Deliverable report
Deliverable No: D5.3
Dissemination level: Public (PU)
Title: Report on the energetical conversion efficiency of BtL drop-in biofuel

Date: 11/04/2022
Version: FINAL
Author(s): Anne van den Oever, Daniele Costa, Maarten Messagie
Reviewed by: Inkeri Kauppi, Rupali Tripathi (NESTE)
Approved by: Technical Coordinator – Benedikt Heuser (FEV)

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

One of the project goals of REDIFUEL was to reach higher energy conversion efficiencies for renewable fuel production. High efficiency is a prerequisite for sustainable fuel production. This deliverable demonstrates that this goal was achieved for conversion efficiency. However, the biomass-to-fuel efficiency should be interpreted with caution.

At first, it presents a literature review that explains why energy efficiency is important for the sustainability of renewable fuels and how energy efficiency is measured. Different metrics for energy efficiency are explained and typical numbers for synthetic diesel, other renewable fuels, and fossil diesel are given.

The most relevant metrics for REDIFUEL are the overall conversion efficiency, the biomass-to-fuel efficiency, and the cumulative energy demand (CED). The results have shown that the REDIFUEL plant concept has a high overall conversion efficiency (53%) when compared to what is known from the scientific literature. On the other hand, the biomass-to-fuel efficiency is below (39%) or above (45%) the average value, depending on the calculation method.

The cumulative energy demand measures how much primary energy is required throughout the whole life cycle of the fuel, from the extraction of the primary energy carrier (e.g., crude oil extraction for fossil diesel, biomass generation for biofuels) to the final use in the vehicle, in this deliverable a truck. Based on the preliminary plant concept developed in the project the CED of REDIFUEL is 15%-17% higher than for biodiesel from used cooking oil when REDIFUEL is produced from wastes or low-value residues, 23%-27% lower than for fossil diesel, and 10% lower than hydrogen produced from the same feedstock.

The main objective was thus partially achieved, with a high overall conversion efficiency and a lower CED than fossil diesel. Improving biomass-to-fuel efficiency is possible with further development of the Fischer-Tropsch catalyst to obtain higher conversion rates. This would directly affect the biomass-to-fuel efficiency and the CED. Note that the CED results for biodiesel and fossil diesel are based on known industrial processes, whereas the REDIFUEL results are based on a preliminary process concept, which will likely improve with further research and development. Consequently, it is expected that the objective of reaching higher energy conversion efficiencies for renewable fuel production can be fully achieved in the future.

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Introduction

This deliverable is part of Work Package 5, task 5.3: the energetical conversion efficiency evaluation of biomass-to-liquid drop-in biofuel. It contributes to the overall project goal of reaching higher energy conversion efficiencies for renewable fuel production. The objective of task 5.3 was to assess to what extent the new technologies, solutions and processes developed in this project and upscaled in WP4 effectively lead to a high energy conversion efficiency.

The first chapter is a literature review on the concept of energy efficiency and answers the questions: (i) why energy efficiency is so important?, (ii) how can it be measured?, (iii) what is known about the conversion efficiency of Fischer-Tropsch (FT) diesel?, (iv) and what is known about the energy use performance of other fuels from both fossil and biological origin?

Based on this literature review, several metrics for energy efficiency were calculated for the evaluation of REDIFUEL. These metrics were explained more in-depth in chapter 3. The results for the REDIFUEL plant concept were compared to what was known from the scientific literature. The objective of reaching high energy conversion efficiency was partially achieved for the current plant design. Future improvements of the REDIFUEL concept and the FT catalyst, as described in Deliverable 5.5, can ensure the full achievement of such objective.

2 Literature review

2.1 THE IMPORTANCE OF ENERGY EFFICIENCY

The "energy efficiency first" principle is a critical element of the Energy Union strategy of the European Union (EU) as explained in Council directive 2018/2002/EU. It states: "Increasing energy efficiency throughout the whole energy chain, from extraction of primary energy, its conversion and transmission to its distribution and final end-use", is expected to lead to many benefits in terms of environmental performance, energy security and economy. Examples of these benefits are reduced greenhouse gas (GHG) emissions and air pollution, reduced dependence on energy imports and reduced energy bills for economic operators and households (**Error! Reference source not found.**).

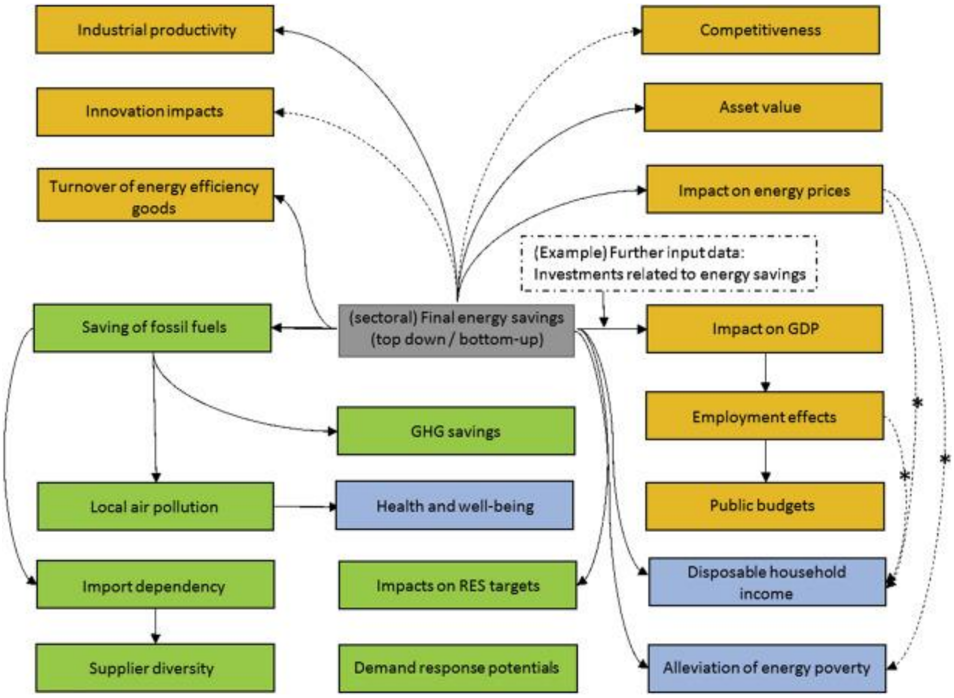

Figure 1: Overview of multiple benefits of energy efficiency and a selection of their interconnections (environmental: green, economic: orange, social: blue). Dashed arrows indicate an indirect relationship with final energy savings. Source: Reuter et al. (2020)

Although these benefits can, in principle, be the result of improved energy efficiency, there is no linear relationship with energy efficiency. Often, a trade-off exists between energy efficiency and the desired benefit. For example, achieving improved energy efficiency generally requires additional investments and operating costs. Therefore, not all improvements are cost-efficient and desirable (Erbach and Members' Research Service, 2015; Petersen, Farzad et al., 2015). Another trade-off is commonly found concerning GHG emissions when comparing fossil fuels with biofuels (JEC, 2013): a less efficient process that uses high shares of renewable energy might lead to higher savings than a very efficient process dependent on fossil energy. Also, energy efficiency improvement in one part of the whole energy chain can be offset by higher energy spending elsewhere and consequently does not always lead to final energy savings. This rebound effect is also known as the energy efficiency gap. It can be have several causes, such as market failures, incomplete information and behavioural changes (Bukarica and Tomšić, 2017).

It is thus clear that (i) the assessment of REDIFUEL’s conversion efficiency is of high importance, but (ii) it is also necessary to determine whether this leads to final energy savings and (iii) that the results of this deliverable should be compared to the results of the environmental life cycle assessment and techno-economic assessment (deliverable 5.4 and 5.5).

2.2 METRICS FOR ENERGY EFFICIENCY

Energy efficiency can be calculated for different levels of the energy chain. A variety of energy efficiency indicators exist and, in what follows, the distinction is made between *energy conversion efficiency* and *energy use*. *Energy conversion efficiency* expresses how completely energy is transformed from one form into another, e.g., when diesel is converted to electricity (Hall et al., 2009). This indicator is generally calculated at plant level, i.e., from gate to gate (Figure 2). Therefore, for the assessment of REDIFUEL, it is a good measure to compare the performance of different FT plants (sections 2.3).

On the other hand, *energy use* expresses how much energy is used to deliver one unit of energy (Hall et al., 2009) and can take any value depending on the definition used. It is generally calculated from a well-to-tank or well-to-wheel perspective (Figure 2). *Energy use* indicators are well suited for comparing different fuels, as they consider the whole life cycle of the fuel (section 2.4).

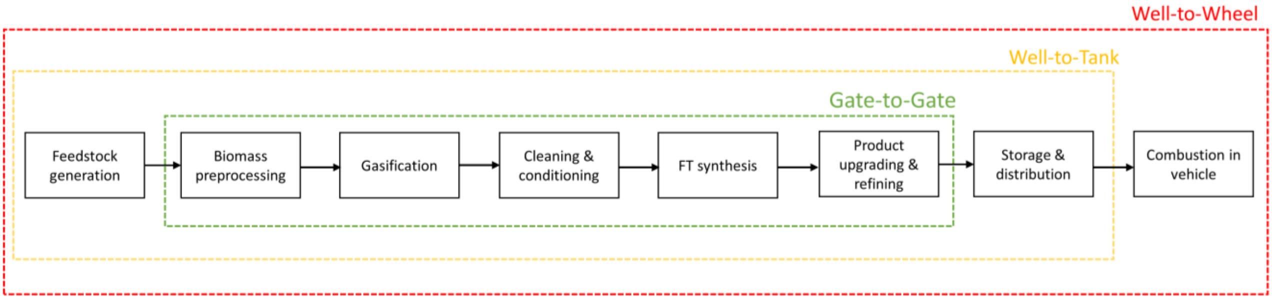

Figure 2: Different system boundaries for energy efficiency analysis on Fischer-Tropsch (FT) fuel production. The gate-to-gate system boundary is used for energy conversion efficiency calculations to compare different FT plants. The well-to-tank and well-to-wheel system boundaries are used for energy use calculations to compare between different fuels.

Regarding energy conversion efficiency, a further distinction can be made between overall efficiency (Eq.1) and biomass-to-fuel efficiency (Eq. 2) (Peduzzi et al., 2018). The first expresses how well the plant transforms energy inputs into fuels and co-products, while the biomass-to-fuel efficiency expresses how well the energy contained in the biomass is transformed into liquid and gaseous fuels only.

$$\eta_1 = \frac{Fuels_{out} + [E_{net}^{+}] + Q_{net}}{Biomass_{in} + [E_{net}^{-}]} \qquad \text{(Eq. 1)}$$

$$\eta_2 = \frac{Fuels_{out}}{Biomass_{in}} \qquad \text{(Eq.2)}$$

$Fuels_{out}$ is the energy contained in the liquid and gaseous products, E_{net} is the net electricity flowing in (positive) or out (negative) of the FT plant, and it equals electricity generation (E_{out}) minus electricity consumption (E_{in}). E_{net} in eq. 1 is in brackets as it appears either in the numerator or the denominator, depending on the sign (positive or negative). Q_{net} is the net heat exported for district heating, while Q_{in} and Q_{out} are the consumed and generated heat. $Biomass_{in}$ is the energy contained in the biomass.

The energy use calculations with well-to-tank system boundaries include the feedstock generation and the conditioning & distribution step of the fuel production life cycle (Figure 2). This allows for comparison with other types of diesel-like fuels with similar combustion efficiencies. Different indicators for energy use exist, such as cumulative energy demand (CED), energy return on energy investment (EROI), primary energy consumption, energy expended, fossil energy demand (FEU), non-renewable energy demand (NRCED) and net energy balance (NEB). This list is non-exhaustive and for more details on the different approaches, the reader can refer to Arvidsson and Svanström (2016), Frischknecht et al. (2015) and Mayer et al. (2020).

Based on these publications, an overview of the choices when defining energy use indicators will be given. First, it has to be decided if the energy source used in the calculation is primary (i.e., the energy source that has not been transformed) or secondary (i.e., the energy source that has been transformed). In the first case, using 1 MJ of coal is not equal to using 1 MJ of diesel, as coal is a primary energy source, while diesel is not. This is why the energy related to crude oil refining must be added to the energy content of the diesel. When secondary energy is used in the calculation, the combustion of 1 MJ of coal or 1 MJ of diesel would be considered equal because the transformation step is neglected. Another important choice is whether renewable energy is considered. Some authors stress the importance of including renewable and non-renewable energy sources together (Arvidsson and Svanström, 2016; Mayer et al., 2020), whereas others recommend reporting the renewable and non-renewable energy use separately (Frischknecht et al., 2015).

The first method is more comprehensive and might be easier to comprehend when comparing many different fuels, as only one number per fuel has to be compared. The second method leads to more numbers to compare but allows for a better interpretation of the environmental impact. A way to combine the advantages of both methods is to use weighting factors for each type of energy, although this is a less objective method. Weighting factors could, for example, be based on the distance to the targeted ratio of renewable and non-renewable energy or the formation/regeneration time of the energy source (Frischknecht et al., 2015). Lastly, it must be decided whether energy embodied in materials is considered and how co-products are dealt with, i.e., they can be included or not, with or without allocation criteria.

2.3 ENERGY CONVERSION EFFICIENCY OF BIO-FT PLANTS IN LITERATURE

2.3.1 DISTRIBUTIONS OF THE OVERALL AND THE BIOMASS-TO-FUEL EFFICIENCY

In total, 18 studies (Table 1) presenting 232 estimations of the overall efficiency of bio-FT fuels and 60 estimations of biomass-to-fuel efficiency have been reviewed. The studies were identified in the Web of Science, Scopus, and ScienceDirect databases. The search used the following string: ("synthetic fuel" OR "synthetic diesel" OR "Fischer-Tropsch" OR "Biomass-to-Liquid") AND ("energy efficiency" OR exergy) AND (biomass OR biofuel) in the title, abstract, and keywords. Additional studies were retrieved through one iteration of backward snowballing [20]. Grey literature identified through the Web of Science, Scopus and backward snowballing were included in the assessment. Reviews were excluded as they do not represent original cases. The identified studies were further analyzed when meeting the following criteria:

- The production pathway comprises gasification of biomass and FT synthesis.
- The production pathway is stand-alone (no integration in a pulp and paper mill).
- The study reports the energy or exergy efficiency of the plant according to Eq.1 or Eq.2.
- The study reports at least the following information about the plant: feedstock type, gasifier type, power generation type.
- The study represents an original case (studies reusing previously published data were excluded).

All but one of the reviewed studies relied on secondary data for the process simulations and energy efficiency calculations. The overall efficiency ranges from 16.8% to 64.0%, outliers excluded (Figure 3). Half of the observations lie between 34.9% and 47.0%, while the median is 41.5%. The results for biomass-to-fuel efficiency are similar. The results of Chen et al. (2016) show that both indicators are complementary and how important it is to report both. Their overall plant efficiency (Eq.1) is very high (72%), but their biomass-to-fuel efficiency (Eq.2) is on the lower end of the spectrum (24%). This is the only study that assumed that over 50% of the waste heat can be used for district heating and is thus a co-product. Consequently, their high overall plant efficiency is mainly due to a high level of process integration and heat valorisation, but it does not mean that the biomass is efficiently transformed into fuel. It is thus important to report both energy efficiency indicators.

Less than half of the reviewed studies reported both the overall plant and biomass-to-fuel efficiency, which is an important shortcoming in the current literature. Most studies have calculated the energy flows of the fuels ($Fuels_{out}$) and the feedstock ($Biomass_{in}$) by multiplying the mass flows with the lower heating value (LHV) or with the higher heating value (HHV). Frischknecht et al. (1998) argue that using higher heating values is more appropriate, as they represent the intrinsic value of energy carriers better. In reality, not all the water that was contained in the fuel and that was formed during combustion is in a liquid state at the end of a process. Consequently, the use of lower heating values is more customary (VTT, 2016).

Four studies have reported the efficiency based on exergy (Table 1), representing the maximum amount of useful work that a system can do, i.e., it is a measure of energy quality (Sciubba and Wall, 2007). In contrast to the energy that can only be lost from the system through exchanges with the environment, exergy can also be lost through destruction due to irreversibility in the system (Cruz et al., 2017). The exergy efficiency is always lower than the energy efficiency for FT-plants because, in the process, high-quality energy (biomass) is transformed into lower-quality energy (heat), leading to exergy destruction. The advantage of using exergy instead of heating values is that it considers this energy quality degradation. If the results of Chen et al. (2016) were given based on exergy analysis, the discrepancy between the biomass-to-fuel efficiency and the overall plant efficiency would be lower because the co-product heat has a low quality and would contribute less to the overall plant efficiency.

Table 1: Overview of the reviewed techno-economic studies on biomass-based Fischer-Tropsch plants. N = number of estimates per study, Eq = Equation, M = moisture content after drying, LHV = lower heating value, HHV = higher heating value, NA = not available.

Study	N	Eq	Energy basis	M	Gasifiers	Tar removal	Syngas cleaning	CO_2 removal	Single-pass CO conversion	Recycle off-gas
Tijmensen et al. (2002)	24	η_1	LHV	10%/15%	CFB	Catalytic	Hot/cold	Yes/No	40%/60%/80%	Yes
Hamelinck et al. (2004)	21	η_1	HHV	15%	CFB	Thermal/Scrubber	Hot/cold	Yes/No	70%/90%	Yes/No
Prins et al. (2004)	41	η_1	Exergy	10%/15%/20%	CFB	None	Cold	No	10%-90%	No
	13	η_2	Exergy							
Kreutz et al. (2008)	4	η_1	LHV, HHV	NA	CFB	Catalytic	Cold	Yes	80%	Yes
	4	η_2	LHV, HHV							
Larson et al. (2009)	1	η_1	LHV	NA	CFB	Catalytic	Cold	Yes	NA	No
	1	η_2	LHV							
Swanson et al. (2010)	2	η_1	LHV	10%	CFB, EF	None	Cold	Yes	40%	Yes
	2	η_2	LHV							
Tock et al. (2010)	5	η_1	LHV	25%	CFB, EF, FICFB	None	Cold	No	85%	Yes/No

Zhu et al. (2011)	2	η_1	LHV	12%	CFB, DFB	Catalytic	No	Yes	70%	No
Piekarczyk et al. (2013)	2	η_1	Exergy	10%	CFB	NA	NA	No	80%	No
Trippe et al. (2013)	2	η_1	HHV	NA	EF	None	Cold	Yes	80%	No
Tunå et al. (2014)	1	η_1	LHV	NA	BFB	NA	NA	NA	80%	Yes
	1	η_2	LHV							
Petersen et al. (2015)	1	η_2	Unknown	5%	CFB	NA	Cold	NA	53%	Yes
Chen et al. (2016)	2	η_1	LHV, HHV	NA	DFB	None	Cold	Yes	93%	Yes
	2	η_2	LHV, HHV							
Im-orb et al. (2016)	35	η_1	HHV	NA	DDFB	Catalytic	NA	No	38%-63%	Yes
Cruz et al. (2017)	3	η_1	Exergy	NA	DFB	Catalytic	Cold	Yes	85%	Yes/No
Ail et al. (2017)	4	η_2	Unknown	1%	DDFB	Scrubber	Cold	Yes	43%-73%	No
Dimitriou et al. (2018)	2	η_2	LHV	10%	CFB, EF	Catalytic/None	Cold	Yes	80%	No
Peduzzi et al. (2018)	27	η_1	LHV	10%	EF, FICFB	Thermal/Catalytic/None	Hot/Cold	Yes	80%	Yes/No
	27	η_2	LHV							
Tuomi et al. (2019)	8	η_1	LHV	8%/20%/30%	DFB	Catalytic	Cold	No	82%-92%	No
Ben Hnich et al. (2020)	3	η_1	Exergy	28%	DFB	NA	Cold	Yes	40%	Yes
	3	η_2	LHV							

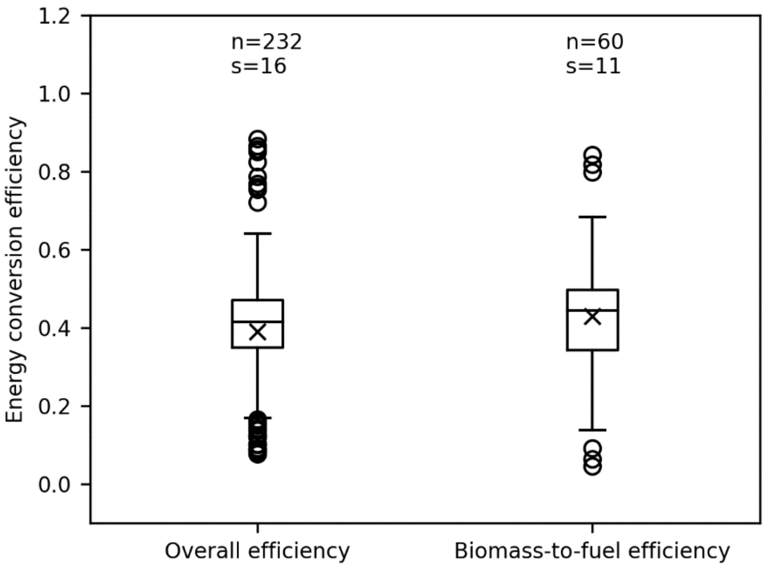

Figure 3: Distributions of the overall efficiency and biomass-to-fuel efficiency observations of the reviewed techno-economic assessments of biomass-based Fischer-Tropsch plants.

2.3.2 VARIABLES AFFECTING THE OVERALL AND BIOMASS-TO-FUEL EFFICIENCY

The studies differ greatly in the considered technology (Figure 4), not allowing a direct comparison of results. This contributes to the large variability observed in Figure 3. Pre-treatment of the biomass may be required, depending on the feedstock characteristics and the gasifier type. The latter also affects the syngas cleaning conditions and requirements (E4Tech, 2009). A reformer and a shift reactor may be used to adjust the syngas composition, and hydrogen may be recovered for downstream upgrading. The FT reactor catalytically converts the syngas into hydrocarbons that must be separated and upgraded for final use. It can operate in a once-through configuration or with a recycle loop.

In the case of a once-through concept, the off-gas goes to the boiler. Part of the generated steam is used at the plant, and part may be sold or sent to a steam turbine for electricity generation. The off-gas is split into two sub-streams used for FT synthesis and a boiler in a recycle loop. The refining of the FT-crude may occur at the FT plant, but the FT crude can also be sent to a dedicated refinery (Prins et al., 2004), where different end products may be co-produced in different ratios. Although the specific distribution of hydrocarbons may vary, the main product in all plant concepts reviewed is a range of FT liquids. Excess steam may be used for district heating or nearby industrial purposes.

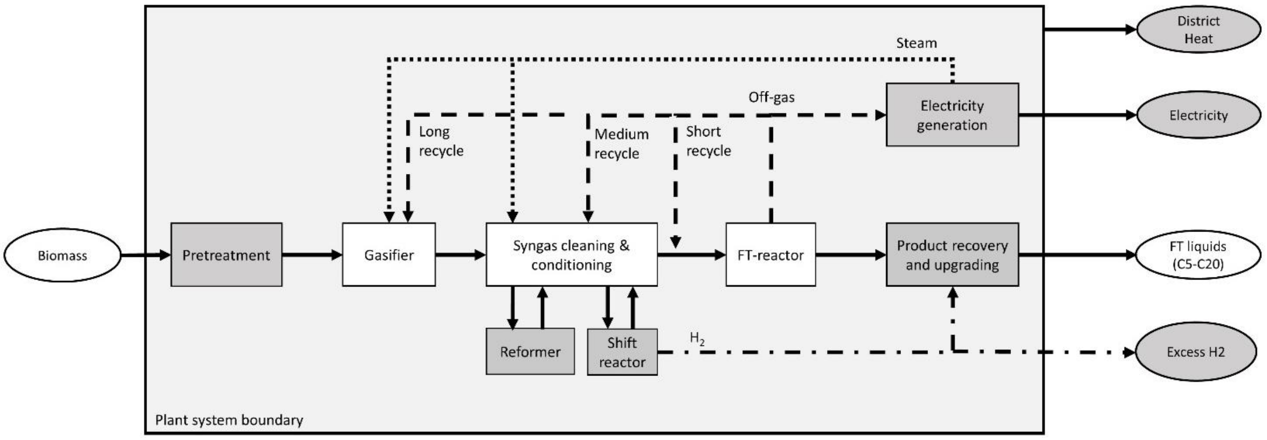

Figure 4: Process configurations in reviewed studies (Table 1). White boxes are considered in all studies and grey boxes are not considered in all studies. Adapted from Hamelinck et al. (2004).

According to the reviewed studies, the following plant design features affect the energy conversion efficiency of bio-FT plants:

1. **The feedstock moisture content**. It is advised to dry the feedstock as thoroughly as possible (Prins et al., 2004; Tuomi et al., 2019).
2. **The gasifier type**. Generally speaking, Entrained flow (EF) gasifiers lead to higher or equal overall efficiency (Eq. 1) than Fast Internally Circulating Fluidized Bed (FICFB) gasifiers (Peduzzi et al., 2018; Tock et al., 2010), EF gasifiers also lead to higher overall efficiency (Eq. 1) than Circulating Fluidized Bed (CFB) gasifiers (Swanson et al., 2010; Tock et al., 2010). Zhu et al. (2011) showed that a Dual Fluidized Bed gasifier has a lower overall efficiency (Eq. 1) than a CFB gasifier (39.8% vs. 45.6%).
3. **The gasifier pressure**. Pressurized gasification might offer economic advantages and increase the overall efficiency (Eq. 1) due to the higher throughput and smaller downstream equipment size (10%-point reported in (Tijmensen et al., 2002)).

4. **The tar removal technology**. Catalytic removal leads to higher overall efficiency than thermal removal, and both of these options lead to higher overall efficiency than tar scrubbers (Dimitriou et al., 2018; Hamelinck et al., 2004).
5. **The syngas cleaning**. Hot or dry syngas cleaning positively affects overall efficiency compared to cold or wet syngas treatment (Hamelinck et al., 2004; Tijmensen et al., 2002).
6. **The syngas CO_2 removal**. The removal can improve overall efficiency (Eq. 1) by 0.3% and potentially affect the biomass-to-fuel efficiency (Eq. 2).
7. **The single-pass CO conversion**. Higher conversion rates lead to higher overall efficiency (Hamelinck et al., 2004; Tijmensen et al., 2002).
8. **A recycle loop.** Recycling off-gases increases overall efficiency when the same syngas-to-FT liquid conversion efficiency is assumed (Cruz et al., 2017; Tock et al., 2010).
9. **On-site electricity generation.** Electricity generation is one of the primary sources of exergy destruction in an FT plant, and prioritizing fuel production over electricity production leads to higher overall exergy efficiencies (Cruz et al., 2017; Prins et al., 2004).
10. **Heat integration and valorisation.** With a pinch analysis for optimal heat integration, Petersen et al. (2015) could improve the overall efficiency (Eq.1) from 51.6% to 55.7%. In addition, the highest overall efficiency estimations in Figure 3 were derived from studies that consider excess heat for district heating purposes (Chen et al., 2016; Tuomi et al., 2019).

2.3.3 CONCLUSIONS FROM ENERGY CONVERSION EFFICIENCY OF FT FUELS

In the scientific literature, broad ranges of overall (8%-88%) and biomass-to-fuel (5%-84%) efficiencies of bio-FT plants were found due to many different energy efficiency definitions and plant designs. Direct comparison of studies is therefore not possible, but various important conclusions for the energy assessment of REDIFUEL can be drawn from the analysis:

- None of the reviewed papers were directly comparable to each other, proving the need for a more standardized way of energy efficiency calculations. In particular, a clear definition of the used equations must be given.
- Studies on the energetic conversion efficiency of FT-plants, this REDIFUEL deliverable included, should report both overall efficiency (Eq.1) and biomass-to-fuel efficiency (Eq.2).
- To evaluate the energy efficiency of FT-plants, HHV or LHV may be used. The first considers the theoretical maximum energy content of the fuels, while the second relates to the useful part of the energy content. To allow for harmonization and comparison with other studies, the values of the mass flows and used heating values must be given.
- The ten plant design features discussed in section 2.3.2 can explain the cause of high or low energy conversion efficiencies and identify potentials for process improvement.

2.4 ENERGY USE OF CONVENTIONAL FUELS IN LITERATURE

Although many different studies exist that report *energy use* indicators of fuels, it was decided to discuss a selection of the result of the study of JEC (2020a) to understand the main differences between various fuels. This report investigates over 180 production pathways for fuels (fossil, bio and e-fuels) relevant in the European Union. Due to the EU scope, this report is very pertinent for REDIFUEL. Only one indicator for energy efficiency, the *expended energy*, is used and the methodology is consistent for all 180 pathways ensuring comparability between them. The figures shown in this report are expressed as net total primary energy expended per MJ of fuel delivered to the vehicle tank, based on lower heating value (Eq. 3), and renewable and non-renewable energy sources are reported separately. Primary energy embedded in used materials (such as fertilizers) is included, but primary energy embedded in facilities is not. Also excluded is the primary energy transferred to the fuel itself. For example, 1 MJ of fossil diesel requires 1.2 MJ of primary energy, but 1 MJ is contained in the fuel itself. Hence the expended energy is 0.2 MJ/MJ diesel (JEC, 2020a). The energy embodied in co-products is subtracted from the energy inputs without allocation.

$$Expended\ energy = \frac{E_{biomass} + E_{non-renewable} - W_{gen} - E_{products}}{E_{fuel}} \qquad \text{(Eq. 3)}$$

The results are also shown with well-to-wheel system boundaries that include the combustion step in the vehicle. This allows comparing fuels fairly, for example, diesel, CNG and gasoline. The figures shown in this report represent the expended energy expressed in MJ/ton-km for heavy-duty vehicles.

2.4.1 WELL-TO-TANK SYSTEM BOUNDARY

The expended energy for several diesel alternatives taken from JEC (2020b) ranges from 0.11 to 1.83 MJ/MJ_{fuel} (Figure 5). Fossil diesel is the reference fuel and 0.26 MJ must be expended to deliver 1 MJ of fuel to the vehicle tank. When 90% CO_2 from the refinery flue gasses is captured and stored (CCS), the energy requirements increase by 20%.

Hydrotreated vegetable oil (HVO) from waste cooking oil has a very low energy use, and this biofuel performs even better than fossil diesel. Waste cooking oil has to be collected and disposed of in any case. Therefore, no energy is allocated to its generation (production & conditioning) and transportation. HVO from palm oil and rapeseed perform quite similarly in terms of total energy use, but the fossil energy requirements of HVO from rapeseed are much higher than for HVO from palm oil. In fact, the heat required for rapeseed oil production in Europe is generated in natural gas boilers, whereas the heat required for palm oil production is generated by the combustion of the palm residues (palm kernel meal, mesocarp fiber and shells). Moreover, rapeseed production requires almost twice as many energy inputs as palm oil bunch production. Both pathways are roughly six times more energy-intensive than HVO from waste cooking oil. This illustrates the issue with first-generation biofuels requiring many inputs for crop production, harvesting, and biomass pre-processing. However, some authors consider waste cooking oil as a residue with economic value and allocate part of fresh vegetable oil production emissions to this residue (Johnson, 2017). This assumption would significantly increase the result for waste cooking oil and bring the gap between first- and second-generation fuels closer together.

Fatty Acid Methyl Ester (FAME) production requires slightly less energy than HVO production. FAME only complies with the international standard for diesel EN590 in blends with at least 93% fossil diesel and it is in this sense inferior to HVO that has fuel properties closer to fossil diesel (European Biofuels Technology Platform, 2011; Neste Corporation, 2015).

Synthetic diesel from black liquor is the best performing fuel in Figure 5, as the production is assumed to be integrated into a pulp mill, and the feedstock is considered a waste. But, it can be expected that more high-value applications such as phenolic resins will be developed in the coming years (Dessbesell et al., 2020). This would create competition for black liquor and increase its economic value. In that case, it would be more appropriate to allocate part of the kraft pulp mill process to black liquor generation and result would probably be closer to FT diesel from wood.

Synthetic diesel production via pyrolysis and hydrothermal liquefaction is more energy-efficient than the FT pathway, but the latter process is less dependent on fossil fuels and more renewable. When synthetic diesel (FT) is produced from farmed wood (short rotation forestry) instead of waste wood, the energy use requirements increase by 10%.

Compared to the synthetic diesel from biomass, the synthetic diesel from natural gas is produced at a much higher efficiency, although almost 100% of the energy comes from fossil sources. This example shows, in particular, how important it is to present the total energy expended, but also the origin of the energy. FT-diesel production from CO_2 requires more or less energy than FT-diesel from wood, depending on the CO_2 source. When CO_2 from biogas upgrading is used, the pathway is 100% renewable and as the CO_2 has to be separated from the methane in any case, no extra energy has to be expended. In the case of CO_2 from ambient air or flue gases, a significant amount of additional energy is required for capturing the CO_2, 62% and 37%, respectively. However, this result should be put somehow in perspective. The idea behind this pathway is that only renewable energy is used for hydrogen production at times of excess electricity generation. This green hydrogen production has thus the function of storing otherwise lost energy. This shows the limitation of the indicator energy expended that does not distinguish between flow, fund and stock types of energy.

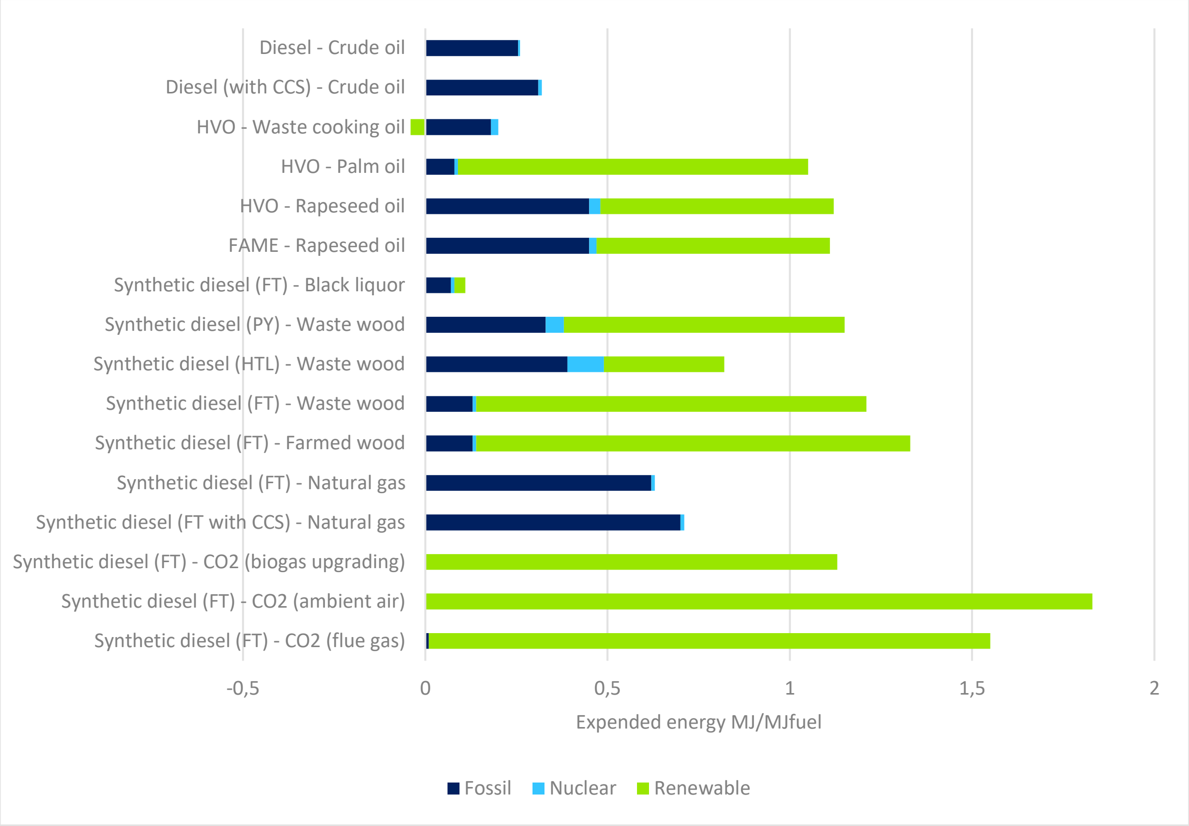

Figure 5: Well-to-tank expended energy of fossil diesel and several biodiesel alternatives. CCS stands for carbon capture and storage. HVO stands for hydrotreated vegetable oil and FAME stands for fatty acid methyl ester. FT stands for Fischer-Tropsch synthesis, PY for pyrolysis and HTL for hydrothermal liquefaction. Source: adapted from JEC (2020b). The fuel codes used in the original source are listed in the Appendix.

2.4.2 WELL-TO-WHEEL SYSTEM BOUNDARY

The energy expended on a WTW and TTW basis for different fuel-drivetrain combinations is given in Figure 6. It is clear that TTW results vary less than the WTT results (Figure 5). Trucks with CI engines consume more or less the same amount of energy (TTW), independent of the fuel. The results show that methane-fuelled trucks generally consume 25% more energy on a TTW basis and also the WTT energy requirements are higher. From an energy perspective, it is thus more interesting to produce synthetic diesel or Dimethyl Ether (DME) from a given feedstock than SNG. In Figure 6, this is exemplified by the results for fuel production from residual wood.

The most efficient fuel to produce from this feedstock is synthetic diesel, followed by DME. The most efficient drivetrains are battery and catenary electric. They also offer the most potential from a well-to-wheels basis, up to 60% energy savings compared to fossil diesel. Although these options are not yet on the market for long haul trucks, Daimler expects to introduce its first battery-electric long haul truck with a range of 500 km to the market in 2024 (Daimler AG., 2020). This range would be sufficient for 95% of the road freight trips in the EU, although many infrastructural hurdles still need to be overcome (Transport & Environment, 2020). Fuel cell electric vehicles are also more efficient than diesel trucks. Still, hydrogen production is energy-intensive and the well-to-wheel range for hydrogen-fuelled trucks lies higher than those for synthetic fuels and conventional biofuels (B100, HVO).

A few less common fuels are included in Figure 6. ED95 is a blend of 95% ethanol and 5% ignition improvers (MTBE, i-butanol, Polyethylene glycol) (JEC, 2020b). Although it is commercially available, the uptake is limited as dedicated vehicles are required (European Commission, 2017). The range of WTW results is very narrow because JEC (2020a) only considered two pathways (wheat and straw). However, in theory, many other feedstocks can be used for ethanol production. However, the energy intensity of the selected pathways is representative of the average ethanol pathway. It can be concluded that this fuel does not offer energy savings compared to fossil diesel or commercially available biofuels. OME are oxymethylene ethers and this fuel could significantly reduce particulate matter emissions compared to diesel, but its well-to-wheel energy use is the highest of all fuels considered.

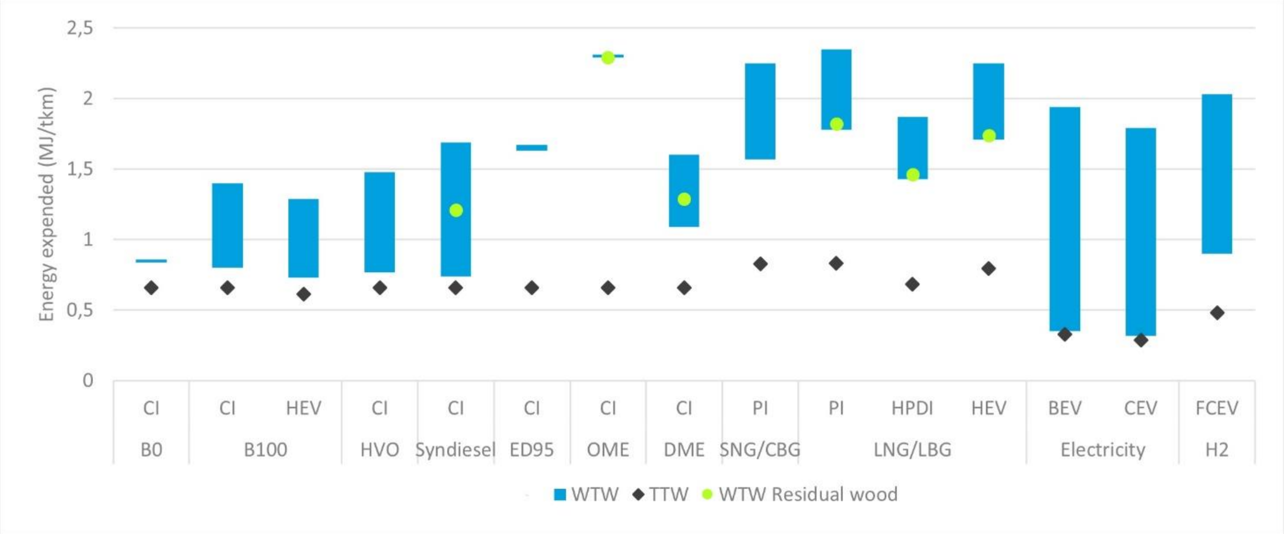

Figure 6: Well-to-wheel and tank-to-wheel energy expended for 40-ton long-haul trucks for a selection of fuels and drivetrains. TTW emissions were modelled for 2025+ trucks (JEC, 2020c). Diamonds represent TTW energy expended and are fixed for each fuel-drivetrain combination. Green dots show the WTW expended energy for a particular pathway (residual wood). Variation in WTW results is due to differences in WTT results (different feedstocks). CI = Compressed Ignition engine, HEV = Hybrid Electric Vehicle, PI = Positive Ignition engine, HDPI = High Pressure Direct Injection engine, BEV = Battery Electric Vehicle, CEV = Catenary Electric Vehicle, FCEV = Fuel Cell Electric Vehicle, B0 = 100% fossil diesel, B100 = 100% biodiesel (FAME), HVO = Hydrotreated Vegetable Oil, Syndiesel = synthetic diesel via Fischer-Tropsch, hydrothermal liquefaction or pyrolysis, ED95 = ethanol with ignition improver, OME = Oxymethylene Ether, DME = Di-methyl Ether, SNG/CBG = Synthetic Natural Gas or Compressed Biogas, LNG/LBG = Liquefied (synthetic) Natural Gas or Liquefied Biogas. Adapted from JEC (2020a).

2.4.3 CONCLUSIONS FROM ENERGY USE OF FUELS IN LITERATURE

Based on the reviewed literature, the following points must be considered in the energy use assessment of REDIFUEL:

- The energy use indicator calculation chosen must be clearly defined. This includes the choice for primary or secondary energy, differentiation by origin (fossil, nuclear, renewable), whether weighting is applied and whether the energy embodied in materials is considered.
- The WTT energy use of synthetic diesel via Fischer-Tropsch is higher than HVO and FAME, but less fossil energy is required.
- The WTT energy use of synthetic FT diesel via CO_2 and electrolysis is highest when CO_2 comes from direct air capture (DAC) and lowest when CO_2 comes from biogas upgrading. In the latter case, the total WTT energy use is lower than bio-FT diesel.
- The WTW energy use variation is mainly due to the WTT phase while the TTW part varies less.
- Trucks with the lowest WTW energy use potential are battery or catenary electric, while trucks with the highest WTW energy use run on CNG or LNG.
- The most efficient use of forestry residues for fuel production is synthetic diesel (FT).

3 Methods

3.1 ENERGY CONVERSION EFFICIENCY CALCULATION

We have calculated the overall plant efficiency (Eq.1) and the biomass-to-fuel efficiency (Eq.2) of REDIFUEL. As the main objective of the REDIFUEL plant is to produce the REDIFUEL blend, an additional indicator, the biomass-to-REDIFUEL efficiency was calculated as follows:

$$\eta_3 = \frac{REDIFUEL}{Biomass_{in}} \qquad \text{(Eq. 4)}$$

REDIFUEL is the energy contained in the final REDIFUEL blend, and *Biomass$_{in}$*, is the energy contained in the biomass feed. For all three indicators, two different approaches were taken for defining the energy contents of the bark, the fuels, and the steam. The first is the theoretical maximum energy content approach. The energy contents of the bark and the fuels are calculated by multiplying their respective mass by their HHV, and the maximum amount of energy that could be subtracted from superheated steam equals its enthalpy which is given by equation 5:

$$Q_{max} = H = m * (h_f + h_{fg} + C_{ps}(T_2 - T_s)) \qquad \text{(Eq.5)}$$

Where H =enthalpy (kJ), m= mass (kg), h_f= specific enthalpy of the water phase (kJ kg^{-1}), h_{fg}=specific latent heat (kJ kg^{-1}), C_{ps}=specific heat capacity of steam (kJ $°C^{-1}$ kg^{-1}), T_2 = steam temperature, T_s= saturation temperature. The values for h_f, h_{fg},and C_{ps} were derived from steam and property tables (Çengel et al., 2012).

The second approach is based on useful energy. The energy contents of the bark and the fuels were calculated by multiplying their respective mass by their LHV. The useful energy content of the steam is given by its enthalpy (Eq.5) multiplied by the Carnot efficiency (Council directive 2018/2001/EU, 2018) :

$$Q_{useful} = H * \left(1 - \frac{T_0}{T_2}\right) \qquad \text{(Eq.6)}$$

Where T_0 is the reference temperature (273.15 °C) and T_2 is the steam temperature.

3.2 ENERGY USE CALCULATION

The energy use indicator chosen for the assessment of REDIFUEL was the CED as described by Frischknecht et al. (2007), considering primary energy carriers. It differs from the energy expended indicator from section 2.4, as the energy transferred to the fuel is included, and the assessment is based on the HHV. Due to the first difference, the CED better represents the total energy requirements of the service transport. The CED is calculated for each of the following subcategories:

- Fossil
- Nuclear
- Primary forest (non-renewable)
- Biomass (renewable)
- Wind
- Solar
- Geothermal
- Water

An aggregated CED was calculated as the sum of the disaggregated CEDs. No weighing is applied, as this is the simplest and most widespread practice (Frischknecht et al., 2015). The energy embodied in materials is considered.

The CED was calculated for all scenarios in Table 2 with the same model as the LCA. The data, assumptions, scenarios and methodology are explained in deliverable 5.4.

Table 2: Explanation of scenario codes used in this deliverable. ICEV-d = internal combustion engine vehicle (diesel), FCEV = fuel cell electric vehicle. UCOME = Used Cooking Oil Methyl Ester.

Scenario code	Fuel	Drivetrain
B0	Pure fossil diesel	ICEV-d
RF40B060	40% REDIFUEL (from bark chips) + 60% B0	ICEV-d
RF93UCOME7-Bark	93% REDIFUEL (from bark chips) + 7% 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
H2-BM	Hydrogen from bark chips gasification	FCEV
H2-EL	Hydrogen from electrolysis	FCEV

4 Results

4.1 REDIFUEL ENERGY CONVERSION EFFICIENCY

The REDIFUEL plant has two energy external inputs and six output streams (Table 3). Considerable amounts of co-products (diesel, C5-C10 iso-paraffins, Wax, LPG, steam) are produced. REDIFUEL's overall efficiency is part of the 25% highest values found in literature, outliers excluded (Figure 7). The biomass-to-fuel efficiency is in the second quartile, and the biomass-to-REDIFUEL efficiency is an outlier. Only 10% of the energy contained in the biomass ends up in the REDIFUEL blend.

Table 3: Inputs and outputs of the REDIFUEL plant.

Inputs	*Mass flow (kg/h)*	*Energy flow-max (MW)*	*Energy flow-useful (MW)*	***Outputs***	*Mass flow (kg/h)*	*Energy flow-max (MW)*	*Energy flow-useful (MW)*
Bark chips	20155	60	49	**REDIFUEL blend**	407	5.2	4.9
Electricity		7.4	7.4	**Diesel**	500	6.6	6.1
				C5-C10 iso-paraffins	740	8.9	8.3
				Wax	63	0.8	0.8
				LPG	202	2.7	2.6
				Steam (56 bar, 450 °C)	12998	11.4	7.1

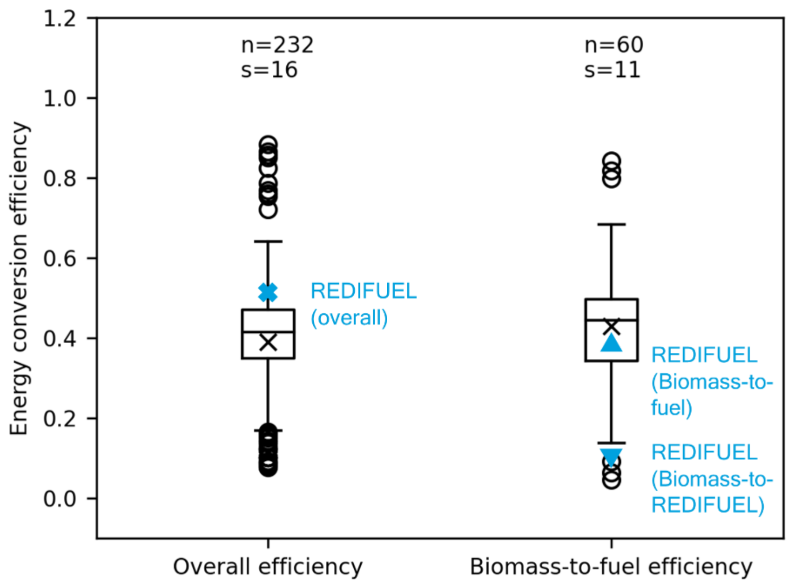

Figure 7: Comparison of the energy conversion efficiency (based on HHV) of the REDIFUEL plant concept compared to literature values of Fischer-Tropsch plants.

REDIFUEL's overall efficiency does not depend on the calculation approach (Table 4). Still, the biomass-to-fuel efficiency and biomass-to-REDIFUEL efficiencies are 15% and 13% higher when the useful energy approach is used, compared to the theoretical maximum energy content approach. For REDIFUEL's biomass-to-fuel efficiency means it is in the third quartile instead of the second.

Table 4: The energy conversion efficiencies of the REDIFUEL plant concept.

Approach	*Overall efficiency*	*Biomass-to-fuel efficiency*	*Biomass-to-REDIFUEL efficiency*
Theoretical maximum (HHV)	53%	39%	9%
Useful energy (LHV)	53%	45%	10%

4.2 REDIFUEL ENERGY USE

The investigated renewable fuels fall into two categories: fuels from wastes and residues, which have a lower cumulative energy demand than fossil diesel (B0), and fuels from purposely-grown biomass or electricity, which have a higher cumulative energy demand than B0 (Figure 8). In particular, the electricity-based pathways (RF93UCOME7-CCU and H2-EL) have high cumulative energy demands due to the low electrolyser efficiency, but the share of fossil energy is lower than for all the other fuels. RF93UCOME7-bark has the lowest cumulative energy demand of all blends containing REDIFUEL, meaning that it is a more efficient pathway than H2-BM or RF93UCOME07-SCR.

For all scenarios, two differences are notable between the worst and the best case. In the best case, the total cumulative energy demand is 2%-8% lower than in the worst case due to efficiency improvements throughout the life cycle. Additionally, the share of fossil energy decreases by 9%-24% compared to the worst case.

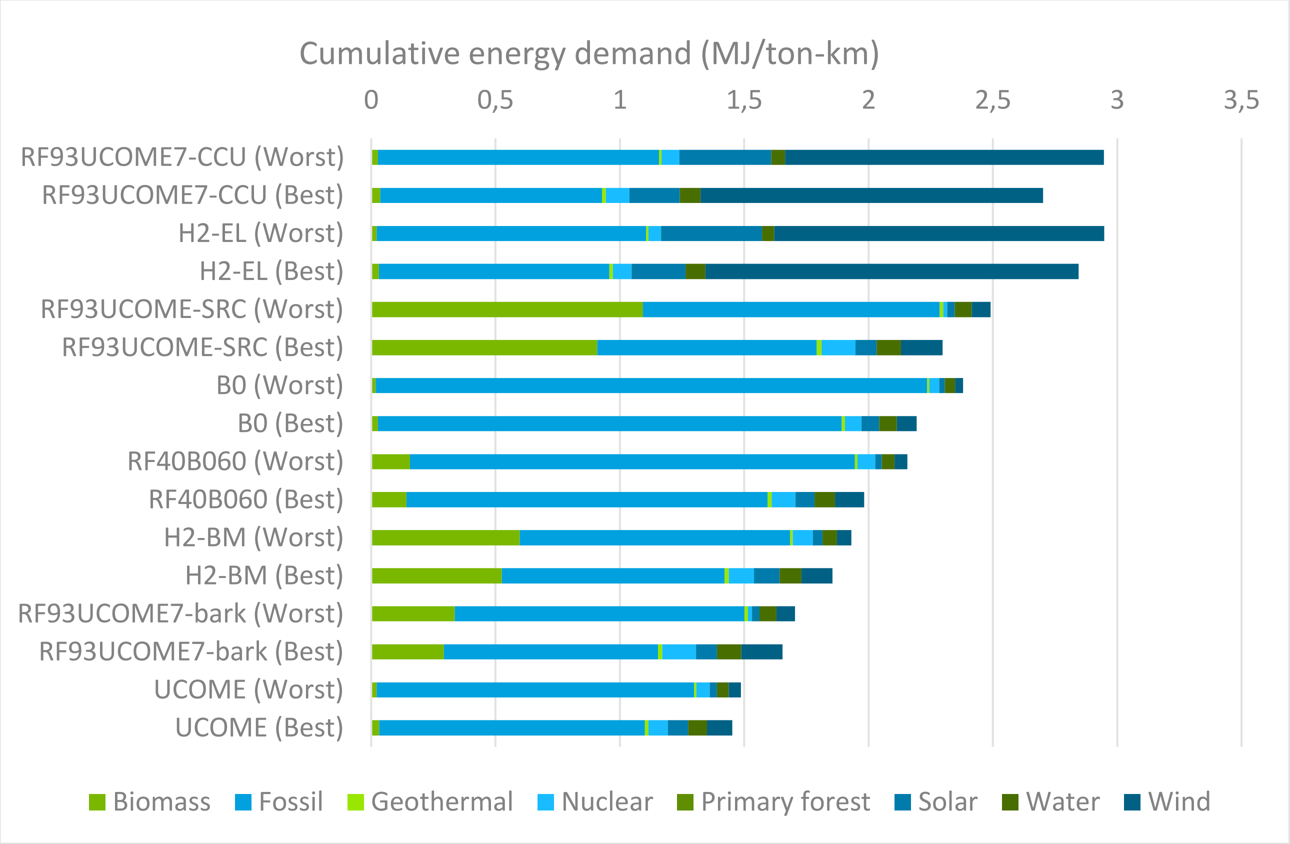

Figure 8: Well-to-wheel cumulative energy demand of trucks running on various fuel blends. Percentages represent the increase or decrease relative to fossil diesel (B0).

5 Discussion and Conclusions

5.1 DISCUSSION

There is potential for improvement of the three energy conversion efficiency indicators of REDIFUEL, particularly for the biomass-to-REDIFUEL and the biomass-to-fuel efficiency. From the ten plant design features discussed in 2.3.3, the single-pass CO conversion of the syngas in the FT reactor is the most crucial bottleneck for improving the biomass-to-REDIFUEL and the biomass-to-fuel efficiencies. The current CO conversion is low compared to industrial catalysts and reported values in the scientific literature (Table 1). How this challenge could be addressed in the future is discussed in detail in the techno-economic assessment (D5.5).

The feedstock moisture content of the bark at the arrival of the plant is relatively high (50%). The energy requirements for drying could be reduced if fewer wet feedstocks were used or if the feedstock were stored for some time to dry. This would increase the overall efficiency without affecting the biomass-to-fuel and the biomass-to-REDIFUEL efficiency.

Further improvement of the overall efficiency is also possible with further optimization of the heat streams. In the current assessment, it was considered that only high-pressure steam was valuable enough to be sold as a co-product. However, the energy balance in the techno-economic assessment has shown that there is also an excess of low-pressure steam that is currently considered a waste, but that could still be used by nearby industries. For example, the overall plant efficiency of REDIFUEL could be improved if the REDIFUEL plant were to be located close to a facility requiring low-pressure steam for heating purposes, such as a brewery, a pharmaceutical production facility or an anaerobic digestor.

In line with what was found in the literature review (section 2.4) for conventional FT pathways, the substitution of fossil diesel by REDIFUEL blends also reduces fossil fuel consumption from a well-to-wheel perspective (Figure 8). REDIFUEL production via electrolysis and carbon capture (RF93UCOME7-CCU) or via short rotation coppice gasification (RFUCOME7-SRC) leads to a higher CED than fossil diesel. These pathways may result in climate change benefits due to lower fossil fuel consumption throughout the life cycle. Still, the total amount of primary energy required for these pathways is higher than fossil diesel. If the CO_2 used for RF93UCOME7-CCU were not obtained from the atmosphere but from biogas upgrading, the CED could be decreased, as shown by the literature review. Integration with an anaerobic digester could have the double advantage of increasing the overall efficiency of REDIFUEL by valorising low pressure steam and decreasing the energy requirements for direct carbon capture.

The results from JEC (2020a) had already shown that from a WTW perspective, it was more efficient to use woody residues to produce FT diesel than to produce DME, CNG, LNG or OME. Furthermore, the WTW results of this deliverable have also shown that for the same feedstock (bark), it is more efficient to produce REDIFUEL than hydrogen for transportation purposes.

However, REDIFUEL's CED is not lower than UCOME, a very efficient biofuel pathway, as was already clear from the literature review (Figure 5). When REDIFUEL is produced from low-value residues, the total CED is lower than fossil diesel's CED and the pathway can lead to final energy savings in the economy.

The energetic assessment presented in this deliverable is based on based on a preliminary plant design. Future developments of the FT catalyst may lead to higher CO conversion and process efficiency. Although the results are indicative of the potential of REDIFUEL, the accuracy of the results needs to be improved as the process design matures. The overall and biomass-to-fuel efficiency of REDIFUEL is comparable with the biomass-based Fischer-Tropsch plant designs derived from the literature, as the latter were also based on theoretical process design simulations. The CED results should be interpreted with more caution though, since the production processes of fossil diesel and biodiesel are well-known industrial processes for which reliable data was available. The process design of REDIFUEL is likely to change as research and development progresses, which may affect the results.

5.2 CONCLUSIONS

It can be concluded that the project goal to reach higher energy conversion efficiencies for renewable fuel production is partially achieved. The overall plant efficiency of the REDIFUEL concept plant is among the 25% highest values of FT plant efficiencies found in the scientific literature. The biomass-to-REDIFUEL efficiency is very low (10%), but the biomass-to-fuel efficiency, including all co-products, is in the normal range for FT plant designs (34%-49%).

When REDIFUEL is produced from waste streams or low-value residues, the fuel can lead to final energy savings from a WTW perspective of 23-27% compared to fossil diesel and 10% compared to hydrogen produced from the same feedstock.

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, the biomass-to-fuel efficiency, and consequently to decrease the CED. In addition, dryer feedstocks and valorisation of the waste low-pressure steam flows could improve the overall conversion efficiency and the CED.

6 Deviations from Annex 1

This deliverable was submitted after month 40, but was originally due in month 18, according to Annex 1. This delay was initially caused by a planning mistake since input from task 4.4 (starting in M18) was required for the energy efficiency evaluation of REDIFUEL. When this mistake was discovered, the planning was revised and the new submission date was Month 36. However, the delay of tasks 4.2, 4.3 and 4.4 further delayed this deliverable. This did not impact the work of other work packages.

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8 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 partners in the project for their valuable comments on previous drafts and for performing the review.

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

9 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.	With the current FT catalyst, it may not be possible to achieve a better CO conversion without also decreasing the olefin selectivity. This would mean that the biomass-to-REDIFUEL and the biomass-to-fuel efficiencies could not be improved much.	High	Medium	More extensive screening of different catalysts and reaction conditions to find another catalyst candidate. Research the possibility for tandem catalysis concept by integrating the Fischer-Trospch and the Hydroformlyation steps into one process. Upgrading the co-products to increase their value, in particular the C5-C10 iso-paraffin fraction. When the co-products are valuable enough, the average biomass-to-fuel efficiency is acceptable.

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

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

Appendix

Table A 1: Corresponding codes used in JEC (2020b) for the fuel pathways in Figure 5.

Fuel pathway in Figure 5	**Pathway code in** JEC (2020b)
Diesel – Crude oil	COD1
Diesel (with CCS) – Crude oil	COD1C
HVO – Waste cooking oil	WOHY1a
HVO – Palm oil	POJY1a
HVO – Rapeseed oil	ROHY1a
FAME – Rapeseed oil	ROFA1
Synthetic diesel (FT) – Black liquor	BLSD1a
Synthetic diesel (PY) – Waste wood	WWPD1
Synthetic diesel (HTL) – Waste wood	WWSD2a
Synthetic diesel (FT) – Waste wood	WWSD1a
Synthetic diesel (FT) – Farmed wood	WFSD1a
Synthetic diesel (FT) – Natural gas	GRSD1
Synthetic diesel (FT with CCS) – Natural gas	GRSD1c
Synthetic diesel (FT) – CO2 (biogas upgrading)	RESD2b
Synthetic diesel (FT) – CO2 (ambient air)	RESD2c
Synthetic diesel (flue gas)	RESD2a