CHARGED WITH POSSIBILITIES

REPORT

The price of e-petrol in Europe

Report
“For internal uses”

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Executive summary

The purpose of this study was to quantify the cost of the production of e-petrol following two pathways, the Fischer-Tropsch (FT) and Methanol-to-Gasoline (MtG) route. The analysis was based on the SkyPower report, using the same Fischer-Tropsch and, similar, Methanol-to-Jet (MtJ) routes, which have intrinsically varied products, categorized under LPG, naphtha, kerosene (or jet fuel) and diesel. Different simulations were made to either maximize the e-kerosene production or produce e-petrol, produced from naphtha.

In order to properly understand the possibilities for production of e-kerosene and e-petrol, the production pathways, their product slate, and the available additional conversion routes were investigated. The focus was on conversion of LPG and naphtha as by-products of the e-kerosene and e-petrol pathways in order to increase the value of the total product slate. It was found that conversion of LPG and naphtha leads to blend components for (e-)petrol via isomerization and catalytic reforming. Conversion to e-kerosene is considered only possible by application of a syngas generation unit.

A first simulation was focused on producing 100% e-kerosene via the FT route by recycling all other hydrocarbons via a syngas generator unit into the synthesis unit. This led to a 12% increase (from 5580 to 6270 €/t for a production plant of 50 kt/year) in production costs due to the syngas unit and recycle stream; however, e-kerosene is considered more valuable than e-naphtha and the margins were similar on the production.

In a second simulation, processing units are added to convert e-naphtha into e-petrol, resulting in an additional production cost of 1452 €/t (from 5580 to 7030 €/t) for the e-petrol product stream. However, assuming an identical pricing level of (e-)kerosene and the gasoline blending components, this still results in a slightly better overall margin.

Finally, a third simulation was focused on the MtG route, recycling all LPG, and maximizing the e-petrol. Due to the high recycling stream and syngas generator unit, the CAPEX was similar to the MtJ route, even though the latter has a more complex separation step. The production costs were around 5160 €/t for the e-petrol, resulting in a consumer cost price of 5,11 €/l excl. taxes and VAT. As a comparison, currently the fossil fuel price is around 0,73 €/l excl. taxes and VAT. If the e-petrol is produced as a by-product of the FT route, the cost price increases even higher to 6,96 €/l excl. taxes and VAT.

Various routes were considered to convert the product slate of both the FT and the MtG routes to a 100% e-fuel end-product. Based on this study, both concepts are expected to be technically feasible. A comparison shows that the routes based on methanol show a better margin. Levelized costs of production of all routes are expected to decline in a similar way as these are in all cases mainly driven by cost of renewable energy and CAPEX of electrolyzers.

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Introduction

Transport & Environment (T&E) advocates for clean transport and clean energy in transport in Europe, with the goal to achieve zero-emission in the transport sector while keeping mobility affordable for all. With study reports and campaigns, they inform European legislation.

T&E has been heavily involved in the European legislation to phase out internal combustion engine vehicles. This resulted in the CO_2 emission performance standards, Regulation (EU) 2019/631, which was amended in 2023 (Regulation (EU) 2023/851) to ban the sales of vehicles with combustion engines by 2035. The amendment includes an option for potential derogation, for vehicles that run exclusively on CO_2 neutral fuels. This is generally understood to concern e-fuels. During the negotiations on the 2023 amendment, German car maker industry pledged for this derogation. European Commission president Von der Leyen has recently said that “she will push for an exemption for cars running on so-called e-fuels".[1]

T&E is concerned that e-fuels contribute less than desired to greening transport, will be expensive for consumers, delay the electrification of passenger cars, and eat into the renewable energy supply that may be more effective in other sectors. T&E assessed various aspects of e-fuels for road transport several years ago and would like to review and update their understanding. Therefore, they have requested Ionect to study further optimization of the product slate of e-SAF production routes based on the SkyPower report by further conversion of the naphtha by-product into e-fuels as well as an improved understanding of production cost differences in comparison to the base case as presented in said report.[2]

The study will focus on two production routes. The first route involves the Fischer-Tropsch (FT) process, which produces at least four product classes: naphtha, kerosene, diesel, and waxes, all requiring further processing. The second route involves the e-methanol to e-petrol pathway (also known as Methanol-to-Gasoline).

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[1] Bloomberg 16 July 2024: EU’s Von Der Leyen Eyes E-Fuels Carve-Out for Cars, Key Lawmaker Says.

[2] SkyPower 22 November 2024: Accelerating the take-off for e-SAF in Europe.

In the SkyPower report exactly these two routes are modelled in detail. We compare them to our own modifications of these models to assess the following situations:

A. Fischer-Tropsch process (mixed output of e-kerosene and e-naphtha)
    1. 100% e-kerosene scenario
        i. At similar e-kerosene production output
        ii. At similar plant capacity of the SkyPower simulation
    2. E-naphtha to e-petrol scenario
B. Methanol-to-Jet (mixed output of e-kerosene, e-diesel and e-naphtha)
    3. Methanol to Gasoline scenario (100% e-petrol)

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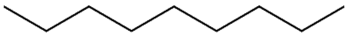
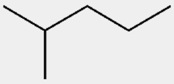
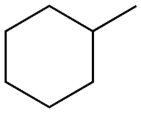
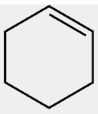
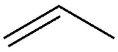
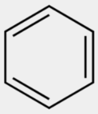
Basic process technologies

Before deep-diving into the possibilities for production of e-petrol or e-kerosene based on the FT or MtG pathway, some more background is provided to explain the basic chemistry and chemical processes.

Terminology

Hydrocarbons are compounds consisting mostly of hydrogen and carbon atoms. They can occur in a wide variety of lengths and molecular structures. Hydrocarbons can be classified as follows: saturated (only single carbon-carbon bonds, can be cyclic), unsaturated (one or more double or triple carbon-carbon bonds, can be cyclic), and aromatic (contains aromatic ring). In technical language additional terms such as aliphatic (no aromatic rings), paraffinic (saturated aliphatic hydrocarbons), and olefins (unsaturated aliphatic hydrocarbons) are commonly used. The chains formed by the carbon-carbon bonds can be straight or branched. Below, some graphic representations of various types of hydrocarbons are given:

Table 1: *Various types of hydrocarbons.*

Chemical structure	**Name (CxHy)**	**Characteristics**
	Nonane (C9H20)	• saturated • paraffinic • straight
	Isohexane (C6H14)	• saturated • paraffinic • branched
	Methyl-cyclohexane	• saturated • paraffinic
	Cyclohexene (C6H8)	• unsaturated • olefin
	Propene (C3H6)	• unsaturated • olefin
	Benzene (C6H6)	• aromatic

Besides naming of individual components, mixtures of components with defined physical properties are identified by commonly used product names. Some names relevant for this report include:

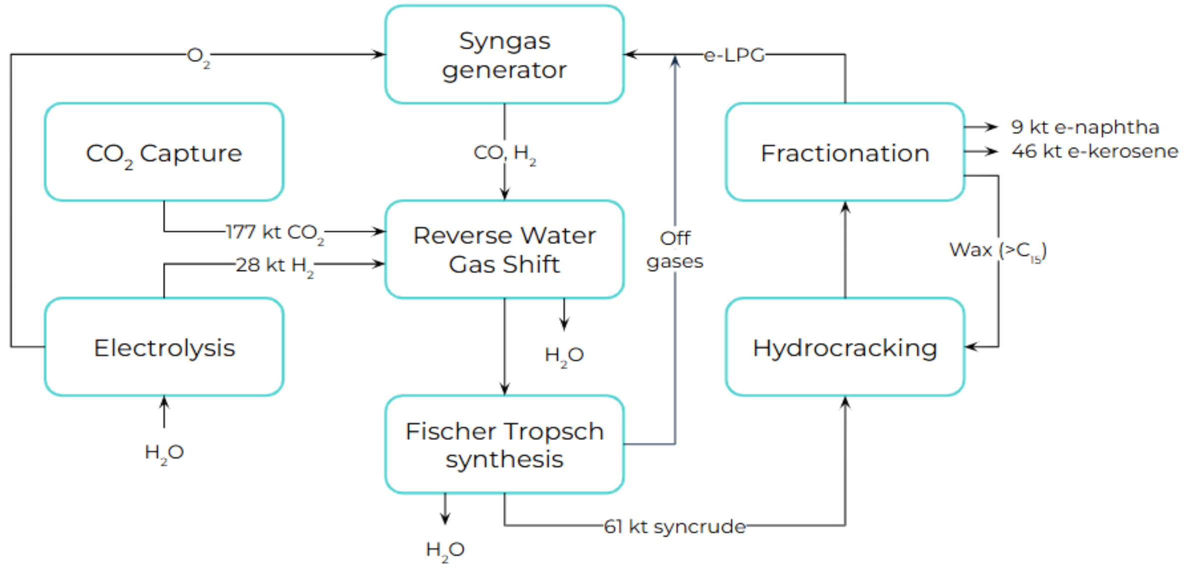
Table 2: *Commonly used product names.*

Category	**Composition**	**Characteristics**
LPG *(Liquified Petroleum Gas)*	Mixture of C3-C4 hydrocarbons	Boiling point < 30°C
Light Naphtha	Mixture of mostly C5-C6 hydrocarbons	Boiling point <90°C
Heavy Naphtha	Mixture of mostly C6-C12 hydrocarbons *(can contain aromatics)*	Boiling point <180°C
Kerosene	Mixture of C9-C16 hydrocarbons	Boiling point <190°C Freezing point <-40°C
Gasoline *(Petrol)*	Mixture of C4-C12 hydrocarbons *(contains aromatics)*	Boiling point <210°C Research Octane Number (RON)
Diesel	Mixture of C9-C25 hydrocarbons	Boiling Point <350°C Cetane Number (CN)
Wax	Mixture of C20-C40 alkanes (linear, branched, cyclic)	Melting point between 45 and 90°C

Technology

The basis for this study is the SkyPower report and associated model. This report focuses on two production routes for e-kerosene namely Fischer-Tropsch and Methanol-to-Kerosene. The two production routes are explained below (Bube 2024, Dieterich 2020, Keunecke 2024).

Figure 1: *Fischer-Tropsch kerosene pathway.*



CO_2 is captured from a biogenic point source or direct air capture and delivered to the Reverse Water Gas Shift Reactor, where it is combined with hydrogen produced via electrolysis. The reaction

$$CO_2 + H_2 \rightarrow CO + H_2O \tag{1}$$

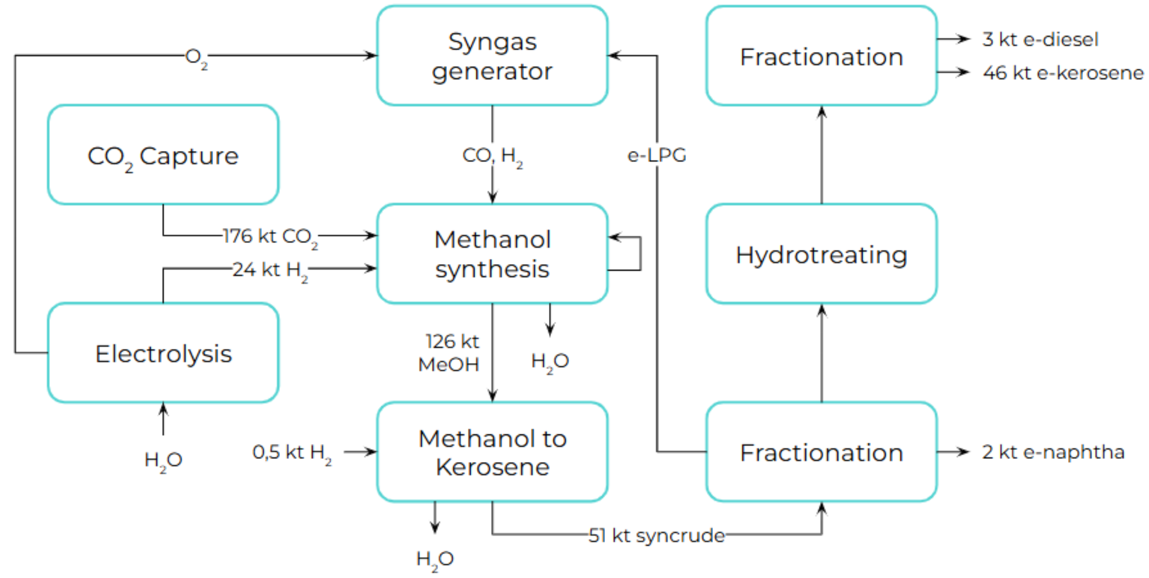
is endothermic and requires high temperatures (700 – 900°C) and a metal-based catalyst.

The water produced in the reaction is separated from the CO, after which the CO is sent to the FT synthesis reactor. In this reactor, CO and H_2 are reacted to form hydrocarbons and water according

$$nCO + (2n + 1)H_2 \rightarrow C_nH_{2n+2} + nH_2O \tag{2}$$

The exothermic reaction takes place at moderate pressures of 20-40 barg and elevated temperatures of 200-350°C in presence of a cobalt-based catalyst. The conversion in the reactor is not complete, with the unreacted reactants being recycled to the inlet of the reactor. Heat released during the reaction needs to be removed by cooling. The composition of the product mixture can be influenced by the reactor conditions. The product consists predominantly of straight-chain paraffins with a carbon number of 10-20. This mixture is called syncrude. The composition depends on the specific characteristics of the catalyst and the reactor conditions. The heavier products in this syncrude (waxes) are treated in a hydrocracker, where the larger molecules are broken down into smaller saturated hydrocarbons in a hydrogen rich environment under high pressure (75 – 150 barg) and high temperatures (400 – 800°C). The main products are classified as LPG, naphtha, and kerosene.

Figure 2: Methanol-to-Kerosene pathway.



In the Methanol to Kerosene (or Jet Fuel) route, CO_2 is captured from a biogenic point source or direct air capture and delivered to the Methanol Synthesis Reactor, where it is combined with hydrogen produced via electrolysis. The reaction

$$CO_2 + 3H_2 \rightarrow CH_3OH + H_2O \tag{3}$$

is exothermic and limited to 15-25% conversion, resulting in a large recycle of unreacted CO_2 and H_2. The reaction conditions are 50-100 barg and 210-270°C in presence of a metal-based catalyst (Ruokonen 2021). The methanol is separated from the water and any light-ends before being transferred to the Methanol-to-Kerosene conversion unit where hydrocarbons are produced in a multi-step process. First, methanol is converted into short-chain olefins via a dimethylether (DME) intermediate in the Methanol-to-Olefins (MTO) reactor (conditions: 2 barg, 400°C).

$$2n\, CH_3OH \xleftrightarrow{ZSM-5} n\, CH_3OCH_3 + n\, H_2O \tag{4}$$

$$n\, CH_3OCH_3 \xleftrightarrow{ZSM-5} 2(CH_2)_n + n\, H_2O \tag{5}$$

In the next step, olefins are reacted to form long-chain hydrocarbons in the Olefins-to-Gasoline-Distillate (OGD) reactor (conditions: 40 barg, 200°C).

$$2(CH_2)_n \xleftrightarrow{ZSM-5} C_{2n}H_{4n} \tag{6}$$

For the heavier products, additional hydrotreatment is required to produce saturated hydrocarbons (conditions: 40 barg, 300°C)

$$C_{2n}H_{4n} + H_2 \rightarrow C_{2n}H_{4n+2} \tag{7}$$

Main products are classified as LPG, naphtha, diesel and kerosene. The product slate can be influenced by reactor conditions. Separation of the various products may require additional steps depending on product specification.

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Optimization of product slate of Fischer-Tropsch process

The product distribution of the Fischer-Tropsch (FT) route depends on the selected catalyst and process conditions. Data from commercial reactors indicate that this method can yield 40 - 60% e-kerosene in the Fischer-Tropsch reaction, while a small part is too light, and another part is too heavy. Subsequent hydrocracking and isomerization brings the heavy share into the kerosene range. Through optimization, the overall e-kerosene yield could become 75% (Concawe's study). Newly developed reactors (see Topsoe brochure in references) claim 85% and perhaps even higher (Atsonios' study). The Fischer-Tropsch process typically produces LPG and naphtha as by-products.

The request by T&E to study further conversion of the naphtha by-product is divided into three key questions:

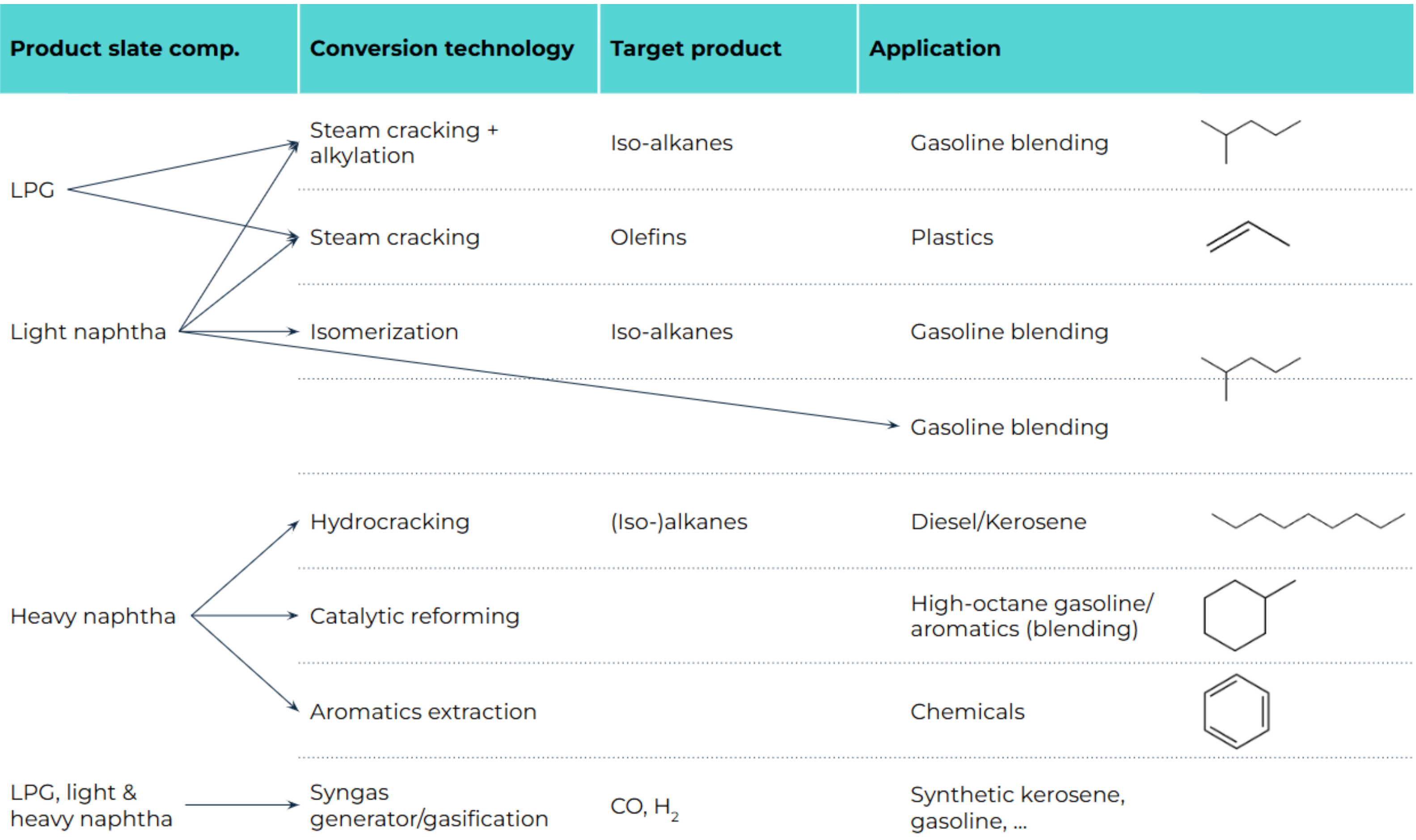
A. Can the naphtha by-product be completely converted to e-petrol?
B. Can the naphtha by-product be completely converted to e-kerosene?
C. Can the naphtha by-product be completely converted to e-plastics ?

Due to the intrinsic properties of the FT reactor, a widespread distribution of hydrocarbons is produced (following the Anderson-Schulz-Flory theory). Type of catalyst and operational conditions are the main parameters for this distribution. Unsurprisingly, each technology supplier has a different output. For example, Topsoe/Sasol has high quantity of paraffinic molecules, while Honeywell UOP produces more olefins and aromatics. In the study of Atsonios (2023), an ideal environment is created for the production of jet fuel reaching a selectivity of 90.7%. This value can be considered an upper level for the kerosene distribution under this catalysts' generation. In this work they have excluded small side-reactions, which would have brought the selectivity to a more realistic 85%.

The SkyPower model limits products to e-kerosene, and e-naphtha with a relative yield on product weight basis of 86%, and 14% respectively. Full mass balance is not shown in the report or model. Due to the inherent chemistry of the process, water and light ends (<LPG) will also be produced. These are not accounted for in the report. After detailed analysis of the model, it appears that the LPG is converted to syngas in a syngas generation unit (SGU) and therefore not presented as by-product. For sake of completeness of the analysis of potential conversion routes, LPG is also taken into account, as conversion in an SGU is only one of the possibilities for this by-product

stream. Below, a schematic overview and short description of possible conversion routes for LPG and naphtha based on existing technologies.

Figure 3: *Overview of conversion technologies for LPG and naphtha.*



Product slate comp.	Conversion technology	Target product	Application
LPG	Steam cracking + alkylation	Iso-alkanes	Gasoline blending
	Steam cracking	Olefins	Plastics
Light naphtha	Isomerization	Iso-alkanes	Gasoline blending
			Gasoline blending
Heavy naphtha	Hydrocracking	(Iso-)alkanes	Diesel/Kerosene
	Catalytic reforming		High-octane gasoline/ aromatics (blending)
	Aromatics extraction		Chemicals
LPG, light & heavy naphtha	Syngas generator/gasification	CO, H_2	Synthetic kerosene, gasoline, ...

Steam Cracking: Produces olefins from LPG/naphtha by thermally breaking down the hydrocarbon molecules at high temperatures (850°C) in the presence of steam. Steam cracking is highly endothermic and requires significant external heat input.

Alkylation: The alkylation process combines light iso-paraffins, most commonly isobutane, with C3–C4 olefins, to produce a mixture of higher molecular weight iso-paraffins (i.e., alkylate) as a high-octane number blending component for the gasoline pool. The process uses strong acids (sulfuric, hydrofluoric) as catalyst. Reaction takes place at mild conditions.

Isomerization: Converts linear paraffinic molecules branched-chain hydrocarbons, which have higher octane ratings and better performance characteristics as gasoline components. Also used to convert linear normal butane into isobutane for use in the alkylation unit. Process takes place at 30 bar and 200-300° with a highly active alumina catalyst. Adding hydrogen is required depending on the amount of olefins in the feedstock.

Hydrocracking: Hydrocracking is a catalytic cracking process assisted by the presence of excess hydrogen gas. Unlike a hydrotreater, hydrocracking uses hydrogen to break C–C bonds. The process is exothermic and executed in fixed-bed reactors. Typical operating conditions are 75-150 barg and 400–800°C.

Catalytic reforming: This process converts low-octane linear paraffins into branched alkanes (isoparaffins) and cyclic naphthenes, which are then partially dehydrogenated to produce high-octane aromatic hydrocarbons. The process requires a high hydrogen partial pressure and takes place at 5-45 barg and approximately 500°C in the presence of a platinum-based catalyst.

Aromatics extraction: Selective isolation of aromatic components (benzene, toluene, xylene) from petroleum fractions such as naphtha by solvent extraction usually at mild conditions.

Syngas Generator: Syngas ($CO+H_2$) is produced from hydrocarbons via steam reforming or partial oxidation. Reactor conditions are 700-1000°C and 10-30 barg. This is an exothermic reaction that requires cooling (e.g. by producing steam).

Naphtha uses and differences

Above presented overview of conversion routes shows that several options are available. These technologies are fully matured in existing refinery and petrochemical complexes and both drop-in of e-naphtha and dedicated conversion of e-naphtha can be considered. The selection of the conversion routes depends on the composition of the e-naphtha and the perceived off-take markets. In this study, focus is on e-petrol, e-kerosene, and e-plastics as target application.

Although an indicative composition of the naphtha stream is not provided in the SkyPower report, it is logical to assume that it consists of a wide boiling range of components that can be classified as light naphtha (30°C< boiling point <90°C), and heavy naphtha (90°C < boiling point < 180°C). Furthermore, it could contain aromatics and branched alkanes.

As the basis of the study is production of e-kerosene, the first route to consider is converting the e-naphtha/LPG to e-kerosene. For this, the only identified production route is the syngas unit, which converts the hydrocarbons to the basic building blocks of CO and H_2 from which e-kerosene can be produced via the FT process or the MtK process. In this case, this means recycling all hydrocarbon by-product to the start of the process.

The second route to consider is conversion to e-petrol. Based on the expected composition of the e-naphtha full conversion to an on-spec petrol is considered unlikely. At best, the e-naphtha/LPG can be converted to petrol blending components. Direct blending of the light naphtha blending in a (e-)petrol is also a possibility. Conversion requires at least two different process, namely isomerization for light naphtha/LPG and reforming for heavy naphtha. The products of these two conversion processes (iso-alkanes, paraffins, aromatics) can then be blended in an (e-)petrol pool.

The third route is conversion to e-plastics. Steam cracking of naphtha is the work horse of choice for conversion to olefins, which are the starting components for many plastics. Typically, steam crackers can handle naphtha with a wide boiling range, however for high efficiency a consistent feedstock is critical. Realization of a dedicated steam cracker for this naphtha does not seem feasible due to the scale (minimum a few hundred kton per year for a cracker). For drop-in application of the naphtha in existing steam crackers, the naphtha composition needs to be checked against the existing cracker design.

Depending on the complexity of the (e-)naphtha feedstock, a whole range of catalytic cracking technologies is also available. As the naphtha composition is not known and for the sake of simplicity, these technologies have not been further considered.

The analysis is based on more or less standard conversion technologies and then still limited in view of the scope of the present study. However, as technologies for production of e-fuels are introduced and further developed, also adjacent technologies based on by-product from the main production target receive increasing attention. One interesting development in this respect could be the Flexiforming process of Universal Fuel technologies (Flexiforming for FT processors brochure), which is aimed at converting the low-octane naphtha and LPG by-products into aromatic components for blending in the e-kerosene by coprocessing with methanol. In this way, all products could be accounted for in the e-kerosene end-product.

As a summary, the three key questions are answered:

A. Can the naphtha by-product be completely converted to e-petrol?

> Yes. Via isomerization (light naphtha) and catalytic reforming (heavy naphtha) the two product streams are further upgraded to e-petrol, as shown below in the e-petrol blending component scenario.

B. Can the naphtha by-product be completely converted to e-kerosene?

> Yes. By recycling the naphtha (and LPG) to a gasification unit to produce CO & H2, which can then be reinserted in the FT unit.

C. Can the naphtha by-product be completely converted to e-plastics ?

> Yes (technically). The light naphtha is often already added to the steam cracker producing monomers, which are the building blocks for plastics. Although it is currently not common practice to use heavy naphtha as feed for steam crackers, most existing crackers are expected to be able to process heavy naphtha as part of the feed blend. If volumes of e-naphtha would become significantly larger in the future, steam cracker re-design for the specific mix of light and heavy naphtha to produce feed for e-plastics should be feasible.

04

Price of e-petrol via the Fischer-Tropsch and e-methanol pathways

For this part of the study, the SkyPower model will be used as a reference for e-petrol calculations for both the FT and Methanol-to-Gasoline (MtG) pathways. This recently published open source techno-economic model of SkyPower calculates the price of e-kerosene for FT and Methanol-to-Jet (MtJ) pathways via a modeling of the costs. As the MtJ and MtG processes are similar (except for the final production steps), the model will serve well and allow for comparison between the costs of e-petrol and e-kerosene.

While a detailed discussion of this model is beyond the extent of this report, it is important to know that it includes parameters as e-fuel production capacity, electricity prices, CO_2 source and prices, assumed full load hours for renewables, use of renewable electricity and assumed production locations. Our modifications are limited to the CAPEX (capital expenditures) and OPEX (operational expenditures) and selectivity. The financial parameters (e.g. discount rate on CAPEX, depreciation, operating costs, financing, profit margin, distribution and retail costs) affecting the price remain the same.

The base case for all simulations is that the final investment decision is taken in 2025, the plant is to be built in Norway, using their renewable energy and related costs, the H_2 is stored in line packing and CO_2 is captured from biogenic point sources.

For each simulation described below, a detailed overview is presented in Appendix 1, dividing the costs into its main components (feedstock, OPEX, CAPEX and cost of capital).

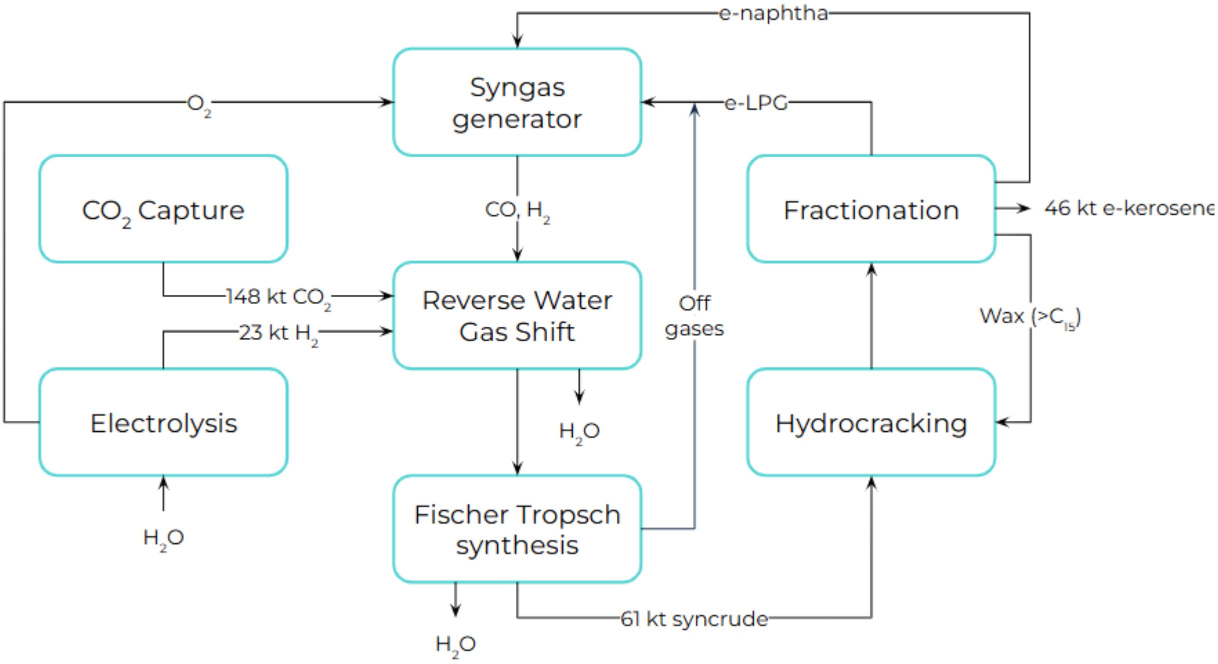
100% e-kerosene scenario via FT

Methodology

One method to obtain 100% e-kerosene within the FT Kerosene pathway is by recycling the lighter streams (LPG, light & heavy naphtha). In the SkyPower model and literature (e.g. Bube 2024, et. al.) the off-gases and LPG stream are already recycled to improve carbon efficiency. In this scenario, we add the complete naphtha stream to the already existing recycle stream (see doc 'Project SkyPower e-SAF model 2024 - 100pr eSAF with gasifier - MtG with Gasifier.xlsx'). As the feed of a FT unit consist of CO and H_2 (see reaction 2), these light streams have to be converted via a syngas generator. As oxygen is available from the electrolysis step, we have selected a unit using partial oxidation of the hydrocarbons, leading to CO and H_2 (complete oxidation, similar to combustion, would lead to CO_2 and H_2O).

This scenario leads to two changes in the model. First, the syngas generator unit is expanded to handle the naphtha stream as well (see Figure 4). The price of this unit is scaled following the initial input delivered by SkyPower expert (scaling factor 0.6, recycling stream is 22% of the initial feed). Second, the CAPEX (and subsequent the fixed OPEX linked to it) has to be increased to incorporate the recycle stream. The three units (RWGS, FT, Hydrocracking) all increase with 22% in size. The product selectivity changes from 84% e-kerosene and 16% e-naphtha to 100% e-kerosene.

Figure 4: *Recycled e-naphtha stream to maximize the e-kerosene stream.*



Results

The main parameters to assess the price difference of the additional recycling step are the financing needs and levelized cost of the e-fuels (LCOX). Important to know, the model is driven by the production of e-kerosene. By increasing the product selectivity towards e-kerosene, the total plant capacity will reduce automatically. There is less throughput and the CAPEX/kg product increases; however, the total investment decreases. Therefore there are three simulations:

01 The original simulation by SkyPower (e-kerosene output 50 kt/year, plant capacity 60 kt/year)

02 Original simulation with recycle stream with same e-kerosene output (50 kt e-kerosene/year)

03 Original simulation with recycle stream with same plant capacity (60 kt e-kerosene/year)

Table 3: *100% e-kerosene route cost comparison.*

	SkyPower simulation	**e-kerosene 50 kt/year**	**Plant capacity 60 kt/year**
CAPEX (mn €)	1059	1063	1223
LCOX (€/t efuel)	5578	6267	6096
Margin on cash cost (€/t efuel)	-808	-847	-809

Note that the price of e-SAF is estimated as 2500 €/t e-kerosene. This price merely serves as reference price for the margin on cash cost, following the SkyPower report and current prices of SAF production via the HEFA route. This reference price leads to negative values as the production cost is higher. More important than the value is the absolute difference between the categories: a plant capacity with a recycled stream of similar size (scenario 3) has a higher CAPEX and LCOX than the SkyPower simulation, but due to the higher revenue (e-kerosene is worth more e-naphtha) the margins are similar.

By comparing the three simulations, it is clear that any modification to the plant leads to a higher CAPEX and LCOX. Only by increasing the production of e-kerosene, the margins become similar to the initial production rate. The main driver for the increase in price is the cost of the syngas generator.

When looking at the breakdown costs of these three simulations (see Appendix 1), costs for the H_2 production (renewable energy + electrolyzers) remain the same. The CAPEX, on the other hand, increases with 7 and 5% in relative weight for 50 and 60 kt plant capacity, resp. However, the cost of the CAPEX should not be overestimated, as previously mentioned in the SkyPower report and in more detail in Bube (2025), the major variation on the cost price comes from the CO_2 and H_2 price.

E-petrol blending component scenario via FT (co product)

Methodology

In this scenario, the e-naphtha is not recycled back to the FT unit, but further processed into a gasoline blending component (see doc ‘Project SkyPower e-SAF model 2024 naphtha to epetrol.xlsx’). Since the naphtha consists of two different streams (light and heavy naphtha), two different technologies are added: isomerization for the light naphtha and catalytic reforming for the heavy naphtha.

Assuming that one third is light naphtha and two third being heavy naphtha, the CAPEX units are scaled to this capacity based on expert advice. Note that the size of the units (3 and 6 kt/year, respectively) is the size of a small demo plant. Below is a schematic of this process:

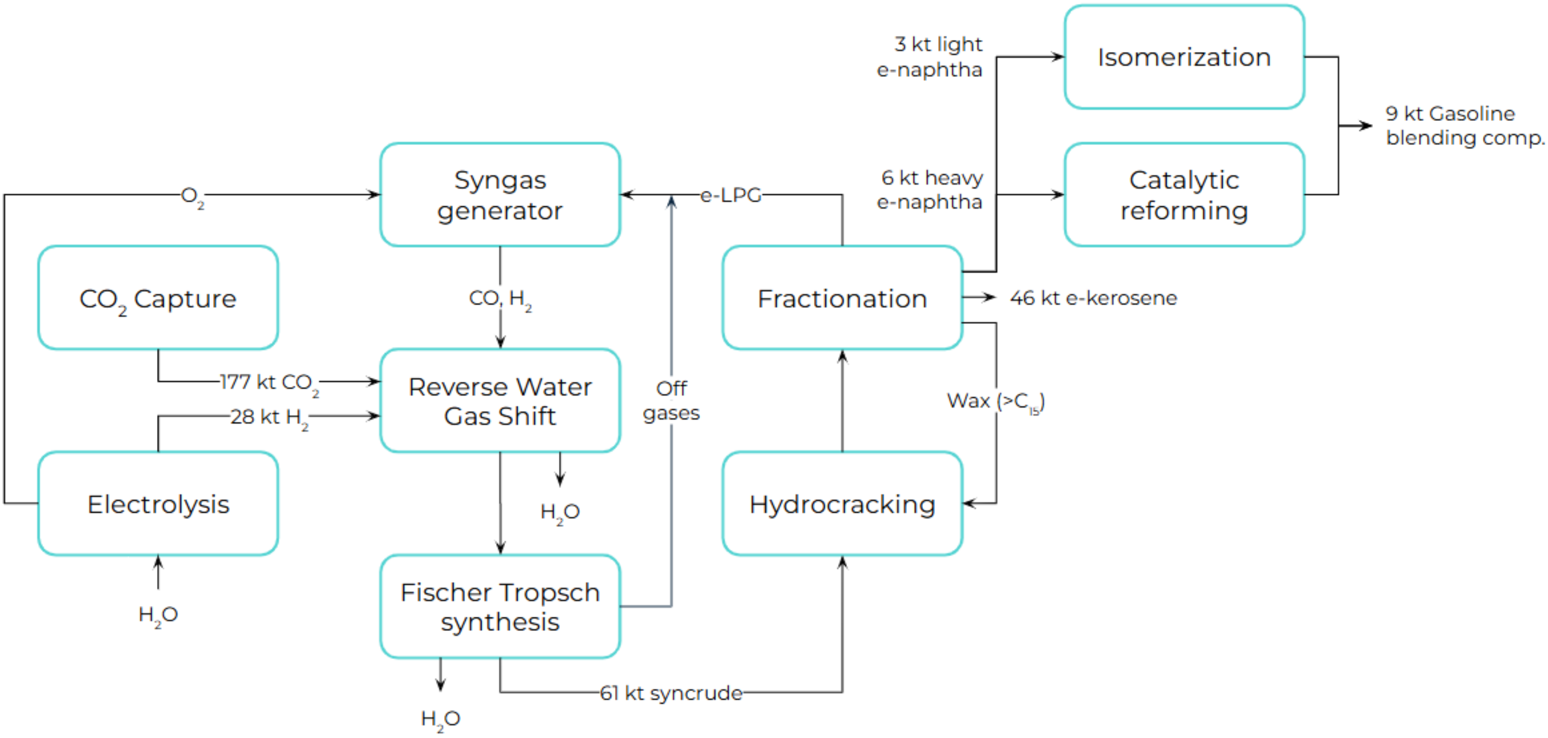


Figure 5: *Conversion of naphtha stream into e-petrol/Gasoline.*

The capital cost for the isomerization is between 60 and 110 million € for approximately 400 kt per year depending on complexity of the installation (i.e. number of fractionation columns) (Osman 2023). Operating costs are significant with a lot less fluctuation indicating approximately 200-400 €/t excluding feedstock price. In this installation, the light naphtha stream is around 3 (!) kt per year. With a scaling factor of 0.6, a CAPEX price of 5.5 million € is found. However, given the small factor and based on expert input, a minimum CAPEX price of 20 million € is used in the simulation.

As for the catalytic reforming unit, there is less information available in literature. Based on expert input, for a relatively small-scale unit of 10 kt per year an installed cost of approximately 30 million € is considered reasonable with an operational cost of 300 – 400 €/t excluding feedstock price.

Results

The same main parameters to assess the price difference of the additional recycling step are the financing needs and levelized cost of the e-fuels (LCOX). Important to know, the model is driven by the production of e-kerosene, with optimization of e-naphtha into e-petrol. We report two simulations:

01 The original simulation by SkyPower (e-kerosene output 50 kt/year, plant capacity 60 kt/year, the Naphtha stream is sold as such)

02 Original simulation with additional production step for the e-naphtha.

Table 4: *e-naphtha to e-petrol/gasoline route cost comparison.*

	SkyPower simulation	**e-naphtha to e-petrol**
CAPEX (mn €)	1059	1132
LCOX (€/t efuel)	5578	5815
Margin on cash cost (€/t efuel)	-808	-746

Note that the price of e-SAF and e-petrol is estimated as 2500 €/t, whereas the price of e-naphtha was set at 1796 €/t.

As units are added to convert the e-naphtha into e-petrol blending component, the CAPEX is going to increase adequately. More interestingly, in these scenarios the LCOX of the second simulation indicates what the additional price value creation of the e-petrol should be compared to e-naphtha. In other words, what the minimal price difference should be in order to make the additional investment viable. In the SkyPower simulation the LCOX is 5578 €/t efuel (same for e-kerosene and e-naphtha as there is no difference in production). For the e-petrol, a unit specifically dedicated to e-naphtha is added, via following formula the levelized cost of e-petrol can be calculated:

$$x_{eK} LCOeK + x_{eP} LCOeP = LCOX \tag{8}$$

Where x_{eK}=0,84 and x_{eP}=0,16. LCOeK is equal to the LCOX of the SkyPower simulation. Then, LCOeP is 7030 €/t e-petrol, meaning a surplus of 1452 €/t in costs has to be compensated in the value of the e-petrol (compared to the e-naphtha).

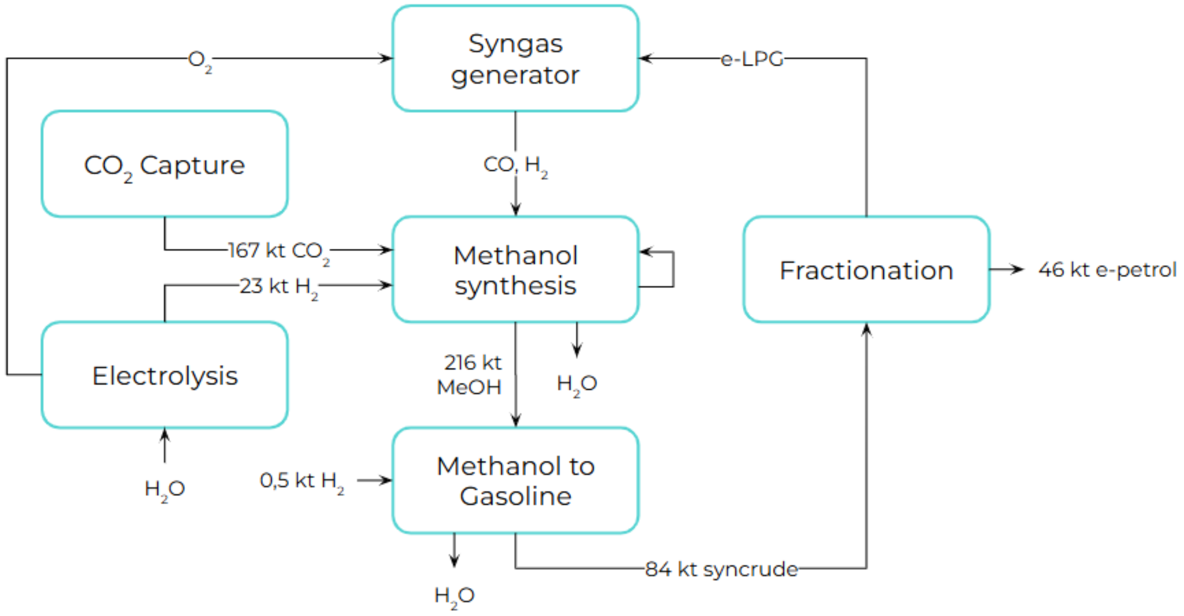
E-petrol via MtG

Methodology

In this scenario, the Methanol to Jet simulation is converted to Methanol to Gasoline, with a product selectivity of 100% gasoline (or e-petrol), see doc ‘Project SkyPower e-SAF model 2024 - 100pr eSAF with gasifier - MtG with Gasifier.xlsx’. The operational parameters (carbon efficiency, product selectivity, methanol to product ratio, …) and capital costs are derived from Hennig (2021). These capital costs (especially for the methanol synthesis unit) offer a good comparison with the values used in the SkyPower model. Our opinion is that the CAPEX numbers of both the methanol synthesis and the MtK are well above industry standard, and this does not allow for comparison between the MtJ and MtG simulation. Therefore, we have adapted the original methanol synthesis price in the SkyPower simulation (MtJ), following the data from Hennig (2021).

In addition to the modified CAPEX data in the MtG route, the product selectivity is 55% Gasoline and 45% LPG. The latter has been recycled in the MtJ route, which we have continued in the MtG route. However, the recycling stream has strongly increased in size (requiring a bigger gasification unit), as well as affecting the CAPEX units of the Methanol synthesis and MtG unit.

Figure 6: *Methanol to Gasoline route.*



Results

Similar to the previous simulations, the MtJ and MtG route are compared with the same main parameters: financing needs and levelized cost of the e-fuels (LCOX). Important to know, the model is driven by the production of e-petrol and all LPG is recycled. As the LPG is 45% of the products, the recycle stream is considerable (82%) and affecting the CAPEX (addition of syngas generator unit, plus increase of MeOH synthesis and MtG unit) in comparison with the MtJ route. We report two simulations:

01 The original simulation by SkyPower (e-kerosene output 50 kt/year, plant capacity 56 kt/year)

02 MtG simulation with recycling stream for the LPG.

Table 5: *e-naphtha to e-petrol/gasoline route cost comparison.*

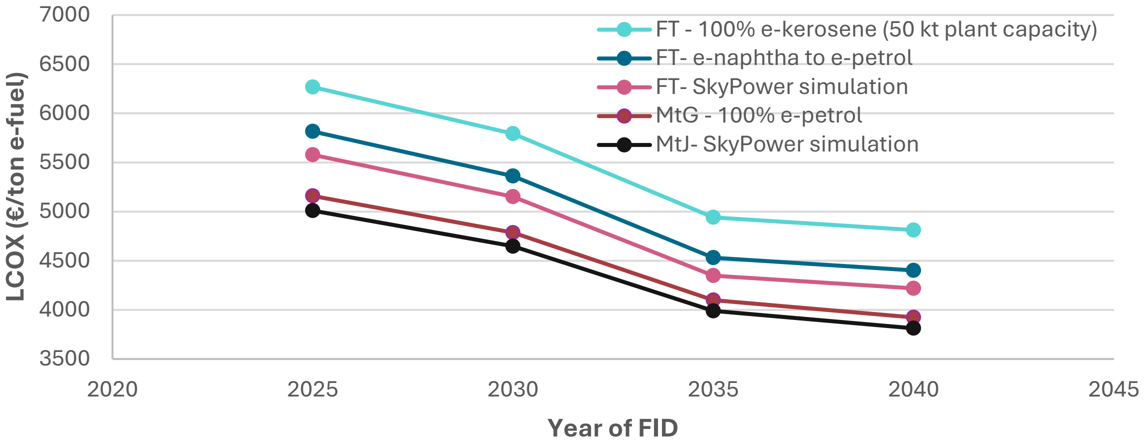
	SkyPower simulation (MtJ)	**Methanol to Gasoline**
CAPEX (mn €)	876	804
LCOX (€/t efuel)	5010	5159
Margin on cash cost (€/t efuel)	-447	-507

Note that the price of e-SAF and e-petrol is estimated at 2500 €/t. As the MtG route is much more simpler in terms of product separation steps, it would seem logical that the CAPEX is lower. Especially as the MtK unit of the SkyPower simulation has a surprisingly high investment cost due to their assumptions. However, the difference between the two simulations is relatively low due to the high recycling stream. Nearly double the plant size for the same product output is required.

Price over time

By plotting the levelized cost of e-fuels over time (shown as year of final investment decision) with the data presented in Appendix 2, the five different simulations can be compared relatively to each other and over longer duration. Perhaps considered contra intuitively by some, maximizing the e-kerosene via the FT is the most expensive route. The cheapest is the MtJ route[3], followed shortly by the MtG route.

Figure 7: *Cost evolution over time in function of the year at which FID is taken.*



The main driver for all simulations decrease over time, is the reduction in cost of the renewable energy and CAPEX of the electrolyzers (especially the first 10 years). The other installations are assumed to remain similar in value over time.

If we take a closer look at the e-naphtha to e-petrol route using FT, the additional price to produce e-petrol over time can be estimated:

Table 6: *Difference in cost for e-naphtha to e-petrol/gasoline route.*

	2025	2030	2035	2040
LCOX (€/t efuel)	5815	5361	4531	4402
LCOeK (€/t efuel)	5578	5151	4348	4219
LCOeP (€/t efuel)	7030	6434	5463	5334
Additional gasoline cost vs naphtha (€/t efuel)	1452	1283	1114	1114

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[3] *Keep in mind that a small modification was made to the original MtJ simulation in the SkyPower report by changing the CAPEX value of the methanol synthesis unit to a more realistic value (from 244 million € to 62 million €).*

Via the FT route, there will have to be a surplus on the produced e-petrol of around 1000 €/t. As the mandated e-SAF volume in 2030 is 660 kt per year (ReFuelEU Aviation) spread over 10-15 plants, which gives 45-70 kt per year per plant (e-SAF output), a mere 92 kt per year over all plants is produced based on a 14 wt-% naphtha in the product slate. This is a negligible amount in the total naphtha (40 Mt[4] per year) and gasoline (100 Mt per year) production volumes in Europe. One could question if this justifies the additional investments in dedicated upgrading of the e-naphtha produced via the FT route. Blending of this e-naphtha in the main naphtha market (possibly at a premium) seems worthwhile to consider in the medium term to save on CAPEX.

E-petrol cost

For this section, the prices of the e-petrol of the MtG route are used as the MtG e-petrol can be directly used as fuel (albeit close to the upper limit of aromatics section), and has the lowest LCOX. With a density of 0.75 kg/l, the LCOX becomes 3,86 €/l. A comparison is made with fossil fuel petrol, using their same margins ratio. Excluding taxes and VAT, the consumer price is roughly 7x higher than fossil fuel based petrol.

Table 7: *Difference in cost for e-naphtha to e-petrol/gasoline route for a plant with a FID in 2025.*

	e-petrol (MtG)	**e-petrol (by-product FT)**	**Fossil fuel petrol[5]**
LCOX (€/l efuel)	3,86	5,26	0,53
Distribution costs	0,02	0,02	0,02
Margins (producer and retailer, 32%)	1,23	1,68	0,17
Total (excl taxes and VAT) (€/l efuel)	**5,11**	**6,96**	**0,73**

Extrapolating the LCOX prices over time, an estimate of the e-petrol prices over time can be derived.

Table 8: *e-Petrol price over time (excl. taxes and VAT) in €/l efuel.*

	2025	**2030**	**2035**	**2040**
100% e-Petrol (MtG)	5,11	4,75	4,07	3,90
Naphtha to e-Petrol	6,96	6,37	5,42	5,29

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[4] Mt = 10^6 ton or mega ton.

[5] *Data derived from https://www.rac.co.uk/drive/advice/fuel-watch/ (accessed on 18/12/2024), with a GBP/EUR=1,20.*

05

Assumptions & recommendations

The authors followed the philosophy of the SkyPower report and model to a maximum extent, except for the previously mentioned modified CAPEX price for the methanol synthesis route. Based on the experience in the chemical industry and these technologies, a number of remarks are listed below.

The selectivity of the synthesis units, both in FT and MtJ/MtG, is an important parameter affecting the results. In literature different distributions are found, as well as compositions (paraffins, olefins & aromatics), requiring different separation and post-treatment units. This makes it difficult to analyze the results. Especially the selectivity used in the SkyPower report for MtJ (90% e-kerosene) vs MtG (55% e-gasoline, following Hennig 2021), creates impactful differences. Also the hydrogen to methanol ratio is different, while no difference is expected on the conversion to methanol (impactful as H_2 is 55% of LCOX). More research should be dedicated to optimize these selectivities for the MtG route.

General remarks regarding the SkyPower model:

- Construction time of 4 years seems very long for a relatively small development as a 75 kt per year e-SAF plant.
- Total cost for a 50 kt e-kerosene per year plant goes well above 1 bn EUR. Some very conservative assumptions were made, not facilitating the implementation of these technologies. Examples are: multiplier of indirect costs of 6 (typically 2-3), contingency of 50% (typically 30% at this conceptual stage), generalization of catalysts costs (Dieterich 2020 presents a clear overview of the used types and costs). As example to illustrate the impact, by modifying the contingency to 30% and the multiplier to 2.5, the LCOX reduces with 20%.
- Emphasis is put on the FOAK (first of a kind) aspect throughout the SkyPower report. Except for the RWGS technology, all other units have a technology readiness level (TRL) of 9 and commercial suppliers are readily available.

06

Conclusion & outlook

For this study, two different routes were considered, Fischer-Tropsch and Methanol-to-Gasoline with the intent to either maximize the e-kerosene or e-petrol output. After identification of technically feasible routes, an economic analysis was performed via various modifications of the open-source SkyPower model. The original model was modified in a total of 5 simulations to include the additional processing steps required to answer the questions of T&E related to conversion of by-products to either e-kerosene or e-petrol and dedicated e-petrol production. Overall the results from the simulations align with previous research reported in literature.

When the FT production process is modified to maximize e-kerosene production by recycling all by-products to the syngas generation unit, the margins on e-kerosene remain the same albeit at a higher production capacity (60 vs 50 kt per year). This indicates that the additional CAPEX required for increased capacity of the processing units is balanced by the higher revenues.

Conversion of the naphtha by-product of the e-kerosene FT production process to blending components for (e-)petrol via isomerization and catalytic reforming results in a slightly better margin for the entire product slate. Important to note is that this route produces (high-octane) blending components for petrol and is unlikely to yield on-spec commercial grade petrol. Therefore, ability for blending in a (e-)petrol pool is a prerequisite for this route.

The original SkyPower model already showed that production of e-kerosene via the MtJ route is economically more attractive than via the FT route. As e-kerosene produced via the MtJ route does not have ASTM certification yet, the SkyPower report focuses on the FT route. When converting the MtJ model to produce e-petrol (MTG), the result for margin on cash cost is comparable based on identical product pricing. However, the total calculated consumer price for e-petrol would be around 5,11 €/l (excl. taxes and VAT), which would still mean a significant increase in petrol costs for European citizens.

The dedicated conversion of the naphtha by-product to e-plastics is considered to be unrealistic due to the small scale of the processing units even taking into account that the expected mandated amount of 660 kt per year e-kerosene (ReFuelEU Aviation) is strictly produced in Europe. For 2040 and 2050, the respective estimated amount of synthetic jet fuel becomes 5000 and 15000 kton per year and at this stage side products obtain a significant size (minimum 100 kton per year) and dedicated uses can be developed.

Cost price levels of the various routes presented in the report are expected to decline in the future. However, this decline is mainly influenced by reduction of renewable energy cost and CAPEX of electrolyzer units. Significant additional reduction due to scale-up and further maturing of the technology are not in line with expectations due to the fact that most of technologies used already have a high TRL (8-9) with the exception of the RWGS reactor (TRL6-7). Large scale-ups (order of magnitude) are also not expected as the supply of renewable energy and the required investment cost to realize a facility of this magnitude seems prohibitive with current insight.

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Appendix

Attachments

- Project SkyPower e-SAF model 2024.xlsx
    - Modified CAPEX estimation for Methanol synthesis unit
- Project SkyPower e-SAF model 2024 - 100pr eSAF with gasifier - MtG with Gasifier.xlsx
    - Simulation 100% e-kerosene (plant capacity to be modified: 50 or 60 kt per year)
    - Simulation Methanol to Gasoline
- Project SkyPower e-SAF model 2024 naphtha to epetrol.xlsx
    - Simulation e-naphtha to e-petrol