Chemical Looping Gasification for Sustainable Production of Biofuels

H2020 Research and Innovation action
Grant Agreement no 817841

Deliverable D7.4:

Environmental evaluation of biofuel production processes via Life Cycle Analysis

Version No.: 1
Dissemination level: Public

Due date of deliverable: 2023-01-31
Submission date to coordinator: 2023-03-17
Actual submission date: 2023-03-28

Start date of project: 2018-11-01
End date of project: 2022-10-31

Author(s): [1]Juan Felipe Bermeo , [1]Ibai Funcia

Affiliation: [1]National Renewable Energy Centre

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 817841.

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1 Introduction

The CLARA project aims to produce advanced liquid biofuels based on chemical looping gasification (CLG). The value chain comprises stages (pretreatment, CLG, syngas cleaning, fuel synthesis and storage), as shown in figure 1.

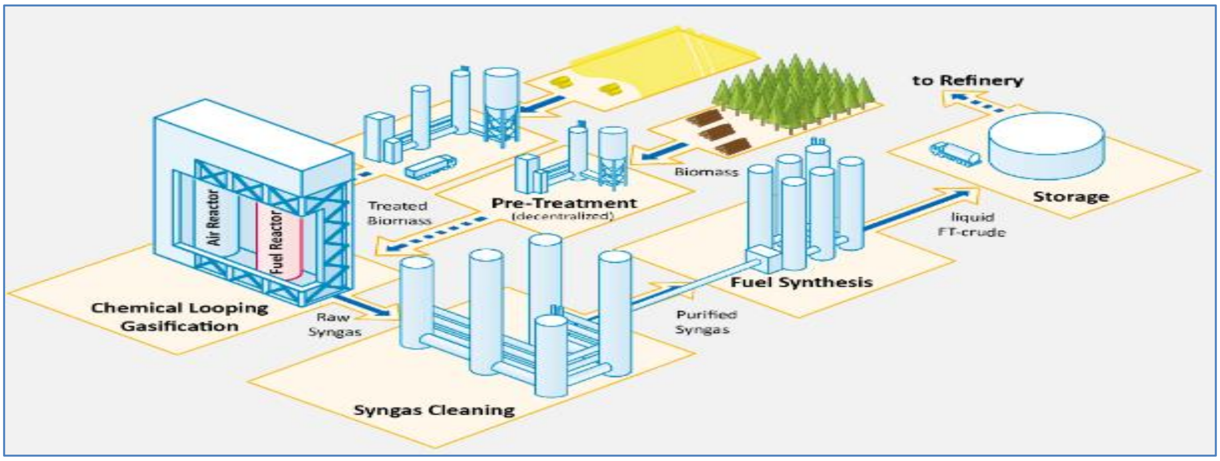

Figure 1. Schematic overview of the biomass-to-liquid process chain investigated in the CLARA project.

The aim of deliverable 7.4 is the Environmental Life Cycle Assessment (LCA) of the value chain and compare different feedstocks such as Wheat Straw (WS), Pine forest Residue (PFR) and Industrial Pellet (IP). LCA is a tool to assess the environmental impact and all resources used throughout the product life cycle, considering stages such as raw material acquisition, transport, production, use and end-of-life [1].

Life Cycle Assessment

According to ISO 14040:2006, the LCA is composed of four stages, as shown below (Figure 2):

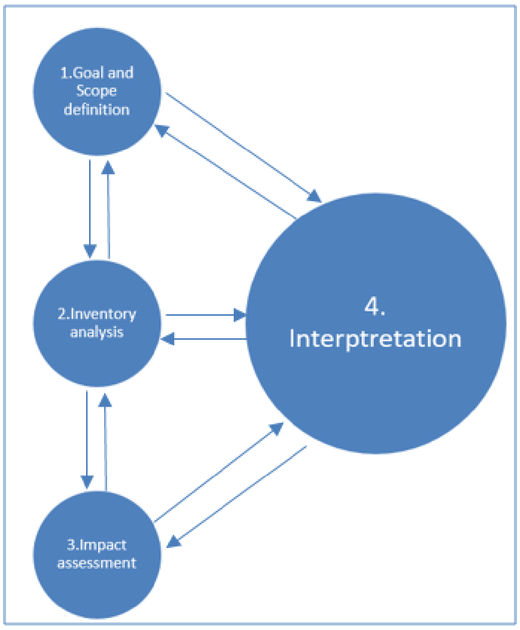

Figure 2. Life Cycle Assessment Stage. Adapted ISO [1]

- **Definition of objective and scope:** This consists of the purpose of the study where the system boundaries, data quality, assumed assumptions, etc., are included. The functional unit should also be included, as it refers to what is being evaluated.
- **Inventory analysis:** The respective inventory of all system input and output data is performed.
- **Impact assessment:** This phase's purpose is to evaluate potential environmental impacts using the inventory results.
- **Interpretation of results:** Final discussion phase and summary of the inventory results.

Only products or services that fulfil the same function can be compared when any comparison is intended. Choosing a functional unit referring to the function performed by the products or services in question is necessary.

Additionally, the study developed has been following international standards such as:

- ISO 14040:2006 Environmental Management—Life cycle assessment –Principles and framework.
- ISO 14044:2006 Environmental management -- Life cycle assessment -- Requirements and guidelines.
- ISO 14025:2006 Environmental labels and declarations - Type III environmental declarations - Principles and procedures.
- Product Environmental Footprint (PEF) Guide
- Suggestions for updating the Product Environmental Footprint (PEF) method.

Biomass Feedstocks

Biomass is characterized by the fact that the CO_2 emissions emitted into the atmosphere during biomass burning have been previously captured during its growth [2,3]. Therefore, the Greenhouse Gases emissions (GHG) generated by biomass converted to biofuels are basically due to the consumption for the cultivation process or tree growth, the production and subsequent distribution to the final product.

Regarding to WS is a potential source of biomass for biofuel production, as it is an agricultural residue produced in large quantities worldwide, and its low cost compared to other feedstocks. It has been demonstrated that wheat straws can be converted into liquid biofuels. The production of biofuels from a wheat straw can positively impact reducing dependence on fossil fuels and mitigating climate change. Several studies have investigated the environmental impact of using WS as a feedstock for the production of biofuels [2-9].

On the other hand, PFR is also an important feedstock for biofuel production, with a lower impact than fossil fuels. However, specific negative impacts of producing biofuels from pine residues have also been identified. For instance, the transport and handling of large quantities of pine residues can negatively impact energy consumption and greenhouse gas emissions. In addition, producing biofuels from pine residues can negatively impact local biodiversity and soil quality.

Therefore, an important aspect when using biomass for biofuel production is the allocation given to the crop or forest. There are different approaches to making the respective allocations [9]. For this case, the allocation proposed by Cherubini et *al.* [6] has been determined, where the inputs required for crop growth are not accounted for in this study, as it is assumed that the allocations are entirely for grain. For WS and PFR, only the required transport from harvesting to the pretreatment plant and from the pretreatment plant to the CLG plant are considered.

Carbon Capture and Storage (CCS)

Excessive carbon dioxide emissions are a global problem. For this reason, it is important to look for mechanisms that allow for effective and gradual de-carbonization of the industrial sectors. The Paris agreement in 2015 sought a global commitment to prevent the earth's temperature from rising by 1.5°C [10]. Different climate summits have been held to meet the objectives set where different strategies have been implemented and directed in the fight against climate change.

De-carbonization is an important point to be able to fulfil the established objectives. One of the current options on which research continues to advance is Carbon Capture and Storage (CCS) [11]. The concept of CCS refers to capturing CO_2 generated from a source to be stored and used as a valorised product [12,13]. For CO_2 capture, there are different options. These are classified as (i) post-conversion, (ii) pre-conversion and (iii) oxy-fuel combustion capture [12–17]. Post-conversion capture develops after post-combustion capture, as the gases pass through a chemical absorption column and the solvent absorbs the CO_2. Pre-combustion is when CO_2 is removed before combustion through gasification, producing a synthesis gas composed of CO and H2, and then CO is transformed into CO_2. While (iii) oxy-combustion uses pure oxygen, generating a mixture of CO_2 and water vapour, the water vapour is condensed, and the CO_2 stream is ready to be stored.

2 Environmental Assessment

The life cycle assessment is composed of different stages (figure 3). The extraction of raw material, the transport of the raw material to the production site, the manufacturing of this raw material to be transformed, the transport of the finished product to the customers, the use and the end of life of the product. Additionally, there are different scopes of analysis: (i) the first scope is from the gate to the gate, the aquamarine box. In this case, only the transformation of the raw material into a product is considered; (ii) the following scope is from the cradle to the gate, including the extraction, transport, and production process. There are other scopes for life cycle analysis, such as (iii) from the cradle to the grave, where all the stages are included, from the extraction of the raw material until the product reaches the end of its life cycle, and (iv) from cradle to cradle, for this last case apart from including all the stages of the previous scope, it also includes the circularity of the product once it has completed its life cycle.

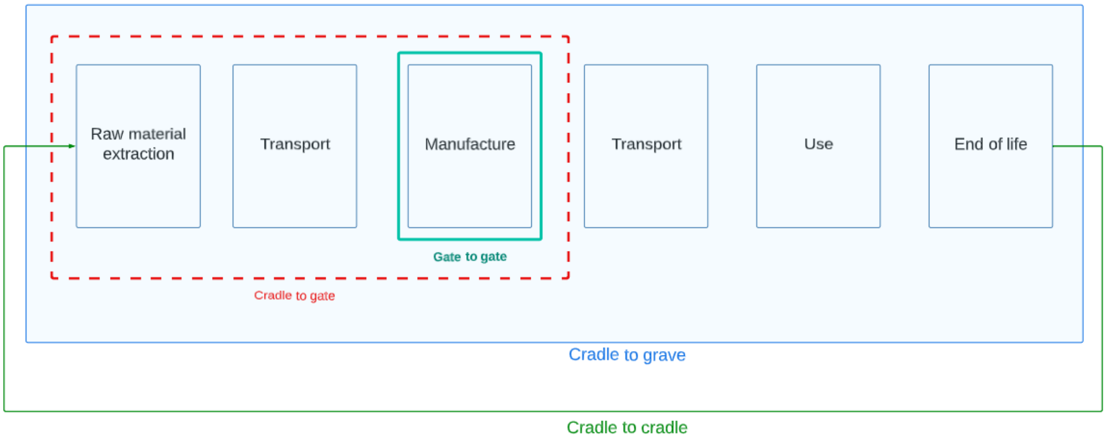

Figure 3. LCA system boundaries

2.1 Goal and scope

The main objective of this deliverable is to compare and quantify the environmental impact of a one-year life cycle of fuel production with different feedstocks such as WS, PFR, and IP. Finally, it is important to identify those processes and pollutants with the most significant impact.

2.2 System boundaries

The system under study is the LCA of the fuel production activity, from cradle to gate, as shown in figure 4.

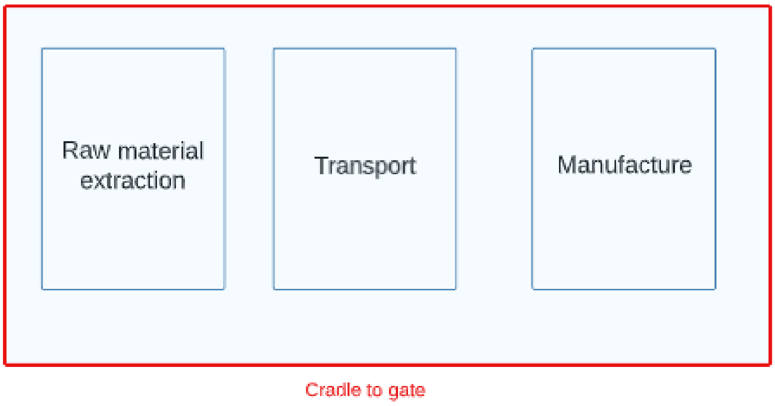

Figure 4. System boundaries CLARA project

2.3 Functional unit

The functional unit is the reference unit on which the results are normalised. The cradle-to-gate life cycle of 1 ton of liquid Fischer-Tropsch (FT) product has been selected.

2.4 System boundaries Advance Liquid Biofuels

Figure 5 shows the boundaries of the system under study, the inputs and outputs of matter and energy, and the processes that make up the system. Based on reference standards, the following procedures have not been taken into account, as their impact is considered to be negligible (impact of less than 1% for each stage of the life cycle):

- The manufacture of the production of capital goods with an expected lifetime of more than three years, buildings and other capital goods;
- Maintenance activities performed with a frequency of less than and more than three years;
- Transport carried out by workers on the home-factory-home route;
- Transport of personnel within the plant;
- Research and development activities; and
- Long-term emissions.

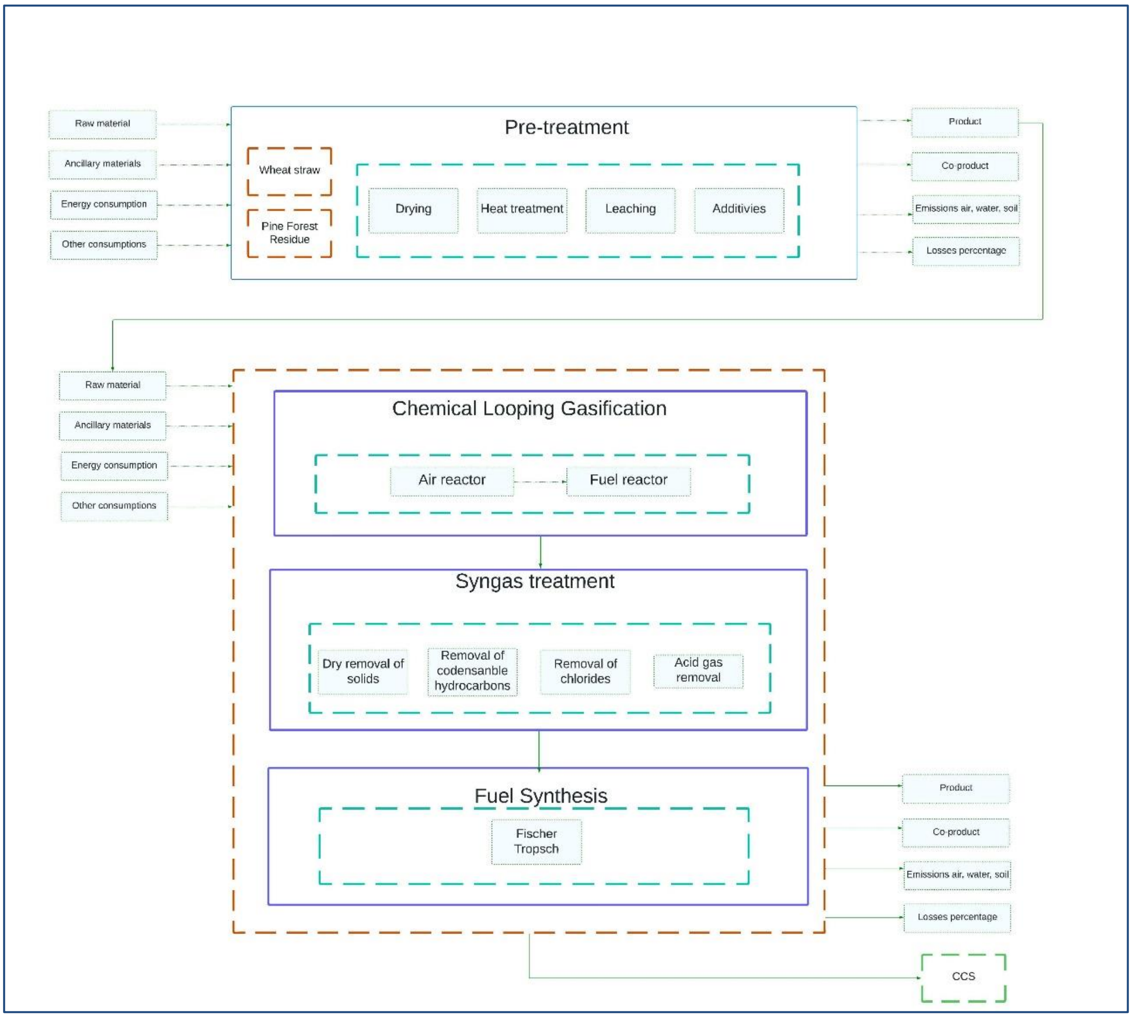

Figure 5. System boundaries

The study covers the cradle-to-gate approach, where the following stages are included:

- Pretreatment
- Chemical Looping Gasification (CLG)
- Gas Cleaning (GC)
- Fuel Synthesis (FS)
- Carbon Capture and Storage. (CCS)

Pretreatment:

Pretreatment is the stage where feedstock is made fit for the CLG process, in this case, just the transport between crop (WS) or forest (PFR), and pretreatment plant is considered.

Table 1. Distance crops to pretreatment plant

Feedstock	Distance to pretreatment (km)	Type of transport
Wheat straw	64	32 tn truck
Pine Forest Residue	58	

The IP has been modelled directly from the ecoinvet 3.8 database. In this case, “Wood pellet, measured as dry mass {RER}| wood pellet production | Cut-off, U” was used.

CLG-GC-FS-CCS

The feedstock treated in the previous stage is the main component to start the CLG process.

The distance between pretreatment and production plant is shown in table 2.

Table 2. Distance pretreatment to production plant

Feedstock	Distance to Plant (km)	Type of transport
Wheat straw	167	32 tn truck
Pine Forest Residue	127	

For more information about each stage's description process, check D1.3, D7.2 and D7.3

CCS

According to D7.3, the scope of this stage included CO2 capture in facilities. The transport and storage are out of range. CO_2 capture is an important tool for minimizing environmental impact, and several studies and guidelines about CCS have been developed[13,14,16,18–23]. To carry out the CO_2 capture using amine, the elements and quantities necessary to capture 1kg of CO_2 are specified in table 3. It is important to highlight that amine capture has an effectivity of 90%.

Table 3. Carbon capture[1] and storage of 1 kg CO2

Inputs	Unit	Value
Electricity	kWh	0.081
Amine	kg	0.0016
Water	kg	0.3

2.5 Cut-off rules

The purpose of applying cut-off rules in an LCA is to facilitate an efficient calculation procedure but not to hide data. All inputs and outputs of a process for which data are available should be included in the calculation.

Wherever possible, the assignment of criteria has been avoided. Specifically for cases where it has not been possible to avoid it (case of energy generation and consumption and waste generation), an allocation of loads based on physical mass criteria (1 ton of liquid FT product) has been made to obtain a better representation of reality.

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[1] In the Carbon Balance presented in D1.3, around of 45% CO_2 is captured.

2.6 Hypothesis

Raw materials have been assimilated into the elements with the highest environmental impact. The selected generic data for raw material production and fuel and electricity production were taken from the Ecoinvent 3.8 database. Simapro 9.4 software has been used to model the life cycle inventory and calculate the results.

Specific data on raw material quantities and energy requirements were obtained from the CLARA members and their different deliverables. In all cases, they refer to the full-year operation.

Regarding electricity production, the national electricity mix of Germany was used,for moelling according to the analysis carried out in Deliverable 7.4 Central Europe (CE) is one of the options regarding biomass logistics in terms of availability and therefore transport distnaces.

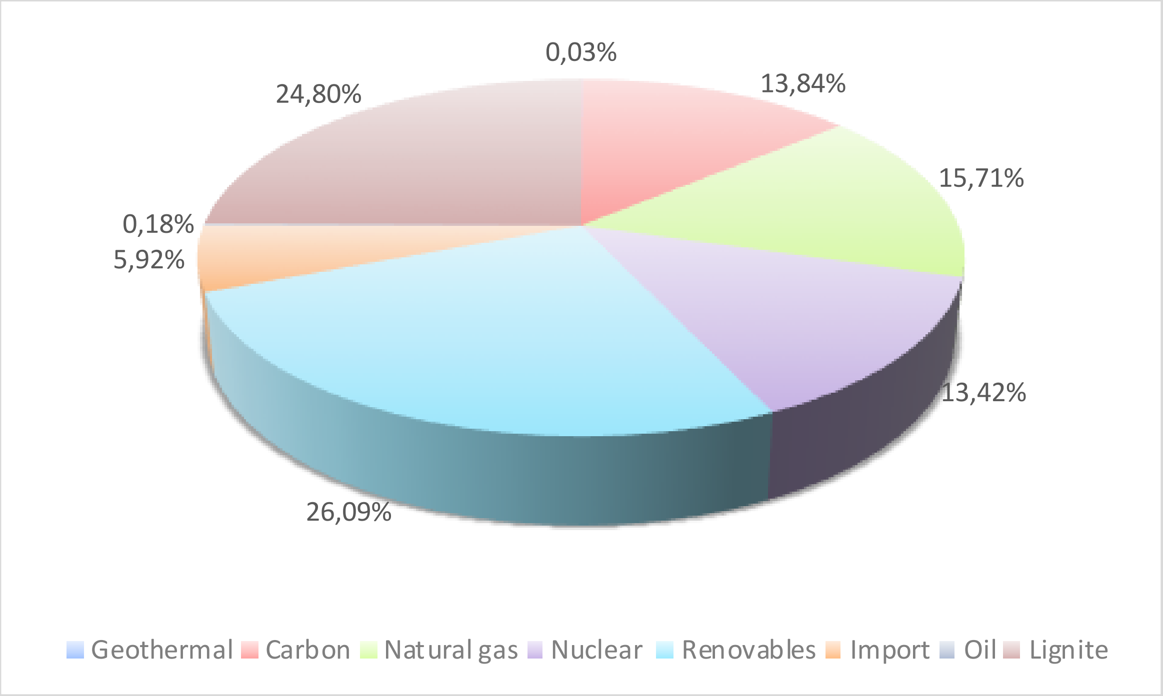

Figure 6. German Electric Mixed

The carbon content of WS, PFR, and IP can vary depending on the specific sample and method of measurement. However, it is possible to estimate the carbon content of these materials based on typical ranges reported [4,24–27].

Based on these estimates, it can approximate the carbon content of 1 tn of each material as follows:

- Wheat straw: 0.45-0.50 tn of carbon
- Pine forest residue: 0.50-0.55 tn of carbon
- Industrial pellet: 0.49-0.53 tn of carbón

Therfore, for this study, it is assumed that the ton of WS pellets contain about 45% CO_2 and PFR pellets and industrial pellet 50% CO_2.

2.7 Data quality requirements

The Environmental Footprint (EF) Method (adapted) impact model was used to calculate the results of the different impact categories. The EF is a methodology to measure the environmental performance proposed by the European Commission. Moreover, Simapro 9.4 software was used together with the Ecoinvent 3.8 database.

The LCA study was carried out at the CLARA project. This ensures that the results obtained are reliable, consistent and transparent. All generic data are from trusted sources and have been checked for plausibility.

- Time coverage: all primary data have been collected for a one-year operation (8000h).

- Technological coverage: the processes selected from the database consider equivalent technology.

- Geographical coverage: the geographical representativeness of the data reflects the region where the production plant is located, Germany in this case.

- Completeness: all relevant process steps are considered and modelled to represent the specific situation. The process chain is considered sufficiently complete concerning the objective and scope of this study.

- Reliability: primary data are collected using spreadsheets adapted for the production processes. Cross-checks of the plausibility of the mass and energy flows with the received data are performed. Similar checks are made on the software model developed during the study. The quality of the data can be described as good. Primary data collection is done comprehensively, and all relevant flows are considered.

- Consistency: to ensure consistency, all primary data are collected at the same level of detail. In contrast, all secondary (background) data are obtained from the Ecoinvent 3.8 databases. Allocation and other methodological choices are made consistently throughout the model.

3 Results

3.1 Life Cycle Assessment

This section shows the results obtained in the LCA.

The following life cycle impact assessment methods and indicators have been used in SimaPro 9.4 and Ecoinvent 3.8 database to calculate these results:

- Climate change: Environmental Footprint Method (adapted) V3.0
- Non-Renewable, Fossil: Energy - Cumulative energy demand V1.11

3.2 Pretreatment

WS

The WS pretreatment stage results are shown below, where 1 ton of liquid FT product has been considered. On the one hand, this process presents GHG emissions of 276 kg CO_2 eq. On the other hand, for the non-renewable energy use indicator, the result is 3175 MJ. As can be seen in the Table 4 and in Figure 7, for the two indicators, the most significant impact is represented by electricity consumption, which supposed about 90.8% of the total contribution in the case of the climate change indicator and 86.8 % for non-renewable, fossil.

Table 4. Impacts of Wheat Straw Pretreatment

Indicator	Unit	Total	Additve	Electricity	Transport
Climate change	kg CO2 eq	276	3	250	23
Non renewable, fossil	MJ	3175	64	2757	354

The figure shows the percentage distribution by source in both indicators analyzed.

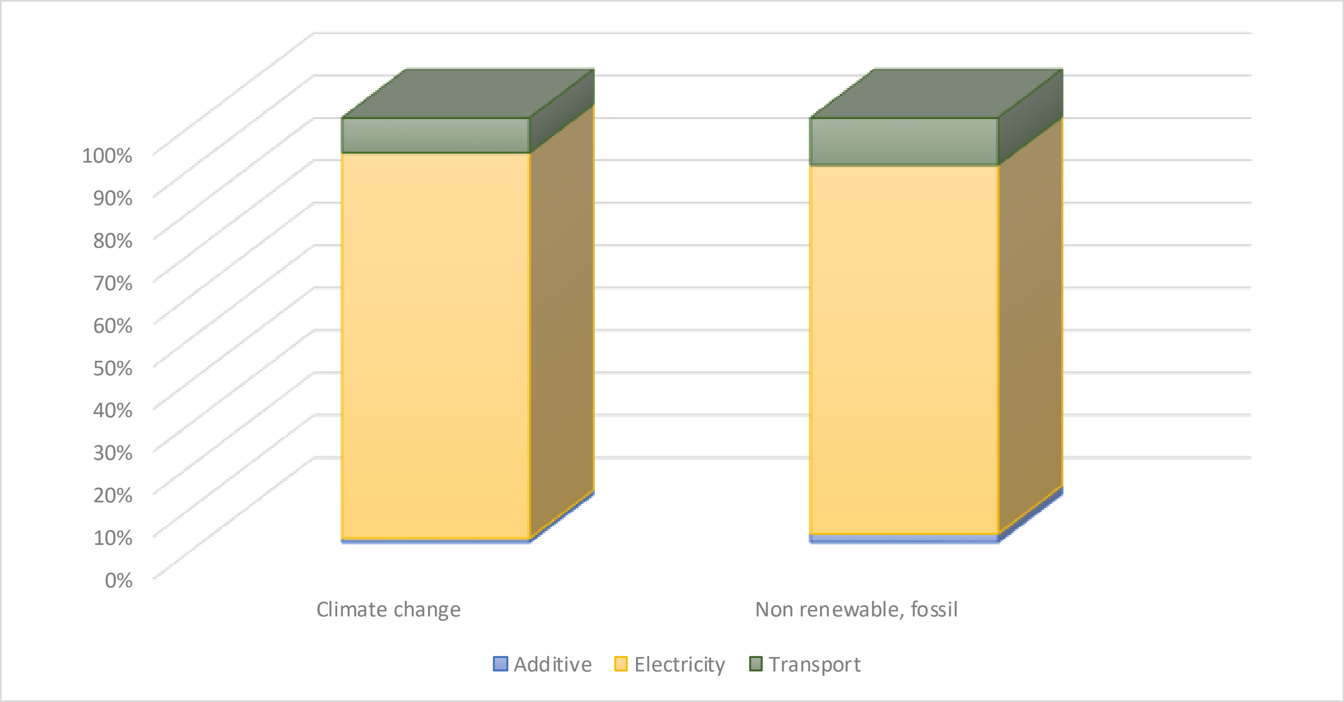

Figure 7. Contribution of sources by indicator - WS

PFR

The PFR pretreatment stage results are shown below, where 1 ton of liquid FT product has been considered. On the one hand, this process presents GHG emissions of 375 kg CO_2 eq. On the other hand, for the non-renewable energy use indicator, the result is 4227 MJ. As can be seen in Table 5 and in Figure 8, for the two indicators, the most significant impact is represented by electricity consumption, which supposed about 89.1% of the total contribution in the case of the climate change indicator and 87.3 % for non-renewable, fossil.

Table 5. Impacts of Pine Forest Residue Pretreatment

Indicator	Unit	Total	Electricity	Transport	Ash	Air
Climate change	kg CO2 eq	376	335	19	0	22
Non renewable, fossil	MJ	4228	3692	298	1	237

The figure shows the percentage distribution by source for both indicators analyzed.

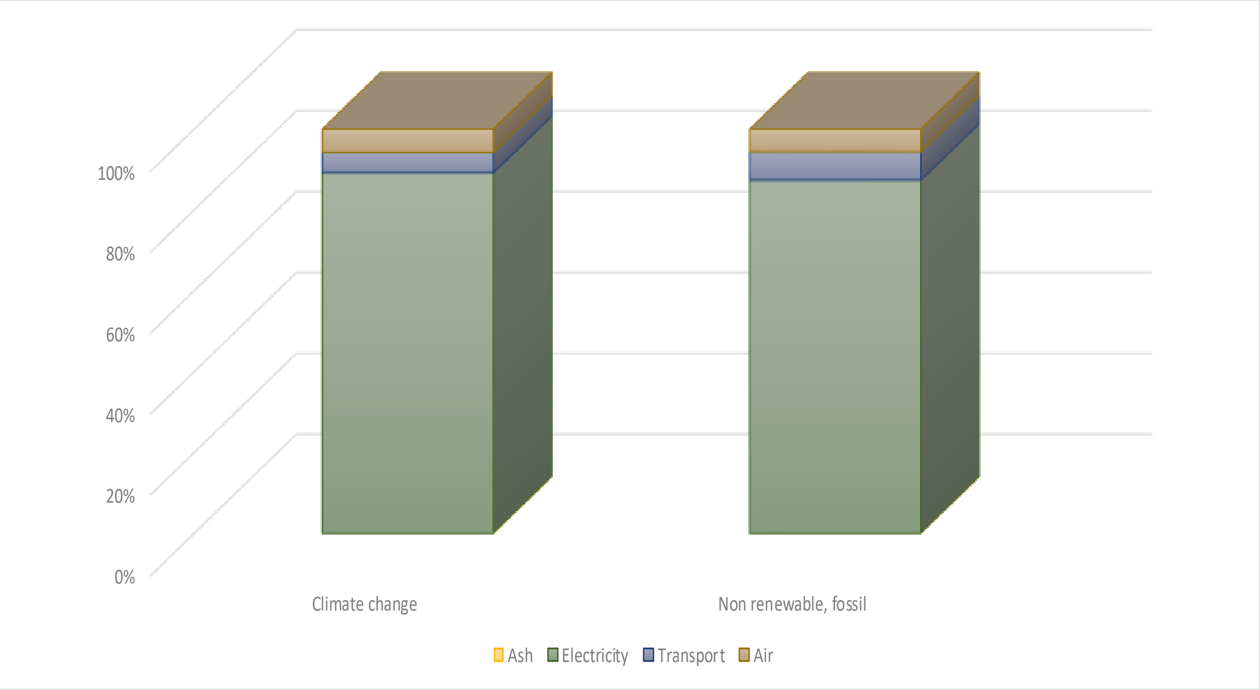

Figure 8. Contribution of sources by indicator - PFR

Pretreatment comparison

The following figures (Figure 9 and Figure 10) show the comparison between WS and PFR in climate change indicator and non-renewable fossil. It can be seen that for the PFR, the electricity impact is higher than the WS.

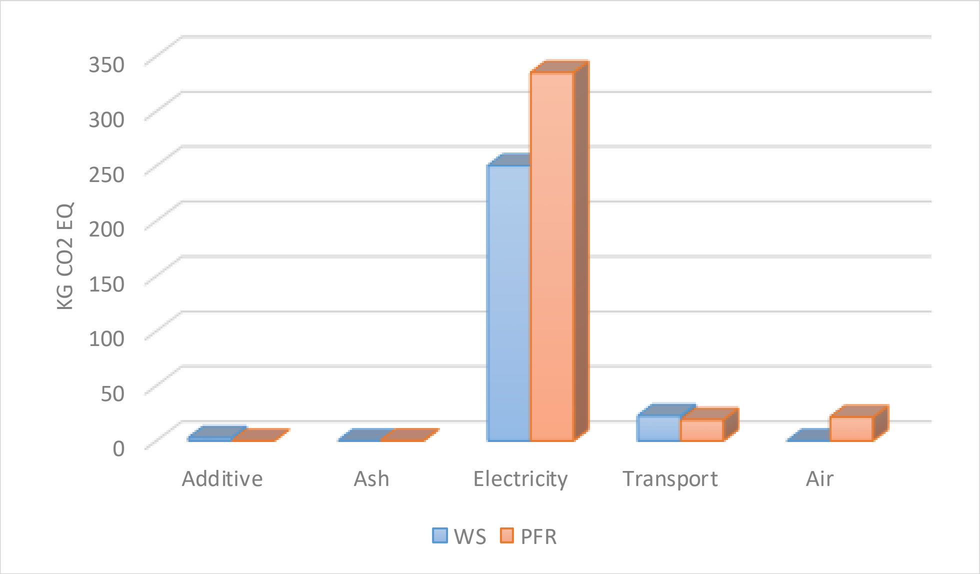

Figure 9. Comparison on kg CO_2 eq –WS vs PFR

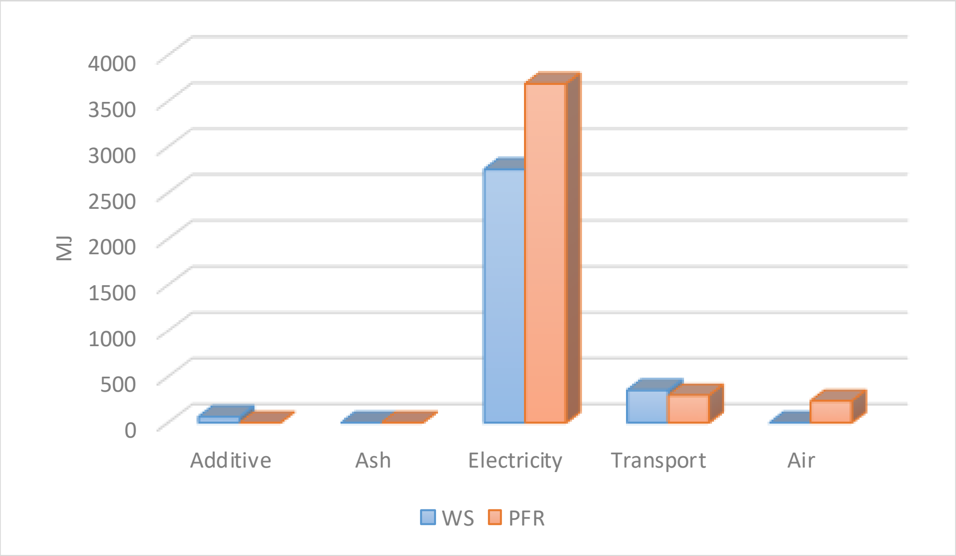

Figure 10. Comparison on MJ -WS vs PFR

3.3 Core process (CLG – GC – FS)

To core process, two types of analysis have been carried out at the acid gas removal stage. The first is a novel method proposed within the lines of work in which amine is used; the second uses Rectisol®. This process has been carried out for WS, PFR, and IP.

Wheat Straw

The results are presented below, first for the novel method and the second part for Rectisol®.

Novel method

For the production of 1 ton of liquid FT product, in the central stage of the process, and referring to the novel method, the greenhouse gas emissions are -2030 kg CO_2 eq, emissions are negative due to CO2 sequestration . On the other hand, for the non-renewable energy use indicator, the result is 15844 MJ. As can be seen in the table 6 and figure 11, for the two indicators, the most significant impact is represented by electricity consumption, which supposed about 37.2% of the total contribution in the case of the climate change indicator and 52.5 % for non-renewable, fossil. The second most significant impact is generated by pre-treatment, with 13.5% and 20.0% for the climate change and fossil energy use indicators, respectively. Finally, the third most representative impact of the whole system is from CO2 capture, with 8.5% for the climate change indicator and 12.4% for the use of fossil energy.

Table 6. Wheat Straw impact - Novel method

Indicator	Unit	Total	Pretreatment	Water	Amine	CO2	Oxygen Carrier	Electricity	Transport	Air	Wastewtaer	Solid residues	CC	WS
Climate change	kg CO2 eq	-2030	276	3	59	1	23	755	12	3	1	2	174	-3339
Non-renewable. fossil	MJ	15844	3175	33	1353	22	704	8333	189	29	9	23	1975	0

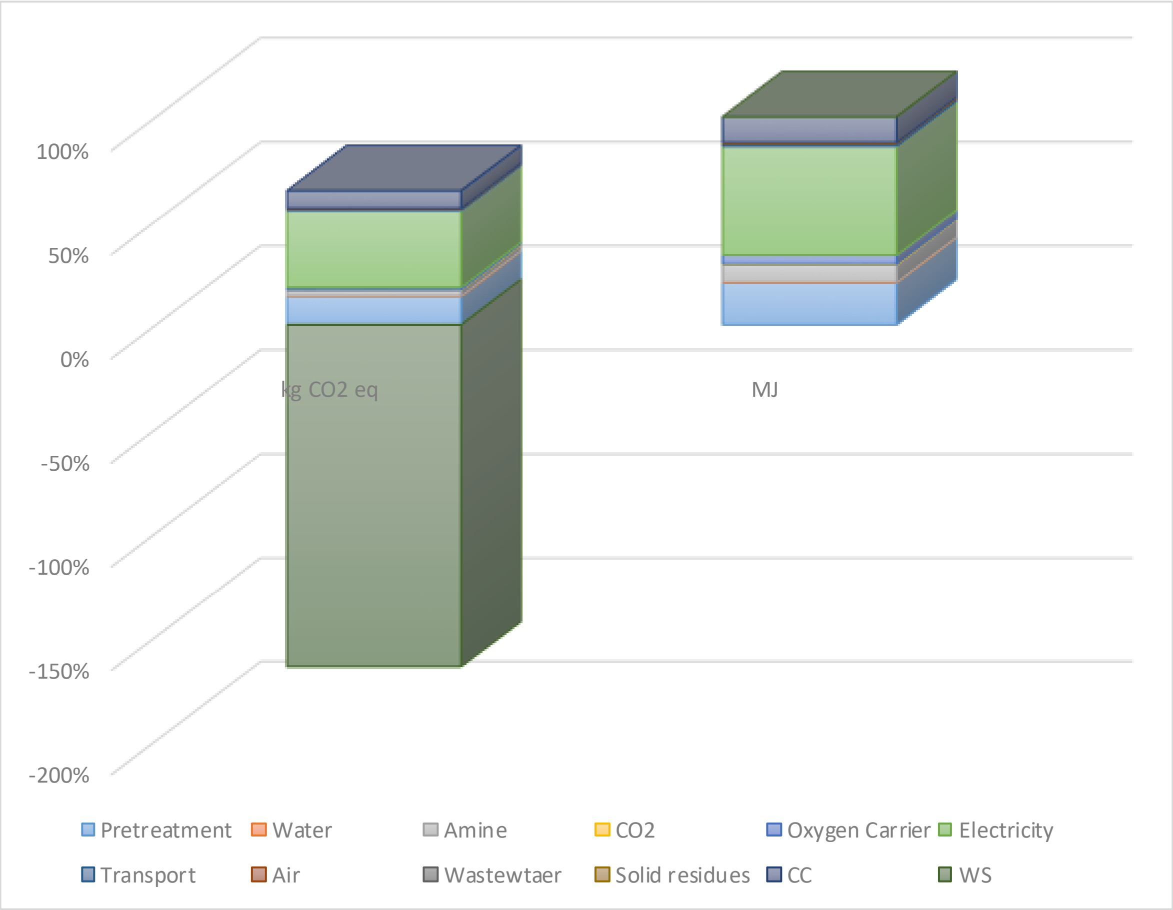

Figure 11. WS – Novel method

Rectisol®

For the production of 1 ton of liquid FT product, in the central stage of the process, and referring to Rectisol® method, the greenhouse gas emissions are -1925 kg CO_2 eq, emissions are negative due to CO2 sequestration. On the other hand, for the non-renewable energy use indicator, the result is 16836 MJ. As can be seen in the table 7 and figure 12, for the two indicators, the most significant impact is represented by electricity consumption, which supposed about 47.1% of the total contribution in the case of the climate change indicator and 59.4 % for non-renewable, fossil. The second most significant impact is generated by pre-treatment, with 14.3% and 19.0% for the climate change and fossil energy use indicators, respectively. Finally, the third most representative impact of the whole system is from CO2 capture, with 9.0% for the climate change indicator and 11.7% for the use of fossil energy.

Table 7. Wheat Straw impact - Rectisol®

Indicator	Unit	Total	Pretreatment	Water	Methanol	CO2	Oxygen Carrier	Electricity	Transport	Air	Wastewtaer	Solid residues	CC	WS
Climate change	kg CO2 eq	-1926	275	3	13	1	23	908	12	2	1	2	174	-3339
Non-renewable, fossil	MJ	16837	3165	33	680	22	704	10012	189	25	9	23	1975	0

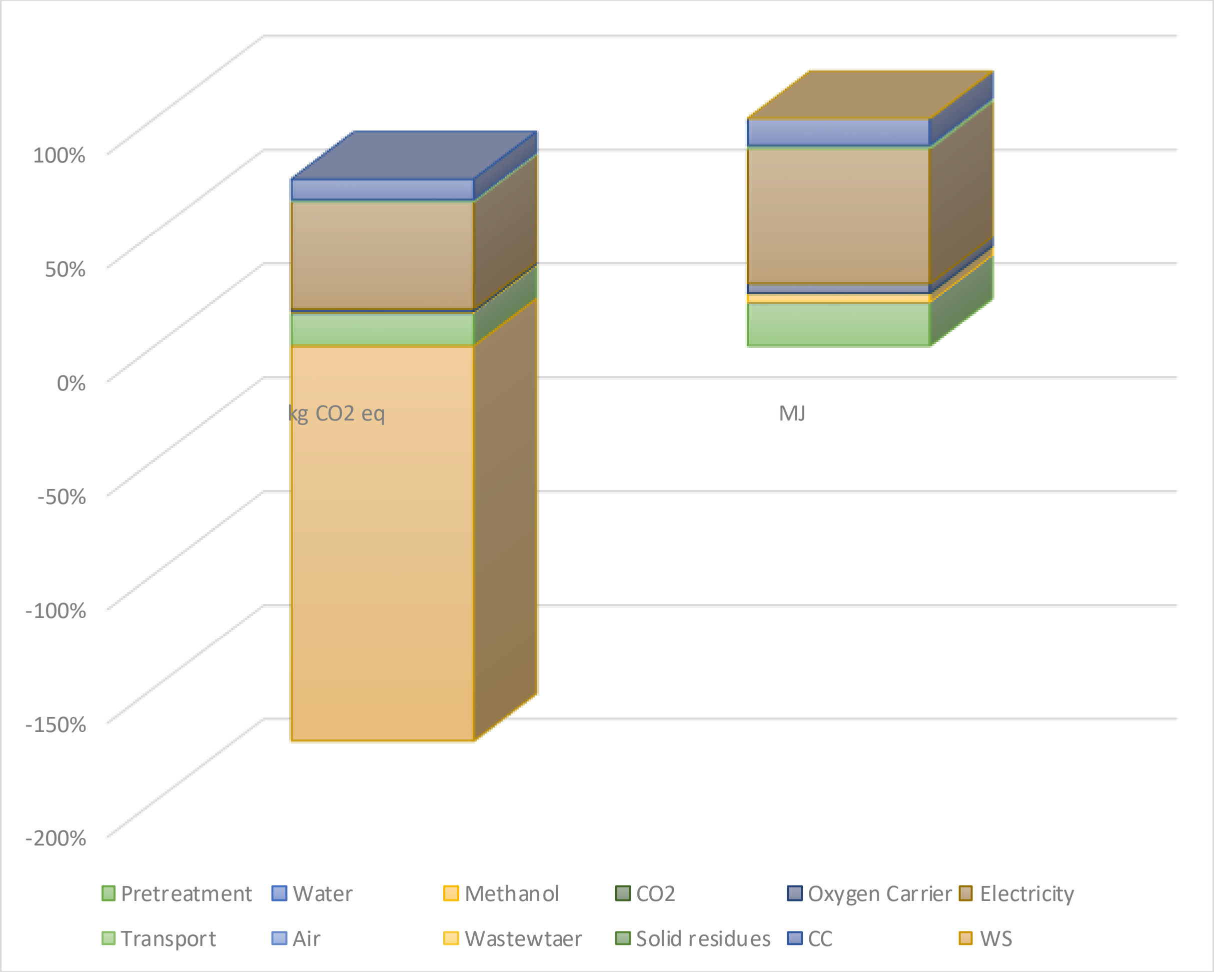

Figure 12. WS – Rectisol®

Wheat Straw - Novel method vs Rectisol®

The following figures (Figure 13 and Figure 14) show the comparison between the novel and Rectisol® method for WS. It can be seen that the environmental impact and the non-renewable energy of fossil origin have a lower impact on the novel method.

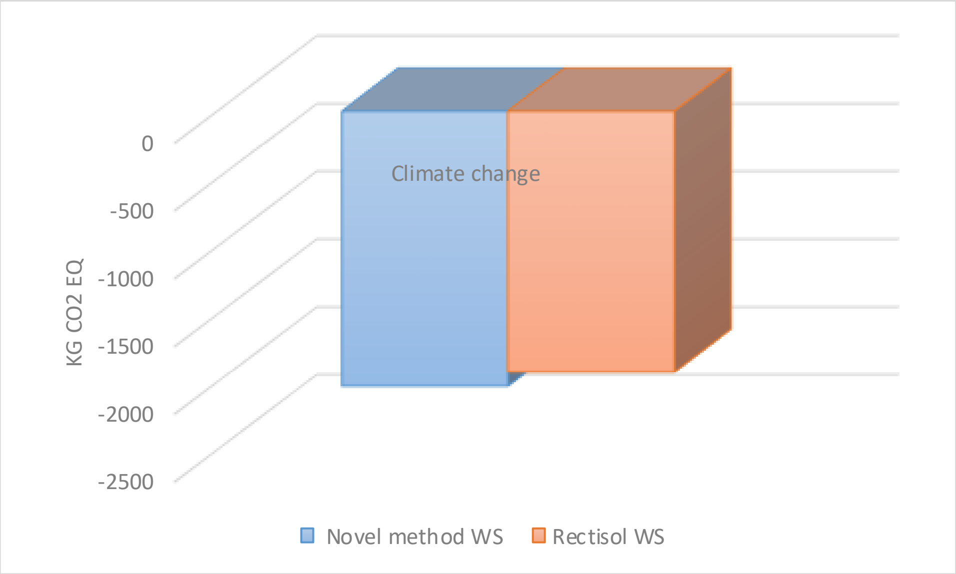

Figure 13. Comparison on kg CO_2 eq -WS Novel method vs Rectisol®

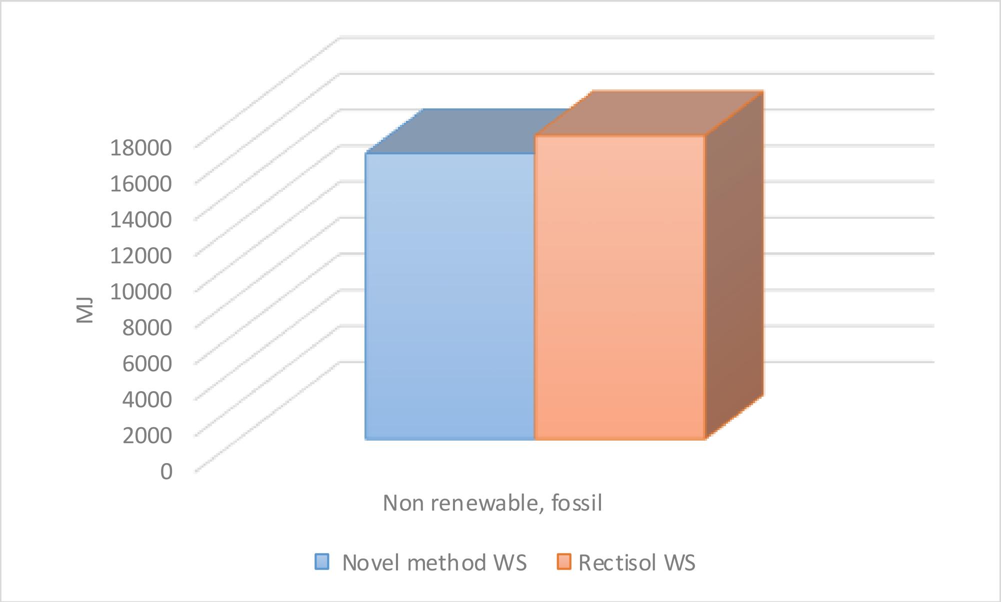

Figure 14. Comparison on MJ -WS Novel method vs Rectisol®

Pine Forest Residue

The results are presented below, first for the novel method and the second part for Rectisol® method.

PFR - Novel method

For the production of 1 ton of liquid FT product, in the core stage of the process, and referring to the novel method, the greenhouse gas emissions are -2074 kg CO_2 eq, emissions are negative due to CO_2 sequestration. On the other hand, for the non-renewable energy use indicator, the result is 17338 MJ. As can be seen in the table 8 and figure 15, for the two indicators, the most significant impact is represented by electricity consumption, which supposed about 38.1% of the total contribution in the case of the climate change indicator and 50.2 % for non-renewable, fossil. The second most significant impact is generated by pre-treatment, with 18.12% and 24.38% for the climate change and fossil energy use indicators, respectively. Finally, the third most representative impact of the whole system is from CO2 capture, with 8.9% for the climate change indicator and 12.1% for the use of fossil energy.

Table 8. Pine Forest Residue Impact - Novel method

Indicator	Unit	Total	Pretreatment	Water	Amine	CO2	Oxygen Carrier	Electricity	Transport	Air	Wastewtaer	Solid residues	CC	PFR
Climate change	kg CO2 eq	-2074	376	3	93	2	24	789	13	4	1	1	186	-3564
Non-renewable, fossil	MJ	17338	4228	34	1242	22	738	8706	197	44	10	10	2108	0

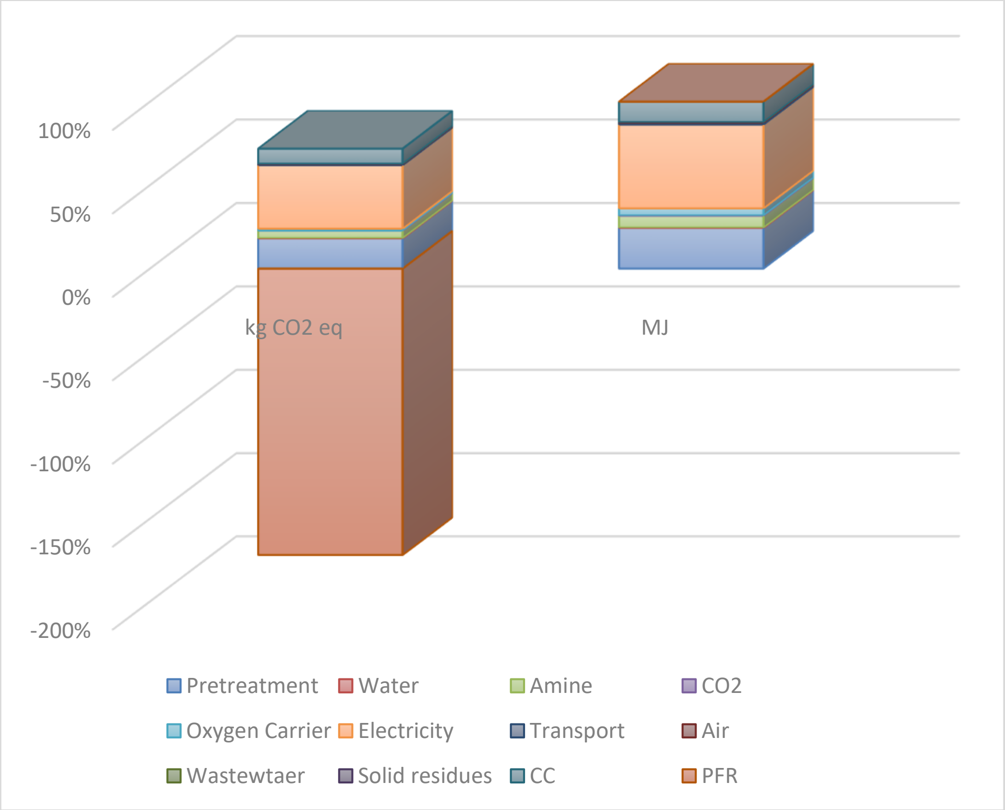

Figure 15. PFR – Novel method

PFR - Rectisol®

For the production of 1 ton of liquid FT product, in the central stage of the process, and referring to the Rectisol method, the greenhouse gas emissions are -2022 kg CO_2 eq, emissions are negative due to CO_2 sequestration. On the other hand, for the non-renewable energy use indicator, the result is 18274 MJ. As can be seen in the table 9 and figure 16, for the two indicators, the most significant impact is represented by electricity consumption, which supposed about 47.7% of the total contribution in the case of the climate change indicator and 60.2 % for non-renewable, fossil. The second most significant impact is generated by pre-treatment, with 19.5% and 25.10% for the climate change and fossil energy use indicators, respectively. Finally, the third most representative impact of the whole system is from CO2 capture, with 9.6% for the climate change indicator and 12.5% for the use of fossil energy.

Table 9. Pine Forest Residue impacts - Rectisol®

Indicator	Unit	Total	Pretreatment	Water	Methanol	CO2	Oxygen Carrier	Electricity	Transport	Air	Wastewtaer	Solid residues	CC	PFR
Climate change	kg CO2 eq	-2023	376	3	14	2	24	919	13	4	1	1	186	-3564
Non-renewable, fossil	MJ	18274	4228	34	747	22	738	10136	197	44	10	10	2108	0

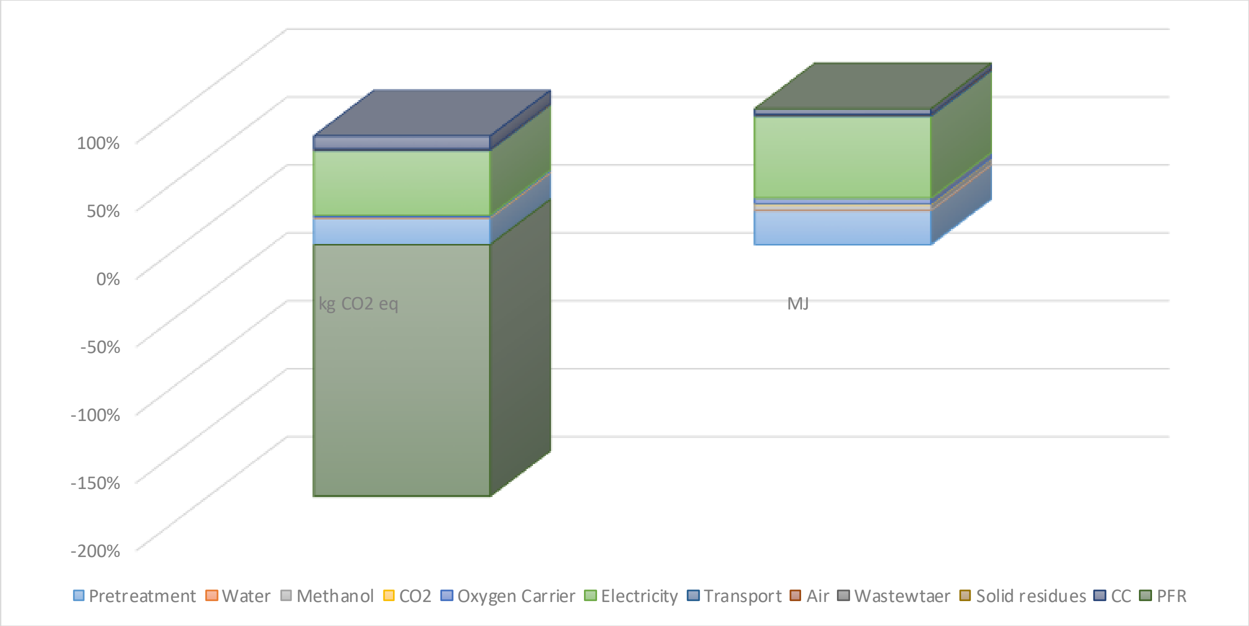

Figure 16. PFR – Rectisol®

PFR– Novel method vs Rectisol®

The following figures (Figure 17and Figure 18) show the comparison between the novel and Rectisol® method for PFR. It can be seen that the environmental impact and the non-renewable energy of fossil origin have a lower impact on the novel method.

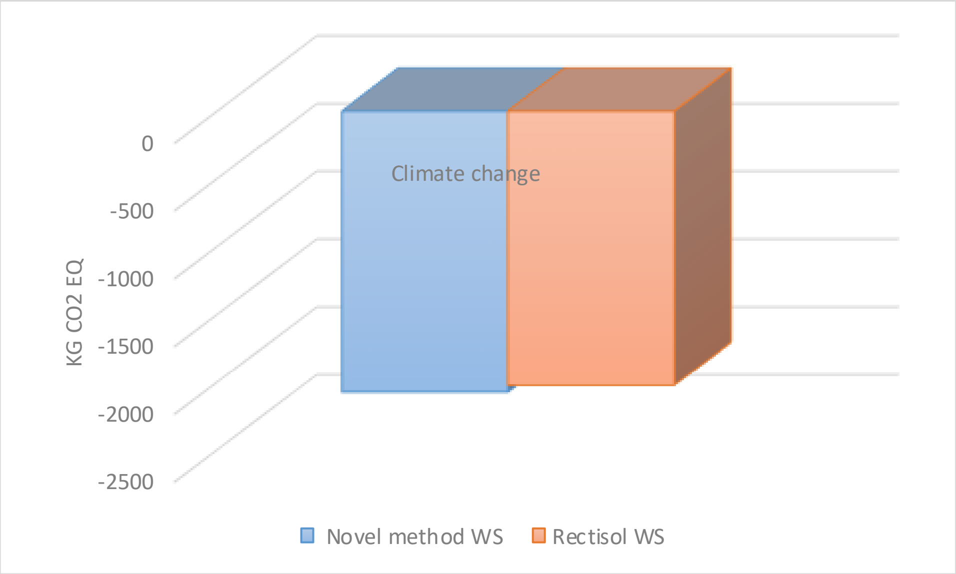

Figure 17. Comparison on kg CO_2 eq -PFR Novel method vs Rectisol

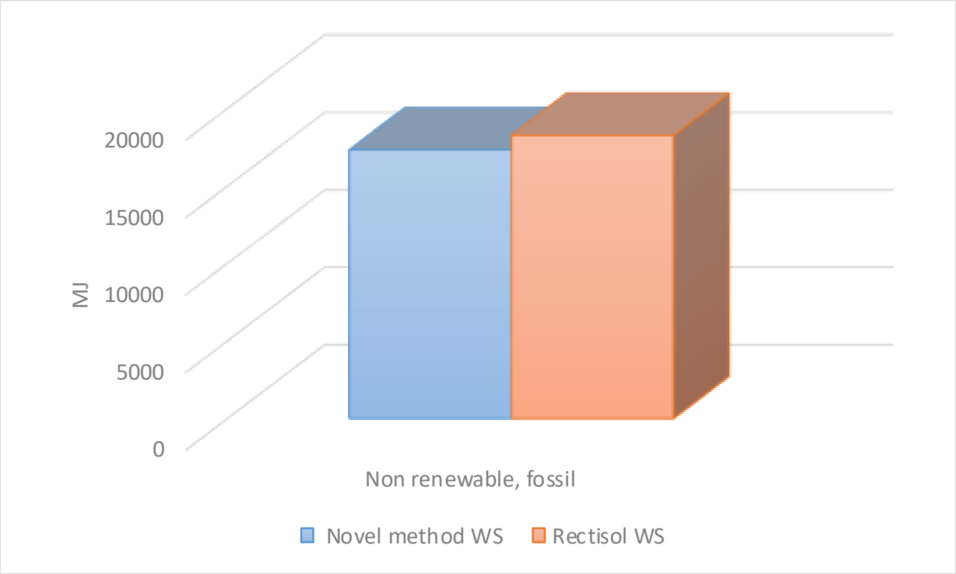

Figure 18. Comparison on MJ -PFR Novel method vs Rectisol®

Industrial Pellet[2]

The results are presented below, first for the novel and the second part for Rectisol®.

IP - Novel Method

For the production of 1 ton of liquid FT product, in the core stage of the process, and referring to the Rectisol method, the greenhouse gas emissions are -2022 kg CO_2 eq, emissions are negative due to CO_2 sequestration. On the other hand, for the non-renewable energy use indicator, the result is 21428 MJ. As can be seen in the table 10 and figure 19, for the two indicators, the most significant impact is represented by electricity consumption, which supposed about 39.1% of the total contribution in the case of the climate change indicator and 40.6 % for non-renewable, fossil. The second most significant impact is generated by pre-treatment, with 30.3% and 38.1% for the climate change and fossil energy use indicators, respectively. Finally, the third most representative impact of the whole system is from CO2 capture, with 9.7% for the climate change indicator and 10.3% for the use of fossil energy.

Table 10. Industrial Pellet Impacts - Novel method

Indicator	Unit	Total	Pretreatment	Water	Amine	CO2	Oxygen Carrier	Electricity	Transport	Air	Wastewtaer	Solid residues	CC	IP
Climate change	kg CO2 eq	-2022	613	3	93	2	24	789	15	4	1	2	196	-3762
Non-renewable, fossil	MJ	21428	8159	34	1242	23	738	8706	227	41	10	23	2225	0

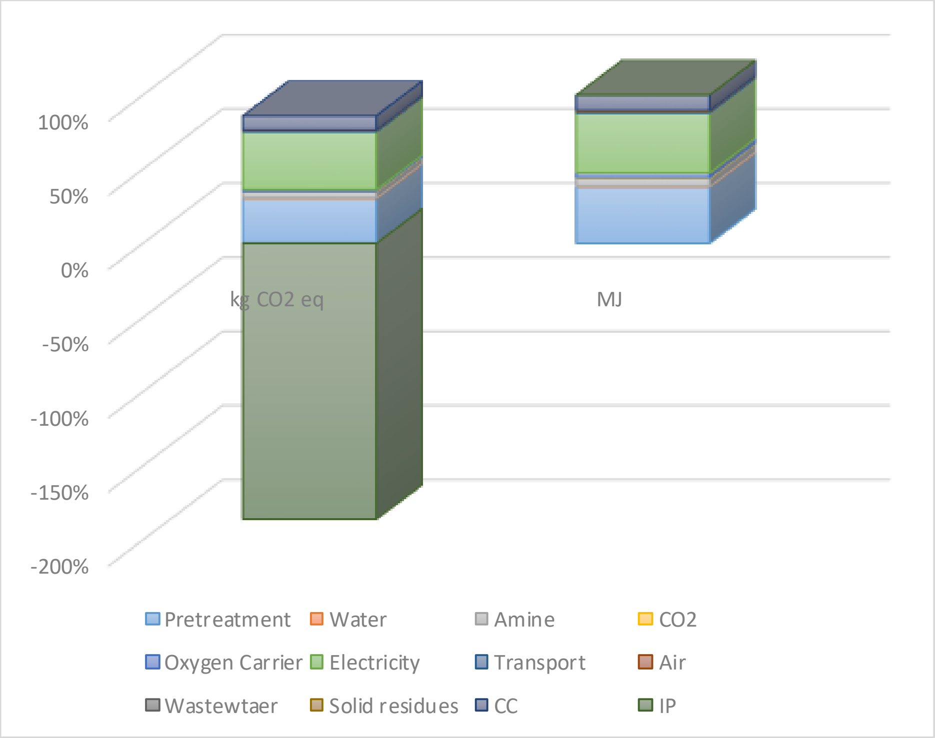

Figure 19. IP – Novel method

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[2] It is important to highlight that IP is not considered a pretreatment stage because the process was taken for Ecoinvent directly.

IP – Rectisol®

For the production of 1 ton of liquid FT product, in the central stage of the process, and referring to the Rectisol method, the greenhouse gas emissions are -1948 kg CO_2 eq, emissions are negative due to CO_2 sequestration. On the other hand, for the non-renewable energy use indicator, the result is 22613 MJ. As can be seen in the table 11 and figure 20, for the two indicators, the most significant impact is represented by electricity consumption, which supposed about 48.8% of the total contribution in the case of the climate change indicator and 61.6 % for non-renewable, fossil. The second most significant impact is generated by pre-treatment, with 31.8% and 48.4% for the climate change and fossil energy use indicators, respectively. Finally, the third most representative impact of the whole system is from CO2 capture, with 10.1% for the climate change indicator and 13.2% for the use of fossil energy.

Table 11. Industrial Pellet Impacts – Rectisol®

Indicator	Unit	Total	Pretreatment	Water	Methanol	CO2	Oxygen Carrier	Electricity	Transport	Air	Wastewtaer	Solid residues	CC	IP
Climate change	kg CO2 eq	-1948	613	3	14	2	24	941	15	4	1	2	196	-3762
Non-renewable, fossil	MJ	22613	8159	34	747	23	738	10385	227	41	10	23	2225	0

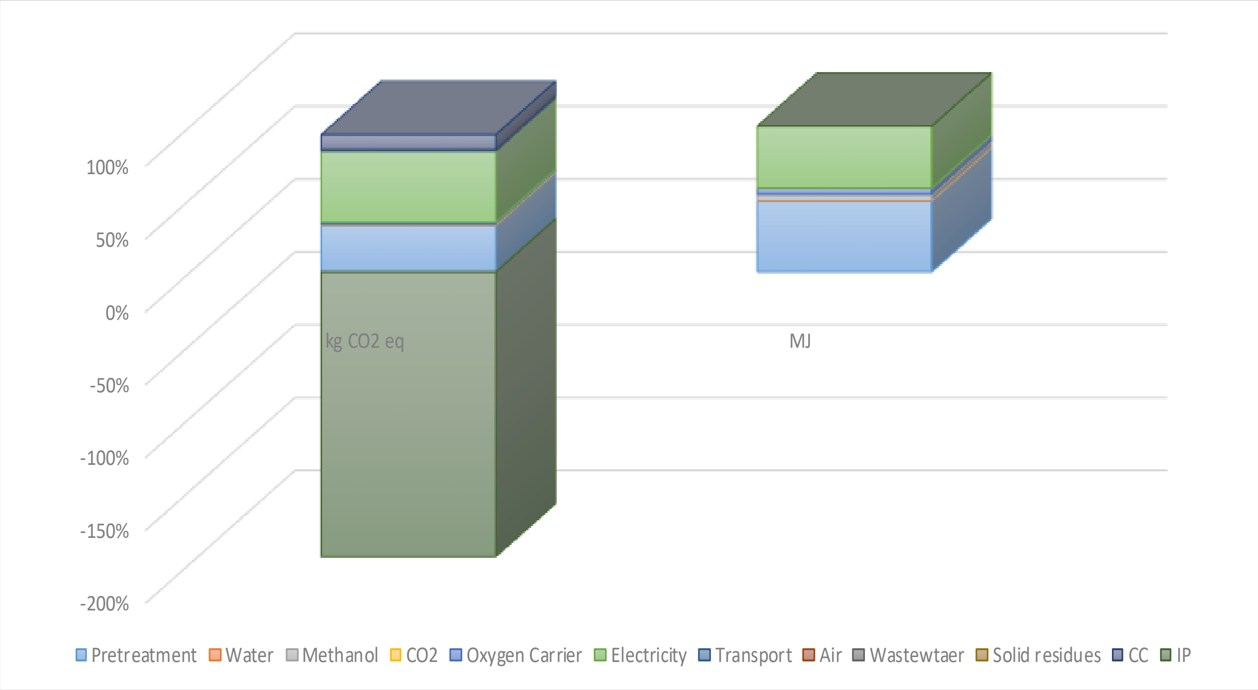

Figure 20. IP – Rectisol®

IP– Novel method vs Rectisol®

The following figures show the comparison between the novel and Rectisol® method for IP. It can be seen that the environmental impact and the non-renewable energy of fossil origin have a lower impact on the novel method.

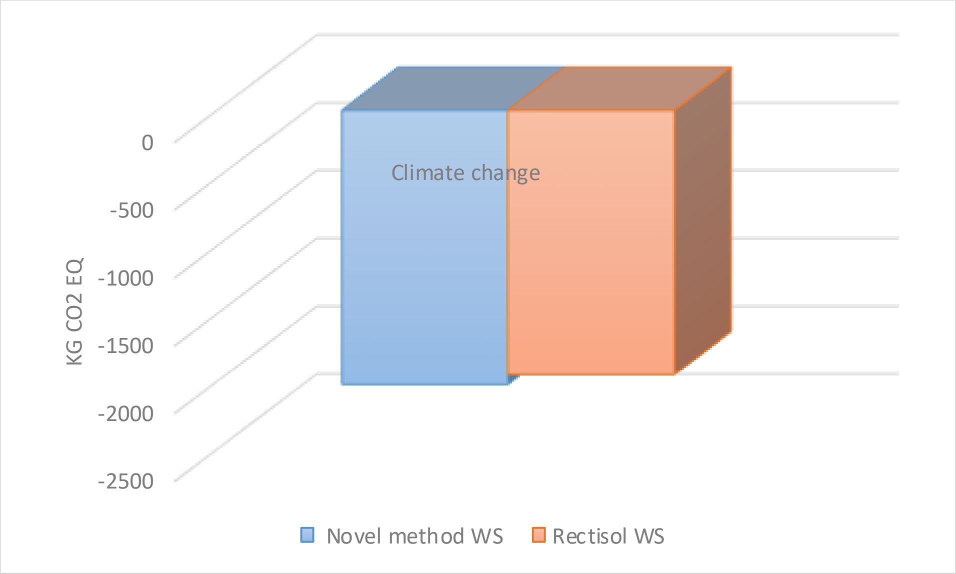

Figure 21. Comparison on kg CO_2 eq -IP Novel method vs Rectisol®

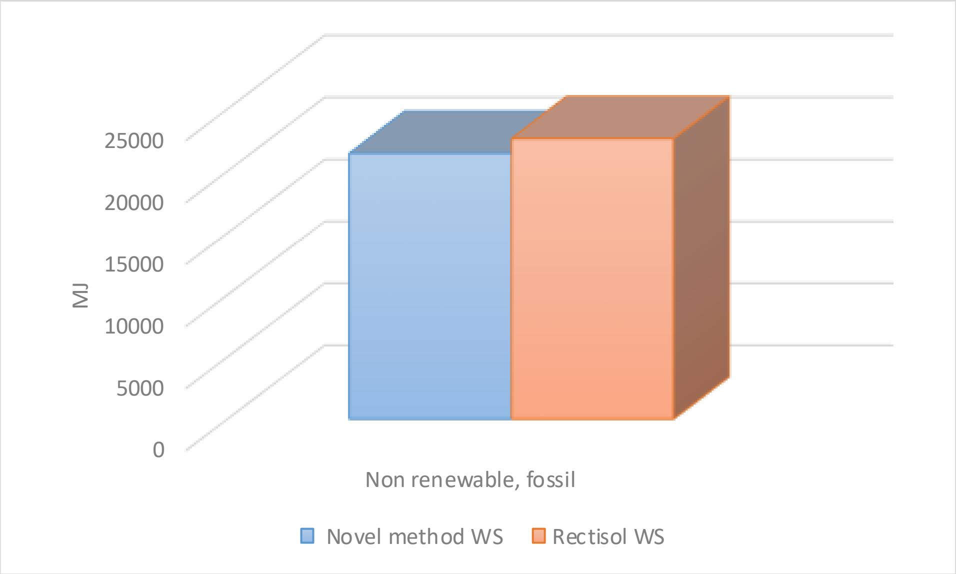

Figure 22. Comparison on MJ -IP Novel method vs Rectisol®

3.4 Carbon Capture

The results shown below refer to the consumption necessary to capture CO_2 from the different feedstock analysed.

Table 12. WS impact CCS

Indicator	Unit	Total	Amine	Water	Electricity
Climate change	kg CO2 eq	174	25	0	149
Non renewable, fossil	MJ	1975	335	3	1637

Table 13. PFR impact CCS

Indicator	Unit	Total	Amine	Water	Electricity
Climate change	kg CO2 eq	186	27	0	159
Non renewable, fossil	MJ	2108	358	3	1748

Table 14. IP impact CCS

Indicator	Unit	Total	Amine	Water	Electricity
Climate change	kg CO2 eq	196	28	0	167
Non renewable, fossil	MJ	2225	378	3	1845

3.5 Comparative analysis

Following a comparison of the two indicators analyzed is present. The first case compares different feedstocks using a novel method, while in the second case, Rectisol® is used.

This comparison shows the impact indicators analysed in terms of climate change and non-renewable, fossil. Regarding climate change, the difference is minimal for the three feedstocks studied after CO_2 capture. The real impact in novel method and Rectisol®, is reflected in the second indicator, referring to the non-renewable, fossil, with IP having the most significant impact, followed by PFR. Lastly, the lowest impact in this indicator is for WS.

To the novel and Rectisol® method, the IP has the most significant impact in both cases, climate change and Non renewable, fossil, followed by WS. Finally the PFR has a lower impact on all life cycle assessment.

Novel method

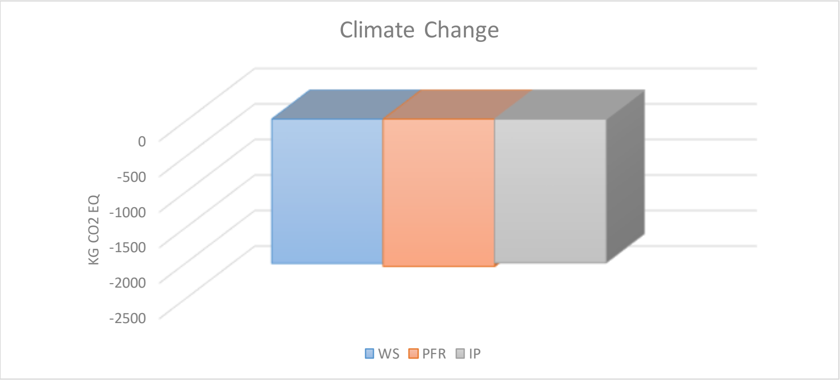

Figure 23. Comparison on kg CO2 eq by Feedstock- Novel method

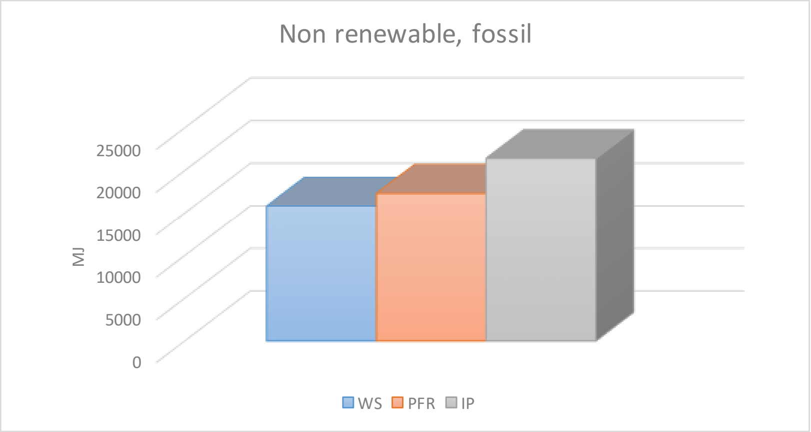

Figure 24. Comparison on MJ by Feedstock - Novel method

Rectisol®

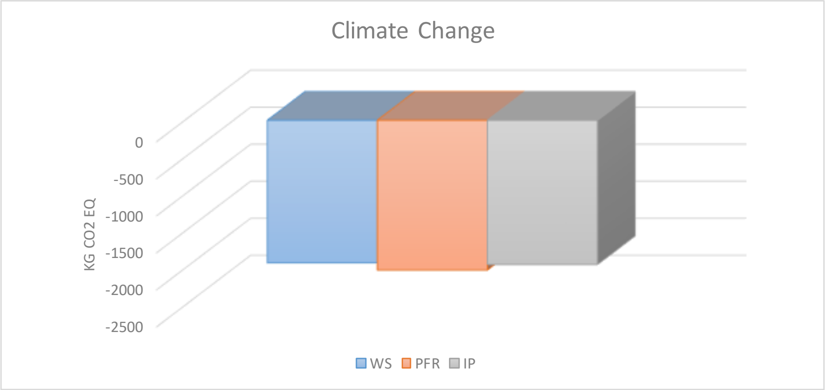

Figure 25. Comparison on kg CO_2 eq by Feedstock - Rectisol®

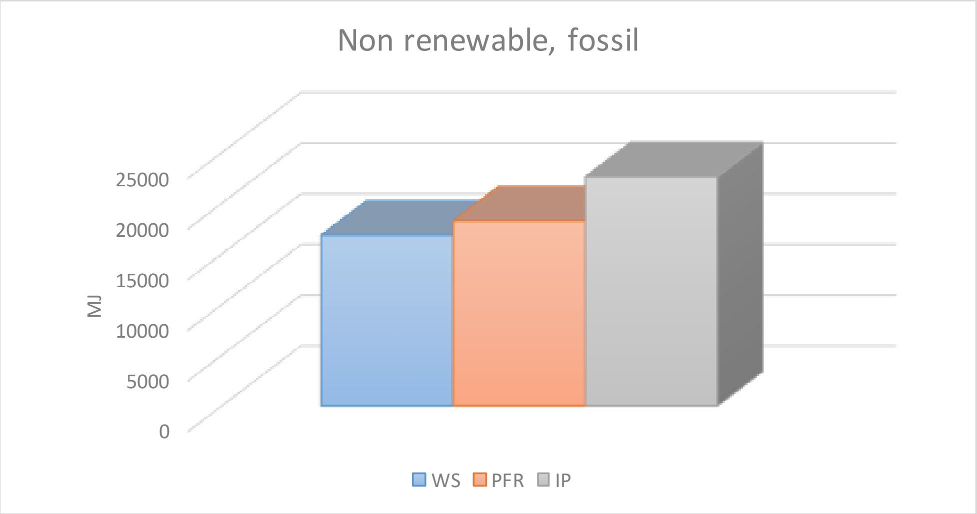

Figure 26. Comparison on MJ by Feedstock - Rectisol®

4 Recommendations

A clear source of emissions in this study is the use of electricity. For this reason, it is possible to suggest some recommendations to minimize the environmental impact.

The first scenario shows the production of 1 kWh using different electricity mix by country, Germany, Spain and Poland.

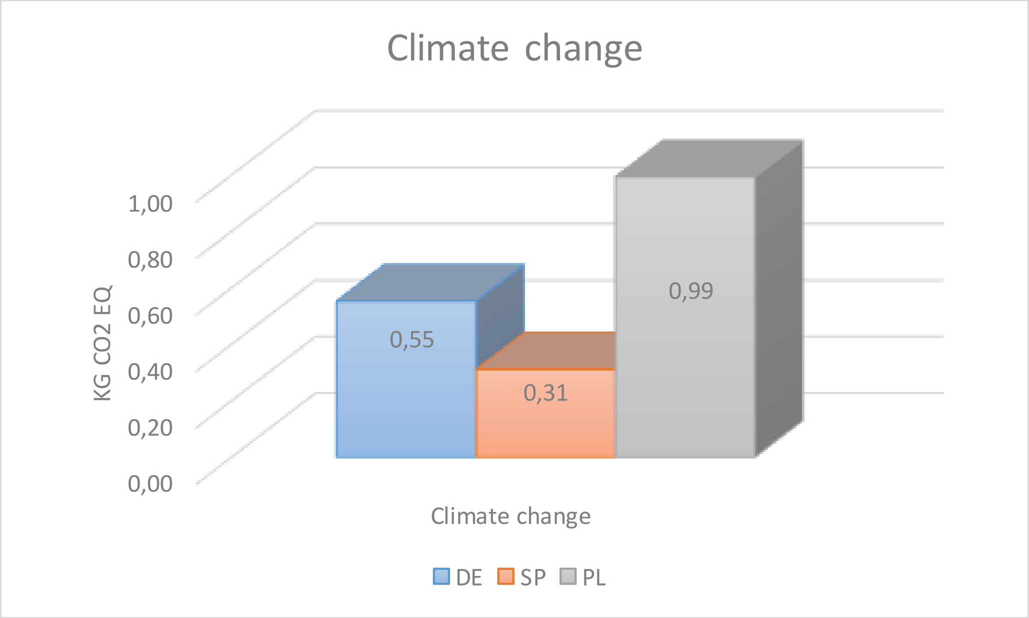

Figure 27. Comparison on Climate change (kg CO_2 eq) impact of Electricity mix by countries. **Source**: prepared by the authors on the basis Ecoinvent 3.8 database [28].

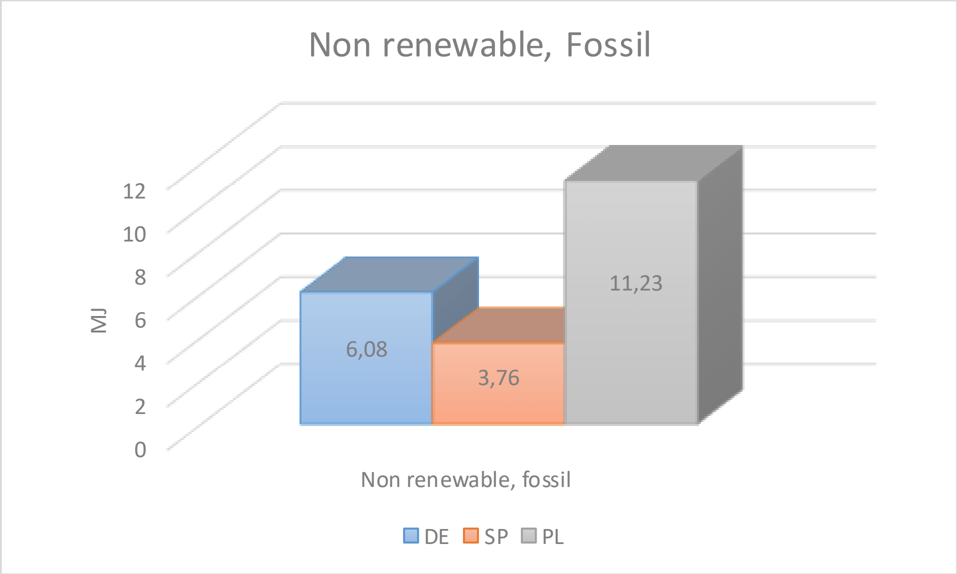

Figure 28. Comparison on Nonrenewable, fossil (MJ) impact of Electricity mix by countries. **Source**: prepared by the authors on the basis Ecoinvent 3.8 database[28].

According to the results, Spain has the lower impact in climate change and nonrenewable, fossil indicators, followed by Germany, and Poland. For the previous explanation Spain has the most sustainable approach to electricity generation among the three countries, as it generates the lowest greenhouse gas emissions and consumes the least nonrenewable fossil. Germany's electricity mix is more sustainable than Poland's, but less sustainable than Spain's, as it generates lower greenhouse gas emissions and consumes less nonrenewable fossil than Poland, but not as low as Spain. Poland has the least sustainable approach to electricity generation among the three countries, as it generates the highest greenhouse gas emissions and consumes the most nonrenewable fossil. The comparison shows that there is a great variability in the sustainability of electricity generation across different countries, highlighting the need for continued efforts to reduce greenhouse gas emissions and fossil fuel consumption.

5 Conclusions

A comprehensive life cycle analysis was carried out for the production of biofuel, including transport, biomass pretreatment, and production from different types of biomass such as wheat straw, pine forest residue, and industrial pellets. Additionally, a CO_2 capture stage was included. For this analysis, system boundaries, inputs and outputs were identified and important results were obtained, which lead to the following conclusions:

- Of the three types of feedstock, the results for the climate change indicator are very similar. A determining factor has been the capture of CO_2, an important tool for mitigating the impacts generated by the climate change indicator.
- About the fossil energy use indicator, wheat straw has a lower impact than Pine Forest Residue, which is in second place, and Industrial Pellets, which has the most significant impact on this indicator.
- For the two indicators analysed, climate change and fossil energy use, the greatest impact is represented by electricity consumption, in pretreatment, core process and carbon capture.
- Life cycle analysis is an essential tool for assessing the environmental impact of biofuel production and making informed decisions to reduce its carbon footprint.
- Using agricultural and forestry residues for biofuel production can contribute to reducing greenhouse gas emissions and the transition towards a more circular and sustainable economy.
- When deciding on biofuel production, it is important to consider factors other than environmental impact and fossil energy consumption, such as economic cost and biomass availability.
- Biofuel production from agricultural and forestry residues can be an opportunity to foster sustainable agriculture and forestry and promote rural development.

6 Disclaimer

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ANNEX I - Inventory

Pretreatment

Inputs			
	Wheat Straw	**Pine Forest Residue**	
Concept	**Amount**		**Unit**
Biomass	5,46	7,06	tn
CaCO3	0,10	NA	tn
Electricity	0,57	1,04	MWh
Transport CaCO3	10,04	NA	Tnkm
Transport feedstock to pretreatment plant	349,44	409,48	Tnkm
Air	NA	67,04	m^3
Outputs			
Pellet	5,06	4,84	tn
Steam	0,35	0,36	tn
Ash	NA	0,017	tn
Flue gas	NA	72,09	tn

Core process - CLG – GC – FS

Input				
	Wheat straw	**Pine forest residue**	**Industrial pellet**	
Concept	**Amount**			**Unit**
Pellet	5,06	4,84	5,03	tn
Electricity	1,34	1,40	1,40	MWh
Water	10,43	10,76	10,88	tn
Oxygen carrier	0,21	0,223	0,226	tn
CO2	0,54	0,5	0,54	tn
Steam	6,50	6,68	6,77	tn
Novel M –Amine	0,020	0,022	0,022	tn
Rectisol® - Methanol	0,020	0,022	0,022	tn
Rectisol®electricity	1,61	1,63	1,67	MWh
Transport pretreatment to principal plant	185	242	213,5	tnkm
Outputs				
Liquid FT product	1	1	1	tn
Wastewater	8,04	7,78	8,10	tn
Solid waste	0,285	0,64	0,66	tn
Steam	82,8	82,8	82,8	tn

Carbon Capture – 1 kg

Input				
	Wheat straw	**Pine forest residue**	**Industrial pellet**	
Concept	**Amount**			**Unit**
Amine	0,0016			Kg
Water	0,3			Kg
Electricity	0,081			Kg
	Output			
CO2	-1			kg