D4.5 Assessment of GHG and socioeconomic performance of RESfuel supply chains

Part A: GHG performance of RESfuel supply chains and impact over time

Part B: Socioeconomic Performance and capacity of RESfuel enterprises

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This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N.º 764799.

Deliverable Information	
Grant Agreement Number	764799
Project Acronym	ADVANCEFUEL
Instrument	CSA
Start Date	1 September 2017
Duration	36 months
Website	www.ADVANCEFUEL.eu
Deliverable Number	D4.5
Deliverable Title	D4.5 Assessment of GHG and socioeconomic Performance of RESfuel supply chains
Expected Submission	M34
Actual Submission	M36
Authors	Ivan Vera, Katharina Sailer, Ric Hoefnagels, Richard Orozco, Philipp Grundmann
Reviewers	Ayla Uslu, Joost van Stralen, Kristin Sternberg
Dissemination Level ***Public (PU), Restricted (PP), Confidential (CO)***	PU

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N.º764799.

Executive Summary

The general objective of WP4 is to assess the current and future sustainable production of RESfuels, and to analyze and assess their performance against sustainability criteria, certification schemes and standards to safeguard and stimulate sustainable production of RESfuels. The sustainability driver is based on the three pillars of economic, social and environmental sustainability. The synergies and trade-offs within these various dimensions represent the key challenges for the development of RESfuels. The present report is composed of two parts: part A, assesses the sustainability impact of RESfuels supply chains in Europe with a detailed focus on GHG emissions; part B aims to capture the impacts of feedstock production and RESfuel supply chain activities on the socioeconomic situation of participating actors and communities; with a particular focus on the social capacity developed by the activities of RESfuel enterprises.

Part A: GHG performance of RESfuel supply chains and impact over time

Part A of this report assessed the sustainability impact of RESfuels supply chains in Europe with a detailed focus on GHG emissions of advanced biofuels produced from dedicated energy crops and including carbon emissions from changes in soil organic carbon and above and below ground biomass from land conversion. A spatial explicit land use model was developed for the ADVANCEFUEL project to assess these impacts. Ranges in WTT GHG emissions were explored for straw and forest residues next to seven different energy crop types, locations of cultivation, transportation distances and six different conversion systems. The results are shown for Base cases and ranges for best and worst estimates for the selected parameters. An Excel based GHG calculation tool, accompanied to this report, can be used to explore the impact of alternative assumptions per pathway. Scenarios of RESfuel deployment from WP6 are linked to the land use model to assess the potential impact of energy crop cultivation on marginal land in the EU over time.

The results of the WTT GHG emission performance show that most of the included advanced biofuel pathways lead to GHG savings well over 70%. These performances are possible when long distance transport of untreated biomass is avoided and fossil energy sources, for example for hydrogen production, are minimized in the supply chain. This also means that the minimum

GHG saving requirement of 65% of the RED II is an important mechanism to improve the performance of advanced biofuels. If long distance transport is required, more advanced feedstock supply chains, such as pellets, transport of liquid intermediates (for example pyrolysis oil) or biofuels, should be integrated in the supply chain to allow for longer transport distances. These advanced feedstock supply chains were however not assessed in this report.

Energy crops cultivated on marginal land are expected to contribute substantially to the future bioenergy supply in the EU. The results of this study demonstrate that if cultivated on land in compliance with the land sustainability criteria of the RED II in most cases results in a net carbon sequestration. Although marginal, LUC-related CO_2 emissions can however also be positive on some locations. Woody crops, such as poplar, store generally more carbon in biomass and SOC pools compared to grassy crops such as miscanthus, but the chemical and physical characteristics of these crops also determine the suitability for conversion to advanced biofuels. The overall GHG reduction performance is therefore determined by its location, the type of feedstock and type of supply chain. Other environmental impact categories, including water use, biodiversity and land use, but also socioeconomic indicators as discussed in Part B of this report should also be included in the decision to avoid possible burden shifting or negative impacts.

On a short and middle term, there is sufficient biomass (produced in marginal lands) to meet the projected energy crop biomass demand in the EU. Furthermore, the biomass potentials are sufficient under strict land criteria that considering only the utilization of biomass that results in negative LUC-related CO_2 emissions. Considerable support from the government would be required to increase cooperation between member states that allow for an efficient biomass trade between and within member states. In addition, efforts should be directed to scale up biomass production and ensure biomass readability for the end use markets. Smart choices while considering different location specific social and biophysical characteristics will be required to smooth up the biomass supply process. On a long term, the role of biomass imports can play a major role as there would be insufficient land with a high level of sustainability constrains to produce biomass. However, biomass imports should be carried out and evaluated under RED II standards to assure sustainability along the whole supply chain.

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Part B: Socioeconomic performance and capacity of RESfuel enterprises

Part B of this report is composed of two main parts. The first part *compares different socioeconomic assessments from literature* regarding the RESfuel sector and the scope, feedstock, end-product, location, method and socioeconomic indicators which have been applied. The most assessed socioeconomic indicators are related to job creation and human health impact (Cambero and Sowlati, 2014). The results of this report reveal that there is an awareness regarding the impacts of biorefineries on their socioeconomic environment, but other relevant aspects remain underrepresented. Less attention has been given to the social and economic capacities being built through the development of RESfuel enterprises and supply chains. For this reason, the second part of the report aims to *enrich the methods for capturing impacts on the socio-economic environment of RESfuel supply chain activities*. This is accomplished by assessing the performance of six RESfuel enterprises in relation to their impact on the social capacities at the individual, organizational and societal level from their RESfuel activities. The analysis uses as a guideline the Capacity Works Framework (GIZ, 2015) which focuses on the five success factors: strategy, cooperation, processes, steering structures, learning and innovation.

The contribution of this report towards the market uptake of RESfuels is two-fold. From a methodological perspective, the report *contributes to the ongoing development of tools and methodologies for Social LCAs and others*. The criteria proposed in this study can provide the foundations for a variety of models of considerable scope and power that can allow for a better understanding of the impacts on the socioeconomic environment of the actors and communities involved in RESfuels supply chain activities. On the other hand, the results obtained are relevant to *demonstrate the sustainability performance of RESfuels from a capacity development perspective*.

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Abbreviations

ALCA	Attributional Lifecycle Assessment
BAU	Business as usual
$CaCO_3$	Calcium Carbonate
CaO	Calcium Oxide
CH_4	Methane
CLCA	Consequential Lifecycle Assessment
CO_2	Carbon Dioxide
CO_2eq	Carbon Dioxide Equivalent
DLUC	Direct Land Use Change
DME	Di-methyl Ether
EC	European Commission
EU	European Union
FU	Functional Unit
FT	Fischer-Tropsch
GHG	Greenhouse Gas
GWP	Global Warming potential
H_2	Hydrogen
HTL	Hydrothermal Liquefaction
ISCC	International Sustainability and Carbon Certification
IPCC	Intergovernmental Panel on Climate Change
JRC	European Commission – Joint Research Centre
K_2O	Potassium Oxide
Kg	Kilogram
LCA	Life Cycle Assessment
LHV	Lower Heating Value
LUC	Land Use Change
MJ	Mega Joule
MC	Moisture Content
NG	Natural Gas
N	Nitrogen
N_2O	Nitrous Oxide
PEM	Proton Exchange Membrane (Electrolyser)
PR	Public relations
PSILCA	Product Social Impact Life Cycle Assessment
Pyr	Pyrolysis
P_2O_5	Phosphorus Pentoxide
RED I	Renewable Energy Directive
RED II	Revised Renewable Energy Directive
RJF	Renewable Jet Fuel
RSPO	Roundtable on Sustainable Palm Oil
SHDB	Social Hotspot Database
SHF	Separate Hydrolysis and Fermentation
SIA	Social Impact Assessment
SIO	Social Input-Output

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SLCA	Social Lifecycle Assessment
SMR	Steam Methane Reforming
SOEC	Solid Oxide Electrolysis Cell
SRC	Short Rotation Coppice
SRI	Social return on investment
SSF	Simultaneous Saccharification and Fermentation
SSP	Supplier Sustainability Portal
TTW	Tank-to-Wheel
WEC	World Energy Council
WTT	Well-to-tank
WTW	Well-to-Wheel

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1. Introduction

Background

The development of advanced and liquid renewable fuels (RESfuels) poses several advantages over conventional (food crops based) biofuels. Potentially, RESfuels can reduce greenhouse gas (GHG) emissions significantly when compared to their fossil counterparts, omit competition with food crops and provide positive socioeconomic benefits (Naik et al. 2010). In addition, the development of this sector has been promoted by regulatory developments. The adoption of the Renewable Energy Directive on the promotion of the use of energy from renewable sources, RED II (European Parlament 2018), aims to limit the production of conventional food based biofuels and promote the development of RESfuels towards and beyond 2030. RESfuels produced from biomass will have to comply with strict environmental sustainability criteria as established in RED II (European Parlament 2018). For example, after 2021 all biofuels consumed in the transport sector will have to demonstrate at least a 65% savings in GHG emissions in comparison to fossil counterparts (European Parlament 2018). The success of RESfuels as a valid strategy for sustainable biofuel supply and climate change mitigation option will however depend on all three pillars of sustainability (environmental, economic and social).

Spatial aspects in supply chain GHG performance

It is expected that lignocellulosic energy crops, amongst other feedstock types such as forest and agricultural residues, will play a major role in future RESfuels production (Uslu, van Stralen, and Pupo-Nogueira 2020). Generally, lignocellulosic energy crops can deliver higher yields in less suitable conditions compared to food based energy crops and contribute to a higher degree of carbon sequestration in the cultivation stage (Richter et al. 2015). The sustainability performance of RESfuels production and use will however rely strongly on biophysical conditions and the socioeconomic context (Espinoza Pérez et al. 2017). Several studies and projects have assessed the GHG performance of RESfuels (Hombach et al. 2016; Rettenmaier et al. 2018). However, a comprehensive and detailed assessment that incorporates geographical, technical and temporal aspects from the most relevant lignocellulosic feedstock types and conversion technologies is still missing. Furthermore, regional environmental aspects from feedstock cultivation and supply, such as Land Use Change (LUC) related carbon stock changes or yields, that are location specific and driven by biophysical conditions (van der Hilst 2018), are often ignored in environmental assessments of RESfuel supply chains.

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Socioeconomic impacts

The social dimension is the least investigated upon when it comes to sustainability assessments (Mauerhofer, 2013). Economic and environmental aspects are more often assessed, since social impacts are more difficult to monitor and quantify, this also makes the data collection more time and cost-intensive (Silva et al., 2017). Nevertheless, including the social dimension and in particular the social capacity dimension in the sustainability assessments offers the potential benefit of better understanding the implications for sustainability of RESfuels and enhancing the opportunities for improvements.

Methodologies used to track the socioeconomic compliance of RESfuel enterprises and value chains to sustainability schemes are Social Life Cycle Assessment (S-LCA), Social Impact Assessment (SIA), Social Input—Output (SIO), Social Return on Investment (SRoI) analysis as well as multi-criteria analysis (Štreimikienė, Girdzijauskas, and Stoškus 2009). S-LCAs on second generation biorefineries or feedstock supply chains are scarce, since the focus lies rather on the assessment of the environmental dimension (Valente, Brekke, and Modahl 2018). The Social Hotspots Database (SHDB) is the first commercially available database with social input-output data (Benoit-Norris, Cavan, and Norris 2012). Another database is the Product Social Impact Life Cycle Assessment database (PSILCA) developed by GreenDelta (https://psilca.net/)(Falcone and Imbert 2018) and SOCA which is an add-on of Ecoinvert developed by GreenDelta (https://nexus.openlca.org/database/soca). Aside, from the classic socioeconomic assessment, which measures the impact of RESfuels, this report aims to investigate the impacts of enterprises producing RESfuels on social capacity. Within this report, social capacity is understood as the aggregate of relationships and institutions used by individuals, groups and/or organizations to be able to act expediently towards a benefit and a larger common purpose (adapted from Smith and Kulynich, 2002).

The overarching objective of this report is to assess the GHG and socioeconomic performance of RESfuels supply chains and enterprises in Europe.

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To this purpose, the report is organized in two individual parts:

- Part A: GHG performance of RESfuel supply chains and impact of energy crop cultivation over time
- Part B: Socioeconomic performance and capacity of RESfuel enterprises

In Part A, first the GHG footprint of different advanced biofuel supply chain combinations are assessed with a dedicated Excel based GHG calculation tool that is accompanied with this report (Supplementary material A1). The GHG supply chain emissions are assessed in line with RED II calculation method (European Parlament 2018). Secondly, a detailed analysis is carried out for, 2030, 2040 and 2050 linked to RESfuel development scenarios (Uslu, van Stralen, and Pupo-Nogueira 2020) while considering the spatial variation in biophysical conditions. A detailed focus is given to dedicated energy crops that are cultivated on marginal lands.

Part B aims to answer the following questions:

- What is the socioeconomic impact of RESfuel supply chains in terms of capacity development?
- How do RESfuel project activities influence strategies, cooperations, steering structures, processes, learning and innovations of actors and determine their socio-economic performance?
- How can RESfuels production be described and assessed in terms of their impact on social capacity?

Part A: GHG performance of RESfuel supply chains and impact over time

2. Methodology

2.1. Greenhouse has performance (and cumulative energy demand)

2.1.1. Geographic scope and temporal scope

Lignocellulosic energy crop cultivation

The geographical scope for the cultivation of lignocellulosic energy crops is the European Union, but Malta and Cyprus are excluded due to data limitations. The assessment is carried out at a spatial resolution of 1 km^2 (mainly for LUC-related GHG emissions and cultivation of lignocellulosic energy crops) while considering the heterogeneity in biophysical conditions. The assessment on the GHG performance of energy crops cultivation is conducted for 2030, 2040 and 2050.

Supply chains

The assessment of supply chain GHG emissions include advanced biofuel production technologies that are already available as well as upcoming conversion processes that are close to commercialization. Several RESfuels supply chain configurations are considered with different feedstock types and conversion technologies. The supply chain GHG emissions are assessed for 7 different lignocellulosic energy crops cultivated on marginal lands as well as forest and agricultural residues (see Section 3.1). These are combined with 7 (see Section 3.3) different type of conversion technologies to produce advanced biofuels for road, aviation and marine applications. The assessment provides relevant insights in the GHG performance of RESfuels supply chains under RED II sustainability criteria and determine whether these RESfuels are able to comply with strict GHG savings criteria. The impact of technology development over time on the GHG performance, for example from efficiency improvements or innovations in conversion technologies, was not assessed in this report. A more detailed description of the individual feedstock supply chains and conversion systems is provided in Section 3.3.

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Temporal scope of impacts

For the analysis, GHG emissions other than CO_2, CH_4 and N_2O are expressed in CO_2 equivalent for a global warming potential (GWP) impact calculated over a 100-year time horizon (GWP100) (IPCC 2006a) consistent with the characterization factors used in the RED II (European Parlament 2018):

- CO_2: 1
- N_2O: 298
- CH_4: 25

2.1.2. System boundaries

The system boundaries cover all stages from biomass cultivation and extraction, transportation, conversion and up to distribution, or Well-to-Tank (WTT) as shown in Figure 1. The RED II calculation rule also includes the emissions from the fuel in use (see Equation 1) (well-to-wheel). However, CO_2 emissions of the fuel in use (e_u) should be assumed zero for biofuels and bioliquids. Non-CO_2 GHG emissions including CH_4 and N_2O should be taken into account. These are however ignored from the calculated default and typical values for biofuels and bioliquids in the RED II (European Parlament 2018). Similarly, the GHG savings in this report are calculated over the WTT GHG emissions as described by Equation 2 as non-CO_2 GHG emissions from the fuel in use, these are not expected to change the results significantly.

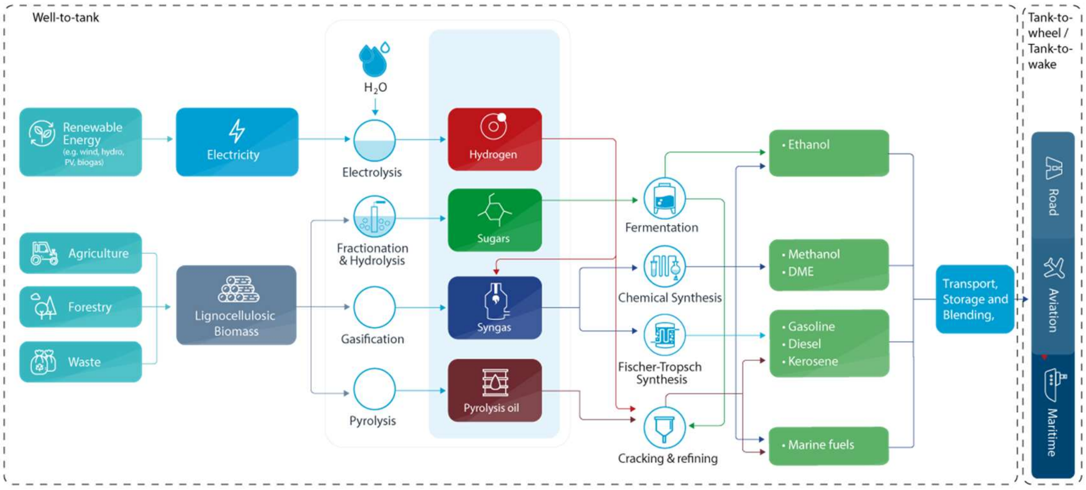

Figure 1 System boundaries and conversion pathways

2.1.3. Calculation method

A life-cycle assessment (LCA) approach is used to calculate the life cycle GHG emissions of advanced biofuels. GHG emissions are calculated according to the rules set in Annex V C of the RED II (European Parlament 2018). The functional unit to compare the conversion pathways is one MJ based on the energy content of the biofuel. Upstream emissions from the production of chemicals and products (e.g. fertilizers) used along the whole supply chain are accounted,

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but emissions involved with the construction of facilities, buildings and vehicles are excluded. Annualized emissions from LUC-related carbon stock changes (e_l) are built upon Report task D4.3 (Vera, van der Hilst, and Hoefnagels 2020). Only marginal lands with specific land use/covers that meet RED II land related sustainability criteria are considered available for the potential production of lignocellulosic energy crops[1].

Equation 1

$$E = e_{ec} + e_l + e_p + e_{td} + e_u - e_{sca} - e_{ccs} - e_{ccr}$$

Where:

E = Total emissions from the use of the fuel, *g CO_2eq/MJ*

e_{ec} = Emissions from the extraction or cultivation of raw materials, *g CO_2eq/MJ*

e_l = Annualised emissions from carbon stock changes caused by land-use change, *g CO_2eq/MJ*

e_p = Emissions from processing, *g CO_2eq/MJ*

e_{td} = Emissions from transport and distribution, *g CO_2eq/MJ*

e_u = Emissions from the fuel in use, *g CO_2eq/MJ*

e_{sca} = Emission savings from soil carbon accumulation via improved agricultural management, *g CO_2eq/MJ*

e_{ccs} = Emission savings from CO_2 capture and geological storage, *g CO_2eq/MJ*

e_{ccr} = emission savings from CO_2 capture and replacement, *g CO_2eq/MJ*

Possible GHG emissions savings from CO_2 capture and geological storage (e_{ccs}) and CO_2 capture and replacement (e_{ccr}) are not assessed in this report.

Greenhouse gas savings from biofuels are calculated following Equation 2.

Equation 2

$$Savings = (E_{f(t)} - E_B)/E_{f(t)}$$

$E_{f(t)}$ = Total emissions from the biofuel

E_B = Total emissions from the fossil fuel comparator of transport (94 g CO_2eq/MJ) (European Parlament 2018).

2.1.4. Co-product allocation

Most of the included conversion pathways produce multiple outputs such as surplus electricity that is sold to the grid. The method to deal with multi outputs has a large impact on the results (Antonissen et al. 2016; Hoefnagels, Smeets, and Faaij 2010). Although substitution is seen as the most appropriate method to assess the impact of policy decisions (Plevin, Delucchi, and Creutzig 2014), allocation is seen more appropriate for a comparative assessment of individual pathways or regulation of individual economic operators (European Parlament 2018). Similar to the RED II requirements, energy allocation is applied for co-products. In case of co-generation

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[1] For more information about land availability and type of land that can be dedicated the potential production of lignocellulosic energy crops please see Report task D4.3 (Vera, van der Hilst, and Hoefnagels 2020)

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of heat and power (CHP), as is the case in the ethanol pathways, exergy allocation is applied. The detailed method of exergy allocation is described in more detail Edwards et al. (2017) and Giuntoli et al. (2017).

2.1.5. Extraction or cultivation of raw materials (e_{ec})

GHG emissions from biomass production are directly related to the activities and inputs used along the cultivation stage. The use of N fertilizers results in N_2O direct and indirect field emissions that are required to be accounted.

N_2O direct and indirect field emissions

N_2O direct field emissions (Equation 3) occur from the application of synthetic fertilizers and manure, from the amount of nitrogen (N) present in crops residues and from the amount of N that is mineralized in association with LUC induced loss of Soil Organic Carbon (SOC) (IPCC 2006b). In this study, it is assumed that crop nitrogen requirements are met only with the application of synthetic fertilizers. It is considered that residues are left on the field. Mineralized N estimations in association with LUC are based upon the loss of carbon when one land is potentially converted to lignocellulosic energy crops. However, such LUC processes can result in soil carbon accumulation for some specific areas depending on the crop type and crop management characteristics. Sequestrated N in association with LUC is not accounted when the potential LUC results in soil carbon accumulation (IPCC 2006b). A default value of 0.01 is considered as emissions factor for N_2O emissions from N inputs (IPCC 2006b).

Equation 3

$$N_2O_{Direct} = (F_{SN} + F_{CR} + F_{SOM}) * EF_1 * 44/12$$

Where:

N_2O_{Direct} = Annualized direct N_2O emissions, *kg N_2O/year*
F_{SN} = Annual amount of applied N synthetic fertilizer, *kg N/year*
F_{CR}= Annual amount of N in crop residues, *kg N/year*
F_{SOM} = Annual amount of N in mineral soils that is mineralized in association with LUC, *kg N/year*
EF_1 = Emission factor for N_2O emissions from N inputs, kg N_2O–N/kg N
44/12 = Conversion factor from N_2O–N to N_2O

The annual amount of N in crop residues include above and below ground biomass residues (Equation 4). The location specific yields assessed in Report task D4.3 (Vera, van der Hilst, and Hoefnagels 2020) are used as input and for each crop the Harvestable Index (HI) is applied to determine the amount of above ground biomass left on the field after harvesting. Below ground biomass residues are calculated in function of the crop specific above to below ground biomass ratios (see table 2 Report task D4.3 (Vera, van der Hilst, and Hoefnagels 2020)). For perennial

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crops the below ground residues are not removed on annual basis and only when the field is renewed. Therefore, the N content in below ground residues is accounted for the lifespans of the lignocellulosic energy crops. For grassy crops, default IPCC factors for perennial grasses N content in above and below ground biomass residues are considered (IPCC 2006b). For woody crops, there are no default values of N content in above and below ground residues. Therefore, it was assumed that the amount of N present in woody crops residues was the same as the one present in the yield (see Table 2).

Equation 4

$$F_{CR\,i} = (AGR_i * N_{AGR\,i}) + (BGR_i * N_{BGR\,i})$$

$$AGR_i = yield_i / HI_i$$

$$BGR_i = (Yield_i + AGR_i) * R_i * Frac_{renew\,i}$$

Where:

F_{CR} = Annual amount of N in crop residues, *kg N/year*

i = Crop type,

AGR = Annual amount of above ground crop residues, *kg AGR/year*

N_{AGR} = N content in above ground residues, *kg N/kg AGR*

BGR = Annual amount of below ground crop residues, *kg BGR/year*

N_{BGR} = N content in below ground residues, *kg N/kg BGR*

Yield= Annual amount of harvested biomass, *kg/ha year*

HI = Harvest index, %

R = Ratio of below ground biomass to above ground biomass,

$Frac_{renew}$ = fraction of total area under crop i that is renewed. For lignocellulosic crops which are renewed on average every 15 years, $Frac_{renew}$ = 1/15

The LUC-related SOC CO_2 emissions assessed on the Annualized emissions from carbon stock changes caused by land-use change section (2.1.6) are used as input to calculate the mineralized N in association with LUC. Mineralized N is determined with a carbon to N ratio of soil in organic matter. A carbon to N ratio default value of 15 (R_{CN}) is applied when grasslands or shrublands are converted towards cropland (IPCC 2006b) . Equation 5 displays the relation between SOC CO_2 emissions and mineralized N.

Equation 5

$$F_{SOM\,i} = (C_{mineral\,i} * 1/R_{CN}) * 1000$$

F_{SOM} = Annual amount of N in mineral soils that is mineralized in association with LUC, *kg N/year*

i = Crop type,

$C_{mineral}$ = Average annual loss of soil carbon, t C/ha

R_{CN} = C:N ratio of the soil organic matter,

1000 = Conversion factor to convert t to kg

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N_2O indirect field emission occur from N volatilization/deposition and leaching. Leaching only occurs in very wet areas characterized by strong precipitation regimes or when irrigation is used (IPCC 2006a). Given the impossibility to determine whether irrigation will be potentially applied on a general scale to produce lignocellulosic energy crops, GHG emissions from leaching were not considered. N_2O emissions from atmospheric deposition occur from the volatilization of N as NH_3 and oxides of N (NO_x), which are deposited in soils. The application of organic fertilizers can increase considerably N volatilization/deposition (IPCC 2006b). However, only synthetic fertilizers are assumed to be applied for the potential production of lignocellulosic energy crops. Default values are assumed for the fraction of synthetic fertilizers that volatizes (0.11, $Frac_{GASF}$) and for the emission factor for N_2O emissions from atmospheric deposition (0.01, EF_4)

Equation 6

$$N_2O_{ATD} = F_{SN} * Frac_{GASF} * EF_4 * 44/12$$

Where:

N_2O_{ATD} = Annual amount of N_2O emissions from atmospheric deposition of volatilized N, *kg N_2O/year*

F_{SN} = Annual amount of applied N synthetic fertilizer, *kg N/year*

$Frac_{GASF}$= Fraction of synthetic fertilizer N that volatilizes as NH_3 and NO_x, kg (NH_3–N + NO_x–N)$_{volatilised}$ / kg N

EF_4 = Emission factor for N_2O emissions from atmospheric deposition of N on soils, kg N_2O–N/ kg (NH_3–N + NO_x–N)$_{volatilised}$

44/12 = Conversion factor from N_2O–N to N_2O

2.1.6. Annualised emissions from carbon stock changes caused by land-use change (el)

Annualised land use change (LUC) emissions from the production of lignocellulosic energy crops are calculated following Equation 7(European Parlament 2018). RED II methodology to assess LUC-related GHG emissions from carbon stock changes is built upon the stock difference approach from the IPCC Guidelines for National Greenhouse Gas Inventories Volume 4 (IPCC 2006a)[2]. Biomass, dead organic matter, litter, harvested wood product and soils are the considered carbon stocks related to LUC GHG emissions (IPCC 2006a). However, RED II emphasizes the accounting of carbon stocks present in biomass and soils. Besides, dead organic matter, litter and harvested wood products are primarily relevant when land is converted to/from forest (IPCC 2006a). Therefore, only the biomass and soil carbon stocks are considered for the assessment (see sections below). Carbon stocks are assessed for each relevant point in time (see temporal scope) for the reference land use/cover marginal land and for the potential carbon stock if such marginal land is dedicated to produce lignocellulosic energy crops. Annualised land use

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[2] There is no difference in methodologies between RED II and IPCC guidelines

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change (LUC) emissions are assessed for each crop while considering location specific biophysical conditions

Equation 7

$$e_l = (CS_r \; - \; CS_A) * 3.664 * \frac{1}{20} * \frac{1}{P}$$

Where:

e_l = Annualised emissions from carbon stock changes caused by land-use change, *g CO_2eq/MJ*

CS_r = Carbon stock in marginal land associated with the reference land use/cover in marginal land, *t C/ha*

CS_A = Potential carbon stock in marginal lands associated with the production of lignocellulosic energy crops, *t C/ha*

3.664 = Conversion factor to convert C to CO2,

1/20 = Factor to annualize emission

1/P = Productivity of the crop, *MJ/ha*

The productivity of each crop is assessed based on each crops HI and energy content (please see section 3.2 for input data)

Biomass

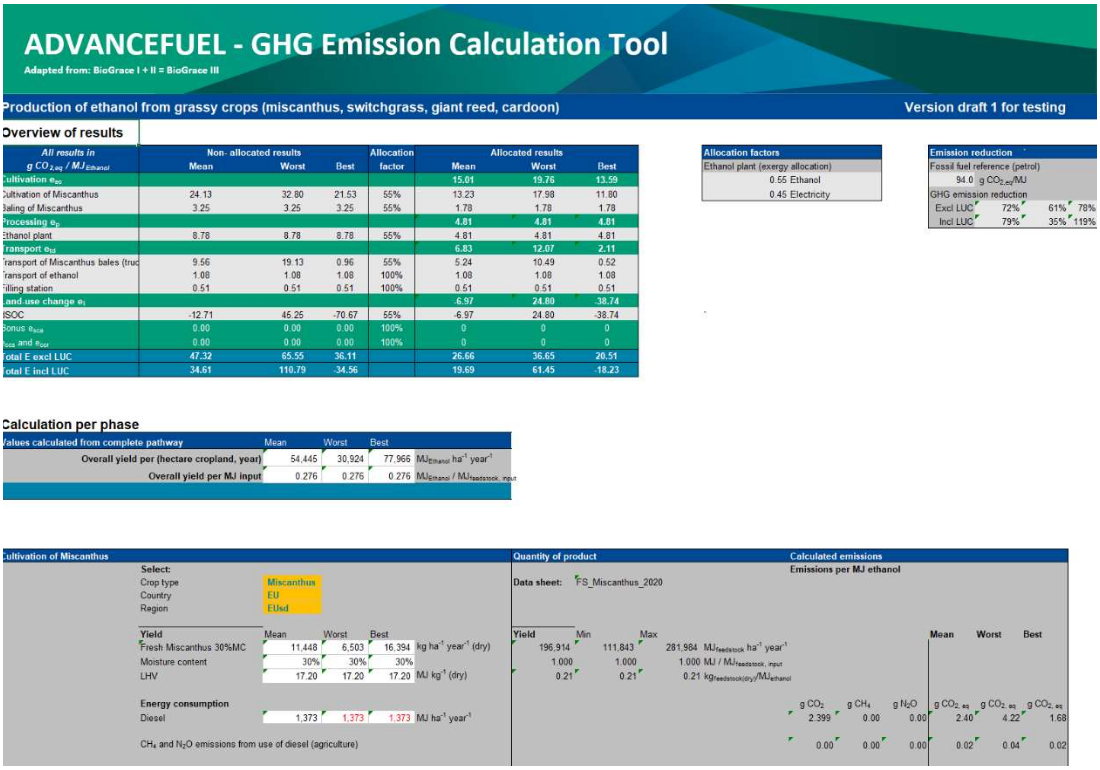
CO_2 emissions from the changes in biomass carbon stock when land is converted towards lignocellulosic energy crops is assessed spatially explicit. Biomass potentials for each crop are estimated based on crop phenological characteristics, location specific biophysical conditions and climatic projections. Climatic parameters are derived from the HadGEM2-ES global climatic model under the Representative Concentration Pathway 4.5 (RCP 4.5) scenario for each relevant point in time. Biomass for each crop is estimated while considering the maximum amount of biomass that can be produced annually given the water use efficiency of biomass production in relation to water loss from evapotranspiration. In addition, crop specific suitability maps are used to include the effect of other biophysical characteristics on potential biomass yield. Biomass prior to conversion is quantified using IPCC default values for maximum amount of above ground biomass in grasslands and spatial data on soil productivity (the degree to which the soil carries out its biomass production service) (Tóth et al. 2013). Carbon stock in the land previous to conversion and lignocellulosic energy crops is derived from biomass specific IPPC carbon content default values. Then, the difference in carbon stock between land prior to conversion and lignocellulosic energy crops is converted to CO_2 emissions. For a detail description of the methods to estimate biomass for each land use/cover category, lignocellulosic energy crops and derived GHG emissions from the potential production of such crops see Report task D4.3 (Vera, van der Hilst, and Hoefnagels 2020)

SOC

Carbon stocks in soil are quantified for each land use/cover prior to conversion and for each lignocellulosic energy crop. The IPCC default values for reference SOC levels are assigned to each land use/cover category while considering soil type and climate zones stratification. IPCC SOC stock change factors are employed to consider the effect of land use, management regime and input of organic amendments. These factors are applied for each land use/cover category based on the description in the IPCC guidelines. CO_2 emissions from the changes in soil organic carbon are estimated by comparing the SOC of the land prior to conversion with the potential SOC when land is converted to lignocellulosic energy crops. For a detail description of the methods to assess SOC for each land use/cover category, lignocellulosic energy crops and derived GHG emissions from the potential production of energy crops see Report task D4.3 (Vera, van der Hilst, and Hoefnagels 2020)

2.2. GHG emission calculation tool

An Excel based GHG calculation tool is made to assess the WTT GHG footprint of advanced biofuel pathways in a transparent way. This tool is an adapted version of the existing Harmonised Greenhouse Gas Calculations for biofuels and bioliquids (BioGrace I 2015) and Harmonised Greenhouse Gas Calculations for Electricity Heating and Cooling (BIOGRACE II 2015). A screenshot of the tool is depicted in Figure 2. The Biograce tools can be found at the website: www.biograce.net. The Excel tool is exclusively made to explore the calculations and results that are presented in this report next to alternative assumptions. It is, however, not intended to be used to conduct harmonised emission GHG calculations for verification purposes under requirements of the European Union. For these applications, we kindly refer to the original BioGrace I and BioGrace II Tools.



ADVANCEFUEL - GHG Emission Calculation Tool

Adapted from: BioGrace I + II = BioGrace III

Production of ethanol from grassy crops (miscanthus, switchgrass, giant reed, cardoon) — Version draft 1 for testing

verview of results

All results in g $CO_{2,eq}$ / $MJ_{Ethanol}$	Non- allocated results Mean	Worst	Best	Allocation factor	Allocated results Mean	Worst	Best
ultivation e_{ec}					15.01	19.76	13.59
ultivation of Miscanthus	24.13	32.80	21.53	55%	13.23	17.98	11.80
aling of Miscanthus	3.25	3.25	3.25	55%	1.78	1.78	1.78
rocessing e_p					4.81	4.81	4.81
thanol plant	8.78	8.78	8.78	55%	4.81	4.81	4.81
ransport e_{td}					6.83	12.07	2.11
ransport of Miscanthus bales (truc	9.56	19.13	0.96	55%	5.24	10.49	0.52
ransport of ethanol	1.08	1.08	1.08	100%	1.08	1.08	1.08
illing station	0.51	0.51	0.51	100%	0.51	0.51	0.51
and-use change e_l					-6.97	24.80	-38.74
SOC	-12.71	45.25	-70.67	55%	-6.97	24.80	-38.74
onus e_{sca}	0.00	0.00	0.00	100%	0	0	0
$_{ccs}$ and e_{ccr}	0.00	0.00	0.00	100%	0	0	0
otal E excl LUC	**47.32**	**65.55**	**36.11**		**26.66**	**36.65**	**20.51**
otal E incl LUC	**34.61**	**110.79**	**-34.56**		**19.69**	**61.45**	**-18.23**

Allocation factors
Ethanol plant (exergy allocation)
0.55 Ethanol
0.45 Electricity

Emission reduction			
Fossil fuel reference (petrol)			
94.0 g $CO_{2,eq}$/MJ			
GHG emission reduction			
Excl LUC	72%	61%	78%
Incl LUC	79%	35%	119%

alculation per phase

alues calculated from complete pathway	Mean	Worst	Best	
Overall yield per (hectare cropland, year)	54,445	30,924	77,966	$MJ_{Ethanol}$ ha^{-1} $year^{-1}$
Overall yield per MJ input	0.276	0.276	0.276	$MJ_{Ethanol}$ / $MJ_{feedstock, input}$

ultivation of Miscanthus

Select:
Crop type: Miscanthus
Country: EU
Region: EUsd

Yield	Mean	Worst	Best	
Fresh Miscanthus 30%MC	11,448	6,503	16,394	kg ha^{-1} $year^{-1}$ (dry)
Moisture content	30%	30%	30%	
LHV	17.20	17.20	17.20	MJ kg^{-1} (dry)
Energy consumption				
Diesel	1,373	1,373	1,373	MJ ha^{-1} $year^{-1}$

CH_4 and N_2O emissions from use of diesel (agriculture)

Quantity of product

Data sheet: FS_Miscanthus_2020

Yield	Min	Max	
196,914	111,843	281,984	$MJ_{feedstock}$ ha^{-1} $year^{-1}$
1.000	1.000	1.000	MJ / $MJ_{feedstock, input}$
0.21	0.21	0.21	$kg_{feedstock(dry)}$/$MJ_{ethanol}$

Calculated emissions

Emissions per MJ ethanol

g CO_2	g CH_4	g N_2O	**Mean** g $CO_{2,eq}$	**Worst** g $CO_{2,eq}$	**Best** g $CO_{2,eq}$
2.399	0.00	0.00	2.40	4.22	1.68
0.00	0.00	0.00	0.02	0.04	0.02

Figure 2 A screenshot of the ADVANCEFUEL – GHG Emission Calculation Tool

2.3. Projections of energy crops and marginal land use change impact over time

The potential GHG impact of energy crop cultivation on marginal land over time to 2050, is assessed with the following approach as summarized in Figure 3:

- In the first step, the projected demand of lignocellulosic energy crops regardless of its final end-uses (heat, electricity, transport) are used. The projected demands are based on the Road Zero and Transport Bio scenarios as described in Report task D6.2 (Uslu, van Stralen, and Pupo-Nogueira 2020). These scenarios explore low (Road Zero) to high (Transport Bio) demands for bioenergy. Both scenarios include relatively large amounts of grassy crops and a substantially lower demand for woody crops. To reduce the complexity of the analysis, total lignocellulosic energy crops demand projections are assumed to be all for grassy crops.
- In the second step, these projections are compared with the potential of energy crops determined with the spatial explicit land use model for energy crop cultivation on marginal lands under RED II land sustainability criteria as described in Report task D4.3 (Vera, van der Hilst, and Hoefnagels 2020). Also, stricter land criteria are included in an additional supply scenario that restricts the conversion of marginal lands to lignocellulosic energy crops if it results in positive net LUC related CO_2 emissions is included (RED II + land criteria).

Therefore, only marginal lands that potentially store carbon (negative LUC-related CO_2 emissions) from the change in land use to lignocellulosic energy crops are considered available in the (RED II + land criteria) supply potential.

- In the third step, the assessment of GHG impact over time is carried out considering the heterogeneity in local biophysical conditions at a 1 km^2 and aggregated to EU member state level by combining supply potentials with demand projections.

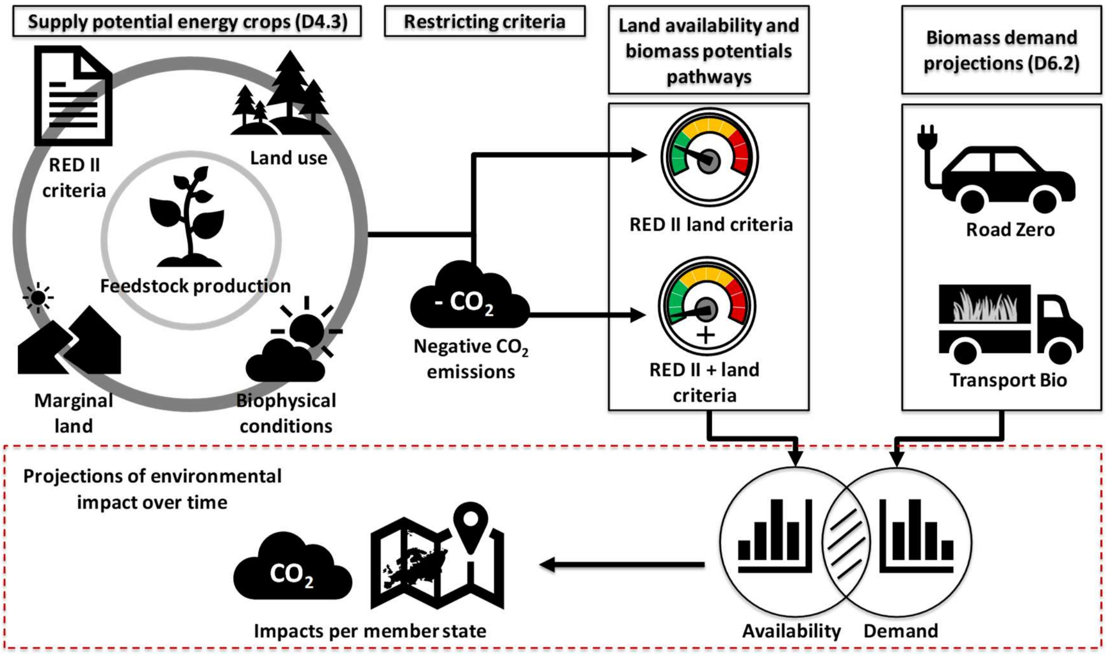


Figure 3 Soft-linking assessment from the supply potential energy crops (D4.3) and biomass demand projections (D6.2).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N.°764799.

3. Supply chain input data

This section provides a description of the different stages along the supply chains from biomass production up to fuel use. Input data and most important assumptions are also included in this section. The input data and assumptions vary according to regional and crop phenological characteristics, and location specific biophysical conditions. Upstream emissions from the production and use of fuels and chemicals/agriculture inputs are also included.

3.1. Extraction or cultivation of raw materials (e_{ec})

3.1.1. Forest residues and agriculture residues

Forest biomass and agricultural residues are considered to have zero GHG emissions upstream of collection (European Parlament 2018) . Emissions for harvesting and collection from diesel use of forest and agriculture machinery are similar to upstream processes in the straw pellets supply chain and forest residue pathways in the European commission Joint Research Center (JRC) Solid and Gaseous biomass workbook (Giuntoli et al. 2017). These pathway assumptions are similar to the default and typical values for ethanol from forest residues and straw in the RED II as described in Edwards et al. (2017).

3.1.2. Dedicated energy crops

For the potential production of lignocellulosic energy crops on marginal lands, diesel consumption is accounted from the use of agricultural equipment during soil preparation, cultivation, pesticides/fertilizers application and harvesting. For grassy lignocellulosic energy crops harvesting includes cutting and bailing while for woody lignocellulosic energy crops it includes cutting and chipping. Table 1 shows the inputs data used for the cultivation and harvesting process for each crop. Diesel, pesticides and fertilizers emissions factors are obtained from JRC (Giuntoli et al. 2017). In addition to GHG emissions from agricultural inputs production and application, fertilizer induced N_2O emissions are considered and calculated in accordance with IPCC (2006) Tier 1 methodology as mentioned and included in the methods section.

Table 1. Overview of input data used for the cultivation and harvesting processes. data is averaged over the crops life spam.

Lignocellulosic energy crop	Pesticides (kg/ha year)	Diesel for cultivation and harvesting (l/ha year)
Miscanthus	0.3[A]	38.3[D]
Switchgrass	0.2[A]	31[D]
Giant Reed	0.2[A]	38[D]
Cardoon	0.2[A]	43[E]

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Willow	4[B]	25[D]
Poplar	4[C]	30[D]
Eucalyptus	1.6[C]	41[C]

[A] (Fazio and Monti 2011)
[B] Assumed from Poplar (Giuntoli et al. 2017)
[C] (Giuntoli et al. 2017)
[D] (Rettenmaier et al. 2018)
[E] (Schmidt et al. 2015)

3.1.1. Emissions from fertilizers

Balanced fertilization is considered to estimate the emissions from fertilizers use. Therefore, the inputs rate is directly proportional to what is removed by harvesting the crop. To account for potential losses from minerals uptake and terrain conditions an additional 15% is accounted for all inputs. Yields are assessed for each point in time based on location specific biophysical characteristics, suitability maps and crops phenological characteristics (see Annualized emissions from carbon stock changes caused by land-use change section). The specific description of methods to estimate yield in different point in time results for each lignocellulosic energy crop across Europe are reported in Report task D4.3 (Vera, van der Hilst, and Hoefnagels 2020)

Table 2 Crop specific yield mineral content used as input for the calculation of GHG emissions from fertilizers use, Data is derived from the S2Biom project (Dees et al. 2017)

Lignocellulosic energy crop	**N content ($kg/t_{crop\ dry}$)**	**P_2O content ($kg/t_{crop\ dry}$)**	**K_2O content ($kg/t_{crop\ dry}$)**	**CaO content ($kg/t_{crop\ dry}$)**
Miscanthus	6.3	2	8.1	5.7
Switchgrass	4.7	2	11.8	1.2
Giant Reed	9.9	1.1	8.8	20.5
Cardoon	13	2.3	2.4	3.1
Willow	4	0.4	3.5	7.7
Poplar	3	0.1	1.4	5.3
Eucalyptus	11	0.6	24.1	3.2

3.2. Annualised emissions from carbon stock changes caused by land-use change (e_l)

The productivity from each crop is based on the HI and Low Heating Value (LHV). The harvest index corresponds to the usable section of the above ground biomass that can be harvested. The HI is applied to obtain the harvestable section from each crop above ground biomass. Table 3 shows the HI and LHV value from each crop.

Table 3 Crop specific harvest index and LHV used to calculate crop productivity.

Lignocellulosic energy crop	**HI[A] (%)**	**LHV (MJ/Kg)**
Miscanthus	70	17.5[B]
Switchgrass	60	17.5[B]
Giant reed	70	17.5[B]
Cardoon	60	15[B]
Willow	65	19[C]
Poplar	60	19[C]
Eucalyptus	65	19[C]

[A] (Dees et al. 2017)
[B] (Fazio and Monti 2011)
[C] (Giuntoli et al. 2017)

3.3. Advanced biofuel processes (e_p)

In this study, the selected conversion processes included are:

- Production of **ethanol from lignocellulosic biomass**. The biomass is pre-treated by steam explosion to split the lignocellulosic into cellulose, hemicellulose and lignin followed by an enzymatic hydrolysis step to break it down into fermentable xylose and glucose sugars. The sugars are fermented to ethanol in a simultaneous saccharification and fermentation process (SSF). The lignin is used in a CHP plant to generate process heat and electricity. Surplus electricity is sold to the grid. The input assumptions are based on JRC (Edwards et al. 2017) and the associated references (Biochemtex 2016; Johnson 2016).

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- Production of renewable jet fuels (RJF) from ethanol (**Alcohol-to-Jet**, **ATJ**). The ATJ process converts alcohols into RJF, diesel and naphtha through dehydration, oligomerization and hydroprocessing. Ethanol from lignocellulosic biomass is used as a feedstock. The process assumptions are based on de Jong et al. (2017) and Staples et al. (2014). Different sources of hydrogen supply are assessed as described in Section 3.3.1.
- Production of hydrocarbon fuels through **fast pyrolysis and upgrading.** Biomass is first dried to a moister content below 10% before entering the reactor using heat from char combustion. The fast pyrolysis produces bio-oil, char and non-condensable off-gases. The bio-oil cannot be used as a drop-in biofuel mainly due to the high oxygen content, low pH and instability. Bio-oil can be catalytically converted into drop-in fuels by hydrodeoxidation and hydrocracking and yield a mixture of hydrocarbon fuels with different chain lengths. The ratio of heavy fuel oil, gasoline, diesel and jet fuel depends on the conditions in the upgrading process. Hydrogen required for upgrading is either produced internally (in-situ) from off-gases or supplied from external sources (ex-situ) as described in Section 3.3.1. If hydrogen is The process assumptions are based on and Tews et al. (2014). Fuel output ratios are based on de Jong et al. (2017). The amount of surplus electricity, which is sold to the grid depends on the moisture content of biomass feedstock and in-situ or ex-situ hydrogen supply.
- Production of syn diesel from forest residues and woody crops through gasification and **Fischer-Tropsch synthesis (FT).** Biomass is gasified to produce syngas (CO and H_2). The syngas is catalytically converted in a range of hydrocarbons in the Fischer-Tropsch reactor. The ratio depends on the CO/H ratio of the syngas, the type of catalyst and process conditions in the reactor. Excess heat is used to generate electricity and sold to the grid. Data from JRC (Edwards et al. 2017).
- Production of methanol through gasification of forest residues or woody crops and **methanol synthesis**. Syngas is produced in a pressurised fluidised-bed steam/O_2-blown gasifier and catalytically converted into methanol. Excess heat is used to generate electricity and sold to the grid. Data from Case MeOH-1 described in Hannula and Kurkela (2013).
- Production of dimethyl ether (DME) through gasification of forest residues or woody crops and **DME synthesis**. DME is either produced simultaneously with methanol over advanced catalysts that are not commercially available yet. Input data are based on Case DME-1 as described in Hannula and Kurkela (2013) with methanol synthesis followed by dehydration to DME in a 2-step process. Excess heat is used to generate electricity and sold to the grid.

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An overview of the main assumptions per pathway is provided in Table 6.

3.3.1. Hydrogen supply

Hydrogen is used in multiple conversion processes. Previous studies have already demonstrated that the source of hydrogen from fossil or renewable sources has a major impact on the total GHG footprint of biofuel supply chains (De Jong et al. 2017). The source of hydrogen is assessed in this report and can be altered in the Excel based GHG calculation tool to explore the possible impact on the supply chain. The different options are summarised in Table 4 External hydrogen production *(Giuntoli et al. 2017; Mehmeti et al. 2018)*. The following assumptions were made for hydrogen supply in this report:

- Base: Steam methane reforming (SMR) of natural gas
- Best: E-PEM (Proton Exchange Mem-brane), renewable electricity (MV)
- Worst: E-PEM (Proton Exchange Membrane), current EU average electricity mix (MV).

More extreme cases that are not assessed in this report include electricity from fossil energy generation (in particular coal electricity). Note also that the GHG intensity of the EU average electricity mix will decrease in the future as a result of the development of renewable electricity generation in the EU.

Table 4 External hydrogen production (Giuntoli et al. 2017; Mehmeti et al. 2018)

Process	**Unit**	**Steam methane reforming (SMR) of natural gas**	**Electrolysis**			
Sub-process			**E-PEM (Proton Exchange Membrane)**		**SOEC (Solid Oxide Electrolysis Cells)**	
Inputs						
Natural gas	$\text{MJ}_{NG}/\text{MJ}_{hydrogen}$	1.375	0.000		0.421	
Electricity	$\text{MJ}_{e}/\text{MJ}_{hydrogen}$	0.033	1.638		1.084	
Source[1]		EU mix MV	EU mix MV	Ren. mix MV	EU mix MV	Ren. mix MV
Outputs						
Hydrogen	MJ	1.00	1.00	1.00	1.00	1.00
Emissions						
GHG emissions	g $CO_2e/\text{MJ}_{hydr.}$	95.31	231.18	0.00	180.79	27.77

1) Electricity: current EU mix EU MV: 141.1 g CO_2e/MJ_e, Renewable mix MV: 0 CO_2e/MJ_e.
Source: JRC (Edwards et al 2017).

The feedstock input (in ton dry) depends on the cellulose, hemicellulose and lignin content of the used biomass. The yield was calculated from straw (5.5 ton straw (dry) per ton ethanol

(Biochemtex 2016) based on carbohydrate content of the biomass feedstock type (Table 5 Ethanol yield).

Table 5 Ethanol yield

Feedstock type	LHV MJ/kg_{dry}	Cellulose[1] (w-% dry)	Hemicellulose[1] (w-% dry)	Carbohydrates[1] (w-% dry)	Feedstock input (dry)[2] ($t_{biomass}$ / $t_{ethanol}$)
Bales straw	17.2	37.0	27.6	64.6	5.50
Woodchips forest residues	19.0	38.7	29.2	67.9	5.23
Woodchips Stemwood	19.0	38.7	29.2	67.9	5.23
Woodchips Poplar	19.0	44.4	25.3	69.7	5.10
Woodchips Willow	19.0	44.4	25.3	69.7	5.10
Woodchips Eucalyptus	19.0	43.0	25.3	68.3	5.20
Bales Switchgrass	17.4	36.9	32.1	69.0	5.15
Bales Miscanthus	17.2	44.6	23.9	68.5	5.19
Bales cardoon	15.0	47.8	22.8	70.6	5.03
Bales giant reed	17.5	32.9	27.2	60.1	5.91

1) Carbohydrate and lignin content: S2BIOM (Lammens et al. 2016). 2) Yield calculated from 5.5 tonnes dry straw per tonne ethanol (26.81 MJ/kg ethanol). Source: JRC (Edwards et al. 2017).

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Table 6 Main assumptions of the selected biofuel processes (Edwards et al. 2017; Hannula and Kurkela 2013; De Jong et al. 2017)

Process	**Unit**	**Ethanol**	**ATJ**	**Pyrolysis + upgrading**		**Gasification**		
Sub-process		**Dilute acid, hydr.**		**Ex situ[1]**	**In situ[1]**	**FT synthesis**	**Methanol synthesis**	**DME synthesis**
Inputs (without allocation)								
Feedstock								
Feedstock type		Wheat straw, perennial crops. Forest biomass	Ethanol	Forest biomass, woody crops	Forest biomass, woody crops	Forest biomass, woody crops	Forest biomass, woody crops	Forest biomass, woody crops
Feedstock	$MJ_{feedstock}/MJ_{main\ output}$	3.33 - 3.71	1.49	3.35	3.35	2.64	1.64	1.68
Utilities								
Electricity[2]	$MJ/MJ_{main\ output}$		0.03	0.00	0.19			
Natural gas[3]	$MJ/MJ_{main\ output}$							
Hydrogen	$MJ/MJ_{main\ output}$		0.08	0.69	0.00			
Hydrogen source[4]			Hydrogen from: steam methane reforming of NG or from electrolysis (E-PEM or SOEC)					
Chemicals:	A detailed list of chemicals used in the conversion processes is provided in the Excel Tool							
Main output								
Type		Ethanol	RJF	Pyrolysis - gasoline	Pyrolysis - gasoline	Syn diesel (BtL)	Methanol	DME
Yield	Normalized	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Co-production[5]								
Diesel	$MJ/MJ_{main\ output}$		0.12	0.37	0.37			
RJF				0.13	0.13			
Heavy fuel oil	$MJ/MJ_{main\ output}$			0.28	0.28			
Naphtha	$MJ/MJ_{main\ output}$		0.21					
Electricity	$MJ/MJ_{main\ output}$	0.40		0.06	0.00	0.24	0.01	0.04
Main data source		Edwards et al (2017)	de Jong et al. 2017	de Jong et al. 2017	de Jong et al. 2017	Edwards et al (2017)	Hannula and Kurkela (2013)	Hannula and Kurkela (2013)

1) Ex-situ: hydrogen supply from external source, in-situ: internal hydrogen production from off-gases pyrolysis process, 2) electricity demand excluding electricity for hydrogen production through electrolysis, 3) natural gas demand excluding natural gas demand for hydrogen production through SMR, 4) for hydrogen supply see Table 6, 5) co-production is normalised per unit main output.

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3.4. Transport and distribution (e_{td})

3.4.1. Biomass feedstock supply

Default assumptions of transport of biomass from the field or forest up to the conversion plant are largely consistent with the advanced biofuels pathway calculations in the RED-II as described in Edwards et al. (2017). For the Best cases, it is assumed a conversion plant close to the source of biomass with an average transport distance of 50 km (Table 7). The Worst case assumptions for straw and grassy crops are limited to 1000 km by road. Transport by rail or ship is considered infeasible without further pre-treatment upstream in the supply chain (for example pelletisation). The Default and Worst cases of forest and woody biomass represent typical feedstock supply chains of Intra-EU and Extra-EU imports such as between the Baltic States and the Netherlands or the US East coast and the Netherlands. Note however that more advanced feedstock supply chains with upstream pre-processing of biomass such as pelletisation, or transport of intermediates, such as pyrolysis oil, are not included in this report. The worst case in this report does therefore not represent a maximum transport distance.

Table 7 Biomass feedstock supply (field or forest to conversion plant)

Feedstock type	**Transport mode**	**Distance (km one way)**		
Transport as		**Base**	**Best**	**Worst**
Straw				
Straw bales	Truck (40 ton)	500	50	1000
Forest biomass (stemwood, forest residues)				
Wood chips	Truck (40 ton)	250	50	250
Wood chips	Ship (Bulk Carrier "Handysize")	2000	0	8000
Grassy crops				
Bales	Truck (40 ton)	500	50	1000
Woody crops				
Wood chips	Truck (40 ton)	250	50	250
	Ship (Bulk Carrier "Handysize")	2000	0	8000

Solid biomass feedstock supply chains and performance characteristics are described in Giuntoli et al. (Giuntoli et al. 2017) and BIOGRACE II.

3.4.2. Transport and distribution of fuels

Transport of biofuels from the processing plant to a blending depot and from a blending depot to a filling station are assumed similar between all pathways and cases as summarised in Table 8 . These assumptions are consistent with the advanced biofuels pathway calculations in the RED-II. Please note that actual biofuel distribution systems will be different between different production pathways and in particular also for different end-users including aviation and shipping.

Table 8 Transport, blending depot and filling station (Edwards et al. 2017)

Transport mode	Payload (t)	Distance (km one way)	Share	Electricity (MJ_e/MJ_{fuel})
Transport from processing plant to a blending depot				
Truck	40	305	13.20%	
Product tanker	15000	1118	31.60%	
Inland ship/barge	1200	153	50.80%	
Train		381	4.40%	
Blending depot				0.00084
Transport from a blending depot to filling station				
Truck	40	150	100%	
Filling station				0.00340

3.5. Emissions from the fuel in use (e_u)

To calculate GHG savings, emissions from fuel in use, CO_2 emissions from biogenic sources are assumed zero for biofuels in line with the calculation rules in ANNEX V of the RED II (European Parlament 2018). Non-CO_2 GHG emission including CH_4 and N_2O from end-use should be included, but are assumed zero consistent with the Default and Typical values calculated for the RED II as calculated by JRC (Edwards et al. 2017).

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4. Greenhouse has performance (and cumulative energy demand)

4.1. Well-to-Tank greenhouse gas emissions of advanced biofuel pathways

4.1.1. Comparison between pathways excluding land use-related net changes in carbon stocks

The WTT GHG emissions for the different conversion systems and feedstock types are depicted in Figure 4. The total emissions are the sum of cultivation and extraction, transport and distribution and processing. Land use-related net changes in carbon stocks and land management impacts are excluded from Figure 4 and are assessed separately in Figure 5. The results demonstrate that all pathways could meet the GHG saving criterion (65%) required for installations starting operation in 2021 with GHG savings well over 70% for most pathways. These performances are possible when inefficient long distance transport of untreated biomass is avoided and fossil energy sources, for example for hydrogen production, are minimized. Gasification and synthesis pathways that are largely self-sufficient (BTL, methanol. DME) and lead to the lowest GHG footprint. In contrast, ATJ produced from grassy or woody crops in combination with long distance transportation leads to the highest WTT GHG emissions (up to 69 g CO_2e/MJ or 27% GHG saving), This is mainly caused by emissions from fertilizer application in energy crop cultivation and fossil fuel used in transportation that become stronger in pathways with a relatively low feedstock to fuel conversion efficiency. Furthermore, if hydrogen is supplied from non-renewable sources, it also adds substantially to the WTT GHG emissions of ATJ pathways.

Feedstock type

Emissions from cultivation and extraction of straw and forest residues are relatively low compared to energy crops because they only include the emissions from diesel use for agricultural and forest machinery to harvest, collect and process biomass (chipping, baling). Note that the assumed biogenic carbon neutrality of in particular forest biomass can only applied to sustainably sourced biomass meeting strict land and sustainable forest management criteria. The impact of carbon debt and land use change can exceed the emissions of fossil fuels (Agostini, Giuntoli, and Boulamanti 2013; Valin et al. 2015). The total emissions and variation in emissions

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from cultivation of miscanthus is larger compared to the emissions of poplar cultivation as a result of diesel consumption in cultivation for agricultural machinery. As a result, higher GHG emissions from diesel use in the cultivation stage are obtained in locations with low yields in comparison to locations with high yields.

Transport and distribution

Emissions from transport and distribution range between 1.8 g CO_2e/MJ for locally sourced biomass (50 km one way) and up to 38.1 g CO_2e/MJ for wood chips (moisture content 30%) that are imported from overseas to produce ATJ (see Table 7). The emissions from long distance transportation can be reduced by upstream preprocessing of biomass, such as drying and pelletisation and the use of larger ships. Drying could even be required as a phytosanitary measure if wood chips are imported from outside the EU. The distance between feedstock supply regions and end-use should therefore be assessed in combination with other supply chain configurations that improve the GHG performance of the supply chain (Vera et al. 2019).

Processing

Variations in process design in this report are exclusively assessed for hydrogen supply in the ATJ and pyrolysis pathways. This is the reason for the lack of ranges in emission for processing of ethanol and gasification and synthesis pathways in Figure 4. For pyrolysis pathways, the lowest GHG emissions are achieved when hydrogen produced from renewable energy is supplied from external sources (ex-situ hydrogen supply) or if hydrogen is produced internally (in-situ). Hydrogen supplied from steam methane reforming of natural gas (Base cases) still leads to lower emission compared to hydrogen supplied from electrolysis if the average EU electricity mix is assumed (Worst case). This applies to the GHG intensity of the current electricity mix that is expected to reduce significantly in the future.

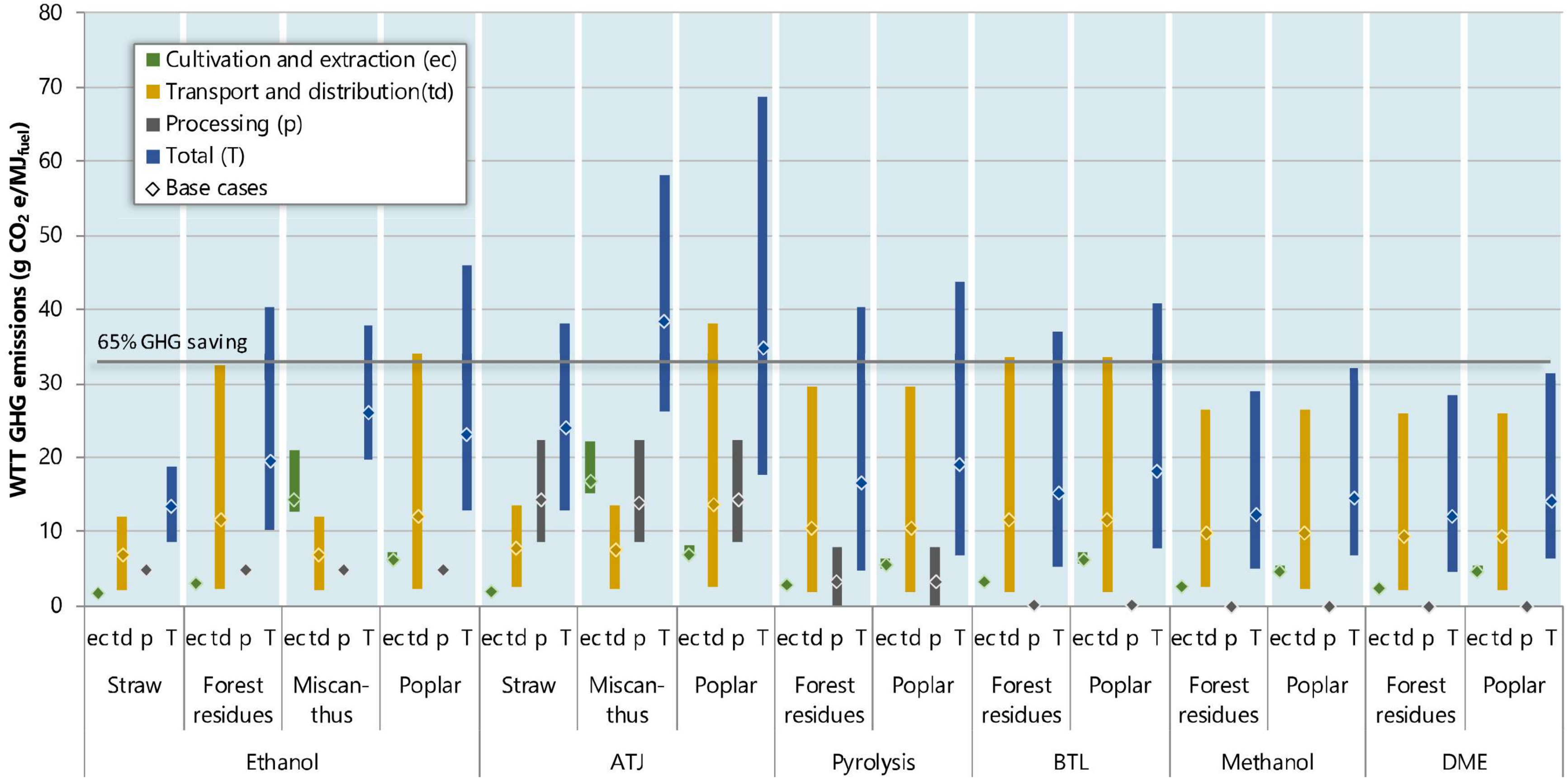

Figure 4 Well-to-Tank greenhouse gas emissions of advanced biofuel pathways. Land use-related net changes in carbon stocks and land management impacts are excluded. Markers represent the default results, the ranges describe the worst and best cases described as in Chapter 3, compared to the 65% GHG saving requirement (32.9 g CO2e/MJ) (European Parlament 2018).

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4.1.1. Comparison between energy crop pathways including land use-related net changes in carbon stocks

Figure 5 shows the results for advanced biofuels produced from miscanthus and poplar energy crops with possible net changes in carbon stock in soil organic carbon and aboveground biomass from land use change. The pathways are similar to the results in Figure 4. The results demonstrate that LUC-related CO_2 emissions can be positive, adding up to 28 g CO_2e/MJ (ATJ from miscanthus) if cultivated on marginal land with a relatively high carbon stock. However, in most cases, net carbon sequestration could be achieved. Woody crops, such as poplar, store generally more carbon in biomass and SOC pools compared to grassy crops such as miscanthus (Vera, van der Hilst, and Hoefnagels 2020). This explains why pathways from poplar in Figure 5 yields the lowest LUC-related CO_2 emissions. The impact of upstream emission becomes larger for pathways with a relatively low feedstock to fuel conversion efficiency, such as ATJ. WTT GHG emissions of ATJ range from -96 g CO_2e/MJ for ATJ produced from poplar at the best location to up to 86 g CO_2e/MJ for ATJ produced from grassy crops at the worst location in the EU. The chosen functional unit (g CO_2e/MJ) could lead to the false conclusions that the least efficient conversion pathways have the best performance when LUC-related CO_2 emissions are negative. Careful interpretation of these results is therefore required.

The impact of different grassy and woody crop choices on the WTT GHG emissions is demonstrated for ethanol pathways in Figure 6. The Excel based GHG calculation tool linked to this report can be used to explore the impact of crop types for other types of advanced biofuels, locations in the EU and other supply chain assumptions. The results show that miscanthus, switchgrass and cardoon as well as willow and poplar show similar ranges at the EU level. Giant reed and eucalyptus show larger ranges. The high carbon sequestration capacity from giant reed and eucalyptus is mainly the result of higher yields and carbon accumulation capacity. Note however that these can only be achieved under the right biophysical conditions including climate, soil type and water availability (Vera, van der Hilst, and Hoefnagels 2020) . Furthermore, the chemical and physical characteristics of biomass feedstock types also determine the suitability for (bio-)chemical and thermal conversion. The chlorine and nitrogen content of grassy crops makes them generally less suitable for thermal conversion compared to woody crops without preprocessing (Lammens et al. 2016). The selection of the most suitable crop type is thus location and supply chain specific.

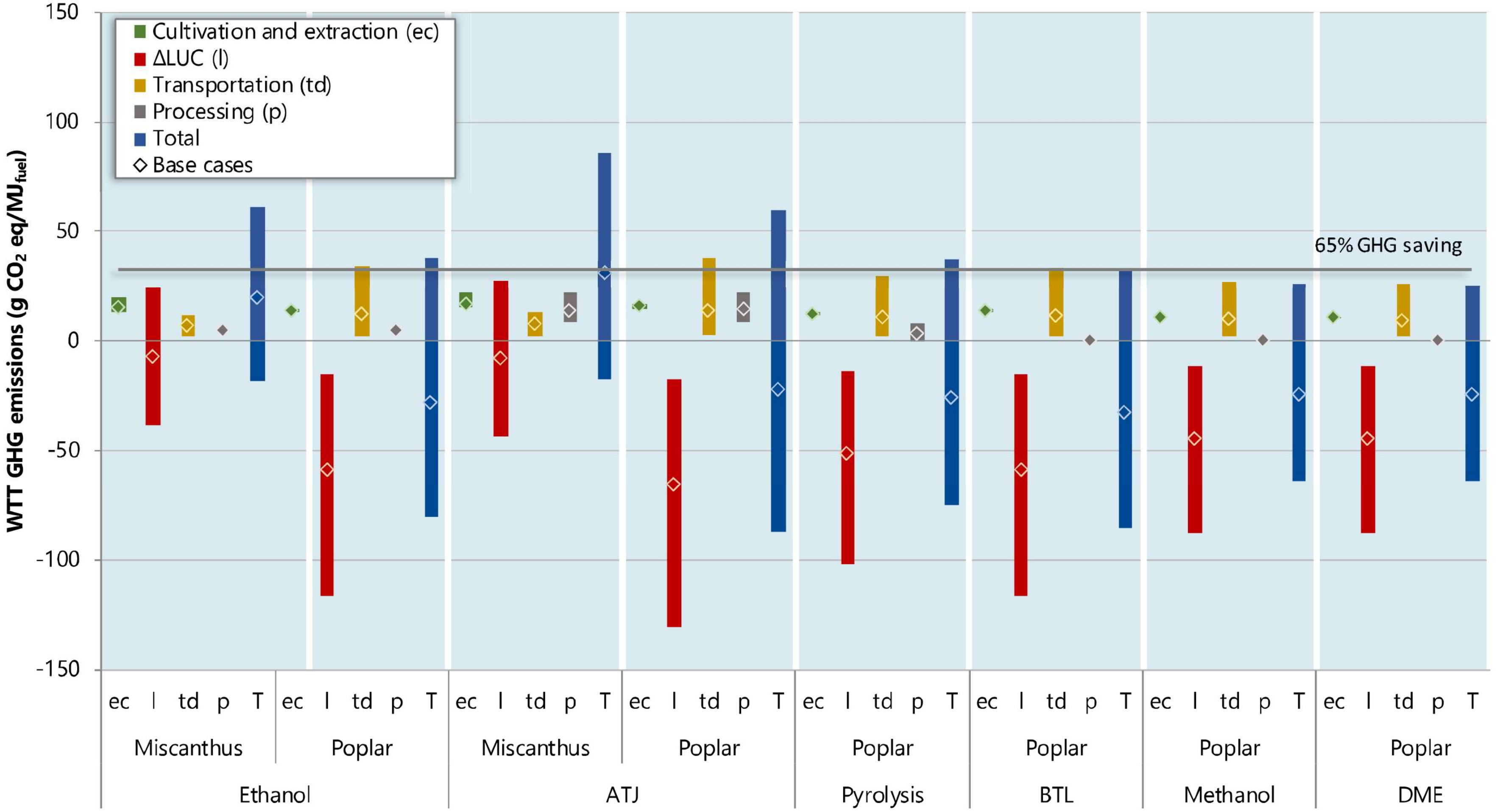

Figure 5 Well-to-Tank greenhouse gas emissions of advanced biofuel pathways from grassy and woody crops including land use-related net changes in carbon stocks. Ranges in the supply chain describe the worst and best cases described in Chapter 3. Ranges in LUC are the standard deviation of the assessed locations in the EU.

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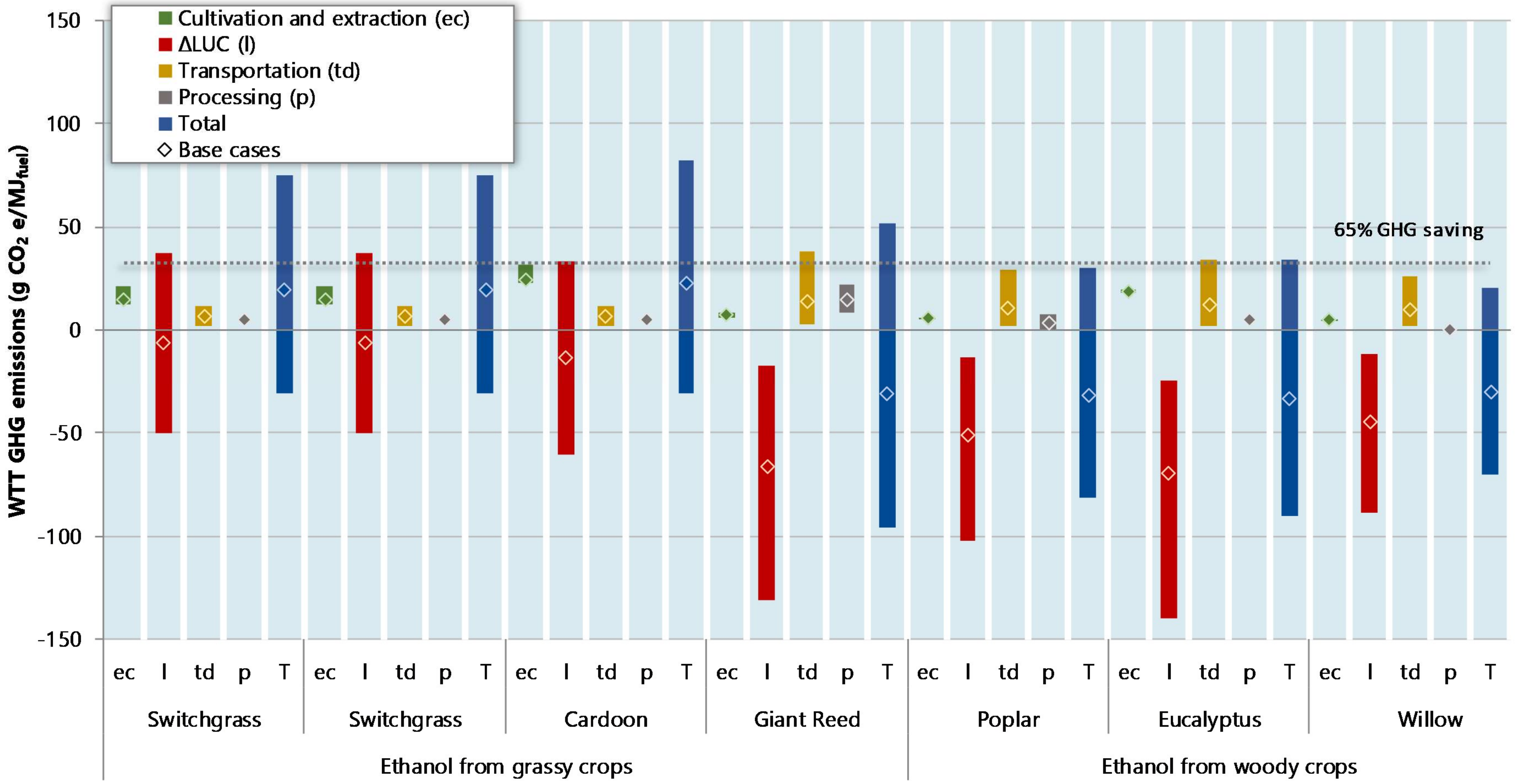

Figure 6 Well-to-Tank greenhouse gas emissions of ethanol pathways from grassy and woody crops including land use-related net changes in carbon stocks. Ranges in the supply chain describe the worst and best cases described in Chapter 3. Ranges in LUC are the standard deviation of the assessed locations in the EU.

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4.2. Projections of energy crops and marginal land use change impact over time

4.2.1. Supply potential of grassy crops cultivated on marginal lands in the EU

The estimated biomass supply potential of grassy lignocellulosic energy crops cultivated on EU marginal lands in compliance with the RED II land criteria in 2030 is approximately 75 million t and it increases up to 88 million t by 2050 (see Figure 7). The supply potential decreases when stricter land criteria are applied that exclude land conversion that lead to positive LUC-related CO_2 emissions (RED + land criteria). The RED + supply potential of grassy lignocellulosic energy crops is estimated to be 52 million t in 2030 increasing to over time to 58 million t by 2050. The biomass potentials for both pathways are projected to increase as a result of the LUC dynamics and the variation over time in climate conditions such as temperature and precipitation. To illustrate, there are some locations in which the local biophysical conditions were unsuitably for the potential production of lignocellulosic energy crops in 2030 and become suitable over time. Between 30 to 35%, depending on reference year, less biomass is projected to be available for the RED II + land criteria pathway given that for several locations the potential production of lignocellulosic energy crops results in LUC-related CO_2 emissions. Similarly, the net increase in biomass potentials over time for the RED II + land criteria pathway is lower compared to RED II land criteria pathway.

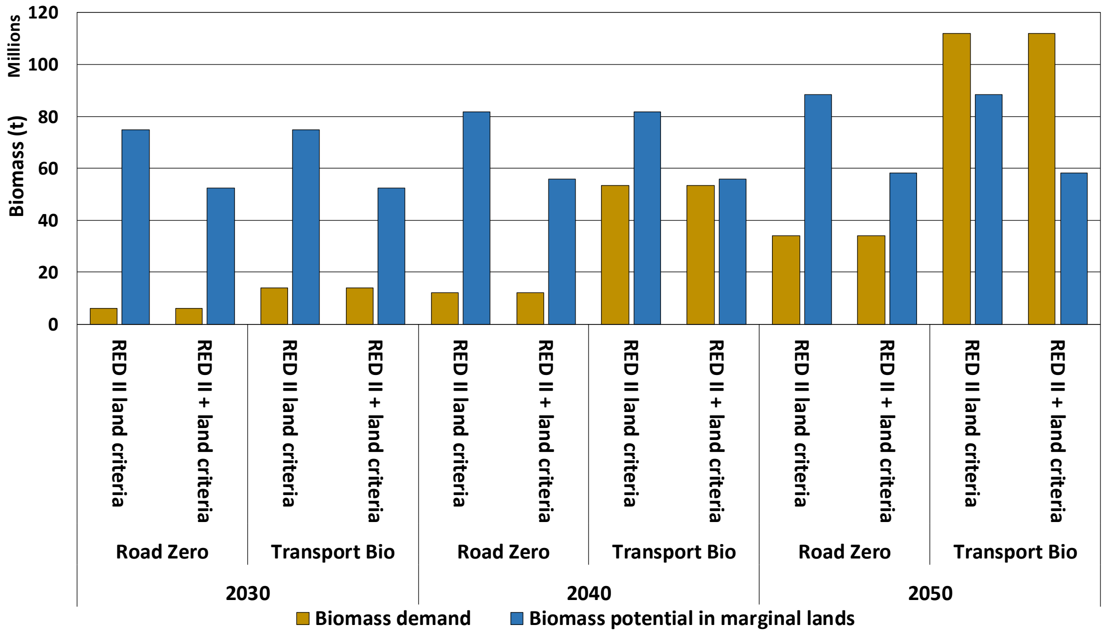

Figure 7 Biomass supply potentials for grassy crops culivated on marginal landsin the EU under RED II and RED II + land criteria, and biomass (grassy energy crops) demand for the Road Zero and Transport Bio scenarios in 2030, 2040 and 2050

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4.2.2. Demand of grassy energy crops

On a short a short term (2030), the grassy energy crops biomass demand in the EU for both scenarios can be supplied by allocating approximately 8-27% (depending on pathway) of the total available marginal lands for the potential production of lignocellulosic energy crops (see Figure 8). Up to the mid-term (2040), the grassy energy crops biomass demand for both scenarios can still be entirely supplied from the use of marginal lands in the EU under RED II land criteria. However, under more strict land criteria (RED +), already 95% of the available marginal land would be exploited in the Transport Bio scenario in 2040. In 2050, when grassy energy crops biomass demand is projected to peak, the amount of marginal land that can be utilized for biomass production is still sufficient to cover the Road Zero scenario biomass demand (indistinctly of the pathway). Instead, this is not the case for the Transport Bio scenario. Regardless of the land criteria, additional land is required to meet the demand for energy crop cultivation in the EU.

4.2.1. Energy crop cultivation on other lands

In 2050, the high grassy energy crops biomass demand for the Transport Bio scenario indicates that other types of land (outside the definition of marginal land) will potentially be required for energy crop cultivation. Note that the biomass supply is strictly limited to lands classified as marginal while biomass demand projections include other land categories such as abandoned grasslands that are not limited to a marginality criteria and therefore, the demand is higher than the supply. Nevertheless, biomass supply in 2050 will still likely need to comply with land sustainably criteria to the successor of the RED II (the RED II covers the period 2020-2030). The use of arable lands for energy crop cultivation is unlikely given that this land category is already fulfilling a food/feed/fibre purpose with higher market values. Furthermore, a change in use of agricultural land can result in indirect land use change (ILUC); ILUC is strongly discouraged by RED II considering the acute and substantial negative social and environmental impacts. Therefore, it is expected that non-marginal abandoned arable land or grasslands will potentially be allocated when marginal lands would be fully exploited, such as the case of the Transport Bio scenario in 2050. Still, the availability and economic potential of non-marginal abandoned land for biomass production is highly uncertain. These results demonstrate that the potential of energy crops under strict sustainability criteria could be limited.

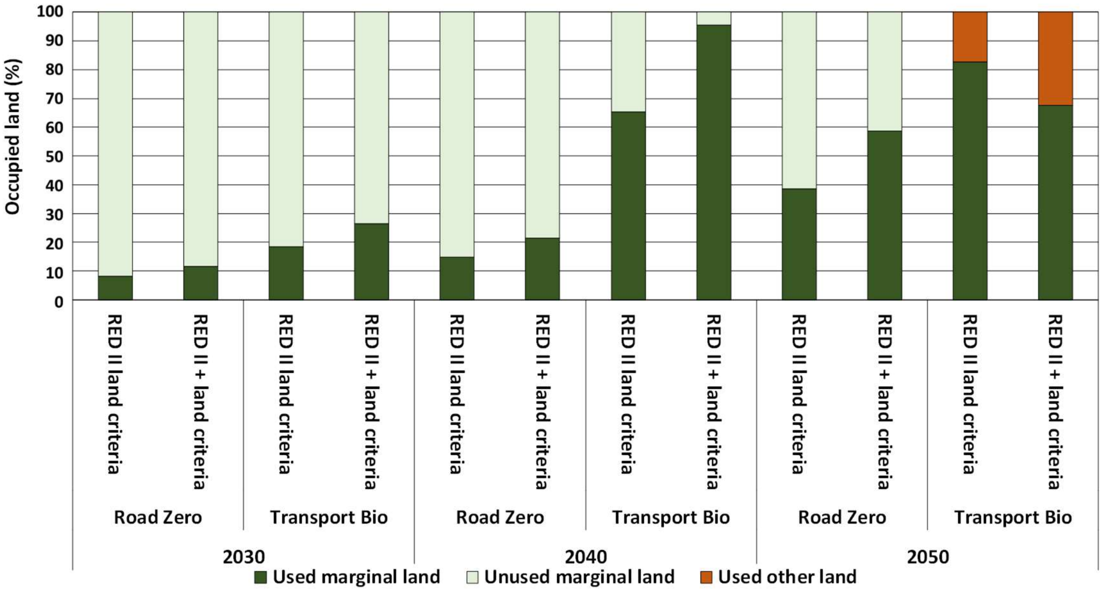

Figure 8.Percentage of utilized land in the EU for the RED II and RED II + land criteria pathways in 2030, 2040 and 2050

4.2.2. LUC related CO_2 emissions in the scenarios

As shown in Figure 9, the LUC related CO_2 emissions from the potential production of lignocellulosic energy crops in the EU varies considerably per year and member state. However, on average (for the EU) both the RED II and RED II + land criteria supply scenarios follow a similar trend. Under RED II land criteria, average LUC related CO_2 emissions increase slightly over time from -0.61 t CO_2/ha year in 2030 to -0.48 t CO_2/ha year in 2050. Under the more strict RED II + land criteria, average LUC related CO_2 emissions improve to -1.33 t CO_2/ha year in 2030 to -1.02 t CO_2/ha year in 2050. The local variation in biophysical conditions, crops phenological characteristics and specifically land use type prior to conversion dictate that for some member states the potential production of lignocellulosic energy crops results on average in CO_2 emissions and for others in carbon sequestration (negative CO_2 emissions). For example, in Finland most of the available marginal land is covered by shrublands. In addition, the local biophysical conditions limit the production of high yields. The combination of both drivers determines that on average the potential production of lignocellulosic energy crops in this member state results in CO_2 emissions. Similarly occurs for countries such as Ireland, Austria and Sweden. Conversely, high yields and land with low biomass content prior to conversion dedicate that high negative CO_2 emissions are reported for countries such as Hungary, Poland and Portugal.

Slovakia reports on average the highest carbon sequestration potential with approximately -4.5 t CO_2/ha year in 2030 under the RED II + land criteria. However, potential CO_2 sequestration reduces considerable for this member state to -0.78 t CO_2/ha year in 2050. The strong increase in Slovakia is explained by the large availability of abandoned marginal lands characterized with low SOC and low biomass content in 2030. The conversion of such land yields high negative

CO_2 emissions. In 2050, the same land is already under use and therefore no emissions are accounted. Some of the member states such as Sweden and Finland that report on average the lowest negative CO_2 emissions in the RED II + land criteria pathway report on average CO_2 emission for the RED II land criteria pathway. This trend is partly explained by the suitability constrains posed by extreme biophysical conditions that result in low attainable yields in comparison to other member states.

Despite meeting RED II land related sustainability criteria, there are several member states that on average report CO_2 emissions from the potential production of lignocellulosic energy crops in marginal lands (under RED II land criteria). Positive LUC related CO_2 emissions can be avoided to some extent for each member state as demonstrated by the RED II + land criteria supply scenario. These criteria would lead to less available marginal land that can be allocated for energy crop cultivation. However, biomass demand could still be met on EU level with negative land related CO_2 emissions up to 2040 for both the Road Zero and Transport Bio scenarios. To meet biomass demand on EU level (in 2040) with negative LUC-related emissions a strong co-operation and logistics between member states is required. Member states would have to allocate and supply biomass production shares in relation to each member state biomass demand (see supplementary material A2) and land availability. Therefore, when the available marginal land (with negative CO_2 emission from biomass production) from one member state is fully utilized and falls short to fulfil the required member state biomass demand, the biomass deficit can be supplied from another member state. However, the other member state must contain a surplus of marginal land after fulfilling its own biomass requirements. Beyond 2040, the cooperation strategy will fall short to supply the increase in biomass demand on EU level in the Transport Bio scenario; and the allocation of other types of land (besides marginal) that is not limited to CO_2 negative emissions criteria at EU level is required.

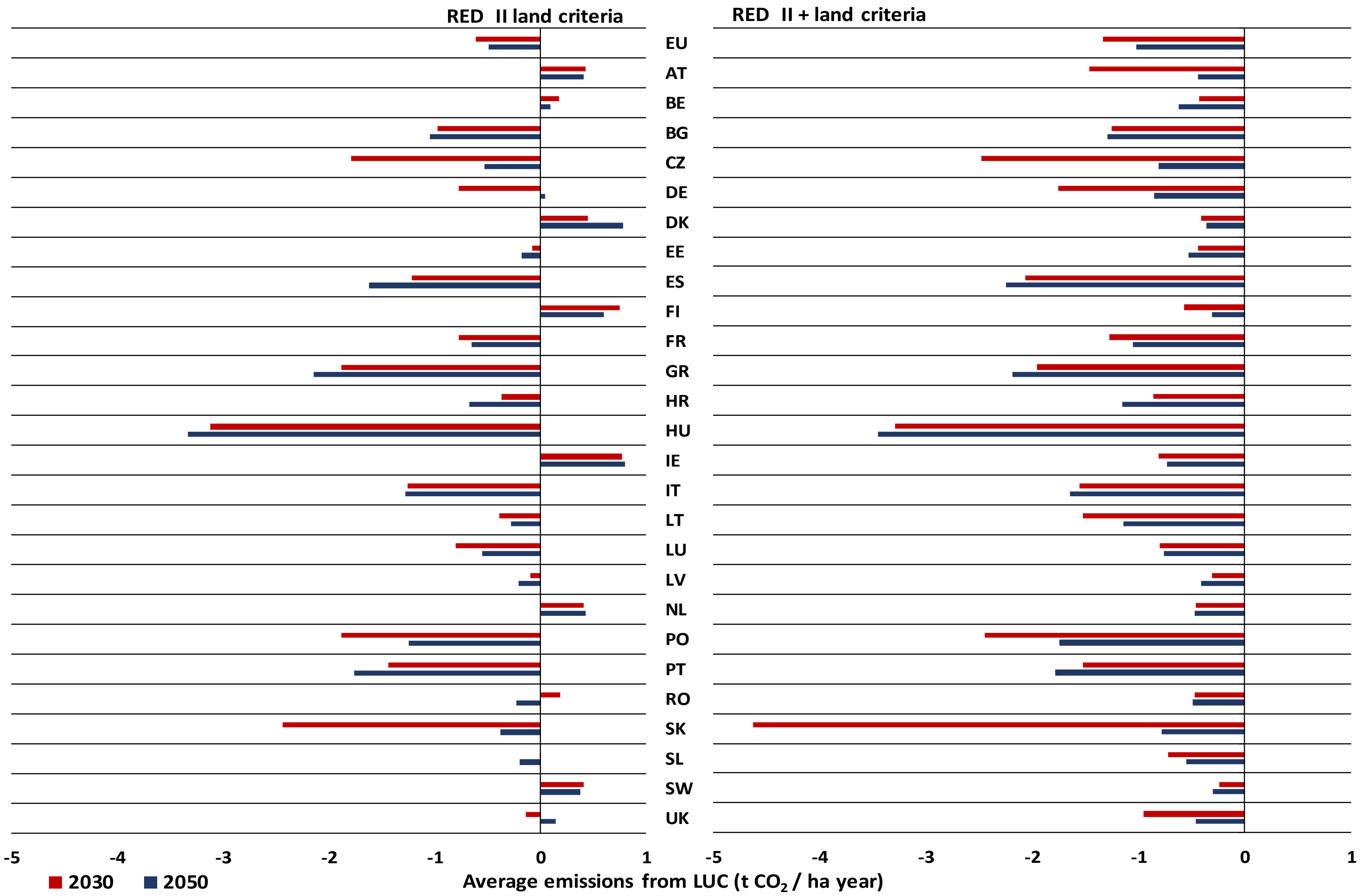

Figure 9 Average LUC related carbon emissions for the cultivation of lignocellulosic energy crops on marginal land in the EU for RED II and the RED II + land criteria in 2030 and 2050

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5. Discussion

5.1. Well-to-tank greenhouse gas performance

This report compared the WTT GHG performance of advanced biofuel pathways with and without land use related net changes in carbon stock. The assessed ranges result from locations of crop cultivation and supply chain assumptions including transport distances and the source of hydrogen in processing. The method to calculate the WTT GHG emissions was based on the calculation rules of the RED II Annex V (European Parlament 2018). The method and results in this report have some key limitations:

- The results are based on modelling work that is inherently uncertain as a result of the methods applied and the input data used. For example, alternative LCA methods including procedures to deal with co-products (substitution or allocation by economic value or mass etc), were not assessed in this report and would result in substantially larger ranges of uncertainty (Cherubini et al. 2009; Kendall and Yuan 2013).

- The results are limited to GHG emissions. Other environmental impact categories, including water use, biodiversity and land use are important to include, in particular when energy crops are assessed as demonstrated in Report task D4.3 (Vera, van der Hilst, and Hoefnagels 2020).

- Biogenic carbon neutrality, as assumed in this report, is not always correct. In particular slow growing systems, such as forest biomass sources, are sensitive to (Lamers and Junginger 2013).

- The selected pathways included in this report are not comprehensive. Several alternative system designs could be assessed that produce the same fuels. Feedstock supply chains are limited to simple pre-processing (baling, chipping). More advanced pre-processing including palletisation, torrefaction or steam explosion, could reduce transport GHG emissions substantially for long distance supply chains (Visser, Hoefnagels, and Junginger 2020).

- Other technologies including iso-butanol and hydrothermal liquefaction (HTL) could potentially result in improved GHG performances compared to ethanol and pyrolysis fuels respectively (Elliott et al. 2014; De Jong et al. 2017). Also, CO_2 capture and storage in combination with bioenergy supply chains (BECCS) have been excluded from the assessment,

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but could be a valuable carbon mitigation technology, in particular in combination with advanced biofuel supply chains.

- The assumption of balanced fertilization results in a linear relationship between fertilizers use and crop yield. Therefore, the use of fertilizers is proportional to each crop attained yield. This linear relationship dictated that for every location (with the same crop type), the GHG emissions from fertilizers use are identical. However, the amount of applied fertilizers can vary according to a country/region specific farming characteristics (Fabio and Smart 2018) and differences in GHG emissions from fertilizers use across regions can be expected.

- N_2O field indirect emission from leaching were not considered. However, in regions characterized by a wet regime leaching can occur as an indirect effect from energy crops production and increase to some extent the overall supply chain GHG emission. This can be expected in regions such as in Scandinavia where leaching is common (Lin et al. 2001), Nevertheless, the additional GHG emissions from leaching are minimal when compared to the overall supply chain GHG emissions.

Table 9 compares the results of this report to the Default values calculated by JRC (Edwards et al. 2017) and de Jong et al. (De Jong et al. 2017). For straw to ethanol, and forest residues to FT, methanol, the Base case results are within similar range to JRC. In contrast, the GHG emissions of forest residues and poplar are substantially higher as a result of the emissions from ethanol processing assumed by JRC. The ATJ pathway is partly based on de Jong et al. (Antonissen et al. 2016), nevertheless the emissions cannot be directly be compared due to differences in allocation (exergy vs energy allocation) and the different model for ethanol supply that lead to higher emissions for ATJ from corn stover (35 g CO_2e/MJ) compared to ATJ from wheat straw (24 g CO_2e/MJ) in this report.

Table 9 Comparison of results with JRC Default values and other studies (in g CO_2e/MJ)

Pathway	**Feedstock**	**This report (excl. LUC)**		**JRC Default values[1]**	**Other studies[2]**	
		Base	**Range**		**Energy all.**	**Substitution**
Ethanol	Straw	13.43	8.71 - 18.67	13.68		
	Forest residues	19.61	10.21 - 40.42	28.22		
	Miscanthus	26.66	20.51 - 36.65			
	Poplar	23.20	12.85 - 46.10	38.91		
ATJ	Straw	23.96	12.94 - 38.01		35 (corn stover)	22 (corn stover)
	Miscanthus	38.40	26.15 - 58.14			
	Poplar	34.90	17.57 - 68.73			
FT	Forest residues	15.15	5.30 - 36.93	13.72	6	-10 - 10
	Poplar	18.07	7.76 - 40.88	20.83	10	-17 - 10
Pyrolysis (in-situ)	Forest residues	14.86	6.14 - 34.15		22-34	22
	Poplar	17.42	8.29 - 37.62			

Pyrolysis (ex-situ)	Forest residues	16.62	4.73 - 40.36		
	Poplar	19.16	6.86 - 43.79		
Methanol	Forest residues	12.43	4.96 - 28.98	13.46	
	Poplar	14.63	6.80 - 31.95	20.01	
DME	Forest residues	12.00	4.56 - 28.47	13.46	
	Poplar	14.19	6.40 - 31.44	20.01	

1) From: Edwards et al. (2017). 2) As summarized by de Jong et al. (2017)

5.2. Projections of energy crops and marginal land use change impact over time

The results of the projected LUC-related CO_2 emissions over time suggest that there is sufficient marginal land in the EU that can be allocated to the production of lignocellulosic energy crops to meet EU biomass (perennial grasses) demand up to 2040; even after limiting the potential production of energy crops with more strict land criteria (RED II +). However, on the long term (2050), additional land besides marginal is projected to be required to meet the demand of the Transport Bio scenario. In addition, the supply of biomass could also be sourced from outside the EU and international biomass trade can play an important role.

The potential production of lignocellulosic energy crops over time results (on average for the EU) in significant carbon accumulation in biomass and soils, while assuring to a large extent a biomass flow for RESfuels production. As shown before, the production and use of RESfuels derives in important GHG savings from the replacement of fossil fuels. Therefore, sourcing biomass from marginal lands while considering appropriate and efficient conversion pathways from biomass production up to conversion can derive in a valuable climate change mitigation strategy.

The results from the soft linking process should be interpreted with care given that there are some key limitations.

- The multiple criteria adopted for the RED II and RED II + land criteria pathway results in lower estimates when compared to other land and biomass projections such as the ones carried out in the JRC-EU-TIMES (Ruiz et al. 2015). For both pathways, land allocation is strictly limited to the use of marginal lands. In addition, land allocation in the RED II + land criteria pathway is limited to marginal land that results in carbon accumulation from the potential production of lignocellulosic energy crops. Such criteria are not adopted in other studies and therefore the land and biomass potential are considerably lower from (Bogaert et al. 2017; Dees et al. 2017; Ruiz et al. 2015). However, if the scope was not limited to high sustainability constrains and land marginality, the biomass demand for 2050 could potentially be supplied entirely from EU land. However, the use and specific location of for example non marginal abandoned agricultural land for biomass production and derived environmental impacts over timer is highly uncertain.

- The accessibility to some locations was not considered. Some of the marginal lands that are suitable for biomass production are in remote areas. Mobilizing biomass from these areas with inadequate infrastructure can be costly and inefficient (Liu et al. 2011). Therefore, allocating difficult access/remote marginal land areas for biomass production can be unsuitable. Excluding the use of remote marginal areas can reduce the potential biomass production capacity and derive in biomass deficits before 2050 for both demand scenarios.
- The projected impacts over time were limited to LUC-related CO_2 emissions over time. Other important environmental impacts categories as well as social impacts (Part B of this report) should be included and considered for possible decision making with regards to the potential production of lignocellulosic energy crops

For some locations, despite that the potential production of energy crops resulted in LUC-related CO_2 emissions, there were still carbon savings over the whole supply chain. These carbon savings can potentially increase if technology development over time was included; for example, considering more efficient and upgraded conversion processes (Yamakawa, Qin, and Mussatto 2018). Therefore, for future assessments, the impact over time from RESfuels production should include (in addition to LUC-related CO_2 emission) technology development over time.

6. Conclusions

Part A of this report assessed the sustainability impact RESfuels supply chains in Europe with a detailed focus on GHG emissions of advanced biofuels produced from dedicated energy crops and including carbon emissions from changes in soil organic carbon and above and below ground biomass from land conversion.

The results of the WTT GHG emission performance show that most of the included advanced biofuel pathways lead to GHG savings well over 70%. These performances are possible when long distance transport of untreated biomass is avoided and fossil energy sources, for example for hydrogen production, are minimized in the supply chain. This also means that the minimum GHG saving requirement of 65% of the RED II is an important mechanism to improve the performance of advanced biofuels. If long distance transport is required, more advanced feedstock supply chains, such as pellets, transport of liquid intermediates (for example pyrolysis oil) or biofuels, should be integrated in the supply chain to allow for longer transport distances. These advanced feedstock supply chains were however not assessed in this report.

Energy crops cultivated on marginal land in compliance with the land sustainability criteria of the RED II, results in most cases in a net carbon sequestration. LUC-related CO_2 emissions can however also be positive on some locations. Woody crops, such as poplar, store generally more carbon in biomass and SOC pools compared to grassy crops such as miscanthus, but the chemical and physical characteristics of these crops also determine the suitability for conversion to advanced biofuels. With a careful selection of the crop type, location of cultivation and design of the supply chain (transport, conversion, fuel supply), advanced biofuels produced form energy crops could provide a substantial contribution to CO_2 mitigation in the EU and rise as a valuable climate change mitigation strategy. Other environmental impact categories, including water use, biodiversity and land use, but also socio-economic indicators as discussed in Part B of this report should however also be included in the decision to avoid possible burden shifting or negative impacts.

On a short and middle term to 2040, the estimated supply potential of energy crops cultivated on marginal land under RED II land criteria is sufficient to meet EU energy crop biomass demand even under more strict land criteria that exclude marginal land with positive LUC related CO_2 emission (RED II +). On the long term (2050), the projected demand for energy crops in the EU could however be larger than the total supply potential on marginal land. Considerable support from the government would be required to increase cooperation between member states that allow for an efficient biomass trade_between and within member states. In addition, efforts

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should be directed to scale up biomass production and ensure biomass readability for the end use markets. Smart choices while considering different location specific social and biophysical characteristics will be required to smooth up the biomass supply process. On a long term, the role of biomass imports can play a major role as there would be insufficient land with a high level of sustainability constrains to produce biomass. However, biomass imports should be carried out and evaluated under RED II standards to assure sustainability along the whole supply chain.

Part B: Socioeconomic performance and capacity of RESfuel enterprises

Chapter 7 describes de methods used in part B of the report. Chapter 8.1 on socioeconomic performance of RESfuels compares different socioeconomic assessments of cases in the RESfuel sector production based on information from the literature. Chapter 8.2, *on social capacity performance of RESfuel enterprises* assesses the strategy, cooperation, steering structures, processes, learning and innovation of the advanced biorefining companies Neste, ST1, UPM, Clariant, C2Biotrade and Btg-btl. This is followed in Chapter 9 by an evidence-based discussion of the findings against the wider literature on socioeconomic assessments and the limitations of the methodology employed. The report finalizes with concluding remarks and provides implications for future research and policy making in Chapter 10.

7. Methodology

7.1. Socioeconomic assessments of RESfuel enterprises and value chains in the literature

In the first part of this report, we provide an overview of socioeconomic assessments of RESfuels in the current literature. For the literature search Web of Science and Scopus were used as databases. We searched the keywords: "(socioeconomic asessment OR socio-economic assessment OR SLCA OR S-LCA OR social impact assessment OR SIA OR social input—output OR SIO) AND (lign* biofuel* OR biorefin*)" and achieved 62 results on the 11th March 2020, while for the same search plus the keyword "OR social*" we received 193 results, which shows that there is an awareness in regard to the social impact of biorefineries, but their assessment is still underrepresented. Our criteria for case study selection are 1) RESfuel related supply chains, 2) application of the classic socioeconomic methods like Social Life Cycle Assessment

(SLCA), Social Impact Assessment (SIA), Social Input—Output (SIO) analysis as well as multi-criteria models , and 3) published latest at 2010. This year was used as a point of reference as in 2010, the EU Comission passed two major directives supporting the increased use of renewable fuels extending to 2020. We compared socioeconomic assessments of seven RESfuel related supply chains in regard to their scope, feedstock, end-product, location, method and socioeconomic indicators which have been applied (Table 10).

7.2. Social capacity assessment

For the second part of this report, the social capacity of six RESfuel enterprises has been assessed. We conducted 6 semi-structured interviews with the biorefining companies Neste (Chapter 8.2.1.), ST1 (Chapter 8.2.2.), UPM (Chapter 8.2.3.), Clariant (Chapter 8.2.4.), C2Biotrade (Chapter 8.2.5) and Btg-btl (Chapter 3.2.6). Neste, ST1 and UPM were interviewed between February and March 2020. Clariant, C2Biotrade and Btg-btl were interviewed in July 2020. The concept of the interview guideline (Supplementary material A3) is based on the Capacity WORKs framework developed by GIZ (2015). The Capacity WORKs framework was developed as an action-oriented methodology which aims to manage international development projects in cooperation with key stakeholders. It identifies the five success factors of projects presented below, i.e. strategy, cooperation, steering structure, processes, and learning & innovation.

Figure 10: The Capacity WORKS Model by GIZ (GIZ 2015).

- *Strategy:* An agreement between key partners that enables them to combine their efforts and steer them in the same direction.
- *Cooperation:* How the company works together with internal and external partners.
- *Steering structure:* Steering refers to task negotiations and the associated hierarchies.
- *Processes:* Supply chain steps (biomass production/ harvest & conditioning/ transport/ pre-treatment & storage/ biomass further processing/ biomass transport/ energy conversion) and the responsible actor(s).
- *Learning & innovation:* Forms and design possibilities of learning and innovation processes.

The questionnaire for this study covers all five factors (Supplementary material A3). The interviews were conducted with representatives of the respective companies via phone and web meeting. All interviews were implemented as a dialogue and lasted between 35 and 60 minutes.

8. Results

8.1. Socioeconomic performance of RESfuel enterprises and value chains

Table 10 provides an overview of the socioeconomic assessments found in the literature. The focus of the search was on second generation biorefineries and lignocellulosic supply chains. The table below illustrates the different indicators covered by the respective studies. It is relevant to mention that these studies cannot be compared on a performance level, since (1) they have different reference points e.g. maize production or first generation biofuel, (2) they have different study aims, e.g. some assess the actual social impacts and others potential social risks (Mattila et al., 2018), and (3) they applied different methods, e.g. top-down by using databases or bottom-up by selecting indicators within focus groups. Nevertheless, the compilation gives an overview of the state of the art as well as intention and relevance of current schemes for evaluating the socioeconomic dimension of second generation biorefineries and feedstock supply chains.

Table 10 Socioeconomic performance of second generation biorefineries and feedstock supply chains

Name	BIOLYFE	Souza et al	Borregaard	Mattila et al	Macombe et al	Henke et al	De la Rúa et al
Author	(Kretschmer et al. 2013)	(Souza et al. 2018)	(Valente, Brekke, and Modahl 2018)	(Mattila et al. 2018)	(Macombe et al. 2013)	(Henke and Theuvsen 2013)	(de la Rúa and Lechón 2016)
Scope	Biorefineries	Biorefinery	Biorefinery	Wood product supply chain	Biodiesel value chain	SRC value chain	Miscanthus value chain
Feedstock	Giant reed/ fibre sorghum/ wheat straw	Sugarcane bagasse and straw	Spruce	Forest biomass	Forest biomass	Short rotation wood	Miscanthus
End-product	Bioethanol, power, heat	Bioethanol	Bioethanol, biochemicals	Finish wood products	Biodiesel	Wood chips	Pellets
Location	Generic European background	Brazil	Norway	Finland	Finland	Germany	France
Method	SLCA	SLCA, Input-output analysis	SLCA	Input-output model	SLCA	SLCA	Input-Output analysis
Social Performance							
Human rights	🟧	▨	▨	-	▨	+	▨
Worker rights	🟧	▨	▨	-	▨	+/-	▨
Human health impact	🟩	+	+	-	+	+	▨
Contribution to local development	+	▨	▨	▨	▨	+	+
Wage profile	🟩	+	+/-	▨	▨	+	▨
Education profile	+	+	▨	▨	▨	▨	▨
Gender profile	🟩	-	-	-	▨	▨	▨
Indigenous people's rights	-	▨	▨	▨	▨	▨	▨
Economic Performance							
Food & price security	-	▨	▨	▨	▨	+	▨
Job creation	+	-	▨	▨	▨	▨	+
Distributed economic value (tax)	+	▨	▨	▨	▨	+	+
Tourism	▨	▨	▨	▨	▨	+	▨
Legend	+	Positive					
	-	Negative					
	+/-	Neutral					
	🟧	Not relevant in EU27					
	🟩	Depends on management, no specific effects					
	▨	Data not available					

Kretschmer et al. (2013) applied their socioeconomic assessment on a hypothetical industrial scale plant based on a demonstration plant in Crescentino, Italy. This study assessed socioeconomic indicators within 5 different stakeholder groups: worker, consumer, local community, society, and supply chain actors (Kretschmer et al. 2013). Human rights have been identified as `not relevant for the EU´, whereas worker rights, human health impact, wage profile, and gender profile were identified as ´management dependent´. This study was the only one which distinguishes among those categories, aside from the common ´negative´, ´neutral´, and ´positive´ categories (Kretschmer et al. 2013).

Souza et al. (2018) assessed an integrated first and second-generation scenario (1G2G scenario) which combines a first generation distillery with ethanol production based on bagasse and straw feedstock. This scenario is compared with a first generation biofuel basic scenario (1G-basic) and a first generation scenario with an increased efficiency level (1G-optimized). The study assessed five social effects: job creation, occupational accidents, wage profile, education profile, and gender profile. The considered scope is from sugarcane planting to ethanol use (Souza et al. 2018).

Valente, Brekke, and Modahl (2018) evaluated a hypothetical biorefinery from cradle to gate based on proxies from a 20 Ml/y full-scale biorefinery and a small demonstration plant owned by Borregaard in Sarpsborg, Norway. The study assessed worker rights, working time, human health impact, wage profile, equal opportunities, and social benefits and social security. Working time in average is 33.6 hours per week. The health impact is lower than in forestry or the chemical industry. The lowest wages have a variation of 7% and the highest wages of 9%. These numbers illustrate a low risk of unfair wages. 14% of the employees are male, 2% are foreigners, and 0% is disabled. The authors recommend establishing gender and minority recruitment policies. Health insurance, pension fund, and options for parental leave are provided (Valente et al., 2018).

Mattila et al. (2018) considered potential risks rather than actual performances. The aim of this study was to identify social issues within forest supply chains. Main social issues found in the forest industry in Finland were health, safety, and gender inequality. Majority of impacts were outside of the forest sector and outside of Finland (56%). The highest social risks outside of Finland were human rights and labour right violations (Mattila et al., 2018).

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Macombe et al. (2013) assessed a 1000 MW hypothetical case from cradle to grave. The paper compares three scenarios: Biodiesel produced from palm oil (scenario A), forest biomass (scenario B), and algae (scenario C). Algae and forest production are produced locally. The socioeconomic assessment takes place on company, regional, and state level. The investigated indicators are occupational accidents, human rights, and work rights. The study assumes that logging with modern machinery might result in fewer accidents than shipping palm oil. The study draws on the assumption that the forest based supply chain is taking place within a defined region. Therefore, the authors conclude that human rights and worker rights are covered by the Finish law (Macombe et al., 2013).

Henke et al. (2013) conducted a SLCA on short rotation coppice (SRC), biogas and maize production regarding three different levels: workers, local community, and society/consumers. Maize production is the reference scenario. The impact of SRC on the environment, local community, regional economic effects, conflict potential with the local community, local tourism and landscape aesthetics was assessed as positive. Also, the impact on food supply, the consumers, on poorer regions in the world, ethical behaviour, national concerns, and the contribution to the state budget were assessed as being positive. Since the work-life-balance was rated very positively for SRC supply chains (0.86), but the share of disabled people was ranked very negatively (-0.78), we stated a “neutral” impact for worker rights. We rated the human right impact as positive, since “ethical behaviour” had a significance of 0.34. The human health impact rated 0.16. Therefore, we assessed it as (slightly) positive. The “regional effect” was rated as 0.51. The wage profile was assessed by the “final money situation” which has a significance of 0.28. The contribution to the state budget was 0.28, impact on food supply 0.22, and impact on tourism 0.39. SRC were also found to have a positive effect on the landscape and conflict potentials in the respective regions (Henke and Theuvsen, 2013).

De la Rúa and Lechón (2016), investigated a real miscanthus case with an annual miscanthus production of 6000 tDM cultivated on 400 ha with a yield of 15 tDM/ha. According to their findings, the global economy will produce 14 million euros from which almost 5 contribute to value added in the GDP, thus the impact on distributed economic value (tax) has been ranked as positive. Job creation was stated to consist of 91 additional jobs. The economic multiplier accounts for 2.44 €, which means that if a consumer demands miscanthus biomass for 1€ there is a total production of costs and services in the whole economy equivalent to 2.44 €. Furthermore, the miscanthus supply chain enhances the local economy and employment to 75%. Generated impacts will be felt to 12% outside of France, in other countries.

8.2. Social capacity assessment of RESfuel enterprises

This chapter describes the performance of the biorefining companies Neste, ST1, UPM, Clariant, C2Biotrade and Btg-btl in terms of their social capacity. Social capacity is understood as the aggregate of strategies, processes, steering structures, cooperations, learning and innovation by which individuals, groups and organizations operate to act expediently towards common purpose or several connected objectives. Our understanding of social capacity builds on Smith and Kulynich (2002) and sets a focus on capacity factors essential to all kinds of project activities. The criteria we use next to describe and assess the impact of RESfuel enterprises in terms of social capacity include: strategy, cooperation, processes, steering structures, learning and innovation.

Neste operates two advanced biofuels plants which convert various oils and waste streams into renewable biodiesel through hydrogenated vegetable oil processing. The Neste plant in The Netherlands is in the largest port in Europe, The Port of Rotterdam, which is a major hub for trade, employment and partnership opportunities. On the other hand, the commercial plant in Porvoo, Finland provides almost half of the national share of compliant biofuels for transport to the country with 200,000 t/y of biodiesel (Christensen et al., 2018).

UPM utilises crude tall oil which is initially extracted in the pulp and paper mill production process and converts it into biodiesel and naphtha through a hydro-treatment process. The company´s commercial plant in Lappeenranta, Finland is co-located with an industrial pulp and paper mill plant and benefits from a facilitated feedstock sourcing. Biodiesel can be blended with fossil diesel or used on its own and is compatible with vehicle engines and fuel distribution systems. Bio-naphtha can be used as a bio-component in fossil gasoline (Christensen et al., 2018).

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ST1 produces waste-based advanced ethanol as well as the by-products fodder, energy, and heat. ST1 utilises annually 133k t of waste including sawdust, recycled wood, bark and waste streams from the chemical forest industry.

Clariant develops the Sunliquid technology to produce ethanol from cellulosic agricultural residues. These residues are produced worldwide in large quantities as a by-product of current agricultural production systems, as in the case of straw from cereal production and bagasse from sugar cane or sorghum.

C2Biotrade focuses on the production of biodiesel from palm oil on degraded pastures in the natural savannah of Altillanura, Colombia. The enterprise currently operates in a 650 ha farm but plans to expand to a 60,000 ha farm.

BTG-BTL aims to commercialize their patented pyrolysis technology and deliver pyrolysis plants to customers worldwide. The technology converts a wide range of non-food residues from forestry and agriculture into a dark brown liquid also known as pyrolysis oil. The liquid can blend with fossil diesel, stored and/or used in other applications for energy, biofuels and bio-based chemicals. Examples of successful feedstock sources include sawdust, pruning residues, sunflower husks, wheat straw, corn stover, bagasse and roadside grass.

8.2.1. Neste

- Strategy

Nestes' aim is to scale-up in the future. This objective has also been indirectly stated publicly through Neste's climate targets. The future target is an annual GHG reduction of 20 Mt CO_2 by 2030. The set CO_2 goal does not seem to correspond well to the actual performance since Neste would need to double its production volumes within only ten years in order to reach the set goal. Last year Neste saved close to 10 Mt of $CO_{2.}$ The main challenges Neste expects when scaling up are (1) the availability of suitable raw materials, (2) availability of locations for constructing industrial facilities, and (3) logistics which must be in place allowing for different transportation modes. Furthermore, most of Neste's raw material is transported by ship. Going forward, Neste expects a lack of raw material in the future, which will require collecting biomass from a larger geographical scope in fewer amounts. This development requires new ways of how suppliers should be integrated, managed and monitored. Furthermore, Neste invests huge efforts in R&D. Another goal is to use 1 Mt of plastic waste by 2030 as a raw material. Neste also aims for a more integrated upstream supply chain in order to secure the supply in the future. Thus, last year the major ownership of a Dutch trading company which specializes on animal fat waste and used cooking oil has been purchased.

Neste sources 10 different biomass types from around the globe. This biomass portfolio is a strategical risk management decision. The refining process is also diversified and takes place in three different locations. In case certain raw materials do not get accepted for certain market areas but save GHG emissions (which is the main market driver), then Neste investigates different market areas. For instance, Germany does not allow animal fat-based materials, so the raw material is used in other markets. Thus, Neste's risk management strategy focuses on higher flexibility based on the diversification of demand and supply.

In the future, Neste expects that a growing number of competitors will target the same raw materials. And companies that create something truly innovative will be the players which win in the long run.

- Cooperation

Between 2005 and 2006, the head of Neste's Health, Safety and Environment Unit, and of the business and supply unit formulated basic rules and selection criteria for the biomass suppliers. Compared to fossil fuel, in the advanced biofuel supply chain it is pivotal to know about the biomass' origin as well as the traceability of the raw material. For example, regarding dedicated energy crops, it is essential to know where the crop has been cultivated, if deforestation took place in order to realize the crop's implementation, what are the working conditions of the farmers. All these issues have to be managed and cleared before entering into the business. The chain of custody has to be in place. The major work regarding sustainability emphasizes on the supplier selection process. When a potential supplier is not able to provide all the necessary compliance information, they are not considered. Neste's Supply Function is in contact in a monthly basis with the respective suppliers. Neste's Singapore office organizes a workshop on relevant issues every year. For a few days, people come together to discuss working conditions and other socioeconomic and environmental issues. Other suppliers who are not supplying to Neste, but work in the same field are also invited to this event. This type of collaboration is unique from Neste’s perspective, which becomes visible, for example, in the following quotation: *“Without having close enough collaborations with the suppliers, and regarding them as partners we would have difficulties in meeting the promises we made.” (Neste, personal communication, 2020)*

When Neste started its sustainability efforts, there was no Renewable Energy Directive (RED) in place or any other type of regulations in that field. Once the certification systems were implemented such as the International Sustainability and Carbon Certification (ISCC) and the Roundtable on Sustainable Palm Oil (RSPO), Neste promoted those schemes among its suppliers in order to secure a certified supply chain. Looking forward, the suppliers will need to commit to more reporting than they have ever done before. The advanced biofuel sector asks for more detailed and accurate data than any other field. Neste introduced a web based tool called Supplier Sustainability Portal (SSP) which enables the company to create closer collaborations and more direct contacts with the suppliers. The suppliers get also ranked on this portal based on their sustainability performance. Neste offers long-term contracts to its suppliers. However, since there is high volatility of the biomass price at the moment, and prices have been increasing, suppliers are not willing to commit to term contracts. Neste, however, still wants the term contracts to be in place because it secures the volumes of known suppliers with which Neste established long-term partnerships. Thus, Neste knows the suppliers’ behaviour and performance. Only occasionally, there are spot contracts in place. Furthermore, Neste cooperates with more than 20 numerous research institutes and universities, despite having their own in-house research department which consists of ~ 1000 employees (every fifth employee).

- Steering Structure

Generally, decisions are taken by the Board of Directors in a top-down fashion. The operational Management decides in which areas the company should grow and within which limits. But, if a new idea is very exotic and entails high risks for all actors who are involved, decision-making takes place on a more collaborative level. In such cases, partners must be getting their voices heard. For instance, if Neste aims to establish collection systems for used cooking oil, Neste is setting sustainability requirements in a top-down manner. Neste also engages in putting bio-based materials on the policy agenda. Hereby, the company has an equal voice compared to other market players who mainly focus on bio-based plastics. Neste plays different roles within different arenas regarding its external and internal steering structure. The company also takes advantage of consultancy services. On strategy issues, there is one main consultancy that provides consultants that are dedicated and specialized to Neste's needs. The annual overarching strategic plan is approved in summer by the top management and the performance plan starts in autumn. The basic structure of the performance plan is agreed upon by the top management and the support functions of Neste by the end of the year. That performance plan entails the different production goals, expansion goals, etc. This information is transmitted to all of the employees who come together and have a workshop for one day and discuss outsider expectations, experience and business goals which are put together in an action plan. Furthermore, every employee has a certain amount of shared team goals and individual goals. The performance plan is informed by all business functions from various angles such as the support function, public affairs, communication, and brand image. This practice is not only beneficial for the annual planning, but also in order to share information within the company. One output of this workshop is a refined action plan for each business unit. The quality of the annual plan is depending on how closely Neste follows up on what the world expects of the company. Are there topics arising among citizens such as biodiversity? The head of the unit communicates the goals to the employees who were not part of the participation process. The employees adjust and refine their personal goals towards the updated company goals. If there are sudden changes in the business environment or new projects the plan needs to be adjusted. It is agreed that it is possible to re-open the planning process and rewrite the annual plan.

- Processes

Neste's biggest customers are big oil companies who are obliged to blend a certain amount of bio-based materials into their fuels. Those companies put a strong emphasis on compliance issues. Therefore, they are interested in Neste's verification system, the supply chain monitoring system, and also details regarding GHG savings. Neste's customers are looking into ways how to create a greener image. The transition in the transport sector requires much closer collaborations with the brand owner at the downstream supply chain, the processing partners, and the biomass suppliers. Harmonizing these different supply chain steps is a challenge.

- Learning and Innovation

The main research is done by external research institutes and universities and based on networks with those entities. The core questions are if the future of Neste will be based on the same technology or if it will it be based on the same raw material type, so biogenic oils and fats or something else. This is currently very intensively studied at Neste and related to the business strategy of the enterprise. Innovation goals focus on (1) improving current processes and their efficiency and (2) identifying further business areas. There is a basic requirement tool to make sure that the documentation of lessons learned takes place and it is easily available.

Neste's current technology is called NEXBTL which was patented for more than 20 years. NEXBTL allows for various feedstock types in the conversion process. Neste is investigating technologies that go beyond the current feedstock base and current technologies. The company investigates on algae as a potential raw material. Research nowadays has to select those options which provide GHG savings over the entire lifecycle of the product. There is an online tool available for Neste employees to promote and exhibit innovative ideas. These ideas are assessed by multi-experts. The best ideas receive an award. A few years ago the winning innovation was to use liquefied plastic waste as a raw material instead of crude oil-based materials. This year this innovation will start on a pilot level in Finland. The process of translating innovations into the company structures and processes depends very much on the individual idea. If it is something practical such as modifying the raw material pretreatment process, it only requires a risk assessment, economic feasibility study, and the modification of one pretreatment unit. That would take approximately 6 months. But innovations that focus on testing different types of raw materials would take a couple of years to be incorporated into the company's structure. One key factor of Neste's success is its size. Neste has 5000 employees. The relatively small size helps to transmit ideas and innovation faster into the business structure. Bigger companies have a more structural slowness in their processes. That is the reason why a lot of companies set up start-ups within their own organization.

In the past, Neste was involved in several sectors such as oil refining, oil retail, chemicals, natural gas, etc. In 1998, Neste was merged with the power company Imatran Voima Oy to create Fortum Oyj. The two companies needed to identify synergies that did not exist at that point. Neste was divested and only left with oil refining and oil retail. Thus, the company was urged to look into new ways how to survive and start growing again. This is how the company came across renewable fuels. The Board was courageous enough to stop investments in the oil sector, but start investing in renewables. The decrease in the company's freedom was so tremendous, that the willingness to take on risks was very high.

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8.2.2. ST1

- Strategy

ST1 has the aim to implement additional biorefineries of sawdust-based ethanol. However, the demand for ethanol on the European market is restricted by the European fuel standards which only allow for a bioethanol blending share of 10%. Some countries only allow 5%. ST1's upscaling efforts are restricted by this legislation. The company's perceived challenges regarding advanced biofuel are (1) the technological maturity level that enables the continuous production of RESfuel, (2) the enabling legislation landscape, and (3) the economic profitability. Having issues with continuous production in the advanced biofuel sector is a common issue that has often to do with the pretreatment of the material. The biorefinery unit is responsible for implementing upscaling efforts. When it comes to technological risks the company decides to just take it and when the risk materialises there is a decision-process taking place whether to continue the investment or not. Objectives are set optimistically. Often, the actual performance needs longer than what has been set in the targets.

- Cooperation

Producing advanced biofuels requires a lot of collaboration between research, companies, local stakeholders, decision-makers, ministries, parliamentarians, etc. It is a big network consisting of actors who are looking at the advanced biofuel sector from different angles. Many of the advanced biofuel conversion technologies are novel processes. Thus, cooperation is a key element. Following the supply chain from the raw material until the final use, the supply chain requires a lot of collaboration. Starting from the feedstocks sourcing which requires agreements on feedstock types, quality, quantities, and timeframe. Novel technologies and processes like the ones taking place in the advanced biofuel sector, require cross-cutting processes. This means that you need to combine the different supply chain steps such as feedstock supply, technology supply, biofuel production, biofuel supply to the oil companies, etc. That project owner has to be very committed and maintain relations with the various partners within the supply chain. For example, regarding feedstock supply the interviewee stated: "Once you identify the suppliers of the feedstock, it requires a lot of negotiations, clarifications, agreements, in order to get the feedstock supply in place. This process can be quite demanding." Consequently, setting up the supply chain structure, in the beginning, is linked to large efforts. When the production and the delivery start, transaction costs can be expected to be high, but in a different way. Then external partners are carrying out the activities and processes. So, the agreements are in place, but now the practical implementation of those agreements needs to be secured. Once the operations are more settled and processes are about to become a routine, the level of required communication and interaction efforts decreases as the operation becomes business as usual (BAU). This development can be observed throughout the supply chain. When ST1 is in a BAU state, meeting with suppliers are taking place every second/third month. It depends on the aim. Sometimes the management of the different companies come together to discuss the performance of the supply chains and what areas of it require improvement. Such meetings are not taking place as frequently as the BAU meetings. Partnerships are regarded as absolutely crucial for the success of RESfuel biorefineries. Partnerships are either build on cooperation contracts or supply contracts or a combination of those two options. Cooperation contracts are overarching broad contracts that cover different types of elements e.g. a feedstock delivery contract, reporting, etc. For some partners, a cooperation contract could be as simple as an agreement on quality, quantity, and price of the feedstock. Regarding the supply contracts, ST1 tends to have long term contracts in order to secure feedstock deliveries. The contracts have a duration of approximately 5 years; sometimes ST1 prefers a contract duration of 10 years.

- Steering Structure

The business units establish a detailed annual plan. The business unit leaders present their plans to their colleagues on a higher level where it gets approved. The plan cascades upwards. And the higher up the plan goes, the more strategically the plan becomes. The business unit/business unit leader is the owner of its annual plan. Consequently, the planning is a bottom-up approach, with some top-down elements in it. If the planning requires investments, certain processes need to be followed to make sure that the appropriate levels are taking the investment. Biomass suppliers are the key input of the annual plan. So, if ST1 is aware that a feedstock supply will exhaust, it has to be reflected in the annual plan. But the biomass suppliers do not take an active part in the annual planning process. However, the partners and other external factors are taking into account and can have a big impact on the annual plan. The last step is to inform all staff members of the annual plan. However, not everyone knows everything. The business unit leaders are responsible to inform other staff members on various levels regarding their plan. But it always has to be decided what the level of detail should be regarding the distributed information. The higher up the information transits, the more general it becomes.

- Processes

The responsible partners for each supply chain step are well defined. On each supply chain step, there are agreements on the operations which need to be executed. The interviewee stated that every step must be in place before the decision on the investment can be made. These include the conversion technology, the off-take agreement, the feedstock supply, capability of operating the plant, secured financing and understanding of the regulations.

- Learning and Innovation

ST1 has an in-house research department and collaborates with external universities and research institutes. The scope, research objective, and tasks within those collaborations are well-defined. Based on that, a project is setup with the respective research entity. Hereby, the subjects are related to enzymes, by-product refinement, etc. For the conversion process, the biomass gets fragmented into various substances. It is in the interest of each market player to maximize the value of each substance. In general, ST1 defines the scope of what the company is interested to find out and then ST1 sets up a contract that describes this in detail. This contract also defines the intellectual property rights of the generated research findings. The research findings are then case-specifically evaluated regarding its economics and potential risks by the internal experts on the respective subject and the top management. Afterwards, ST1 decides internally if it wants to implement the respective innovation or not. Often, the transition of making an innovation commercial requires intensive additional follow-up research in order to get the monetary benefit in place. ST1 documents lessons learned via a web-based tool. It is in the interest of ST1 to learn from past mistakes and development processes. The acceptance of this tool among the employees is on a good level.

8.2.3. UPM

- Strategy

UPM aims to scale-up its RESfuel activities in the future. The company plans to implement a biorefinery with a capacity of 0.5 Mt of advanced biofuels per year. The location of the biorefinery is not determined yet, however, it could be realised in Finland. It will not be based on the same feedstock as the Lappeenranta plant, which is crude tall oil. The planned biorefinery will be based on multiple feedstock types. The main challenge UPM is expecting is the security of the biomass supply. The Vice President of the Biofuels Unit at UPM, and the Vice President of the Biofuels Growth Program at UPM, are mainly responsible for the up-scaling process. UPM's performance has been record-breaking almost every quarter. Thus, it can be concluded that UPM has been successful in implementing its strategies.

- Cooperation

According to UPM, there are no significant differences between collaborations in the advanced biofuel sector, compared to any other sector. A fit regarding target alignments is the basis of a partnership. It depends on the company's strategy to what level partners are integrated within the respective supply chain. One of the main targets of UPM's partnerships is the access to feedstock. Communication is constantly taking place with different stakeholders. The biorefining company sources a lot of their biomass from private forest owners with whom UPM is in regular contact. UPM cooperates with consultancies but is not continuously working with the same consulting firm. It rather picks from a pool of various potential consultancy partners. According to UPM, partnerships are crucial for any kind of business nowadays, not only the advanced biofuel sector. There are several different contracts in place for biomass suppliers.

- Steering Structure

The annual planning follows a bottom-up approach, meaning that the plan is developed in each business unit individually. The different business units of UPM work relatively independent and have different processes in place. At a later stage, the outcomes of the various annual plans are discussed and agreed upon on the company-level. The information regarding the annual plan is shared by employees who hold a leading position. This information cascades through the organisation in various ways.

- Processes

The responsible partners for each supply chain step are well defined. The processing capacity of the machinery is the perceived limitation in UPM's supply chain.

- Learning and Innovation

UPM has an in-house research department and collaborates with external research institutes and universities. Lessons learned have been internally documented via several different tools. These tools are well accepted among the employees. The documentation process of lessons learned lies especially in safety. UPM has a system in place to gather innovative ideas among staff members. UPM tries to involve its employees as much as possible in strategical business activities. The collected innovative ideas get assessed by the relevant experts who work in the field to which the respective innovation is related to.

8.2.4. Clariant

- Strategy

Clariant´s corporate strategy is based on five pillars (1) focus on innovation through research and development, (2) add value with sustainability, (3) reposition portfolio, (4) intensify growth, and (5) increase profitability. Clariant aims to provide a solution to the transport sector by converting abundant sources of feedstocks and residues into cellulosic ethanol.

Clariant owns a commercial-scale plant (currently in the construction phase) to produce cellulosic ethanol from agricultural residues based on the Sunliquid technology in the southwestern part of Romania. The plant has an expected annual capacity of 50,000 t of cellulosic ethanol and the strategy is to create a well-developed supply chain through strong partnerships and long term contracts with local farmers for feedstock supply to the plant. On the other hand, the core business strategy is to sell licenses for their patented Sunliquid technology worldwide. The company has recently sold their first license in China. A full commercial scale plant to produce cellulosic ethanol using the Sunliquid technology is planned in the Anhui province in China. The annual plant production capacity is planned to be 50,000 t of cellulosic ethanol, with an option to double the capacity in a second phase, making it one of the largest in China so far. Detailed project evaluations and preparations are well underway. The produced cellulosic ethanol will be utilized in the Chinese regional fuels market as blend into gasoline to fulfill the national blending mandate

- Cooperation

Regarding the upstream activities of the supply chain, cooperation with local producers is based on a variety of long term contracts for bailing, collecting, transporting and storing of biomass. There are different set ups according to the type of farmers; some have equipment and others not. Farmers are encouraged to purchase bailing and transport equipment to expand their businesses with Clariant. Currently more than 200 partnership contracts with local producers have been concluded. Since straw is usually burned in the fields in Romania due to lack of solutions, the parties are satisfied with the proposed business alternative.

The enterprise also collaborates closely with the University of Craiova (www.ucv.ro) in close vicinity to the plant. Clariant gives clear instructions to educate and train students in several fields including innovative logistics and storage methods for the raw material. This cooperation provides an opportunity for human resource development in the area and provides a qualified pool of staff for Clariant.

In cooperation with the Romanian government, Clariant believes there is a high chance that the government will start developing infrastructure in the area and increase opportunities for further investments in the region.

- Steering Structure

The organizational structure of Clariant comprises seven business units and nine business services where functions are centralized. The different business units work relatively independent and have clearly defined roles and processes in place. Clariant´s Group Biotechnology Center revolves entirely around industrial biotechnology and focuses on the sustainable use of renewable resources.

- Processes

One of the key processes contributing to the success of the enterprise and the value chain is the creation of a local team in Romania since the beginning, which included personnel from

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biotechnology, chemical and mechanical engineers and others. By integrating local stakeholders in the process, trust is built and expectations are managed. The company holds constant workshops to keep the partners busy and engaged with the project.

Regarding the critical bottlenecks in the value chain, the interviewee argued that some permits took longer than expected which delayed the construction of the plant. The reason for this was that due to the innovative nature of the project, environmental risks were unknown and had to be thoroughly assessed. Mainly patience was needed to overcome this issue.

- Learning and innovation

The knowledge is usually created internally and shared with the partners. Agricultural producers who want to become engaged are trained via workshops and value chain videos. There is an extensive PR outreach to the farmers, policy and industrial workshops, parliamentary meetings, plant tours, and constant progress conferences.

Learning and innovation is also enhanced through the cooperation with the University of Craiova. The partnership with the University builds capacities that can further contribute to the prosperity of the organization and the region in which it operates.

8.2.5. C2Biotrade

C2Biotrade aims to expand its business by establishing long-term contracts with European buyers for the delivery of biodiesel from afforestation palm on degraded and underutilised pastures in Colombia. At the moment, the enterprise is working on a 650 ha farm but plans to expand its operations for feedstock supply to at least 60,000 ha. According to the interview partner, to increase the market uptake of their product in Europe, the first step is to change the bad reputation of palm oil. On the other hand, the current political situation in Colombia is also delaying the plans for expansion. The plan is to establish a permanent local settlement near the plant and incorporating producers who have been previously displaced from other plantations. The rural population in the area has been subject to decades of conflicts between the guerrilla, paramilitary forces and the army. Alternative plans for the enterprise are being deliberated upon as certain risks and threats can potentially occur during the upscaling process.

- Cooperation

C2Biotrade cooperates closely with agricultural producers and international buyers. In tandem, the enterprise cooperates with ResGrow (www.resgrow.com), a consultancy company and business operator which combines unused resources in developing countries with international finance and know-how.

Cooperation with Colombian government for urban planning, registration of land rights and keeping law and order, in addition to secure open international transport routes is fundamental for the success of the project.

- Steering Structure

C2Biotrade SAS is a Colombian registered trade company under Norwegian ownership through the companies ResGrow AS and Prestige Colombia SAS. Major decisions are taken in Europe and then communicated in Colombia. The representatives travel several times a year to Colombia and communicate constantly via emails and Skype meetings.

- Processes

The key processes limiting the success of the enterprise and value chain are the ongoing conflicts in the region and the bad image of palm oil in Europe. To overcome such issues, the strategically most important processes of the enterprise include (1) assessing the carbon footprint of the future large scale biodiesel production in Colombia, (2) evaluating the compliance with GHG criteria of the Renewable Energy Directive (RED), (3) designing the cultivation and processing facilities in a carbon friendly way, and (4) focusing on International Sustainability and Carbon Certification (ISCC). Processes are managed in conflict-sensitive ways and lessons learned are currently shared between the partners in Europe and Colombia

- Learning and innovation

The work on the palm plantation is considered as labour intensive. Producers are trained at the plant via workshops. Nevertheless, most of the producers in the area have previous experience from working in other type of plantations, i.e. cacao. Learning and innovation in process optimization is also enhanced by cooperating with research entities and consultancy.

8.2.6. Btg-btl

- Strategy

The overarching goal of the enterprise is to substitute fossil fuels used for energy, gasoline blending, diesel replacements and even chemicals with pyrolysis oil. To achieve this objective, the current strategy is to deliver and deploy their pyrolysis technology at a global scale and to scale up numbers by creating multiple plants near the biomass sources. The enterprise also plans to build an installation for the pre-treatment of roadside grass as future feedstock.

- Cooperation

Btg-btl has a policy of actively seeking cooperation with other companies to gather additional expertise. The interviewee stated that for both the construction of the plants and the development of pyrolysis applications this approach has proven very successful.

Current strategic partners include (1) TechnipFMC, a global leader in subsea, onshore/offshare and surface projects. Technip and Btg-btl collaborate in the development of commercial uses for fast pyrolysis oil as renewable fuel and petrochemical feedstock. (2) Empyro plant in Hengelo, Netherlands converts 5 t/h of biomass into oil, power and steam. The plant designed and built by Btg-btl as a demonstration of its propreitary pyrolysis technology. After succeeding in scaling-up the production capacity of the plant to its full potential, it was sold to Twence (www.twence.nl) in 2018. The ongoing cooperation with Empyro allows the enterprise to show the plant to potential customers, to have access to oil for testing, and vicinity to the technology to increase expertise in pyrolysis. (3) BTG Biomass Technology Group (BTG) is an independent private group of companies focusing in the process of conversion of biomass into useful fuels and energy for the past 25 years. BTG is the primary partner when it comes to feedstock tests and research and technology development.

- Steering Structure

When asked about how decisions were made along the value chain, the interviewee highlighted the importance of creating a common basis of information and knowledge for the decision-making.

- Processes

The Empyro plant in the Netherlands provides a competitive advantage to the enterprise. The plant gives the company a point of reference for the success of their patented fast pyrolysis technology. The plant also allows for a close control regarding the quality of the product and allows for constant optimization of the processes. After achieving optimal status of the technology now the processes focus on marketing the technology.

- Learning and innovation

The enterprise offers students of all educational levels the possibility to do an internship or write a graduation assignment throughout the year. The company also offers a complete training on the required skills and techniques before selling the technology to their customers. Partners are invited to Empyro plant and receive theoretical and practical learning. With the agricultural producers the approach is old school marketing and sales, which means giving presentations, conferences, speaking to people and make an adapted model for their needs.

In the past, BTG moved too quickly opening a plant in Malaysia, which was not successful and is now closed. However, the interviewee stated that it was useful for building up knowledge and learning from their mistakes. Following the opening of the Empyro plant, the enterprise received many requests for pyrolysis oil samples from Empyro. In response, the company opened a web shop. For the past years the enterprise has sold oil samples to universities for research, igniting ideas for further developing pyrolysis technologies and RESfuels.

The following table structures the results obtained from each RESfuel enterprise in relation to the five factors, this provides the basis for discussion in Section 9.2 (Table 11).

Table 11 Overview of the social capacity performance of RESfuel enterprises

Social capacity success factors (GIZ, 2015)	**Neste**	**ST1**	**UPM**	**Clariant**	**C2Biotrade**	**Btg-btl**
Strategy	Double CO_2emission savings Diversification of demand and supply	Increase number of sawdust based biorefineries	Build a second RESfuel biorefinery	Increase delivery and deployment of technology licenses Promote the adoption of their technology in biorefineries worldwide	Promote the cultivation of palm oil on degrade pastures Increase portfolio of European buyers	Increase delivery and deployment of technology licenses Promote the establishment of pyrolysis plants Diversify feedstock sources
Cooperation	Term contracts Spot contracts (occasionally)	Cooperation contracts Supply contract (~5 yrs)	Diversified contracts	Long-term contracts with suppliers Cooperation with Romanian government for development of infrastructure	Long-term contracts with suppliers Cooperation with Colombian government for urban planning, land acquisition and securing law and order	Diversified contracts
Steering Structure	Hierarchical Hybrid[1] Information sharing by managers	Hybrid market and hierarchical Information sharing by managers	Hybrid market and hierarchical Information sharing by managers	Hybrid market and hierarchical Information sharing by managers Cooperative structures of suppliers	Hybrid market and hierarchical Information sharing by managers	Hybrid market and hierarchical Information sharing by managers
Processes	Roles and responsibilities are well-defined, understood and followed by all stakeholders.	Roles and responsibilities are well-defined, understood and followed by all stakeholders.	Roles and responsibilities are well-defined, understood and followed by all stakeholders.	Roles and responsibilities are well-defined, understood and followed by all stakeholders.	Roles and responsibilities are well-defined, understood and followed by all stakeholders.	Roles and responsibilities are well-defined, understood and followed by all stakeholders.

	Focus on certification schemes	Focus on harmonization of actors´ needs		Focus on marketing of technology	Focus on certification schemes	Focus on marketing of technology
Learning and Innovation	Exchange of knowledge with research entities and internal research department Online tool for employees to exhibit innovative ideas	Exchange of knowledge with research entities and internal research department	Exchange of knowledge with research entities and internal research department Online tool for employees to exhibit innovative ideas	Exchange of knowledge with research entities and internal research department Opportunities for practical experiences for students	Exchange of knowledge with research entities and internal research department	Exchange of knowledge with research entities and internal research department Opportunities for practical experiences for students Web-shop selling pyrolysis oil for R&D.

9. Discussion

9.1. Socio-economic performance of RESfuels

The socioeconomic indicator covered by all assessed publications except by De la Rúa and Lechón is the human health impact (2016). Matilla et al. (2018) was the only publication that assigned a negative health impact to the assessed wood product supply chain. It is often argued that human rights and labour rights are covered by EU regulations and are therefore not relevant to investigate, if the respective supply chain is solely operating in the EU (Kretschmer et al., 2013). Souza et al. (2018) argue that second generation biofuels are less labour intensive than first generation biofuels, and that therefore, wage profiles and education profiles are positively influenced. Souza et al. (2018) describes the labour distribution among the various supply chain steps of first and second generation biofuels (Figure 11 and 12). Figure 11 illustrates that first generation biofuel requires more workers in the sugarcane production. Figure 12 illustrates that *advanced biofuel supply chains* have most of their workers in trading. Trading requires more trained workers than the sugarcane production.

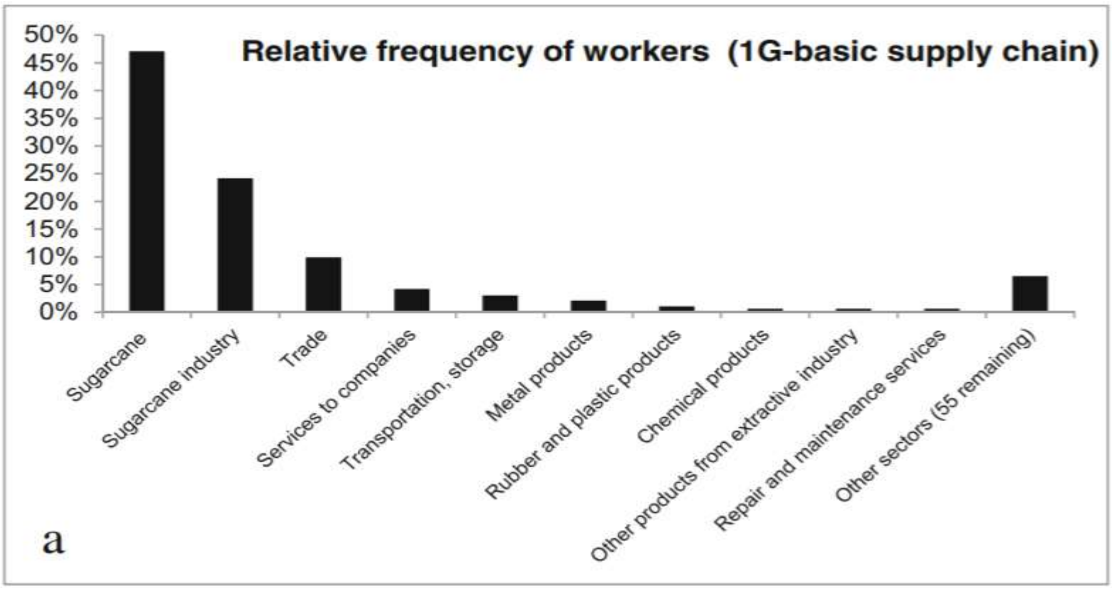

Figure 11 Workers distribution in a first generation biofuel supply chain *(Souza et al. 2018)*

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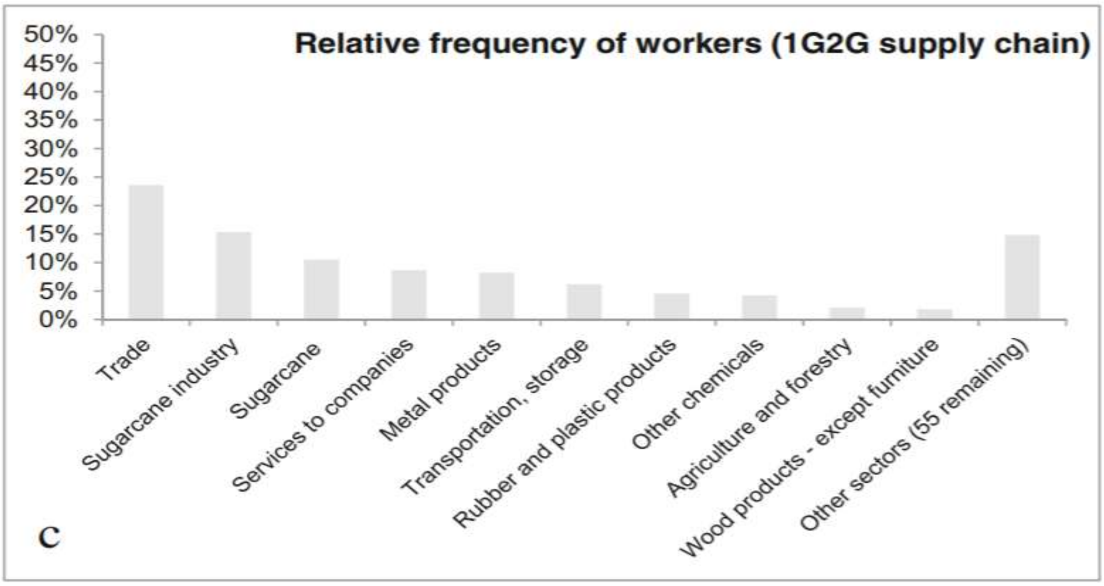

Figure 12 Workers distribution in a second biofuel supply chain (Souza et al. 2018)

To compare the socioeconomic performance of both supply chains, Souza et al. (2018) extracted average values in regard to occupational accidents, wage profile, gender profile, education etc. from national labour databases which are divided by sector. However, in the literature comparison some diverging assessments can be observed. For example, Henke et al. (2013) assessed the impact on food and price security as positive, whereas Kretchmer et al. (2013) found a negative impact due to increased land scarcity. Also in terms of job creation differences in the assessments can be found between Kretchmer et al. (2013) and de la Rúa (2016) who assessed the impact of this indicator as positive due to the provision of highly qualified jobs. Souza et al. (2018) identified a negative impact of RESfuels on job creation due to less labour intensive supply chains. This shows that it is pivotal to regard impacts within its context. For instance, Henke et al. (2013) focuses on SRC which might be grown on land that is not suitable for food production, thus the author concludes that SRC have a positive impact on food production. Whereas Kretchmer (2013) et al. focuses on the biorefinery which is fed by multiple feedstock types that might lead to increased land pressure.

A limitation of comparing different studies on socioeconomic assessments is that separation of social and economic indicators varies. For instance, Schaidle, Moline, & Savage (2011) regard job creation, and food price as part of the social dimension, while according to Raman et al., (2014a) job creation is an economic indicator. Referring to the application of such factors on biorefineries, all socieconomic assessments studies show that socioeconomic indicators cover a vast spectrum, but with a limited standardisation. The reviewed articles cover indicators ranging from job creation all the way to social awareness. Often, SLCA can only assess potential impacts instead of actual impacts, since there is often no site-specific data available for all relevant processes. Therefore, it is often difficult to account for social inequalities (Ekener-Petersen et al., 2014). Another obstacle is that certain socioeconomic indicators are highly sensitive (e.g. corruption and discrimination) and are therefore almost impossible to assess without harming companies' image (own observation). It was challenging to compare different socioeconomic assessments in literature due to different products, scales, reference scenarios, and categorizations or terminologies of indicators. Generally, most assessed socioeconomic indicators are related to job creation (Cambero and Sowlati, 2014).

The biofuel sector created 95,900 direct and indirect jobs in the EU28 (AEBIOM 2017). A standardized SLCA is difficult to develop since the relevance of indicators is strongly scope dependent and furthermore it is also influenced by the priorities of local stakeholders (Rafiaani et al., 2018). ADVANCEFUEL deliverable D.4.2 identifies the harmonization possibilities of RESfuel certification schemes. Hereby, the indicator "worker rights" ranked the highest as being harmonized throughout various certification schemes. "Job creation", "human health impacts", and "compliance with local law rights & international treaties" are ranked as medium. Mai-Moulin et al. (2020), show that the criteria of the certification schemes also play an important role on an application level. However, when focusing on the local supply chains in the EU, human and worker rights are already covered by law.

The study of Cambero and Sowlati (2016), investigated on forest-based bioenergy and biofuel supply chain performances when changing economic, environmental or social parameters (NPV, GHG emission savings or job creation). The study found that higher GHG emission savings and job creation increases supply chain costs, thus reducing profits. A study which compared social risks of fossil and biofuels, concludes that the country of origin plays a bigger role in regard to social risks than the actual fuel type (Ekener-Petersen et al., 2014). A study which compared biofuels produced from corn, switchgrass, soybean, canola and algae, finds algae and switchgrass based biofuels to be the most promising when maximizing the economic, environmental and social impact simultaneously (Ziolkowska, 2014). A comparative SLCA is a suitable instrument for decision-makers in order to estimate socioeconomic impacts at the conception stage of establishing a bioenergy region. Negative impacts can be addressed by measures such as involving the civil society in the planning process at an early stage in order to avoid low social acceptance (Henke and Theuvsen, 2013).

In the future, research needs to further improve available datasets and tools in order to identify the actual socio-economic performance of RESfuels and make them comparable (Rafiaani et al., 2018). With this in mind, the next section of the report aims to enrich current socio-economic assessments by considering capacity related criteria which can be analyzed, discussed and negotiated towards the overall improvement of RESfuel value chains.

9.2. Social capacity performance of RESfuel biorefineries

We assessed the social capacity of Neste, ST1, UPM, Clariant, C2Biotrade and Btg-btl, regarding their strategy, cooperation, steering structure, processes, learning and innovation. As illustrated in Table 11, all six companies aim to scale up their value chain activities, but their *strategies* to achieve this differ. ST1 and UPM have concrete objectives regarding the implementation of further biorefineries, whereas Neste sets its goal by doubling its CO_2 emission savings by 2030. Clariant and Btg-btl focus on promoting the use of local and underutilized sources of feedstock for RESfuels and other bio-based materials. C2Biotrade focuses on promoting the cultivation of palm oil in Colombia to feed the European market. Firms devise strategies to guide their actions. Such strategies differ from firm to firm, in part because of different interpretations of economic opportunities and constraints and in part because firms are good at different things. In turn, the capabilities of the firm are embedded in its organizational structure, which is better adapted to certain strategies than to others. Thus, strategies at any time are constrained by organization. In tandem, a significant change in a firm’s strategy is likely to call for a significant change in its organizational structure (Nelson & Winter 1982).

Other commonalities of six cases are that, the *steering structure* was a hybrid between hierarchical and a market governance structure and the information in regard to the annual plan gets shared by the management on the various management levels (lower-, middle-, and upper management). A hierarchical governance structure is characterized by strong administrative control and weak incentives, whereas a market governance structure is defined by less administrative control and strong incentives (Maaß and Grundmann, 2018; Ménard, 2004). In the case of Clariant, producers are encouraged to develop cooperative structures in which decisions are taken collectively by the producers and negotiated with the enterprise. In all six companies the annual plan is developed in the different business units and cascades up the hierarchy leather

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where it gets approved. The external partners do not play an active part in the development of the companies' annual planning. However, Neste distinguishes between BAU operations and new decisions which are taken. If all actors carry a certain amount of risks regarding new decisions, all voices in the supply chain are equally considered because each partner is also equally exposed to potential risks.

Further similarities are that all six biorefining firms have *processes* in place in which roles and responsibilities are well-defined. All firms cooperate with research entities while having their own internal research department. ST1 finds it challenging to align the different needs of various partners in the supply chain. The further harmonization of such, is one leverage point how to further improve ST1's processes. In order to actively obtain creative inputs from their staff members, Neste and UPM have an online tool for employees to exhibit innovative ideas. On the other hand, Btg-btl opened a web-shop which delivers pyrolysis oil to universities for research purposes. Clariant has a strong focus on learning and innovation as evidenced with their cooperation with the University of Craiova igniting research for the RESfuel sector (learning and innovation).

On *cooperations*, ST1, Clariant and Btg-btl emphasized the importance of securing long-term contracts. Compared to that, Neste offered long-term, but also spot contracts depending on the partners' preferences. Since, not all partners are willing to commit to one market price for 5-10 years, especially, if the market price is expected to increase. Clariant seeks to establish long-term contracts with local suppliers of feedstock for the plant, but contracts are adapted to the "level of entrepreneurship" of the farmer, for example, some are interested acquiring machinery or participating in the logistics process, while others just want the residues removed from their fields. The producers benefit from the partnership as the residues are usually burned in the fields due to lack of alternatives, which causes air pollution associated with health and other risks (cooperation).

All six enterprises show positive evidence on *learning and innovation* in the socioeconomic environment; but in different degrees. The ways in which the enterprises learn and innovate vary, from workshops and trainings to online tools in which partners can showcase their ideas and shape the strategy of the firm. Clariant and Btg-btl provide space for students to have internships in the company. The case of Clariant highlights the positive impacts of cooperating with the neighbouring universities. The company set clear interests on the processes and capacities needed for the enterprise, and interested students are trained accordingly, providing a pool of qualified staff for the enterprise and the region. Btg-btl enhances learning and innovation by selling pyrolisis oil for research and development purposes. These evidences point towards sustainability dimensions and to positive socioeconomic impact in the region in the form of capacity development at the level of individuals, organisations and the society.

The present report is the first study to dissect the social capacity performance of RESfuel enterprises with regards to their strategies, processes, steering structures, cooperations, learning and innovation. The main limitation of this assessment for RESfuel biorefineries is the lack of consistency in the responses obtained. Another limitation is that it cannot be assumed that certain measures are not in place; just because they have not been mentioned e.g. ST1 could also have an online tool for employees to exhibit innovative ideas as well. There is a need for more standardized procedures for describing and assessing the social capacity performance using defined criteria, indicators and verifiers. A higher diversity of different governance structures would have added a value in showcasing how the design of the companies' social capacity reacts to the governance structure in place. This report is a building block towards a better understanding and management of the impact of RESfuel activities on its socioeconomic environments. The applied methodology could be improved by for example enhancing the criteria with indicators and verifiers or assigning values according to different performance levels; this would make the results more comparable and allow for better monitoring of the performance of the enterprises regarding their social capacity.

In relation to current literature, Martinkus et al. (2014) assessed the *social asset* of a community regarding a biomass-to-biofuel supply chain and its siting decision. Social asset combines social capital, creative leadership, and the public health status. The result of the study is that biorefinery plants are best implemented in communities which trust their governments, have good leadership in place, and support new ideas (Martinkus et al., 2014). Martinkus et al. (2017) assesses the social capital of a community and its willingness to accept a new biorefinery within its community as well as the community's ability to develop creative solutions targeting upcoming issues regarding the biorefinery installation. Hereby, the authors apply the Community Capitals Framework, developed by Emory & Flora (2006). The framework consists of social capital, human capital, cultural capital, natural capital, built capital, financial capital, and political capital (Emery and Flora, 2006). While Emery and Flora's approach focuses on healthy ecosystems, a vibrant regional economy, and healthy happy communities, our approach assesses the social capacity from the perspective of the enterprises.

10. Conclusion

The first part of this report compares the socioeconomic assessments of seven second generation biorefineries and feedstock supply chains found in literature. The impact on human health was the indicator with the highest harmonization level throughout the seven cases. Further indicators are: human rights, worker rights, contribution to local development, wage profile, education profile, gender profile, indigenous people's rights, food & price security, job creation, distributed economic value (tax), and tourism. But not all of these indicators are equally covered within the seven investigated publications. Partially, performances regarding the same indicators have been assessed differently in the respective studies. The reasons for that are manifold, such as different reference scenario, geographical scopes, or end-products (raw material vs. biofuel).

Building on these results, five key elements are proposed to assess the socioeconomic performance of RESfuel value chains and enterprises in terms of their implications for the social capacity in the socioeconomic environment. The five criteria used are: strategy, cooperation, processes, steering structures, learning and innovation (GIZ, 2015).

The present report assessed the performance of six biorefining companies Neste, ST1, UPM, Clariant, C2Biotrade and Btg-btl. All six companies aim to scale up *(strategy*), have a hybrid *steering structure*, well-defined roles and responsibilities in place (*processes*), and cooperate with research entities while also having their own internal research department (*learning and innovation).* Major differences in the social capacity have been found. For example, ST1 follows a rather conservative approach by providing long-term contracts to biomass suppliers, whereas Neste provides term contracts and spot contracts in order to flexibly respond to different preferences of their biomass suppliers. Clariant´s contracts depend on the "level of entrepreneurship" of the farmers. For example, some producers are only interested in leaving their residues on the field and have Clariant collect them; while others are interested on acquiring machinery or participating in the logistic process to the plant. A very close linkage was observed between the RESfuel enterprises and their institutional environment; there is substantial evidence that policy works as a driving force that influences the strength and direction of RESfuel technologies.

10.1.1. Implications for research

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N.º764799.

With the purpose of enriching current socioeconomic assessments, we focused on capacity building criteria which are often overlooked. We provide a set of criteria relevant to assess the socioeconomic performance of RESfuels from a capacity building perspective. These concepts can provide the foundations for a variety of models of considerable scope and power. The qualitative examination of the RESfuels enterprises presented in this report allows for analysis and comparison of existing institutional structures and design of alternatives that show promise of superior performance in the actual situation as it exists. Nevertheless, the methodology can be further developed to overcome the aforementioned limitations. The more we can learn about the way in which firms actually behave, how they learn and their impacts in the socioeconomic environment, the more we will be able to understand the processes of evolutionary change that involve many interacting firms in the particular selection environments of RESfuels (Nelson & Winter, 1982). At the same time, it seems likely that in comparison to traditional analysis, our approach would sound more sensible and be more accessible to other participants in the policy discussion.

10.1.2. Implications for policy making

Our approach on capacity development provides an essential background for a more directly policy-oriented exploration of RESfuel value chains and enterprises. The market uptake of RESfuels requires major policy efforts, inter alia, in terms of regulatory compliance and support. The case studies discussed in this report provide “first-hand” evidence on how multi-actor engagement, investments in knowledge exchange and learning can enhance performance and promote capacity development not only for the enterprise itself but also for the surrounding socioeconomic environment. Further development of RESfuel technologies can ignite further research on the topic which can serve for human resource development and to improve processes that can enhance the market roll out of advanced fuels. The report delivers insights and evidence that point towards positive impacts in the socioeconomic environment of actors and communities involved in RESfuels supply chain activities, and that can be used to assess the sustainability of RESfuels. The findings also indicate that in some of the analysed cases there is still significant potential and need to improve the alignment of strategies of actors especially in the production domain and the consumption domain. This has a limiting effect on capacity, which could be overcome by developing more inclusive business models for the sector. Finally, the replicability, transparency, cumulativeness and circularity of RESfuel enterprises could be influenced positively by focusing on building more social capacity with RESfuel production activities.

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This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement N.º764799.

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Supplementary material

A1 Excel based GHG calculation tool

An Excel based GHG calculation tool is made to show the calculated GHG footprint of advanced biofuel production systems (feedstock + conversion combinations) in a transparent way. This tool is an adapted version of the existing Harmonised Greenhouse Gas Calculations for biofuels and bioliquids (BioGrace I) and Harmonised Greenhouse Gas Calculations for Electricity Heating and Cooling (BioGrace II). We used a similar layout to allow for comparison between the results of conventional biofuel systems and advanced biofuel systems. The Biograce tools can be found at the website: www.biograce.net. The presented Excel tool is exclusively developed to explore the calculations and results that are presented in ADVANCEFUEL D4.5, but not intended to conduct harmonised emission GHG calculations for verification purposes under requirements of the European Union. For these applications, we kindly refer to the original BioGrace I and BioGrace II Tools.

The tool is available on request per e-mail to the authors of this report:

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- Ivan Vera: i.c.veraconcha@uu.nl

A2 Percentage of utilized land in the EU for the RED II land criteria pathways

- Figure 13 Percentage of utilized land in the EU for the RED II land criteria criteria pathway in 2030. RZ = Road Zero scenario, TB = Transport Bio scenario
- Figure 14 Percentage of utilized land in the EU for the RED II + land criteria criteria pathway in 2030. RZ = Road Zero scenario, TB = Transport Bio scenario
- Figure 15 Percentage of utilized land in the EU for the RED II land criteria criteria pathway in 2040. RZ = Road Zero scenario, TB = Transport Bio scenario
- Figure 16 Percentage of utilized land in the EU for the RED II + land criteria criteria pathway in 2040. RZ = Road Zero scenario, TB = Transport Bio scenario
- Figure 17 Percentage of utilized land in the EU for the RED II land criteria criteria pathway in 2050. RZ = Road Zero scenario, TB = Transport Bio scenario
- Figure 18 Percentage of utilized land in the EU for the RED II land criteria criteria pathway in 2050. RZ = Road Zero scenario, TB = Transport Bio scenario

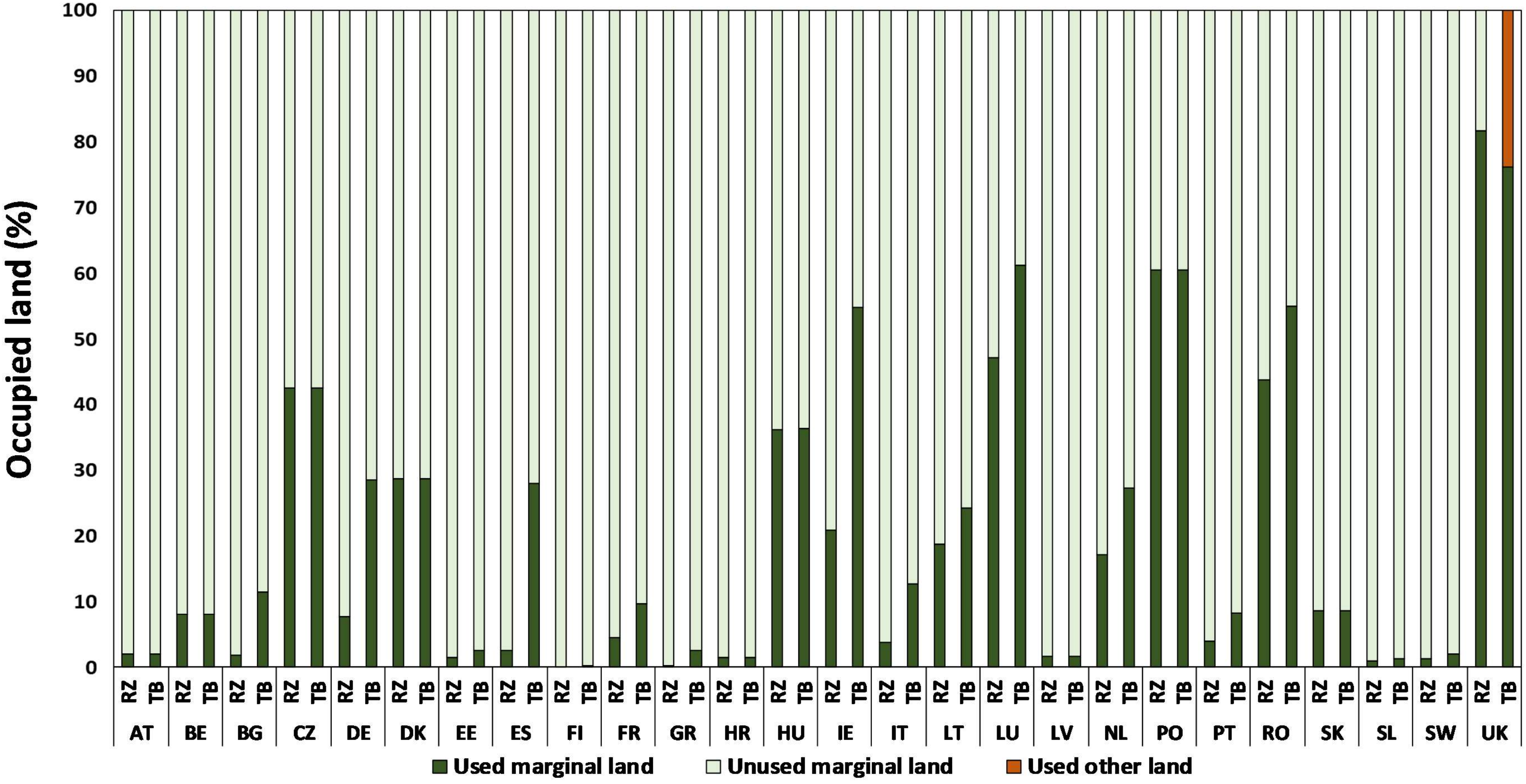

Figure 13 Percentage of utilized land in the EU for the RED II land criteria criteria pathway in 2030. RZ = Road Zero scenario, TB = Transport Bio scenario

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N.°764799.

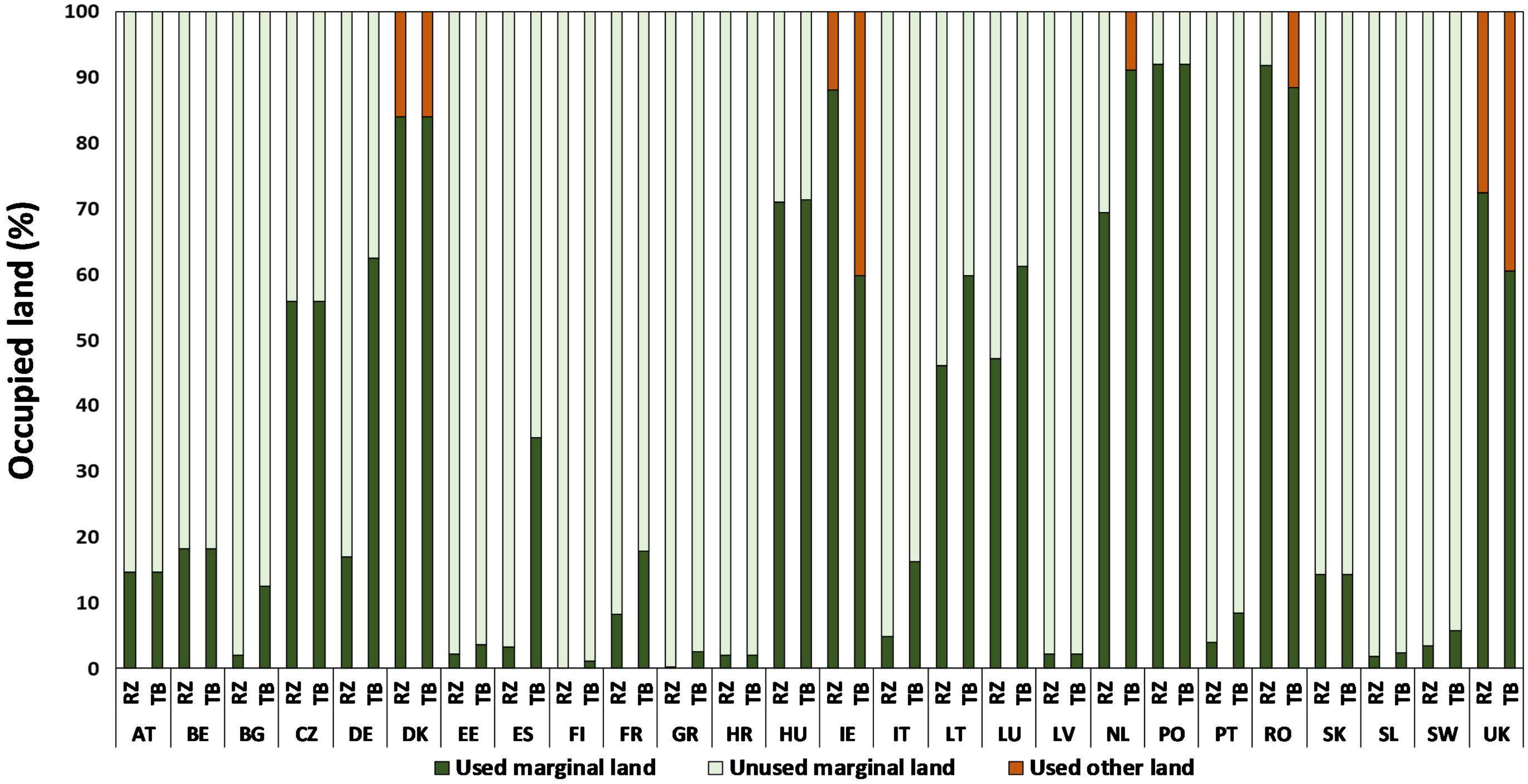

Figure 14 Percentage of utilized land in the EU for the RED II + land criteria criteria pathway in 2030. RZ = Road Zero scenario, TB = Transport Bio scenario

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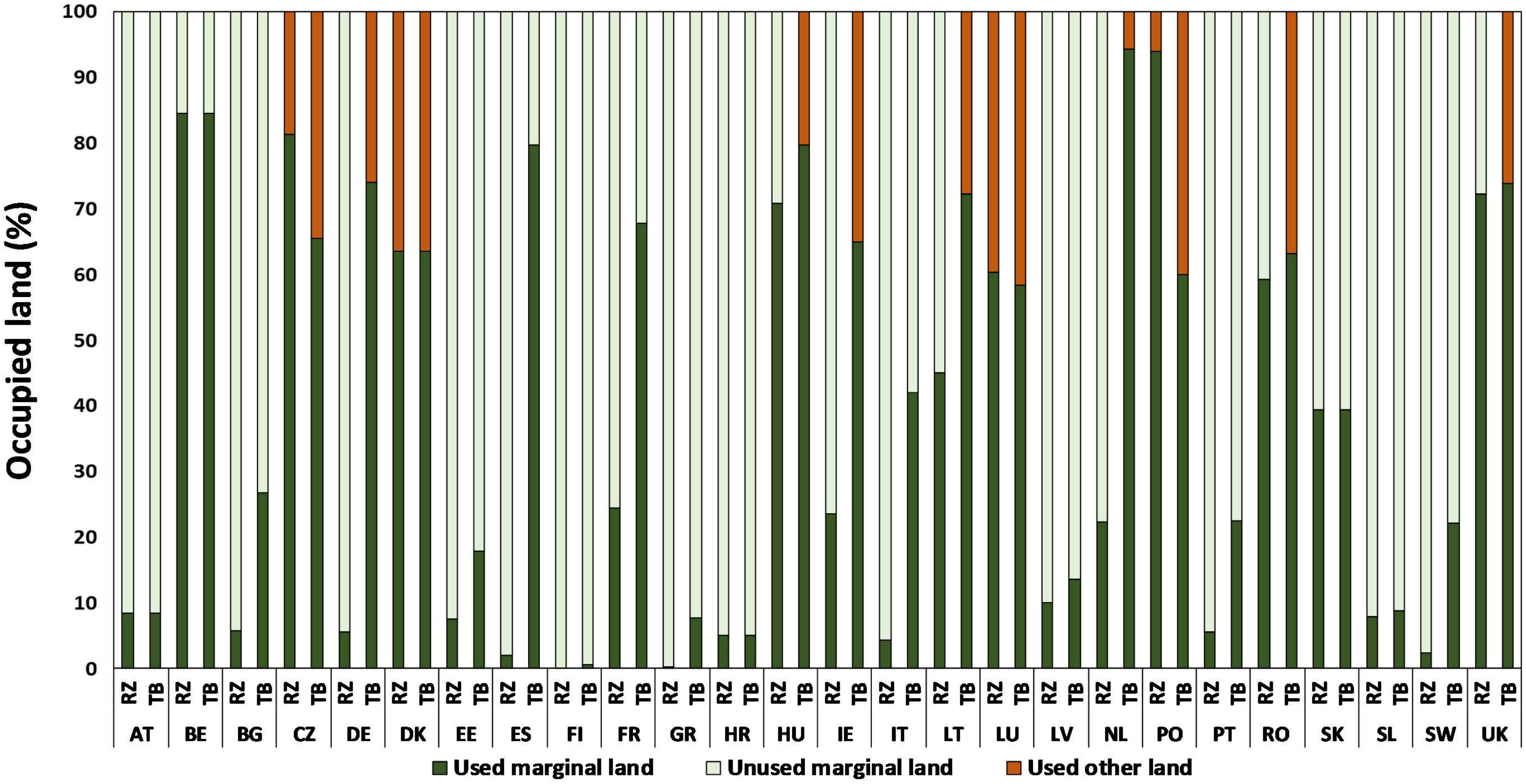

Figure 15 Percentage of utilized land in the EU for the RED II land criteria criteria pathway in 2040. RZ = Road Zero scenario, TB = Transport Bio scenario

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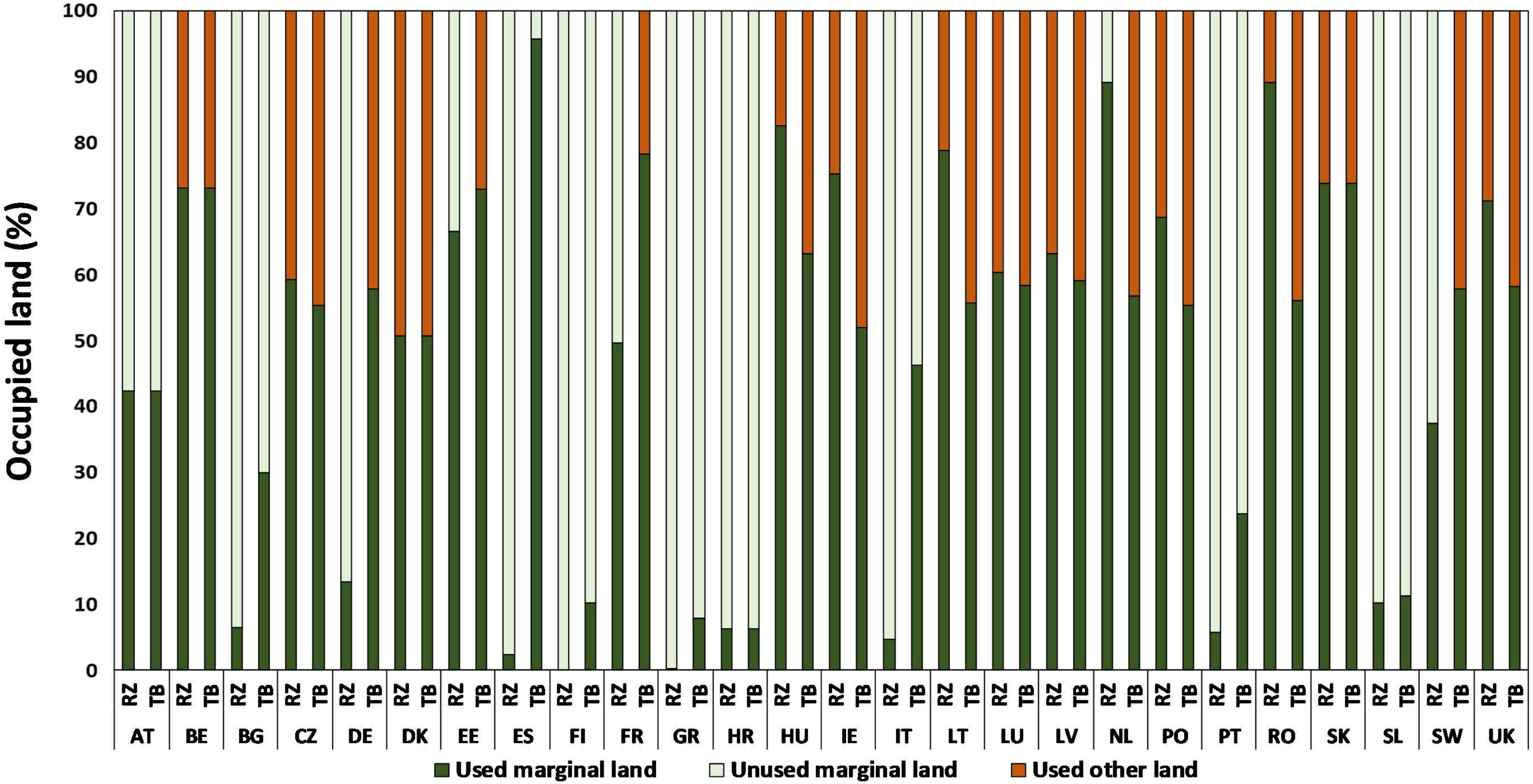

Figure 16 Percentage of utilized land in the EU for the RED II + land criteria criteria pathway in 2040. RZ = Road Zero scenario, TB = Transport Bio scenario

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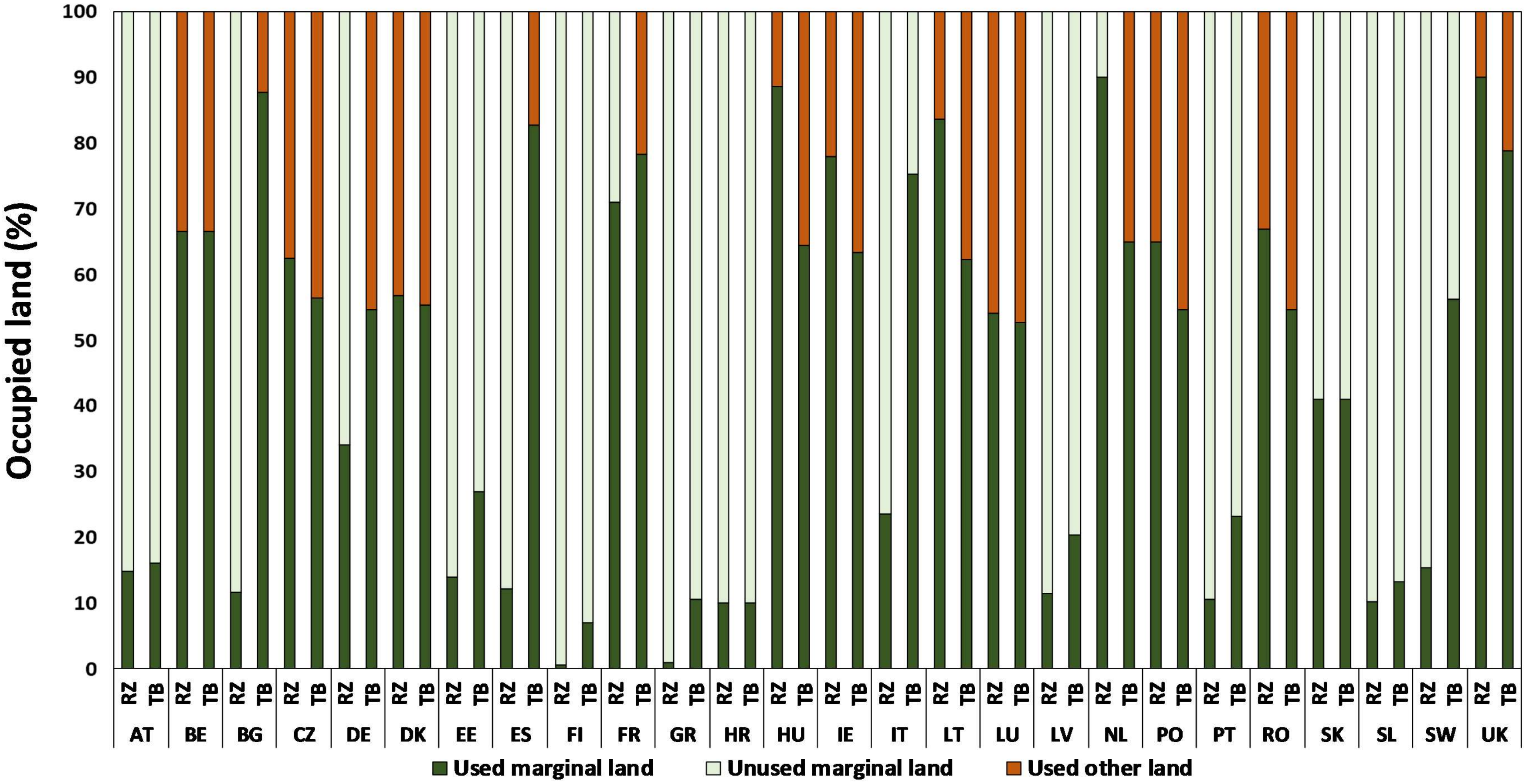

Figure 17 Percentage of utilized land in the EU for the RED II land criteria criteria pathway in 2050. RZ = Road Zero scenario, TB = Transport Bio scenario

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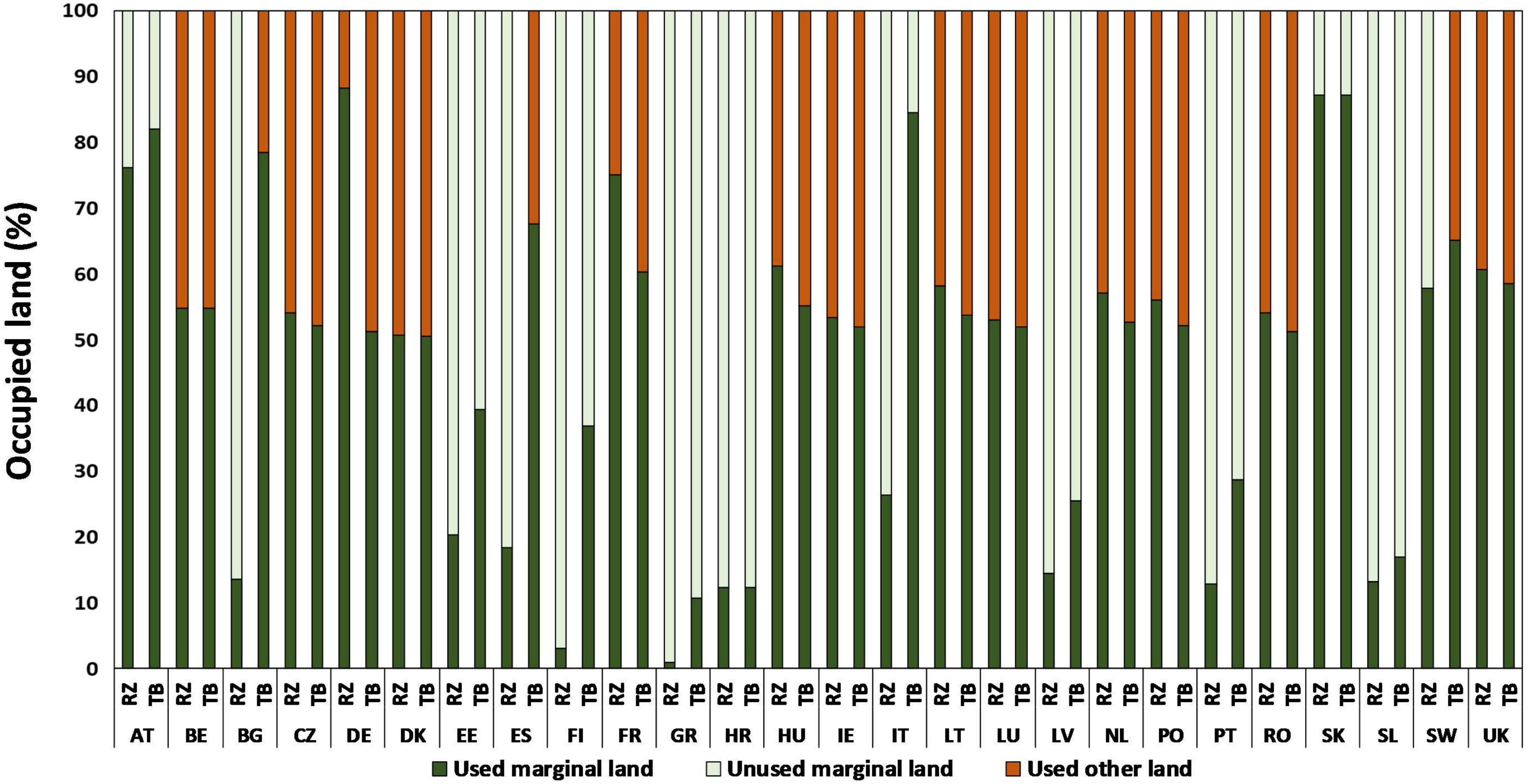

Figure 18 Percentage of utilized land in the EU for the RED II land criteria criteria pathway in 2050. RZ = Road Zero scenario, TB = Transport Bio scenario

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A3 Capacity Building Questionnaire for RESfuel biorefineries

This questionnaire aims to collect information in order to better understand the requirements for capacity building of companies in the advanced biofuel sector. Hereby, the criteria we are interested in are related to the success parameters: Processes, cooperation, strategies, learning processes, and the steering structure.

1. **Strategy**

Strategic action always involves a careful examination of the relationship between resources and end use. With these questions we want to understand how companies define strategies and goals with their partners. A strategy is an agreement between key partners that enables them to combine their efforts and steer them in the same direction. It motivates the actors to pursue the desired objectives.

1.1. Does your company aim to scale-up its second generation biofuel activities in the future?
1.2. What challenges do you expect when scaling up?
1.3. Who will be responsible for the upscaling process?
1.4. What alternative plans are in place should certain risks materialise?
1.5. How well does the selection of agreed outputs correspond to the results that are to be achieved?

2. **Cooperation**

The next step of the survey aims to assess who and how the company works together with internal and external partners.

2.1. How would you describe your experience with your cooperation partners?
2.2. How would you describe the communication among the partnership? Are regular meeting and intensive communication efforts taking place?
2.3. What capacities (human and financial resources) do your partners have in place that are needed for second generation biofuel production? To what extent are those partnerships crucial for the success of second generation biofuel?
2.4. Which strategically important resources would it be worthwhile for the project to acquire?
2.5. On what type of contracts are your cooperations build on?

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3. Steering Structure

In the next chapter we would like to identify your experiences with the existing steering options. Steering refers to task negotiations and the associated hierarchies. Who is responsible for annual planning and the respective sub-goals and who is the executive body? And who is responsible for the distribution of general information, detailed information, consultation before decision-making, participates in decision-making, is responsible for decision-making?

3.1. How are decisions reached e.g. when it comes to the annual planning of the company?
3.2. What role do the other partners take in decision-making processes? For instance, are decisions collectively taken?
3.3. Is somebody (external?) consulted?
3.4. How is information shared?
3.5. Is the steering structure appropriate to the diversity of the tasks to be undertaken, and the risks involved?

4. Processes

In the next step we want to understand the processes which take place in your company. Therefore, we want to collect the different supply chain steps (biomass production/ harvest & conditioning/ transport/ pre-treatment & storage/ biomass further processing/ biomass transport/ energy conversion) and identify the responsible key partner(s). The process selection includes a structured negotiation about which processes should be handled and how. This is absolutely necessary to ensure the acceptance and sustainability of the changed processes.

4.1. Are the responsible partners for each supply chain step well defined?
4.2. What capacities do the partners need to have (knowledge/physical infrastructure) for the respective supply chain step?
4.3. What are the critical events/bottlenecks in the respective supply chain step?
4.4. How well do the key processes for achieving the desired objectives within the project/programme work? Are some processes redundant?

5. Learning and innovation

The following questions are intended to describe forms and design possibilities of learning and innovation processes.

5.1. What learning goals have been formulated?

5.2. How have lessons learned been processed and documented?

5.3. How do you actively obtain creative input from your environment?

5.4. How do you succeed in translating these innovations into structures and processes?

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