Deliverable report

Deliverable No:	D5.4
Dissemination level:	Public (PU)
Title:	Comparison of BtL drop-in biofuels with transport fuels

Date:	11/04/2022
Version:	FINAL
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Grant Agreement Number:	817612
Project Type:	H2020-LC-SC3-RES-21-2018-development of next generation biofuels and alternative renewable fuel technologies for road transport
Project acronym:	REDIFUEL
Project title:	Robust and Efficient processes and technologies for Drop In renewable FUELs for road transport
Project start date:	01/10/2018
Project website:	www.redifuel.eu
Technical coordination	FEV (DE) (www.fev.com)
Project management	Uniresearch (NL) (http://www.uniresearch.com)

Executive Summary

The overall goal of the REDIFUEL project was to enable biomass utilization for renewable EN590 diesel biofuel production sustainably, and one of the project's objectives was to perform a socio-economic and environmental viability performance check of the developed process based on available standards, accepted and validated approaches for Well-to-Wheel (WTW) calculations.

This deliverable presents the Life Cycle Assessment (LCA) of REDIFUEL blends by the quantification of the socio-economic and environmental impacts from biomass extraction (well) to final use in a truck (wheel). This evaluation required a comprehensive inventory of all relevant energy flows and emissions created. The mass- and energy balance constructed in the techno-economic assessment was complemented with literature data to construct a complete WTW Life Cycle Inventory (LCI) of driving a 40-ton truck fuelled with various REDIFUEL blends. In addition, LCIs for trucks fuelled with fossil diesel, biodiesel, and hydrogen from several sources were built for comparison. Various LCA methods were applied to obtain a total of 18 indicators, among which climate change, human health, water consumption, and land use.

The use of fuel blends consisting of 93% REDIFUEL and 7% used cooking oil methyl ester (UCOME) led to a 45-56% decrease in climate change impact compared to fossil diesel. The fuel blends also complied with the Renewable Energy Directive (RED II) targets for greenhouse gases emission savings for renewable fuels. In addition to a reduction in climate change impact, the REDIFUEL drop-in renewable fuel blends lead to a reduction in fossil resources depletion (-43% to -52%), ozone depletion (-59% to -61%), and air pollution-related impacts, i.e. photochemical oxidant formation (-4% to -9%), particulate matter formation (0% to -9%), and terrestrial acidification (-10% to -16%).

There are also several risks related to the production and use of REDIFUEL blends. The human toxicity impact was similar fossil diesel (-4% to +1% difference), but the freshwater ecotoxicity (+5% to + 45%), freshwater eutrophication (+11% to +92%), ionising radiation (21% to +106%), marine ecotoxicity (+4% to + 40%), marine eutrophication (+1% to +240%), metal depletion (+3% to +25%), and water consumption (+21% to 59%) impacts increased.

In conclusion, a mixed picture was found for the REDIFUEL blends. They have a high potential for reducing climate change, ozone depletion and air pollution, but there are also risks of increasing toxicity and water consumption impacts. Limiting Rh catalyst leakage in the hydroformylation step and the plant's electricity consumption is key to reducing these impacts. The pilot plant's electricity consumption, in particular, proved to be an important contributor to several indicators, including climate change. Reducing the electricity consumption, switching to more renewable electricity sources, and on-site electricity generation from excess steam can improve the plant's overall performance.

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1 Introduction

This deliverable is part of Work Package 5, task 5.5: socio-economic assessment and Life Cycle Assessment (LCA). It contributes to the overall project goal of producing renewable fuels sustainably. The objective of task 5.5 was to evaluate the life cycle of REDIFUEL from biomass extraction to final use in a truck and assess to what extent it contributes to human health impacts, environmental impacts and resource depletion.

This objective has been achieved. Chapter 2 describes how a complete well-to-wheel Life Cycle Inventory (LCI) of driving a 40-ton truck fuelled with various REDIFUEL blends was conducted and analysed with a total of 18 socio-economic and environmental indicators, among which climate change, human toxicity, metal depletion, water consumption, and land use. The results in chapter 3 show various opportunities and challenges related to the production and use of the biofuel blends developed and evaluated during the REDIFUEL project. Finally, recommendations were made to exploit the opportunities, such as a high climate change mitigation potential while minimising the potential risks.

As the proposed REDIFUEL blends are not on the market yet, the assessment in this deliverable is done for the year 2030. This prospective approach requires assumptions regarding the future, which are inherently uncertain. Therefore, the results are only valid for the developed prospective scenarios and the target year.

As the objective of this deliverable is to give recommendations for the exploitation of the specific project results, the decision context of this LCA study is on the micro-level. This means that the results can identify opportunities for improvement on the process level or compare specific fuels or fuel blends. But macro-scale changes in the background system are not considered. This means that the results of this deliverable cannot be used to answer questions like: "which quantity of greenhouse gas (GHG) emissions can be avoided if all trucks in the EU are running on blend A" or "what is the effect of using 10% of all forestry residues for the production of blend B".

2 Methods

2.1 INTRODUCTION TO LIFE CYCLE ASSESSMENT

The analysis of the environmental sustainability of REDIFUEL in this deliverable follows the Life Cycle Assessment (LCA) methodology, which will be shortly introduced here. LCA is an approach to quantify the environmental impacts of a system. In addition, it can serve to identify opportunities to improve a product system or choose between alternative product systems. The principles and framework of LCA are presented in the standards ISO 14040:2006 (ISO, 2006a) and ISO 14044:2006 (ISO, 2006b). In addition, the ILCD Handbook (EC, 2010), built upon these standards, was used for the practical implementation and reporting format of this deliverable's REDIFUEL LCA.

An LCA comprises four iterative phases (Figure 1). First, the goal and scope definition determine the level of detail and the system boundaries, depending on the intended application of the LCA. In this phase, the assumptions on which the study will be based are explained, and a functional unit is chosen. The functional unit is the quantification basis to which all inputs and outputs are linked. It assures that the results are comparable by function. For example, the functional unit for biofuels could be one MJ of fuel based on lower heating value, a km of vehicle movement or a kWh of electricity produced, depending on the application.

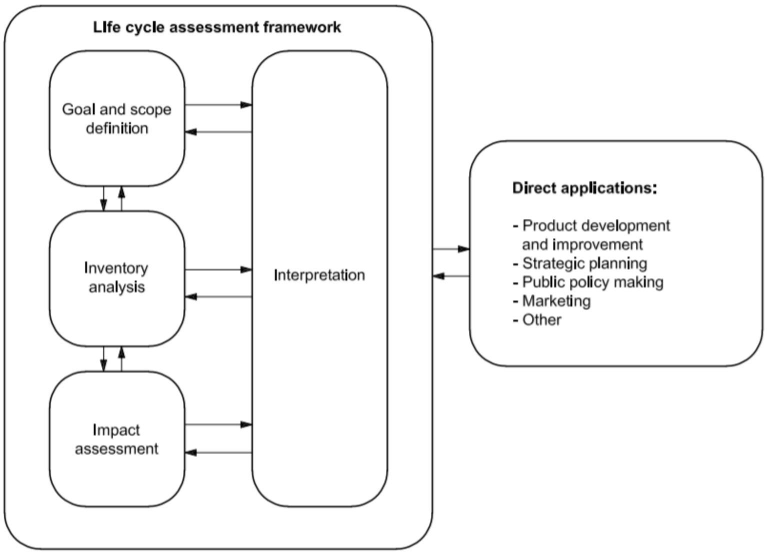

Figure 1: Different stages of an LCA and its application. Source: ISO (2006a)

The second phase is the Life Cycle Inventory (LCI) compilation. In this phase, all inputs and outputs of the system boundaries are collected and quantified, according to the detailed requirements and assumptions set in the earlier stage.

The third phase, the life cycle impact assessment (LCIA), translates LCI data into environmental impact categories based on characterization models. An example of an impact category related to biofuels is global warming potential, expressed in g CO_2 equivalent. The appropriate characterization model would convert all greenhouse gasses (GHG) to this unit using the IPCC conversion factors (IPCC, 2013).

The last phase is interpretation. In this phase, the results obtained can lead to changes in the scope of the study, the identification of the need to complement the LCI with more reliable data or to change the number of studied impact categories. Thus, each iterative step will increase the accuracy of the LCA result while consuming more time and effort.

2.2 GOAL AND SCOPE DEFINITION

The goal of this LCA is to identify the environmental opportunities and challenges of the production and use of the biofuel blends developed and evaluated during the REDIFUEL project. The opportunities and challenges of a fuel are best understood compared to other fuels. Hence, another objective is to compare the REDIFUEL blends to other drivetrain and fuel alternatives suitable for long-haul trips that are currently commercially available or may be available in the future. The results will be used to recommend future possibilities for exploiting the project outcomes.

2.2.1 FUNCTIONAL UNITS

To assess the combined effect of the production and use of the developed renewable fuel blends (Table 1), the functional unit of this LCA study is 1 ton-km displacement of goods, with a 40t gross weight heavy-duty truck and a 8.8-ton payload on a long-haul driving cycle with a range of 800 km simulated with VECTO (EC, 2019).

2.2.2 SCENARIO MODELLING FRAMEWORK

A REDIFUEL plant is assumed to be introduced to the market by 2030, and the assessment was done for this year. Three feedstock types have been selected for this assessment: bark chips and willow chips for biofuel production and CO_2 for e-fuel production. An average European scenario was defined (Table 1) for each fuel blend.

In 2020, 96.5% of the newly sold heavy-duty trucks (HDT) were conventional diesel trucks (ACEA, 2020). Even if the sales share of alternatively fuelled trucks increases in the coming years, the large majority of the HDT fleet will still consist of conventional diesel trucks in 2030. As it is likely that fossil diesel (B0) remains the main fuel, the use of this fuel as a reference was also added as a scenario. Tasks 3.4 and 3.5 provided the input for the fuel consumption and the tailpipe emissions for the REDIFUEL blends and fossil diesel only (B0). Therefore, B0 was selected instead of the blend with up to 7% biodiesel (B7), often found at the pump.

Biodiesel is the most important biofuel in the European Union (EU), and it represents 62.3% of the EU biofuel supply (EEA, 2019). It can be produced from various feedstocks, and the principal feedstocks used in the EU are wastes (42%) and rapeseed oil (38%) (Flach et al., 2019). Therefore, a scenario was added with trucks running on used cooking oil methyl ester (UCOME) as a proxy for all wastes, and another with trucks running on rapeseed oil methyl ester (RME). These scenarios are also a good proxy for HVO produced from the same feedstocks (JEC, 2020; Puricelli et al., 2021).

Two scenarios were added with a fuel cell electric truck (FCET), starting from the same energy carriers as the REDIFUEL blends: bark chips and hydrogen from electrolysis, allowing for a comparison of the better use of feedstocks between

REDIFUEL production or hydrogen production for transport services Other alternative fuel infrastructures exist for heavy-duty vehicles. For example, trucks running on LNG were excluded from the comparison due to data limitations. Catenary and battery electric trucks usually have good energetic and environmental performance compared to other options (Booto et al., 2021; Mojtaba Lajevardi et al., 2019; Sen et al., 2017), but these options are not considered suitable for long-haul application by 2030 (van Grinsven et al., 2021). Consequently, these options were not considered for the comparison.

Table 1: Explanation of scenario codes used in this deliverable. ICEV-d = internal combustion engine vehicle (diesel), FCEV = fuel cell electric vehicle.

Scenario code	Fuel	Drivetrain
B0	Fossil diesel	ICEV-d
RF40B060	40% REDIFUEL (from bark chips) + 60% B0	ICEV-d
RF93UCOME7-Bark	93% REDIFUEL (from bark chips) + 7% Used Cooking Oil Methyl Ester (UCOME)	ICEV-d
RF93UCOME7-SRC	93% REDIFUEL (from willow chips) + 7% UCOME	ICEV-d
RF93UCOME7-CCU	93% REDIFUEL (from CO_2 and H_2) + 7% UCOME	ICEV-d
UCOME	100% UCOME	ICEV-d
RME	100% Rapeseed oil Methyl Ester (RME)	ICEV-d
H2-BM	Hydrogen from bark chips gasification	FCEV
H2-EL	Hydrogen from electrolysis	FCEV

An explorative scenario approach was taken (Börjeson et al., 2006), i.e., a best-case and worst-case were defined for each situation. The best-case is when strong mitigation policies are effectively implemented and the global average surface temperature rise is limited to 1.5 °C. The worst-case refers to a situation where the implementation of climate change policies fails and the world evolves following current trends. The common assumptions for all scenarios from Table 1 are listed in Table 2, whereas the scenario-specific assumptions are given in section 2.3.

Table 2: Common assumptions for all scenarios of the worst-case and best-case

	Worst-case	Best-case
Climate change policy	Implementation of climate change policies failed	In line with 1.5 ° C target
Drivetrain	Current technology	Future technology

2.2.3 SYSTEM BOUNDARIES AND PROCESS DESCRIPTION

The system boundaries of all scenarios are well-to-wheel (Figure 2), which means that all life cycle phases from feedstock generation to the final use in the truck are included. For the pathways that include REDIFUEL, the process details are specified in **Error! Reference source not found.**.

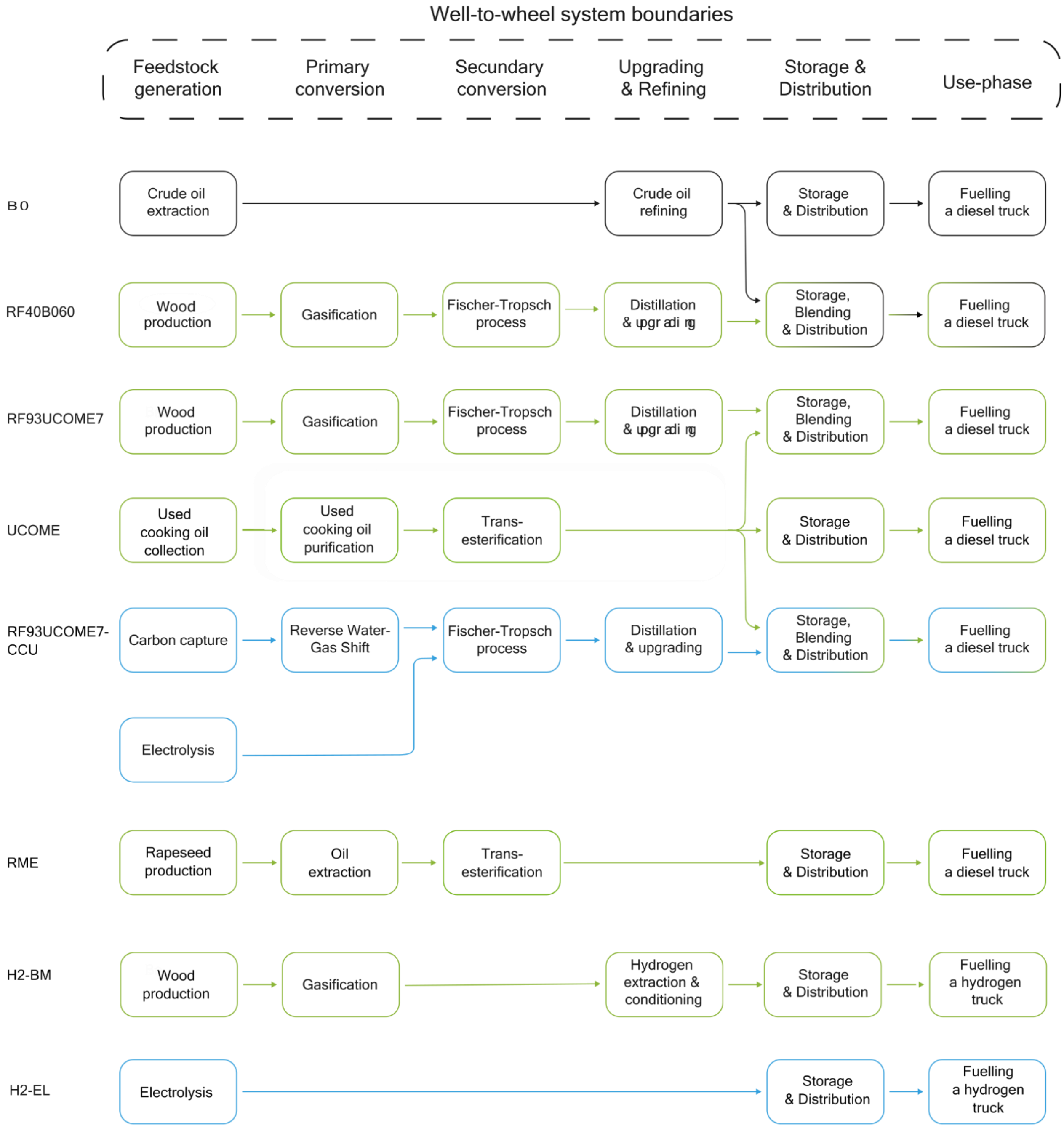

Figure 2: Well-to-wheel system boundaries of each scenario. Black pathway = fossil fuel, green pathway = biofuel, blue pathway = electro-fuel

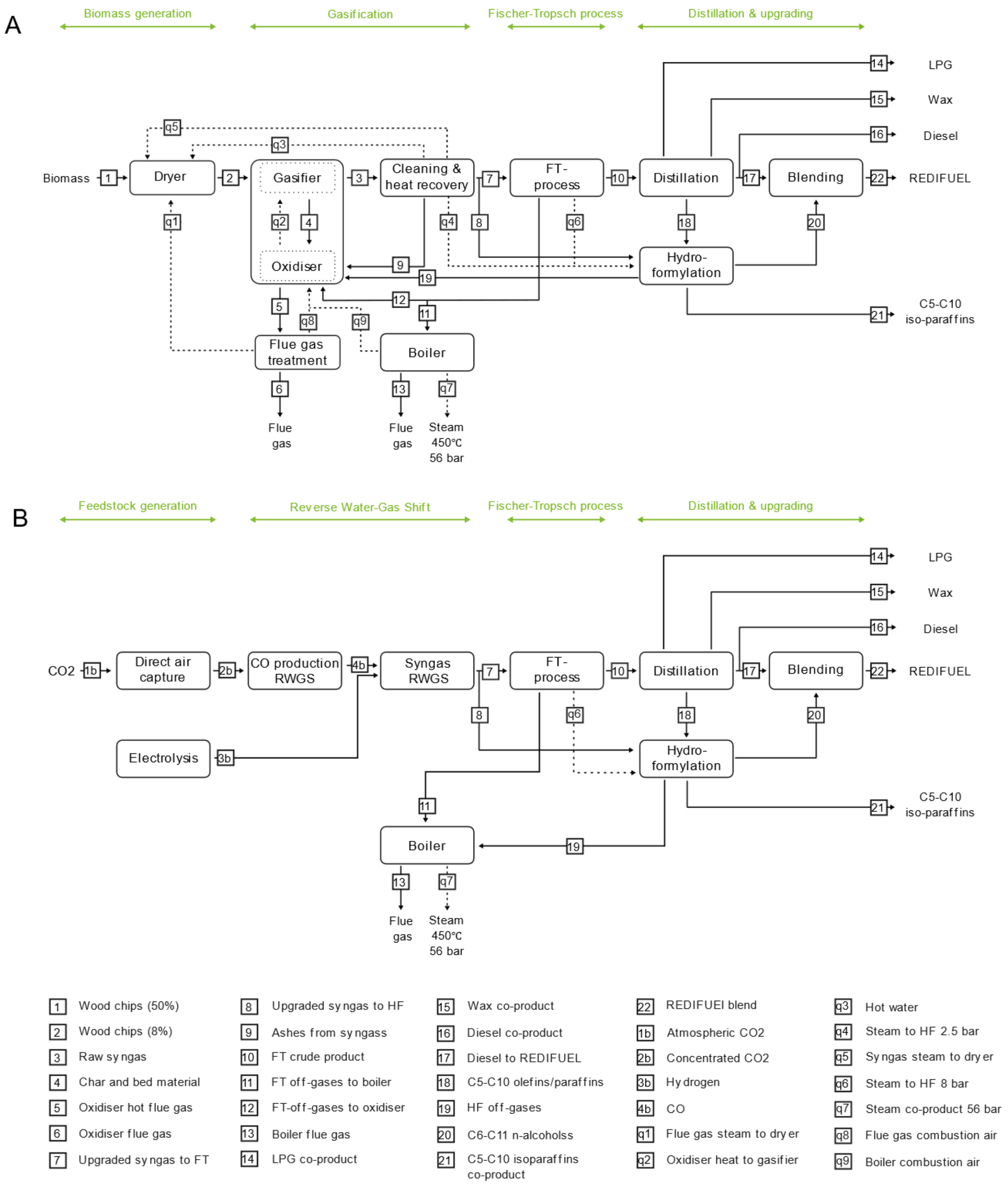

Figure 3: REDIFUEL process description. The green arrows indicate the corresponding life cycle phases in Figure 2.

Part A represents the REDIFUEL process with biomass gasification, as developed in the project.

Figure B represents a hypothetical future adaptation of the REDIFUEL process, with direct air capture of CO_2 and electrolysis.

2.2.4 LCI MODELLING FRAMEWORK

An attributional modelling approach is taken since it is assumed that the production of REDIFUEL does not induce macro-scale system consequences, such as increasing the demand for biomass or changing the diesel market mix in the future economy. Consequently, the foreground and background systems are modelled with average data, as advised by the International Reference Life Cycle Data System (EC, 2010).

The assumptions for the foreground model regarding allocation and recycling were based on the Ecoinvent cut-off system model (Wernet et al., 2016), which distinguishes between allocatable products, recyclable materials and wastes. Allocatable products carry part of their production burden based on their economic value. Recyclable materials do not have economic value, but they can serve as a resource and interest for their collection. Their generation is solely allocated to the primary user, and their collection and recycling process is allocated to the secondary user. Wastes have no economic value and the producer must pay for their collection and disposal. The burdens of the collection and disposal are therefore attributed to the primary producer.

Several co-products generated within the system boundaries are assumed to be sold. For example, neighbouring industries can use excess steam, C5-C10 iso-paraffins could go to the petrochemical industry. Various industries could directly use waxes (cosmetics, adhesives, candle making, etc.) or it could be hydrocracked and sold as a fuel. The specific use and economic value of each of these co-products in the future are uncertain. This variation complicates the use of economic allocation for solving multifunctionality consistently. As all products will have the function of an energy carrier, allocation based on energy content (HHV) was the selected method for solving multifunctionality.

2.3 LIFE CYCLE INVENTORY

A superstructure background database was created with the python library premise (Sacchi et al., 2021b). This database is a prospective transformation of the Ecoinvent 3.7 cut-off database, using output from the integrated assessment model (IAM) REMIND (Kriegler et al., 2017; Riahi et al., 2017; Rogelj et al., 2018). Inventories for the construction, the maintenance, and the use-phase of 40t trucks on a long-haul cycle running on diesel, biodiesel, and hydrogen were generated with the python library carculator_truck (Sacchi et al., 2021a) and added to the superstructure database. The selected scenarios for the superstructure database were REMIND-base (no climate policy) and REMIND-pkbudg900 (1.5 °C climate target) and the target year was 2030. From now on, these superstructure scenarios will be referred to as "worst-case "and "best-case ". The foreground models of scenarios B0, UCOME, RME, H2-BM, and H2-EL were entirely derived from the superstructure database.

One manual change to the superstructure database was made. The European electrolysis production activity ("hydrogen, gaseous, 25 bar, from electrolysis, RER") was initially linked with the European electricity market mix. In the adapted superstructure database used in this report, the European electrolysis activity uses a mix of dedicated renewables and curtailed electricity, as projected by the European Network of Transmission System Operators for gas and electricity (ENTSO-E and ENTSO-G, 2020).

The data for the foreground models of the REDIFUEL blends was generated during the REDIFUEL project and gathered from the different project partners. The compilation of the foreground LCIs (Appendix A) of scenarios RF40B060, RF93UCOME7, and RF93UCOME7-CCU is described in sections 2.3.1 to 2.3.6.

2.3.1 BIOMASS PRODUCTION

Two biomass types have been considered: the industrial residue bark and short rotation coppice (SRC), grown for energy generation. The impact of bark generation was modelled with an average European market mix for bark chips taken from the ecoinvent database version 3.7 (Wernet et al., 2016). It was assumed the transport distance from the sawmill to the Redifuel plant was 100 km.

The moisture content and chemical composition of the Finnish bark used in the project were obtained from VTT (Appendix A). It was further assumed that the average European bark has the same composition as the Finnish bark used in the project. The higher heating value of the bark was calculated with the harmonized equation from (Channiwala and Parikh, 2002), whereas the lower heating value was obtained from VTT. The bark is an allocatable product and the ecoinvent database uses economic allocation to partition the forestry and sawmill impacts between the bark and stem wood. The bark's value per kg is lower than the stem wood's value per kg. Consequently, the bark bears only the burden of a small part (13.5%) of its production processes. The rotation period was considered 100 years, which corresponds to a GWPbio value of 0.44 (Guest et al., 2013). This value aligns with the GWPbio value for bioenergy from European forests (Cherubini et al., 2016). Multiplying the bark's economic allocation factor of 0.135 and the GWPbio of 0.44, a combined GWP for bark of 0.06 was obtained (GWP for fossil CO_2 is 1).

The bark chips arrive at the plant with a moisture content of 50% and are dried to a moisture content of 12% with a belt dryer. This process consumes electricity, air that is heated with hot water that is recovered from the syngas cleaning section, and steam that is recovered from syngas and flue gas cooling. No impact is attributed to the consumption of air or heat generated at the plant.

For SRC, a german production process of willow chips was selected. In contrast to bark, the SRC wood is not a by-product and carries all the burdens of the plantation production and harvesting processes. A rotation period of three years was assumed, corresponding to a GWPbio value of 0.012. It was assumed that the composition of willow wood is similar to bark and it does not significantly change the energy consumption for drying or the gasification process.

2.3.2 CARBON CAPTURE & ELECTROLYSIS

The syngas production process was taken from (Van Der Giesen et al., 2014) and adapted by (Sacchi et al., 2021b). The CO/H2 ratio was adapted to match the REDIFUEL syngas composition. It was assumed that the electricity consumed in all processes (direct carbon capture, electrolysis, CO production via RWGS, and syngas production via RWGS in Figure 3) is derived from renewable sources. The National Trends scenario from ENTSO-E and ENTSO-G (2020) was selected for the worst-case, and the Distributed Energy scenario, which corresponds to a 1.5 °C climate target, was selected to model the best-case. The main difference between the two scenarios is that, in the best-case, there are dedicated renewables installed for power-to-x purposes, particularly offshore wind turbines. In the worst-case only curtailed renewable electricity is available for power-to-x, mainly onshore wind.

2.3.3 GASIFICATION

Gasification occurs in a Dual Fluidised-Bed gasifier (consisting of a gasifier and an oxidiser). Bed material is exchanged with the oxidiser as a heat carrier. The gasifier is heated with steam recovered during syngas cooling and flue gas cooling.

The oxidiser is fed with various streams from the plant (flows 4, 9, 12, and 19 in Figure 3): the char and bed material from the gasifier, the fly ashes that are separated from the raw syngas, and the off-gases from the downstream Fischer-Tropsch (FT) and Hydroformylation (HF) units.

The flue gas from the oxidiser is filtered to separate the remaining fly ashes, which are wastes. In the worst-case, the fly ashes are landfilled, while they are used for landfarming in the best-case.

A particulate filter removes ashes and char from syngas. All ashes are returned to the oxidiser for further combustion. Nitrogen gas is used to regenerate the filter. Then the syngas goes through a reformer with a nickel catalyst and is cooled (with heat recovery). In the worst-case, the lifetime of the nickel catalyst is three years, while in the best-case it is assumed that regular regeneration with excess steam from the plant can double the lifetime to six years. An acid/water scrubber removes ammonia and the traces of chlorine. The wastewater is discarded. Sulphur is removed with activated carbon beds and ZnO-based polishing. Finally, syngas is compressed and CO_2 is partially removed with a pressurized water scrubber.

2.3.4 FISCHER-TROPSCH PROCESS AND FT-CATALYST PRODUCTION

The FT-process converts syngas into crude FT oil. Part of the FT off-gases is burnt in the oxidiser, while the remaining part is combusted in an auxiliary boiler for steam generation. FT-reactor cooling generates additional steam that is used at the hydroformylation step.

The catalyst loading in the FT-reactor was calculated by dividing the syngas feed to the reactor by the weight hourly space velocity (WHSV), which expresses the weight of feed syngas per unit weight of the catalyst per hour. The worst-case WHSV (5 h^{-1}) and the best-case WHSV (33 h^{-1}) were derived from the lab-scale experiments (Jeske et al., 2021).

The production of the novel FT catalyst developed in the REDIFUEL project was modelled based on mass and energy balances from lab-scale experiments provided by CSIC, and the upscaling was done following the framework of Piccinno et al. (2016). The manufacturing steps are pre-calcination of pseudo-boehmite, impregnation, calcination, and activation (Figure 4). It was assumed that at commercial-scale production of the catalyst, the pre-calcination, calcination and activation steps occur in a rotary kiln, and the impregnation in a 1000l rotor-stator type homogenizer (Piccinno et al., 2016), followed by membrane filtration.

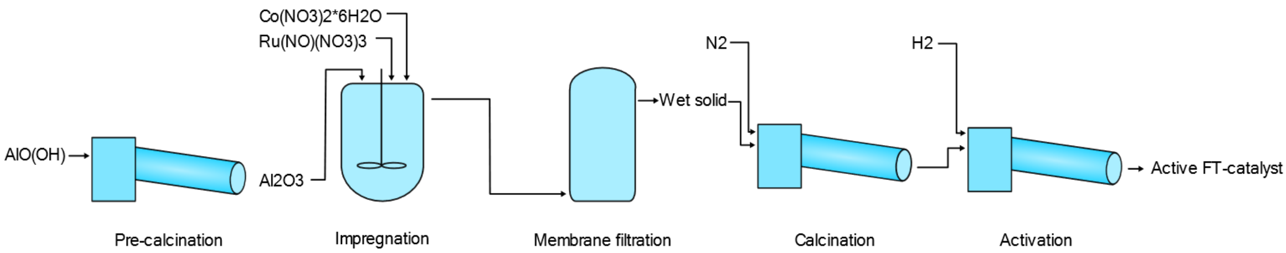

Figure 4: Flow chart of the industrial FT-catalyst production process

The fuel for the rotary kiln was assumed to be natural gas (Hofius et al., 1999), and the heat demand of the lab-scale oven was taken as a conservative estimation of the commercial-scale rotary kiln. The stirring electrical energy required for the impregnation step in the rotor-stator type homogenizer was calculated as suggested by Piccinno et al. (2016):

$$E_{stir} = \frac{N_p * \rho_{mix} * N^3 * d^5 * t}{\eta_{stir}} \quad \text{(Eq. 1)}$$

N_p is a dimensionless number (2.39), ρ_{mix} is the density of the aqueous mixture (925 kg/m^3), N is the rotational speed of the rotor (48.333 s-1), d is the impeller diameter (0.139 m), t is the stirring time (10800 s) and η_{stir} is the agitator efficiency (90%).

The filtration electrical energy demand was 10 kWh/ton wet solid filtered (Piccinno et al., 2016).

The consumables are psheudo-boehmite (AlO(OH)), Cobalt (II) nitrate hexahydrate ($Co(NO_3)2*6H_2O$), and Ruthenium (III) nitrosylnitrate ($Ru(NO)(NO_3)_3$), nitrogen and hydrogen (Figure 4). It was assumed that the quantities of the reactants do not differ between the lab-scale and commercial-scale processes (Piccinno et al., 2016).

The pseudo-boehmite is a co-product of the Ziegler process for fatty acid alcohol production (Diblitz et al., 1998). Background data for the Ziegler process was taken from the superstructure database. It is assumed that 1 molecule of Aluminium is required to produce 1 molecule of C12 fatty acid alcohol, yielding 1 molecule of Aluminium oxide. Recent 3-month average prices for C12-C14 fatty acid alcohols (ChemAnalyst, 2021) and alumina (ISE, 2021) were taken as a basis for allocation.

Background data regarding the production of the other reactants ($Co(NO_3)_2*6H_2O$ and $Ru(NO)(NO_3)_3$) was not available. The Co(NO3)2*6H2O can be supplied by recycling of spent FT-catalyst with a recovery rate of 97.75%, as described in patent No. PCT/CN2013/072119 (Liu et al., 2014). Additional $Co(NO_3)_2$*6H2O is supplied from the market to make up for the non-recovered Co. The overall molecular formulas were derived from Yildiz (2017) to model the mass balance of the production processes.

$$3Co + 8\ HNO_3 + 14\ H_2O \rightarrow 3Co(NO_3)_2*6H_2O + 2NO \quad \text{(Eq.2)}$$

The datasets for the reactants in Eq. 2 were taken from the superstructure database (originally from Ecoinvent). For the production process of $Ru(NO)(NO_3)_3$, The overall mass-balance for $Ru(NO)(NO_3)_3$ production was derived from Fletcher et al. (1959):

$$Ru + 4HNO_3 \rightarrow Ru(NO)(NO_3)_3 + 2H_2O \quad \text{(Eq.3)}$$

No dataset for the production of Ruthenium (Ru) was available. As Ru is a platinum group metal (PGM), the dataset for PGM mining and concentration operations was used, and economic allocation factors were derived from (Nuss and Eckelman, 2014). Not all Ru comes from virgin sources: 23% of the PGM supply consists of recycled material (Loferski et al., 2018), and it is assumed this is the case for Ru as well. The primary applications for Ru are electronics (44%) and catalysts (40%). The recycling processes are approximated with the recovery processes of platinum from electronic scrap and spent automobile catalysts.

The background data for nitrogen and hydrogen were derived from the superstructure database. In the worst-case, the hydrogen for the FT catalyst production process is produced via steam methane reforming and, in the best-case, via electrolysis. Data to model the FT catalyst's production plant's infrastructure was taken from the Ecoinvent database (Wernet et al., 2016), and linear scaling was applied to match the catalyst's production capacity (Piccinno et al., 2016). In addition, it was assumed that a DeNOx unit with a NOx removal efficiency of 90% (VITO, 2020) would be used at the FT catalyst production plant.

As the FT-catalyst's activity decreases over time, recycling or regeneration are required. In the worst-case, the FT-catalyst is assumed to be replaced and recycled after 2 years. As the recycling processes were already considered in the FT-catalyst production process, it is not considered again at the catalyst's end-of-life. In the best-case, ex-situ regeneration is assumed every 2 years, with a 100% regeneration (Rytter and Holmen, 2015). The regeneration steps include wax removal at high temperatures under a nitrogen flow, followed by hydrogenation and calcination/oxidation (Rytter and Holmen, 2015). No quantitative data on the material and energy requirements was available. Hence, it was assumed that the regeneration step consumes the same amount of nitrogen, hydrogen and energy as the activation and calcination step of the primary catalyst production.

2.3.4 DISTILLATION & UPGRADING

The crude FT-product coming from the FT-process is distilled to separate the wax fraction (C22+), the diesel fraction (middle distillate C11-C21), the C5-C10 olefins and the paraffin fraction, and the light fuel gas fraction (C3/C4). The C-C10 olefins/paraffins fraction goes to hydroformylation, producing C6-C11 n-alcohols for the REDIFUEL blend and C5-C10 iso-paraffins, which could be sold as a co-product as a renewable petrol substitute.

2.3.5 STORAGE, BLENDING & DISTRIBUTION

For all scenarios, the storage, blending & distribution were modelled with data from the superstructure database. It was assumed that REDIFUEL would be produced and consumed in Europe and that the storage and distribution impact would be similar to domestically produced biodiesel.

2.3.6 USE-PHASE

The use phase includes the construction of the road and the truck, the fuel consumption, and all direct use phase emissions. Direct use-phase emissions are exhaust emissions, brake and engine-wear emissions, and refrigerant leakage. All data was derived from carculator_truck. The CO_2 exhaust emission data was derived from D3.9 and D3.10 for existing engines (worst-case) and future engines (best-case), respectively. The CO, particulate matter and the hydrocarbon exhaust emissions for all trucks running on blends with REDIFUEL were derived from D3.7 for existing engines and D3.8 for future engines. All other exhaust emissions of blends with REDIFUEL were assumed to be the same as the fossil diesel reference (B0).

2.4 IMPACT CATEGORIES AND LCIA METHODS

For climate change, the latest global warming potential (GWP) values from the fifth assessment report were used (IPCC, 2013). For the scenarios using woody biomass as a feedstock (RF93UCOME7-bark, RF93UCOME7-SCR, and H2-BM) biogenic GWP values were derived from Guest et al. (2013) to assess the effect of the rotation period on the biofuel's climate change impact. The effect of varying the rotation period on the climate change impact was also tested in the sensitivity analysis.

The ReCiPe 2008 life cycle impact assessment method for midpoints was used (Goedkoop and Huijbregts, 2013) for all other impact categories:

- Fossil resource scarcity (kg oil eq)

- Stratospheric ozone depletion (kg CFC-11 eq to air)
- Ionizing radiation (kBq Co-60 eq to air)
- Fine particulate matter formation (kg PM2.5 to air)
- Photochemical ozone formation (kg NOx eq to air)
- Terrestrial acidification (kg SO2 eq to air)
- Freshwater eutrophication (kg P eq to freshwater)
- Human toxicity: cancer (kg 1,4-DCB eq to urban air)
- Human toxicity: non-cancer (kg 1,4-DCB eq to urban air)
- Terrestrial ecotoxicity (kg 1,4-DCB eq to industrial soil)
- Freshwater ecotoxicity (kg 1,4-DCB eq to freshwater)
- Marine ecotoxicity (kg 1,4 DCB eq to marine water)
- Water use (m3 water consumed)
- Mineral resource depletion (kg Cu eq)
- Agricultural land occupation (m^2-year)
- Urban land occupation (m^2-year)
- Natural land transformation (m^2-year)

3 Results

3.1 WELL-TO-WHEEL CLIMATE CHANGE IMPACT

The climate change impact of transport of goods with a 40t truck running on 100% renewable fuels is 45%-56% lower than if the truck is fuelled by fossil diesel, and 18%-22% if the truck is running on the blend with 40% REDIFUEL and 60% fossil diesel (Figure 1). For all scenarios, there is a 20%-40% difference between the worst-case and the best-case. This difference is caused by changes in the background data (e.g., the electricity mix, the engine efficiency, the steel production mix etc.) and, to a lesser extent, by changes in the foreground assumptions (Figure 6).

From scenarios with 100% renewable fuels, the trucks running on RME have the highest climate change impacts, and the trucks running on UCOME have the lowest impacts. Clearly, the feedstock affects the results much. The difference between scenario RF40B060 and RME is only 6%, even though the first still relies for 60% on fossil diesel and the latter scenario is a pure biofuel.

From the three fuel blends consisting of 93% REDIFUEL and 7% UCOME, the one with CO_2 captured from the atmosphere as a feedstock (RF93UCOME-CCU) has the lowest climate impact in the worst-case, but the improvement compared to the scenario with SRC is minor (0.005 kg CO_2eq/ton-km). In the best-case, these two scenarios have the same climate change mitigation potential.

The truck running on hydrogen from bark gasification (H2-BM) has a lower impact than the truck running on the REDIFUEL blend produced from the same feedstock (RF93UCOME7) in the worst-case, but the trend is inversed in the best-case. The same trend was observed when comparing H2-EL and RF93UCOME7-CCU. Thus, it is unclear whether hydrogen or REDIFUEL is better for climate change impacts of long-haul trucks, since it mainly depends on developments in the background energy system. In any case, the WTW difference between H2-BM and RF93UCOME7-bark, and between H2-EL and RF93UCOME7-CCU is small, and the potential higher savings obtained by H2-BM may not outweigh the higher costs and efforts required for the hydrogen infrastructure.

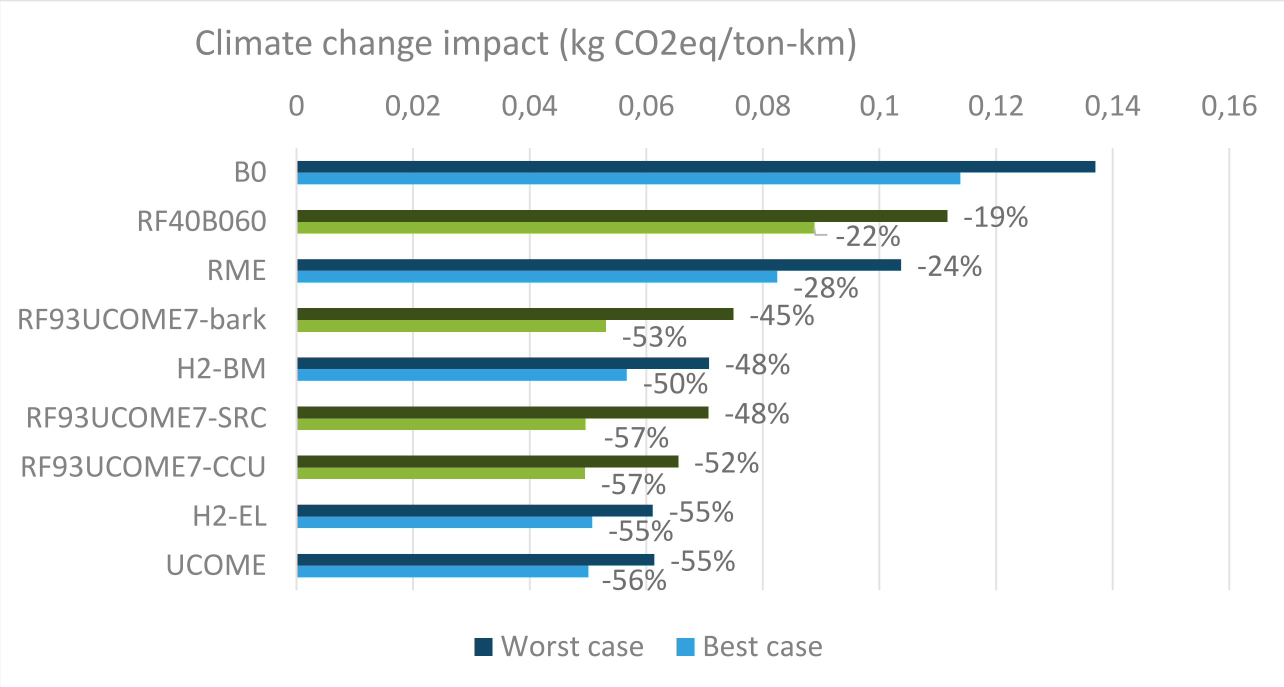

Figure 5: Well-to-wheel climate change impacts of transport of goods by a 40t gross weight truck with 8.8 t payload fuelled by various fuels in 2030 in kg CO2eq/ton-km. The green scenarios are REDIFUEL blends. Percentages indicate the impact reduction compared to the fossil fuel reference (B0).

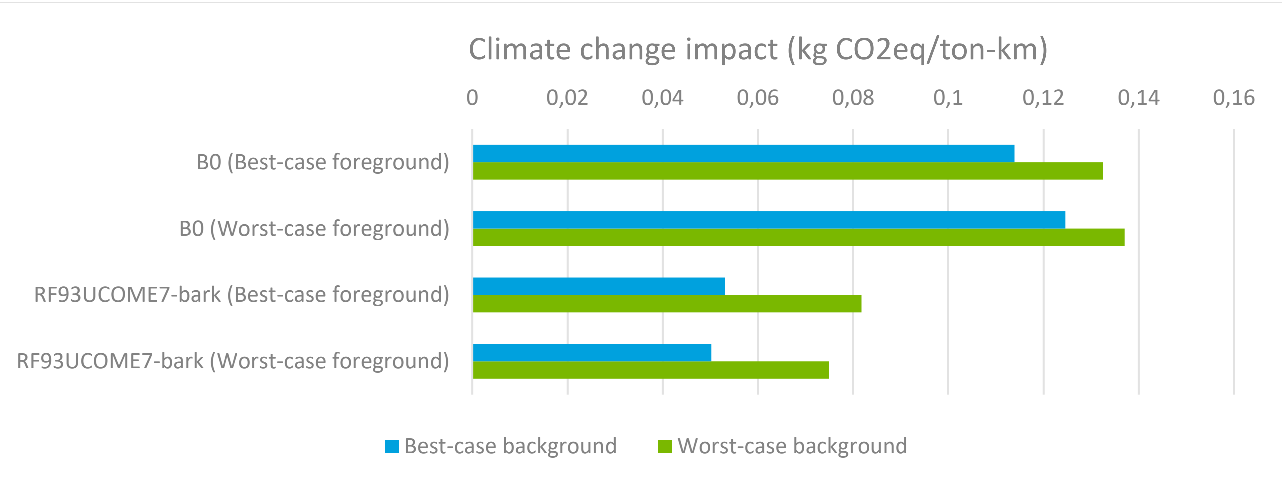

Figure 6: The effect of the worst-case and the best-case assumptions of the background and the foreground on the climate change impacts of B0 and RF93UCOME7.

The impact reductions in Figure 5 may seem unsatisfactory (50% reduction for scenarios with 100% renewable fuels), but the disaggregated results (Figure 7) show that the road and the truck life cycle are an important part of the WTW impacts: from 36% for the B0 scenario to 87% for the H2-EL scenario. Further reduction from a WTW perspective can be obtained when the payload increases. The current payload of 8.8 ton represents 35% of the maximum theoretical payload (ACEA, 2015). This percentage accounts for empty return trips and the fact that trucks cannot always be filled at maximum payload capacity (Sacchi et al., 2021b). Improved logistics management could decrease the number and length of empty trips and increase the effective loading capacity.

For RME, a first generation biofuel, the fuel production impact is at least twice as big as for the other scenarios due to the agricultural activities to produce the feedstock.

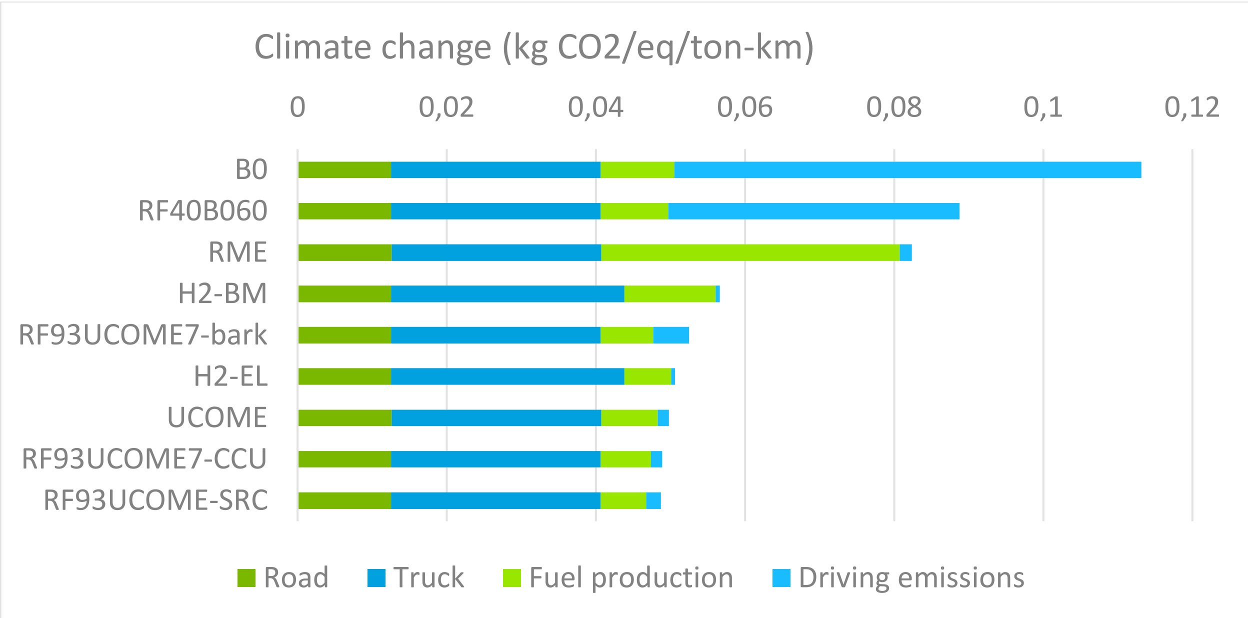

Figure 7: Disaggregated best-case well-to-wheel climate change impacts of transport of goods by a 40t gross weight truck with 8.8 t payload fuelled by various fuels in 2030 in kg CO2eq/ton-km.

3.2 WELL-TO-TANK CLIMATE CHANGE

The disaggregated results for the RF93UCOME7-bark scenario (Figure 8) illustrate that the main difference between the worst-case and the best-case is the contribution of electricity. The amount of electricity consumed throughout the life cycle is the same in both cases, but the climate change impact of the average European electricity grid mix is lower in the best-case, as ambitious climate policies lead to a more renewable energy system. Apart from the gasification and the syngas cleaning processes, none of the individual processes contribute to more than 5% of the total impact. In particular, the impacts of the life cycle of the FT catalyst, the plant infrastructure, and the feedstock production represent less than 1% of the total WTT impact in the worst- and the best-case. The impact of the gasification and the syngas cleaning is mainly caused by the biogenic CO_2 emissions in the flue gasses. This impact is feedstock depended. In general, biomass feedstocks with short rotation periods are more appropriate for bioenergy generation and decrease the climate change impact (Figure 9).

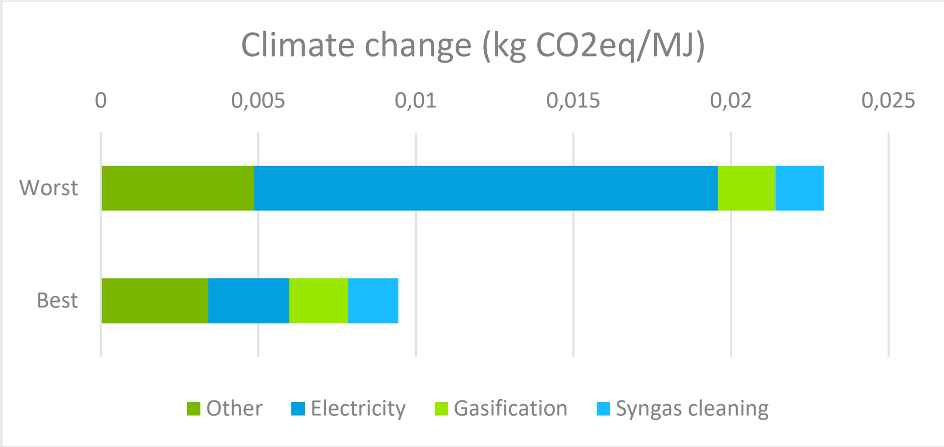

Figure 8: Well-to-Tank climate change impacts of transport of goods by a 40t gross weight truck with 8.8 t payload fuelled by RF93UCOME7-bark in 2030 in kg CO2eq/MJ. All processes contributing to less than 5% of the total impact are aggregated as "Other".

Figure 9: Well-to-tank climate change impacts of transport of goods by a 40t gross weight truck with 8.8 t payload fuelled by RF93UCOME7-bark in 2030 in kg CO2eq/MJ vs. the forest rotation period and the GWPbio from Guest et al. (2013)

When the lower heating value (LHV) is used as the allocation basis, instead of the higher heating value (HHV), the WTT climate change impact of RF93UCOME7-bark increases by 13% (Figure 10). When the estimated production cost of REDIFUEL (5.07 €/l) and the estimated revenues for the co-products (Annex 5.4) are used, the climate change impact increases by 228%, whereas the theoretically minimum production cost of REDIFUEL (0.9 €/l) based in increased revenues of the co-products leads to a 47% reduction compared to the base case. As the majority of the carbon output ends up in the co-products (78%), the climate change impact of the current REDIFUEL concept is very sensitive to the generated value of these co-products. In the worst-case, there are no WTW climate change benefits compared to scenario B0 when the value of REDIFUEL makes up 54% or more of the total value generated by the plant (Figure 11). In the best-case, there is still a 15% climate change impact reduction compared to B0 if REDIFUEL is the only valuable output of the plant.

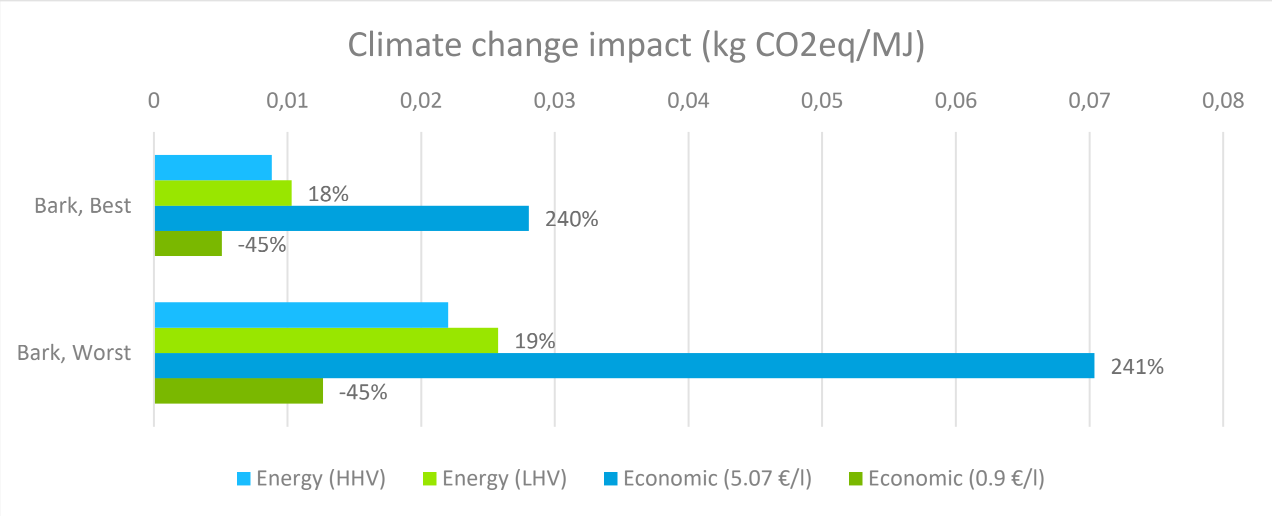

Figure 10: The effect of allocation method on the Well-to-Tank climate change impacts of transport of goods by a 40t gross weight truck with 8.8 t payload fuelled by RF93UCOME7-bark in 2030 in kg CO2eq/MJ. The percentages represent the deviation from the base case (HHV). HHV = higher heating value, LHV = lower heating value. The allocation factors for REDIFUEL are: 14.6% (HHV), 16.5% (LHV), 45.0% (5.07 €/l), and 8.0% (0.9 €/l).

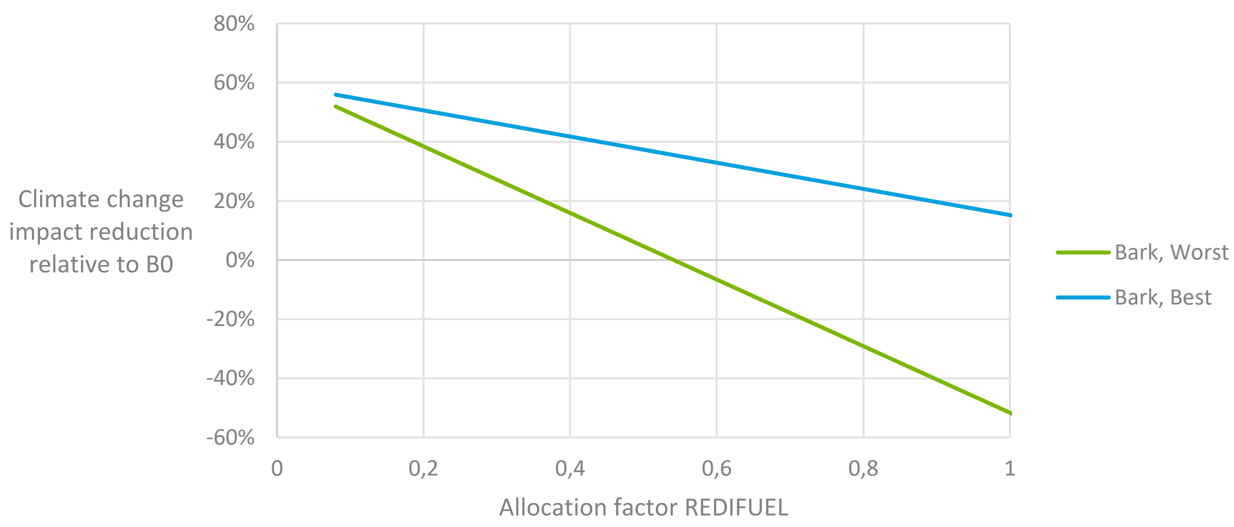

Figure 11: The WTW climate change impact reduction of RF93UCOME7-bark relative to B0.
An allocation factor of 1 represents the case were none of the co-products generate economic value.

3.3 SENSITIVITY ANALYSIS

The sensitivity of the climate change impact results of RF93UCOME7-bark to the carbon allocation factor of bark, the amount of electricity consumed at the REDIFUEL plant, and the feedstock transport distance from the forest to the REDIFUEL plant was tested (Figure 12). In the base case, 13.5% of the unbarked log value ends up in the bark (Wernet et al., 2016). When this ratio of the economic value of bark and stemwood would change by ± 10%, i.e., when the economic carbon allocation factor is varied by ±10%, the total impact is increased by ± 2% in the worst-case, and by ± 5% in the best-case. This result indicates that using feedstocks with little economic value and no competing uses is more appropriate for biofuel production. In line with Figure 8, the results are most sensitive to the electricity consumption in the worst-case (±5%) and half as sensitive (2.5%) in the best-case. The results are relatively insensitive to the transport distance of the feedstock to the REDIFUEL plant (< 0.5% difference in both cases).

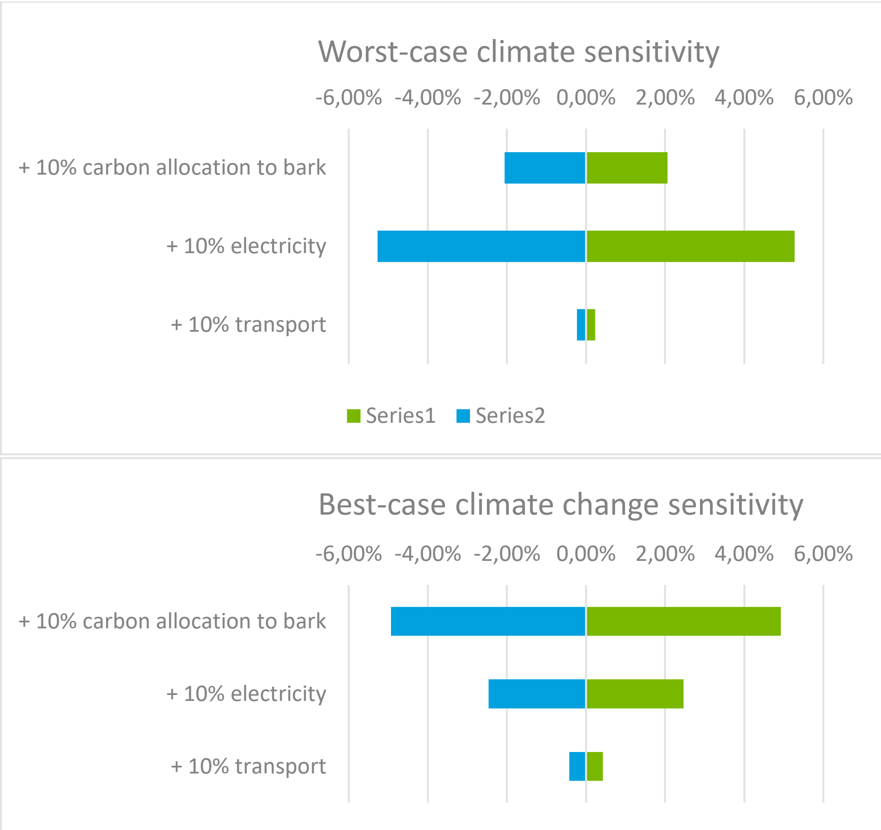

Figure 12: Sensitivity analysis on the WTT climate change impact impacts of transport of goods by a 40t gross weight truck with 8.8 t payload fuelled by RF93UCOME7-bark in 2030 in kg CO2eq/MJ.

3.4 RED II CLIMATE CHANGE

The renewable energy directive (RED II) has set minimum greenhouse gas savings for biofuels and renewable fuels from non-biological origin, such as e-fuels. For REDIFUEL to count towards the national minimum blending targets, it must lead to a minimum of 65% greenhouse gas emissions savings when produced from biomass, and 70% savings when produced from captured CO_2 ("Council directive 2018/2001/EU", 2018). In all cases, the RF93UCOME7 blends comply with these limits (Figure 13), even when the "petrol" fraction consisting of C5-C10 iso-paraffins and alcohols would not be valuable enough to count as a co-product.

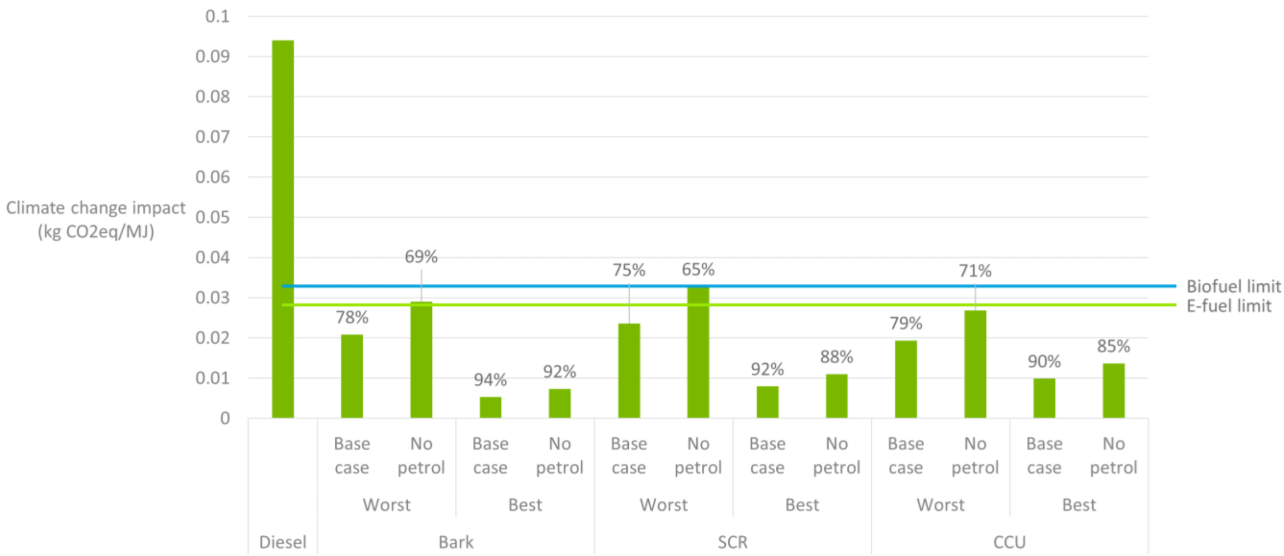

Figure 13: Climate change impact results for three RF93UCOME blend scenarios calculated according to the RED II methodology. The biofuel limit equals 65% greenhouse gas emission savings compared to diesel, and the e-fuel limit equals 70% greenhouse gas emission savings compared to diesel. In the base case, all co-products are accounted. In the "no petrol" case, only LPG, wax, diesel and steam are valuable as co-products.

3.5 OTHER IMPACTS

In addition to a reduction in climate change impact, the trucks running on 93% REDIFUEL blends lead to a reduction in fossil resource depletion, ozone depletion, particulate matter formation, photochemical oxidant formation, and terrestrial acidification (Figure 14). Apart from fossil resource depletion, these impacts are related to air pollution. The impact reductions compared to fossil diesel are all caused by the differences in the fuel production chain, while the differences in exhaust emissions are less influential (Appendix B). However, different RF93UCOME7 blends also lead to an increase in freshwater ecotoxicity, freshwater eutrophication, human toxicity, ionising radiation, marine ecotoxicity, marine eutrophication, metal depletion, terrestrial ecotoxicity, and water depletion. Processes in the REDIFUEL life cycle that contribute to freshwater marine, and terrestrial ecotoxicity are wastewater treatment and Rh leakage in hydroformylation. The higher impact for metal depletion is mainly caused by the Rh demand to make-up for the Rh leakage. The higher impacts on freshwater eutrophication, human toxicity, ionising radiation, and marine eutrophication are all directly related to the higher electricity consumption throughout the REDIFUEL life cycle.

The higher terrestrial ecotoxicity in the best-cases compared to the worst-cases is due to the use of wood ashes for landfarming in the best-case, instead of landfilling. The wood ashes may contain trace amounts of heavy metals that can affect plant growth, which is why the wood ash dosage to forest soils needs to be managed (Rodríguez et al., 2019). The impact of wood ash use for landfarming has a higher impact than landfilling because, in the latter, the heavy metals are contained in the landfill. However, this LCA does not capture all potential benefits of wood ash application to forests. For example, wood ashes replenish nutrient stocks in forests. When this effect is taken into account, the environmental impact of landfarming in nutrient-deficient forests is lower than the impact of landfilling (Gaudreault et al., 2020).

The scenario RF93UCOME7-SCR has a very high impact on marine eutrophication due to fertilizer use and high NOx emissions of agricultural machinery used for planting and harvesting activities at the willow plantation. Fertilization optimizes biomass production and, consequently, the farmer's revenues. But from an energetic point of view, the additional biomass does not always compensate for the energy required to produce the fertilizers (Djomo et al., 2019). Thus, SCR production without fertilizing would make sense for bioenergy generation, although it would require more land.

RF93UCOME7-CCU has higher freshwater ecotoxicity, human toxicity, marine ecotoxicity, and metal depletion impacts than RF93UCOME7-bark and RF93UCOME7-SCR. These impacts related to the metal mining and concentration processes required to construct renewable technologies (photovoltaic cells and wind turbines) required for the higher electricity demand for power-to-syngas production compared to gasification (60 MW vs. 4 MW).

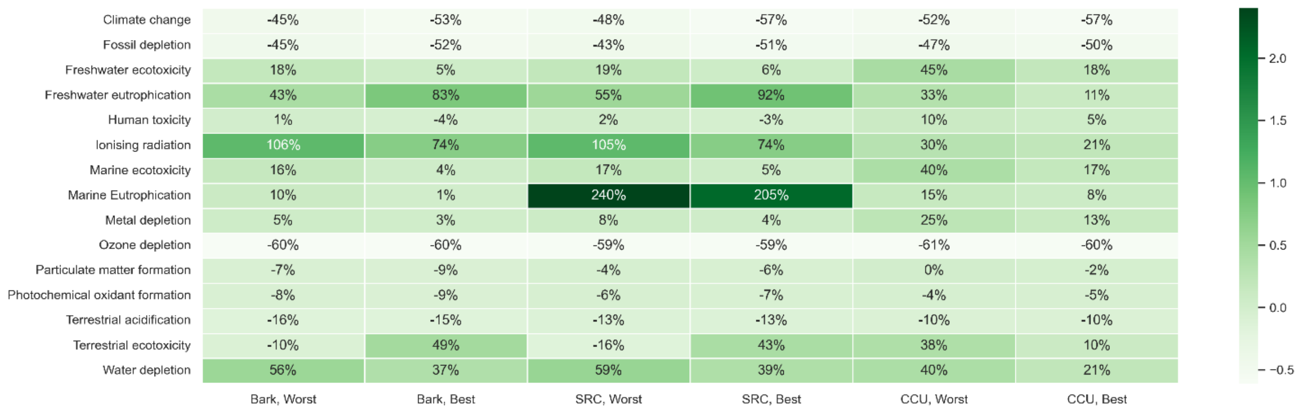

Figure 14: Well-to-wheel relative impacts of RF93UCOME7 blends compared to fossil diesel.
The percentages express the increase or decrease of the impact.

Considering the efficiency range (35% - 49%) of thermal power plants (Zhang, 2020), the excess steam could also be used to produce 4.4 – 6.2 MW, which is a 40% to 16% decrease to the current electricity consumption estimation. The effect of reducing energy consumption and displacing grid-electricity by on-site electricity generation to reach electric self-sufficiency on the environmental performance of RF93UCOME7-bark was tested (Figure 15). The overall picture is positive for the worst-case, and the climate change impact, fossil depletion, freshwater ecotoxicity, freshwater eutrophication, ionizing radiation, and ozone depletion impacts are reduced by 7% to 38%. All other impact categories change by less than 4%. In the best-case scenario, the impact of ionizing radiation is again reduced (-33%), but now the terrestrial ecotoxicity impact increases (16%). When excess steam is used for electricity generation, the REDIFUEL plant produces one co-product less. Consequently, a larger part of the REDIFUEL plant burdens is allocated to the REDIFUEL blend. The best-case is more sensitive to this change since the terrestrial ecotoxicity impact is higher (Figure 14).

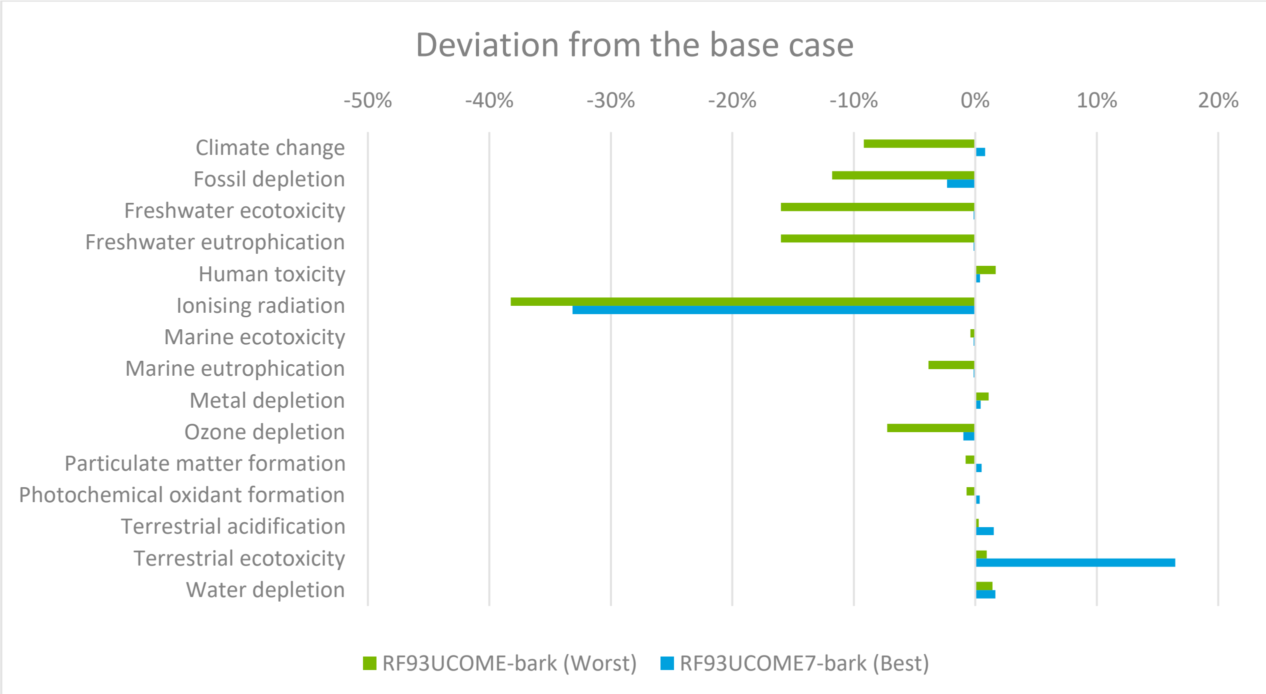

Figure 15: Deviation from the base case when excess steam is used for on-site electricity generation.

The water depletion impact of the RF93UCOME7 blends was 13%-25% lower than RME, and 6%-32% higher than UCOME (Figure 16). Except for RME, which has a high water depletion impact due to rapeseed irrigation, the RF93UCOME7 scenarios that are based on gasification consume more water during their life cycle than the other renewable fuel pathways. Only 4% of the WTT water consumption is related to direct water consumption at the REDIFUEL plant. The main contributor to the water consumption is the oxygen consumed in the reformer (58% of WTT impact), followed by electricity consumption (38%). Consequently, REDIFUEL's water footprint could decrease when the electricity consumption is reduced or when steam is used in the reformer instead of oxygen.

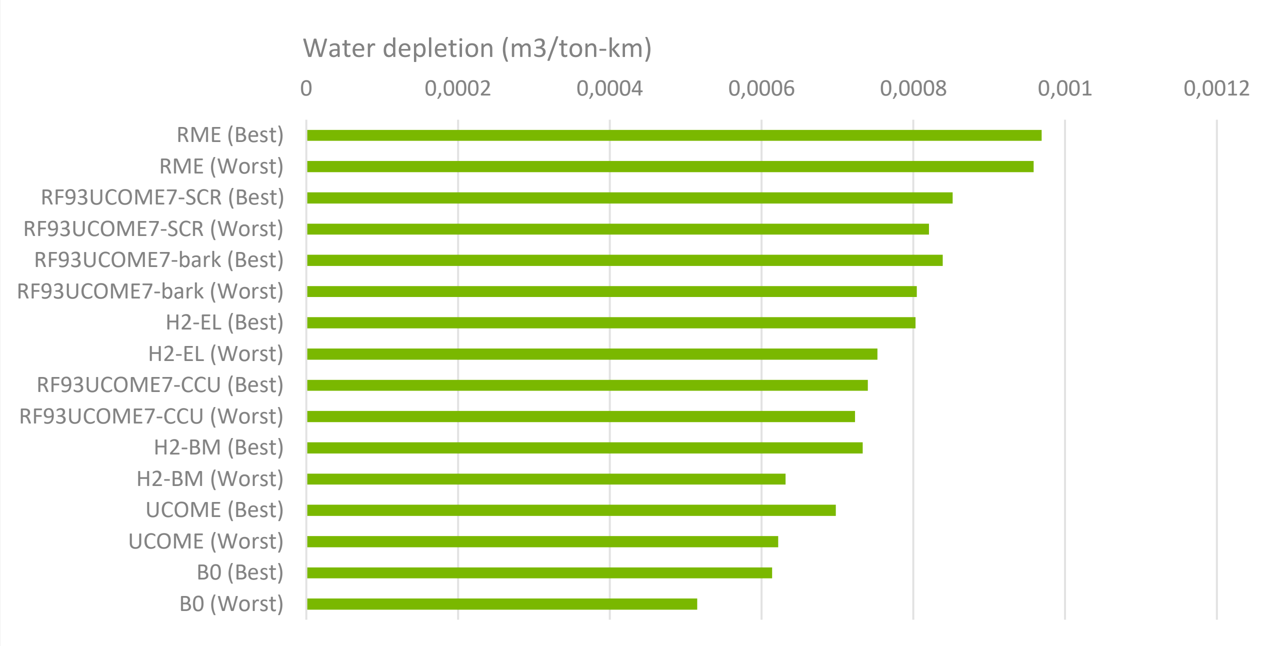

Figure 16: The Well-to-Wheel water depletion impact of all scenarios in m^3/ton-km.

The land use and land transformation impacts of all best-case scenarios are given in **Error! Reference source not found.**. Land use and land use transformation are considered good indicators for various ecosystem service and biodiversity impacts, such as climate regulation potential, biodiversity damage potential, biotic production potential, freshwater regulation potential, erosion potential, and water purification potential (Milà I Canals et al., 2013). Natural land transformation takes negative values, but the absolute quantities of natural land transformed in all scenarios are very small (0.1 -0.4% compared to land occupation). The urban land use is roughly the same for all trucks because the main contributor to this impact category is the road construction phase, which is the same in all scenarios. The agricultural land use of RME and the wood pathways (H2-BM, RF93UCOME-SCR, RF93UCOME-bark, RF40B060) stand out. Scenario H2-BM requires more bark chips than the REDIFUEL blends, due to the low hydrogen content (6.1%) of the dry bark. RME has the highest agricultural land use, since rapeseed productivity is lower than SRC productivity (Zurba and Matschullat, 2015). UCOME has the lowest agricultural land use of all biofuels because the feedstock is a waste and does not bear any burden of production.

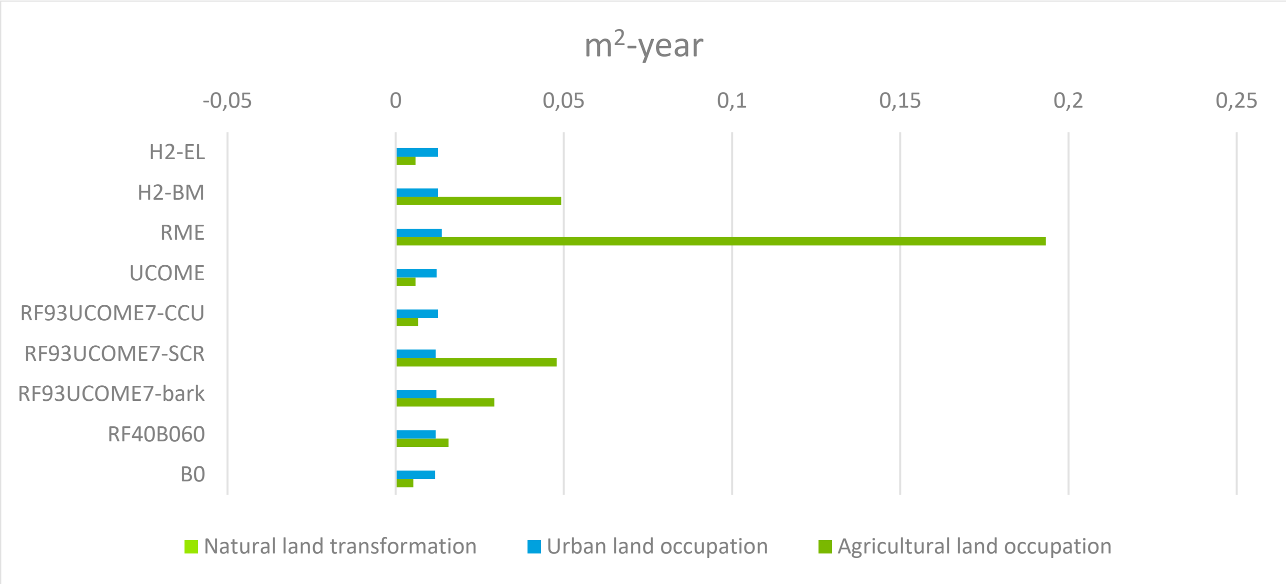

Figure 17: Well-to-wheel land use and transformation impacts of transport of goods by a 40t gross weight truck with 8.8 t payload fuelled by various fuels in 2030 in m^2-year.

4 Discussion and Conclusions

4.1 DISCUSSION

Three different feedstocks were assessed in this deliverable, but the results can be generalized to other feedstocks. The results for bark are valid for all industrial woody residues with similar economic value. The results for SCR are a good proxy for all non-edible bioenergy crops. The biodiesel scenarios (UCOME and RME) have shown the effect of using wastes and edible crops on a biofuels climate change impact. It can be expected that when wastes and edible crops would be used for REDIFUEL, similar trends would be observed: lower climate change impacts in the first case and higher climate and land use impacts in the latter.

In this LCA, all biogenic carbon dioxide emissions using bark and SCR were accounted for in the scenarios. The GWPbio for bark derived from Guest et al. (2013) was based on a rotation period of 100 years. This rotation period is a little higher than the average rotation period of 89-90 years for 235 forest units among 28 European countries found by Cardellini et al. (2018). The average found by Cardellini et al. (2018) does not include thinning, which may further lower the actual rotation period of the harvested wood. However, wood removal volumes during thinning are usually much lower than during regeneration felling and represent only 14% of the total wood volume removed within a rotation period (Cardellini et al., 2018). Therefore, it can be expected that the selected rotation period of 100 years is still a relevant estimate, albeit higher than average. The GWPbio value (0.44) of (Guest et al., 2013) corresponding to 100 years was in line with the GWPbio (0.45) of an average European forest calculated by Cherubini et al. (2016).

The geographic scope of this deliverable was the European Union, and average European data was used as far as possible. As feedstock type and forest management also affect the environmental impacts, the national availability and forest management practices will also determine the local environmental impact of the REDIFUEL plant. Thus, it can be expected that the environmental impact of a REDIFUEL plant would differ among the Member States. For example, Cherubini et al. (2016) give GWPbio values for each Member State of the EU at different forest residue extraction rates. At a 50% extraction rate, the GWPbio of the MS range between 0.41 (Malta) and 0.52 (Cyprus), which would decrease the WTT climate change impacts by -5% and + 10% compared to the average European value (Figure 9). The forest residue extraction rate may also differ among MS. For example, in Ireland, forest residues are left in the forest and at zero extraction, the GWPbio of Ireland is 0.39. On the other hand, the forest residue extraction rate of Sweden and Finland is rather high (72%) (Thiffault et al., 2015), and their GWPbio at this extraction rate is between 0.53-0.55.

The geographic scope also determines the electricity grid mix, which has proven important. The results of the worst-cases are a proxy for Member States with low penetration of renewables, while the best-cases represent Member States with high penetration of renewables.

Based on the obtained results, several recommendations on future exploitations of the project results can be made. The potential for GHG emissions savings of all REDIFUEL blends compared to fossil diesel is clear, and further development of the process can contribute to Europe's transition to a cleaner energy system. Nonetheless, the allocation methodology proved to have a big influence on the outcomes, in particular economic allocation. When the generated co-products represent less than 46% of the total generated value, the analysed REDIFUEL concept plant would not make sense anymore, since the use of the fuels would lead to very low GHG emissions savings (0%-15%)

compared to diesel. Future research should address this risk, for example, by further exploration of co-product valorisation options to increase co-product revenues.

Another road to ensuring the climate change mitigation potential of REDIFUEL is improving the FT catalyst performance to obtain higher CO conversion while retaining a high olefin selectivity. This would lead to a higher REDIFUEL output. Consequently, the REDIFUEL plant environmental burdens would be divided over a larger quantity of fuel, and the WTW impact of fuelling a truck with REDIFUEL blends would decrease.

The plant's electricity consumption proved to be an important contributor to the plant's overall environmental impact, particularly to climate change, freshwater eutrophication, human toxicity, ionising radiation, marine eutrophication, and water depletion impacts. Reducing electricity consumption may be possible with more efficient equipment, but changing the electricity source may be more feasible. Switching to a more renewable electricity source, like in the best-case, would lead to a higher climate change mitigation potential. If the future electricity mix still depends on fossil energy, like in the worst-case, the on-site generation of electricity with excess steam is also desirable from an environmental point of view. However, this would lead to additional costs, and additional techno-economic assessment are required to test to what extent this negatively affects the plant's economic feasibility.

The small Rh leakage (0.1%) in the hydroformylation step caused higher metal depletion and ecotoxicity impacts than fossil diesel. Monitoring and limiting this leakage as much as possible is important to ensure REDIFUEL's environmental performance and also the economic performance (the current Rh price ±500,000 €/kg (Umicore, 2022)). Contrary to the hydroformylation catalyst, the FT catalyst did not affect any of the investigated impact categories more than 1%, and its impact can be neglected

The transport distance of the feedstock to the plant did not affect the climate change impact much. Consequently, it can be concluded that it is not crucial to locate the plant near a forest. It is more important to locate the plant close to consumers of the various co-products to ensure their valorisation. Further upscaling the plant to obtain higher production capacities and better plant economics may also prove more interesting than having small-scale plants with short feedstock transportation distances.

The LCA presented in this report is based on a preliminary plant design. Future developments of the FT catalyst may lead to higher CO conversion and process efficiency. This would affect the LCA results in several ways. Less off-gases would be produced, and consequently, less flue gases from the boiler. A larger part of the biomass would end up in high value products, and less steam would be produced. In general, it can be expected that these changes would have a positive effect on all impact categories, since the burdens related to the plant would be shared by a larger amount of fuel. Consequently, the impact per unit of fuel would be lower. The results presented in this deliverable give a conservative first estimate of the future environmental performance of REDIFUEL. The general trends of the different variables that have been analyzed in this report, like the allocation factors, the forest rotation period and GWPbio, the electricity consumption, and the transport distance will remain valid.

The results presented in this deliverable were mainly focused on the burden shifts that occur when switching from fossil diesel to REDIFUEL blends in 2030, which was most relevant for the project objectives. Future work should address the full comparison of all relevant impact categories among all long haul truck alternatives, including also trucks running on LNG, and battery electric trucks in the long-term.

4.2 CONCLUSIONS

The environmental and socio-economic evaluation of various drop-in fuel blends containing REDIFUEL have been presented in this deliverable. Comparisons have been made with fossil diesel, biodiesel, and hydrogen from various sources. The WTW climate change impact of drop-in fuel blends consisting of 93% REDIFUEL and 7% UCOME is 45-56% lower than fossil diesel. The fuel blend consisting of 40% REDIFUEL and 60% fossil diesel leads to 19%-22% WTW GHG savings compared to fossil diesel.

All REDIFUEL scenarios complied with the RED II GHG emission savings targets for renewable fuels, regardless of whether the C5-C10 iso-paraffin fraction could be sold as a co-product. Consequently, the production and consumption of REDIFUEL would count towards the national blending targets.

In addition to a reduction in climate change impact, the REDIFUEL drop-in renewable fuel blends lead to a reduction in fossil resources depletion (-43% to -52%), ozone depletion (-59% to -61%), photochemical oxidant formation (-4% to -9%), particulate matter formation (0% to -9%), and terrestrial acidification (-10% to -16%) compared to diesel. These reductions are mainly caused by differences in the fuel production chain and not by differences in exhaust gases. Thus, air pollution could also be decreased if REDIFUEL replaces fossil diesel in lower blends, which would lower the selling price at the pump and increase the economic viability.

The human toxicity impact was similar for REDIFUEL and fossil diesel (-4% to +1% difference), while the freshwater ecotoxicity (+5% to + 45%), freshwater eutrophication (+11% to +92%), ionising radiation (21% to +106%), marine ecotoxicity (+4% to + 40%), marine eutrophication (+1% to +240%), metal depletion (+3% to +25%), and water consumption (+21% to 59%) impacts increased.

Overall, a mixed picture was found for the REDIFUEL blends. They have a high potential for reducing climate change, ozone depletion and air pollution, but there are also risks of increasing toxicity impacts. Limiting Rh catalyst leakage in the hydroformylation step and the plant's electricity consumption are critical to reducing these impacts. The pilot plant's electricity consumption, in particular, proved to be an important contributor to several indicators, including climate change. Reducing the consumption, switching to more renewable electricity sources, and on-site electricity generation from excess steam can improve the plant's overall performance.

The energy efficiency analysis presented in D5.3 has shown that REDIFUEL can also lead to energy savings from a WTW perspective of 23-27% compared to fossil diesel and 10% compared to hydrogen produced from the same feedstock. However, it has also shown that to fully achieve the objective of reaching high energy conversion efficiency for renewable fuel production, further development of the FT catalyst is required to increase the CO conversion while retaining high olefin selectivity. The techno-economic assessment presented in D5.5 has also stressed the importance of improving the alcohol recovery after hydroformylation as an important step to decreasing the REDIFUEL production costs. Both these improvements will also lead to a more favorable picture for all impact categories assessed in this LCA and they should be the first steps in the further development of the REDIFUEL concept.

5 Deviations from Annex 1

The description of task 5.5, to which this deliverable is related, in Annex 1 of the Grant Agreement mentions the assessment of regional differences regarding feedstocks and gasifiers. Including different feedstocks and different gasification plants in the environmental analysis would have required the development of additional models in WP4 (which provided the input for the LCA). However, due to the delay in WP4 related to the catalyst unloading, it was decided that this was not feasible in the timeframe of the project. Therefore, only the use of woody biomass in a dual-fluidized bed gasifier has been considered in the LCA. Potential regional differences in biogenic greenhouse gas emissions related to different forest management practices, i.e., forest rotation period and residue harvesting, have been assessed in the sensitivity analysis.

Regionality also plays a role in the climate change impact of the electricity grid mix to which the REDIFUEL plant is connected. The effect of two different electricity grid mixes on the results has also been assessed and discussed.

An additional scenario not mentioned in Annex 1 was added to evaluate the potential of combining REDIFUEL with carbon capture for potential e-fuel production.

Although the quantitative environmental assessment of using non-woody feedstocks for REDIFUEL production was not possible, the potential effect of using different feedstocks on the total life cycle impact has been considered qualitatively in the discussion.

Estimating the effect of using different gasifiers is more complicated since the gasifier type determines the plant scale, the syngas composition and the syngas cleaning requirements. Indirectly this also affects the utility demand of the plant. Each of these factors influences the plant's environmental impacts differently. Detailed process modelling is required to estimate the combined effect and this can be a starting point for future research. Regardless, the dual-fluidized bed gasifier proposed in the REDIFUEL project was selected as the most appropriate gasifier type since it is an economically attractive choice for smaller-scale plants allowing for short feedstock transportation distances. Therefore, the results discussed in this deliverable are considered the most representative of a future commercial plant.

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7 Acknowledgement

H2020-LC-SC3-RES-21-2018-DEVELOPMENT OF NEXT GENERATION BIOFUELS AND ALTERNATIVE RENEWABLE FUEL TECHNOLOGIES FOR ROAD TRANSPORT

Acknowledgement:

The author(s) would like to thank the project partners for their valuable comments on previous drafts and for performing the review of this deliverable.

Project partners:

1 - FEV – FEV EUROPE GMBH - DE
2 - MPI – MAX-PLANCK-GESELLSCHAFT ZUR FORDERUNG DER WISSENSCHAFTENEV - DE
3 - CSIC – AGENCIA ESTATAL CONSEJO SUPERIOR DE INVESTIGACIONES CIENTIFICAS - ES
4 - VTT – Teknologian tutkimuskeskus VTT Oy - FI
5 - RWTH – RHEINISCH-WESTFAELISCHE TECHNISCHE HOCHSCHULE AACHEN - DE
6 - OWI – OWI Science for Fuels gGmbH - DE
7 - VUB – VRIJE UNIVERSITEIT BRUSSEL- BE
8 - NESTE – NESTE OYJ – FI
9 – MOL - MOL HUNGARIAN OIL AND GAS PLC - HU
10 – INER - INERATEC GMBH - DE
11 – T4F - TEC4FUELS - DE
12 – UNR - UNIRESEARCH BV - NL

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement no. 817612

8 Risk register

Risk No.	WP	What is the risk?	Probability of risk occurrence[1]	Effect of risk[2]	Solutions to overcome the risk
1	n.a.	Displacement of fossil diesel by REDIFUEL blends could lead to higher toxicity, eutrophication, ionizing radiation, metal depletion, and water consumption impacts.	Medium	High	Reducing the plant's electricity consumption, or using excess steam for on-site electricity production. Replacing oxygen by steam in the reformer. Monitoring and limiting the Rh leakage at the hydroformylation step.

[1] Probability risk will occur: 1 = high, 2 = medium, 3 = Low

[2] Effect when risk occurs: 1 = high, 2 = medium, 3 = Low

9 Appendix A

Appendix%20A.xlsx

10 Appendix B

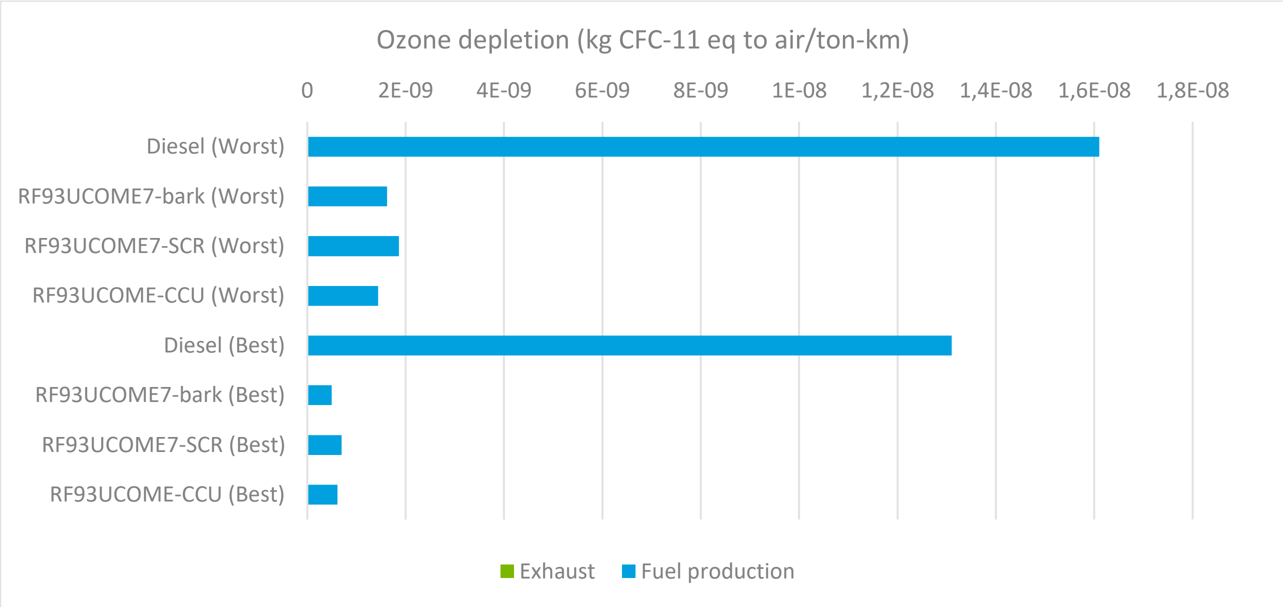

Figure B 1: Ozone depletion impacts of all scenarios in kg CFC-11 eq/ton-km.
The road and truck life cycles are the same for all scenarios and they were excluded here.

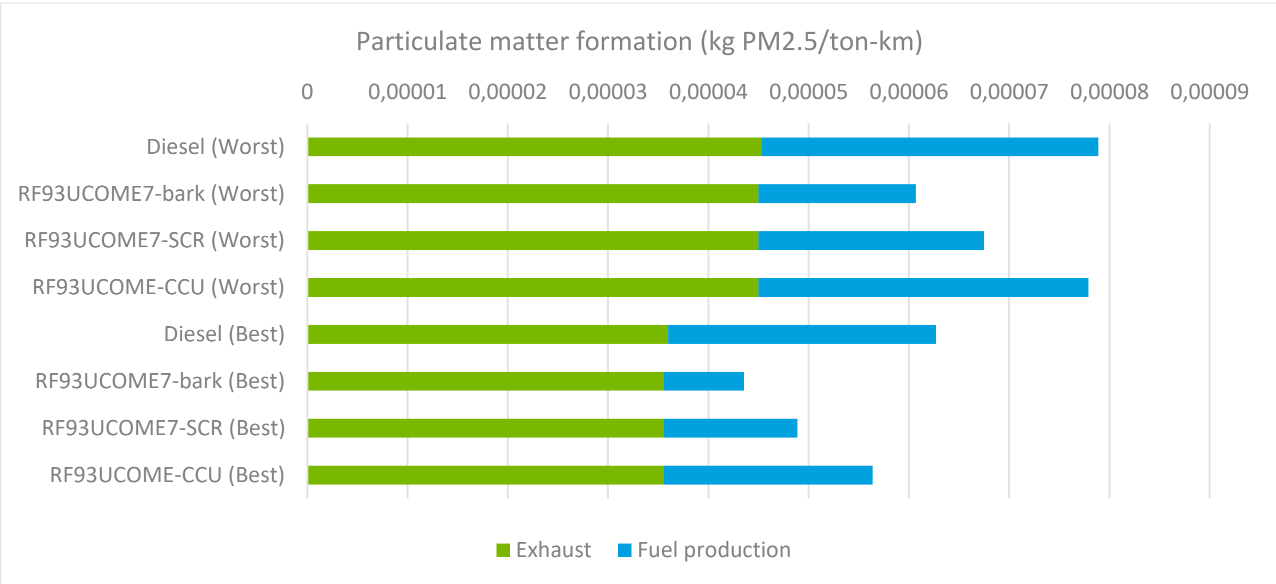

Figure B 2: Particulate matter formation impacts of all scenarios in kg PM2.5 eq/ton-km.
The road and truck life cycles are the same for all scenarios and they were excluded here.

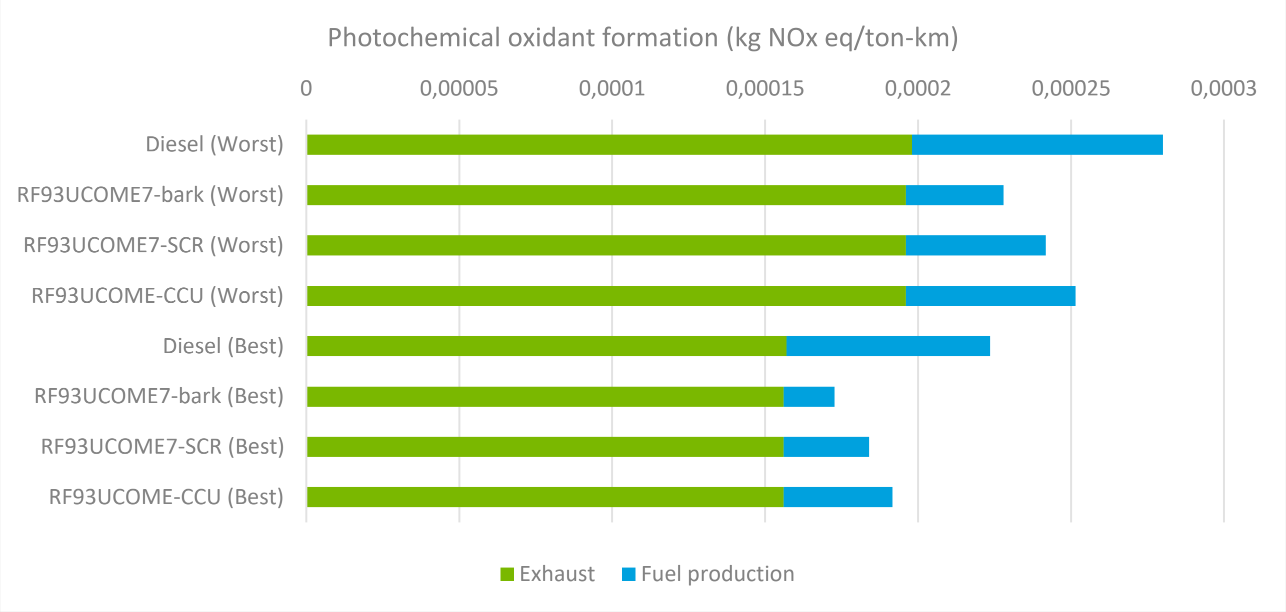

Figure B 3: Photochemical oxidant formation impacts of all scenarios in kg NOx eq/ton-km.
The road and truck life cycles are the same for all scenarios and they were excluded here.

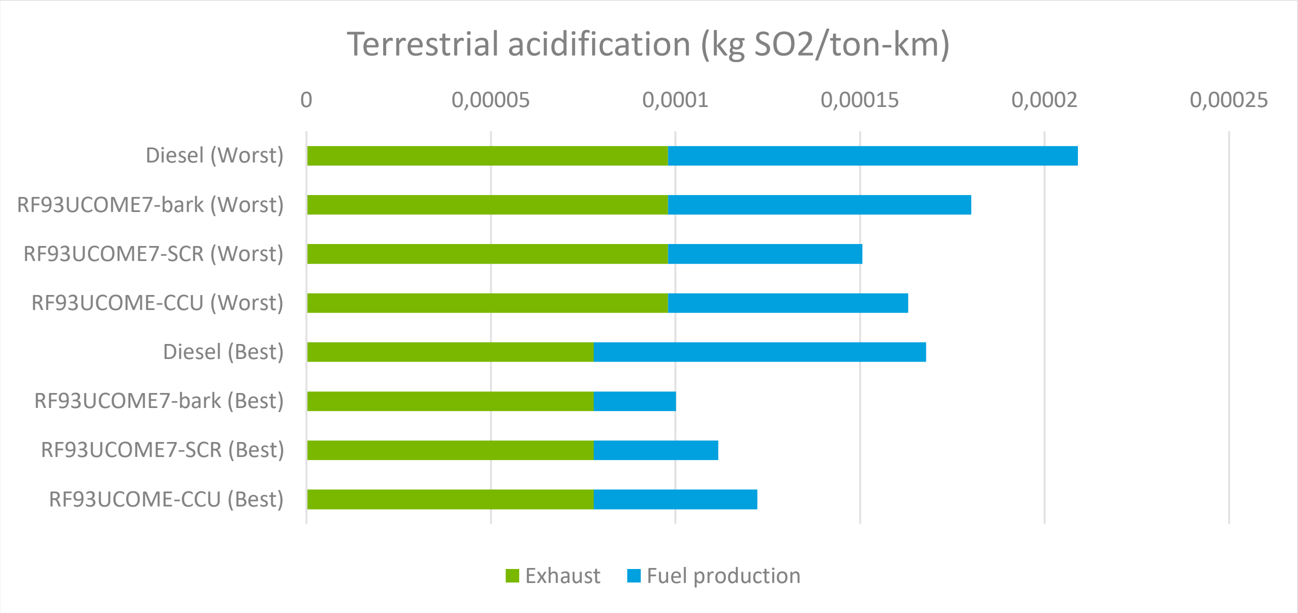

Figure B 4: Terrestrial acidification impacts of all scenarios in kg SO_2 eq/ton-km.
The road and truck life cycles are the same for all scenarios and they were excluded here.