Technical, Economic and Environmental (TEE) Assessment of Integrated Biorefineries

Gasification based biorefinery case studies

IEA Bioenergy: Task 42 & Task 33

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1 Introduction

Biorefining is one of the key enabling strategies of the Circular Economy[1], closing loops of raw biomass materials (re-use of forestry, agro, process and post-consumer residues), minerals, water and carbon. Therefore, biorefining is the optimal strategy for large-scale sustainable use of biomass in the bioeconomy. It will result in cost-competitive co-production of food/feed ingredients, biobased products and bioenergy combined with optimal socio-economic and environmental impacts (reduced GHG emissions, efficient use of resources, etc.). IEA Bioenergy Task42 "Biorefining in the Circular Economy" aims at enhancing the commercialisation and market development of biorefinery systems and the related technologies while considering environmental, social and economic aspects. Providing quantitative, scientifically sound, and understandable data on the technical, economic and ecological added-value of biorefining to co-produce bioenergy and bio-products in a sustainable way is an essential facilitator in this context. Therefore, an integrated assessment (technical, economic and environmental – TEE assessment) of integrated biorefineries is performed. The main objective of the current report is to

- maintain and update the TEE approach and methodology for generic biorefinery assessments on technical, ecological and economical aspects;
- disseminate the TEE approach and methodology and enable accessibility of primary calculations;
- publish updated & new factsheets based on the TEE approach and methodology and inform industry about market perspectives;
- discuss approaches to calculate the metrics on ecological aspects (e.g., GHG reduction effects of biorefineries) with other working groups (e.g. IEA IETS Annex XI and IEA Bioenergy Task 45) for alignment and further standardisation;

Since, the provision of data is essential for the TEE assessment, an online questionnaire was built up and relevant stakeholders were requested to fill it out. The knowledge generated is a potential environmental and economic lever, that unravels incentives and barriers to the further development and market deployment. Addressing these enables to support investment decisions considering focal areas for further research needs, education or raising societal acceptance. For this reason, it is the aim to maintain and update the TEE approach and methodology, resulting generic assessment models and case studies to be representative and accessible to all relevant stakeholder and interested audience.

[1] Circular Economy (CE): The efficient use of finite resources, i.e. resource use efficiency, to ensure that these resources are reused as long as possible. The bioeconomy is an integral part of the Circular Economy.

2 Online Questionnaire

2.1 AIM OF THE ONLINE QUESTIONNAIRE

An expert interview built up as an online questionnaire was conducted in order to get to know where specific knowledge on integrated biorefinery concepts and implemented cases can be assessed for the technical, economic and environmental (TEE) assessment. The goal is to generate robust data for characterization through interaction with key stakeholders in the field.

In the beginning of the online questionnaire following **biorefinery definition** is given in order to provide a common understanding:

> "Sustainable processing of biomass into a portfolio of marketable biobased products (food and feed ingredients, chemicals, materials, fuels, energy, minerals, CO_2) and bioenergy (fuels, power, heat)"

The questionnaire is built up with single choice questions (e.g. "Yes" or "No"), multiple choice questions and open questions. The following key questions were included and addressed to stakeholders:

1. Could you **provide input for our characterization of biorefineries**, which potentially will lead to so called **fact sheets** on specific biorefinery cases?
2. Which biorefinery systems are you involved in?
3. Which core **technologies** are part of the systems you are involved in?
4. What major **Technology Readiness Level** (TRL) is the biorefinery system you are involved in currently?
5. Which are the **materials/products AND bioenergy carries** that are part of the biorefinery?
6. Could you **provide information or data** for the TEE assessment?
7. What kind of **data & information** could you provide?
8. Could you provide information about the **cost structures**?
9. Do you have any information already available in terms of **environmental aspects**?
10. Could you provide any **further information** (weblinks, literature references, technical reports, etc.)?

11. Who can we **contact** to get more data & information?

12. Could you please provide an **e-mail address** of a contact person?

13. **Feedback on the survey** is highly welcome. Please provide your suggestions

The following chapter represents the results of the questionnaire.

2.2 RESULT ANALYSIS

2.2.1 Completion rate and drop-off rate analysis

In total 182 people visited the questionnaire website. 112 people started with the questionnaire and 34 actually completed it. This is a completion rate of 30.4%. On average, it took 19:33 minutes to answer all the questions.

In the first three steps of the questionnaire, the general purpose of the survey is described, the importance of data generation is outlined and as already mentioned before, a definition of biorefinery is given for a common understanding. The drop-off rates for these three steps were 32%, 11% and 4%, respectively. However, 50 people made it to the first actual question, where they are asked if they could provide input for the characterization of biorefineries, which potentially will lead to so called fact sheets on specific biorefinery cases. This is the question with the highest drop-off rate of 36%.

2.2.2 Provision of information

When the respondents are asked for providing information, 66% answered with “Yes” when it comes to the provision of input for the characterization of biorefineries, which potentially will lead to fact sheets on specific biorefinery cases. This result allows the assumption that those people are likely to have heard about the fact sheets. Furthermore, as it can be seen in Figure 2, 85% claim that they are able to provide information for the TEE assessment.

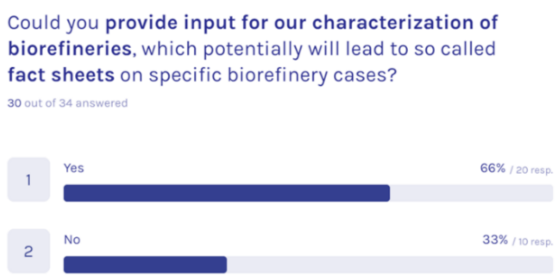

Figure 1 Answers given to the question for the provision of input for characterization of biorefineries

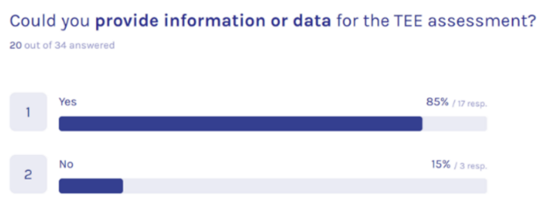

Figure 2 Answers given to the question for the provision of information or data for the TEE assessment

2.2.3 Type of biorefinery systems

In a next step the stakeholders are asked to define in which biorefinery systems they are involved in. They have the option to choose between “lignocellulosic feedstock biorefineries (based on wood, straw, miscanthus etc.)”, “marine biorefineries (aquatic biomass)”, “green biorefineries (wet/green biomass)”, “conventional biorefineries (1st generation sugar/starch based)", "whole crop biorefineries (including grain+straw)" and "oleochemical biorefineries (based on oil crops)". Additionally, they have the option to select "OTHERS (to be specified afterwards)" and individually specify in which other biorefinery they are involved in. For this question the stakeholders can select multiple answer options. Figure 3 shows the answers. 20 out of the 34 people that completed the online questionnaire answered this question. And more than half of them (55%) state that they are involved in lignocellulosic feedstock biorefineries. The second most chosen response option is the "OTHERS (to be specified afterwards)" option. The other biorefinery systems mentioned by the stakeholders include micro algae based, food residues, lignocellulosic 1st generation pulp and paper production and waste based biorefineries. 35% of the stakeholders that answered this question state that they are involved in green biorefineries. This was the 3rd most selected answer. "Oleochemical biorefineries (based on oil crops)", "conventional biorefineries (1st generation sugar/starch based)", "whole crop biorefineries (including grain+straw)" and "marine biorefineries (aquatic biomass)" where chosen of 25%, 15%, 15% and 10% respectively.

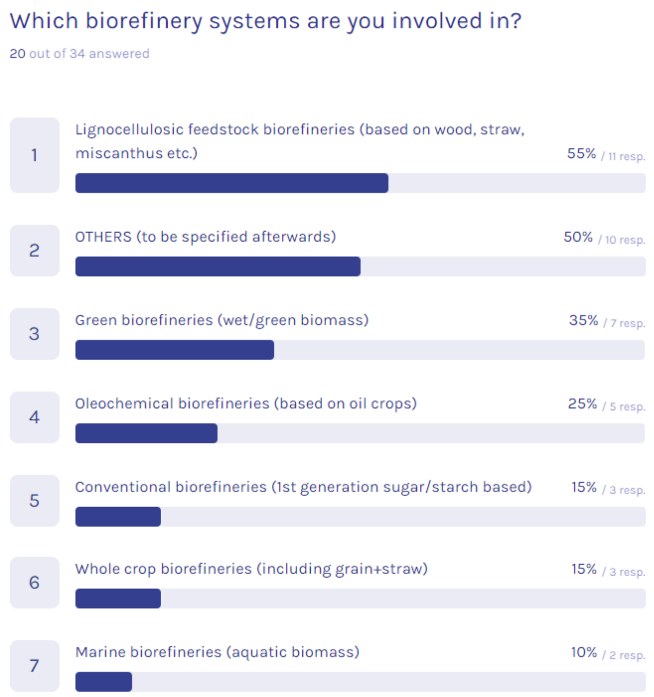

Figure 3: Type of biorefinery systems involved in the study.

2.2.4 Core technologies of the biorefinery systems

In a next step the stakeholders are asked to specify which core technologies are part of the systems they are involved in. 18 out of 34 people answered this open question. The stakeholders mentioned following technologies: "fermentation", "strain improvement", "gasification", "pyrolysis", "esterification", "hydrolysis", "MeOH and DME synthesis", "lignocellulosic biomass pre-treatment", "pre-treatment (especially dilute acid or hydrothermal - combined or not with CO_2)", "deoxygenation (hydrogenation)", "catalytic chemical conversion", "separation technologies", "thermochemical, biochemical and oleochemical conversion technologies", "photoautotrophic biomass production", "downstream processing", "distillation" and "lignin valorisation processes".

Fermentation is mentioned the most often (4 out of 18 people). Strain improvement, gasification and pyrolysis each are pointed out by three stakeholders. Furthermore, esterification is stated twice. All the other technology answers are mentioned by only one stakeholder.

2.2.5 Technology Readiness Level of the biorefineries

9 out of 35 people answered the question regarding the Technology Readiness Level (TRL) of the biorefinery systems where the stakeholders are involved in. The results of the questionnaire show that these specific biorefinery systems are all at a TRL 4 or higher. Most of the stakeholders (3 of the 9 that answered this question) indicate a TRL 6 and TRL 9 is stated twice. For the data generation for the TEE assessment, it offers an advantage that all the stakeholders mentioned an TRL 4 or higher, since could further be relevant for the development of the success stories.

2.2.6 Materials, products and bioenergy carriers of the biorefinery mentioned by the stakeholders

In another open question the stakeholders have the opportunity to specify what the materials or products and the bioenergy carriers are that are part of the biorefinery system. Here, many different answers were given.

2.2.7 Provision of quantitative and qualitative data

In the online questionnaire the stakeholders are asked what kind of data and information they could provide in order to find out whether quantitative, qualitative or both is available for the TEE assessment. 16 people answered this question. Figure 4 shows the different options, whereby multiple answers could be chosen. Regarding qualitative information the answering possibilities include the description of the biorefinery system and the description of the technologies. For the quantitative data it is asked for data regarding mass, as well as energy balance. Moreover, there is again the option to individually specify which kind of data and information could be provided. When looking at the results of this question in Figure 4, it is obvious that more stakeholders are able to provide qualitative than quantitative data. On the one hand, 75% claim that they could provide a qualitative description of the biorefinery system

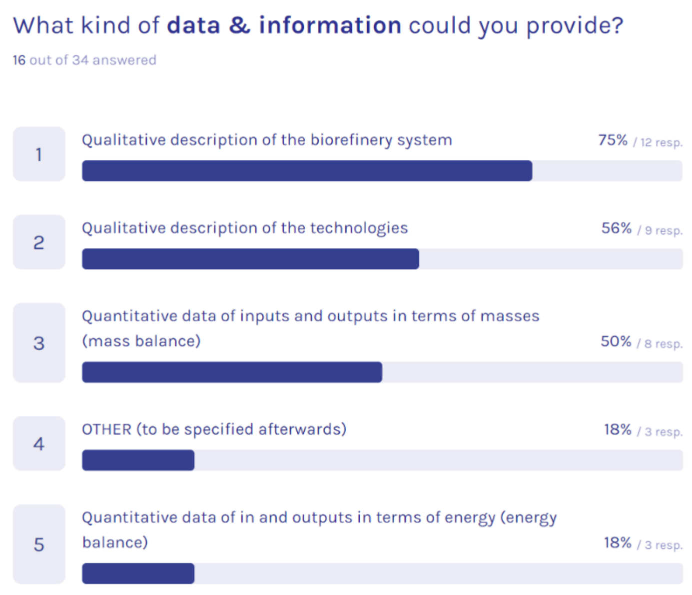

Figure 4: Data and information provided by the stakeholders.

and 56% that they could give a qualitative description of the technologies. However, on the other hand, when it comes the quantitative data, 50% could provide data of inputs and outputs in terms of masses and only 18% inputs and outputs in terms of energy. It seems to be “easier” to get qualitative data and descriptions of the biorefinery systems and related technologies, but the availability of quantitative data from the stakeholders seems to be limited and quite challenging for the TEE assessment.

2.2.8 Source of information

Figure 5 shows the answers of the stakeholders concerning the source of information. Again 16 people answered this question. 43% of the information originates from “real-world” operation data, 18% from pilot or demonstration plant data, 18% from literature-based data, such as scientific papers or technical reports and 12% is upscaled data from laboratory scale. Furthermore, there was again the possibility to select that the origin of source is any other than the provided answers. For the TEE assessment it is very useful to not only have data from literature, but also “real-world” operation data and measured values from the plants.

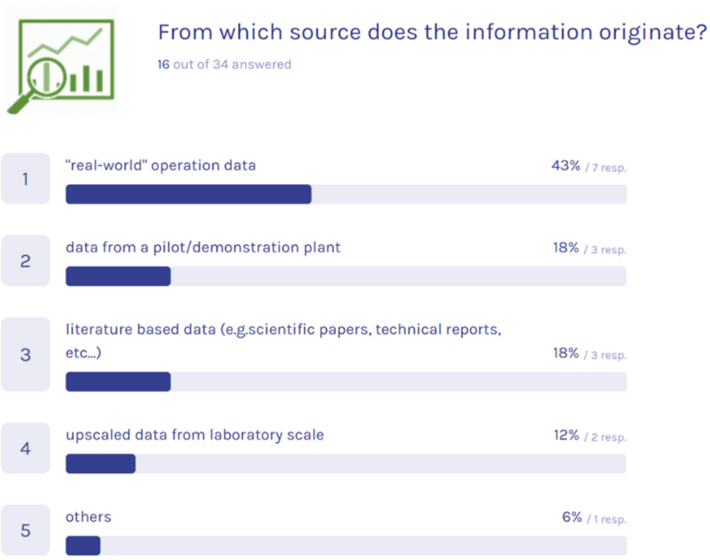

Figure 5: Information source as outlined in the questionnaire.

2.2.9 Further information provided

The stakeholders are also asked if they could provide information about the cost structures. 15 people answered this question, whereby only 40% answered with “Yes”.

Additionally, the stakeholders are asked in the questionnaire if they have any information available in terms of environmental aspects. Again 15 people out of 34 answered this question. 53% of them answered with “Yes”. These stakeholders further specified this information and claimed that it includes information about renewable chemicals, sustainable green economy, WTW performance data and the CO_2 footprint.

Moreover, 19 out of 34 stakeholders answered the question whether they could provide any further information, such as for instance weblinks, literature, references or technical reports. Here, 73% gave a positive answer. In a next step again, they are asked to further specify the kind of additional information that could be provided. The answers include potential analysis, case studies, operational data, best practice examples, facility descriptions, weblinks, published data on the developed technology, reports, publications and expert insights.

It again became obvious that quantitative data is harder to get for the TEE assessment, since it is not possible or challenging for the stakeholders to make it available.

2.2.10 New contacts and visibility through the online questionnaire

In the end of the questionnaire the stakeholders are asked for contacts to get more data and information. 16 people answered this question. Through the online questionnaire it was possible to gain new contacts. There are 5 additional contacts where we actually interact and at the moment, we are confident to get 1-2 case studies. Furthermore, it the online questionnaire was an opportunity to get more visibility from outside the “IEA-Bioenergy Task World”.

Questionnaire conclusions

The online questionnaire was a good opportunity to get insights and knowledge about integrated biorefinery concepts from the stakeholders involved. The results show that it is especially a challenge to get quantitative data that would be relevant for the TEE assessment. However, some stakeholders mentioned that they could provide also some quantitative information. Another positive result of the survey is that not only literature-based data is the source of information, but rather “real-world operation data and data form a pilot or demonstration plant. Furthermore, additional contacts and visibility could be generated through the online questionnaire.

3 Technical, Economic and Environmental (TEE) assessment approach

The TEE-Approach was described in detail in IEA-Task 42 publications. The following chapter is based upon them as a whole and should be seen as a short reintroduction. [1], [2]

In order to battle global challenges such as climate change, mass extinctions and the dwindling resources available, sustainable biorefineries are regarded as a vital measure by important government bodies such as the European commission.

While biorefining is not a new concept and sustainable installations have been realised in a real-life plant, assessing the sustainability in a simple way which is easy to compare is a challenging task. With carbon capture and storage/utilisation (CCS/CCU) also slowly entering the game of biorefining, exact system boundaries and system definitions are required. Moreover, not only “classic” measurements such as global warming potential (GWP) or primary energy demand (PED) are relevant, also more abstract parameters such as land-use need to be included. These impacts are then to be distributed, as most biorefinery systems yield more than one useful product. Additionally, to put the whole system into perfect, social and economic aspects are to be regarded as well.

Additionally, when assessing the sustainability of biorefineries scale plays an important role, as scale-ups and different TRL-levels change results in a considerably manner. Therefore, “a consequent bottom-up and refinery specific assessments are essential”.

Important measures are techno-economic assessments (TEA) and life cycle assessments (LCA), which are based upon measurements of real-life data or calculated data from literature. These tools are usually combined with a mathematical uncertainty analysis in order to estimate the robustness of the results obtained. Although some literature exists, there is no real standard operating procedure dealing with the scalability of these results during a considerable scale up. Hence, TEE evaluations should be performed only for technologies having reached a TRL of 6 or higher.

While for example, in LCA numerous ways on how to account for carbon uptakes and emissions and how long they stay active in the atmosphere are reported standardized, simple and feasible TEE-assessments are found seldomly. Hence, an approach was developed in IEA Task 42 by Lindorfer et al. (

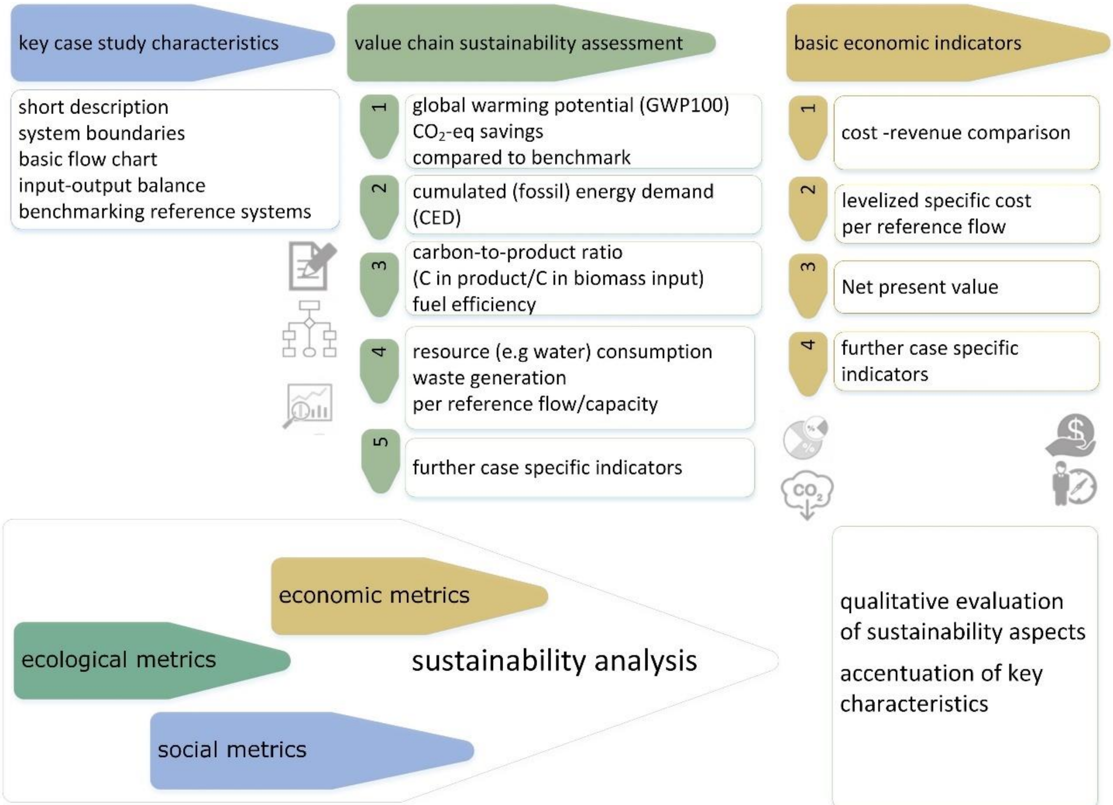

Figure 6)

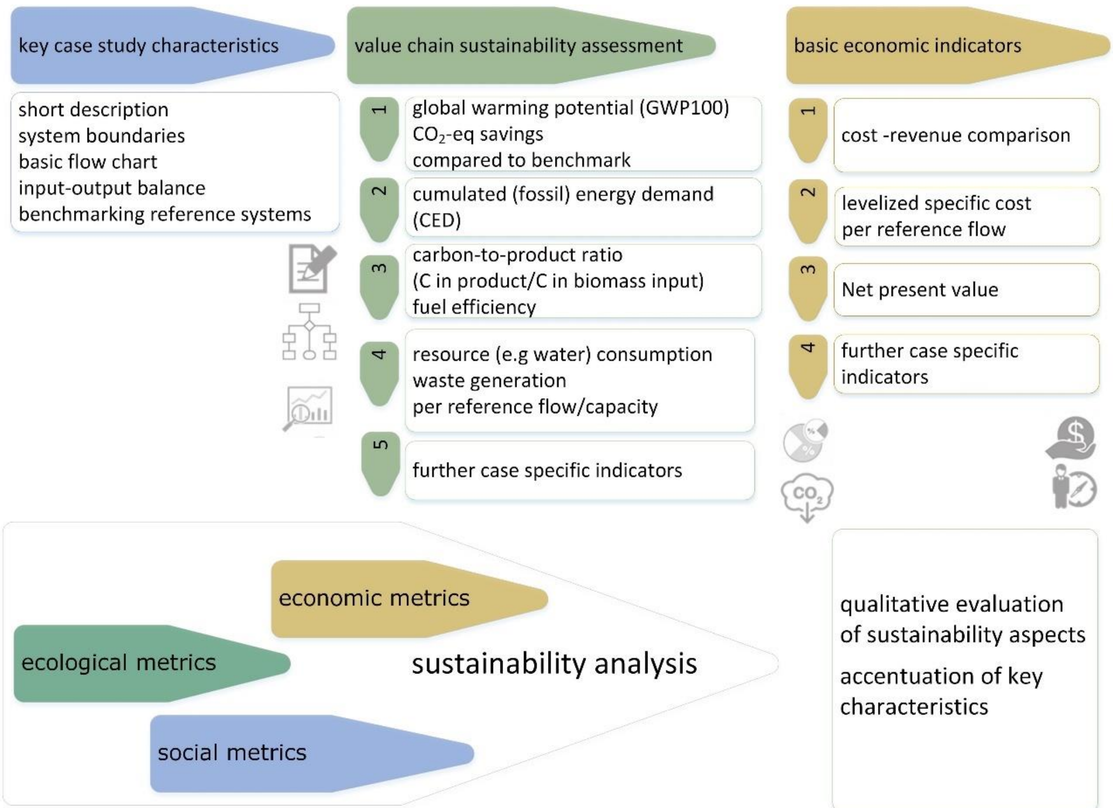

Figure 6: Structure of the proposed TEE-approach.

Ideally, the TEE assessment would focus on comparable functional units such as 1 kg or 1 MJ, however this approach is inherently flawed, as 1 kg of chemical a might have significantly different environmental impacts of market prices. The latter are also considered a flawed unit as fluctuations may change results dramatically.

Consequently, there is no easy answer to this question and a considerable amount of academic literature is available on the topic.

Hence, creating a full-scale TEE-assessment is a time-consuming endeavour. Therefore, only a limited number of indicators was chosen to allow for easy comparison of key points and numbers.

3.1 Goal & Scope

The goal of this work is to create so called “fact sheets” which are easy to compare. In all of this case studies biomass is used at a commercial scale for gasification. The synthesized intermediates are then reformed to yield a gasoline substitute. Byproducts are butane, propane and propylene. The system boundary is cradle-to-gate. The functional unit is 100,000 tons of (synthetic) fuel produced. The data is based upon the results of IEA Task 33.

3.2 Methodology: Environmental Impact

According to VDI 6310 [3] and other sources [4], [5], an ideal LCA should examine the system boundary “cradle-to-grave” to encompass all life cycle stages of a biorefining product. Due to high data demand and the relatively high heterogeneity of biomass compared to conventional refineries, a cradle-to-gate approach is used instead as it is in this study. The main reason is that manufacturers normally cannot be certain on how their product is used or disposed of. Moreover, accounting the release of biogenic carbon at the end of life is a highly controversial topic in the scientific community. [6]

In order to complete the life cycle inventory (LCI) the following steps are performed, as described in [1]

- list all relevant incoming material streams (raw materials);
- list all processes involved;
- list all internal material streams (intermediate products);
- specify the resulting platform(s);
- list all outgoing material streams (products);
- prepare the associated diagram

Finally, existing and comparable technologies are compared against the biorefinery case study setup. The benchmark includes, energy efficiency, energy usage and conversion losses from a technical characteristic perspective. More over GHG-savings and PED are examined and are the main points of focus in the environmental analysis, while other important and well-known indicators such as ozone depletion or acidification are excluded. Reasons are for the sake of simplicity, the current international focus on climate impacts and a lower scientific consensus on how to transcribe the physical results to endpoint-category indicators such as loss of biodiversity e.g.

While all full LCA should follow strictly ISO 14044 this works features an short cut approach which adheres to specific emission factors for mass and energy flows which are also used in current international legislative framework as e.g. the renewable energy directive (RED) from the European commission [7] or the Renewable Fuel Standard Program in the United States. [8] The RED is a simple and standardised characterisation scheme, yet however a simplification when compared to a full LCA. Shortly, the RED-framework is used to compare the GHG emissions of a fuel oriented biorefinery product to a suitable fossil reference.

RED II's equation, found in Annex V (Commission), with the following variables:

Equation 1: The formula used to calculate GHG emissions according to the RED II

$$E_{Ec} + E_L + E_p + E_{Etd} + E_U + E_{Sca} + E_{CCS} + E_{CCR}$$

- E_{Ec} = Emissions from the extraction or cultivation of raw material (biomass in the framework of this scheme)
- E_L = Annualized emissions from carbon stock changes caused by land-use change per year
- E_p = Emissions from processing
- E_{Etd} = Emissions from transport and distribution
- E_U = Emissions from the fuel in use
- E_{Sca} = Emission saving from soil carbon accumulation via improved agricultural management
- E_{CCS} = Emission savings from CO_2 capture and geological storage
- E_{CCR} = Emission savings from CO_2 capture and replacement

In order to more towards the life cycle concept, the emission profiles of fossil reference systems were taken from frequently applied and maintained databases. Emission factors for the GWP-100 indicator, as well as primary energy demand were taken from Sphera's GaBi™ 10.6 database. [9] A list of used reference processes is found below in Table 1.The only exception was the PED and GHG emissions factors of biomass used, which were taken from the scientific literature.

Table 1: The obtained products in the biorefinery and reference systems and the equivalent model processes used in the study.

Reference flow	GaBi-equivalent	Source
Synthetic Gasoline	EU-28: Gasoline mix (regular) at refinery	[10]
Synthetic Diesel	EU-28: Diesel mix at refinery	[11]
Propane	EU-28: Propane at refinery	[12]
Propylene	EU-28: Propene (propylene)	[13]
Butane	EU-28: Butane at refinery	[14]
Biomass (Feedstock)	n/A	[15], [16]

Another important metric in this report is energy efficiency, which is defined in three steps as introduced by Rauch and Koroveshi in the underlying work. [17] Defining efficiency as a percentage of energy usable in form of work (Carnot) or as fuel in this case is a well-established approach. [18] The fuel efficiency (η_{fuel}) is the narrowest definition, as it only features the amount of energy converted to fuels. The product efficiency ($\eta_{products}$) also includes the energy content of side products and finally, the total efficiency (η_{total}) yielding the highest percentages also includes thermal energy streams such as heat or electricity.

Equation 2: The equation used to determine the fuel efficiency of the gasification plant.

$$\eta_{fuel} = \frac{m_{fuel} * LHV_{fuel}}{m_{biomass} * LHV_{biomass}}$$

Equation 3: The equation used to determine the product efficiency of the gasification plant.

$$\eta_{products} = \frac{m_{fuel} * LHV_{fuel} + \sum mass_{\,side\ product} * LHV_{side\ product}}{m_{biomass} * LHV_{biomass}}$$

Equation 4: The equation used to determine the total efficiency of the gasification plant.

$$\eta_{total} = \frac{m_{fuel} * LHV_{fuel} + \sum m_{\,side\ product} * LHV_{side\ product} + \dot{Q}_{Steam+\ Heat+Refinery\ Gas}}{m_{biomass} * LHV_{biomass}}$$

3.3 Methodology: Financial Impact

According to the VDI 6310 the Net present value (NPV) is used in this assessment if enough data is available. The simplified mathematical relationship is shown in Equation 5.

Equation 5: The formula used to calculate net present value.

$$NPV = -C_0 + \sum_{t=0}^{n} \frac{(\text{Earnings} - \text{payments})}{(1+i)^t}$$

$-C_0$ denotes all of the taken investments, n the number of years observed and I is the calculated interest rate.

All earnings and payments are discounted over a certain period of time, in this case 10 years. If the final value is positive, so is the investment's rating. The number is directly proportional to profitability of the plant.

Clearly, this does not reflect entrepreneurial depreciation periods, however this is longer than the expected lifetime of such plants and for ecologically relevant investments with multi-round effects for a local economy, depreciation periods of 7 years for mobile units (e.g., wheel loaders), 10 years for stationary machinery and 20 years for buildings are frequently applied assumptions in technoeconomic studies in the field.

A common way to calculate payments is to divide costs between operational expenses (OPEX) and capital expenditures (CAPEX). This was done in this study, results in prices per litre of fuel of biobased product.

OPEX are comprised of mainly raw materials, operating expenses and maintenance. All of these values were based on Rauch and Koroveshi [17].

CAPEX was based on initial estimates available to the work of Rauch and Koroveshi. [17] The cost scaling factor is based upon high-esteemed standard literature [19] and used as it can be difficult to find costs for equipment in the needed size. Moreover, additional expenses were covered in Equation 7 to account for more robust results. Moreover, depreciation effects were incorporated over a life time of 10 years, 5 % interest rate and an average uptime of 8600 h/a.

Equation 6: The formula used to calculate the total annual product cost according to [20] and [1]

$$I = \sum_i \left[I_0 * \left(\frac{S}{S_0}\right)^k * (1 + IDC + PC) \right]_i$$

I_0 is the initial cost estimate, $\left(\frac{S}{S_0}\right)^k$ a factor to scale cost relative to equipment size, IDC includes indirect project costs and PC is used to mathematically include project risks.

Equation 7: The formula used to calculate the final CAPEX. Additional charges for equipment, administration and interest were included.

$$CAPEX = I * (1 + f_{equipment} + f_{admin} + f_{personal} + f_{interest})$$

For a detailed assessment, the production cost factors are ideally provided for each part of the system, e.g. raw material sourcing, pre-treatment/conditioning and biorefinery conversion to multi-product output. If, due to confidentiality constrains and data availability, a detailed assessment is impossible, aggregated values related to the relevant physical biorefinery inputs and outputs can be used to provide an assessment with lower granularity.

Specific full product costs can help to determine the potential economic feasibility and marketability of biobased products in respect to fossil counterparts and its marginal revenues without considering specific price structures and economic boundary conditions. With the help of such basic calculations, a trend can be provided for the mid- to long-term perspective for process concepts at low TRLs and to elaborate which major reductions in the cost’s structures are required in order to be competitive and economically feasible.

4 Core technologies and basic technical characteristics

Gasification is not a fully new technology. In fact, it has been around for over 200 years since coal was used to illuminate cities such as London or Baltimore. But not only, coal was used, peat was also gasified, thus marking the first use of biomass in gasification. [21], [22]

After these short periods of usage, the technique lost attention as oil refineries and electrification started its world-wide victory. A sidenote worth mentioning is the extensive use of gasification in World War two in which the Fischer-Tropsch Process (FT) was served to produce fuels for domestic supply in many countries. [23]

After the war gasification found one of its main purposes: The reformation of fossil resources such as natural gas or heavy fuel oil into hydrogen. [8] To this day in 2022 over 95 % of all hydrogen is reformed from fossil energy carriers. [24] The other, in this case more important usage, is the production of syngas which is then converted into intermediates later.

As outlined in Jafri et al., gasification is not a new technology, however the gasification and all of the sub-sequent scaling up can be considered novel. Especially the different flue gas composition is deemed a challenge. In the report 10 gasification technologies ranging from commonly found two stage-gasification to more exotic technologies including plasma, were analysed and TRL levels were awarded accordingly. In principal, there are applications with high TRLs such as 7-8 covering a wide variety of feedstock, e.g., classic input materials such as wood chips, pellets, saw dust, and perennial crops, but also extending into municipal solid waste, SRF and RDF with lower TRL technology. But not only the generation of heat, power and syngas are of interest, multiple technologies are also working of recovering minerals such as phosphorus in order to further efficiency. [25]

In another IEA bioenergy work [26] the feedstock and gasification technologies were studied in a detailed manner, showcasing again the technologies' high versatility, depending on the type of feedstock.

With respect to TEE, those findings about TRL, plant design and feedstock, should now be complemented with the financial and ecological assessments generated in this report.

Similarly to [1] open-source factsheets for gasification based biorefinery systems are targeted within this report. The four cases based on Hrbek et al., are listed below: [26]

- **Case 1:** Methanol-to-gasoline gasification (MtG)
- **Case 2:** Dimethyl ether (DME)-to-gasoline.
- **Case 3:** Fischer-Tropsch to produce gasoline and diesel substitutes (FCC)
- **Case 4:** Fischer-Tropsch to produce gasoline and diesel substitutes (HG)

4.1 METHANOL-TO-GASOLINE (MTG)

The process was invented in the 1970s by Exxon Mobil as oil prices were at a high in these times. Specifically, syngas was converted into hydrocarbons by zeolite ZSM-5. [27] The first commercial installation was finished in the 1980s. [28] German professor Frerich J. Keil called the process "*the first major synfuel development in the 50 years since the development of the Fischer-Tropsch process*". [29] Methanol produced by MtG process is not a clean product, it features around 50 other compounds mostly hydrocarbons, similar to a conventional refinery. A big upside of the process is the given scalability as methanol from syngas is a highly researched, selective and well-documented reaction. [30]

While a fix-bed reactor type marks the conventional method there is also research going on about a fluid-bed type. Details will be discussed in the environmental and economic sections.

According to Hunter and Trimm [28] and other sources [29], [31] the MtG synthesis always consists of the following steps.

1. **Gasification**: Biomass or other type feedstock is converted to producer gas using one of two types of gasifiers, one being heated directly, the other one indirectly. After gasification it is called producer gas, after cleaning and conditioning (purification and reforming) syngas is produced. Synthesis gas is a mixture of CO and H_2.
2. The producer gas can be combusted directly, if clean feedstock is used, otherwise it must be cleaned (e.g. sulphur) in order not to damage the combustion engine.
3. **Tar reforming and gas scrubbing**: Minor amounts of biomass from tar and hydrocarbons during gasification which is then cracked. Resulting ammonia is cracked into its gaseous components as well. The resulting syngas is cooled to 149 °C and sent to a wet scrubber for further purification.
4. **Gas purification and steam reforming**: The resulting syngas is compressed to 31 bar and further desulphurized using a specialized process followed by a ZnO bed reducing the catalyst poison to less than 1 ppmv. The gas leaving the purification is heated up via steam to circa 800-900 °C. Subsequently it enters a reformer to convert the remaining light hydrocarbons to syngas and to adjust the H_2/CO ratio to roughly 2. After recovering excess heat, the purified syngas is cooled by water and air and compressed to 100 bars.
5. **Methanol Synthesis**: The synthesis takes place according to the following reaction
$$CO + 2H_2 \rightarrow CH_3OH$$
Reaction conditions are temperatures between 230-270 °C, pressures around 35-100 bars. The reaction is highly exothermic; thus, the excess heat is used to produce steam. The product is then separated from gaseous side products in a flash tank, yielding 95 % pure Methanol, ready for MtG synthesis.
6. **Pressure swing adsorption (PSA)**: Part of the removed gas is treated in a pressure swing adsorption out of which very pure hydrogen (99.99 %) is obtained. This H_2 can be used in the heavy gasoline treating unit (HGT), introduced later.
7. **MtG Process**: The chemical reaction type for the MtG is a so-called dehydration reaction, as water is removed from the educts yielding hydrocarbons. Again, two reactor types are available, a fixed-bed and circular fluidized bed type. Often a dimethylether (DME) reactor type is combined with a few MtG reactors in order to control the high exothermicity (1.74 MJ /kg methanol). Due to catalyst properties gasoline is yielded with a purity of circa 85 %. Carbon chain lengths hardly exceed 10 due to stereoselective effects of the catalyst. 100 % conversion is possible until the catalyst is deactivated by coke which can be easily removed by burning it off.
8. **Gas fractionation and HGT**: The produced hydrocarbons are separated in a gas

fractionation unit into the following fractions.

a. **Fuel gas**
b. **LPG**
c. **Light gasoline**
d. **Heavy gasoline**

The heavy gasoline is hydrogenated with H_2 from the PSA (Step 5) in order to increase yield and to remove durene (1,2,4,5-tetramethylbenzene, which can cause problems in the engine). Sometimes the LPG is used as a fuel in the burner and other times it is sold as a byproduct.

4.1.1 Basic environmental characteristics

Besides the referenced case studies performed by IEA Bioenergy Task 33 additional case studies are documented in literature. Gonzalez et al investigated biomass' conversion via FT and MtG. While this part is focusing on MtG is important to point out that the first primary conversion steps are the same for FT and MtG. The gasification of biomass and the subsequent cleaning are needed for both applications. In their work they used data from publicly available literature to build a high-performing and a low-level case. The overall chemical energy efficiency for the conversion from syngas (HHV /Syngas / HHV / Products) was 80 – 99 % for low and high case. The comparable rates when starting from biomass were 29.5 - 51.8 % indicating much higher conversion losses, especially compared with the high efficiency of petroleum, 85 %. In the future the authors predict a possible efficiency increase of 9 %, thus reaching a value of 48.4 %. The reasons for the low efficiency are found in biomass conversion and gasification, as it has high energy inputs followed by an exothermic conversion at lower temperature, meaning the waste heat cannot be fully exploited. [32]

A different study was performed by Sundaram et al., who compared conventional MtG starting from natural gas with a novel approach in which biogas and pyrolysis oil are used to make syngas for subsequent MtG conversion. [33] Different to the first study, this work features an ASPEN™ simulation. The authors did not report a chemical energy efficiency but carbon efficiencies. Depending on the process design 0.40 (for thermally coupled reactors, performing two reactions; CR) and 0.56 for autothermal reformation (ATR) of both educts in one reactor. The benchmark lies at 0.48 for the conventional route. Gonzalez et al., reported 44.4 % for the best case scenario, thus reporting comparable values. [32]

For the LCA 1 kg of gasoline produced was compared under the CML 2001 method[2] in a cradle-to-gate analysis. For the GWP values of 0.23 (ATR) and 1.26 (CR) kg CO_2-eq. per kg gasoline are reported in contrast to the base case with 2.40. This means significant GHG savings for the biorefinery approach, mostly caused by the uptake of timber pine as feedstock. Contrary to many other biorefinery studies the PED is higher for the base case in this study. Moreover, acidification potential also features comparable values, which is unusual for this sort of comparison. For the biotic production indicator, the groundwater replenishment and erosion the fossil-based process shows clearly better results. Nevertheless, the study did show that both processes can be a viable alternative.

[2] CML is a procedure used to estimate the measure of environmental impact that is caused by the product. This method uses various impact categories such as eutrophication, ionization radiation, aquatic ecotoxicity, land use, and human toxicity and was developed by the Institute of Environmental Sciences, Leiden University, The Netherlands.

A third, the most recent, study by Dimitriou et al., performed another energy efficiency calculation and found 45-47.6 % for an MtG process based upon biomass. Again, this value fits well in the already presented results. [34]

The following Table 2 summarizes different LCA studies in this area. When comparing the reported global warming potentials, the high range of results becomes clear, which limits comparability.

Table 2: Comparison of some LCA studies on biomass gasification.

Main (biofuel) product	Feedstock	Quantified Environmental Impacts	GWP (g CO_2 eq km^{-1})	Foreground data	Assumptions	References
SNG	Sawmill residues	GHG	202	Empirical	Zero upstream emissions	[35]
FT diesel	Wood	GHG	16	n.d.	n.d.	[36]
H_2, SNG, FT diesel	Poplar wood	GWP, AP	58-132	Literature	Exergy allocation	[37]
FT diesel	SRCk wood	GWP, AP, EP, POCP	200	Literature	Exergy allocation	[38]
SNG	Forest residues	GWP	32-40	Literature	No by-products considered or used	[39]
H_2	Poplar wood	GWP, AP, EP, ODP, POFP	385	Aspen Plus™	Fertilizer use	[40]
FT diesel	Willow	GWP, AEP,	68	Literature	Different energy scenarios	[41]
H_2	Wood	ReciPe 2008	130	Literature	Various	[42]
FT diesel	SRC wood and straw	Eco-indicator 99	100-130	Literature	Heavy use of fertilizer	[43]

Source: [44]

Current limitations (e.g., methodological choices, transparency, etc.) of environmental assessments of biorefinery systems are leading to poor comparability.

4.1.2 Basic economic characteristics

Gonzalez et al also performed economic evaluation for the MtG process. The results were 22-34 € per GJ fuel which is comparable to the price of fossil fuels (29 €/GJ) with a barrel price of 129 €. [32] Dimitrou et al., found 25.41 to 23.17 € /GJ, depending on the reactor type. [34] They assumed a daily throughput of wood of 2016 t dry biomass, a plant life of 20 years, and a 10 % loan interest rate. These values also do not hold up to values in this work as gasoline was valued at 16.6 € and diesel at 16.2 € per GJ at the time. Tunå et al., also simulated various case studies in the biomass-to-fuel sector. Assuming the same financial conditions as Dimitrou et al., an efficiency of 50.6 % was found and a price of 31 $ / GJ. [45]

4.2 DIMETHYL ETHER (DME) TO GASOLINE PROCESS (DTG)

The DtG-process is very similar and closely related to the MtG process design. The DtG process was introduced as an improvement to the MtG process. In the latter, the first stage is the synthesis of methanol from syngas, which then forms an equilibrium between methanol, DME and water. In the DtG process DME is directly produced from syngas, thus one reaction step. Lee et al., who introduced the concept in 1995, proposed better heat management, higher efficiencies and yield for the process. Especially conversions for CO, hydrogen and syngas showed improved figures, due to limited water formation. Lastly, due to the omission of one reactor (methanol drying) reductions in space demand as well as capital and operating costs were to be expected. [46], [47]

While both use the same catalyst, other differences are found, the most influential one being the reduced H_2/CO_2 ratio of roughly 1. Moreover, a commercial scale plant has been partly realized. [47] In 2014 the bioliq™ demo plant was put into operation with an installed capacity of 2-5 MW. [48]

4.2.1 Basic environmental characteristics

Due to comparably low TRL and not very numerous large installations literature is more focused on laboratory and demo results. One of the comparable works comes from Haro *et al.*, who took results from the bioliq™ project and subjected them to a TEA. Depending on process variables and conditions an efficiency syngas-products of 67.2 – 68.8 % and a biomass-product efficiency of 37.5 – 38.7 % was achieved for the DtG process. [49]

4.2.2 Basic economic characteristics

Haro et al., found the following economic data: Gasoline was produced for 36.80-41.25 €/GJ, which is based on the assumptions at the time of consideration more expensive than fossil gasoline. In order to achieve compatibility either high CO_2-certificate prices or a tax change on mineral oil is needed. DtG-gasoline can be produced for 1.12 €/L, while the fossil benchmark lies at 0.63 €/L at the study time.[49]

4.3 PART A: QUALITATIVE DESCRIPTION OF THE GASIFICATION SYSTEMS FOR TEE ASSESSMENT

3-PLATFORM (BIOCRUDE, SYNTHESIS GAS, ELECTRICITY&HEAT) BIOREFINERY USING WOOD BIOMASS FOR GASOLINE, REFINERY GAS, PROPYLENE, ELECTRICITY& HEAT WAXES WITH ENTRAINED FLOW GASIFICATION AND METHANOL/DME SYNTHESIS

The case study analyses possibilities for integration of gasification systems into conventional oil refineries for the production of synthetic bio-fuels. The wood biomass feedstock is gasified with steam to produce producer gas which contains a mixture of compounds. The producer gas must be cleaned and conditioned to get a mixture of CO and H_2 – the synthesis gas - which is then converted to methanol/DME via a catalytic reaction system (methanol/DME synthesis). The final quality of the transportation synthetic biofuels is reached in the refinery upgrading. Butane, propane & polypropylene are valuable side products.

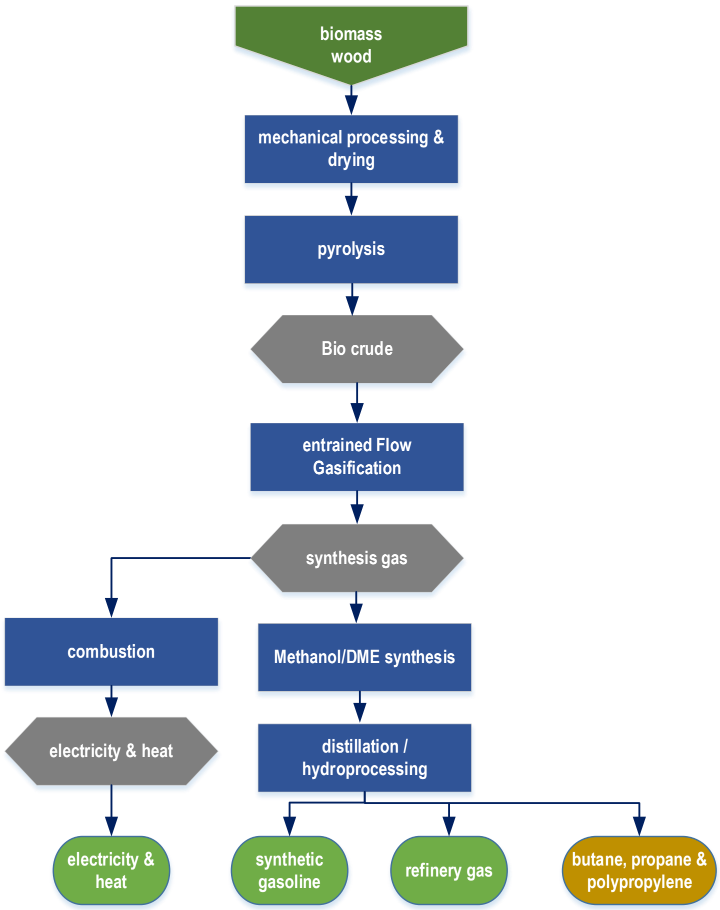

Figure 7: Accumulated results for the DtG system. Basic flow chart of Methanol/Dimethoxymethane (DME) processes for high-quality gasoline blend

4.4 FISCHER-TROPSCH

Contrarily to many important discoveries, Fischer was well aware of the importance of his discovery, albeit it was done almost 90 years ago. The first commercial plant went into operation in 1935 in Germany in order to deal with surplus coke and to produce highly versatile chemicals and fuels. [23]

Nowadays, with dwindling oil reserves and significantly rising fuel prices it is more relevant as it ever was. In the meantime, it was important in various countries facing various oil shortages due to political issues, so coal could be turned into oil and fuels. Later on, different catalyst systems such as iron or cobalt were developed, allowing for a flexible process design with a broad variety of possible products. This was only increased by more reactor designs. Over time the main target compounds were gasoline, Diesel, waxes or chemicals such as olefins or alcohols. [50]

While the overall reaction scheme looks straightforward, see Equation 8, over 10 reaction steps are needed. [50]

Equation 8: The simplified net reaction scheme for the FT process.

$$CO + 2H_2 \rightarrow (CH_2) + H_2O$$

While the overall process is tremendously complicated and depends on many different choices such as catalyst, temperature, syngas ratio etc, the basic steps are always the same. [51]

Steynberg and de Klerk provided comprehensive overviews, which are summarized here. [23], [51]

1.) Syngas preparation

Syngas comes from carbon. It does not matter is the carbon stems from coal or biogenic material like in this case. In a preferable case the starting material also contains hydrogen, otherwise energy demand increases as water needs to be split. Coal is the most common educt, with considerable amounts of waste heat which are usually converted to electricity in order to improve efficiency. Natural gas is much cheaper to turn into syngas and moreover reduced amounts of CO_2 in the syngas can be achieved with a clean gas feed. This is the most expensive part of the whole process., due to lower overall efficiencies. On the upside FT products often have a higher quality compared to conventional products as contaminants such as nitrogen or sulphur-containing compounds are easily removed during gasification.

While reusing renewable materials or waste is definitely an improvement from an environmental point of view it reduces process flexibility as narrowly defined feedstock quality would be needed then.

2.) FT synthesis

As mentioned, the actual synthesis depends on the syngas feedstock, e.g., iron catalysts are favoured for coal and many other different factors. Common reactor types are low and high temperature FT reactors with different layouts such as fixed beds, fluidizes beds or slurry reactors. The three most common types of intermediates are iron-based low and high temperature Syncrude as well as cobalt-catalyzed low temperature Syncrude.

3.) Product upgrading

The first step usually marks the removal of light hydrocarbons and gases to account for storability. Olefins may be removed from the liquid by means of extractive distillation and then transformed by operations such as hydroformylation or alkylation to final products. Side product such as oxygenated hydrocarbons are usually further hydrogenated into naphtha and diesel. Naphtha can then be further refined to yield gasoline. The main reason for hydrogenation is the possibility to increase storability.

But again, many different transformations are possible, e.g., the production of monomers such as ethylene, propylene or butene, which have high market values.

4.4.1 Basic environmental characteristics

Ail et al. performed a review on FT also including biogenic FT sources, highlighting that diesel from FT can be advantageous if biogenic carbon is used but that this is not a given. E.g., diesel form waste wood can reach low values such as 0.15 g CO_2-eq./km, while short rotation forestry already emits 80 – 120 g CO_2-eq./km. These values are still lower than natural gas (155-185) but already show disadvantages for 1st-generation biofuels. [52]

Trippe et al, whose work was already introduced in the DtG chapter, also found values for FT diesel and gasoline. The analysis was done with a model from Aspen Plus ™ with an input flow of 2.7 kmol/s. They found values are slightly higher than those for DtG but only on a low scale. Efficiencies from syngas to fuel ranged from 68.1 – 68.7 % and the full efficiency from biomass to fuel was 38.1 – 38-7 %. However, coal proved to be more efficient with values around 43.7 - 43.9 %., due to fewer conversion losses and reduced energy demand. [53]

The efficiencies provided by Trippe et al, were verified in a later work by Rafati et al who reported slightly higher values ranging from 39-43 % fuel efficiency over a variety of configurations, with alterations of catalyst and syngas ratio. [54]

4.4.2 Basic economic characteristics

Trippe et al also performed a TEA and found that FT products were not competitive with the respective fossil benchmarks. Prices ranged from 1.557 € - 1.601 € ton, which was significantly higher than the anticipated benchmark, 0.981 €. [53]

Rafati et al., investigated several processes via Aspen™ with the same results as seen in other conversions, that the BtL paths could not compete with their fossil competitors, even though, a 400 MW input of raw biomass was assumed, according to this literature smaller sizes can hardly be competitive in terms of economics. Characteristic results in terms of specific product costs were 35.8 or 42 $ per GJ for cobalt and iron-based catalysts based conversion technologies. However, in a hypothetical process in which 50 % of the syngas was produced from natural gas values of 19 – 22 $ were found due to reduction in costs for the more expensive biomass gasification. This value was still above the applied fossil benchmark of 15 $ / GJ but did mark the best result. [54]

4.5 PART A: QUALITATIVE DESCRIPTION OF THE GASIFICATION SYSTEMS FOR TEE ASSESSMENT

The gasification under study features an approach in which biomass is gasified, followed by an MtG-process which then finishes with a FT conversion into fuels. The energy and mass balances are taken from [17] and scaled to 100,000 tons of synthetic fuel per anno. The scope in the original study was 50 t/h with a runtime of 8600 h/a marking an annual production almost fourfold in volume.

The gasification models were based on stoichiometries and efficiencies previously known by the Karlsruhe Institute for Technology (KIT). Wood was the feedstock in this model. The MtG step of the synthesis was performed with the help of commercial software ASPEN™ Plus V10, based upon laboratory data and confirmed with literature. [46], [55] The FT-step is based on the Anderson-Schulz-Flory (ASF) distribution model with value of 0.9 for α. This value translates to diesel of the highest quality. The processing of the syncrude was performed with internal simulation software. Moreover, produced diesel does not need further refining after the distillation step. The waxes included in the syncrude were cracked in two different simulated ways: The catalytic cracker (FCC) and the hydrocracker (HG).

3-PLATFORM (BIOCRUDE, SYNTHESIS GAS, ELECTRICITY&HEAT) BIOREFINERY USING WOOD BIOMASS FOR FT-DIESEL, FT-GASOLINE, REFINERY GAS, PROPYLENE, ELECTRICITY&HEAT WITH ENTRAINED FLOW GASIFICATION AND FISCHER-TROPSCH SYNTHESIS

The case study analyses possibilities for integration of gasification systems into conventional oil refineries for the production of synthetic bio-fuels. The wood biomass feedstock is gasified with steam to produce synthesis gas containing CO and H_2, which is then converted to raw FT-biofuels via a catalytic reaction system (FT-synthesis). The final quality of the transportation FT-biofuels (diesel & gasoline) is reached in the refinery upgrading. Refinery gas and propylene are valuable side products.

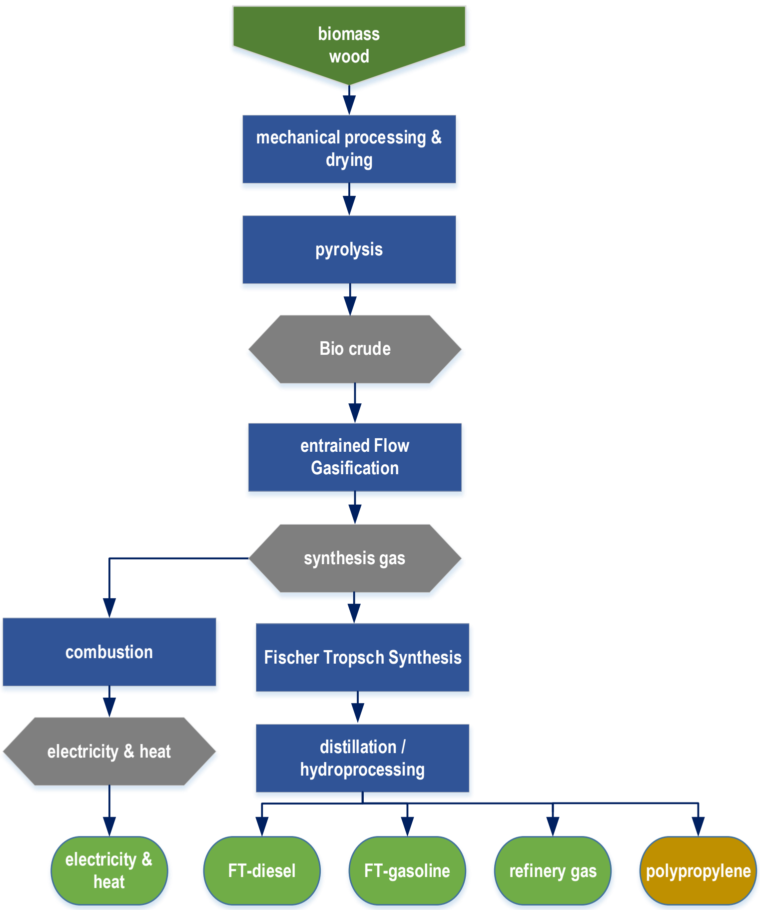

Figure 8: Basic flow chart of Fischer-Tropsch (FT) process for high-quality synthetic diesel & gasoline

4.5.1 MtG

Figure 9 shows the inputs and outputs of the system as well as energy inputs in form of biomass and the energy contained in intermediates and final products. With a biomass consumption of 1,061,934 t a more than tenfold input is needed when compared to the 100 kt of product obtained. This can be interpreted as an increase in energy density from educt to product, as the overall energy efficiency is 87 %. Without utilities like steam or electricity the product efficiency ($\eta_{products}$) goes down to 43.2 %. This lies within the range of results introduced in chapter 4.1.1 but also slightly below as many authors reported findings in the range of 46-48 % via simulation results. The efficiency only for the synthetic gasoline lies at 28.9 %.

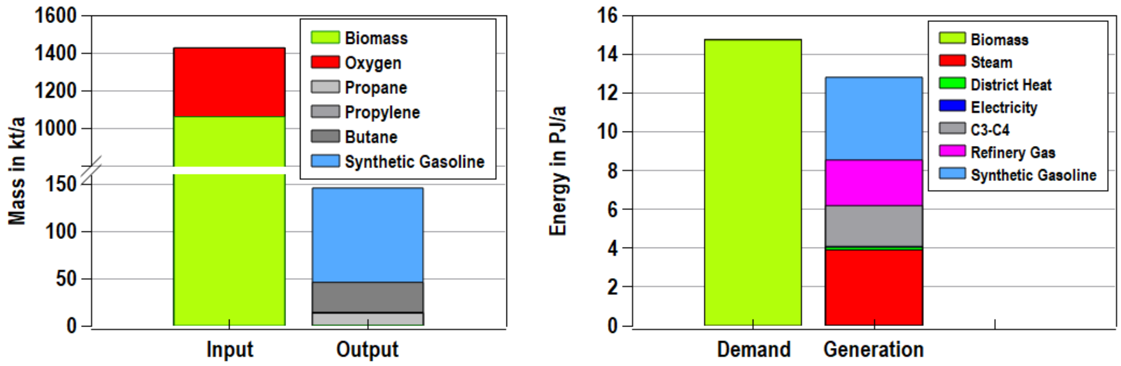

Figure 9a & b: 9a (left) displays the mass balances of the MtG system. 9b (right) shows the energy input in form of biomass compared with the energy content of the products and energy carriers obtained in the transformation.

Detailed results are listed in Table 3.

Table 3: Detailed overview over in- and outputs (in t/a), energy inputs and outputs in (PJ/a) and efficiencies.

Inputs		**Outputs**	
Biomass	*1,061,934*	*Synthetic gasoline*	*100,000*
Oxygen	*364,653*	*Butane*	*31,722*
		Propylene	*906*
		Propane	*13,293*
Energy Inputs		**Energy Outputs**	
Biomass	*14.73*	*Steam*	*3.9*
		District Heat	*0.14*
		Electricity	*0.04*
		C3-C4 products	*2.10*
		Refinery gas	*2.35*
		Synthetic gasoline	*4.26*
Overall efficiency	***86.69 %***		
Product efficiency	***43.22 %***		
Gasoline efficiency	***28.94 %***		

For the economic evaluation Rauch and Koroveshi assumed OPEX of 0.23 € per litre and CAPEX of 0.52 € per litre of product. Moreover, a propylene price of 800 €/t, a butane/propane price of 0.586 €/t and a gasoline price of 844 €/t was assumed. The results are shown in Figure 10 &Figure 11.

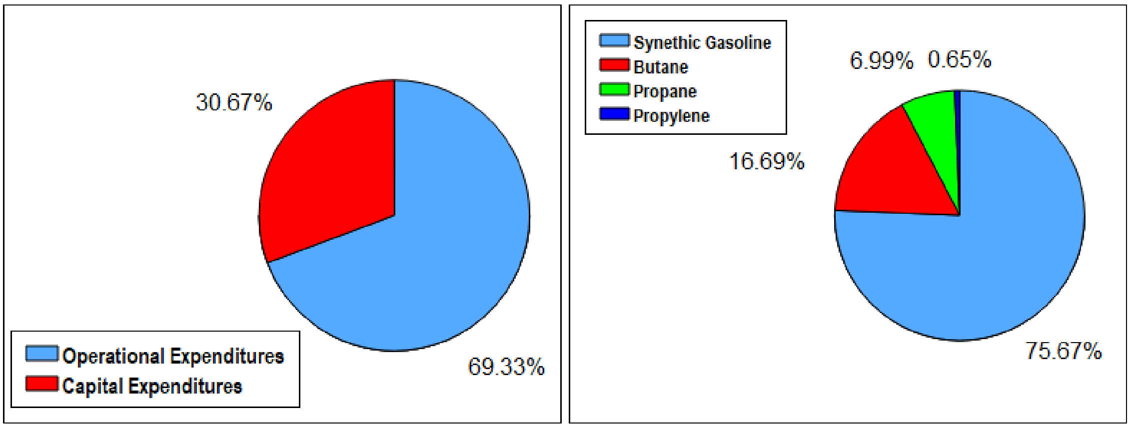

Figure 10a & 10b: 10a (left) shows the share of total costs between CAPEX and OPEX. 10b (right) shows the share of revenues generated by the products types.

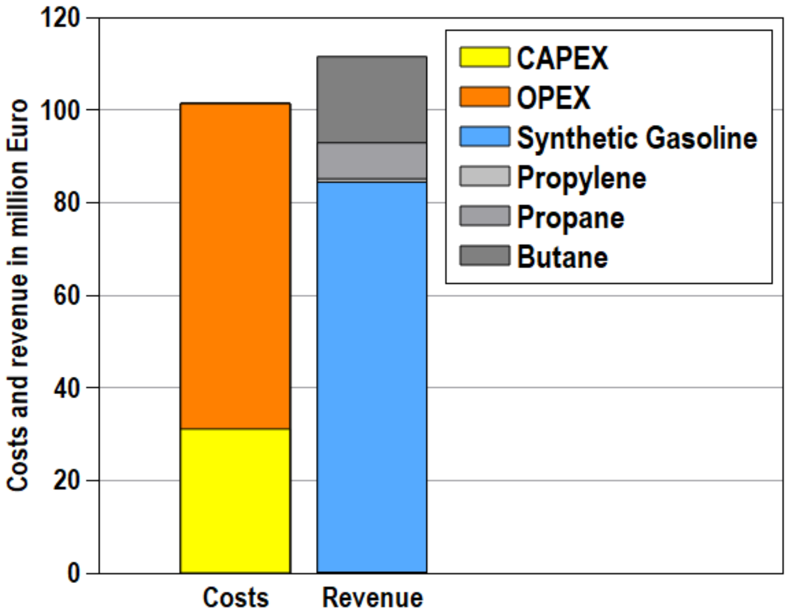

Figure 11: Costs and revenues and their detailed composition for the specific reference case.

The comparison or the shares of OPEX and CAPEX in total expenses are relevant, as mostly high initial investment costs are a big challenge for biorefineries as it is reported that these can hinder implementation, due to the fact that they often make up the biggest share of costs in a challenging market thus marking a big factor of insecurity for potential investors. [56], [57] This can be interpreted as a hint that a high level of maturity is reached within the technology, however, widespread application and roll-out depend very much on the specific economic framework conditions. Another specific finding is that, synthetic gasoline yields more than ¾ of the total revenue, while only making up for 68.5 % of product mass. With the cost of 0.75 €/l fuel a price of 25 €/GJ was calculated with an estimated energy density of 30 MJ/l for the synthetic gasoline, which is within the literature values presented, but lower figures have been reported before. This assumption is of course also highly sensitive to current subsidies and legal framework conditions for advanced biofuels.

All results of the simplified economic assessment are displayed again in Table 4 & Table 5.

Table 4: CAPEX and OPEX of the gasification plant.

CAPEX (€/l) & (€/kg)	**0.23**	**0.31**
in %	30.67	30.67
OPEX (€/l) & (€/kg)	0.52	0.70

Table 5: Costs and revenue of the gasification plant, in Million €/a.

	Cost	Revenue
CAPEX	31.08	0
OPEX	70.27	0
Synthetic Gasoline	0	84.37
Propylene	0	0.73
Propane	0	7.80
Butane	0	18.60
Total	***101.35***	***111.50***

Ultimately, GHGs were also compared for the reference scenario and the biorefinery in Figure 12.

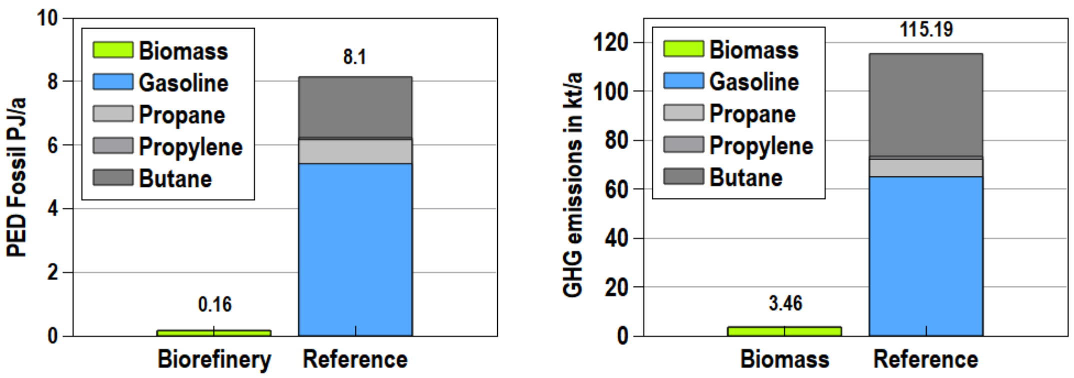

Figure 12a & 12b: Figure 12a (left) shows the fossil primary energy demand and Figure 10b the GHG emissions of the reference products.

According to the RED energy from renewable energy should carry no burden, therefore in this comparison bioenergy is far superior to the fossil references. Figure 12b highlights that replacing more refined products such as butane bring considerable advantages from an environmental perspective. Figure 13 shows that the total primary energy consumption is much higher for the biorefinery. This is in accordance to previously discussed points as it was concluded that the biorefinery turns low-energy-density materials into high-energy-density materials. Figure 14 shows a graphical abstract of the two systems compared and Table 6 summarizes results for energy and GHG emission savings.

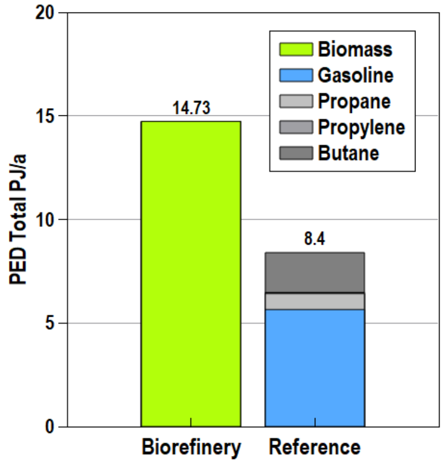

Figure 13: The total primary energy demand including renewable energy is compared between the benchmark and the biorefinery.

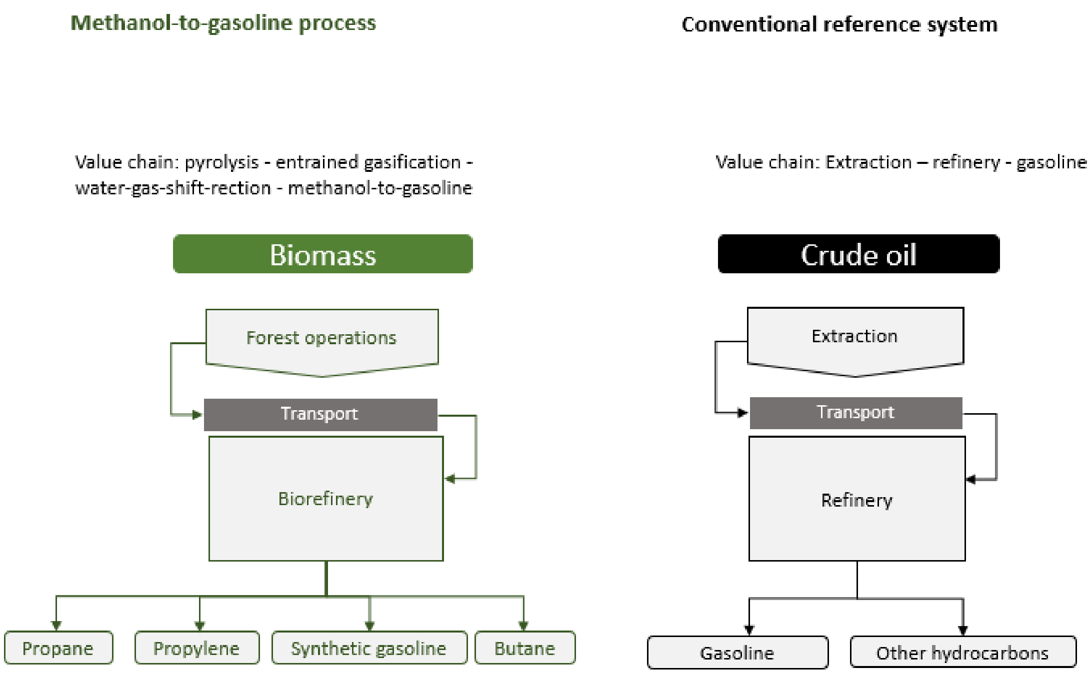

Figure 14: Biorefinery and reference system - value chain (cradle to gate)

Table 6: Accumulated results for the MtG system.

Greenhouse gas emissions		
Biomass	0	kt CO_2-eq/a
Biorefinery auxiliary materials and supplies	3.46	kt CO_2-eq/a
Crude oil refinery reference system	115.19	kt CO_2-eq/a
Savings	-111.73	kt CO_2-eq/a

Cumulated (total) Primary energy demand	
Fossil Reference system	8.4PJ/a
Biomass	14.73PJ/a
Reference system versus biorefinery total primary energy demand	+6.33PJ/a
Reference system versus biorefinery fossil primary energy demand savings	-7.94PJ/a

4.5.2 DtG

Figure 15 highlights that only a rough ninefold amount of biomass is needed for the production goal of synthetic gasoline. Other resources follow this trend, as less oxygen and energy are needed. While side product yields are also lower than for the MtG case, gasoline can be produced with a higher efficiency, indicating a highly specific but overall efficient process.

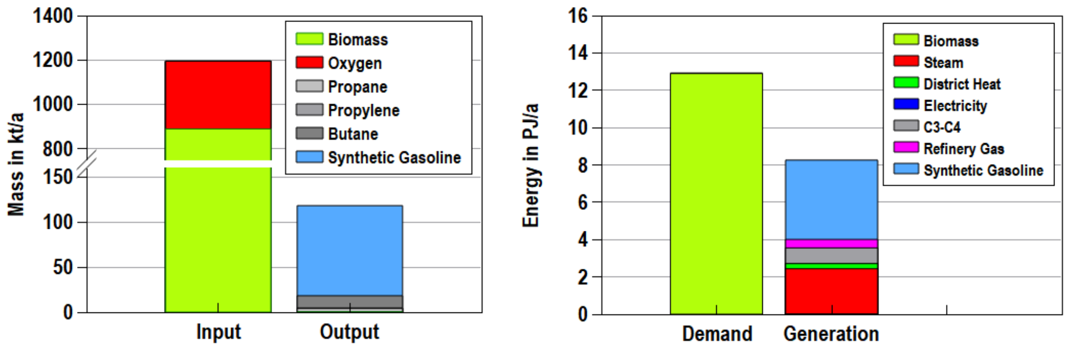

Figure 15a (left) displays the mass balances of the DtG system. 15b (right) shows the energy input in form of biomass compared with the energy content of the products and energy carriers obtained in the transformation.

Detailed results are listed in Table 7.

Table 7: Detailed overview over in- and outputs (in kt/a), energy inputs and outputs in (PJ/a) and efficiencies.

Inputs		Outputs	
Biomass	*889.153*	*Synthetic gasoline*	*100,000*
Oxygen	*305.291*	*Butane*	*13,571*
		Propylene	*4,233*
		Propane	*265*
Energy Inputs		**Energy Outputs**	
Biomass	*12.89*	*Steam*	*2.4*
		District Heat	*0.27*
		Electricity	*0.01*
		C3-C4 products	*0.83*
		Refinery gas	*0.45*
		Synthetic gasoline	*4.24*
Overall efficiency	***66.94 %***		
Product efficiency	***41.19 %***		
Gasoline efficiency	***34.44 %***		

For the economic evaluation CAPEX of 0.22 €/L and OPEX of 0.63 €/L were found by Rauch and Koroveshi. [17] Results for the economic evaluation are found in Figure 16.

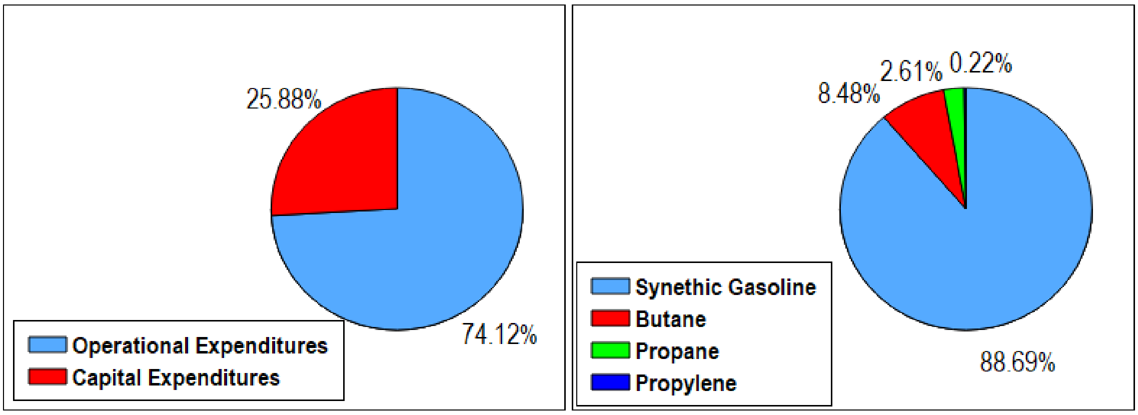

Figure 16a & b: 16a (left) shows the share of total costs between CAPEX and OPEX. 16b (right) shows the share of revenues generated by the products types.

While the OPEX values for DtG lie only 1c lower per litre compared to the MtG case, the CAPEX value is 11c higher per litre. This is in accordance with the literature presented above which forecasted savings in initial investments. In the balance sheet the savings of roughly 2 million € in the CAPEX are eradicated by an increase in OPEX by circa 15 million €/a compared to the CAPEX in the MtG case. Besides the technical complexity the lower TRL of DtG is not able to fully utilize economies of scale such as the more established MtG process. Products from the MtG process are dominated by aromatic and branched aliphatic hydrocarbons belonging to the gasoline fraction, and the gasoline selectivity is about 80%. MtG gasoline has a high-octane number of 90-95 and needs no enhancement. The MtG process thus has actual advantages in terms of product selectivity and lower plant investment cost. While the fuel efficiency is higher than for the MtG case, higher production cost and lower yields from side products result in a negative balance as presented in Table 8 & Table 9 and Figure 17 with the specific assumptions taken into account.

Table 8: CAPEX and OPEX of the DtG plant.

CAPEX (€/l) & (€/kg)	**0.22**	**0.31**
in %	25.88	74.12
OPEX (€/l) & (€/kg)	0.63	0.70

Table 9: Costs and revenue of the gasification plant, in Million €.

	Cost	Revenue
CAPEX	29.79	0
OPEX	85.14	0
Synthetic Gasoline	0	84.37
Propylene	0	0.21
Propane	0	2.48
Butane	0	8.07
Total	***114.86***	***95.14***

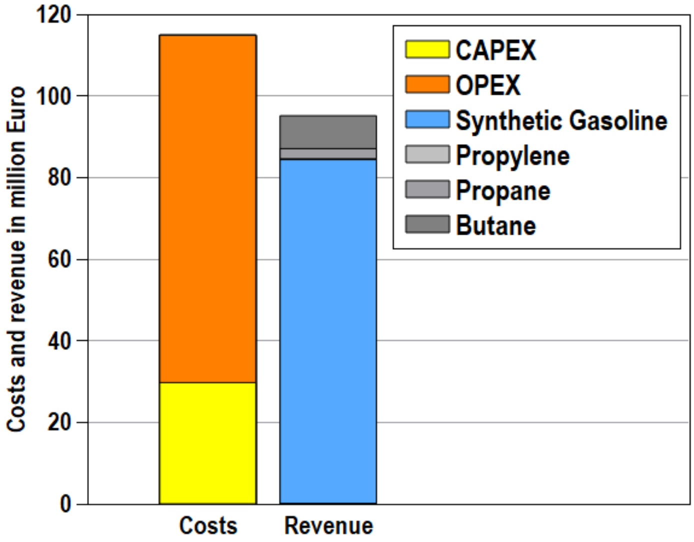

Figure 17: Costs and revenues and their detailed composition.

GHG, PED and NREU emissions were also compared for the DtG process in Figure 18 &Figure 19. All values are lower when compared to MtG. The reasons are obvious, as less biomass is used and fewer side products are produced, thus the renewable energy input, as well as fossil energy demand as well as greenhouse gas emissions go down. While economic figures favoured MtG, the environmental data outlines DtG as more energy-efficient. However, MtG's reference system emits more GHGs as more by-products are obtained. In this sense on a static comparison the preferences go to MtG over DtG but are again very case specific relying on the basic assumption of the biorefinery set-up. In addition to featuring a high-octane number, the DTG-produced gasoline has high aromatics and paraffins content, and relatively low content of naphthenes and olefins. Many countries currently set limits on aromatics and olefins contents in gasoline; the DTG gasoline would need to be refined to meet the new regulations in the most countries, and it also can be used as a blending agent in gasoline pool. These additional aspects can only be added in a qualitative discussion and can hardly be depicted quantitatively in the the respective case studies.

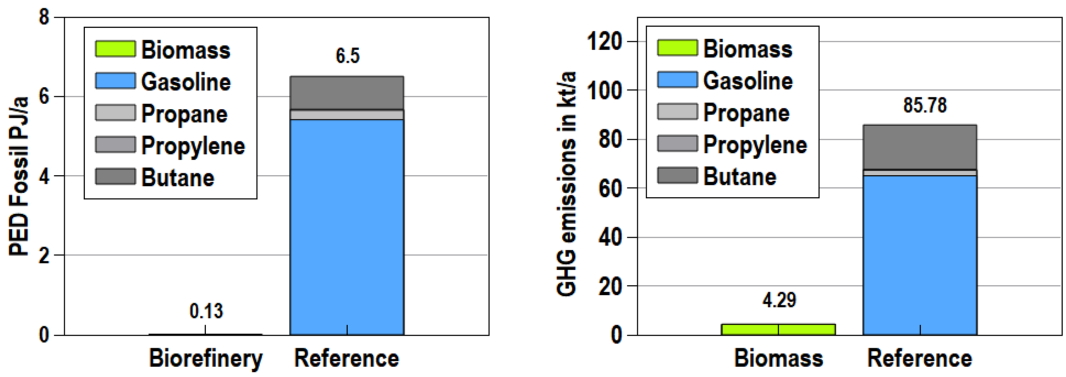

Figure 18: Figure 18a (left) shows the fossil primary energy demand and Figure 18b the GHG emissions of the reference products.

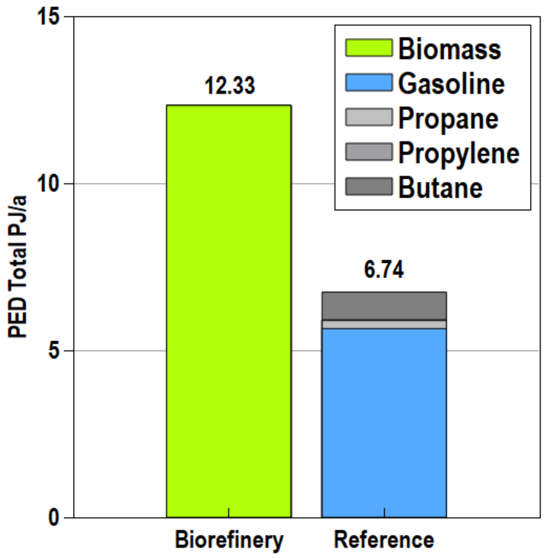

Figure 19: The total primary energy demand including renewable energy is compared between the benchmark and the biorefinery.

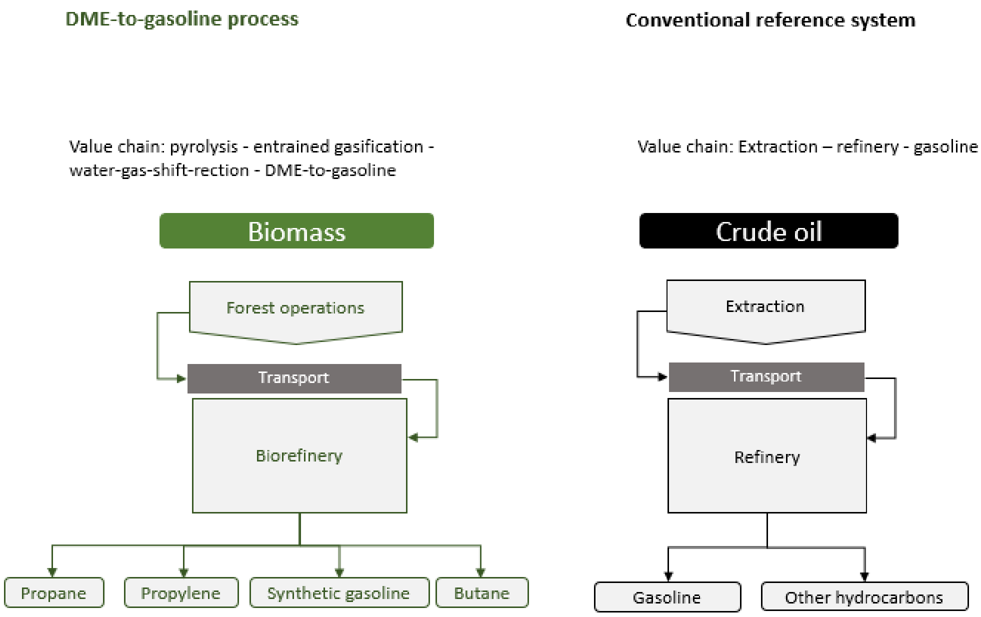

Figure 20: Biorefinery and reference system - value chain (cradle to gate)

Table 10: Accumulated results for the DtG system.

Greenhouse gas emissions		
Biomass	0	kt CO_2-eq/a
Biorefinery auxiliary materials and supplies	4.29	kt CO_2-eq/a
Crude oil refinery reference system	85.78	kt CO_2-eq/a
Savings	-81.49	kt CO_2-eq/a

Cumulated (total) Primary energy demand		
Fossil Reference system	6.74	PJ/a
Biomass	12.33	PJ/a
Reference system versus biorefinery total primary energy demand	+5.59	PJ/a
Reference system versus biorefinery fossil primary energy demand savings	-6.37	PJ/a

4.5.3 Fischer Tropsch

The results for both cases (FCC & HG) are presented in Figure 21 and

Table 11. Evidently, HG is the more efficient case, irrelevant if mass efficiency or energetic efficiency is regarded. Moreover, HG is superior to FCC in all three efficiency measures. The main reason is that a considerably smaller amount of input materials is used in the HG case while the output stays nearly identical with the exception of a small amount of propylene.

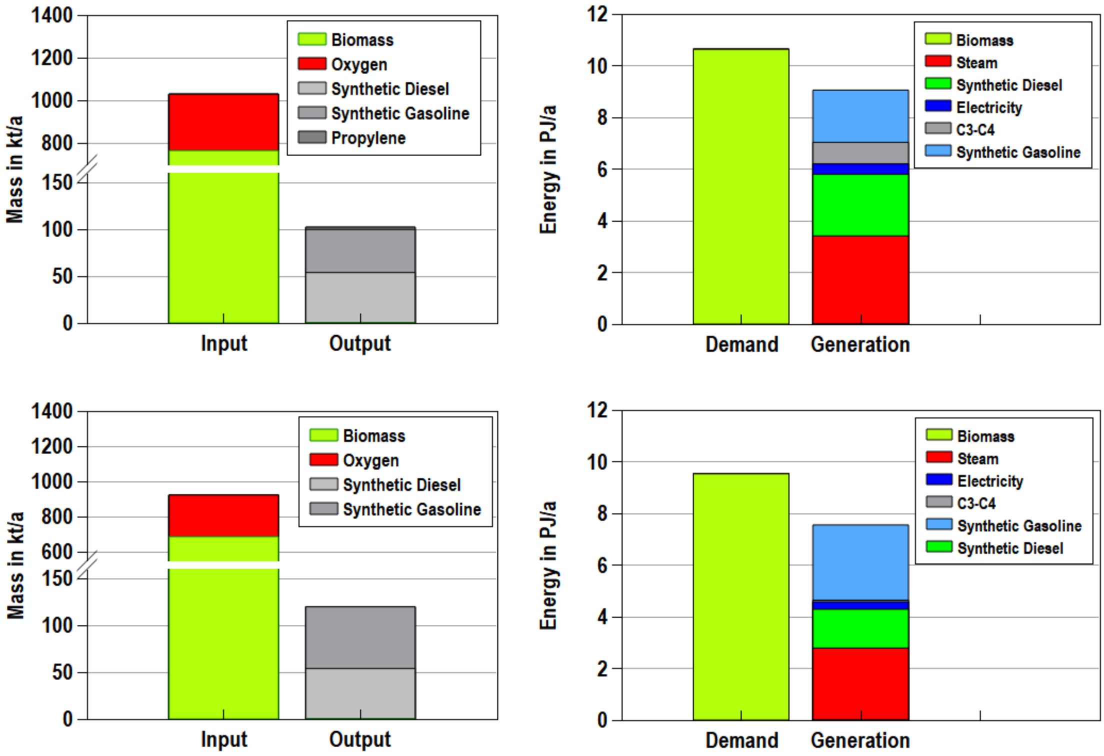

Figure 21a (top) displays the mass and energy balances of the FT FCC system. 21b (bottom) shows the same information for the FT HG model.

Table 11: Detailed overview over in- and outputs (in kt/a), energy inputs and outputs in (PJ/a) and efficiencies.

Inputs	FCC	HG	Outputs	FCC	HG
Biomass	*766.849*	*687.050*	*Synthetic gasoline*	*46.027*	*34.053*
Oxygen	*263.014*	*235.971*	*Synthetic diesel*	*53.973*	*65.947*
			Propylene	*2.466*	*0*
Energy Inputs			**Energy Outputs**		
Biomass	*10.63*	*9.53*	*Steam*	*3.41*	2.79
			District Heat	*0*	*0*
			Electricity	*0.40*	0.29
			C3-C4 products	*0.12*	0.06
			Synthetic gasoline	*2.02*	*2.91*
			Synthetic diesel	*2.39*	*1.50*
Overall	***78.45 %***	***79.22%***			
Product	***42.58 %***	***46.97%***			
Fuel efficiency	***41.47 %***	***46.29%***			

FCC…catalytic cracker
HG … hydrocracker

Economic data is presented in Table 12 -Table 13 & Figure 22 - Figure 23.

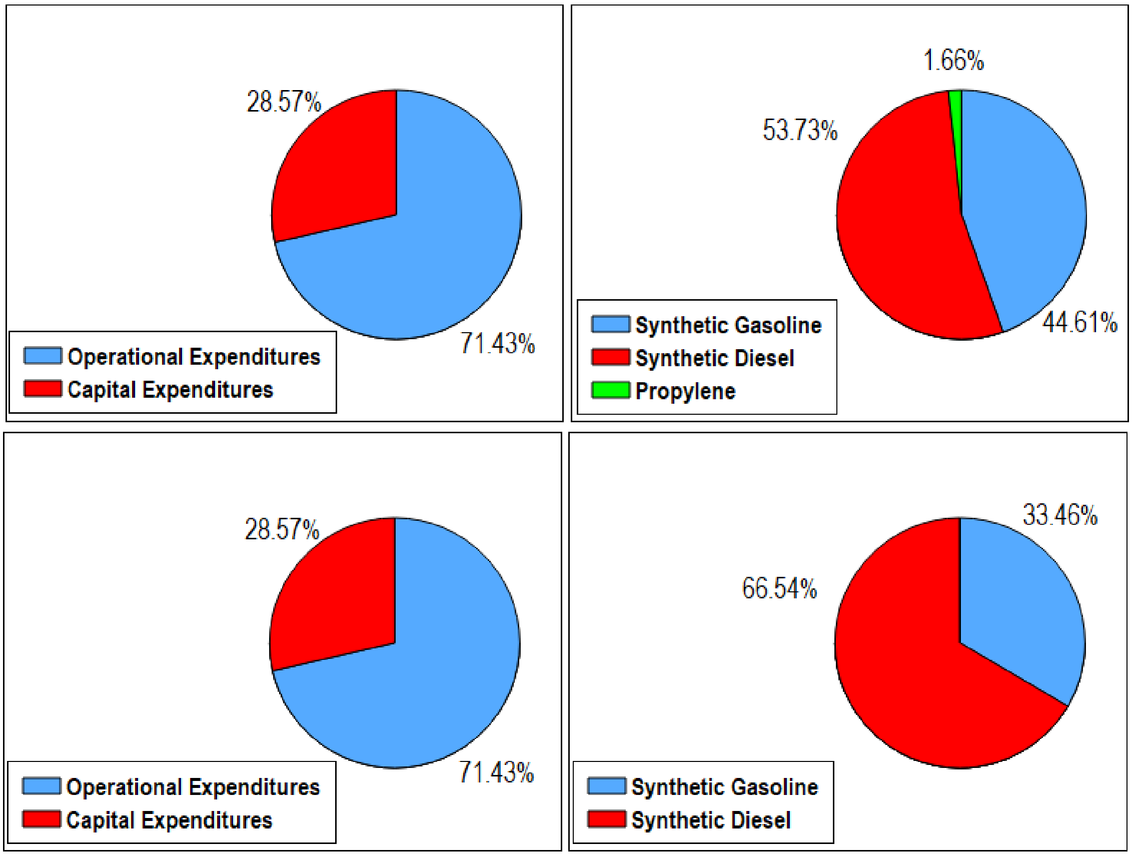

Figure 22a (top) shows the share of total costs between CAPEX and OPEX and the revenue generated by different products for the FCC design. 22b (bottom) shows the same data for the HG process.

Table 12: CAPEX and OPEX of the respective Fischer Tropsch plants.

CAPEX (€/l) & (€/kg) & %	0.22	0.31	25.88
OPEX (€/l) & (€/kg) & %	0.63	0.70	74.12

Table 13: Costs and revenue of the FT plants, in Million €.

FCC	Cost	Revenue	HG	Cost	Revenue
CAPEX	25.48	0	CAPEX	25.48	0
OPEX	63.69	0	OPEX	63.69	0
Synthetic Gasoline	0	38.84	*Synthetic Gasoline*	0	28.73
Synthetic Diesel	0	46.77	*Synthetic Diesel*	0	57.14
Propylene	0	1.45	*Propylene*	0	0.00
Total	***89.17***	***87.05***	***Total***	***89.17***	***85.87***

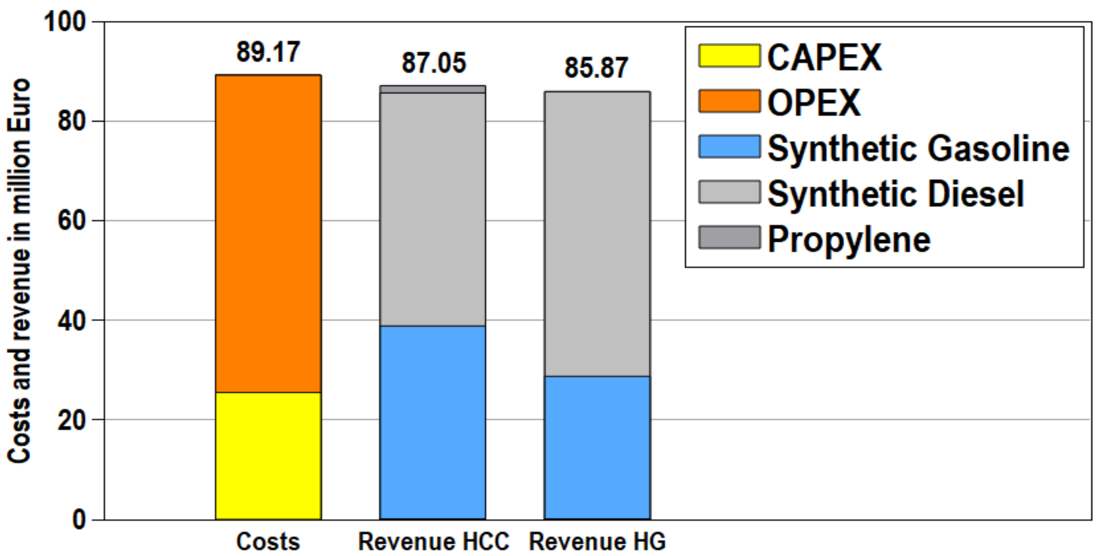

Figure 23: Costs and revenues and their detailed composition.

For both cases the same CAPEX and OPEX were assumed. While the FCC yields circa 45 % gasoline, and a minor portion of propylene, the HG process specialises in the production of Diesel making up roughly 2/3s of production. While this would normally lead to higher revenue, the additional propylene makes the FCC process more feasible. However, as the all the figures are relatively similar in size market shifts and price changes may easily change the final result, as market prices tend to fluctuate and are also subject to influences from the outside E.g.:

- + 3 % revenue increase (+2.6 Mio €/a) completely changes the picture towards + NPV
- CO_2 emission certificates are at levels that can be considered tipping points to generate business cases (e.g. + 2.04 – 2.40 Mio.€/a at 50 €/ton CO_2eq)
- Expansion of the material product portfolio can bring additional value creation
    - => Additional valorization of waste heat can bring additional value creation

PED and the GHG emissions for the reference substances are presented in Figure 24 - Figure 25. Not only does the additional propylene add additional revenue, it also leads to higher primary energy demand in the reference system and thus to a higher possible reduction of GHGs. Due to the relatively low share of renewable energy the PED and the fossil PED behave alike for the reference systems. The amount of bioenergy needed is lower in the HG case due to the higher efficiency. Due to the fact that the mini LCA is of the scope “Cradle-to-Gate” HG yields lower savings due to the fact that the main product is diesel, which has a considerably lower footprint in production. If a combustion were to be included too the opposite could be expected.

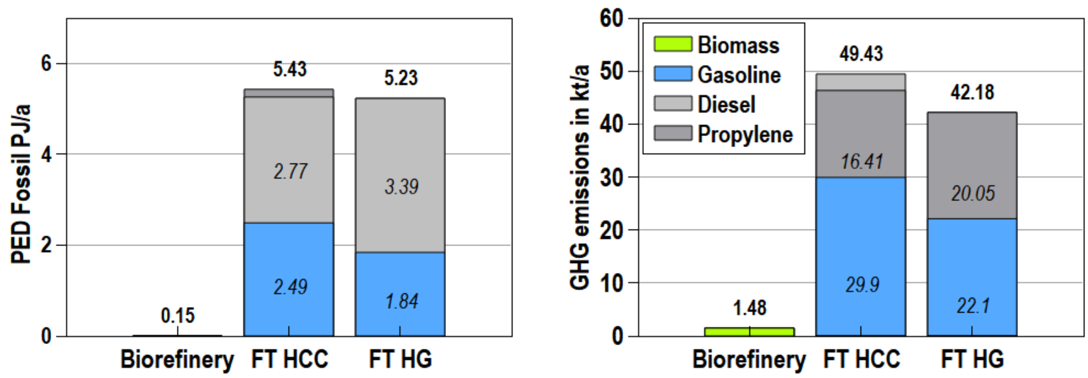

Figure 24: Figure 24a (left) shows the fossil primary energy demand and Figure 24b the GHG emissions of the reference products.

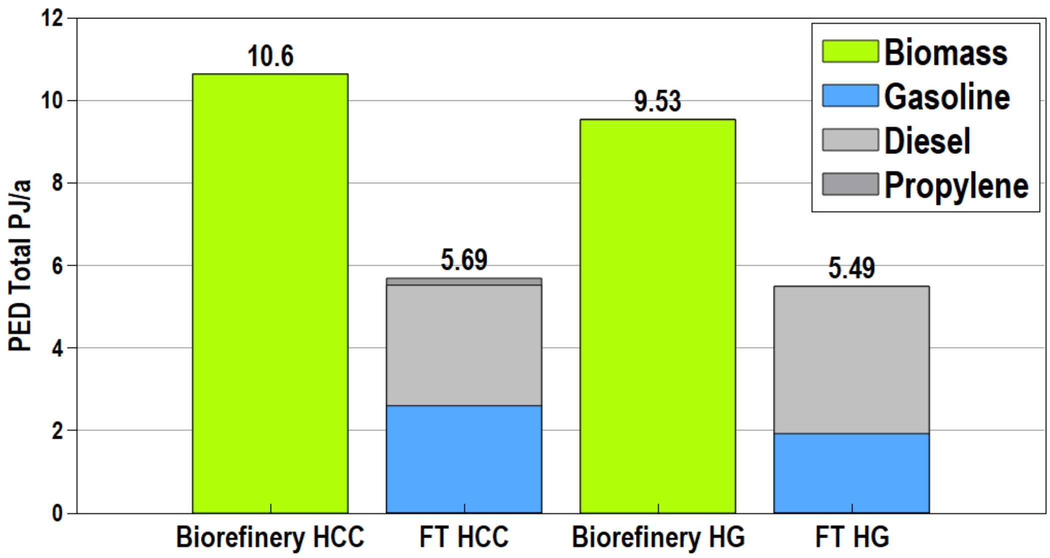

Figure 25: The total primary energy demand including renewable energy is compared between the benchmark and the biorefinery.

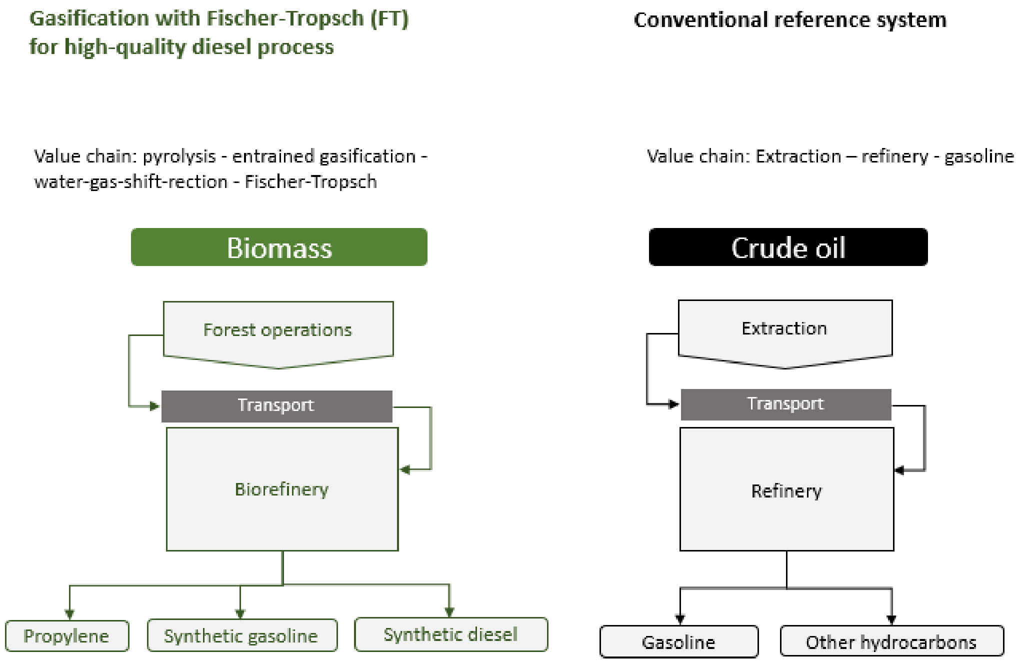

Figure 26: Biorefinery and reference system - value chain (cradle to gate)

Table 14: Accumulated results for the FT systems.

Greenhouse gas emissions	FT HCC	FT HG	
Biomass	0	0	kt CO_2-eq/a
Biorefinery auxiliary materials and supplies	1.48	1.48	kt CO_2-eq/a
Crude oil refinery reference system	49.43	42.18	kt CO_2-eq/a
Savings	47.95	40.70	kt CO_2-eq/a
Cumulated (total) Primary energy demand			
Fossil Reference system	5.43	5.23	PJ/a
Biomass	10.6	9.53	PJ/a
Reference system versus biorefinery total primary energy demand	+5.14	+4.3	PJ/a
Reference system versus biorefinery fossil primary energy demand savings	-5.32	-4.45	PJ/a

4.6 FINAL OVERVIEW AND DISCUSSION

In order to ease comparisons a short overview of all processes investigated should be presented here. The first points are in- and outputs, as found in Table 15.

Table 15: Overview of biomass and oxygen inputs for the four gasification plants.

	MtG	DtG	FT FCC	FT HG
Biomass input in kt/a	1062	889	767	687
Oxygen input in kt/a	365	305	263	236
Total input in kt/a	1427	1194	1030	923

It is evident that the MtG plant has the highest input demand compared to the other processes, as presented in Table 15. While logistics might not play the biggest role in chemical transformation processes from an LCA point of view, they do economically and strategically. On the one hand (gaseous) side products are formed in the MtG process but it still needs around 55 % more input than the FT HG design to yield the same amount of fuel.

In order to further this kind of discussion efficiencies were also investigated. The results were benchmarked with relevant literature in Figure 27 Figure 28. [32], [34], [49], [52]-[54]

Evidently, the overall efficiency defined in this work is a rather exotic measure as in literature results are not calculated as in this work. However, one can see that MtG reaches the highest value, due to its high share of steam production and a considerable amount of side products. While the DtG design yields more fuel than MtG side products and the elevated production of steam, electricity and gaseous side products account for the high overall efficiency. The product efficiency, only focusing on the synthetic fuel and gaseous side products is pretty much uniform with a small advantage for the MtG. This changes in the fuel efficiency, with the DtG being superior to the MtG process, as predicted in the early literature. The low value for MtG should be treated with care though as in different works the side products obtained re-enter the feed to yield more gasoline. Therefore, the distinction between fuel and product efficiency is not easily made and not sharp. This is confirmed by the relevant works of Gonzalez et al., and Dimitrou et al., who gave an optimum and minimum case with different results. [32], [34] Moreover, a comparison is made more unprecise as the use of higher heating value and lower heating value is not uniform throughout the studies. In conclusion are the obtained values comparable and fit nicely with the presented previous works, especially for DtG. For MtG the product efficiency seems to be the more suitable value, as a differing approach was taken in this work.

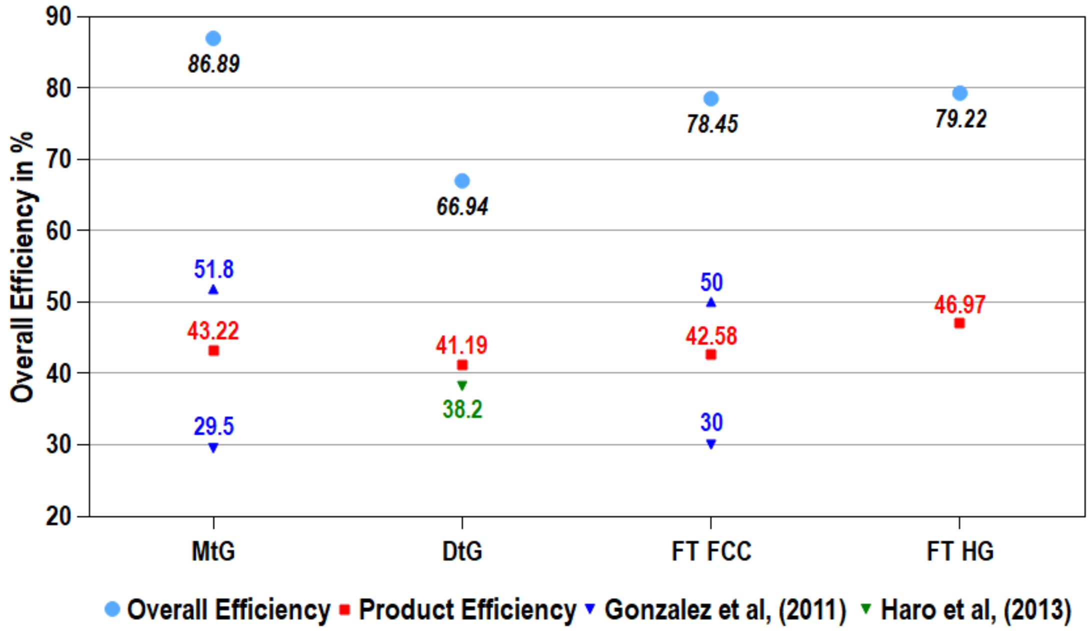

Figure 27: Overall and product efficiencies for the biorefineries compared with relevant literature.

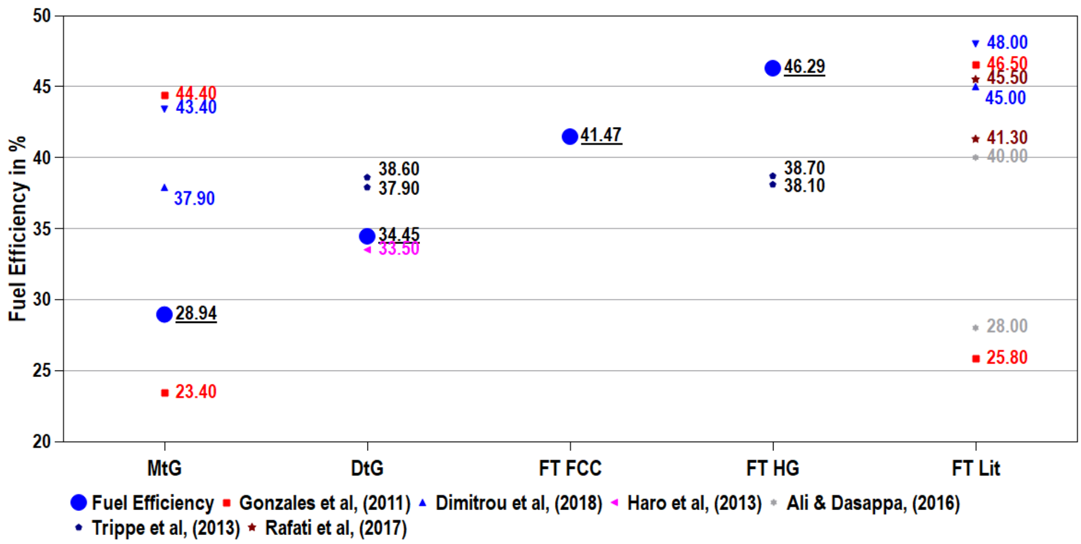

Figure 28: Fuel efficiency for the biorefineries compared with relevant literature.

The FT processes in this work used cracking to further refine the obtained fractions. Unfortuntely, only for the Hydrocracking (HG) a literature benchmark was found, which was exceeded considerably. [53] The other works used other techniques or the process was not described this exactly. Therefore, a bandwidth of literature results was plotted. Except for the two lower points of the works [32], [52] with an optimum and pessimistic case the found values find nicely within the range of previous works. One can easily see that FT has a very “narrow” product distribution as fuel and product efficiency are nearly equal.

Financial findings are presented in Figure 29 Figure 30. Figure 29 indicates that only the MtG process route shows a positive annual cash flow. While profitability would be better accounted for with an NPV approach it can be ruled out that DtG and FT would yield a desirable investment, which is a direct result of said negative cash flow. While revenues for fuels such as gasoline or diesel are all in a similar range of 80 – 90 million € the valorisation of by-products such as propane, butane or propylene made the MtG route more profitable than the others.

Of course, this does not account for the high volatility of commodity prices such as fuels, or C3-C4 chemicals. Over the course of the last year the price for gasoline went up to an intermediate high of 33.69 %, only to plummet to -11.33 % a little later, compared to the starting price. [58] Under the right circumstances the other plant designs are also likely to yield positive cash flows hence. Finally, the assumed product prices represent averaged values over longer periods of time. Consequently, it can be concluded that margins are, if present at all, very tight. The following take-aways were identified:

- Strong impact of the anticipated specific revenue for the main fuel products
- Revenues of > 25 €/GJ are essential
- The variables are highly sensitive to current subsidies and legal framework conditions for advanced biofuels
- Strong influence of process economics
- by the price (& availability) of feedstock/raw material

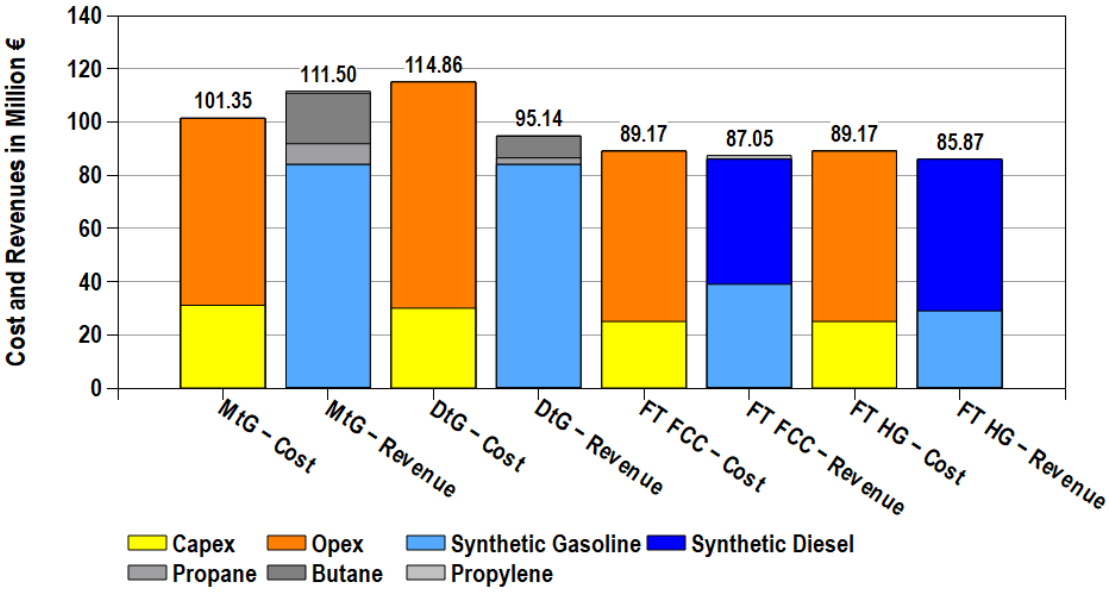

Figure 29: Overview of costs and revenues generated by the different refinery systems.

The results broken down to cost / GJ fuel produced are benchmarked against the presented literature in Figure 30. To account for comparability accurate exchange rates were used and prices were adjusted to EU-28 inflation, where due using online tools. [59], [60] Apparently, the MtG process design lies well within the range of the presented works. This is easily plausible as it presents a somewhat established process design with an abundance of data available. However, due to varying feedstock prices price fluctuations can be expected. The data for DtG implies a significantly better result for the simulation in this work. However, this result should be treated with utmost care as reference cases are scarce and the ones presented in this work refer to a demonstrator project with a relatively small scale. [49], [53] Earlier in the report it was mentioned that DtG is supposed to be superior to MtG in terms of financials, but this could not be verified in this model.

The results for FT products are very similar to the ones of MtG, as they lie well within the benchmarks but more on the lower end. No distinction between product choice or refining was made due to reasons of simplicity. Additionally, emphasis was on works which also focused on another included pathway in order to achieve comparable assumptions and data foundations.

In Conclusion, the obtained results seem robust and well comparable to available literature. It was found that MtG is the only route with a positive cash flow, while FT managed to yield the cheapest price per GJ.

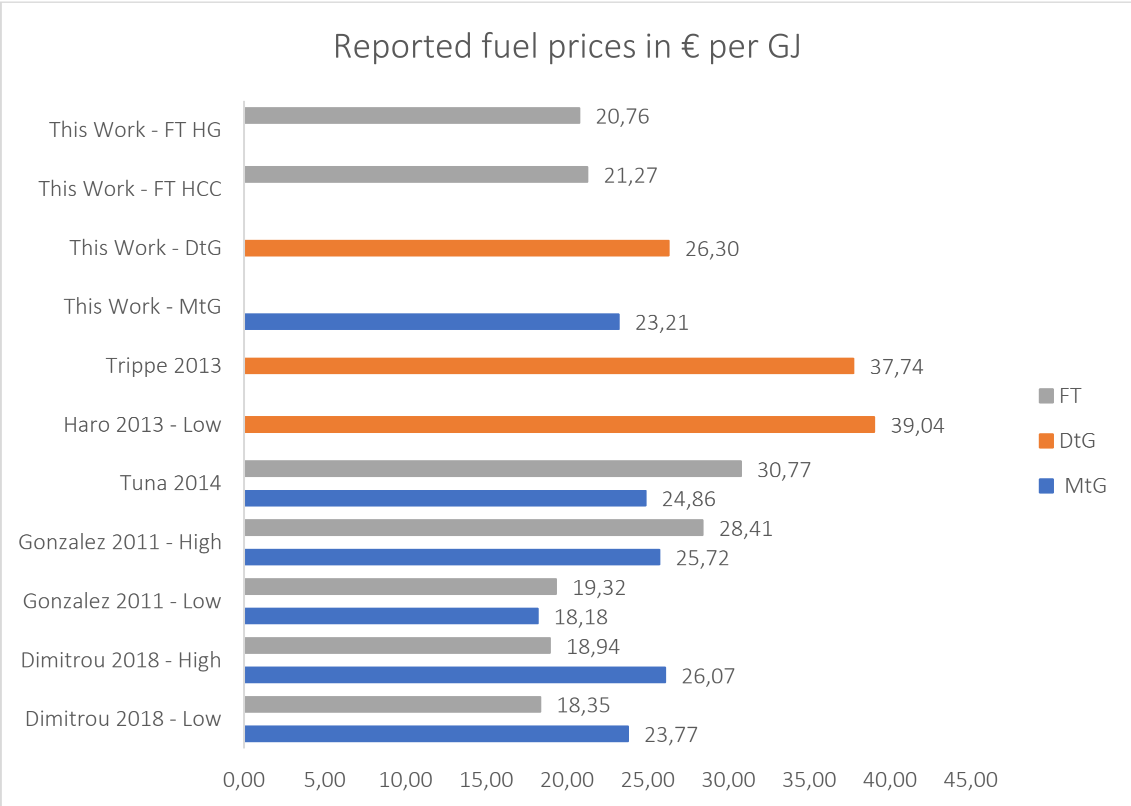

Figure 30: Costs of production for fuels produced in literature and in this work normalised to € / GJ.

Ultimately the GHG savings were compared in Figure 31. The reference processes were excluded, as biomass is considered carbon neutral in the RED directive. Again, MtG yields the most favourable result with the most carbon dioxide equivalents saved. While the savings for the produced gasoline are equal between MtG and DtG the additional butane really makes a difference. With a saving of 1.32 kg CO_2-eq / kg it achieves a value which is roughly twice the value for gasoline and the fourfold saving compared to diesel.

The lack of side products is also a big factor to which FT owes its inferior performance. Moreover, also the higher amount of diesel produced is unfortunate, as in the chosen cradle-to-gate approach diesel has an advantage over gasoline, with 0.32 kg CO_2-eq compared to 0.65 kg CO_2-eq for diesel. This is somewhat misleading as combustion leads to more emissions for diesel thus again levelling the playing field.

However, due to the oversimplification which is the RED and a complex refinery model which is subject to many allocation factors the exact numbers should not be relied upon too much.

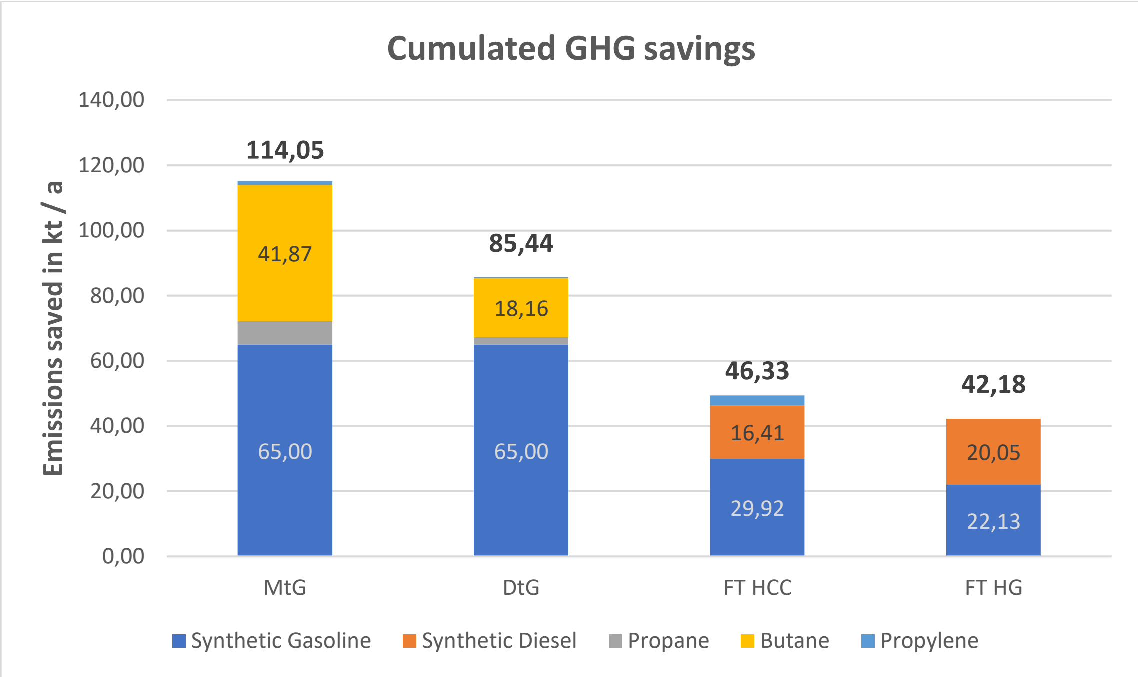

Figure 31: Cumulated savings in the gasification plants as fossil reference products are substituted by biobased equivalents.

4.7 SENSITIVITY ON UPDATED FUEL PRICES

When the majority of this work was written the world was a different one. Due to the surging of fuel costs the authors decided to redo parts of the financial analysis with updated values. Actually there is a strong economic momentum for integration of gasification based biorefineries. Spot prices were obtained for the whole world, the United States and the EU-28. They are presented in Table 16. Dollar prices were converted using an exchange rate of 0.96 € / 1 $. The percentual increase is based upon the values used for the first set of calculations.

Table 16: Updated prices for substitutable fuels and chemicals.

Gasoline - World	***1.39***	***€/L***	***1.76***	***€/kg***	***209%***	***43.01***
Gasoline - EU28	*2.016*	*€/L*	*2.56*	*€/kg*	*303%*	*62.38*
Gasoline - Eia.Gov (22)	*1.032*	*€/L*	*1.31*	*€/kg*	*155%*	*31.93*
Diesel - World	*1.36*	*€/L*	*1.64*	*€/kg*	*189%*	*39.50*
Diesel - EU 28	*2.036*	*€/L*	*2.45*	*€/kg*	*283%*	*59.14*
Diesel - Eia.GOV (22)	*1.189*	*€/L*	*1.43*	*€/kg*	*165%*	*34.55*
Propylene (May 2022)	*1.133*	*$/t*	*1.09*	*€/kg*	*136%*	
Propane/Butane (May 2022)	*0.30644*	*€ / L*	*0.62*	*€/kg*	*106%*	

Comparing this table with Figure 30 it becomes obvious that all of the works in literature would be likely to be financially competitive with fuel prices this high. Apparently, the increased prices cannot be compared directly, as most of literature works are already a few years old. As not only, fuel prices rose, the CAPEX and OPEX of plants is assumed to increase by 20 % in order to account for recent price developments. The CE Plant Cost Index (CEPCI) estimated an increase of 20.5, % for investments into chemical plants, therefore being in line with our assumption. [61] The results are presented in Figure 32.

Upon reviewing the updated financial results further conclusions can be drawn. E.g., the MtG process, the only profitable process design with the historical values the past years, is now far more profitable irrelevant the region. A similar result can be drawn for DtG, which now has a positive cash flow in all of the mentioned regions, which was not the case before. The same statement is true for both kinds of Fischer-Tropsch conversions.

The reasons for those results are not only fuel prices which have increased tremendously, also the Dollar/Euro exchange rate went from 0.84 to 0.96 thus increasing prices for Euro customers.

While the 20 % cost increase might not be close to reality, due to increasing interest rates, supply chain issues etc, the European case highlights that with even doubled costs a positive cash flow could be realised.

As fuel prices are not expected to drop significantly in the near future, the new market situation could be a catalyst for a desperately needed shift towards green bioenergy.

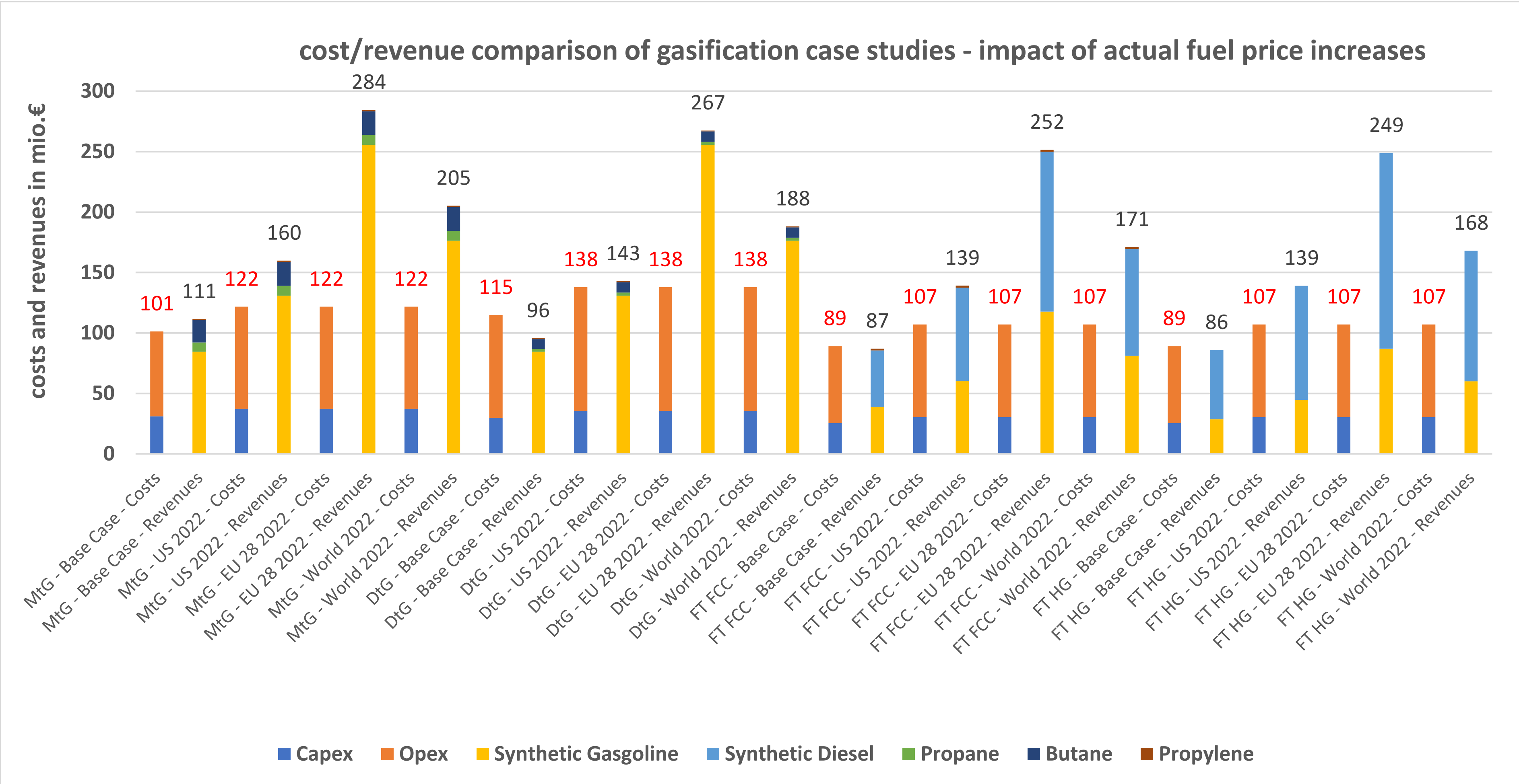

Figure 32: Updated financial data for the different gasification options compared to the averaged historical data. Costs are displayed in red, while revenues are coloured in black numbers.

TEE-Assessment – technical conclusions

- The integration of gasification in biorefineries offer flexibility in end products by predominant formation of gases rich in calorific value CO, H_2 (and less CO_2) and thus **high net energy and organic chemicals production potential**
- target variable is a **high overall efficiency and feedstock valorization** towards high value hydrocarbons
- Flexible fuel gasifiers with high feedstock flexibility lower requirements for raw material quality

TEE-Assessment – environmental conclusions

- **Main focus is to showcase the significant carbon dioxide / global warming reduction** potential via emission factor-based calculation including upstream emissions
- **Allocation procedures are avoided** by extending the systems for the multi-products on the biorefinery case and fossil reference system
- **all variants investigated here showed CO_2eq savings potentials of > 90 % compared to fossil reference product systems** based on the biogenic feedstock and process integration
- Environmental **performance highly dependent on process energy supply**. An integrated set-up based on renewable supply in the plant may lead to higher primary energy consumption, but it is essential for a comprehensive sustainability claim.
- As with all renewables scale up and market division needs to be linked to **stringent sustainability criteria** to take full advantage. A framework for analysis is currently evolving.

TEE-Assessment – economic conclusions

- there are **few high TRL projects in operation** for which **little economic data has been published**, so economic considerations are reserved for difficult prediction and simulation-based analysis
- to characterize biorefinery technologies, **specific production costs** from input/raw material to standardized products based on HHV (higher heating value) can be used, but for such multi-product systems, the **overall balancing of reference plants in case studies** appears to be anyhow equally adequate
- The main factors influencing the economic evaluation are the **full-load operating hours, the time horizon, the scaling of the reference plant**
- Despite significant investments, we deduce from our case studies that it is necessary to focus more on **OPEX optimization in the sense of favorable feedstocks**
- **Current price increases** for fuel commodities and CO_2 emission certificates are at levels that can be considered **tipping points to generate business cases**

TEE in early implementation stages

„In an early design stage of a technological implementation usually the degree of freedom for design choices is high, while the costs for adaptions are low“

- Underpin sustainability claim of integrated biorefineries

- via Technical, Economic and Environmental (TEE) Assessment
- quantitative environmental and economic assessment approach
- with generic initial biorefinery models for iterative refinement
- encourage stakeholders for the technology valuation
  of biorefinery technologies
- **Derive recommendations for an environmental sustainable & economically beneficial set up & implementation**
- Support decision making, give advice to policy makers, ensure compliance
- **Striking comparison of alternatives and scenarios**
  - Modular definition of unit processes, process energy sources, decide on materials, etc…
  - Identification of hotspots and opportunities towards sustainable processes, as shown in Figure 33.

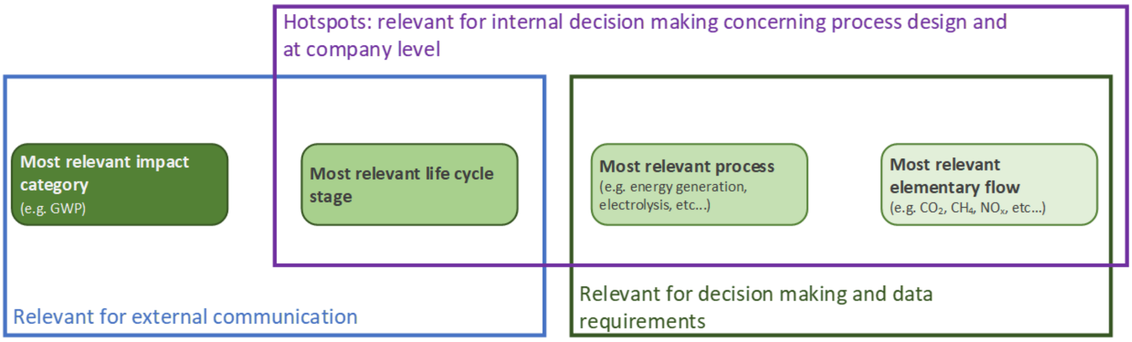

Figure 33: Identification of hot spots to communicate life cycle assessment effectively.

Biorefining is one of the key enabling strategies of the Circular Economy, closing loops of raw biomass materials (re-use of forestry, agro, process and post-consumer residues), minerals, water and carbon. Therefore, biorefining is the optimal strategy for large-scale sustainable use of biomass in the bioeconomy. It will result in cost-competitive co-production of food/feed ingredients, biobased products and bioenergy combined with optimal socio-economic and environmental impacts (efficient use of resources, reduced GHG emissions, etc.).
Biorefineries apply a cascaded-use of biomass for the production of food, feed, biobased products & materials, chemicals and energy. There is great potential to enhance the use of biomass by smart and highly integrated processing to deliver both products and energy. An integrated assessment (technical, economic and environmental - TEE) of technology pathways could provide a better understanding of the potential of biorefineries. IEA Bioenergy Task 42 is working in the field to generate and publish relevant results on TEE assessment of integrated biorefinery pathways whereas collaborations with other IEA Bioenergy Task, specific industry stakeholders and developers on identification and primary data mining is highly valuable and to be intensified. The goal is to generate robust data for characterization through interaction with key stakeholders in the field. Besides the aggregation of key results in fact sheets to be published, the accessibility of the primary data as an open-source knowledge capacity building repository in the field is part of the approach and an option to broader disseminate the method and results.

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