Report

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A Clean Planet for all. Impact assessment on the potential implications for our refining system and the link with Refinery 2050

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A Clean Planet for all. Impact assessment on the potential implications for our refining system and the link with Refinery 2050

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At the request of:

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ABSTRACT

The "A Clean Planet for All" [ACP4A 2018] long-term strategy published by the European Commission (DG CLIMA) in 2018 analyses different long-term scenarios that could lead to significant GHG emission reduction levels on the way towards a carbon-neutral and circular European economy by 2050. Focussing on three of these scenarios as defined in the DG CLIMA publication (2050 baseline, Power-to-X and 1.5TECH), this report examines the implications for the EU refining sector, the CO_2 emissions reductions that could be achieved through the whole value chain and the key barriers and enablers.

With the appropriate combination of resources, including some crude oil (driven by the domestic jet fossil fuel component defined in *A Clean Planet for all*), bio-feeds and e-fuels (from captured CO_2 and electrolytic hydrogen), the European refining system, even adapted to suit the domestic demand as much as possible, is forced to export important surpluses of oil-base gasoline, gasoil and heavy fuel oil components, and even some bio-based ones, to match the domestic demand of Jet Fuel. The fossil fuels consumption mix foreseen by the European Commission's report is indeed so weighted towards Jet fuel that no refinery can come close to technically realising this yield on the crude barrel. One can question whether these levels of 'fossil' and 'bio' exports could be sustained in the low carbon world of 2050.

Overall, this Concawe study points out the risk of these scenarios, which will add significant burdens to the EU refining system in 2050. Based on the points described above, this could potentially reach a point where meeting the defined domestic demand (and fuel composition), as described in the European Commission's report, could not be economically feasible for the refining system in Europe with the consequent refinery closures, being replaced by fossil jet fuel imports from other regions of the world to Europe, with no benefit for climate change globally.

KEYWORDS

Clean Planet for all, DG CLIMA, long-term strategy, 1.5TECH scenario, P2X scenario, climate change, net zero emissions, carbon-neutral, circular economy, refinery, refining, CO_2, emissions, e-fuels, biomass.

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SUMMARY

Objective

The "A Clean Planet for All" [ACP4A 2018] long-term strategy published by the European Commission (DG CLIMA) in 2018 analyses different long-term scenarios that could lead to significant GHG emission reduction levels on the way towards a carbon-neutral and circular European economy by 2050.

In this context, this report:

- Focusses on three of the ACP4A scenarios (compared to 1990):
  - **Baseline:** with current policies to 2030[1] where 45% GHG emission reduction by 2030 and 60% by 2050 are achieved;
  - **P2X (Power-to-fuels / e-fuels)** achieving 80% GHG reduction across the whole EU economy;
  - **1.5 TECH (Climate neutral scenario)** achieving 100% net GHG reduction (including sinks).
- Aims to answer the following key questions:
  - What are the **implications for the European refining system** in 2050?
  - What are the results in terms of **GHG emission reductions** that could be achieved **across the whole value chain?**
  - What are the **external requirements** as well as key **barriers and enablers** for the realisation of such scenarios?
  - How is the **domestic production/import/export balance** impacted?

Modelling

The three scenarios were simulated on a pan-EU basis using Concawe's RafXI model, with the objective to match demands in terms of both tonnage and origin distribution (fossil/bio/e-fuels) for each main product pool. The feedstocks and processing schemes considered were as follows:

- Crude oil and conventional refinery processes
- Lipids (vegetable oils) hydrotreated to middle distillates
- Woody biomass to liquids via gasification and Fischer-Tropsch synthesis
- Own (captured) and imported CO_2 plus electrolytic hydrogen (using 2050 low carbon electricity) to e-fuels

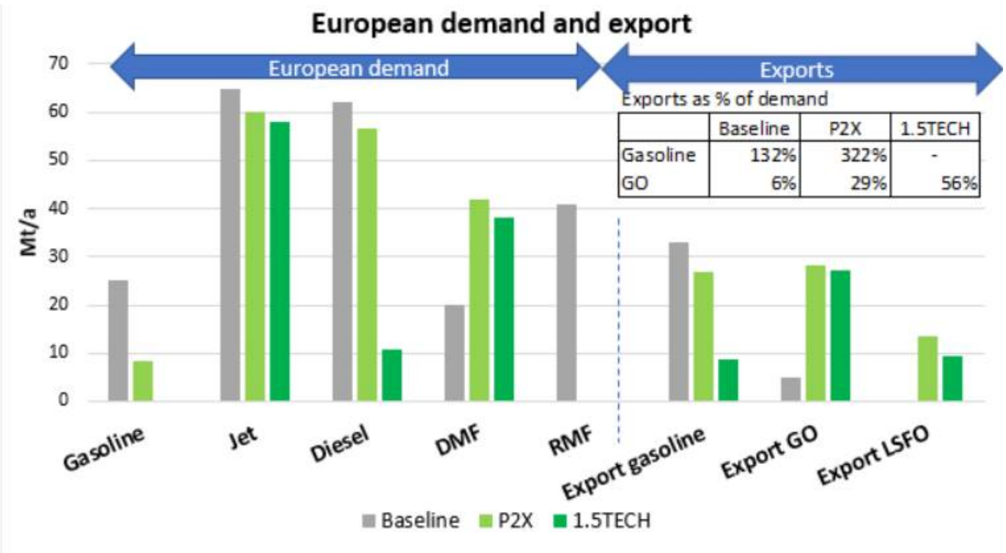
[1]-45% GHG emissions by 2030 and -60% by 2050

Results

<u>Domestic demand</u>

With the level of flexibility afforded by the segregation of fossil, bio and e- streams, and the availability of a "max jet" hydrocracking mode, it proved possible with RafXl to meet the *Clean Planet for all* 2050 domestic demand of the main products in all three selected scenarios, both in terms of tonnage and origin (feedstock) distribution, as well as demands for the other products.

Figure 1 European domestic demand and export



D/RMF: Diesel/Residual Marine Fuel
LSFO: Low Sulphur Fuel Oil (RMF or other grades)
GO refers to exported gasoil, all the middle distillates left over

The large quantities of middle distillates required, and particularly jet fuel with a significant fossil component, coupled with weak to very weak gasoline and diesel demand and the disappearance of marine fuel oil in the most advanced scenarios, results in significant **surpluses** of gasoline, gasoils and heavy fuel oil (exports out of Europe and overwhelmingly comprised of fossil components).

Surpluses can be reduced, but not totally eliminated, by relaxing the origin distribution constraints defined in the European Commission's report.

Technologies that address the gasoline/distillate balance (such as oligomerization) or modifications of existing Hydrocrackers would only have a limited impact.

Main challenge: The fossil fuels consumption mix foreseen by the European Commission's report is so weighted towards Jet fuel that no refinery can come close to technically realising this yield on the crude barrel.

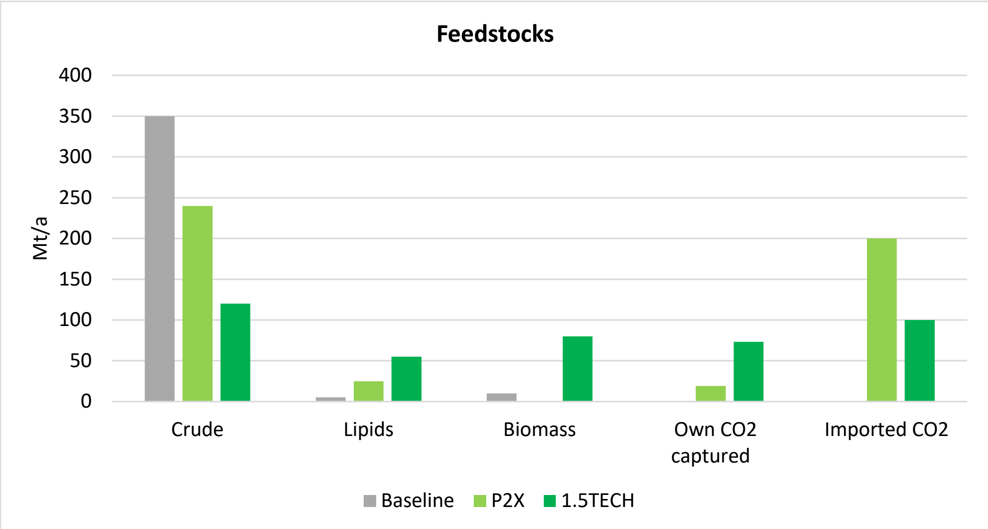
Besides, although the surplus volumes of oil-base gasoline, gasoil and heavy fuel oil are of a similar order of magnitude to historical EU trading figures, it is questionable whether such levels of 'fossil' exports could be sustained in the low carbon world of 2050 (as the EU would be exporting emissions to other regions to lower its own GHG emissions), impacting on the practical feasibility of these scenarios as defined today.

<u>Implications for the refining industry</u>

Feedstock requirement

In all cases, the **crude oil** required to meet the whole demand/share of fossil components for transport fuels was higher than the minimum of about 65 Mt/a set by the bitumen demand (which is therefore not a constraint).

Figure 2 Required feedstocks



Lipids and biomass demands were within the maximum availability forecast for 2050 [JRC 2019].

Main challenge: The big emphasis on **e-fuels (domestically produced in Europe in this assessment)** sets a very **high target for CO_2 'imports'** as own production only covers a fraction of the total requirement (9% in the P2X scenario and 42% in the 1.5TECH scenario). **This requirement of CO_2 as a feedstock for the refinery system could foster the creation of industrial hubs (where the CO_2 comes from other industrial sites) or the development of technologies such as direct air capture.**

Key issues such as the mobilisation of high volumes of sustainable feedstocks at European level are also main caveats around these 2050 demand scenarios.

Refinery plant utilization and new capacities

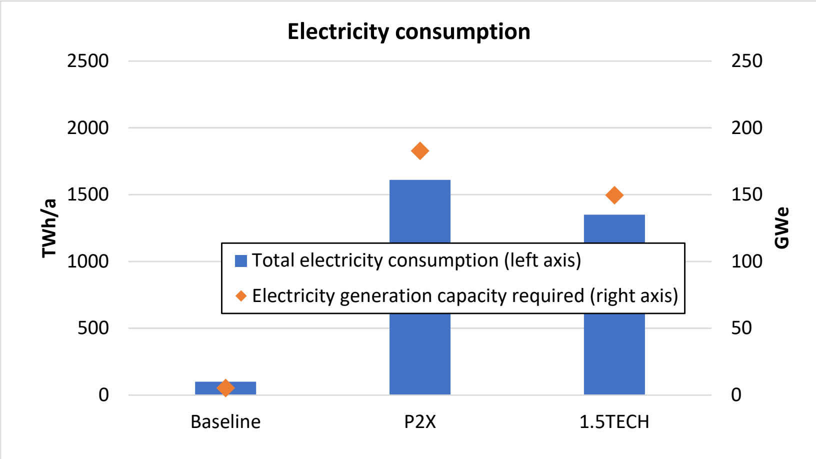
Conventional refinery plants were heavily underutilised with the exception of hydrocrackers, kerosene hydrotreaters and residue converters. Processing the raw synthesis material required up to doubling the existing EU hydrocracking capacity or the repurposing of some existing hydrotreaters.

Main challenges: Major challenges would lie ahead for **scale up of biomass-to-liquids** plants and development of large e-fuels plants in terms of **CO_2 availability** and distribution/transport systems, electricity **generation** capacity and supporting infrastructure, and very **large electrolyser banks**.

<u>Energy and CO_2 emissions</u>

Energy consumption was dominated by electricity required to produce hydrogen for the refinery and, overwhelmingly for e-fuels manufacture.

Figure 3 Electricity consumption



Main challenge: In the P2X scenario, electricity consumption would account for about half of today's total demand in the EU.

With low crude intake and CO_2 capture, fossil site emissions are very low in P2X (about 5% of today's) and virtually eliminated in 1.5TECH.

Investment estimate

Investment, dominated by e-fuels, could range between 250 and 400 G€ for the whole EU refining system.

Although the combination of the alternative feedstock pathways has been modelled to happen simultaneously in the same refinery, different combination of routes may be followed by individual refineries (depending on factors such as the proximity to a specific resource, geographic location, initial refining configuration, etc). All of this subject to individual strategic plans and it is out of the scope of the current study.

Thus, the present study cannot be considered as a Roadmap for the whole European refining system but as an initial exploration of the potential consequences at macro-level.

This Concawe study points out the risk of these scenarios, which will add significant burdens to the EU refining system in 2050. Based on the points described above, this could potentially reach a point where meeting the defined domestic demand (and fuel composition), as described in the European Commission's report, could not be economically feasible for the refining system in Europe with the consequent refinery closures, being replaced by fossil jet fuel imports from other regions of the world to Europe, with no benefit for climate change globally.

1. BACKGROUND

The European Commission has published on the 28th November 2018 its Long-Term Strategy for a climate neutral economy *A Clean Planet for all* [ACP4A 2018]. This strategy is in line with the Paris Agreement objective to keep the global temperature increase to well below 2°C and to pursue efforts to keep it to 1.5°C.

[ACP4A 2018] considers the implementation of different measures structured around key technology pillars including electrification (large scale generation of renewable electricity used either as such or indirectly via hydrogen or Power-To-fuels (P2X)), energy efficiency, circular economy and CCS. The scenarios explore the resulting demand and the share of different energy sources in relevant sectors and particularly transport.

Figure 4 A Clean Planet for all [ACP4A 2018]

The EU Commission strategy:

- Confirms Europe's commitment to lead in global climate action.
- Provides an assessment, in accordance with the Paris Agreement, to reduce EU greenhouse gas emissions, starting at -80% going up to -100% by 2050 compared to 1990.

To meet the -100% goal will require almost complete decarbonisation of electricity generation, buildings, transport and industry.

2. OBJECTIVE

This study is part of the Concawe's Low Carbon Pathway programme and it was undertaken in order to assess the practical feasibility and better understand the implications of the "*A Clean Planet for all*" (ACP4A) scenarios developed by the European Commission on the EU refining industry, and with particular focus on transport fuels, ultimately allowing Concawe to:

- Provide better scientific understanding of the impact and potential implications of some of the Commission's long terms strategy options [ACP4A 2018] for our refining system exploring, among others, domestic demand vs export balance or total feedstock requirements by 2050.
- Without having access to the whole granularity behind the PRIMES model used to define these scenarios, the main inputs for this assessment as reported in *A Clean Planet for all document* are: the total domestic demand for refining products as well as and the fossil fuels/biofuels/e-fuels ratio within specific sectors (mainly transport).
- Expand the analysis initiated with the Concawe Refinery 2050 work conducted in 2019 [Concawe Ref2050 2019], producing a consistent assessment allowing comparison with the different demand scenarios/alternative feedstocks explored there, in terms of CO_2 emissions, process plants utilisation, electricity and hydrogen requirements and a first CAPEX estimate for the whole EU refining system.

Out of the 8 scenarios included in *A Clean Planet for all* (**Table 1**), this study investigated the ones considered as most representative of all the options considered in the Commission's study and interesting in terms of potential implications for the EU refining system:

1. **Baseline:** with current policies to 2030 where 45% GHG emission reduction by 2030 and 60% by 2050 compared to 1990 are achieved across the whole EU economy;
2. **P2X (Power-to-fuels)** achieving 80% GHG reduction by 2050 compared to 1990 across the whole EU economy;
3. **1.5 TECH (Climate neutral scenario)** achieving 100% net GHG reduction by 2050 compared to 1990 (including sinks) across the whole EU economy.

The 1.5 TECH scenario has been prioritized versus the 1.5LIFE as the most probable one, aligned with the 1.5 degrees' ambition in the Paris Agreement, inspiring the drafting of the European Green Deal (not published at the time of conducting the present assessment).

Table 1 Summary table of the A Clean Planet for all scenarios. Highlighted in red the ones selected for this study

Long Term Strategy Options								
	Electrification (ELEC)	Hydrogen (H2)	Power-to-X (P2X)	Energy Efficiency (EE)	Circular Economy (CIRC)	Combination (COMBO)	1.5°C Technical (1.5TECH)	1.5°C Sustainable Lifestyles (1.5LIFE)
Main Drivers	Electrification in all sectors	Hydrogen in industry, transport and buildings	E-fuels in industry, transport and buildings	Pursuing deep energy efficiency in all sectors	Increased resource and material efficiency	Cost-efficient combination of options from 2°C scenarios	Based on COMBO with more BECCS, CCS	Based on COMBO and CIRC with lifestyle changes
GHG target in 2050	-80% GHG (excluding sinks) ["well below 2°C" ambition]					-90% GHG (incl. sinks)	-100% GHG (incl. sinks) ["1.5°C" ambition]	
Major Common Assumptions	• Higher energy efficiency post 2030 • Deployment of sustainable, advanced biofuels • Moderate circular economy measures • Digitilisation				• Market coordination for infrastructure deployment • BECCS present only post-2050 in 2°C scenarios • Significant learning by doing for low carbon technologies • Significant improvements in the efficiency of the transport system.			
Power sector	Power is nearly decarbonised by 2050. Strong penetration of RES facilitated by system optimization (demand-side response, storage, interconnections, role of prosumers). Nuclear still plays a role in the power sector and CCS deployment faces limitations.							
Industry	Electrification of processes	Use of H2 in targeted applications	Use of e-gas in targeted applications	Reducing energy demand via Energy Efficiency	Higher recycling rates, material substitution, circular measures	Combination of most Cost-efficient options from "well below 2°C" scenarios with targeted application (excluding CIRC)	COMBO but stronger	CIRC+COMBO but stronger
Buildings	Increased deployment of heat pumps	Deployment of H2 for heating	Deployment of e-gas for heating	Increased renovation rates and depth	Sustainable buildings			CIRC+COMBO but stronger
Transport sector	Faster electrification for all transport modes	H2 deployment for HDVs and some for LDVs	E-fuels deployment for all modes	Increased modal shift	Mobility as a service			• CIRC+COMBO but stronger • Alternatives to air travel
Other Drivers		H2 in gas distribution grid	E-gas in gas distribution grid				Limited enhancement natural sink	• Dietary changes • Enhancement natural sink

This report aims to answer the key following questions:

– What are the **implications for the European refining system** in 2050 in terms of domestic demand reduction, feedstock diversification, existing unit utilization and order of magnitude of the changes/investment required?

– What are the results in terms of **GHG emission reductions** that could be achieved **across the whole value chain** including direct and indirect emissions linked to EU refineries (Scope 1 &2) and the final use of products (Scope 3)?

– What are the **external requirements** as well as key **barriers and enablers** for the realisation of such scenarios?

– How is the domestic production/import/export balance impacted?

3. PRODUCT DOMESTIC DEMAND AND ORIGIN DISTRIBUTION

The three scenarios imply a significant reduction of the domestic demand for refining final fuel and products. Compared to today: 45% for Baseline, 55% for P2X and 65% for 1.5TECH. The demand reduction is highest in the road fuel pool because of the big reduction of the share of ICE in the vehicle pool, whereas jet fuel becomes dominant (over 50% in 1.5TECH)

Note: The demand for olefins, BTX, Bitumen and Lubes and waxes are kept constant in all the scenarios (not reported in [ACP4A 2018]).

The share of fossil components in transport fuels decreases strongly across the three scenarios from 91% in Baseline to 24% in 1.5TECH. Jet fuel, however, retains a significant fossil share (40%) even in the most demanding 1.5TECH scenario.

3.1. GENERAL

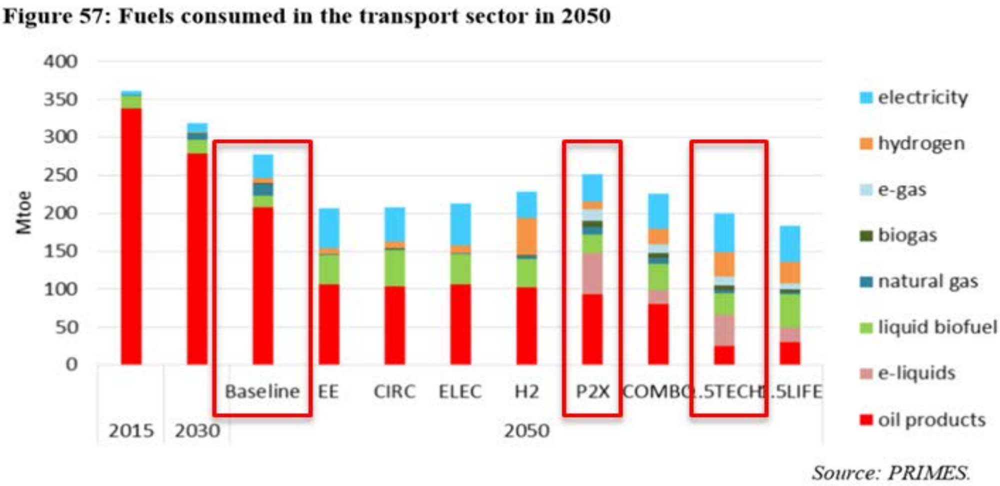
The Commission's *long term strategy options* define a **significant reduction in final energy demand** due to the combination of energy efficiency measures together with the penetration of more efficient technologies in different sectors of the economy. For each demand scenario, the **combined use of different energy carriers** (electricity, H_2 and other conventional and alternative fuels) are presented as a result of the penetration of different technologies used for power generation or alternative powertrains in transport, among others compatible with the GHG reduction levels defined in each scenario.

Regarding the EU refining system, the combination of fossil, biomass/waste and e-fuels resources are also reported in the *A Clean Planet for all* document, in more or less detail depending on the specific sector/segment, to meet the remaining demand for liquid fuels and feedstocks for other industries (such as petrochemicals or lubes).

3.2. A LOOK INTO TRANSPORT SECTOR

The estimate in terms of fuel consumption within the whole transport sector is reported in the *A Clean Planet for all* document for each scenario analysed:

Figure 5 Fuels consumed in the transport sector in 2050 (Figure 57 extracted from [ACP4A 2018])



All scenarios rely on a combination of energy sources and carriers to satisfy the domestic demand for transport, substitution of fossil fuels increasing with the GHG reduction ambition.

- Although the contribution of total liquid fuels (oil products, e-liquids, liquid biofuel) to transport is reduced, they retain a significant share with 50% of the 2050 domestic demand in the most ambitious (1.5TECH) scenario.
- Domestic demand for oil-based products by 2050 decreases more steeply, by up to 90% compared to current level. Aviation fuel becomes dominant in the total transport fuels demand and retains the largest proportion of fossil The baseline case still shows a large fossil contribution in all liquid product pools. The fossil contribution is significantly reduced in P2X (45%) and even further in 1.5TECH (10%).

It is important to highlight that:

- The documents available from the Commission **do not include detailed figures** for either demands or origin distribution in each fuel pool.
- The figures used in the foregoing analysis were therefore estimated from the graphs available (see **Figure 6**).
  - Except from for the jet fuel, the information is particularly scant for road fuels, for which the available data focusses on vehicle population rather than actual fuel demand. For marine fuels, the available data is not provided for each of the scenarios, so H2Mar50[2] case has been taken into account for the P2X scenario and the 1.5LIFEMar case for the 1.5TECH scenario.

[2] H2Mar50 scenario definition according to A Clean Planet for all: reduction by 50% in the EU GHG emissions by 2050 compared to 2008, based on the H2 scenario

- There is still a significant fraction of fossil fuel in the jet pool even in the most ambitious scenarios, as the 1.5 TECH, meanwhile there is almost no fossil fraction in the road or marine pools for this same scenario. Because of the interrelation between refinery products, and as detailed in the modelling section, aiming to match this fossil fraction in the jet pool would provoke a surplus of fossil gasoline and diesel in the refining modelling output (RafXL tool used for the purpose of this analysis – consistent with the Refinery 2050 report [CW Ref2050 2019].
- As the Commission's study focusses on transport fuels, it does not include data for petrochemicals (olefins and aromatics), LPG, bitumen and lubes, and therefore, the demand figures used in the "Refinery 2050" Concawe study [CW Ref 2050 2019] for these products were used for all three scenarios. The only adaptation was to reduce the lubes demand by 25% for the Baseline, P2X and 1.5TECH scenarios (4.3 Mt/a) compared to the Refinery 2050 lubes demand (5.7 Mt/a) to account for the estimated decreasing share of ICE powertrains in the road vehicle population.

Figure 6 Details of fuel/powertrain shares per transport segment as reported in [ACP4A 2018]

Figure 49: Shares in total cars stock by drivetrain technology in the Baseline and scenarios reaching -80% to net zero emissions by 2050

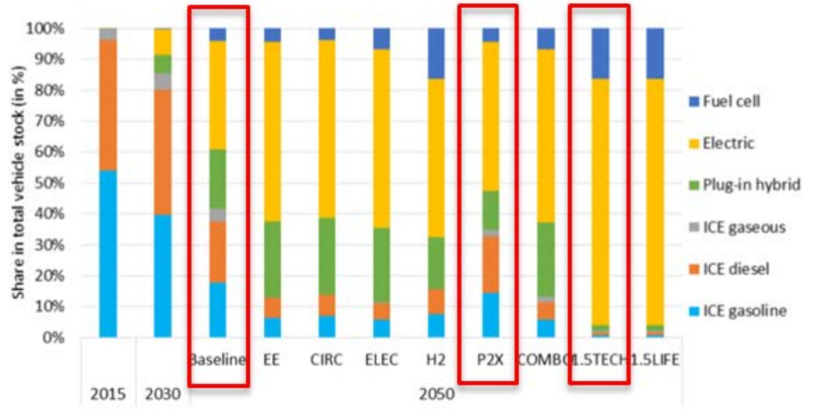


Figure 51: Shares in total heavy goods vehicles stock by drivetrain technology in the Baseline and scenarios reaching -80% to net zero emissions by 2050

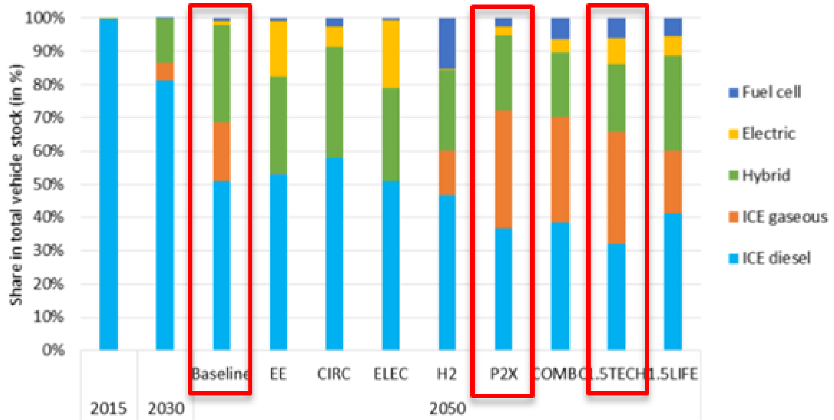


Figure 54: EU international maritime fuel mix in the Baseline and decarbonisation variants

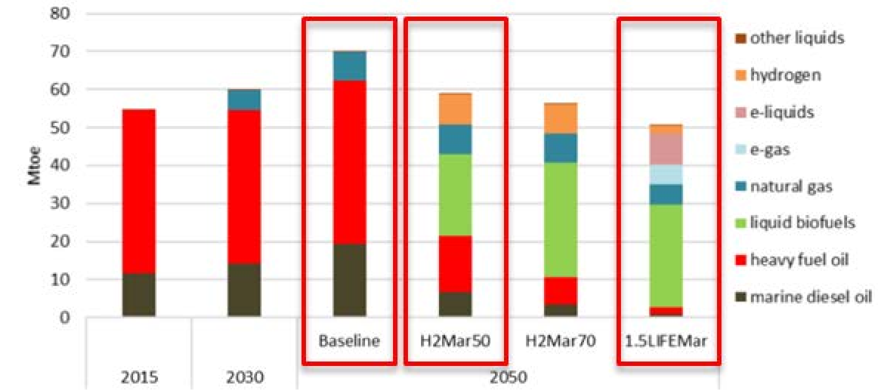
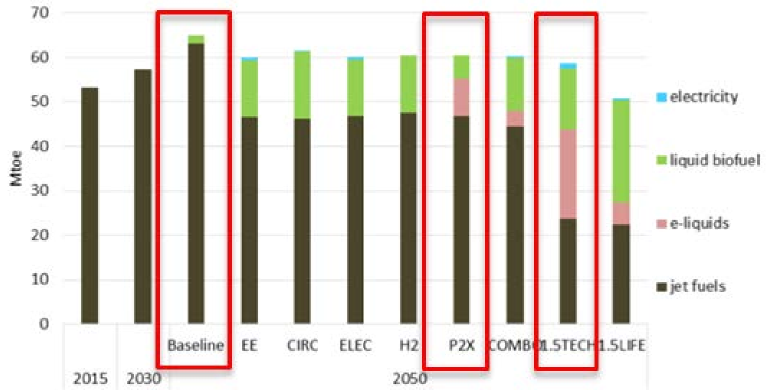
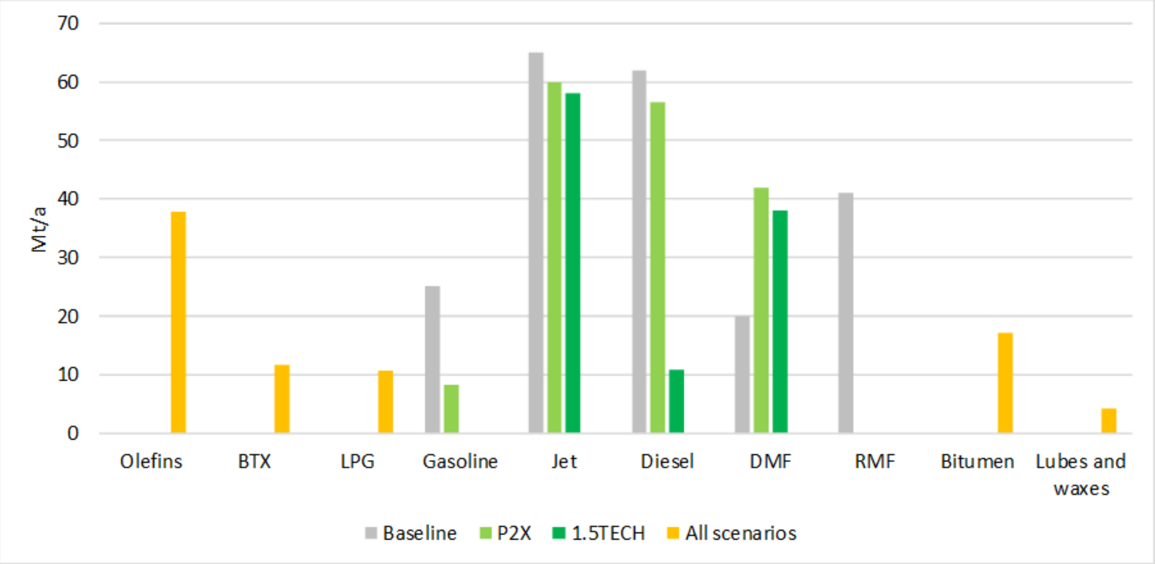


Figure 52: Aviation fuels mix in the Baseline and scenarios reaching -80% to net zero emissions by 2050 in 2050



The estimated domestic demands based on the Commission scenarios presented in the previous sections and used as inputs for the Refinery 2050 modelling, described in section 5, are shown in **Figure 7**. **Figures 8a/b/c** detail the implied origin distributions implied by the data in **Figure 6** for the three transport fuel pools namely: Aviation (jet fuel), Road (diesel and gasoline) and Marine fuels.

Figure 7 Domestic demands



D/RMF: Diesel/Residual Marine Fuel

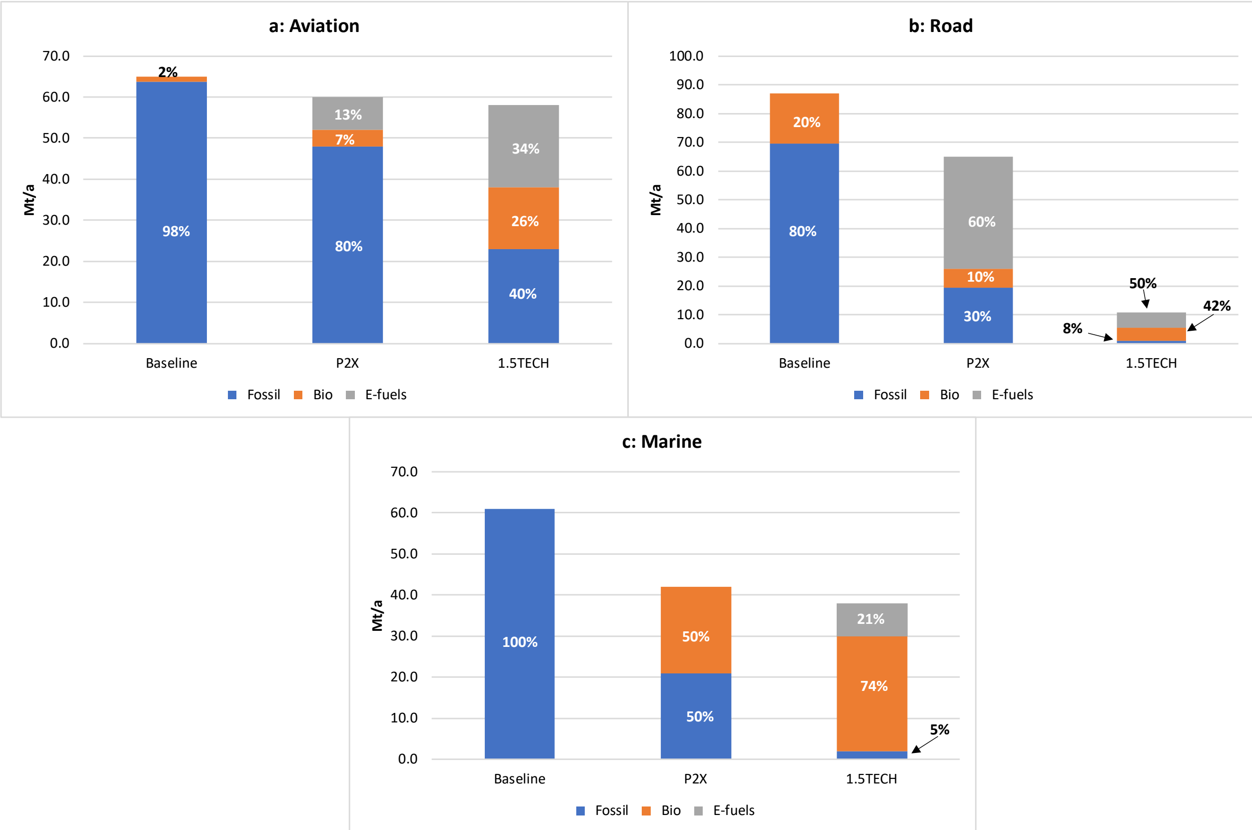
Table 2 Domestic demands

	Baseline	*P2X*	*1.5 TECH*
Products	Mt/a	Mt/a	Mt/a
Olefins	37.9	37.9	37.9
Benzene, Toluene, Xylenes (BTX)	11.7	11.7	11.7
Liquified Petroleum Gas (LPG)	10.6	10.6	10.6
Gasoline	25.0	8.3	0.0
Jet	65.0	60.0	58.0
Diesel (mixed uses)	61.9	56.5	10.8
Diesel Marine Fuel (DMF)	20.0	42.0	38.0
Residual Marine Fuel (RMF)	41.0	0.0	0.0
Bitumen	17.1	17.1	17.1
Lubes and waxes	4.3	4.3	4.3
Total liquid products	**294.5**	**248.5**	**188.4**
Transport fuels	**172.0**	**166.9**	**106.8**

Domestic demand for liquid transport fuels decreases across the scenarios as some of the transport duty is carried out through alternative - mostly electric - powertrains. In view of the convenience and practicality of liquid fuels, another option would be to keep a larger proportion of liquid fuels and endeavour to maximise their renewable content.

For each transport sub-sector, the following share between fossil and alternative feedstock based (biomass/e-fuels) **liquid fuels** have been inferred from the [ACP4A 2018] and described in the figure below. This was the basis for the modelling work.

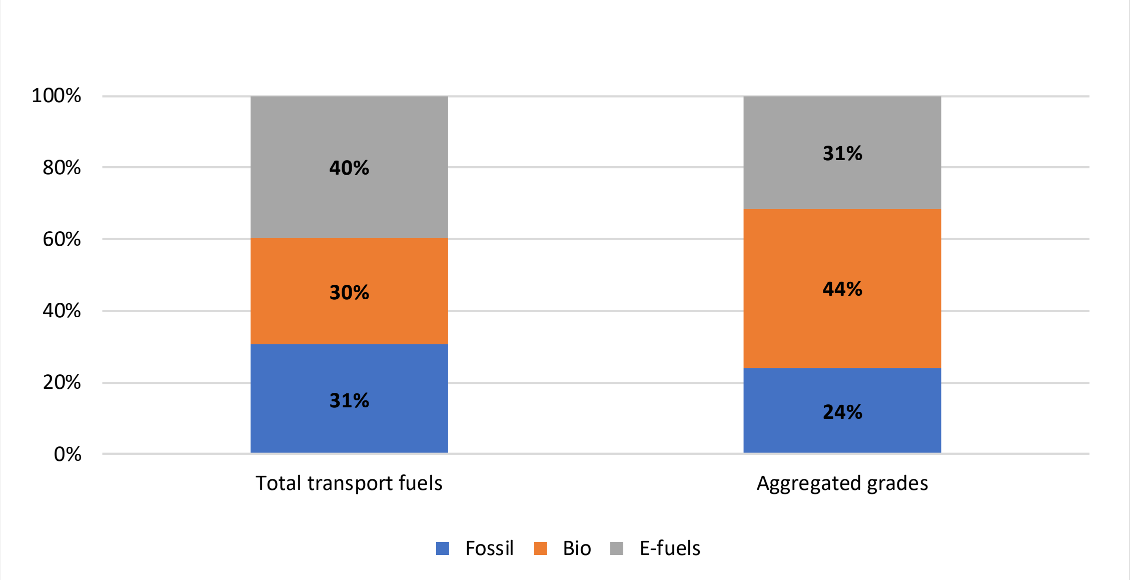
Figure 8 Implied origin distributions for the three transport fuel pools (Liquid fuels)



The baseline case has a large fossil contribution in all sub-segments. The fossil contribution is significantly reduced in P2X and even further in 1.5 TECH with large shares for biomass and e-fuels (46% and 69% respectively). P2X is particularly ambitious for e-fuels in road transport (up to 60%).

The Commission data includes information on both the total transport sector (**Figure 5**) and individual pools (**Figure 6**). Whereas both sets of data are reasonably consistent for Baseline and P2X, there is a notable discrepancy in 1.5TECH (**Figure 9**) (although we have noted above that the intended origin distribution of the road fuels is somewhat ill-defined, this inconsistency could not be resolved by changing it due to the small share of road fuels in the total). We have endeavoured to match the origin distribution of each individual pool.

Figure 9 Apparent inconsistency between total transport fuel and individual pools origin distributions (1.5TECH**)**



4. MODELLING

Concawe's RafXl model was used to simulate the EU refining system in the context of the three Clean Planet for all scenarios.

The scope included hydrotreating of lipids, conversion of woody biomass into liquids and production of e-fuels from own and imported CO_2. A "high jet" mode was introduced for hydrocracking of raw synthesis products.

The large amount of hydrogen required for e-fuels was assumed to be produced by electrolysis, using the low-carbon grid electricity available in 2050.

Some of remarkable aspects of the modelling work conducted are summarized below:

a) The tool: Concawe RafXL

As in [Concawe Ref2050 2019], we used Concawe's RafXl simulation model with the objective to best match both the EU domestic demand and origin distribution for all three transport fuel pools, while also meeting demands for other products and minimising surpluses (exports out of Europe). The modelling exercise was done for the whole of the EU refining industry notionally operating as a single refinery, with the total European refinery plant capacities.

b) Feedstocks and Boundary limits of the analysis:

For the purpose of reporting, the envelope of the modelling included **electrolysis for hydrogen production** (to satisfy future additional refinery and e-fuels needs) and the **biomass to liquids plant** but not the facilities to turn bio material (seeds, algae) into lipids. The feedstocks and utilities into the system were therefore:

- Crude oil
- Lipids
- Woody biomass
- Note. *Waste* is not explicitly included as a potential feedstock in the [ACP4A 2018] document but it could potentially alleviate the requirements for forestry/agricultural residues.
- CO_2
- Electricity (grid)
- Natural gas (minor amounts)

c) Processing schemes

- The **"bio" components** were assumed to be a mixture of lipids (vegetable oils) and woody biomass, the relative quantities of which was adapted to produce the best demand match. Both resources were assumed to be 100% renewable (i.e. without any residual fossil component acquired e.g. during production, transport, etc. as a simplification). A sensitivity case was, however, included with figures of 80% renewability for lipids and 90% for woody biomass (in line with some date inferred from JEC WTW version 5 study).

- **Lipids** were processed in either diesel hydrotreaters or hydrocrackers. Woody biomass was turned into liquids by gasification followed by Fischer-Tropsch (FT) synthesis with a further hydrocraking step (so-called BTL process).
  - Some of the lipids were assumed to be co-processed in existing refineries (20% of the total intake in diesel hydrotreaters and 20% in hydrocrackers (HC)).
  - The balance of lipids and the raw FT product from woody biomass and/or e-components were assumed to be respectively processed in dedicated hydrotreaters/hydrocrackers so that they could remain segregated at the blending stage. This maximum flexibility was found to be essential to match the origin distributions suggested by the Commission's study.
- **E-fuels** were produced by combination of CO_2 and hydrogen (produced from electricity) into syngas, followed by Fischer-Tropsch synthesis and hydrocracking.
  - **CO_2** for e-fuels manufacture was sourced from capture within the refinery (assuming 70% capture), supplemented by imports. Imported CO_2 was assumed to have no fossil footprint resulting from its supply, as it is considered a waste and emissions have been already allocated to the products (following JEC WTT methodology)
- **Hydrogen** was assumed to be primarily sourced from electrolysis using grid electricity, internal refinery production being limited to the use of surplus fuel gas.
- **The g**rid electricity emission factor was set at a different value for each scenario, derived from the Commission's forecast on the 2050 electricity mix, see **Appendix 1**).

Table 3 Electricity CO_2 intensity factor (g CO_2/kWh)

Baseline	P2X	1.5TECH
59.8	17.1	5.2

- The bulk of the **olefins** were produced in steam crackers fed primarily with naphtha supplemented with light gasoil and "hydrowax" (the heavy material produced by hydrocrackers) as required. A small amount of propylene originated from the FCC (where operational). Aromatics were produced in the steam crackers and dedicated catalytic reforming plants.
- **Bitumen** demand imposes a minimum intake of heavy crude oil in the refinery. Additional crude, where needed, was assumed to be light, low sulphur grades.
- Lubes and waxes were assumed to be sourced from hydrowax[3].

Yields considered for lipids, biomass and e-fuels pathways are shown in **Appendix 1**.

[3] There is a (conventional) lube base oil plant in RafXI but it is not used, under the assumption that all lubes would be synthetic by 2050. So hydrowax is a proxy for the whole lubes and wax demand.

d) *Exploring hydrocracking modes to maximize jet fuel*

All three scenarios, and particularly the more ambitious ones, call for a large proportion of jet fuel in the total middle distillate pool. The RafXL model already had some flexibility to adapt hydrocracker modes to increase jet production. As a result of the drive towards electrification of road vehicles, jet fuel is expected to become the dominant hydrocarbon-based fuel, which has raised the interest in maximising jet production from FT products.

Although there is very little publicly available data on this concept, Concawe was able to access proprietary data on a confidential basis from two technology developers. Both datasets show jet yields on total FT product as high as 78%, diesel being virtually eliminated. Discussion with the developers suggested that such a radical change is technically achievable but currently not industrialised yet. (Note: a third report by E4Tech for the Dutch Government[4] implies a lower jet-yield but gives no information about other products or TRL).

For the current modelling work, **RafXL had both "Max GO" and "Max Jet" options available** for the FT/HC component of both BTL and e-fuels routes (**Table 4**) to be used in combination. In all the scenarios considered, it is important to highlight that the objectives in terms of demand/share of fossil/bio/e-fuels could be met with a combination of the two modes. The yield structure for the Max Jet mode presented in **Table 3** is quite extreme compared with Max-GO mode, and makes no road diesel. FT-based components are required in both the diesel and the jet pools therefore the Max Jet mode is always used in parallel with the Max GO mode (See details of the composition of both road and aviation pool in Section 3).

Table 4 **Yields for FT products for different** Hydrocracking modes[5]

	Max GO	Max jet
C1	1.0%	0.7%
C2	1.8%	1.3%
C3	2.4%	1.8%
C4	3.4%	2.1%
Naphtha	14.1%	16.0%
Jet	19.7%	78.0%
Diesel	36.6%	0.0%
Heavy	21.0%	0.0%

It was considered that components from different origins would be mostly produced in separate plants (or even sites) so that they could be routed independently to the appropriate product pool. Given the existing infrastructure and facilities already available at refineries, some of which would be underutilised, and the potential synergies, it is reasonable to assume that existing refining sites will attract a good number of these new plants.

[4] https://www.rijksoverheid.nl/documenten/rapporten/2020/03/03/bijlage-1-onderzoek-e4tech-sgu-obligation-for-aviation-in-the-netherlands-final-v3

[5] RafXL requires a breakdown of C1 to C4 breakdown but none of the developers provided this for the Max-Jet case. We have therefore stepped the values from the MaxGO case with additional adjustments to maintain the overall C- and H-balances).

5. RESULTS

Domestic demand for all main products could be met both in terms of volumes and origin distribution.

Significant surpluses of mainly fossil gasoline, middle distillates and heavy fuel oil could not be altogether avoided due to the severe constraints imposed by the intended origin distributions. Surpluses could be reduced, but not totally eliminated, when relaxing these constraints but it resulted in a lower overall proportion of fossil material in transport fuels.

In the low carbon world of 2050, it is unlikely that exporting such surpluses would be a viable option.

Detailed modelling results are shown in **Appendix 4.**

5.1. DOMESTIC EU DEMAND VS EXPORTS

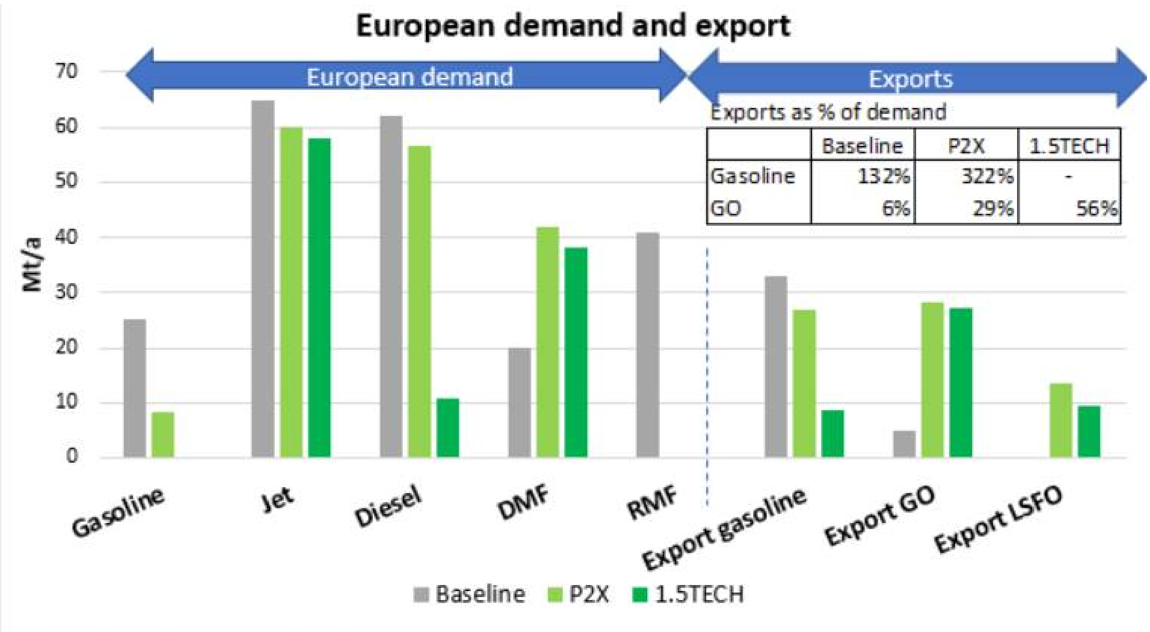
With the level of flexibility afforded by the segregation of fossil, bio and e- streams, and the availability of a "max jet" hydrocracking mode, it proved possible with RafXl to meet the ACP4A domestic demand of the main products in all three scenarios, both in terms of tonnage and origin distribution (see **Figure 7** and **8**), as well as demands for the other products. However, the constraints that a fixed fossil/bio/efuels composition in the final fuels is defined, including a big share (>50%) of fossil jet fuel in the jet composition, resulted in significant **surpluses** of some products as shown in **Figure 10** (exports out of Europe and overwhelmingly comprised of fossil components).

Refineries are complex integrated installations, design to satisfy the demand of a whole range of different products in the most efficient way. Although they have a certain degree of flexibility to adapt their feedstocks, operations and, on a longer time scale, their configuration to best meet their market demand (e.g. jet versus gasoil described in the Hydrocracker modes), it is seldom possible to achieve a perfect match. This implies that, when an alternative feedstock is fed into the refinery, a whole set of different products is generally obtained (as described in the yield tables reported in **Appendix 2**). Practically speaking, this means that a potential mismatch between the total production of specific products within the EU refining system and the internal domestic demand may occur when attempting to match the product demand profile established in the ACP4A scenarios.

The imbalances are generally resolved by intra- and inter-regional trade. Although the implied surpluses are, in absolute terms of an order of magnitude that is commensurate with current and historical trade figures for the EU [IEA], they represent a significant fraction of the greatly reduced demands and may be problematic in a future world with reduced hydrocarbon fuels demand (typically the EU exports some 20-30% of the gasoline it produces and imports 5-10% of the gasoil it consumes).

Figure 10 shows the described EU 2050 domestic demands [ACP4A 2018] as well as the unavoidable product surpluses (export) within the EU refining system.

Figure 10 Main fuel pool domestic demand and exports



D/RMF: Diesel/Residual Marine Fuel
LSFO: Low Sulphur Fuel Oil (RMF or other grades)
GO refers to exported gasoil, all the middle distillates left over

In the Baseline scenario the main surplus is gasoline, a reflexion of the imbalance in demand between gasoline and middle distillates, particularly jet fuel where a high percentage of fossil jet (>95%) is required in the jet pool.

Some additional important considerations:

- Quality

Gasoline blending is challenging due to the relatively large proportion of high aromatics components in the pool (a/o from steam crackers and BTX units). A reasonable blend quality could be achieved for the domestic gasoline in the Baseline. In all cases, the export grade should, however, be regarded as a blending component rather than a marketable product. It might be possible to export some of the surplus as heavy naphtha if a suitable use could be identified but this would put extra pressure on the quality of the domestic grade by concentrating the high aromatics streams there. Within the demand constraints, there might be some limited scope to reduce crude intake and thereby export volumes by e.g. changing crude slate but we believe this is limited.

- Catalyst developments in Hydrocracker to increase kerosene yield and minimize exports

It is considered that through catalyst developments and plant adaptations (including a revamping, with the associated CAPEX), the kerosene yield from conventional existing hydrocrackers with fossil VGO as feedstock could be increased significantly from 25-30% to maybe up to 50%. We have included a 1.5TECH sensitivity case to show the impact such changes could have (see Appendix 4): The results show that crude intake could be reduced by 17%, leading to a 50% reduction of export gasoil and, to a lesser extent, LSFO surpluses (28% reduction).

- New technological opportunities to reduce the mismatch / minimize exports

The RafXL model already incorporates most of the conventional refinery options for addressing gasoline/distillate balance, but one might also ask whether new process technologies might help convert surplus lights (LPG and gasoline) into distillates.

In this regard, paraffins and aromatics are generally too unreactive, so the main candidates are C3-C6 olefins produced by FCC units (if in operation, which is only the case in the Baseline case[6]):

  – Currently these are routed to LPG, feedstock for production of chemicals or gasoline (C3=, C4=). C5 and C6 olefins are found in light FCC naphtha (LCN). These can be converted into distillates using technologies such as Axens "Flexene" and "Polyfuel", UOP "Catalytic Condensation" or the C4= conversion technologies being developed for "Alcohols-to-Jet" (e.g. Gevo). Examination of the RafXL mass balances shows that these options together might reduce gasoline production by <5% relative and LPG production by ~12%, split roughly equally between the C3=, C4= and LCN routes. These strategies are probably also constrained by the resulting impact on gasoline octane and aromatics levels.
  – A more advanced option might be to increase FCC severity to increase C3/C4 olefin production and reduce FCC gasoline, but this also might be constrained by gasoline pool quality.
  – A more extreme (and likely more expensive) solution would be to gasify surplus naphtha/gasoline and use the syngas for FT feed.

- P2X and 1.5TECH: relaxing the constraints to minimize exports

In P2X and 1.5TECH scenarios, the surpluses are mostly caused by the origin distribution requirements, particularly in terms of fossil jet fuel.

As an alternative case, the RafXL model has been used to explore different scenarios in terms of the share between biomass/e-fuels/fossil for the same ACP4A demand, with a view to minimise exports by relaxing the constraint of the origin distributions (no exceeding, however, the overall transport fuel fossil content set by the Commission's data). The following table shows the detailed results where the main conclusion is that the only practical way to achieve an export minimization (especially in the fossil derived gasoline components) is to reduce the total crude intake thereby decreasing somewhat the fossil fraction in the combined transport fuel pool (and increasing, therefore, the requirements for alternative feedstocks beyond the initial estimate from *A Clean Planet for All*).

Table 5 shows the changes in feedstocks, the achieved surplus reduction and the impact on the transport origin distribution for P2X and 1.5TECH.

[6] Unless there would be an economic incentive to increase the FCC activity with these new technologies (which seems improbable).

Table 5 Scope for reducing exports. Modified P2X and 1.5TECH cases (Mt/a)

	P2X		1.5TECH	
	Full compliance	Min export	Full compliance	Min export
Feedstocks				
Crude	240.0	160.0	120.0	90.0
Lipids	25.0	35.0	55.0	55.0
Biomass	0.0	0.0	80.0	90.0
Imported CO2	200.0	250.0	100.0	120.0
Surplus				
Gasoline	26.7	5.9	8.6	8.8
Diesel	28.1	0.1	27.2	6.6
LSFO	13.7	9.8	9.5	9.1
Origin distribution				
Combined				
Fossil	54%	43%	24%	23%
Biomass	19%	25%	45%	41%
e-fuel	26%	32%	31%	35%
Jet				
Fossil	80%	53%	40%	29%
Biomass	7%	10%	26%	29%
e-fuel	13%	37%	34%	42%
Road				
Fossil	38%	37%	8%	8%
Biomass	9%	18%	42%	43%
e-fuel	53%	45%	50%	50%
Marine				
Fossil	50%	45%	5%	20%
Biomass	50%	55%	74%	59%
e-fuel	0%	0%	21%	21%

In the alternative (modified) P2X and 1.5TECH scenarios presented above:

- The diesel surplus could be almost eliminated in both scenarios.
- Gasoline and LSO surpluses could be reduced in P2X but become “incompressible” in 1.5TECH as they are a collection of by-products that have no potential alternative use so far (mostly high aromatic and heavy material from steam crackers and BTX units).
- Important to note that it seems possible to stay within the constraining fossil fuel content of each pool in all cases except Marine in 1.5TECH. For that ***minimum export*** scenario, the fossil share in the total marine pool (20%) is higher than originally considered in the 1.5TECH scenario (5%) because the very limited domestic demand for fossil diesel in road transport cannot absorb the total fossil production of middle distillates, exceeding the amount needed to meet the jet domestic demand.

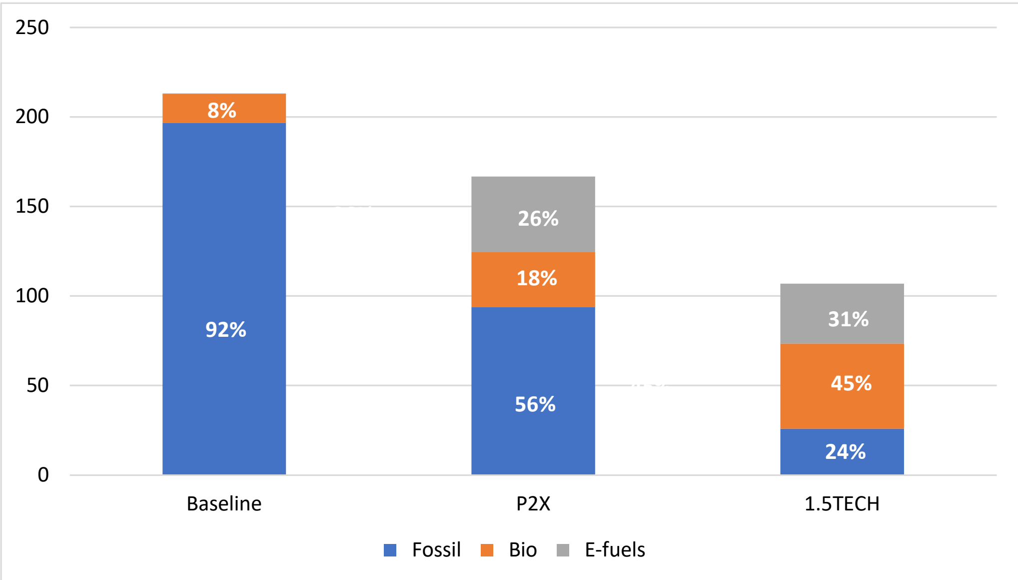
- A word of caution: Product quality in 2050. A qualitative assessment.

Although the RafXI model tracks all relevant properties, the blending routines are generic and, in some cases, not as sophisticated as would be the case in a real-life refinery. In addition, the properties and exact blending behaviour of the products from unconventional processes are not fully known. For these reasons we believe only qualitative statements can be made on the inspection properties of the final products.

For jet fuel and diesels, the main issues are linked to the high paraffin content of FT product, potentially leading to problems with low-temperature properties, lubricity and materials compatibility. These are solvable by processing (e.g. isomerisation), blending and use of additives. Jet fuel needs a minimum amount of aromatics. It needs to be resolved with additional aromatic molecules in jet range.

In the Baseline scenario, the overall gasoline pool is fairly conventional albeit with a large proportion of reformate fractions. As mentioned above it is likely that a marketable domestic grade could be made. The Baseline export grade and the whole gasoline pool in P2X and even more 1.5TECH are mostly a collection of by-products from steam cracker pygas and BTX extraction. There is no other practical disposal route for such streams and, although they are indeed normally used as blending components today, they cannot, on their own, amount to a finished gasoline grade.

Figure 11 Transport fuels combined origin distribution



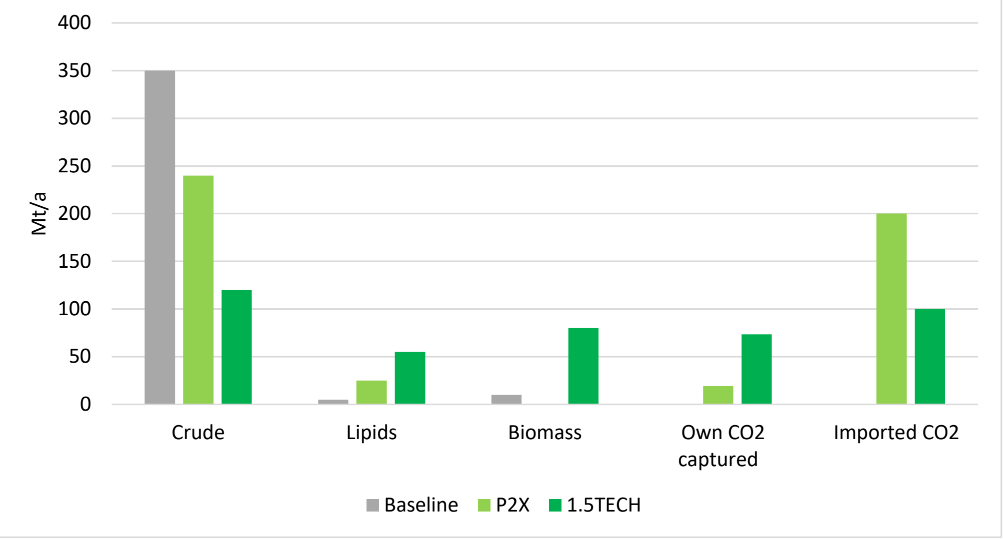
Note. The share of the different alternative feedstocks in the mix (proportion between lipids, biomass or e-fuels) is intending to represent only one potential combination of these pathways and it should not be taken as a roadmap or as the only plausible option for the industry.

5.2. FEEDSTOCK REQUIREMENT

Along with relatively modest requirements for lipids and biomass (well within the generally accepted availability forecast for 2050), the largest contributor was imported CO_2 to produce the massive quantities of e-fuels foreseen by the P2X and 1.5TECH scenarios.

The required feedstocks for each case are shown in **Figure 12**.

Figure 12 Feedstocks (Mt/a, in dry basis)



Note 1: The electricity requirement is not shown in this chart as it is considered as an energy source rather than a feedstock (the other feedstock for e-fuels is indeed water). Electricity consumption is discussed in section 6.4.

Note 2: The amount of crude oil needed for bitumen production is about 65 Mt/a.

In all cases, the crude oil required to meet the whole demand/share of fossil components for transport fuels is higher than the minimum of about 65 Mt/a set by the bitumen demand (which is therefore not a constraint). **Lipids and biomass** demands are relatively modest.

The big emphasis on **e-fuels**, however, sets a very high target for CO_2 imports as own production only covers a fraction of the total requirement (9% in the P2X scenario and 42% in the 1.5TECH scenario).

As a reference, the EU potential biomass availability by 2050, according to [JRC 2019], could range between ~190 and ~500 Mtoe/a in the low/high scenario (~300 Mtoe/a [7] in the reference case).

Table 6 EU potential biomass availability by 2050 [JRC 2019]

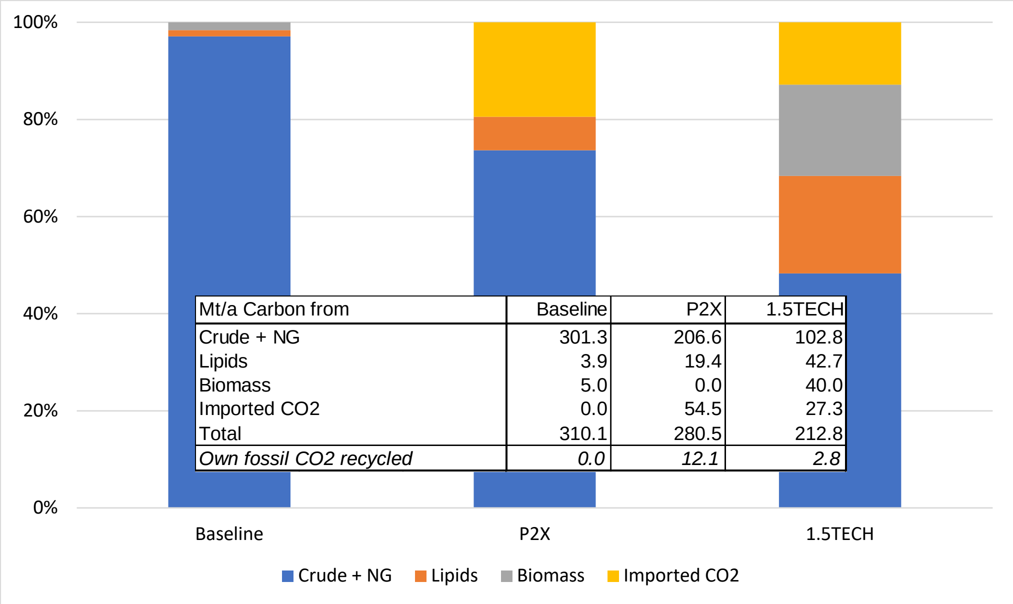
Units: Mtoe/year	**EU-28, 2050**		
	2050 Low	**2050 Reference**	**2050 High**
Agriculture	107	143	215
Forestry	72	96	239
Waste	12	48	72
TOTAL	**191**	**287**	**525**

While **Figure 12** shows actual tonnage of each feedstock, the carbon content of which varies a great deal. To put this in perspective **Figure 13** shows the contribution of each feedstock to the total carbon intake[8] (whether fossil or not) as

[7] *Around 800 Mt/a (using an average factor of 0.38 toe/t, according to [JRC 2015]*
[8] *Total physical carbon in all the feedstocks*

well as the actual figures (in the embedded table). Even in 1.5TECH, the fossil carbon intake is still significant (just under 50%), although some 30% of this ends up in the export products. Note that some fossil carbon is also recycled through capture e-fuels manufacture: 2.8 Mt/a of CO_2 in 1.5TECH and 12.1 Mt/a in P2X (the site emissions have a much larger fossil proportion in the latter).

Figure 13 Contribution of each feedstock to the total carbon intake



Mt/a Carbon from	Baseline	P2X	1.5TECH
Crude + NG	301.3	206.6	102.8
Lipids	3.9	19.4	42.7
Biomass	5.0	0.0	40.0
Imported CO2	0.0	54.5	27.3
Total	310.1	280.5	212.8
Own fossil CO2 recycled	*0.0*	*12.1*	*2.8*

Note: This chart refers to the total physical carbon intake (not only fossil). It is calculated as carbon content multiplied by volume.

5.3. REFINERY PLANT UTILISATION AND NEW CAPACITIES

Conventional refinery plants were heavily underutilised (or even not used at all), with the exception of hydrocrackers, kerosene hydrotreaters and residue converters.

Processing the raw synthesis material required up to doubling the existing EU hydrocracking capacity.

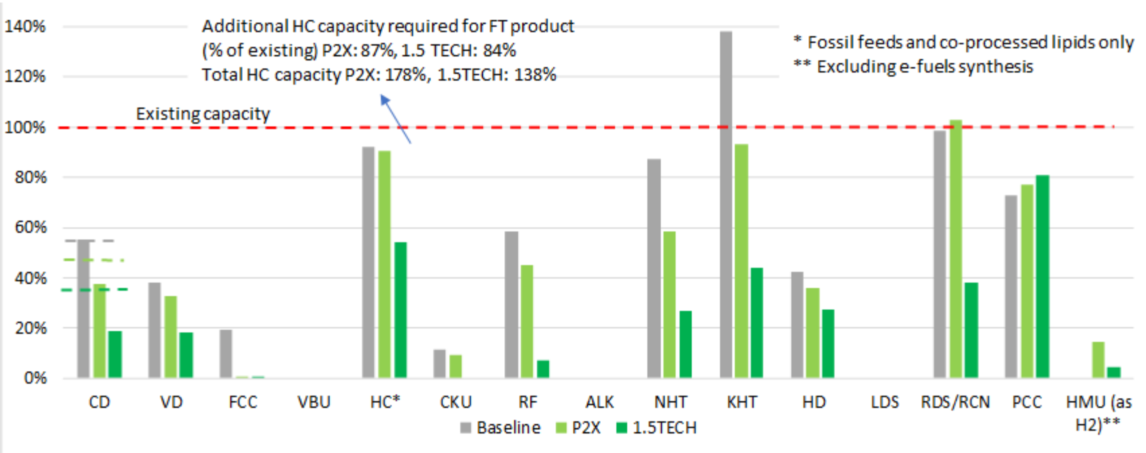
Major scale up challenges would lie ahead for biomass-to-liquids plants and electrolyser banks.

Utilisation of conventional refinery plants is affected by both demand reduction (see section 4) and by substitution of crude oil by alternative feedstocks.

Figure 14 shows the resulting utilisation of conventional refinery plants as a percentage of the total current EU capacity in each scenario.

It should be noted that the total current capacities may not be a good guide for the future availability as it is probable that the number refineries would cease their activities. This would reduce the surplus of low utilisation processes but exacerbate the need for popular ones such as hydrocrackers as some such plants are likely to be located in sites that would shut down.

Figure 14 Refinery plant utilisation



Note 1: The remaining activity in the SMR in the P2X and 1.5TECH cases is due to the remaining fuel gas.

Note 2: The reduction in each individual unit utilisation is due to the combination of two effects: **demand reduction** and **impact due to the alternative feedstocks** fed into the refinery, replacing crude oil (Note that, in some cases, the alternative feedstocks will be fed directly into HC or FCC units, minimizing CD/VD utilisation). As a visualisation of the impact of these combined effects, the dotted lines included in **Figure 14** indicate the current capacity and the general level of demand reduction in each scenario, applied to the crude processing capacity.

Note 3: The residue streams (vacuum bottoms) are used for the fuel oil and bitumen production, as well as a feedstock to the residue hydroconversion unit.

Process plants abbreviation key	
CD	Crude distillation
VD	Vacuum distillation
FCC	Fluid Catalytic Cracking
VB	Visbreaking
HC	Hydrocracking
CKU	Coking
RF	Catalytic reforming
ALK	Alkylation
NHT	Naphtha hydrotreating
KHT	Kerosene hydrotreating
HD	Gasoil hydrodesulphurisation
LDS	Atmospheric residue desulphurisation
RDS/RCN	Vacuum residue desulphurisation / conversion
PCC	Petrochemical cracker
HMU	Hydrogen manufacturing (SMR)

Compared to current levels, crude intake is reduced by 40, 60 and 80% in the Baseline, P2X and 1.5TECH respectively. Not surprisingly in view of the modest crude intakes, most plants are heavily underutilised with the exception of hydrocrackers, kerosene hydrotreaters and residue conversion plants.

Some key additional assumptions:

- Hydrogen production in 2050

Although different proportions of low carbon (SMR+CCS) and renewable hydrogen (e.g. electrolysis) could be foreseen in the future, this assessment considers, as a simplification, that the additional hydrogen needs for these scenarios are met by water electrolysis using grid electricity (with the average carbon intensity of the mix in 2050 – as defined in **Appendix 1**). As a result, conventional hydrogen manufacturing units (SMR) are particularly underused as a result of the assumption that the bulk of hydrogen needs are met by electrolysis using grid electricity as shown in **Table 7** (the residual SMR activity in the P2X and 1.5TECH cases processes the small excess of fuel gas).

Table 7 Hydrogen sources

Mt/a	Baseline	P2X	1.5TECH
Conventional SMR	0.0	0.2	0.1
Electrolysis for refinery	1.0	1.5	2.5
Electrolysis for e-fuels	0.0	30.8	24.4

- Cold properties adjustment:

As mentioned in section 4.1 (note on product quality), raw FT products are mainly straight-chain hydrocarbons which require hydrocracking and isomerisation to make desirable liquid products with adequate low-temperature properties (e.g. diesel CFPP[9]; jet freezing point). Hydrocracking catalysts usually have some isomerisation activity, but this might need to be supplemented (by catalyst design; process conditions; additional reactors) depending on the desired product slate (e.g. jet-optimised; diesel-optimised) and on the local options for plant design (e.g. new build; re-use of existing refinery equipment).

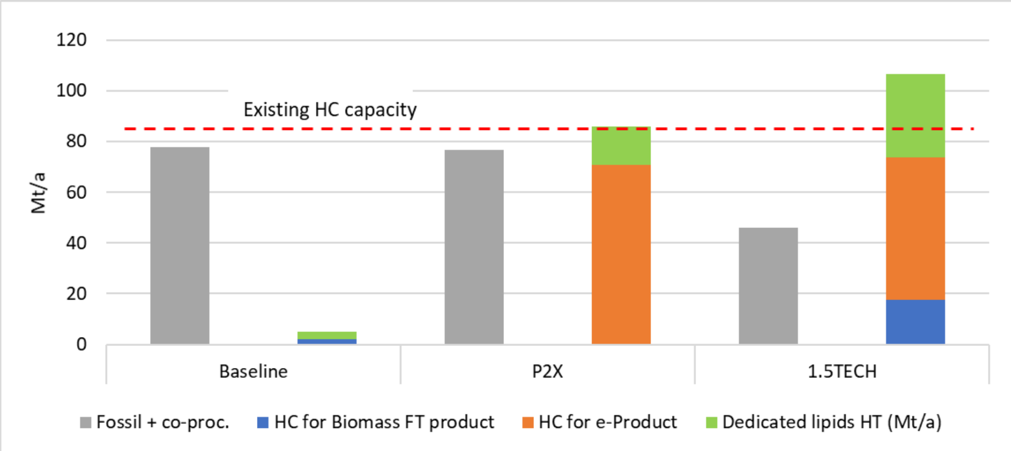
This has not been modelled in RafXl, and would somewhat increase site energy consumption (by maybe 5-15%). Site fossil CO_2 emissions would also be affected, albeit to a lesser extent as the majority of the additional energy used would not be fossil.

- Additional hydrocracker capacity:

Beyond the traditional refinery hydrocracker duties, much more HC capacity would be needed to further process raw FT products from biomass and e-fuel origins (**Figure 15**):

[9] CFPP: Cold Filter Plugging Point

Figure 15 Total hydrocracking (HC) capacity requirements



Note: The grey bars (fossil + co-processing) are the ones we were referring in the previous **Figure 14**.

- In both P2X and 1.5 Tech, the total HC capacity required is about twice the total existing in Europe, pointing out to a significant contribution to the investment.
- In P2X close to all existing capacity would be required for traditional fossil feeds and some lipids co-processing so a new HC/hydrotreatment would be needed for lipids and e-fuels.
- The lower share of fossil material in 1.5TECH frees up about half of the existing HC capacity which could be used, probably with some adaptation, as either dedicated units for FT material or in co-processing mode depending on the specific requirements and circumstances of each site.
- The balance would need to be covered by new HC/hydrotreatment capacity. In both cases new lipids hydrotreating capacity would also be required (15 and 33 Mt/a for P2X and 1.5TECH respectively).
- Note that some of the, otherwise idle, high pressure distillate hydrodesulphurisation capacity may be adaptable to FT material cracking duty.

- Composition of petrochemicals (Olefins, BTX)
  - o Feedstock to petrochemicals:

  Olefins were overwhelmingly produced by steam crackers. The low utilisation to complete absence of FCC - in the routes initially explored in this report - meant that little or no olefins were available via that route (although FCCs were run in olefins mode where applicable). The need to minimize gasoline production precluded higher FCC utilisation. The composition of the steam crackers feed is shown in **Table 8:**

Table 8 Composition of feedstock to steam cracker

	Base	P2X	1.5TECH
Tops	34%	24%	11%
Naphtha virgin	27%	17%	24%
Naphtha HC	24%	38%	29%
GO	15%	0%	27%
Hydrowax	0%	21%	9%

Note: Tops refers to light naphtha and lighter fractions

Note: Currently, GO and Hydrowax feedstocks to steam crackers are <6% each [CEFIC 2014]. To be able to process the feedstocks in P2X and 1.5TECH with a higher proportion of GO and Hydrowax (>20%), modifications in Steam Crackers may be required.

Feedstocks to steam-cracker (European level) [CEFIC 2014]

	2012	2013	2014
Tops	15%	21%	24%
Naphtha	75%	70%	68%
GO	6%	5%	4%
Hydrowax	4%	3%	4%

BTX were partly generated as steam cracker by-products, supplemented by existing catalytic reformers as required **(Table 9):**

Table 9 BTX production routes

	Base	P2X	1.5TECH
Steam crackers	59%	56%	75%
Cat reformers	41%	44%	25%

- Petrochemicals composition (fossil/bio/e-fuels):

Table 10 **Olefins and** BTX composition

Olefins

	Base	P2X	1.5TECH
Fossil	98.0%	72.4%	50.3%
Bio	2.0%	2.0%	33.1%
e-fuels	0.0%	25.6%	16.7%

BTX

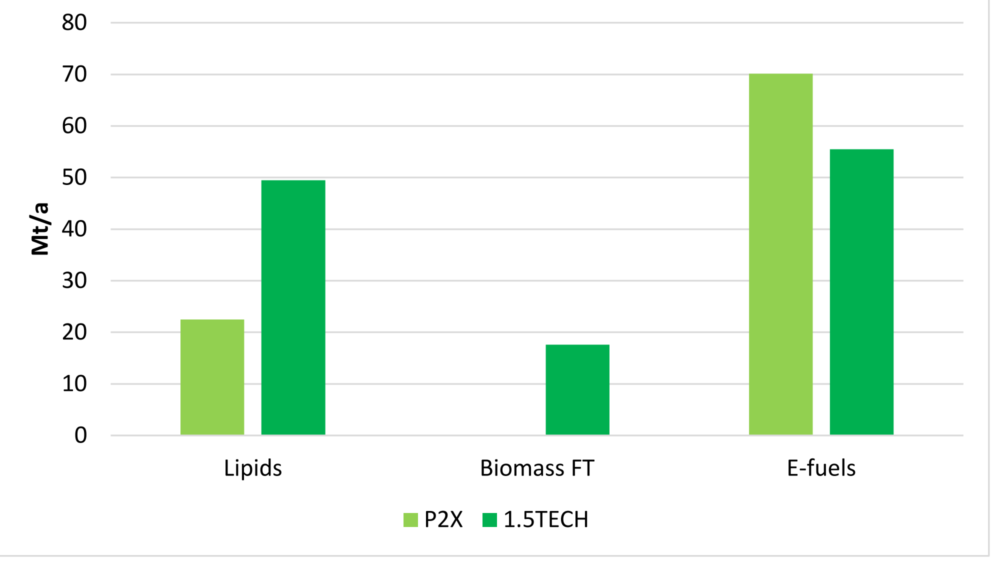
	Base	P2X	1.5TECH
Fossil	99.4%	84.6%	62.6%
Bio	0.6%	1.1%	24.8%
e-fuels	0.0%	14.2%	12.5%

- ***New plants***. Non-conventional refinery processes

Beyond conventional refineries, new plants would be required to process lipids into marketable diesel, biomass and CO_2 into liquid fuels. **Figure 16** shows the (total) liquids production from each feedstock type. To put these numbers in perspective and focussing on the most demanding 1.5TECH scenario:

- Current state-of-the-art lipids hydrotreating plants have a capacity of 0.5 to 1 Mt/a. With demand up to 50 Mt/a and say 80%[10] processed in dedicated plants, maybe 40 plants/trains would be required.
- BTL-type processes have not been developed to full commercial scale today. Although this may increase in the future, individual plant capacities of maybe 200 kt/a are considered feasible (sourcing and handling of woody biomass – roughly 5 times the amount of liquids – is one of the issues). Possibly upwards of 50 plants/trains could be required.
- E-fuels plants are very much uncharted territory in terms of hydrogen production at scale and CO_2 conversion. The Fischer-Tropsch stage would be very similar to proposed Biomass-to-liquids (BTL) plants and small sizes could potentially be envisaged in Europe (~0.2 Mt/a of liquid product). However, there is a big uncertainty around the future capacity of these plants and larger ones – closer to Gas-to-liquids (GTL) plants - could also be deployed in certain favourable areas with sizes up to 1 Mt/a of liquid product. As a reference, they will require, about 3 Mt/a CO_2 and 3GW of electricity generation capacity for 1 Mt/a of liquid product, supporting supply infrastructure and massive banks of electrolysers, all likely to be the major challenge.

Figure 16 Liquid products from non-conventional refinery processes



[10] 20% assumed to be co-processed in existing plants

5.4. ENERGY AND CO_2 EMISSIONS

Electricity consumption in P2X and 1.5TECH would be in the order of 50-60% of the total current EU electricity consumption (about 3,200 TWh/a).

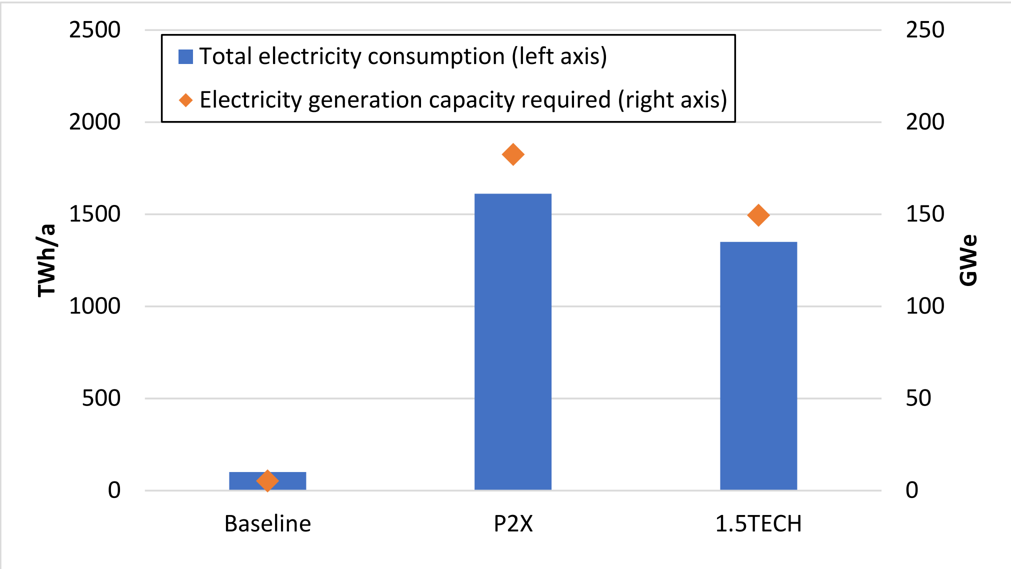
As a result of the intake of the different feedstocks and unit utilization, **Table 11 and 13** respectively show energy-related information and the breakdown of CO_2 emissions.

Table 11 Direct fuel and electricity

		Baseline	P2X	1.5TECH
Refinery direct fuel	PJ/a	783	482	266
Total electricity consumption	TWh/a	100	1611	1351
Process units (inc. own CO2 capture)		52	54	56
Electrolysis		48	1557	1295
Electricity net import		46	1600	1310
Electricity generation capacity required	GWe	5	183	150

As further highlighted in **Figure 17**, the electricity consumption is a course very large for P2X and 1.5TECH as a consequence of the massive introduction of e-fuels.

Figure 17 Total electricity consumption



Note: losses not considered (assumed to be limited if generation happens reasonably locally). As imported grid electricity is not assumed to be fully renewable, there is still a fossil component in the imported utilities.

The majority of electricity consumption comes from e-fuels production:

Table 12 Electricity consumption breakdown

		P2X	1.5TECH
General use	TWh	126	176
e-fuels		1485	1175

Note: General use refers to utilities balance for the standard refinery units (including HC).

To provide an order of magnitude, electricity consumption in P2X and 1.5TECH would be in the order of 50-60% of the total current EU electricity consumption (about 3,200 TWh/a).

P2X and 1.5TECH cases assume a large proportion of e-fuels in the transport fuel mix leading to the very high electricity consumptions seen above. Other scenarios such as COMBO and/or 1.5LIFE entail a larger proportion of bio components and therefore less e-fuels. Electricity requirements are therefore lower (in the order of 500 TWh/a) but still considerable, representing about 15% of the total current EU electricity consumption.

Table 13 CO_2 emissions breakdown

Mt/a	Baseline	P2X	1.5TECH
Total net from site	60	-192	-69
Total from fuel products	842	784	506
Fossil from site	46	5	1
Fossil from fuel products	825	552	222
Fossil from utility imports	6	30	7
Direct CO2 emissions reduction vs 1990	62%	96%	99%

Explanatory note on terminology

Total net from site	*Total (fossil + non-fossil) CO_2 emitted on site. Can be negative where CO_2 is absorbed by e-fuels*
Total from fuel products	*Total (fossil + non-fossil) potential CO_2 from all carbon in fuel products combustion (including exports)*
Fossil from site	*Fossil CO_2 emitted on site: the fossil content of the actual emissions*
Fossil from fuel products	*Potential CO_2 from fossil carbon in fuel products combustion (including exports)*
Fossil from utility imports	*Fossil CO_2 emitted when generating imported electricity and gas*

Notes:

- An annual efficient improvement of about 0.6% per year on average is considered for the whole period to 2050 from 2008 level [CW CO2 reduction 2019].
- Capture refers to own capture only. Imported CO_2 is assumed to be available in a usable form for the synthesis process (it is considered a feedstock).
- The Baseline case assumes not capture. If this was to be included (at the 70% rate applied in the other cases), site emissions would be reduced from 46 to 15 Mt/a partly compensated by an increase of indirect emissions from gas imports (to fuel capture) from 4 to 9 Mt/a.
- In terms of the origin of CO_2 for e-fuel production, there is a huge uncertainty around how the future regulation will evolve. So far and for the purpose of this analysis, we are considered thatCO_2 for e-fuels as a waste (no CO_2 burden) regardless the origin (flue gases, biomass production sites or Direct Air Capture)
- EU-28 refineries direct emissions in 1990 (fossil from site): 122 Mt CO_2/a [Concawe Ref2050 2019]

With low crude intake and CO_2 capture, fossil site emissions are very low in P2X and virtually eliminated in 1.5TECH. At the same time, potential emissions from fuel products decrease with the decreasing proportion of fossil material in their make-up.

The direct (fossil from site) CO_2 reduction versus 1990 in the EU refining system ranges from 62% in the Baseline to 96% (P2X) and 99% (1.5TECH). The P2X case is achieving a higher CO_2 reduction in EU refineries (96%) than the claimed one across the whole EU economy (80%). The 1.5TECH case is almost achieving in EU refineries the net zero emissions as it is claimed for the whole EU economy (100%).

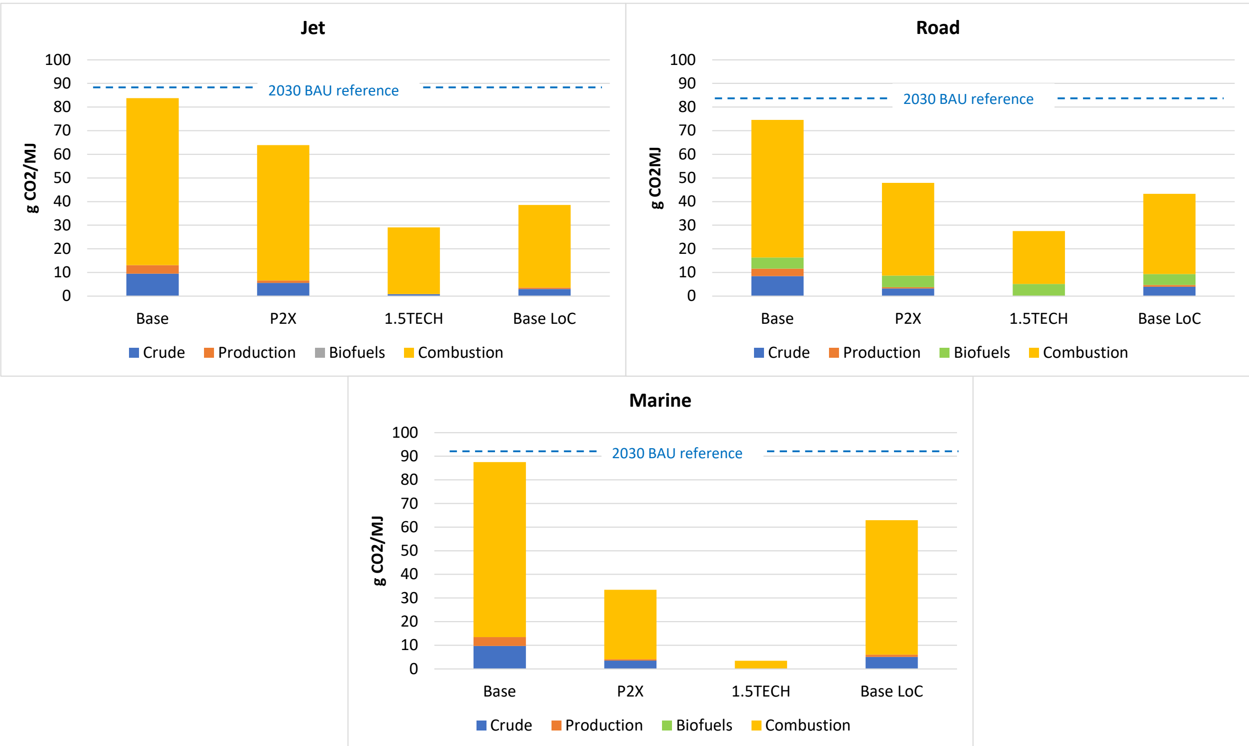
As imported grid electricity is not assumed to be fully renewable (see Section 3), there is still a fossil component in the imported utilities (it is also the case for natural gas but imports are kept to a minimum so that the impact is insignificant). This contribution is proportional to the assumed grid electricity fossil CO_2 emission factor (assumed to be 5.2 t CO_2/GWh, see Section 5).

The fossil carbon intensity of the three transport fuel pools is shown in **Figure 18** on a "Well-to-Wheels" basis, i.e. including contributions from:

- Crude oil production and transport
- Refining / fuel production (including utilities imports)
- Contribution of blend-in biofuels (ethanol in gasoline and biodiesel in road diesel)
- Combustion (potential emissions according to the fossil carbon content of the fuel)

The fuel combustion emission factors and petrochemicals carbon content figures are also shown in **Appendix 3**.

Figure 18 Fossil carbon intensity



The potential CO_2 emissions from fuel products combustion decreases sharply with increasing non--fossil carbon intake.

5.5. INVESTMENT (CAPEX) ESTIMATE

Investment, dominated by e-Fuels could range between about 250 and 400 G€ for the whole EU refining system in the P2X and 1.5 TECH scenarios.

Introducing alternative feedstocks in the refinery environment at the scale discussed above would require investment in brand new plants for the frontend processing of these feedstocks, extensive modifications and revamping of existing plants for further processing and treating of the raw products, and extensive adaptation of ancillary facilities such as import terminals, tankage etc.

An attempt to estimate the CAPEX associated to the new processes has been included considering that the main investments required to implement the scenarios are related to the processing of lipids and biomass and, most importantly, to the massive production of e-fuels that is envisaged.

Based on the best estimated of the specific capex ranges for such plants discussed in [Concawe Ref2050 2019], the figures show the total investments that could be required.

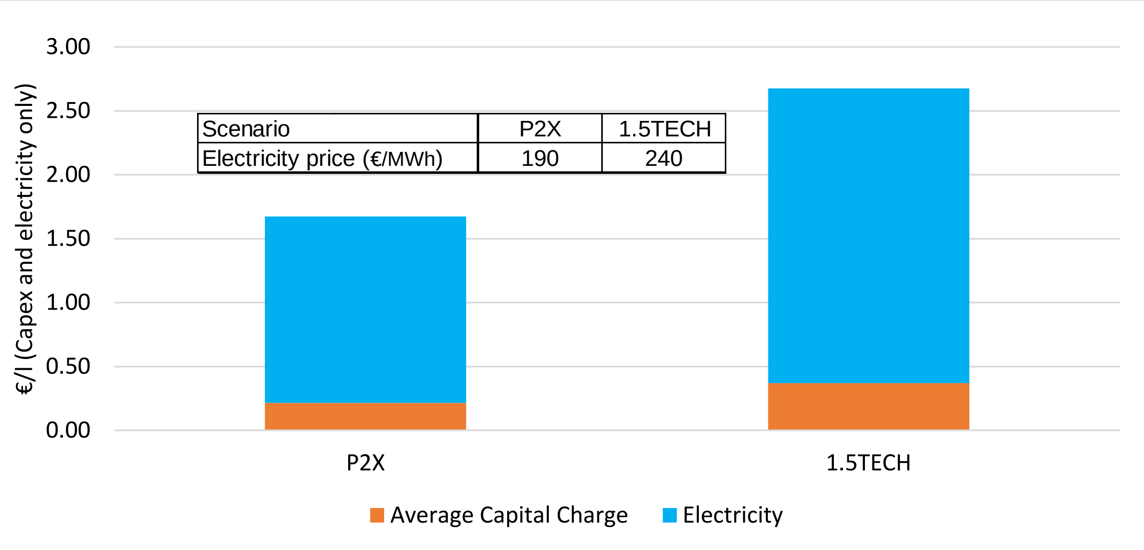
Figure 19 Ranges of Capex (figures in G€)

Basis	Capacity (per unit) Mtoe/y	CAPEX (M€) per plant	M€/kt/a product (1,2)
New HVO plants	0.5	275	0.55
Lignocellulosic	0.15	610 -900	4.0 – 6.0
e-Fuels	0.2	400 - 650	2.0 – 3.3 (3)

Notes:
(1) Capacities are expressed in terms of liquid product. toe/t factor=1 for liquid products
(2) CAPEX data aligned with [Concawe Ref2050 2019]
(3) Other new sources [Joule 2019] are reporting lower CAPEX figures (below 3 M€/kt/a) than in [Concawe Ref2050 2019] (3.77-4.43 M€/kt/a)

Capex accounts for only a fraction of the costs involved. The main variable cost would be electricity. **Figure 20** shows the contributions to the unit fuel cost in €/l, taking into account annualised capex (average of above figures and 15% capital charge) and electricity price in line with the Commission's forecast (see **Appendix 1**). The cost of the small amount of natural gas and other operating costs such as personnel, maintenance etc. are not represented here but they would be dwarfed by the very high cost of electricity.

Figure 20 Contribution of CAPEX (average capital charge) and electricity to fuel unit cost



Note: Own CO_2 capture related cost are not expected to be major contributions to the increase in the operational cost of the future low carbon fuels (100 €/t CO_2 for both CAPEX and OPEX [Concawe CO_2 reduction technologies 2019], which would amount to between 2-8 G€ across the cases considered). Worth mentioning that CO_2 capture for e-fuel production are already included in the e-fuel related figures.

However, it is important to note that the present report is a conceptual assessment and further implications in terms of the level of investment required across the whole refining system have not been assessed in detail.

6. IMPLICATIONS FOR EU REFINERIES

The main implications for EU refineries according to *A Clean Planet for all* 2050 scenarios are:

- Crude intake reduction by 40 to 80% compared to current levels.
- Low plant utilisation. Conventional refinery plants would be heavily underutilised or even not required at all for some process units (such as FCCs in P2X and 1.5TECH), with the exception of hydrocrackers, kerosene hydrotreaters and residue converters.
- Development of a sizeable capacity of BTL-type plants and large to very large e-fuels facilities, either stand alone or integrated into existing refinery complexes.

  This will imply an increasing support in R&D across the whole value chain including:

  - Boosting development and scale-up of these production technologies (some of them currently at lower Technology Readiness Level (TRL)) to new feedstock
  - Conversion efficiency improvements to reduce feedstock and energy needs leading to cost reduction of the technologies (e.g. key for e-fuel production routes).
  - At refinery level, overcome specific technical challenges such as how to ensure continuous operation when processing different feedstocks.

- High external requirements, that go beyond the refinery battery limits:

  - Own CO_2 capture and large to very large CO_2 or e-fuels liquids imports, creating a competition among other sectors for the same low carbon electricity.
  - High electricity imports. Therefore, accessibility to a highly and affordable decarbonised electricity grid will be essential at EU level by 2050 to meet the defined (net) GHG emission reduction objectives.
  - Maximizing availability of sustainable alternative feedstocks to ensure lipids and biomass/waste resources at scale.
  - Developing a large supply chain to mobilize lignocellulosic / residue resources from the source points to the production sites.

- Sizeable surpluses of (mostly fossil) middle distillates, gasoline (up to about 30 Mt/a) and heavy fuel oil (up to 12 Mt/a) due to the origin distribution constraints implied by *A Clean Planet for all* 2050 scenarios.

  Although these volumes are of a similar order of magnitude than historical EU import / export, fossil material export opportunities might be limited at the 2050 horizon.

  - Exporting the fossil gasoline and diesel may be heavily constrained if we assumed that in 2050 the rest of the world may follow similar EU decarbonisation targets, as EU would be exporting emissions to other regions to lower its own GHG emissions, impacting on the practical feasibility of these scenarios as defined today.

- Besides, some surplus of low carbon fuels will be inevitably produced under the current conversion processes, with a higher production costs than with conventional oil-based fuels, which could lead to additional difficulties when marketing those products in countries which do not recognize the positive value of decarbonisation as Europe.
- This Concawe study highlights the risk of these scenarios, which will add significant burdens to the EU refining system in 2050. Based on the points described above, this could potentially reach a point where meeting the defined domestic demand (and fuel composition), as described in the European Commission's report, could not be economically feasible for the refining system in Europe with the consequent refinery closures, being replaced by fossil jet fuel imports from other regions of the world to Europe with no benefit for climate change globally.
- Middle distillates export volumes could be substantially reduced through relaxing the constraints in the fossil/bio/E-fuels distribution in the road/marine/jet pools determined by *A Clean Planet for all*.
- Some fossil gasoline components and heavy fuel oil would remain for which alternative use may have to be found (potentially, out of EU), or as gasification being an ultimate option.

• High investments would be required to adapt the refineries to the *Clean Planet for all* scenarios, dominated by e-Fuels, which could range between about 250 and 400 G€ for the whole EU refining system as a very initial bulk estimate.

Although the combination of the alternative feedstock pathways has been modelled to happen simultaneously in the same refinery, different combination of routes may be followed by individual refineries (depending on factors such as the proximity to a specific resource, geographic location, initial refining configuration, etc). All of this subject to individual strategic plans with strong implication on the investment costs, and it is out of the scope of the current study.

Thus, the present study cannot be considered as a Roadmap for the whole European refining system but as an initial exploration of the potential consequences at macro-level.

In summary, it implies a transformation of the refineries as we understand them today to a *Refinery 2050* concept.

7. GLOSSARY

ACP4A	A Clean Planet for all
BTL	Biomass-to-Liquid
BTX	Benzene, Toluene, Xylene
CAPEX	Capital Expenditure
CCS	Carbon Capture and Storage
CFPP	Cold Filter Plugging Point
CO_2	Carbon dioxide
CW	Concawe
DMF	Diesel Marine Fuel
EU	European Union
FCC	Fluid Catalytic Cracker
FT	Fischer-Tropsch
GHG	Greenhouse gas
GO	Gasoil
HC	Hydrocracker
ICE	Internal Combustion Engine
IEA	International Energy Agency
JEC	JRC, EUCAR and Concawe Consortium
LCN	Light FCC naphtha
LPG	Liquified Petroleum Gas
P2X	Power-to-X
RMF	Residual Marine Fuel
SMR	Steam Methane Reformer
WTW	Well-to-wheel

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APPENDIX 1: ELECTRICITY MIX

1. PROJECTED CARBON INTENSITY ELECTRICITY MIX

The carbon intensity in power generation in 2050 in 1.5TECH scenario is 5.2 gCO_2/kWh according to [ACP4A 2018] and [ACP4A Sup 2018][11]. See summary table and details on the calculation approach hereafter.

Table 1A. Summary of Carbon intensity values for the three scenarios considered in the analysis

			Baseline	P2X	1.5
Step 1	2015 baseline	TWh	3234	3234	3234
Step 2	% additional vs 2015 baseline	TWh	42%	140%	146%
	Gross electricity generation in 2050	TWh	4576	7762	7956
Step 3	Gross electricity demand (10% losses)	TWh	4118	6985	7160
Step 4	CO_2 emissions from power sector (as reported in [ACP4A 2018]	Mt CO_2eq	246	119	38
	CI power generation	g CO_2/kWh	59.8	17.1	5.2

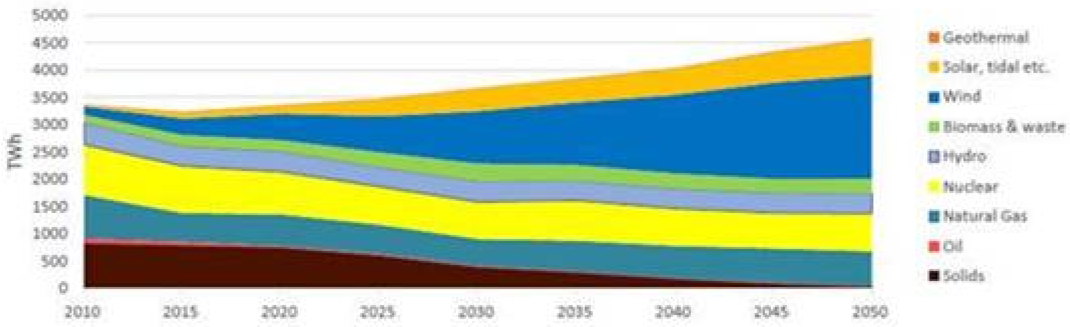
DETAILS – 1.5 TECH SCENARIO – CARBON INTENSITY ELECTRICITY MIX

1) Step 1. Gross electricity generation (production) in 2015 (baseline) - INPUT

Source: Figure 8 from [ACP4A 2018]
Gross electricity generation in 2015 baseline à **total: 3234 TWh**

Figure 8: Gross electricity generation in the Baseline

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Solids	829	792	751	607	395	298	180	92	37
Oil	87	61	24	24	20	13	8	10	8
Natural Gas	799	530	585	537	492	565	593	632	637
Nuclear	917	857	773	695	677	730	681	647	688
Hydro	408	371	375	362	380	366	370	372	376
Biomass & waste	143	201	208	269	325	289	274	254	268
Wind	149	302	487	664	955	1149	1440	1761	1905
Solar, tidal etc.	23	108	147	307	412	430	475	546	641
Geothermal	10	13	7	7	9	9	10	17	17

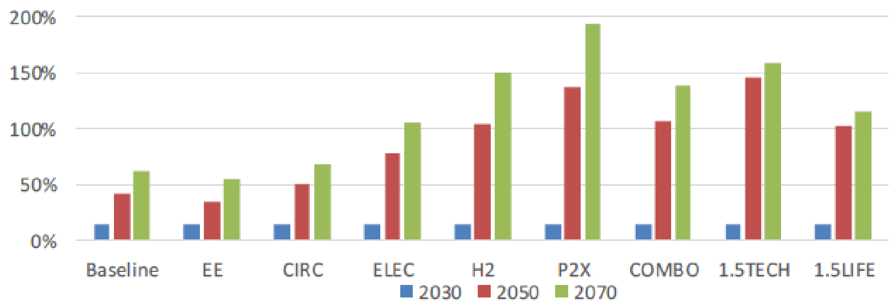


[11] Note that in Refinery 2050 work [Concawe Ref2050 2019], a factor of 40 gCO_2/kWh was used.

2) Step 2: Gross electricity generation (production) in 2050 (1.5 TECH) - INPUT

- Source: Figure 22. Increase in gross electricity generation compared to 2015 -> 146% (on top of the 2015 electricity value)
- CALC:
    - o Delta: 3234 (2015) * 146% = 4721 TWh
    - o 2050 value (1.5TECH): 3234 + 4721 = 7955 TWh

Figure 22: Increase in gross electricity generation compared to 2015



Source: Eurostat (2015), PRIMES.

3) Step 3 -> Gross electricity demand in 2050 (1.5TECH) - CALC

Assumption: 10% as losses (during the transmission and storage)

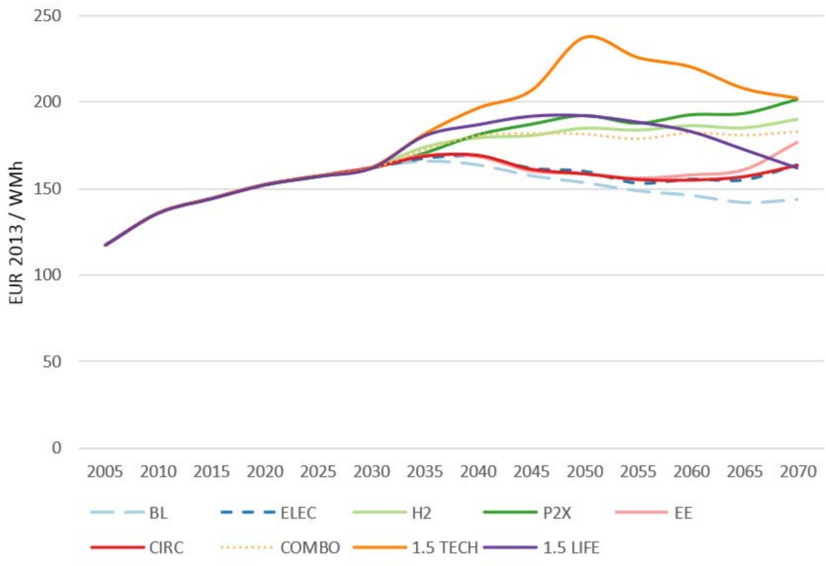
Calc (2050 – 1.5 TECH) = **7159 TWh**

4) Step 4 -> CO_2 intensity calculations:

- Emissions from the power sector (1.5 TECH): 37.5 $MtCO_2eq$ (as reported in page 113 of the supplementary information accompanying [ACP4A Sup 2018].
  It is worth noting that these CO_2 emissions have been taken as the best available data to be aligned with the reported European Commission report. However, it is a proxy as we are assuming that the upstream emission factors for each of the power generation routes have been also considered within these emissions.
  E.g.: For 1.5TECH case: 37.5/7159 *1000 = 5.2 g CO_2/kWh. Same for the rest of the scenarios (see Table 1A).

2. PROJECTED AVERAGE ELECTRICITY PRICES

Figure 99: Projected average electricity prices for final users



Source: PRIMES.

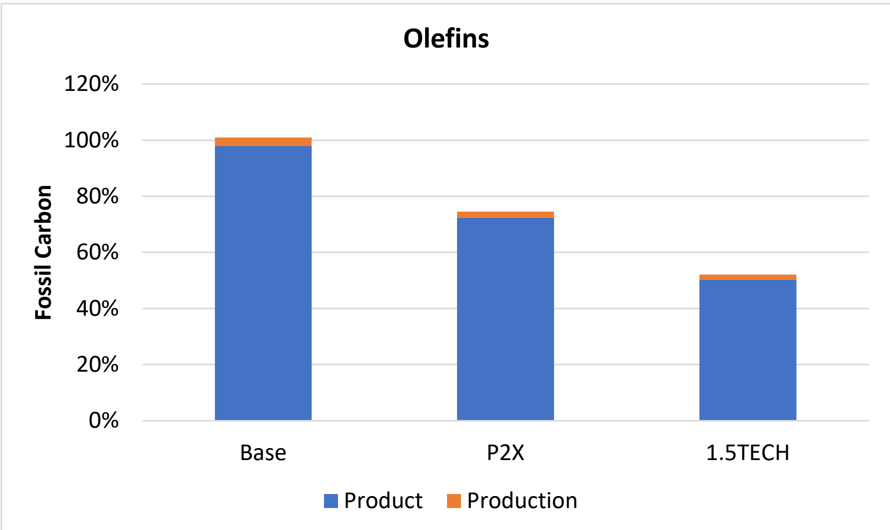
APPENDIX 2: ALTERNATIVE FEEDSTOCKS PROCESSING YIELDS

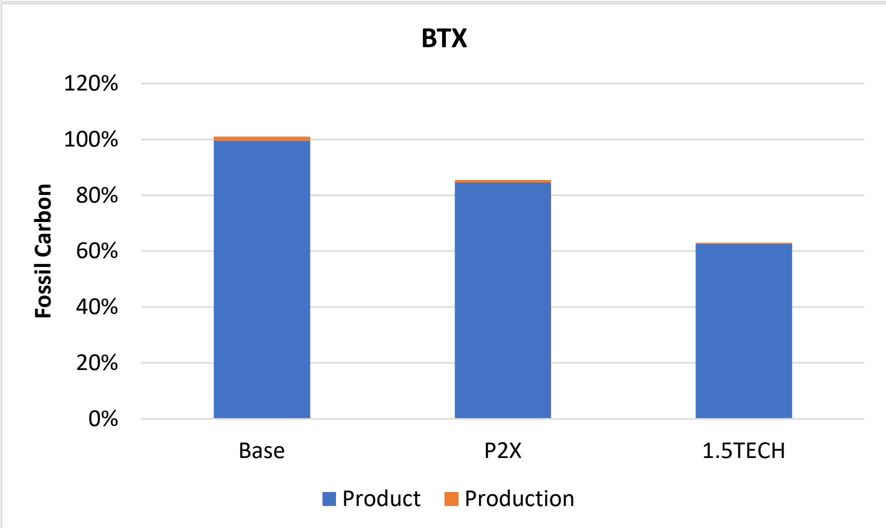
	e-fuels			**BTL**		
	FT synthesis	Hydrocracking		FT synthesis	Hydrocracking	
		on 100% FT product			on 100% FT product	
CO2	-100.00			111.59		
H2O	-44.73			23.17		
O2	112.49			-58.14		
Biomass				-100.00		
H2	0.00	-0.12	-0.02	0.05	-0.03	0.04
Tar				1.00	0.16	0.22
C1	0.32	0.24	0.32		0.29	0.40
C2	0.58	0.43	0.58		0.40	0.53
C3	0.78	0.58	0.78		0.47	0.74
C4	0.94	0.70	1.09		3.53	3.11
Naphtha (C5-C9)	5.88	5.18	4.56		17.22	4.33
Jet (C10-C12)	3.70	25.24	6.34		0.00	8.05
Diesel (C13-C22)	9.87	0.00	11.80		0.00	4.63
Heavy (C22+)	10.16	0.00	6.79			
Total FT product	32.24			22.00		

Lipids hydrotreating	Co-processing	Dedicated	
		Max GO	Max Jet
Lipid	-100.00	-100.00	-100.00
H2O	-3.35	-3.24	-3.60
C3	5.90	5.85	5.84
C4	2.55	0.81	5.17
Naphtha (C5-C9)	7.65	1.81	6.96
Jet (C9-C12)	6.80	12.89	49.12
Diesel (C12-C18)		68.56	23.17
Diesel (C12-C22)	67.13		
CO2	5.15	5.15	5.15
H2O	8.18	8.18	8.18

APPENDIX 3: PRODUCT EMISSION FACTORS

	Base	P2X	1.5TECH
		t CO_2/t	
Olefins	3.08	2.28	1.58
BTX	3.35	2.84	2.10
		t CO_2/TJ	
LPG	64.4	40.7	21.9
Gasoline	71.6	69.8	
Export Gasoline	73.3	73.4	46.0
Jet	70.7	57.3	28.2
Road diesel	54.5	21.4	5.9
DMF	72.2	35.7	3.7
Export GO	56.2	66.4	62.9
RMF	78.3		
Export LSFO		68.6	52.2





APPENDIX 4: DETAILED MODELLING RESULTS

Case	Baseline	P2X	1.5TECH
Feedstocks (Mt/a)			
Crude	0.4	0.6	0.8
Lipids	350.0	240.0	120.0
Biomass	5.0	25.0	55.0
CO2 for E-fuel	10.0	0.0	80.0
Own CO2 captured	0.0	219.2	173.4
Imported CO2	0.0	19.2	73.4
Hydrogen	0.0	200.0	100.0
C1 (SMR feed)	1.0	1.5	2.5
Products (Mt/a)			
Olefins	0.0	0.0	0.0
BTX	37.7	37.9	37.9
LPG	11.8	11.7	10.5
Gasoline	13.2	12.1	9.1
Export gasoline	25.0	8.3	0.0
Jet	33.1	26.7	8.6
Diesel	65.0	60.0	58.0
DMF	62.0	56.5	10.9
Export GO	20.0	42.0	38.0
RMF	4.9	28.1	27.2
Export LSFO	41.0	0.0	0.0
Bitumen	0.0	13.7	9.5
Lubs and waxes	17.3	17.3	17.3
Total liquid products	4.6	4.0	4.1
Transport fuels	335.6	318.4	231.0
Energy			
C1 import (fuel) (Mt/a)	0.0	0.0	0.0
Internal fuel (PJ/a)	4	3	0
Total elec cons (TWh/a)	783	482	266
Elec net import (TWh/a)	100	1611	1351
Total energy (PJ/a)	46	1600	1310
CO2 emissions (Mt/a)			
Total from site	0.0	0.0	0.0
Total from fuel products	60.1	-191.8	-68.6
Fossil from site	841.6	783.6	506.0
Fossil from fuel products	45.6	5.2	1.2
Fossil from utility import	825.0	552.4	221.8
Hydrogen consumption (Mt/a)			
HMU	1.0	32.5	26.9
Electrolysis for refinery	0.0	0.2	0.1
Electrolysis for e-fuels	1.0	1.5	2.5

APPENDIX 5: HIGHER KEROSENE YIELD IN EXISTING HYDROCRACKERS

In the P2X and 1.5TECH scenarios the amount of crude oil required was set by the desired fossil content of the jet fuel pool. As indicated on Section 4 it is believed that kerosene yields from existing hydrocrackers could be increased. Although the precise scale of such changes is somewhat speculative at this point, this would relieve this constraint. Starting from the 1.5TECH case, we have run a sensitivity case with a kerosene yield increased from 30 to 45% (150-250ºC) assuming that a revamp would be required in the Hydrocracker unit, with the associated CAPEX.

Table 5A. Yields for fossil VGO in existing Hydrocracker

	Conventional kerosene yield	Higher kerosene yield (via revamping)
C1-C4	3%	4%
C5-85C	6%	7%
85-150C	17%	17%
150-300C	31%	50%
300-370C	41%	20%
370C+	2%	2%

The results are shown below compared to the original 1.5TECH case.

Case	Original	High kero	*Delta*
Feedstocks (Mt/a)			
Crude	120.0	100.0	*-20.0*
Lipids	55.0	55.0	*0.0*
Biomass	80.0	80.0	*0.0*
CO2 for E-fuel	173.4	182.5	*9.1*
Own CO2 captured	73.4	82.5	*9.1*
Imported CO2	100.0	100.0	*0.0*
Hydrogen	2.5	0.3	*-2.2*
C1 (SMR feed)	0.1	0.0	*-0.1*
Products (Mt/a)			
Olefins	37.9	37.8	*-0.1*
BTX	10.5	6.5	*-4.0*
LPG	9.1	9.3	*0.3*
Gasoline	0.0	0.0	*0.0*
Export gasoline	8.6	7.9	*-0.8*
Jet	58.0	58.0	*0.0*
Diesel	10.9	10.9	*0.0*
DMF	38.0	38.0	*0.0*
Export GO	27.2	13.3	*-13.8*
RMF	0.0	0.0	*0.0*
Export LSFO	9.5	6.9	*-2.6*
Bitumen	17.3	17.3	*0.1*
Lubs and waxes	4.1	4.1	*0.0*
Total liquid products	231.0	210.1	*-20.9*
Transport fuels	106.9	106.9	*0.0*
Energy			
C1 import (fuel) (Mt/a)	0.2	0.0	*-0.2*
Internal fuel (PJ/a)	266	258	*-8*
Total elec cons (TWh/a)	1351	1307	*-44*
Elec net import (TWh/a)	1310	1270	*-40*
Total energy (PJ/a)	8480	8226	*-254*
CO2 emissions (Mt/a)			
Total from site	-68.6	-64.3	*4.2*
Total from fuel products	506.0	452.7	*-53.2*
Fossil from site	1.2	1.0	*-0.2*
Fossil from fuel products	221.8	169.4	*-52.4*
Fossil from utility imports	7.1	6.6	*-0.5*

Crude intake could be reduced by 20 Mt/a (17% reduction), leading to a notable reduction of export gasoil (-13 Mt/a, meaning a 50% reduction) and, to a lesser extent, LSFO surpluses (-2,6 Mt/a, meaning a 28% reduction). It was, however, not possible to match the desired BTX yield because of a lack of catalytic reformer feed.

Energy consumption and CO_2 emissions were also reduced in line with the reduction of total products.

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