Case study: the economic and environmental assessment of selected Biomass-to-Fischer Tropsch (FT) diesel chains in the EU

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Abstract:

The core objective of this paper is to determine and compare the present economic and environmental performance of (a) forestry wood-to-fischer-tropsch (FT) diesel, (b) straw-to-FT diesel, (c) pine forest residue-to-FT diesel, (d) wheat straw-to-FT diesel chains and conventional diesel for the EU, as well as to provide an outlook for the expected economic and environmental performances of the mentioned biomass-to-fuel chains and conventional diesel in 2030 and 2050. Building upon previous literature (Ajanovic et al. 2012; Dimitriou et al. 2018) concerning the economic and environmental performance of biomass-to- Fischer-Tropsch (FT) diesel chains, this paper aims to include recent data from the EU Horizon 2020 CLARA project to facilitate a comparison to previous outlooks. In order to highlight the importance of increasing the share of biofuels in the transport sector to achieve climate neutrality, a section of this paper will be dedicated to policies and future targets related to biofuels in Europe.

Keywords: biofuels, economics, CO_2 emissions, fischer-tropsch (FT) diesel

1 Introduction

In light of the European Green Deal's target to reduce net greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels and to render Europe the world's first climate-neutral continent by 2050 (EEA 2021), it is crucial to increase the market share of biofuels in the European transport sector. With regards to biofuels as final energy carriers, however, it is also important to distinguish between their different categories (BF-1, BF-2 and BF-3) and corresponding maturity levels. While first generation fuels have the advantage of being produced by an already fully mature technology, this is presently not entirely applicable for second generation biofuels and not at all for third generation fuels. As first generation biofuels have been associated with inefficiencies such as high cost, low net energy yields, as well as potential land use changes and competition to food production, second generation biofuels have been considered as a promising way to render biofuels cleaner (Ajanovic et al. 2012). This paper builds on literature (Ajanovic et al. 2012; Dimitriou et al. 2018; Gruber et al. 2021) that have suggested that 2nd generation biofuels, such as Fischer Tropsch (FT) diesel, are expected to become economically competitive between 2020 and 2030. This paper aims to make use of recent data on selected biomass-to-FT-Diesel chains from the EU Horizon 2020

CLARA project[1] to analyze and compare the ecological and economic performance of selected biomass-to-FT diesel chains to previous literature.

A schematic overview of the biomass-to-FT diesel technology employed in the CLARA project can be seen below (Fig. 1)

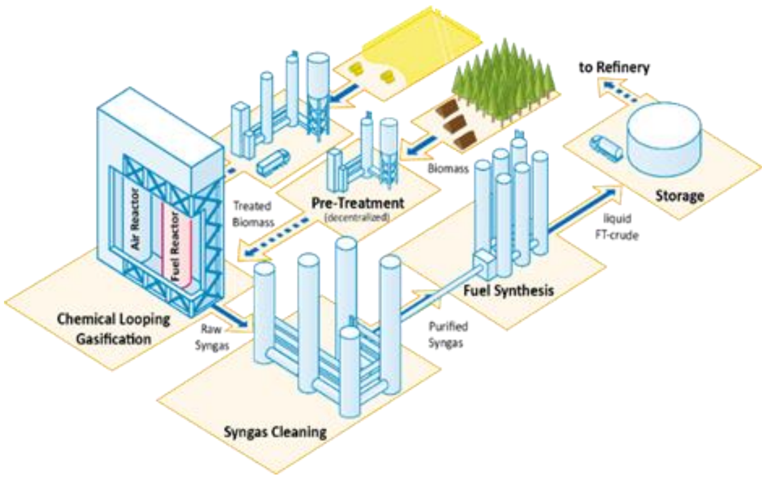

Fig. 1. Schematic overview of the biomass-to-FT-Diesel process chain of the EU Horizon 2020 CLARA project

The aim of CLARA is to develop a novel concept for the production of biofuels based on the chemical looping gasification (CLG) of biogenic residues. By investigating the complete biomass-to-fuel chain and combining advantages such as utilizing locally available biogenic residues and the economy of scales effect, the CLARA project aims to bring the production of Fischer-Tropsch (FT) diesel, through decentralized feedstock pre-treatment facilities and a centralized fuel production plant of 200 MW_{th}, to market maturity. The fuel production plant itself consists of a chemical looping gasifier for the production of a syngas, a gas treatment train to provide the required syngas composition for the subsequent synthesis, a Fischer-Tropsch (FT) reactor to convert the syngas into liquid transportation fuels, and a hydrocracking unit for the production of drop-in fuels from FT-wax (Dieringer et al. 2020).

For the scope of this paper, the economic and environmental performance of (a) forestry wood-to-fischer-tropsch (FT) diesel, (b) straw-to-FT diesel, (c) pine forest residue-to-FT diesel, (d) wheat straw -to-FT diesel chains and conventional diesel for the EU is analyzed. While chains (a) and (b) are based entirely on data from a previous study on the long-term prospects of biofuels in the EU-15 countries, see Ajanovic et al. (2012), chain (c) and (d) is partially based on recent data from the EU Horizon 2020 CLARA project, as well as on (Ajanovic et al. 2012) This paper argues that selected biomass-to-FT diesel chains have a particularly high potential as alternative fuel due to increased ecological performance (lower life-cycle carbon emissions) and financial competitiveness due to an expected economies of scale effect, thus making a case for their contribution to achieving the European Green Deal's climate targets.

[1] This work has received funding of the European Union's Horizon 2020-Research and Innovation Framework Programme under grant agreement No. 817841 (Chemical Looping gasification foR sustainAble production of biofuels-CLARA).

2 Major Literature with respect to reviews

In their review of the economic feasibility of various biomass-to-liquid process configurations for the production of liquid transport fuels, Dimitriou et al. 2018 came to the conclusion that Fischer-Tropsch synthesis seems to be the most promising fuel synthesis technology for the commercial production of liquid fuels via biomass gasification, since it achieved higher efficiencies and lower costs compared to other technologies. Further, Dimitriou et al. 2018 argue that fuel synthesis concepts that incorporate circulating fluidized bed gasification technology have higher fuel energy efficiencies and lower production costs. This is in line with this paper's argument that FT diesel has a particularly high potential as alternative fuel in terms of economic performance, especially as the technology employed in the refinery of the CLARA project also employs chemical looping gasification.

As already mentioned previously, Ajanovic et al. 2012 have suggested that 2nd generation biofuels, such as Fischer Tropsch (FT) diesel, will become economically competitive between 2020 and 2030. Further, they argue that better ecological performance due to lower life-cycle carbon emissions, no associated land-use- changes and economic competitiveness due to an economies of scales effect is expected for BF-2, such as FT diesel. To contrast BF-2, (Ajanovic et al. 2012) have also pointed out that first generation biofuels (BF-1) are associated with inefficiencies such as high cost, low energy yields, as well as potential land use changes and competition to food production.

The economic assessment carried out by Gruber et al. 2021 as part of their review of different experimental set-ups for the production of FT diesel indicates good preconditions towards commercialization of different proposed biomass-to-FT diesel systems as well. Further, Gruber et al. 2021 stress the importance of increasing the share of renewable fuels in the transport sector and point out that in Germany the share of renewable energy consumed by transportation settled to 5.2% with stagnating tendencies in 2017, which is, compared to 2007 rates (7.5%), a decrease.

In their review on the techno-economic feasibility of various alternative fuels to conventional diesel, Kargbo et al. 2021 mention that the primary sources of cost related to FT Synthesis are feedstock cost (40-60% of the total production cost), followed by syngas cleaning and conditioning (12-15% of the total production cost). Further, Kargbo et al. 2021 point out that biomass gasification followed by Fischer Tropsch synthesis is considered to be the most promising technique for alternative liquid fuel production due to its flexibility in feedstock acceptance and the ability to produce relatively high yields. Further, it has been argued that biomass gasification followed by Fischer Tropsch synthesis is in the forefront of development for liquid fuel production, as currently other techniques are still in their early development stages (Kargbo et al. 2021).

Dieringer et al. 2020 point out the importance of the de-carbonization of the transport sector, citing it is responsible for almost one quarter of the European GHG emissions and consumes 36% of the global final energy, thus signifying a key issue on the path to a closed carbon cycle. Further, the replacement of conventional fuels in the heavy freight transport and aviation industry, where electrification is currently not viable remaining a major hurdle, renders significant advances in the production of second generation biofuels through thermochemical conversion of biomass-based residues necessary (Dieringer et al. 2020). Chemical looping gasification as a novel biomass gasification technique that allows for the nitrogen-free production of high calorific synthesis gas from solid hydrocarbon feedstocks, without requiring a costly air separation unit (Dieringer et al. 2020), poses a promising technologic advancement facilitating a potential earlier market-maturity of larger scale production of Fischer Tropsch diesel.

3 Policies for Biofuels in Europe and future Targets

In order to highlight the importance of increasing the share of biofuels in the transport sector to achieve climate neutrality, this section is dedicated to policies and future targets related to biofuels in Europe. The transition towards a sustainable energy and transport system is an integral part of the European green deal (European Commission 2019). Goals for GHG emission reductions stated by the European Commission are 55% in 2030 and 90% in 2050 compared to the reference year 1990. The EU sustainable and smart mobility strategy (Mobility and Transport 2022) defined several milestones towards a sustainable future:

- 2030: at least 30 Mio. zero-emissions passenger cars
    - Market-readiness of zero-emission ships
- 2035: availability of emission-free air transportation
- 2050: Multimodal Trans-European Transport Network (TEN-T)
    - All heavy-duty vehicles are based on zero-emission technologies

The RED II (EU Parliament & Council 2018) proposes a target of 14% for the share of renewable fuels in 2030. The transport sector is currently heavily dependent on fossil fuels. Decarbonization can be achieved through carbon-neutral technologies e.g. electric vehicles powered with renewable energy or bio-based fuels. GHG emission reduction through biofuels was introduced through blending mandates such as bioethanol with gasoline (E10). However, the main sources for these so-called first-generation biofuels are food crops. This controversial usage of food crops for energetic utilization caused discussion on how the food prices are affected by the increased demand (Ajanovic 2011). Second-generation biofuels are made of agricultural and forest residues and are therefore more promising in terms of environmental sustainability. These advanced biofuels are currently not available on the market, but they will eventually be promoted in the next years as a consequence of the restricted share of food crops used for fuels in the RED II. The EU encourages also a circular economy strategy for recycling and utilization of residues to preserve natural resources. The production of advanced biofuels e.g., Fischer-Tropsch diesel, is a way to convert residues into valuable products and decrease emissions in the transport sector.

Another strategy for the promotion of biofuels is carbon taxation as a mitigation of external effects. The carbon tax as a regulating instrument of the consumption of fossil fuels functions as price per ton CO_2, which can either be applied on the carbon content of a fuel type or directly on CO_2 emissions e.g., of a power plant.

For several years the carbon tax was only a few EUR/ ton, but increased significantly in the last years (Hájek et al. 2019). Within the EU, Nordic countries are leading, with Sweden being the country with the highest CO_2 tax of 200 €/ton CO_2 in 2021; overall it is expected that this trend will continue EU-wide in future years.

4 Economic & Environmental assessment

4.1 Method of approach

While chain (a) and (b) will be based entirely on data from a previous study on the long-term prospects of biofuels in the EU-15 countries (Ajanovic et al. 2012), chain (c) and (d) will be partially based on recent data from the EU Horizon 2020 CLARA project, as well as on Ajanovic et al. (2012).[2]

For the economic analysis we consider energy costs, capital costs, as well as the following other costs: transport, operation & maintenance (O&M), labor, electricity and heat. The sum of these variables represent the total costs, C total, for the production of a certain biofuel (BF) from a selected feedstock (FS) for a specific year.

$$C_{total} = \frac{P_{FS}}{n_{ref}} + \frac{IC.\alpha}{T} + \frac{C_{O\&M}}{T} + R_{SP} \qquad [€/kWh] \qquad (1)$$

where:

EC……Energy content [kWh/ton FS]
FS…. Feedstock
P_{FS}……price FS [€/ton FS]
IC……investment costs [€/kW]
n……..efficiency of refinery
$C_{O\&M}$…..∑operation & maintenance, transport, labor, electricity, heat etc. [€/Kw]
R_{SP}…. Revenues side-products
T…. full load hours [h/yr]

For the environmental analysis, we consider the CO_2 input and the conversion efficiency for the selected feedstock, as well as the CO_2 input of the final biofuel product.

$$CO_{2\_SP} = n_{FS} \,.\, CO_{2\,input\,feedstock} + CO_{2\,input\,biofuel} \qquad (2)$$

where:

η_{FS}……Feedstock conversion efficiency
$CO_{2\ input\ feedstock}$……∑CO_2 (passive/sink, fertilizer, $fuel_{feedstock}$, $fuel_{transport}$) [kg CO_2/ kg FS]
$CO_{2\ input\ biofuel}$….∑CO_2 ($credit_{by\text{-}products}$, pressing, BF conv., other WTT, $transp._{fill.\ stat.,}$TTW) [kg CO_2/kg BF]

Abbreviations: WTT… well-to-tank, TTW…tank-to-wheel

4.2 Economic assessment: results & discussion

For the economic assessment of (a) forestry wood-to-fischer-tropsch (FT) diesel, (b) straw-to-FT diesel, (c) pine forest residue-to-FT diesel and (d) wheat straw-to-FT diesel chains, the total production costs for each biomass-to-fuel chain were calculated as outlined in the method of

[2] It is important to note, that at this point the only data for the overall biomass-to-fuel chains available from the CLARA project are the feedstock prices (€/tonne) for pine forest residues (PFR) and wheat straw (WS). The rest of the data for the calculations for chains (c) and (d) have been taken from Ajanovic et al. 2012 A second paper including a complete set of recent data from the CLARA project is planned as soon as the latter becomes available.

approach (1.4). As mentioned earlier, for chains (a) and (b), data was taken from (Ajanovic et al. 2012) and for chains (c) and (d) recent data on feedstock costs (€/ ton FS) were taken from the EU Horizon 2020 CLARA project, whereas the other data was taken from (Ajanovic et al. 2012), as the CLARA project is still in progress and further data collection is currently underway.

Fig. 2 below describes the structure of the current total production cost (for the year 2020) of forest wood-to-FT diesel and straw-to-FT diesel (chains (a) and (b)) and compares these with the corresponding total production cost for diesel for 2020 (€/kWh). Note, that for each biomass-to-fuel chain, next to the segmented production costs, the total production costs including CO_2 taxes are given (denoted in green). While the advantages of CO_2 tax can be seen in its contribution to a decrease of the total costs / kWh of fuel for both biomass-to-FT diesel chains, in 2020 it is evidently more economically feasible to produce conventional diesel, including CO_2 taxes.

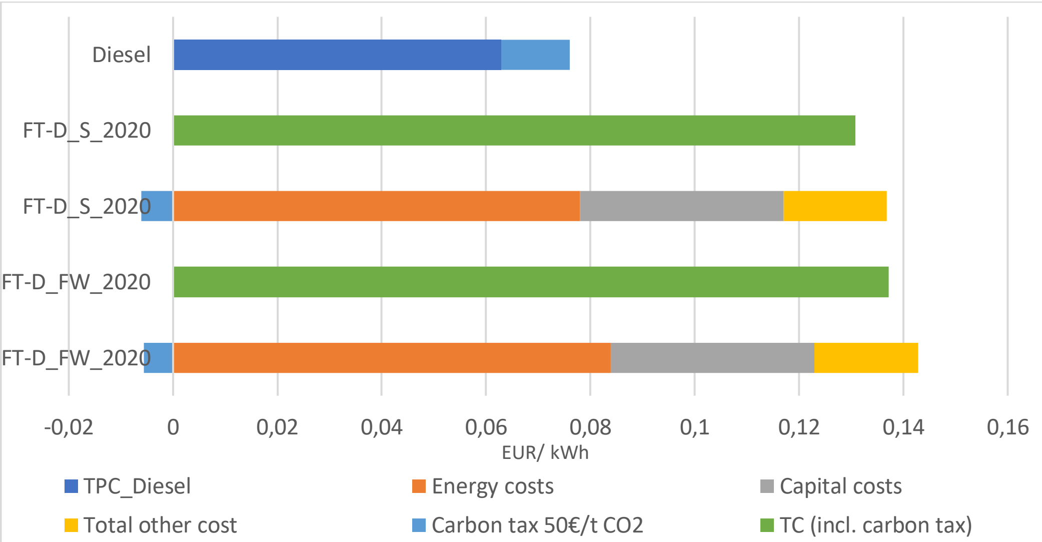

Fig. 2. Segmented total production costs for forest wood-to-FT diesel & straw-to-FT diesel chains incl. CO_2 taxes for 2020 (based on Ajanovic et al. 2012) compared to corresponding Diesel price (EUR/kWh) for the EU[3]

Fig. 3 below describes the structure of the total production cost (for the year 2020) of pine forest residues-to-FT diesel and wheat straw-to-FT diesel (chains (c) and (d)) and compares these with the corresponding total production cost for diesel for 2020 (€/kWh). Note, that for chains (c) and (d), recent feedstock prices (€/ton FS) were taken from the CLARA project, but all other data had to be taken from (Ajanovic et al. 2012) due to lack of data. Again, for each biomass-to-fuel chain, next to the segmented production costs, the total production costs including CO_2 taxes are given (denoted in green).

Similar to chains (a) and (b), the advantages of CO_2 tax can be seen in its contribution to a decrease of the total costs / kWh of fuel for both biomass-to-FT diesel chains. Interestingly, the costs of production of FT diesel from wheat straw and those for conventional diesel in 2020 seem to be approximately equal when including CO_2 tax. This can be attributed to the lower

[3] Abbreviations: TPC… total production cost, FT-D_FW…FT-diesel produced from forest wood, FT-D_S… FT-diesel produced from straw

than expected feedstock prices for wheat straw. According to new data from the CLARA project those were 36 €/ ton wheat straw, which is significantly lower than the straw prices of 119 €/ton for 2020 assumed by (Ajanovic et al. 2012). However, it also needs to be stated that all other parameters except for the feedstock prices do not reflect new data from the CLARA project and this below chains do not represent the status quo accurately.

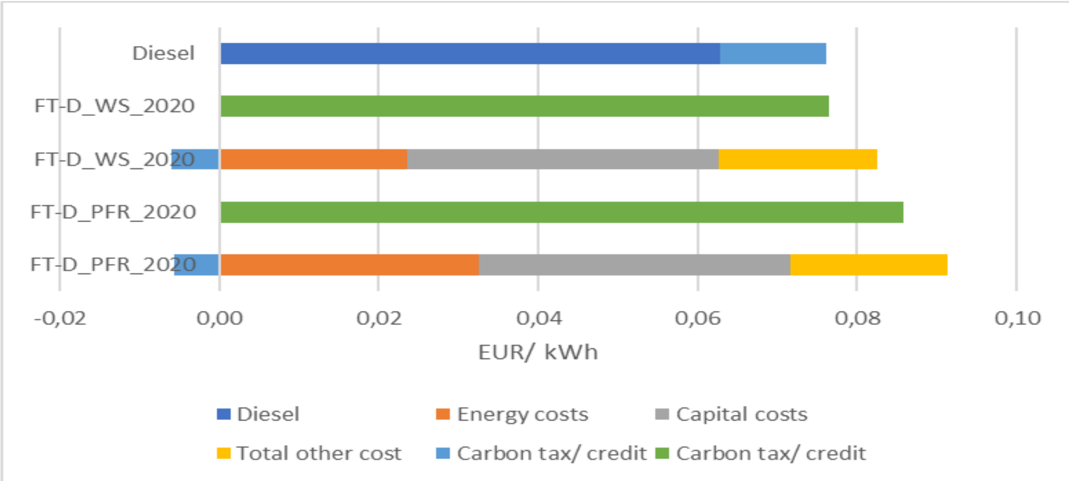

Fig. 3. Segmented total production costs for forest wheat straw-to-FT diesel & pine forest residues-to-FT diesel chains incl. CO_2 taxes for 2020 (based on CLARA project and Ajanovic et al. 2012) compared to corresponding Diesel price (€/kWh) for the EU

Fig. 4 depicts the total production cost structure scenarios for 2030 and 2050, calculated with data from (Ajanovic et al. 2012), and compares these with the corresponding forecasts of total production costs of diesel (€/kWh). It is evident that already in 2030 the production of FT diesel could be economically feasible and lower than that of conventional diesel, given our assumption that CO_2 taxes of ~180 €/ t CO_2 are going to be implemented. In 2050, both production costs as well as CO_2 taxes on conventional diesel are expected to increase, accompanied by a further decline of both costs for FT Diesel, thus rendering FT diesel a valuable alternative, both economically and environmentally.

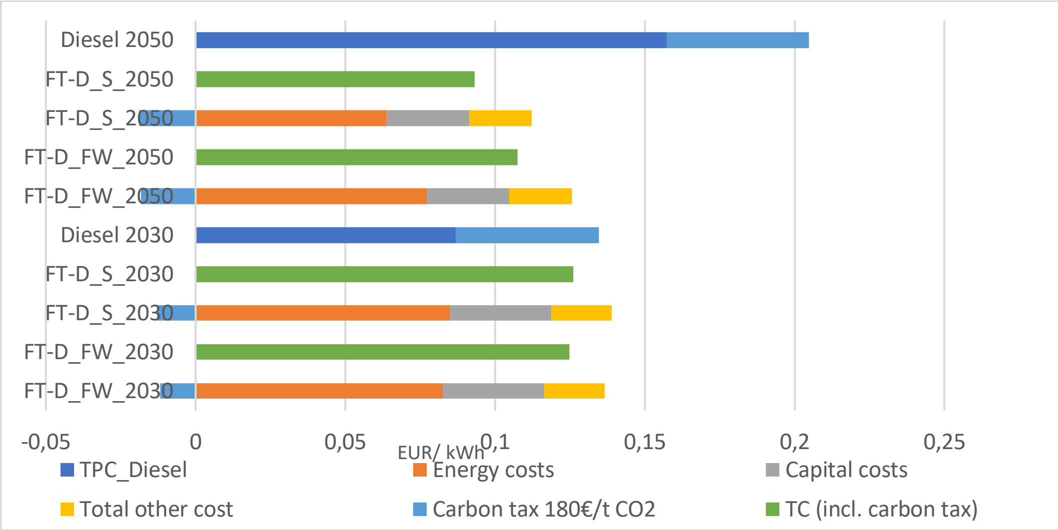

Fig. 4. Segmented total production costs scenarios for forest wood-to-FT diesel & straw-to-FT diesel chains incl. CO_2 taxes for 2030 and 2050 (based on Ajanovic et al. 2012) compared to corresponding Diesel prices (EUR/kWh) for the EU[4]

4.3 Environmental assessment: results & discussion

An environmental assessment in terms of CO_2 balances has only been carried out for chains (a) and (b) due to lack of data from the CLARA project at this point.

Fig. 4 below depicts the CO_2 balances of forest wood-to-FT diesel and straw-to-FT diesel chains for the years 2020, 2030 and 2050 and compares these to the corresponding conventional diesel CO_2 balance. While it is evident that, at present, the ecologic performance of FT diesel is already superior to that of conventional diesel, the environmental benefits in terms of negative lifecycle carbon emissions (kg CO_2/kg fuel) are expected to continuously increase until 2050 for both biomass-to- FT diesel chains under study.

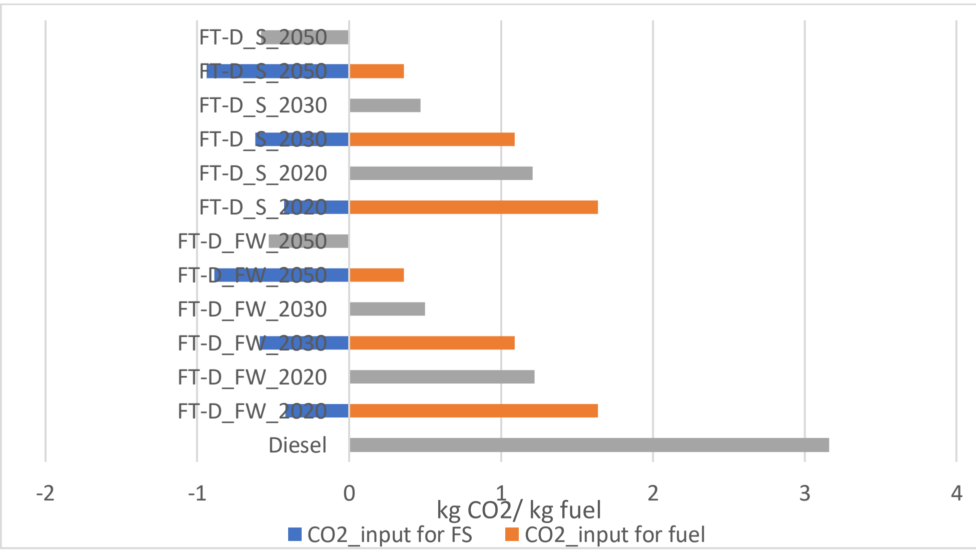

Fig. 4. CO_2 balances for forest wood-to-FT diesel & straw-to-FT diesel chains for 2020, 2030 and 2050 (based on Ajanovic et al. 2012) compared to corresponding Diesel CO_2 (TTW emissions) for the EU

[4] Where FT-D_S and FT-D_FW signify Fischer Tropsch diesel obtained from straw and forest wood, respectively

5 Conclusions & areas of further research

The major conclusions of this analysis are: (i) The way towards an increased share of 2nd generation biofuels, such as FT diesel, in the overall energy mix has to be accompanied by rigorous policy measures (e.g. regulations for min. share of renewable fuels in total energy mix); (ii) in order for 2nd generation biofuels to play a significant role in the energy transition a proper mix of CO_2-taxes and intensified R&D in order to improve the conversion efficiency from feedstock to fuel, thus leading to lower feedstock cost and improved ecological performance, are needed; (iii) the increase in production price and CO_2 taxes of conventional diesel, combined with the increase in ecologic and economic performance of 2nd generation biofuels, such as FT diesel, is highly likely to cause the latter to supersede conventional diesel by 2030, if not earlier.

In addition to the above, it should be pointed out that recent data on the feedstock costs for both straw and forest residues from the CLARA project suggested that these are significantly lower (36 €/ ton wheat straw & 50 €/ ton pine forest residue) than the estimate by Ajanovic et al. 2012 (119 €/ ton for straw & 129 €/ ton forest wood) for the year 2020. The cost of feedstock (€/ton) seems to have a significant effect on the overall costs of the full biomass-to FT diesel chain and the lower than expected feedstock prices combined with CO_2 taxes could lead to FT diesel production from wheat straw being economically feasible earlier than expected and approximately equal to conventional diesel in 2020, as is visualized in Fig. 5 below.

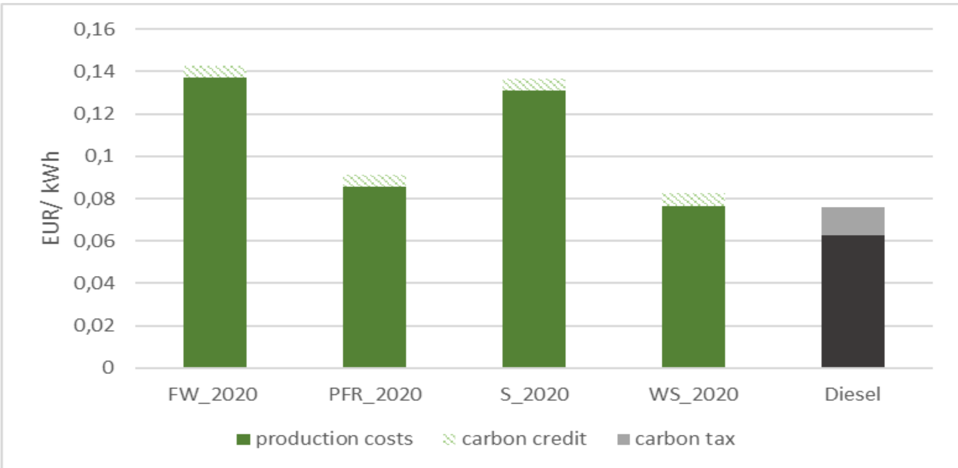

Fig. 5. Total production cost scenarios for forest wood-to-FT diesel (a), pine forest residue-to-FT diesel (c), straw-to-FT diesel (b) and wheat straw-to-FT diesel (d) chains incl. CO_2 taxes for 2020 (based on Ajanovic et al. 2012 & CLARA project) compared to corresponding Diesel prices (EUR/kWh) for the EU

We conclude, that the forecast of previous literature has proved to be correct and that the production of FT diesel is highly likely to become economically feasible by the mid-2020s, if not already earlier.

An area of further research to complement this paper would be to carry out an economic & environmental assessment of the biomass-to-FT diesel chains (c) and (d) with a complete set of data from the CLARA project. This is planned in form of a second paper upon completion of the project in April 2023.

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