™ fractionation process based on acetone organosolv technology. Beech wood is pre-heated with steam after which Fabiola™ fractionation is performed in batch-wise mode using a mixture of acetone with water and sulphuric acid.

C6 pathway

From the resulting slurry, pulp is separated and washed with a solvent/water mixture and then with water. The resulting liquid streams are recycled and the wet cellulose pulp is sent to *enzymatic hydrolysis*. Here, cellulase enzymes are added to produce glucose from the pulp. Enzymes are bought from outside the biorefinery. From the resulting slurry the solid residue is filtered off, and the export aqueous C6 sugars stream with mainly glucose is obtained.

Lignin is precipitated using the LigniSep process: The liquor from pulp filtration is mixed with solvent depleted lignin dispersion and is pumped to a falling film evaporator where solvent preferentially evaporates and that is connected to a precipitation vessel.

The preferential evaporation of solvent in the falling film evaporator results in a low solvent content of the slurry, which induces the lignin precipitation in precipitation vessel. The solvent rich overhead vapour of the falling film evaporator is sent to a distillation where part of the water and the small amounts of furfural are removed. Minor amounts of CO_2 being formed during fractionation are stripped off before this stream is recycled. With this stream also some other light components are removed, if present.

Afterwards, nutrients, sodium hydroxide for pH control and microorganisms inoculum are added for the *fermentation*. The fermentation is aerobic and hence, the fermenter is sparged with air and is a batch process. Acetone is both recovered from the condensate of the overhead vapour as well as from the fermentation broth. Both streams are sent to an acetone recovery column where acetone is obtained via the top stream and stillage as the bottom product.

Lignin pathway

The lignin slurry from precipitation is sent to a separation step to recover lignin. The lignin is washed with water to recover the attached acetone. The resulting wet lignin is dried to obtain the core process lignin intermediate. From the large variety of possible lignin valorisation the route selected for the UNRAVEL project is to modify lignin with EC (ethylene carbonate) for application in PUR/PIR foams. For this, lignin is first milled to a sufficiently small particle size. The PUR/PIR application requires a very low moisture content of the lignin and drying is necessary. The dried lignin is then undergoing the *EC-modification* in which it is functionalized into a polyol with desired properties. The lignin-based polyol then replaces parts of the polyol that is used as one of the two main feedstocks for PUR/PIR production.

C5 pathway

Spent liquor is sent to the C5 column where the remaining solvent is removed and recycled to produce a crude C5 sugars stream. This stream is sent to detoxification to remove toxic compounds for the fermentation process and results in the C5 sugars product stream (hemicellulose sugar).

Nutrients and microorganisms inoculum is added to the hemicellulose sugar stream for the *fermentation* to xylonate. The fermentation is aerobic hence the fermenter is sparged with air, and is a (fed) batch process. Sodium hydroxide is added for pH control. The product stream is then *purified* using small amount of sorbent for decolouration. Multi-effect evaporation of water is used to concentrate after which the sodium xylonate is obtained via cooling crystallisation, after which it can be filtered, dried and obtained as the final xylonate product stream. More specifically, this stream is sodium xylonate, which is the sodium salt of xylonic acid.

Solvent recycling and residue valorisation

All recycle streams containing a mixture of solvent and water are recycled to the organosolv pulping feed stream. A make-up solvent stream compensates for any solvent losses. All residues emerging within the above mentioned life cycle stages inside the biorefinery are used as feedstock in a combined heat and power plant (CHP). The obtained heat and power is used in the biorefinery and therefore reintegrated.

Replaced conventional products

1 kg of modified lignin replaces 1 kg of polyols that are synthesised from fossil-based petrochemicals in an application for PUR/PIR foams. Acetone replaces chemically identical fossil-based acetone, which is produced by standard petrochemical processes (mainly via the cumene process). Xylonate replaces gluconate that is otherwise produced via a similar fermentation process as modelled for the UNRAVEL scenarios from a range of conventional "1st generation" sugars on a 1:1 molar basis in an application as concrete dispersal agent.

3.2.2 Lignin to fillers

In the scenario 'lignin to fillers', the lignin is undergoing a *trimethyl phosphate* (*TMP)-modification* instead of EC-modification. The TMP-modified lignin then replaces glass bubbles that are used as light weight polymer fillers.

3.2.3 Residues to heat only

In the scenario 'residues to heat only', all residues emerging in biorefinery processes are used as feedstock in a heat plant instead of a CHP. Therefore, only heat is reintegrated in the biorefinery processes that would otherwise be produced by natural gas.

3.2.4 Lignin combustion

In the scenario 'lignin combustion', the lignin is not used for producing high value chemicals but energetically as a solid biofuel.

3.2.5 Reference

In the reference scenario the currently common state-of-the-art ethanol organosolv fractionation process is used instead of the Fabiola™ acetone organosolv process utilising acetone instead of ethanol as a solvent. Using ethanol as a solvent instead of acetone impacts the fractionation yields. Ethanol also reacts with C5 sugars to produce ethylated sugars for which no application is considered. The relative volatility of solvent (compared to water) is lower for ethanol resulting in a higher heat demand in solvent recovery, as well as the necessity for an additional rectification column to achieve the required solvent concentrations in the lignin precipitation section.

3.2.6 Wheat straw

In the 'wheat straw' scenario wheat straw is used as biomass feedstock instead of beech wood. Alternatively, other cereal straws such as barley straw could be used with similar performance.

3.2.7 Wheat straw, pre-extraction

In the scenario 'wheat straw, pre-extraction' also wheat straw is used as biomass feedstock instead of beech stemwood (Figure 4). Furthermore, a pre-extraction process using water and acetone is added before fractionation of the biomass: The biomass is washed with water/solvent mixtures at elevated temperature to wash out unwanted components primarily to improve biomass fractionation characteristics. The biomass including residual acetone is sent to the fractionation process. The resulting extractives stream is sent to *wastewater treatment*. Currently, no technically viable route for valorisation of extractives obtained during pre-extraction could be identified and valorisation therefore has not been considered.

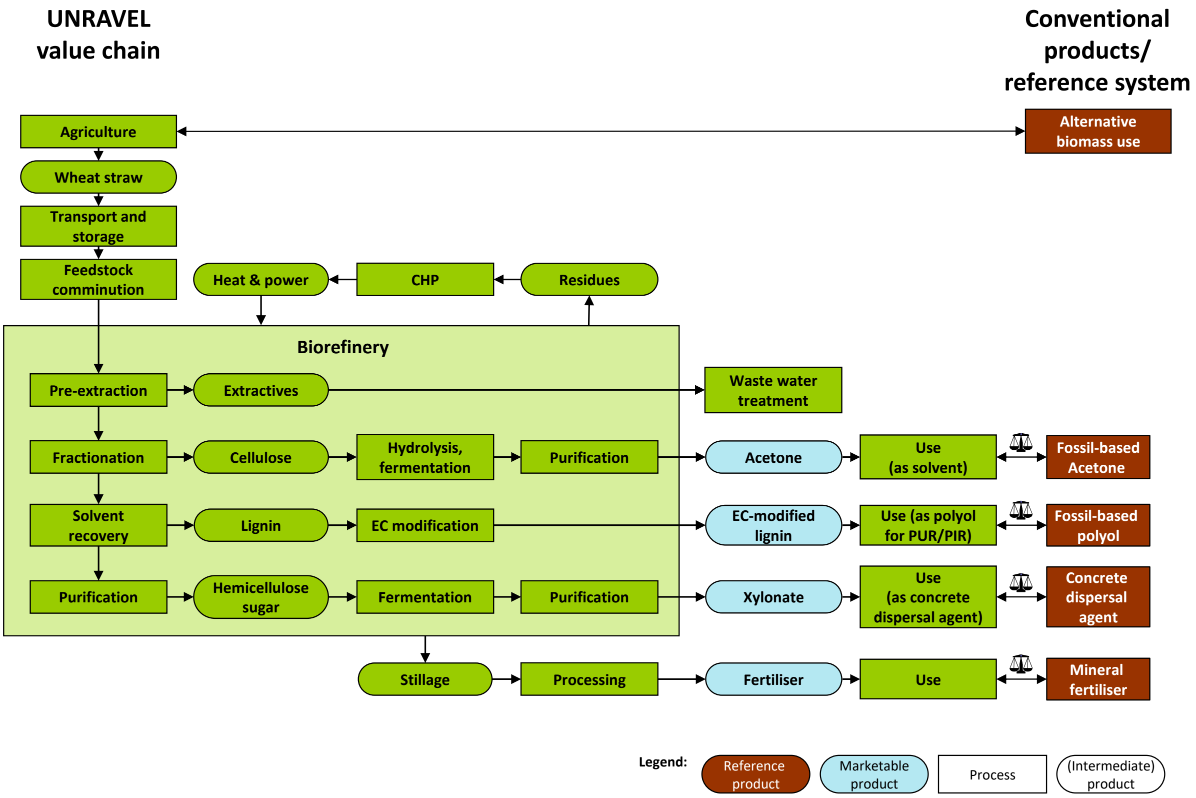

Figure 4: Life cycle scheme of the scenario 'wheat straw, pre-extraction'.

3.2.8 Roadside grass, pre-extraction

In the scenario 'roadside grass, pre-extraction', roadside grass is used as biomass feedstock instead of beech stem wood. As in scenario 'wheat straw, pre-extraction', the fractionation process is preceded by a pre-extraction process (see section 3.2.7)

3.2.9 Birch & bark

In the 'birch & bark' scenario branches and tops of birch trees including their bark and residual foliage is used as biomass feedstock instead of beech stemwood.

3.2.10 Birch & bark, pre-extraction

In the scenario 'birch & bark, pre-extraction' also branches and tops of birch trees including their bark and residual foliage is used as biomass feedstock instead of beech stemwood. Furthermore, as in scenario 'wheat straw, pre-extraction', the fractionation process is preceded by a pre-extraction process (see section 3.2.7).

3.2.11 Mixed feedstock, alternating

In the scenario ‘mixed feedstock, alternating’ wheat straw and branches and tops of birch trees including their bark and residual foliage are used in alternating campaigns as biomass feedstock instead of beech stemwood. Furthermore, as in scenario ‘wheat straw, pre-extraction’, the fractionation process is preceded by a pre-extraction process (see section 3.2.7). The feed considered is 50% for each feedstock on a dry weight basis.

3.2.12 Physically mixed feedstock

In the scenario ‘physically mixed feedstock’ wheat straw and branches and tops of birch trees including their bark and residual foliage are mixed physically and then used as biomass feedstock instead of beech stemwood. Furthermore, as in scenario ‘wheat straw, pre-extraction’, the fractionation process is preceded by a pre-extraction process (see section 3.2.7). The feed considered is 50% for each feedstock on a dry weight basis.

4 Results sLCA

A social life cycle assessment (sLCA) was carried out for the conversion of second generation biomass from forestry and/or agriculture into chemicals and building materials. For details on the methods and analysed systems see chapter 2 and 3, respectively. First, an overview over social risks connected to the basic scenario (see definition in section 3.2.1) is given in section 4.1. Afterwards, the influence of several parameters on these risks is analysed: feedstock, location and pre-extraction in section 4.2, core process in section 4.3 and product portfolio in section 4.4.

4.1 Overview over social risks: basic scenario

Social risks associated with different inputs of the biorefinery are assessed for all social risks provided by the SHDB aggregated in 25 subcategories (compare section 2.2). These risks are contrasted with the avoided risks in order to put them into context. Figure 4-1 shows the social risks for the basic scenario displayed in work-hours needed for the conversion of 1 tonne of dry biomass that are equivalent to work-hours at medium risk.

The category "Health and safety" comprising the subcategories "Occupational toxics & hazards" and "Occupational injuries & fatalities" as well as the category "Governance" comprising the subcategories " Legal system" and "Corruption" dominate the social risks (Figure 4-1). Furthermore, the subcategory "High conflict zones" in the category "Human rights" shows high risks. For all sub-categories, the contributions of the individual biorefinery inputs and products to the risks and avoided risks as well as the ratio of risks to avoided risks are very similar. Therefore, the further analysis can be based on aggregated social risks (Figure 4-2).

Figure 4-2 shows that social risks connected to the UNRAVEL biorefinery concept and risks that are avoided because conventional products are replaced are similarly high under typical conditions. Under optimistic and conservative boundary conditions, risks are moderately lower and higher, respectively, than avoided risks.

The highest risks in the supply chain arise from the provision of lignin modifier and biomass, followed by energy and transportation. Work in the biorefinery itself only contributes to a smaller extent to overall risks. Within the biorefinery, highest risks are to be expected for occupational health and safety issues. Although the analysed location of the plant and of its direct (tier 1) suppliers is the Netherlands, more than 85% of the work-hours at risk are done at higher tier suppliers outside of the Netherlands and mostly outside of the EU.

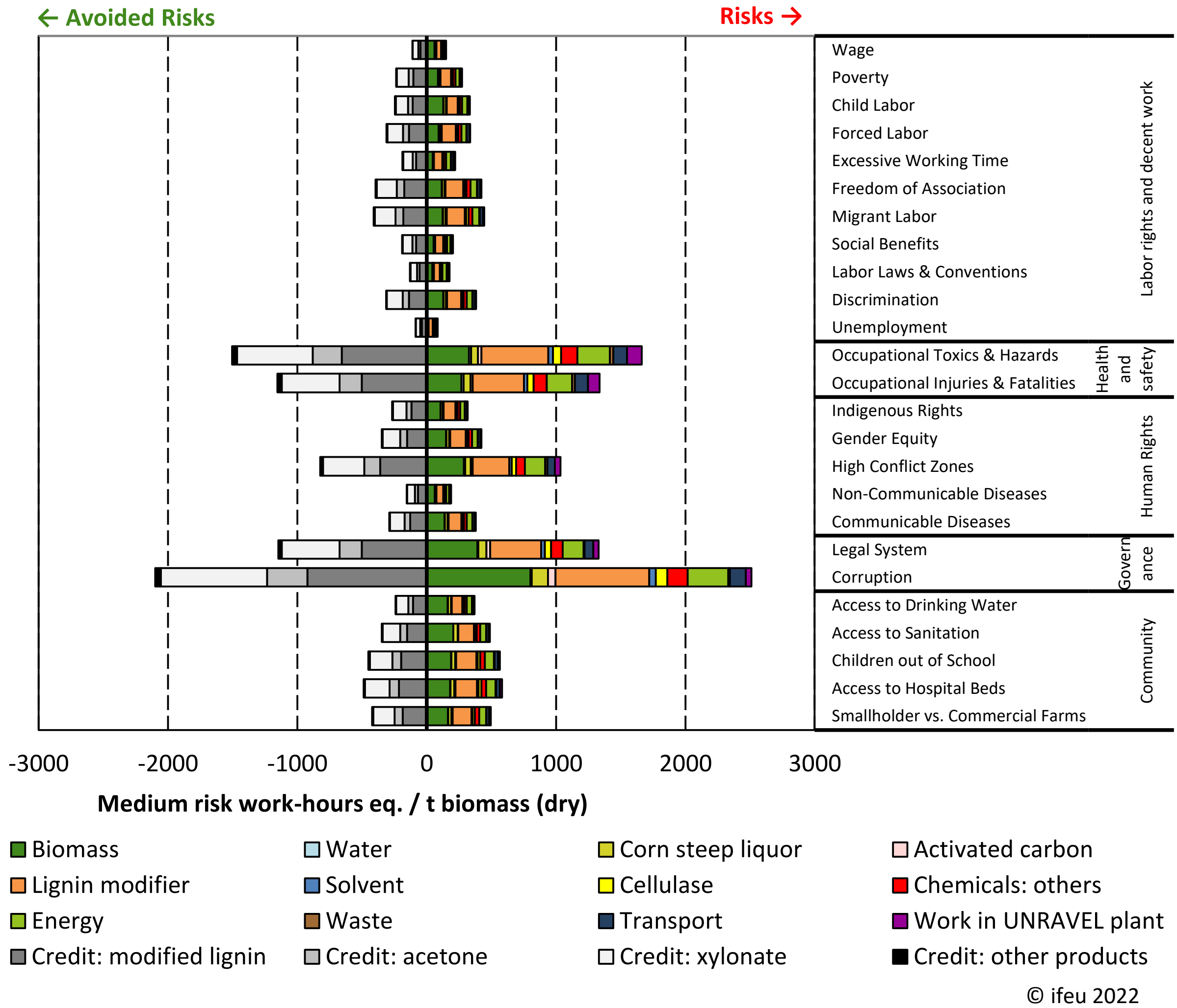

Figure 4-1: Overview of social risks and avoided risks at subcategory level of the basic scenario: Biomass feedstock: beech wood; country: Netherlands; boundary conditions: typical.

How to read the figure: Using the example of the social subcategory 'occupational toxics & hazards' belonging to the social category "Health and safety": the bar sections on the right illustrate that the work in the UNRAVEL plant and in the supply chain in the basic scenario is associated with about 1700 work-hour equivalents at medium risk in this subcategory per ton of dry biomass input. About 1500 work-hour equivalents at medium risk can be avoided because conventional products and their production are replaced by the UNRAVEL products.

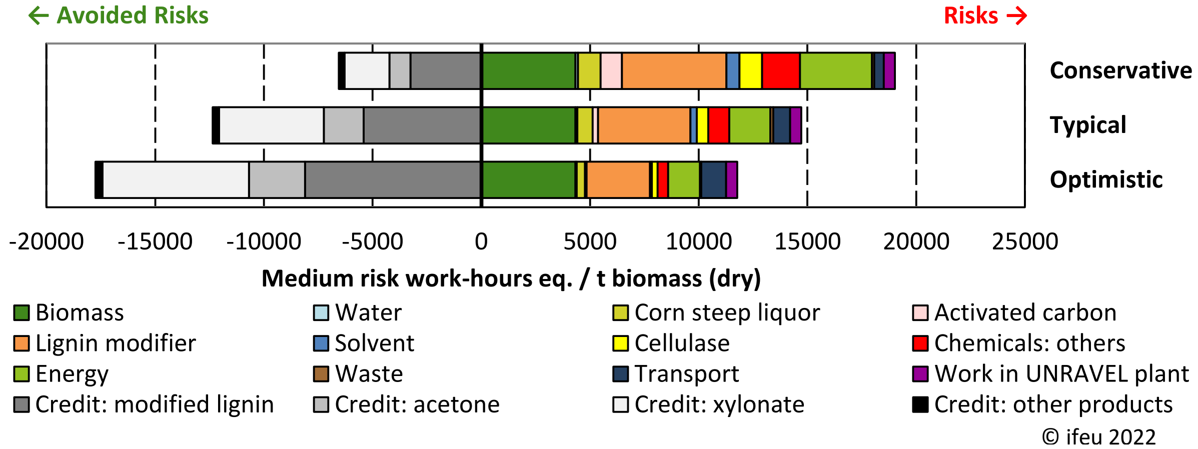

Figure 4-2: Range of aggregated social risks associated with the basic scenario. Results for sub-scenarios under conservative, typical and optimistic boundary conditions are displayed. Contributions are grouped by kind of inputs and outputs. Biomass feedstock: beech wood; country: Netherlands.

How to read the figure (2nd bar): Under typical boundary conditions, the work in the UNRAVEL plant and in the supply chain is associated with overall social risks corresponding to about 15 000 work-hour equivalents at medium risk per ton of dry biomass input. About 13 000 work-hour equivalents at medium risk can be avoided because conventional products and their production are replaced by the UNRAVEL products. These overall social risks correspond to the sum of all individual social risks displayed by sub-categories in Figure 4-1. The other bars represent the same scenario modelled under more or less favourable boundary conditions including technological development.

Key findings:

- Highest social risks in the basic scenario for a potential future UNRAVEL biorefinery are connected to the provision of lignin modifier and biomass. Considerable further risks arise from other input chemicals and, depending on process efficiency, also from used energy and transportation.
- Most relevant social risks originate from Occupational Toxics & Hazards, Corruption, Injuries & Fatalities, Legal system, High conflict zones
- Work in the plant itself is only connected to comparatively low risks, mainly related to occupational health and safety.
- Although the analysed location of the plant and of its direct (tier 1) suppliers is the Netherlands, more than 85% of the work hours at risk take place at higher tier suppliers outside of the Netherlands and mostly outside of the EU.
- This scenario of the biorefinery is connected to social risks overall comparable to those of competing conventional products. Nevertheless, appropriate mitigation measures for social risks are necessary in particular for these hot spots.

4.2 Influence of feedstock, location and pre-extraction

This section analyses the influence of feedstock-related choices of biorefinery designers and operators on social risks.

The different options for feedstocks and pre-extraction of these feedstocks analysed in this project show very similar social risks in the Netherlands, which are set as primary example of a potential location (Figure 4-3). Although lower value feedstocks like roadside grass are mostly associated with lower risks this is compensated by lower product yields from these feedstocks and thus also lower avoided risks.

Comparing feedstocks from different European countries, substantial differences in social risks can be observed (Figure 4-4). It is however difficult to compare these risks because the social hotspot database, from which the risk data originates, is based on an economic multi-regional input/output model that averages risks on a quite coarse level of economic sectors and based on 2011 price levels in US$. Thus, different developments of price levels and exchange rates for each country and for local and international trade have to be taken into account that. This could only be done in a rough approximation in this study for some examples (Figure 4-5).

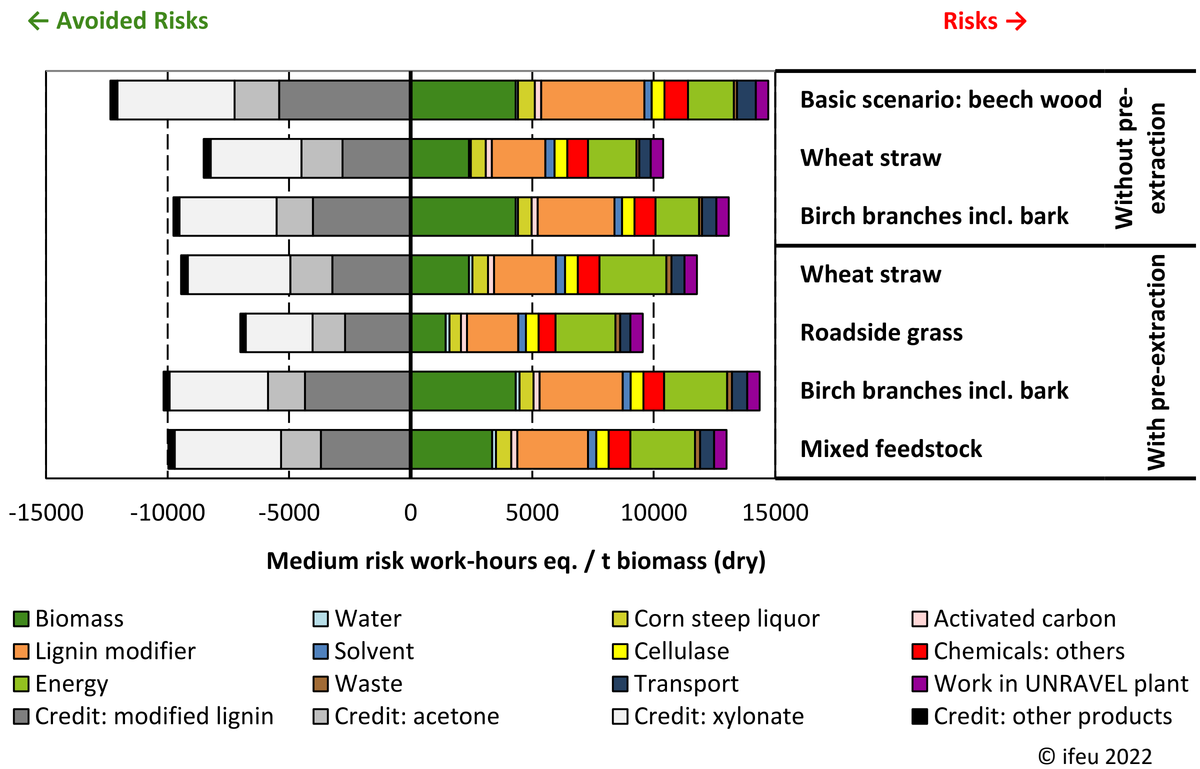

Figure 4-3: Aggregated social risks associated with different biomass feedstocks and with or without biomass pre-extraction. Country: Netherlands; boundary conditions: typical.

Figure 4-5 shows that levels for social risks tend to be higher for biomass originating from Eastern European countries although differences are much smaller than in a comparison that does not take different price levels into account (compare to Figure 4-4). This is also reflected in the fact that the biggest share of social risks associated with Western European biomass does not stem from Western European but is contributed by higher tier foreign suppliers (for example suppliers that supply suppliers of European farmers), which are mostly located outside of the EU. In contrast, domestic risks are more relevant or even dominant in Eastern European countries. In any case, social risks for biomass supply are relevant and need to be managed with priority.

The social hot spots in the biomass supply chains as they are provided by the social hotspot database seem more or less conclusive depending on the sector of origin of the biomass. As a very intuitive example, the highest risks given for wheat straw provision in the Netherlands arise from wheat farming itself but make up only around 30% of the total risks. The next biggest contributors are chemical industries in various countries including China and USA supplying Dutch farmers and "business services" summarising various activities not contained in other sectors. In contrast, highest risks given for wood provision in the Netherlands are specialty crops sectors in Nigeria, Ghana, Kenya, Uganda and Ivory Coast totalling 35% of the risks while forestry in the Netherlands itself contributes 6% of overall risks. This seems to be an artefact from the connection of respective sectors in the underlying model possibly originating from strong trade of life plants in the Netherlands, which could be seedlings for forestry but may in this case be exceptionally dominated by ornamental plants. Thus, social hotspots identified based on the social hotspot database are a good starting point for a risk management concept but need to be analysed in detail to derive concrete measures.

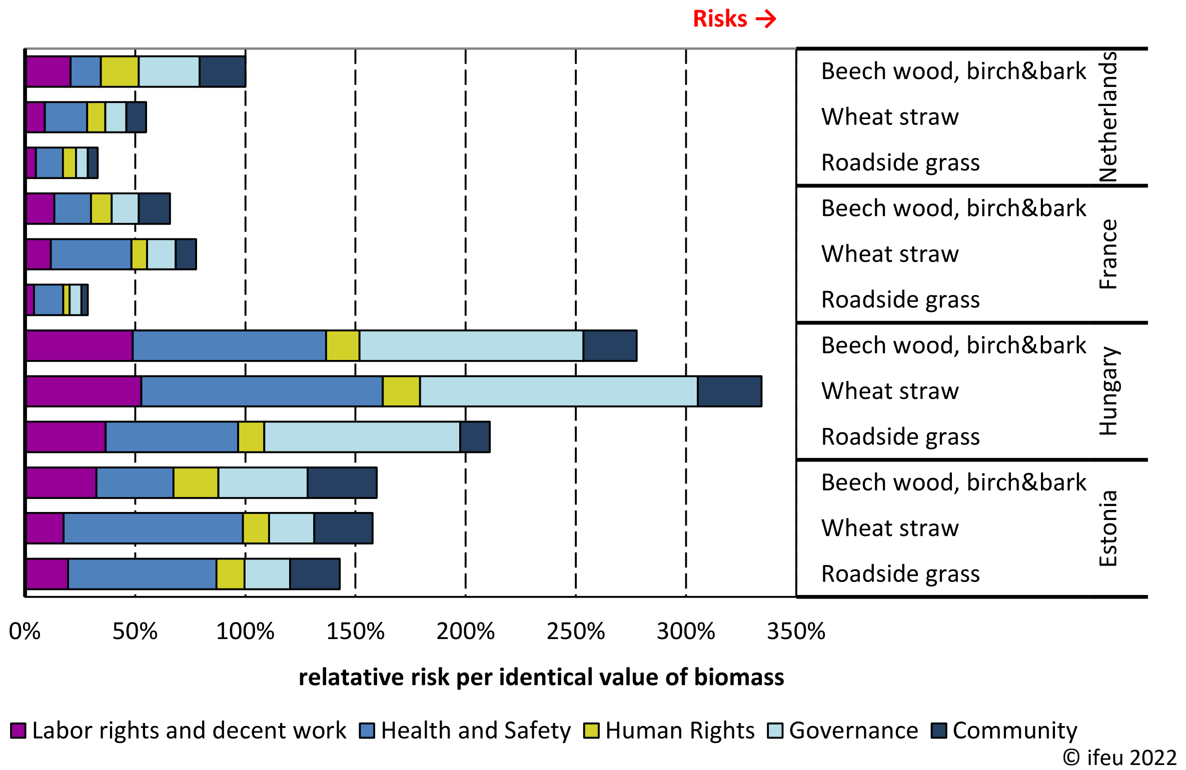

Figure 4-4: Relative aggregated social risks for different biomass feedstocks from different countries of origin.

How to read the figure: The 1st bar shows the social risks connected to the feedstock and country of origin of the basic scenario and is set to 100%. The other bars show relative social risks for other feedstocks and countries of origin for the purchase of identical values of biomass. For further analyses, different price levels for each country and for local and international trade have to be taken into account.

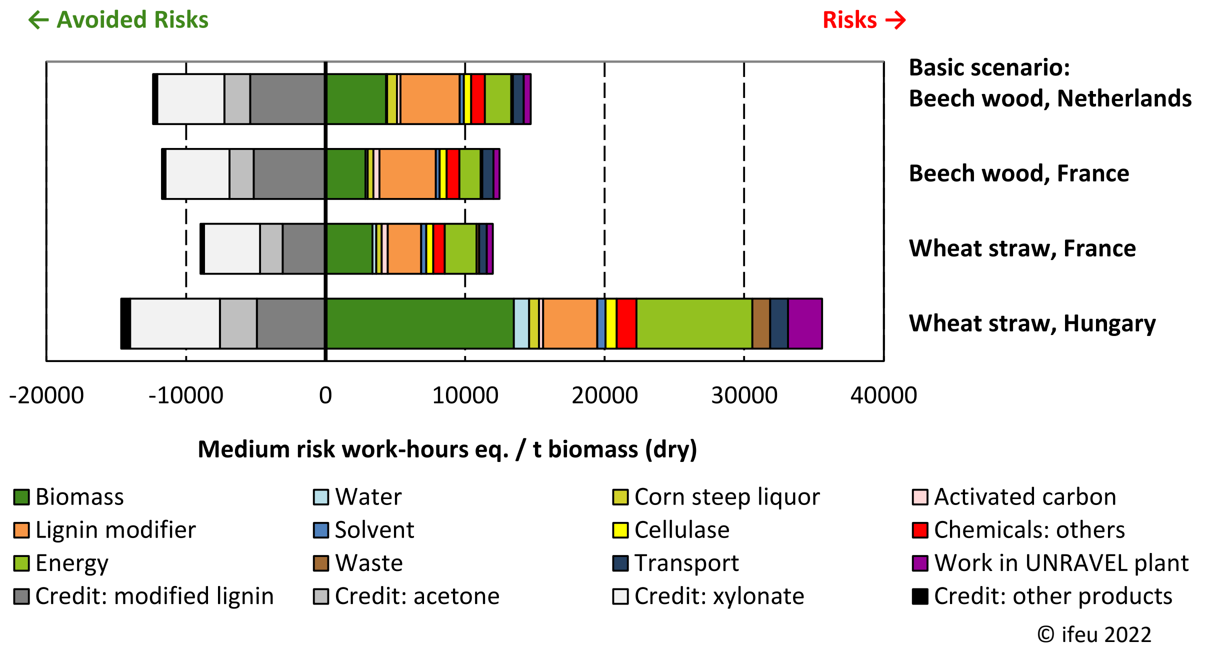

Figure 4-5: Aggregated social risks associated with different biomass feedstocks and countries of origin. Boundary conditions: typical.

Key findings:

- The choice of biomass can substantially influence overall social risks. However, the country of origin of a feedstock tends to be more important for the connected social risks than the kind of feedstock from any given country.
- Feedstocks from analysed Western European countries tend to show lower risks than from analysed Eastern European countries despite uncertainties in the data.
- Some data provided by the Social Hotspot Database on supply chain risks in whole sectors seems less suitable for the concrete feedstocks analysed here. This particularly applies to Dutch forestry. For these feedstocks, overall risks are expected to be overestimated.
- None of the analysed European biomass feedstocks brings about exceptionally high risks further down in the supply chain that could hardly be managed. Therefore, feedstock choice can concentrate on other selection criteria if risk mitigation measures are ensured.
- The combination of feedstock and pre-extraction concept does not substantially change social risks or social hotspots. Therefore, overall social risks and risk mitigation measures are largely independent of the presence of a pre-extraction process.

4.3 Influence of core process

One central goal of the UNRAVEL project is to improve a variant of the organosolv process using acetone instead of ethanol as solvent for biomass fractionation. In terms of social risks, both processes perform very similar (Figure 4-6). Specific differences originate mainly from different conversion efficiencies of the individual lignocellulose fractions and thus different shares of the products in the product portfolio. This is in agreement with the previous finding that chemical engineering variants do not influence social risks much (compare Figure 4-3). Despite gradual changes, social hot spots in the supply chain that require monitoring stay the same.

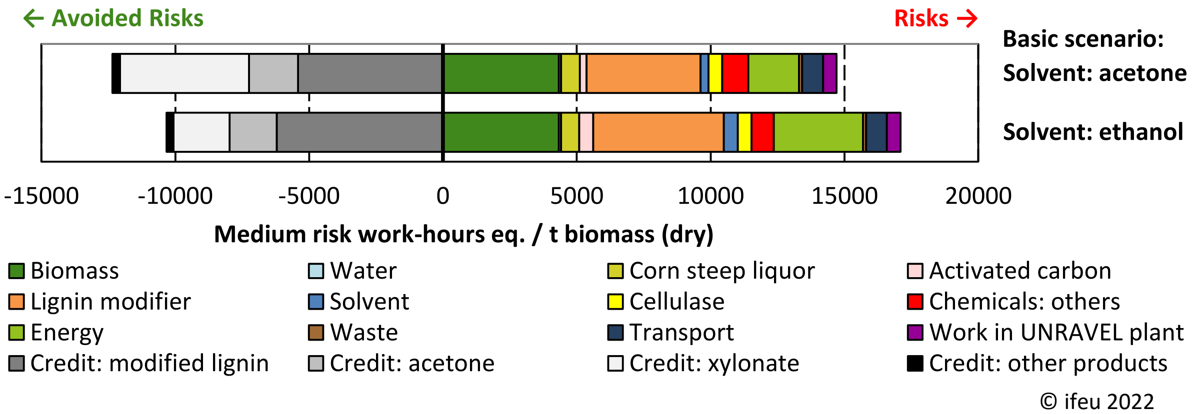

Figure 4-6: Aggregated social risks associated with different versions of the organosolv process. Country: Netherlands boundary conditions: typical.

4.4 Influence of product portfolio

The lignocellulose fractions cellulose/C6, hemicellulose/C5 and lignin can each be converted into a variety of products. Conversion processes can be very different and each of these products replaces other conventional products thus avoiding other social risks. One example that is central to the UNRAVEL concept is the variety of lignin use options. Lignin can be modified with ethylene carbonate to yield polyols for PUR/PIR foams, modified with trimethyl phosphate to be used as light-weight filler in polymers or it can be combusted for energy recovery. Resulting social risks are shown in Figure 4-7. The choice between the options for the use of lignin has a substantial influence on the work-hours at risk for the provision of chemicals needed for lignin modification while other parts of the supply chain are less affected. However, risks associated with waste disposal from TMP-modification is likely to be substantially underestimated because the produced hazardous waste poses higher risks to health and safety than the average waste disposal that is represented in the underlying data. Both the production of chemicals needed for lignin modification and hazardous waste disposal are social hot spots to be considered with higher priority if these inputs or services are required for the value chain to be implemented.

The influence of product choice on avoided risks is very high because completely different conventional products are replaced. It has to be taken into account, though, that the resolution of sLCA databases does not allow the comparison of concrete reference products but just the comparison of risks associated with a certain turnover in the respective sector producing this product.

Taken together, the use of TMP-modified lignin as light-weight filler tends to show the most favourable ratio of risks to avoided risks. There is however no robust difference to the use of EC-modified lignin for PUR/PIR foams because of uncertainties on the side of the replaced conventional product and known underestimated risks for the disposal of hazardous waste related to TMP. Combustion is associated with lowest risks and lowest avoided risks. Therefore, no clear preference on lignin use can be deduced from this sLCA.

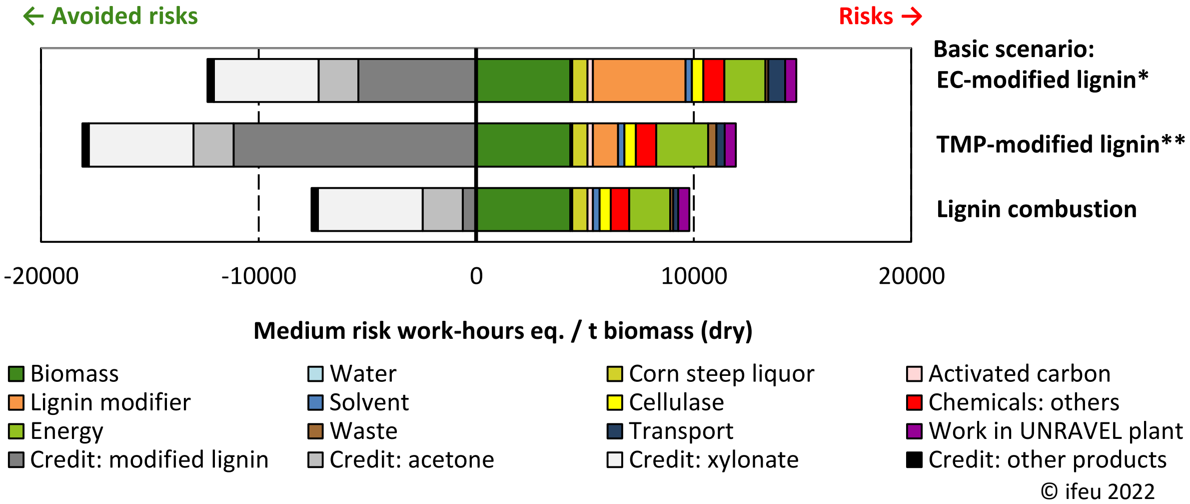

Figure 4-7: Ranges of aggregated social risks associated with different products. Country: Netherlands; boundary conditions: typical.

** ethylene carbonate-modified lignin use for PUR/PIR foams*

*** trimethyl phosphate-modified lignin use as light-weight filler*

Key findings:

– Optimisations of the processes inside the biorefinery do not alter social risks much. Social hot spots in the supply chain that require monitoring are not affected.

– The choice of the product made from the lignin fraction has a noticeable influence on risks, avoided risks and social hotspots to be monitored.

– The use of TMP-modified lignin as light-weight filler tends to show the most favourable ratio of risks to avoided risks but differences to the other considered products are not robust taking uncertainty in underlying data into account.

5 Results SWOT analysis

To evaluate the strength, weaknesses, opportunities and threats (SWOT) regarding social aspects specific for a potential biorefinery according to the UNRAVEL concept, a SWOT analysis has been conducted. It supplements the sLCA analysis that mainly focusses on social risks in the supply chain (see chapter 4). Starting with a workshop with all project partners, positive and negative social aspects connected to the UNRAVEL concept were analysed, clustered, extended and summarised in SWOT matrices.

The SWOT analysis covers positive and negative impacts on different stakeholder categories (for detailed method description please see chapter 2.3). The four sections of the SWOT matrix are formed by looking at the quality and origin of social impacts. **Helpful** and **harmful** (to achieving the objective) are distinguished regarding the quality, while **external** (attributes of the environment) and **internal** (attributes of the organisation/product) are distinguished in terms of origin.

The SWOT analysis is structured according to life cycle stages. In that it follows the approach of the overarching integrated life cycle sustainability assessment (see chapter 2). The three analysed life cycle stages are:

- Biomass provision (chapter 5.1)
- Biomass conversion (chapter 5.2)
- Use phase of products (chapter 5.3)

Besides impacts on sustainability, potential threats and barriers against implementation originating from society are addressed (chapter 5.4).

5.1 Biomass provision

For biomass provision the considered stakeholder categories are:

- Biomass supplier (e.g. forest owners or farmers),
- Employees,
- Competing users
- Local communities.

Due to the characteristics of roadside grass, “car drivers” and the “road/rail maintenance agencies” are considered also.

Please find the respective matrices in Figure 5-1 - Figure 5-4.

The bold printed bullet points highlight aspects unique to one feedstock.

	Helpful to achieving the objective	Harmful to achieving the objective
Internal origin (attributes of the organisation/product)	STRENGTHS **Suppliers (forest owners)** 1. Additional income 2. Stable market because of regular demand 3. Higher sales prices because of more demand **Employees** 1. Safer jobs **Competing users** 1. No direct or indirect competition to food production **Local communities** 1. Building value chains on local resources 2. Entrepreneurship and economic development **3. Higher income from community/state forests** and taxes	WEAKNESSES **Suppliers (forest owners)** 1. Dependency on a single big customer (biorefinery) -> lack of risk distribution **Competing users** 1. Rising prices for/lower availability of biomass for existing users, which may harm other businesses **Local communities** 1. Rising prices for/lower availability of beech wood that is often used for heating in households 2. Increased traffic, noise and pollution from transportation
External origin (attributes of the environment)	OPPORTUNITIES **Suppliers (forest owners)** 1. Higher overall demand brings opportunities for smaller suppliers **Local communities** 1. More direct, indirect and induced jobs, in particular in rural areas **2. Incentive for community investment in/maintenance of forests**	THREATS **Suppliers (forest owners)** **1. Less support from community because of concerns (deforestation, transportation)** **2. Increased demand could be incentive for unsustainable forest management (forest considered production asset rather than a nature asset)** **Employees** 1. Increased health & safety risks for workers **2. Seasonal jobs are often associated with bad working conditions especially for foreign workers** **Competing users** 1. Loss of business, unemployment **2. Need for new heating technologies, potentially more burning of fossil fuels** **Local communities** **1. Overexploitation of resources** **2. General aversion towards cutting trees** 3. Business interest potential threat to local biodiversity programmes 4. Negative public perception caused by biodiversity concerns

Figure 5-1: SWOT matrix on social aspects of ***provision of beech stemwood.***

	Helpful to achieving the objective	Harmful to achieving the objective
Internal origin (attributes of the organisation/product)	STRENGTHS <u>Suppliers (forest owners)</u> 1. Additional income from residues 2. Stable market because of regular demand 3. Higher sales prices because of more demand and higher value uses 4. Potentially sense of purpose because use is perceived as innovative and more sustainable <u>Employees</u> 1. Safer jobs <u>Competing users</u> **1. Less competition over stem wood by using branches and residues** 2. No direct or indirect competition to food production <u>Local communities</u> **1. Higher income from community/state forests** and taxes 2. Building value chains on local resources 3. Entrepreneurship and economic development	WEAKNESSES <u>Suppliers (forest owners)</u> 1. Dependency on a single big customer (biorefinery) -> lack of risk distribution **2. Potentially investment needs for changed practices/additional infrastructure for harvesting residues** <u>Employees</u> 1. Potential additional jobs will probably be seasonal <u>Competing users</u> 1. Rising prices for/lower availability of biomass for existing users, which may harm other businesses <u>Local communities</u> 1. Increased traffic, noise and pollution from transportation
External origin (attributes of the environment)	OPPORTUNITIES <u>Suppliers (forest owners)</u> 1. Additional demand brings opportunities for smaller suppliers <u>Local communities</u> 1. More direct, indirect and induced jobs, in particular in rural areas **2. Incentive for community investment in/maintenance of forests** **3. Training programmes for local/regional workforce**	THREATS <u>Suppliers (forest owners)</u> **1. Local/regional scepticism or low willingness of owners to harvest residues** **2. Loss of nutrients and organic matter reduces biodiversity and may increase risks of high losses e.g. in extreme weather conditions** **3. Increased demand could be incentive for unsustainable forest management (forest considered production asset rather than a nature asset)** <u>Employees</u> 1. Increased health & safety risks for workers **2. Seasonal jobs are often associated with bad working conditions especially for foreign workers** <u>Competing users</u> 1. Loss of business, unemployment <u>Local communities</u> **1. Influx of low-wage workforce may limit local employment opportunities and create social friction** **2. Loss of nutrients and organic matter reduces biodiversity and may make forest less attractive for recreation** 3. Business interest potential threat to local biodiversity programmes 4. Negative public perception caused by biodiversity concerns

Figure 5-2: SWOT matrix on social aspects of ***provision of birch branches with bark.***

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	Helpful to achieving the objective	Harmful to achieving the objective
Internal origin (attributes of the organisation/product)	STRENGTHS **Suppliers (farmers)** 1. Additional income from residues 2. Stable market because of regular demand 3. Higher sales prices because of more demand and higher value uses 4. Potentially sense of purpose because use is perceived as innovative and more sustainable **Employees** 1. Safer jobs **Competing users** 1. No direct or indirect competition to food production **Local communities** 1. Building value chains on local resources 2. Entrepreneurship and economic development 3. Additional income (taxes)	WEAKNESSES **Suppliers (farmers)** 1. Dependency on a single big customer (biorefinery) -> lack of risk distribution **2. Harvest once a year may increase seasonal work overload** **3. Biorefinery as big customer may press suppliers to harvest more straw than sustainably available, which could deteriorate soil quality and thus harm the basis of the farmers businesses** **Employees** 1. Potential additional jobs will probably be seasonal **Competing users** 1. Rising prices for/lower availability of straw for existing uses such as animal bedding, which may harm other businesses **Local communities** 1. Increased traffic, noise and pollution from transportation
External origin (attributes of the environment)	OPPORTUNITIES **Suppliers (farmers)** 1. Higher overall demand brings opportunities for local smallholders and smaller suppliers **2. Long stem varieties could be used by farmers to generate even more income** **Local communities** **1. Additional income helps to keep local/regional farming infrastructure** 2. More direct, indirect and induced jobs, in particular in rural areas	THREATS **Employees** **1. Seasonal jobs are often associated with bad working conditions for especially for foreign workers** **Competing users** **1. More severe straw shortages in unusual weather/climate conditions (regional/national)** 2. Loss of business, unemployment **Local communities** **1. Influx of low-wage workforce may limit local employment opportunities and create social friction** 2. Business interest potential threat to local biodiversity programmes 3. Negative public perception caused by biodiversity concerns

Figure 5-3: SWOT matrix on social aspects of ***provision of straw.***

	Helpful to achieving the objective	**Harmful** to achieving the objective
Internal origin (attributes of the organisation/product)	STRENGTHS <u>Road/rail maintenance agencies</u> 1. Additional income from previously unvalorised residues 2. Stable market because of regular demand 3. Potentially sense of purpose because use is perceived as innovative and sustainable **4. Potentially sense of purpose because biomass removal can contribute to nature preservation** <u>Car drivers</u> **1. Better appearance through more biodiversity** <u>Local communities</u> **1. Lower net costs for roadside mowing** 2. Additional income (taxes) 3. Building value chains on local resources 4. Entrepreneurship and economic development	WEAKNESSES <u>Road/rail maintenance agencies</u> 1. Dependency on a single big customer (biorefinery) -> lack of risk distribution 2. Very high effort for transportation/storage <u>Employees</u> 1. Potential additional jobs will most likely be seasonal <u>Car drivers</u> **1. Possibly increased traffic disturbance due to additional harvesting** <u>Local communities</u> 1. Increased traffic, noise and pollution from transportation
External origin (attributes of the environment)	OPPORTUNITIES <u>Local communities</u> **1. Training programmes for local/regional workforce** 2. More direct, indirect and induced jobs, in particular in rural areas	THREATS <u>Employees</u> 1. Increased health & safety risks for workers **2. Seasonal jobs are often associated with bad working conditions for especially for foreign workers** <u>Car drivers</u> **1. Harvesting equipment could increase risk of accidents** <u>Local communities</u> 1. Business interest potential threat to local biodiversity programmes 2. Negative public perception caused by biodiversity concerns (though expected to be unfounded) **3. Displacement of semi-natural sheep grazing in case this is local practise**

Figure 5-4: SWOT matrix on social aspects of ***provision of roadside grass.***

5.2 Biomass conversion

In terms of biomass conversion the biorefinery and specialty supplies are considered for SWOT analysis.

Biorefinery

For the biorefinery, two configurations are compared:

- A configuration with a single (or dominant) feedstock and without pre-extraction (Figure 5-5)
- A feedstock-flexible configuration with pre-extraction (Figure 5-6)

The bold printed bullet points highlight aspects unique to one configuration. The foreseen stakeholder categories for the biorefinery are:

- Employees
- Local community
- Local suppliers (small entrepreneurs)
- Neighbours

Specialty supplies

Furthermore, impacts of high-end service providers and suppliers to the biorefinery including enzyme provision, research and development or quality management are addressed in the SWOT matrix on specialty supplies (Figure 5-7).

The stakeholder categories for this part are:

- Employees
- Scientific community
- Local communities

5.3 Use of biorefinery products

In this part the focus is laid on the social impacts of the use phase of the biorefinery products (Figure 5-8). The analysis includes the following stakeholder categories:

- Industrial customers
- End users
- Policy makers
- Industrial competitors

	Helpful to achieving the objective	Harmful to achieving the objective
Internal origin (attributes of the organisation/product)	STRENGTHS **Employees** 1. Wide range of employment opportunities (across qualifications and technology/business areas) for current and future employees 2. Jobs are expected to be of high quality and future-proof 3. Education/qualification of current and future employees 4. Expansion and diversification of the fields of tasks for highly qualified workers 5. Sense of purpose (perception of biorefinery as innovative and sustainable, use of un/underutilized streams) **Local community** 1. Nearby work opportunities 2. Local supply of end products 3. Skilled workforce, knowledge and infrastructure available in region **Local suppliers (small entrepreneurs)** 1. More stable businesses because of increased sales	WEAKNESSES **Employees** 1. Health and safety risks in some biorefinery jobs (e.g. through certain dangerous chemicals) 2. Biorefinery as potentially dominating local employer may have overweight in negotiations **Neighbours** 1. Certain decrease of life quality due to increased noise, increased traffic, dust and smell due to biomass storage **Local community** 1. More competition for products/services/utilities 2. Impairment of landscape 3. Potentially reduced availability and quality of water 4. Influx of a non-local workforce could lead to intercultural issues or decreased community cohesion **Local suppliers** 1. Biorefinery as one dominating customer may create dependencies and thus uncertain income
External origin (attributes of the environment)	OPPORTUNITIES **Employees** 1. Additional employment opportunities in companies settling around the biorefinery (lignin-based industry) **Neighbours** 1. Value of properties may increase **Local community** 1. Structural strengthening of community (influx of people, diversity, incoming workforce with families -> increase in cultural/leisure offers) 2. Additional infrastructure (better roads, public transport, education etc.) 3. Regional empowerment based on bio-economy development (local/regional clusters) 4. More jobs in collaborating companies/services, gastronomy 5. Education on bio-based products and processes **Local suppliers** 1. Business opportunities with companies settling around the biorefinery	THREATS **Employees** 1. Traditionally male-dominated industry and value chain may not create opportunities for women **Neighbours** 1. Decrease of life quality and/or value of properties due to increased noise, increased traffic, dust and smell due to biomass storage 2. Land use tenure may be at risk 3. Worries about safety of biorefinery may decrease of life quality **Local community** 1. Industrialisation of (rural) communities (depending on biorefinery scale and location) may be perceived as detrimental **Local suppliers** 1. Loss of business due to increased competition by newly attracted external suppliers, price battles **All stakeholders** **1. Dependence on one major feedstock may threaten biorefinery as a whole if shortages occur**

Figure 5-5: SWOT matrix on social aspects of ***biorefinery without pre-extraction, single feedstock*** *(incl. transportation).*

	Helpful to achieving the objective	Harmful to achieving the objective
Internal origin (attributes of the organisation/product)	STRENGTHS **Employees** 1. Wide range of employment opportunities (across qualifications and technology/business areas) for current and future employees 2. Jobs are expected to be of high quality and future-proof 3. Education/qualification of current and future employees 4. Expansion and diversification of the fields of tasks for highly qualified workers 5. Sense of purpose (perception of biorefinery as innovative and sustainable, use of un/underutilized streams) **6. Safer jobs because of feedstock flexibility** **Local community** 1. Nearby work opportunities 2. Local supply of end products 3. Skilled workforce, knowledge and infrastructure available in region **Local suppliers (small entrepreneurs)** 1. More stable businesses because of increased sales **2. Additional business opportunities for a diverse group of suppliers based on mixed feedstocks**	WEAKNESSES **Employees** 1. Health and safety risks in some biorefinery jobs (e.g. through certain dangerous chemicals) 2. Biorefinery as potentially dominating local employer may have overweight in negotiations **Neighbours** 1. Certain decrease of life quality due to increased noise, increased traffic, dust and smell due to biomass storage **Local community** 1. More competition for products/services/utilities 2. Impairment of landscape 3. Potentially reduced availability and quality of water 4. Influx of a non-local workforce could lead to intercultural issues or decreased community cohesion **Local suppliers** 1. Biorefinery as one dominating customer may create dependencies and thus uncertain income
External origin (attributes of the environment)	OPPORTUNITIES **Employees** 1. Additional employment opportunities in companies settling around the biorefinery (lignin-based industry) **plus industry based on extractives, such as pharma for betulin etc.**) **Neighbours** 1. Value of properties may increase **Local community** 1. Structural strengthening of community (influx of people, diversity, incoming workforce with families -> increase in cultural/leisure offers) 2. Additional infrastructure (better roads, public transport, education etc.) 3. Regional empowerment based on bio-economy development (local/regional clusters) 4. More jobs in collaborating companies/services, gastronomy 5. Education on bio-based products and processes **Local suppliers** **1. Wider range of business opportunities with companies settling around the biorefinery**	THREATS **Employees** 1. Traditionally male-dominated industry and value chain may not create opportunities for women **Neighbours** 1. Decrease of life quality and/or value of properties due to increased noise, increased traffic, dust and smell due to biomass storage 2. Land use tenure may be at risk 3. Worries about safety of biorefinery may decrease of life quality **Local community** 1. Industrialisation of (rural) communities (depending on biorefinery scale and location) may be perceived as detrimental **Local suppliers** 1. Loss of business due to increased competition by newly attracted external suppliers, price battles

Figure 5-6: SWOT matrix on social aspects of ***biorefinery with pre-extraction, mixed feedstock*** *(incl. transportation).*

	Helpful to achieving the objective	Harmful to achieving the objective
Internal origin (attributes of the organisation/product)	STRENGTHS **Employees** 1. Increased number of jobs in research, development, innovation and service sector (quality management, research and development consultancy) 2. Jobs are expected to be of high quality and future-proof 3. Education/qualification of current and future employees 4. Sense of purpose (perception of biorefinery as innovative and sustainable) **Scientific community** 1. Research and innovation opportunities in industrial setting and partnerships (e.g. research contracts from industry, living lab scenarios) **Local communities** 1. Higher income from taxes 2. Skilled workforce, knowledge and infrastructure available in region	WEAKNESSES **Employees** 1. Employment insecurity due to dependence on uncertain policy support 2. Uncertainty for start-ups about how the new products/services will be taken up by industry **Scientific community** 1. Uncertainty if competencies are in demand in the future: high specialisation needed in a field that is dominated by competing technologies
External origin (attributes of the environment)	OPPORTUNITIES **Local communities** 1. Well paid jobs can contribute to improved economy of region 2. Region gains attractiveness for businesses and research based on bio-economy development (local/regional clusters) 3. Entrepreneurial opportunities and environment based on high-end services and research, development and innovation 4. Community revival (schools, public infrastructure) by increased number of young scientist/employees in the region 5. Increasing environmental awareness through "green" businesses **Scientific community** 1. Knowledge gain/scientific exchange/synergies from research-industry cooperation in industrial setting 2. Building of a scientific community in the area including transnational exchange in Europe	THREATS **Employees** 1. For employees in small and medium-sized enterprises: employment insecurity if high dependence on one big customer (biorefinery) 2. Uncertain whether jobs can be created due to extensive regulation and bureaucracy potentially blocking market entry 3. General uncertainty due to possibly low uptake of new materials/chemicals by end users

*Figure 5-7: SWOT matrix on social aspects of **specialty supplies** (enzymes, high-end services e.g. research and development).*

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	Helpful to achieving the objective	Harmful to achieving the objective
Internal origin (attributes of the organisation/product)	STRENGTHS **Industrial customers** 1. Less dependence on fossil-based resources -> risk distribution, price stabilisation 2. Receive support from extensive policy framework in the EU that should help boost the bioeconomy **End users** 1. Sense of contributing to a more sustainable world through new opportunities to buy (potentially) more sustainable products 2. Larger variety in product choice **Policy makers** 1. Contribution to sustainability policies (e.g. Low-Carbon Society, UN sustainable development goals)	WEAKNESSES **Industrial competitors** 1. Increased competition by new bio-based products, in particular for fossil-based products **Industrial customers** 1. New feedstock may require changes/change management 2. Low financial support 3. Lack of technology and infrastructure 4. Might need to adapt processes and/or change specifications of materials and products 5. Does not reduce CO_2 emissions of the plant itself but creates dependencies on credible certification **End users** 1. Possibly higher purchase prices compared to fossil-based products
External origin (attributes of the environment)	OPPORTUNITIES **Industrial customers** 1. Novel pre-products and compounds may lead to new value-added products 2. Novel pre-products and compounds may improve existing products 3. Bio-based feedstock may add value to products via increased sustainability 4. Scientific and technology collaboration 5. New products may lead to lower carbon footprint of company 6. Green Image -> increase in consumer demand **End users** 1. Potentially improved product quality (e.g. improved polyurethane/polyisocyanurate foam)	THREATS **Industrial competitors** 1. Loss of sales and business for fossil-based products 2. Unemployment **Industrial customers** 1. Security of supply needs to be stable and large enough 2. Oil prices can negatively influence the attractiveness of bio-based solutions 3. Risk of low acceptance of end users due to higher prices 4. Potentially reduced product quality (e.g. polyurethane/polyisocyanurate foam) 5. More variability in product quality because, because biomass feedstock is more variable. **End users** 1. Unaffordability of biorefinery products 2. Scepticism towards changes (product may look different) 3. Scepticism towards credibility of sustainability promise of biorefinery products (in particular as there is no green label certification in place yet) 4. Potentially reduced product quality (e.g. polyurethane/polyisocyanurate foam) 5. More variability in product quality because, because biomass feedstock is more variable.

Figure 5-8: SWOT matrix on social aspects of the ***use of biorefinery products*** *(industry and consumers).*

5.4 Threats and barriers

The SWOT workshop intended to collect potential positive and negative impacts on social aspects. The following valuable points rather identified threats/barriers caused by social processes, which have the potential to block the implementation of the biorefinery concept at least in certain variants. That would affect not only all stakeholder groups and all life cycle stages but also environmental and economic sustainability. Therefore, they are collected separately in the following:

1. General opposition by general public triggered by strong opinions and/or false perceptions related to topics of general concern, potentially amplified by dedicated groups. This may include:
    - GMOs
    - New technologies and their potential hazard risks
    - Debates about the sustainability of biomass feedstocks may leave well-founded grounds and turn into irrational conflicts, which may not differentiate between feedstocks and between applications (bioenergy, biofuels and bio-based materials).
2. Competitors with better lobby, political/regulatory support, financial capabilities etc. may absorb limited biomass.
3. Forest ownership in EU may hinder wood mobilisation for centralised processing.

Similarly, other threats/barriers may affect the implementation:

Legal/regulatory

1. Regulations may restrict forest/agricultural residue use.
2. Legal barriers may prevent the use of roadside grass (can be considered a waste that might exclude it to be used for certain products).

Technical

1. Contaminations in grass with (plastic) waste
2. Logistics may be a barrier especially for straw, forest residues and roadside grass.

6 Results biomass potentials analysis

The availability of biomass is recognised as a central barrier to the large-scale implementation of new biomass conversion facilities such as those envisaged by the UNRAVEL concept. The limited availability of agricultural land motivated a shift towards focussing on residue use. This chapter analyses the sustainable availability of those lignocellulosic feedstocks primarily targeted in the UNRAVEL project. Social barriers such as existing biomass uses and environmental barriers including conservation of soil organic carbon content and biodiversity are analysed based on the definition of terms and methods described in section 2.4. As a first feedstock, beech stemwood is analysed in section 6.1. This feedstock is not a residue but is still considered in the UNRAVEL project because of its technically favourable properties. This is followed by the analysis of the major lignocellulosic residues forest residues and wheat straw in sections 6.2 and 6.3. Roadside grass is analysed as one example of many underutilised lignocellulosic residues occurring in smaller amounts in section 6.4.

6.1 Beech stemwood

This section discusses the sustainable availability of beech stemwood of lower qualities (pulpwood / energy wood) in the EU. Beech (*Fagus sp.*) accounts for 12% of the European forest stock [Ministerial Conference on the Protection of Forests in Europe 2020]. It is particularly widespread in Central and South-Eastern Europe (Figure 6-1, [Durrant et al. 2016]). Pulpwood and energy wood largely refer to the same biomass that can interchangeably be used in the pulp industry as a feedstock for the production of cellulose or in the form of chips, pellets or logs in CHPs as well as in industrial, district and domestic heating.

The wide range of uses for beech stemwood results in that all beech wood that is available/can be mobilised is largely used. A large-scale use of beech stemwood by biorefineries would most likely result in displacement effects. Thus, either more trees of all species would have to be felled for the provision of additional pulpwood/energy wood, or the use for biorefineries would result in biomass being taken away from other uses.

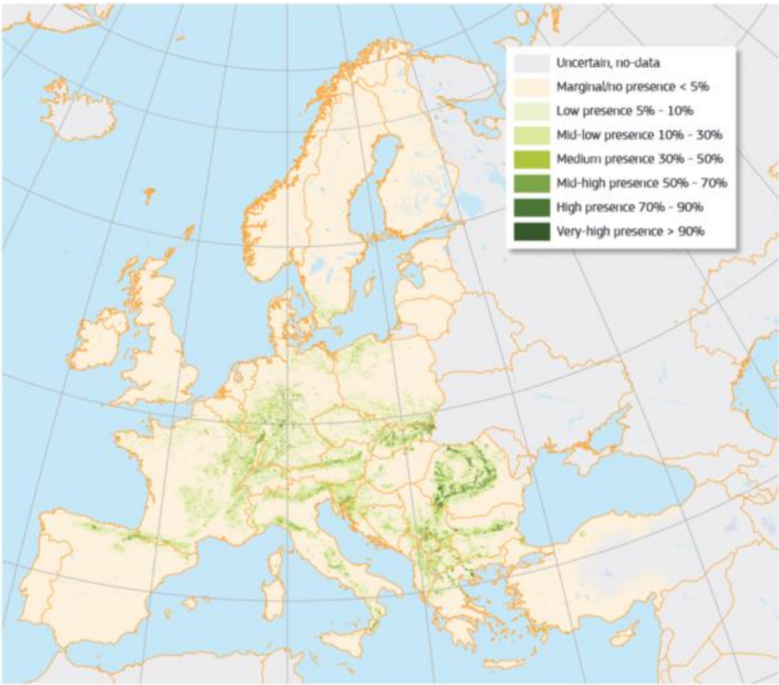

Figure 6-1: Potential locations for growth of beech trees (distribution map estimating the relative probability of presence of beech [Durrant et al. 2016]).

The growing stock in European forests increased over the last years and is theoretically available for usage [Ministerial Conference on the Protection of Forests in Europe 2020]. Whether harvest should be increased, is discussed controversially. Economically, increased wood harvests are mostly favoured. From a climate change perspective, on the one hand, harvests would reduce forest carbon stocks immediately with similar stocks growing back only slowly. On the other hand, the use of the wood could reduce fossil carbon emissions. How long “carbon payback times” are or how high “carbon debts” could become depends on each use pathway. Their acceptability has led to controversies among scientists and has to be defined politically in accordance with other climate change mitigation measures. In the end, it will depend on which peak atmospheric greenhouse gas concentrations are considered to pose an acceptable risk of irreversible severe damages to planet earth.

Climate change and other effects increasingly cause damages to forests via storms, increase of pests such as the bark beetle, fires etc. Firstly, all of these damages have the potential to substantially reduce the growing stock of forests, which leaves less potential to increase wood harvests. Instead, they might need to be decreased substantially. Secondly, high amounts of damaged wood are becoming available irregularly in the last years. They could be used e.g. for biorefineries in addition to regularly occurring pulpwood/energy wood if logistical challenges can be solved.

Current trends show an increased use, production and, even more so, **net import** of wood pellets to Europe [UNECE & FAO 2021] for energy applications. This can be an indication that an increased use of wood grades destined for energy production (lower grade stemwood/energy wood and forest residues) is already now meeting its limits. Furthermore, because parts of the imported pellets stem from logging primary forests, an increase of imports is connected with severe risks of various unsustainable consequences.

An option to increase the amount of forest residues available for material use would be the **replacement of other uses**, i.e. primarily combustion for heat and power generation, by other renewable alternatives such as solar and wind power and by substantially decreasing the demand through better insulated buildings. This would create business opportunities and employment in wind and solar power as well as the construction sector. A shift from central energy use e.g. in CHPs to material use e.g. by biorefineries of the same biomass may require a socially demanding transition process that would require management but has the potential to provide future-oriented employment for the same employees. In particular if use in residential heating was to be restricted, this would however require support to balance socio-economic impacts on households with low incomes. From an environmental perspective, the withdrawal of lower grade stemwood from combustion is uncritical as long as sufficient additional renewable electricity primarily from wind and photovoltaics can be steadily provided and additional energy generation from fossil fuels can be largely excluded.

6.2 Forest residues

This section discusses the availability of forest residues in general as well as of birch tops and branches with bark.

Two **main residue streams** can be identified: Forest residues could remain in the forest as stumps, roots, tops and smaller branches. They are counted as primary wood residues, besides the secondary residues, which accrue within the value chain as saw dust or black liquor. The amount of forest residues mainly depends on the demand for wood for sawn products and pulp mill needs. Dependent on the forestry management, forest residues can be largely used in pulp mills and as fuel wood [EUwood 2010].

According to [EUwood 2010; Mantau 2012], 118 million m^3 of forest residues are technically "available" in Europe every year in a medium mobilisation scenario. In the future (2030), a small increase to 120 million m^3 is expected, of which 44 million m^3 are estimated to be "available" in Northern Europe. Another publication reported the total forest residue biomass potential at 77 million m^3 (EU-27, 2008) [Asikainen et al. 2008]. Similar figures are reported by [BioSustain et al. 2017] for scenarios under similar conditions. Especially the use for fuel wood and partly the utilisation by the pulp industry show a demand for forest residues as other forestry products (e.g. stems) are used for construction wood and panel production. This use in 2010 amounts to 39 million m^3 forest residues, which is part of the above mentioned „available" forest residue biomass potential [Mantau 2012].

For **biodiversity and soil carbon storage**, forest ecosystems need deadwood, especially after felling and subsequent removal of stems. Due to no litter fall on clear-cut harvested sites, forest residues could serve as gap-filling nutrient source for soil life and soil protection due to shading and water erosion protection until new trees have been raised. Furthermore, removal of excess biomass quantities (especially of leaves, needles and small branches) can lead to nutrient depletion.

Several country-specific guidelines for the sustainable use of forest biomass state that about 30% of forest residues should remain in the forest. [Bessaad et al. 2021] (see chapter 2.4). A study that took similar sustainability constraints into account is EUwood [2010]. It reported 70 million m^3 (34 million $tonnes_{DM}$/year) of sustainably available forest residues considering competing uses, too. BioSustain [2017] confirms these figures and highlights policy options that could substantially increase or decrease the sustainable, available potential of forest residues depending on various options for the decarbonisation of the energy sector e.g. via fuel wood and pellet production.

In practise, guidelines for sustainable forestry are currently not met in many places and the share of residues actually remaining in the forest can be even less than 10% instead of reaching the recommended level of about 30% [Bessaad et al. 2021]. This means that in such places, the amount of residues currently extracted and used mainly for energy provision should be reduced in the future. This can result in negative sustainable available potentials in certain regions, as also confirmed by [DBFZ 2019; Fehrenbach & Rettenmaier 2020]. Although the cumulative effect of such local/regional overuses on the overall forest residue potentials in the EU has not been quantified, the net sustainable available potentials for the EU as a whole could be close to zero representing the lower end of a large range.

Birch tops and branches with bark

For technical reasons, a particular focus in UNRAVEL was laid on the use of birch tops and branches including bark. For that reason, their potentials are analysed separately. Birch (*Betula sp.*) is the sixth most important tree species in Europe based on the growing stock with an overall abundance of 6,6 % [Ministerial Conference on the Protection of Forests in Europe 2020], (Figure 6-2, [Beck et al. 2016]). Birch forest residues, like branches and thinning material remain in the forests or can be used mainly for energy production in CHPs or power plants.

Northern Europe, with Finland, Sweden, Norway and the Baltic States, is the region with the highest birch density [Brus et al. 2012; Beck et al. 2016]. In some countries like Lithuania, with 22% the presence of birch is much higher compared to the rest of Europe [Varnagirytė-Kabašinskienė et al. 2019].

The tops and branches of birch make up to 10-20% of the entire biomass above ground level, dependent on tree species (e.g. *B. pendula*, *B. pubescens*, *B. utilis*), age and location of growth [Repola 2008; Alam & Nizami 2014].

Taking into account several boundary conditions, up to 2.3 million $tonnes_{DM}$/year of **sustainable birch forest residues** could be available. As discussed for forest residues in general, it can however depend very much on the location if these resources are already overused, which seems plausible for well accessible locations, or truly sustainably available, which is more likely for remote locations.

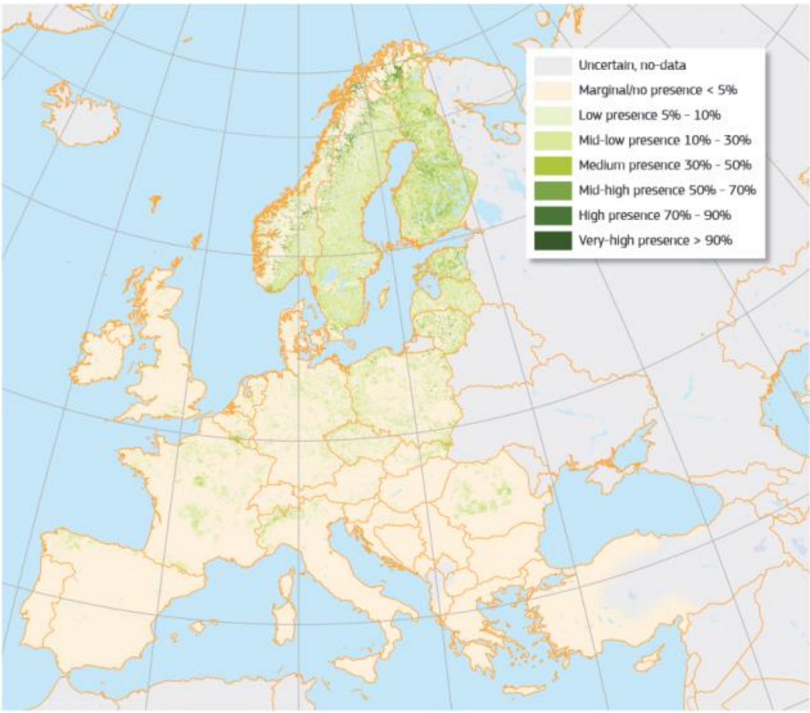

Figure 6-2: Potential locations for growth of birch trees (distribution map estimating the relative probability of presence of birch [Beck et al. 2016].

The **withdrawal of forest residues from their current use** mainly for combustion is less critical than for stemwood as discussed in section 6.1. Social and environmental implications of shifting forest residue use in large facilities from energy to material use are similar to those for stemwood. Since forest residues are not primarily used in residential heating, social impacts on house owners would be substantially lower.

6.3 Wheat straw

In this section, the sustainable, available biomass potential of wheat straw and other cereal straw (barley, rye, oat and rice straw) is analysed. Starting with the overall technical potential, the sustainable, available potential is derived by deducting the biomass that cannot be used due to sustainability constraints (e.g. for maintaining the soil organic carbon content) and the biomass that is already used (see section 2.4 on definitions).

The overall **technical potential** reported differs greatly between the different studies, since the boundary conditions varied (see chapter 2.4.2). The largest deviations resulted from the varying feedstock pools, to which the wheat straw was counted, as well as from the different methods applied. The results of the overall technical and the overall sustainable potential are depicted in Figure 6-3.

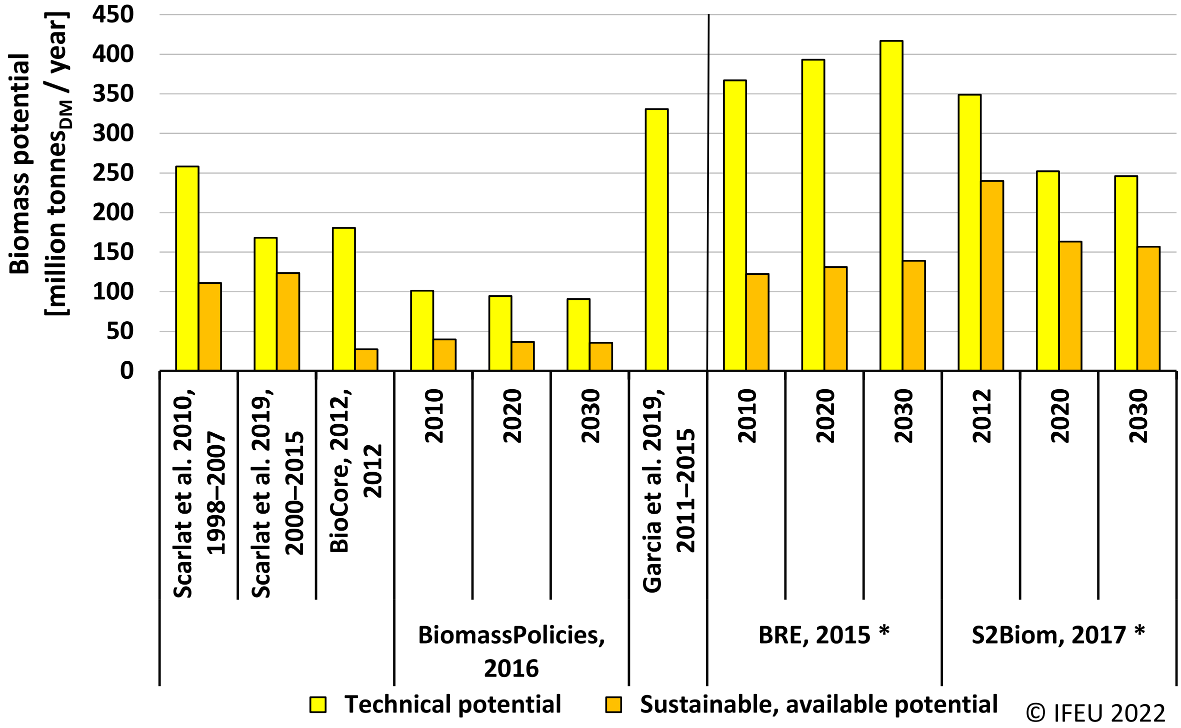

*Figure 6-3: Biomass potentials for wheat straw, wheat straw-like and further agricultural crop residues in million tonnes$_{DM}$/year in the European Union by base year of reporting/scenarios. * Some studies include additional biomass and therefore report higher values (BRE [2015] and S2Biom [2017], see text for details).*

Out of seven studies, three reported results for the overall technical potential within the EU in 2010-2015 of around 350 million tonnes$_{DM}$/year [BRE et al. 2015; S2Biom et al. 2017; García-Condado et al. 2019], whereas three other studies reported results between 100 and 200 million tonnes$_{DM}$/year [BioCore 2012; BiomassPolicies et al. 2016; Scarlat et al. 2019]. One further earlier study (1998-2007) calculated a value of 250 million tonnes$_{DM}$/year [Scarlat et al. 2010]. The large differences in the technical potential can be partially explained as BioCore [2012] and BiomassPolicies [2016] did not include any other agricultural residues besides cereal straw in their evaluation of the technical potential[1]. Additionally, these differences might come due to different methods used for estimation of the technical potential (statistical approach for BioCore and BiomassPolicies vs. spatially explicit approach in other studies). Results by BRE [2015] might be overestimated, as residues from crop processing were partially included.

Three studies [BRE et al. 2015; BiomassPolicies et al. 2016; S2Biom et al. 2017] applied **scenarios for the future development** of straw biomass potentials. Looking at the future of

[1] They did, however, include further agricultural residues for the sustainable potential. Therefore this graph does not show a meaningful ratio between technical and sustainable potential.

straw biomass potentials, an approximation has to come with major uncertainties. On the one hand, an increase is possible due to high economic margins for cereals, new cultivation areas due to climate change, a lower use of straw-shortening growth regulators (used to reduce the risk of crop lodging) or an increased straw demand for energy or fuel production. Furthermore, an increase of organic agriculture might come with an increased use of long-straw varieties due to lower pathogen susceptibility but also with increased demand for livestock bedding material. On the other hand, also a decline is possible due to a reorganisation of the EU´s common agricultural policy (CAP), an increase in so called “Greening areas” or due to climate change and the conversion of areas in southern Europe.

The described uncertainty can be observed in the results for the years 2020 and 2030. Whereas BiomassPolicies [2016] and S2Biom [2017] reported a decrease in the total technical potential down to 120 and 250 million t_{DM}/year, respectively, BRE [2015] projected a slight increase to 416 million t_{DM}/year till 2050.

The **sustainable, available potential** shown in Figure 6-4 (by deducting shares for soil organic carbon maintenance and the shares for competitive use from the technical potential), clearly shows differences in the extent of deductions between the studies examined. They are a result of different sustainability and competing use assumptions of the studies (see chapter 2.4).

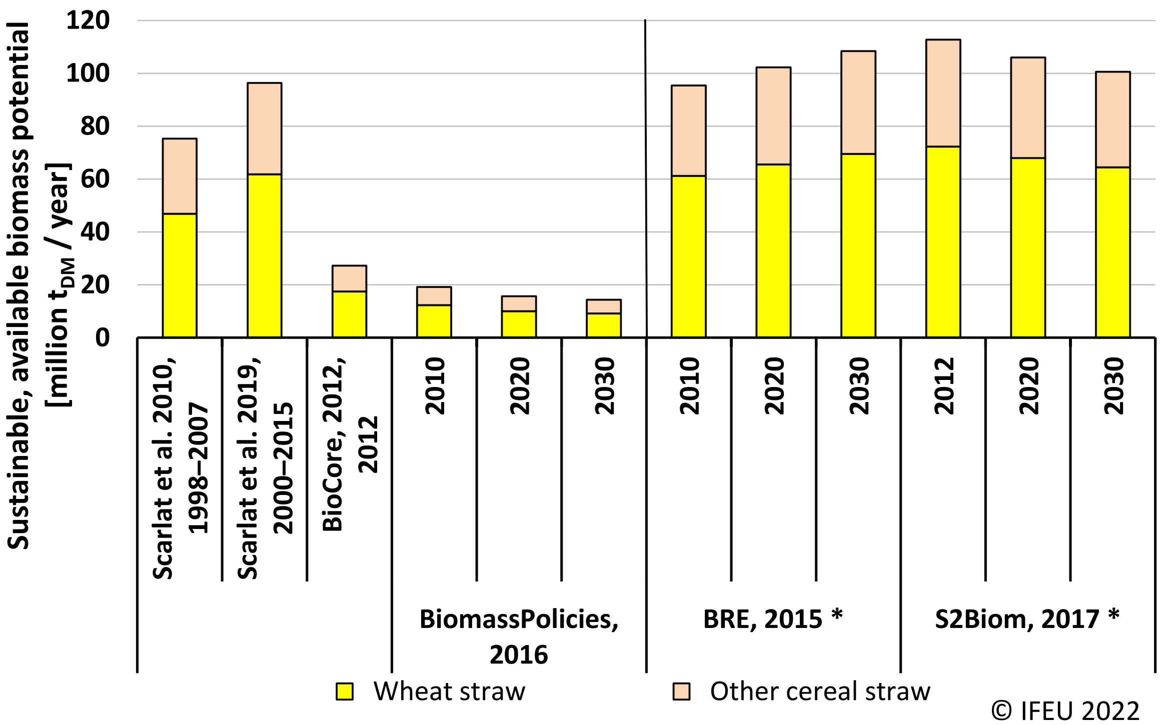

*Figure 6-4: Sustainable, available biomass potential for wheat straw and straw from other cereals in million tonnes$_{DM}$/year in the European Union. * Some studies include additional biomass and therefore report higher values (BRE [2015] and S2Biom [2017], see text for details).*

The four studies BRE [2015], Scarlat et al. [2010], S2Biom [2017] and Scarlat et al. [2019] reported similar results of around 100 million tonnes$_{DM}$/year for cereal straw in general. Around 60 million tonnes$_{DM}$/year have been counted as wheat straw and around 35 million tonnes$_{DM}$/year as wheat-straw like material/other cereal straw, which is relevant for UNRAVEL, too. The overall results of BioCore [2012] and BiomassPolicies [2016] are lower than the results of the other studies analysed. For both studies, this could largely be explained by methodological reasons in terms of calculation of the technical potential, e.g. due to the application of statistical approaches instead of other methods like spatially explicit approaches. For BioCore [2012] particularly high sustainability constraints have been taken into account in addition. BRE [2015] report higher values because residues from crop processing were partially included. Results of S2Biom [2017] rather depict the sustainable but not the sustainable, available potential because competing use has not been accounted for (see chapter 2.4).

The existing, competing uses were calculated differently in the studies examined. While some studies used fixed proportions for competing usage in general [BRE et al. 2015; BiomassPolicies et al. 2016], others calculated the amount of straw for bedding used for animal bedding and for mushroom production based on statistical data on livestock population and mushroom production [Scarlat et al. 2010; BioCore 2012] (for details, please see chapter 2.4.2). Other uses including informal trade are not explicitly covered. This should not affect the amounts of sustainably available straw decisively but can be of importance for social impacts. Therefore, the existing users of straw in a specific region need to be identified and their livelihoods need to be secured before introducing a large-scale straw-based biorefinery to avoid negative social implications.

All in all, sufficient straw is available in Europe for a certain number of selected new applications. This still applies if sustainability guidelines to maintain soil organic carbon stocks are applied and current straw users continue to receive the quantities they need. Locally, the high demand of big facilities may however cause increased competition and its potential negative effect on small straw users has to be managed.

6.4 Roadside grass

Roadside grass is analysed as one example of many smaller volume lignocellulosic residues, which are available in the EU (see e.g. [S2Biom et al. 2017]), to explore a wider spectrum of resources within the UNRAVEL project.

Roadside vegetation usually includes a woody and a grassy component with different use options. Focussing on the grassy component, we found three studies with statements about the biomass potential in the EU. This biomass fraction consists mainly out of stalks and leaves of grasses and herbs. Roadside grass, which is currently left on site after mowing, can be collected with a suction device on the same machine and collected in a trailer. The methods and adjustments of the boundary conditions to derive the biomass potential are described in chapter 2.4.2.

The analysed studies agree on a technical biomass potential around 3 million $tonnes_{DM}$/year if the grass feedstock fraction is collected and dried (Figure 6-5). If grass would not be dried with high energy use, which is not foreseen in the UNRAVEL concept, it may require a sophisticated logistics concept or technical potentials may be substantially reduced.

The yield of roadside grass is expected to decrease by about 25 % if it is extracted regularly as result of nutrient deficiency, which was not accounted for by S2Biom [2017] and BiomassPolicies [2016]. A slight increase in the number of roads may not compensate this development. Both studies might overestimate the biomass potential of roadside grass as the proportion of large roads to smaller roads, which is important for the estimation, was taken from the Netherlands and has been extrapolated to all other EU countries.

The 2.5 million $tonnes_{DM}$/year reported by the third study [Hamelin et al. 2019] are lower than figures reported by the other two studies although (i) the technical accessibility of roadside grass was not accounted for resulting in a theoretical potential instead of the technical potential and (ii) railway side vegetation has been included, too.

Limitations to the usability may result from partially substantial contaminations with heavy metals and waste such as plastics packaging.

For roadside grass, the sustainable, available potential should almost equal the technical potential because:

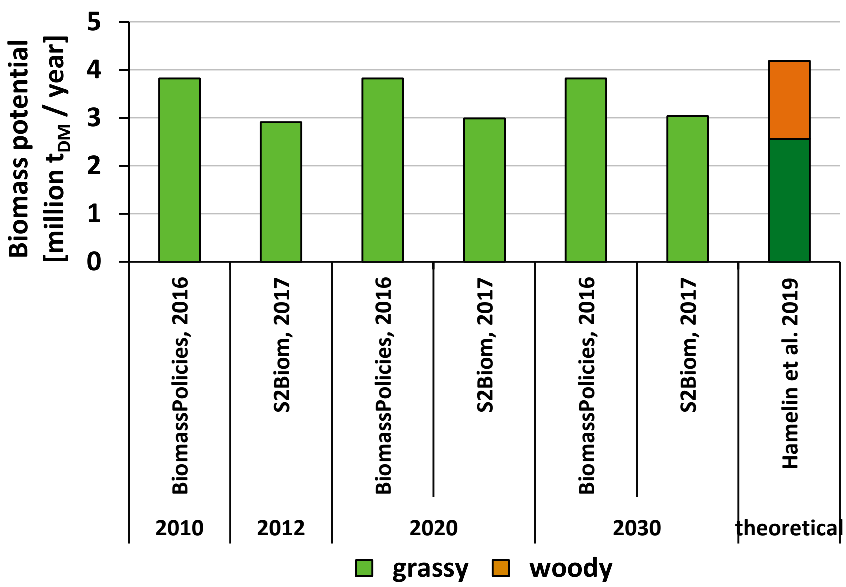

Figure 6-5: Overall technical biomass potential of roadside grass in the EU. For Hamelin et al. [2019] railway grass and wood has been included in the theoretical potential.

– There are very few environmental restrictions: In areas of high biodiversity along the roadside, it may be necessary to schedule mowing according to ecological criteria, which could limit logistical usability. In other locations with excess nutrient availability, biodiversity may be increased by regular removal of mowed grass for several years.

– Very few competing uses are currently established.

Expected social impacts are largely neutral to positive because additional income may reduce net road maintenance costs and a certain number of additional jobs may be generated.

The spatial concentration/density of roadside grass is however low compared to other feedstocks like for example cereal straw. The cost of collecting and possibly drying can exceed the potential benefit in many places in the EU. There are nevertheless countries and regions with higher amounts of roadside grass per unit area like the Netherlands, Belgium, Denmark and the Western parts of Germany (Figure 6-6) [S2Biom-Project 2012].

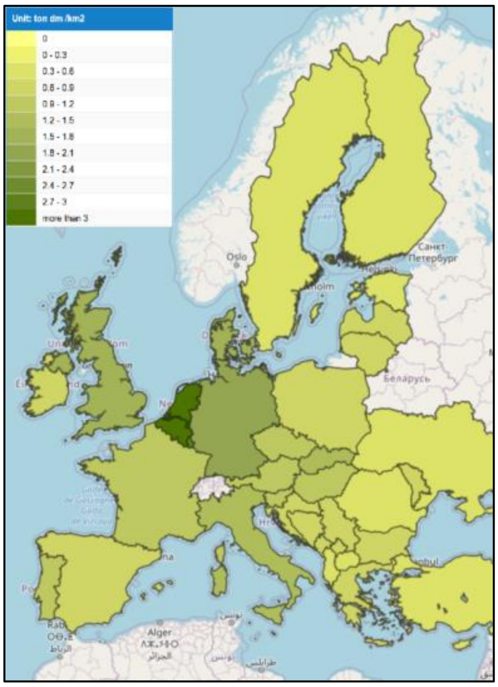

Figure 6-6: Technical biomass potential for grassy road side vegetation in 2030, Source: S2Biom-Project [2012].

7 Conclusions and recommendations

The conclusions regarding social risks in the supply chain, further social impacts and biomass potentials in sections 7.1 - 7.3 are based on the results discussed in chapters 4 - 6. Recommendations to various stakeholder groups were deduced from these results and conclusions (section 7.4).

7.1 Conclusions on social risks in the supply chain

The following conclusions are based on the results of the sLCA presented in chapter 4.

- The general level of social risks in the supply chain is comparable for potential biorefineries according to the UNRAVEL concept and their conventional competitors, which is largely independent of the analysed technical configuration. These risks mostly arise from indirect suppliers outside of the EU and are in particular related to occupational health and safety, governance aspects including corruption, and procurement from high conflict zones.
- No extraordinary or unacceptable social risks have been identified in the supply chain that could not be managed. Therefore, technical processes do not have to be redesigned to avoid certain inputs. This includes biomass supply unless relevant amounts of biomass are imported from outside of the EU.
- Relevant social risks (social hot spots) associated with the assessed potential biorefinery supply chains are in particular:
    - Biomass supply, in particular in Eastern European countries
    - Provision of lignin modifiers and, to a lower extent, also of other input chemicals
    - Energy and transportation (depending on process efficiency)

  These social risks in the supply chain should be taken as starting points to design a strategy of monitoring and mitigating risks.

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- Work in the biorefinery itself is only connected to comparatively low risks, mainly related to occupational health and safety, which are expected to be comparable to the risks in the current manufacturing of fossil alternatives.

7.2 Conclusions on further social impacts

The following conclusions are based on the results of the SWOT analysis presented in chapter 5.

- The internal SWOT workshop on social aspects of the UNRAVEL project, which involved project partners with diverse stakeholder backgrounds, yielded important additional insights complementing or confirming the results of the sLCA. At the current stage of technology development, at which no concrete candidates for biorefinery locations have been identified yet and implementation plans are not concrete enough to involve stakeholder organisations without existing connections to the project, this approach has proven successful.
- A wide variety of both positive and negative potential impacts of several life cycle stages (biomass provision/specialty supplies, biorefinery, use phase) on various stakeholder groups have been identified. This should be taken as a starting point for a more concrete stakeholder engagement in a later stage of development once in particular the geographical scope can be narrowed down sufficiently.
- The analysis revealed several additional social risks in the life cycle of the biorefinery products. This includes a cluster of risks connected to the emergence of a single powerful economic actor in a rural environment, which the operator of a large biorefinery is likely to be considered. This requires fair negotiations in particular about wages and biomass supply as well as strategies aiming at local employment and procurement.
- Additionally, social risks were identified that are connected to the substitution of fossil-based products currently on the market. This is very likely to cause adverse social impacts on the stakeholders such as employees connected to processes that are to be phased out. This transition needs to be actively managed by politics to mitigate social impacts in particular on employees in regions with a strong fossil-based industry. Additionally, products could become more expensive for consumers at least in a transition phase especially because of high investment requirements. Impacts of potentially increased inflation on vulnerable societal groups need to be mitigated by politics.
- Social benefits are expected regarding the creation of jobs and prospering local economies in rural areas via creating a stable demand for biomass and thus income and jobs in agriculture and forestry, generating taxes and income for state forests and reducing costs for road maintenance if roadside grass is used.

Additionally, high quality jobs are created in the biorefinery itself and at high-tech specialty suppliers although their number is expected to be lower than for indirect or induced employment.

- To fully realise the potential benefits strive for a location in less privileged rural areas and a local procurement approach and ensure equal employment opportunities. Furthermore, training programmes and enhanced health and safety measures for local workforce may be needed to improve local employment instead of causing an influx of external workforce and/or bad working conditions that could create social friction.
- Further social and socioeconomic chances could be the creation of a sense of purpose and identity in the bio-based industry and local communities as well as the settlement of further related businesses around the biorefinery.

7.3 Conclusions on biomass potentials

The following conclusions are based on the results of the biomass potentials analysis in chapter 6 which are graphically summarised in Figure 7-1.

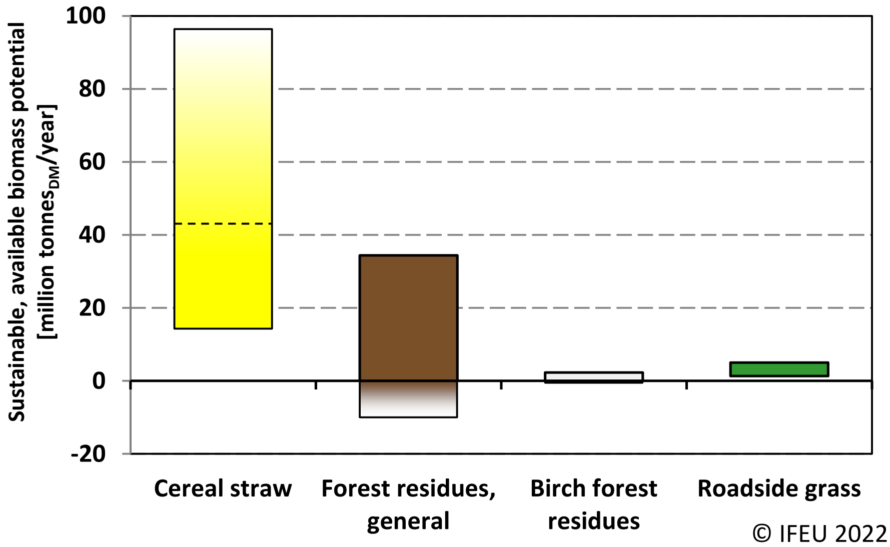

Figure 7-1: Overview of sustainable, available biomass potentials for lignocellulosic residue feedstocks considered within the UNRAVEL project.

- The biggest sustainable, available potential can be found for **cereal straw**. While some studies report up to around 100 million tonnes dry matter (Mt_{DM}) per year, the lower part of the range of **around 30 Mt_{DM}/year** seems more realistic because it results from taking a wider range of limitations to sustainable use into account. To illustrate, this theoretically corresponds to the demand of 100 biorefineries of the scale analysed in this report, which however does not take restrictions from local distribution and logistics into account. Besides environmental constraints, which are mainly related to the conservation of soil organic carbon, the existing uses of the straw must also be considered, including the shares that are not traded, to avoid negative social impacts. A current increase in biofuel production capacity from straw triggered by a dedicated mandate in the current renewable energy directive (RED II) may however absorb substantial parts of this straw in the next years.

- The use of **lower-grade stemwood** (pulpwood/energy wood) and **forest residues** is currently heavily debated among researchers who come to different conclusions. How much residues can be extracted from forests where and under which conditions is mainly limited by conserving soil ecology and carbon stocks in the top soil. While stemwood potentials seem to be largely used, it is unclear whether at EU level substantial additional amounts of **up to 35 Mt_{DM}/year** can be used sustainably or whether even the current level of use has to be restricted, which would leave no additional forest residues for other applications.
- Specific fractions of forest residues such as **tops and branches of birch trees**, which were exemplarily analysed in the UNRAVEL project, represent only a minor share of overall forest residues of **up to 2 Mt_{DM}/year**.
- An option to **increase the amount of forest residues available for material** use would be to replace other uses, i.e. primarily combustion for heat and power generation, by other renewable alternatives such as solar and wind power and by substantially decreasing the energy demand through better insulated buildings. This could have substantial negative social impacts while environmental impacts could be rather beneficial. In particular if the use of wood by small businesses or for domestic heating was to be restricted, financial support would be required to balance socio-economic impacts, in particular on low-income households.
- Besides the major residues straw and forest residues, a **large number of further biomass residues** could potentially be used for biorefineries in particular if the concept has a high feedstock flexibility such as in UNRAVEL. Most further residues are generally available in relatively small amounts but at certain locations their use can be worthwhile for a biorefinery if it is technically feasible. This has been exemplarily explored for roadside grass in the UNRAVEL project.
- **Roadside grass** is a so far largely unused sustainable resource that should be used as far as logistically possible. Its sustainable, available potential amounts to about **3 Mt_{DM}/year** and thus represents a small but nevertheless worthwhile expansion of the biorefinery's feedstock spectrum.
- The sustainably available amounts of lignocellulose biomass feedstock are **sufficient to feed several large-scale biorefineries**. Locations outside of the main cereal producing regions will however require a feedstock-flexible concept such as the one developed in UNRAVEL to avoid potential negative impacts on environmental and social sustainability.

7.4 Recommendations

The following recommendations to crucial stakeholder groups can help to improve the social sustainability of future biorefineries according to the UNRAVEL concept.

To process developers and research funding agencies

- Focus on feedstock flexibility in the further process development to reduce social risks due to potential competition for biomass feedstock. Feedstock flexibility is expected to be a competitive edge during location search and operation of a future biorefinery.
- Reduce the demand for input chemicals and energy as far as possible, in particular if they are based on fossil resources, the supply of which tends to be linked to higher social risks.
- Continue establishing a network with high-end service providers and suppliers, in particular with small and medium enterprises (SMEs).

To potential industrial operators of a future biorefinery

Aim to induce a positive change in the region where a new large-scale biorefinery is to be built:

- Target preferentially less privileged rural areas or areas that are particularly affected by the structural transformation and job losses in the fossil-based industry.
- When candidate locations for a future biorefinery are identified, conduct an analysis of current uses (commercial and non-commercial) of the targeted biomass residue flows. Ensure that the buying power of the biorefinery does not endanger the businesses and livelihoods of existing users of the same biomass.
- Engage with local stakeholders early on and take their needs and views into account.

Aim to use the economic power associated with a large-scale biorefinery in particular in a rural setting for the benefit of all stakeholders:

- Source as much as possible of the inputs and services locally.
- Invest in the qualification of the local workforce for the biorefinery itself, provide equal employment opportunities and provide incentives in particular for the biomass suppliers to follow this example. Prevent precarious working conditions at the biomass suppliers in particular among seasonal migrant workers.

- It is recommended that social reporting is taken into account when selecting suppliers in order to minimise negative social impacts in the supply chain of the biorefinery. Examples of these criteria are the provision of manufacturer-specific indicators, suppliers that include social indicators in sustainability reports e.g. following guidelines of the Global Reporting Initiative (GRI), or the possibility to carry out sustainability audits to the suppliers. These indicators, reports and audits should be focused on the hot spots identified in this report. This in particular applies to providers of biomass and providers of chemicals with higher tier suppliers outside of the EU.

To political decision makers

- In the mid- to long-term, biomass allocation plans should be developed at regional, national and European level. Due to the fact that social impacts and environmental burdens of resource scarcity do not possess an adequate price, market mechanisms cannot replace these plans.

- Once the UNRAVEL concept is fully developed and a concrete proposed setup could be shown to be sustainable, the installation of a first large-scale biorefinery should receive support. Connect this support to a socially balanced implementation concept taking into account e.g. the recommendations to potential industrial operators of a future biorefinery above.

- Actively manage the transition from a fossil-based to a bio-based and circular economy to mitigate social impacts in particular on employees in regions with a strong fossil-based industry. Attracting biorefineries to such regions could be one potential measure.

- In case high investments into new installations such as biorefineries, which are needed for a transition to a bio-based and circular economy should lead to higher product prices for end consumers, mitigate impacts on low-income households by compensatory instruments.

Taken together, social impacts and barriers to implementation are not direct physical consequences of processes. They can be influenced to a very large extent by socio-economic implementation strategies. The social risks identified in this study are no reason to refrain from implementation but rather entail obligations. Likewise, the realisation of potential benefits need to be actively pursued during implementation to the benefit of all stakeholders.

8 Abbreviations

C5	Sugars components with 5 carbon atoms (hemicellulosic sugars)
C6	Sugar components with 6 carbon atoms (cellulosic sugars)
CAP	Common Agricultural Policy
CHP	Combined heat and power plant
DM	Dry matter
DMP	Trimethyl phosphate
EC	Ethylene carbonate
EU	European Union
EUROSTAT	European Statistical Office
GA	Grant Agreement
GMO	Genetically modified organism
ISO	International Organization for Standardization
ILCSA	Integrated life cycle sustainability assessment is a methodology for comprehensive sustainability assessment of products (see [Keller et al. 2015] for details) building on the LCSA principle
MRIO	Multiregional input/output
OPEX	Operational expenses or operational cost assessment
PIR	Polyisocyanurate
PUR	Polyurethane
RED	Renewable Energy Directive [European Parliament & Council of the European Union 2009]
RED II	Recast Renewable Energy Directive [European Parliament & Council of the European Union 2018]
sLCA	Social life cycle assessment
SHDB	Social hotspot database
SME	Small and medium enterprises
SWOT	Strengths, weaknesses, opportunities, threats
TMP	Trimethyl phosphate
USA	United States of America
WP	Work Package

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