Concawe
Environmental Science for European Refining

Report

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Appendixes

Refinery 2050: Conceptual Assessment.

Exploring opportunities and challenges for the EU refining industry to transition towards a low-CO_2 intensive economy

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Appendixes

Refinery 2050: Conceptual Assessment.

Exploring opportunities and challenges for the EU refining industry to transition towards a low-CO_2 intensive economy

These appendixes were prepared by Concawe Secretariat:

C. Banner, A. Megaritis, A. Soler and M. Yugo

For:

Concawe Special Task Force *Refinery 2050* (STF-2)

Under the supervision of:

M. Yugo (Concawe Science Executive)

Marta.yugo@concawe.eu

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This report consists of the appendixes of the main Concawe report 9/19.

ABSTRACT (CONCAWE 9/19 REPORT)

The report 9/19 (Appendixes included in the document 9/19A) is the second in a series of publications that explore opportunities and challenges for EU refineries to integrate technologies and feedstocks that would reduce the fossil carbon intensity of petroleum products.

The first Concawe report (*Low Carbon Pathways: CO_2 reduction technologies in the EU refining system. 2030/2050)* explored opportunities to invest in new technologies to reduce the CO_2 emissions from refineries in the short and then medium term. *The Concawe 9/19 report* goes beyond this approach by exploring the potential to substitute crude oil with bio-feedstocks and the use of renewable electricity. Sustainable vegetable oils, lignocellulosic biomass and e-fuels have been selected as initial examples of key low carbon feedstocks in this conceptual assessment.

As the starting point for this analysis, two potential **2050 demand scenarios** are defined, followed by the description of the conversion pathways required for the integration of the selected low-carbon feedstocks within a *notional* mid-range European refinery. Then, the results of the modelling exercise are presented, moving from mostly **oil based cases**, where the EU refineries meet the 2050 demand in the most plausible CO_2 efficient manner, to the progressive integration of low-carbon feedstocks illustrated by two series of cases:

- ***Limited penetration cases*** (individual pathways): where the implications of the production of 1 Mt/a liquid products from each of the selected low carbon feedstocks are described.
- ***Maximum low carbon feedstock*** **cases** (Combined pathways): Based on the different nature of the feeds explored, this report moves further in the analysis by looking at the combination of different low carbon feedstocks.

In all the cases modelled, the implications in terms of feedstock supply, key processing requirements such as hydrogen and electricity and the impact such changes have on the CO_2 emissions intensity both at refinery level and for the end products in Europe are initially assessed and quantified. Potential impacts and synergies with the existing assets, as crude oil is progressively replaced, are also investigated.

Beyond the main report, the Appendixes included in the present document (Concawe 9/19A) complement the analysis of the main low carbon feedstocks/technologies explored by providing an initial view on:

- the potential implications on air quality and safety
- the potential feedstock availability in Europe (Medium and long term)

As mentioned in the abstract of the main report, this conceptual assessment is not intended to be a roadmap for the whole refining industry. The low-carbon feedstocks explored are selected examples. Multiple additional pathways/feedstocks could be also integrated within the EU refining system subject to the location of the sites and individual company strategies.

KEYWORDS

Refinery, refining, pathways, Vision 2050, low carbon fuels, CO_2, vegetable oil, waste, e-fuels, biofuels, climate change.

INTERNET

This report is available as an Adobe pdf file on the Concawe website (www.concawe.eu).

Note. The main Concawe report 9/19 can be found with the following link:

report no. 9/19

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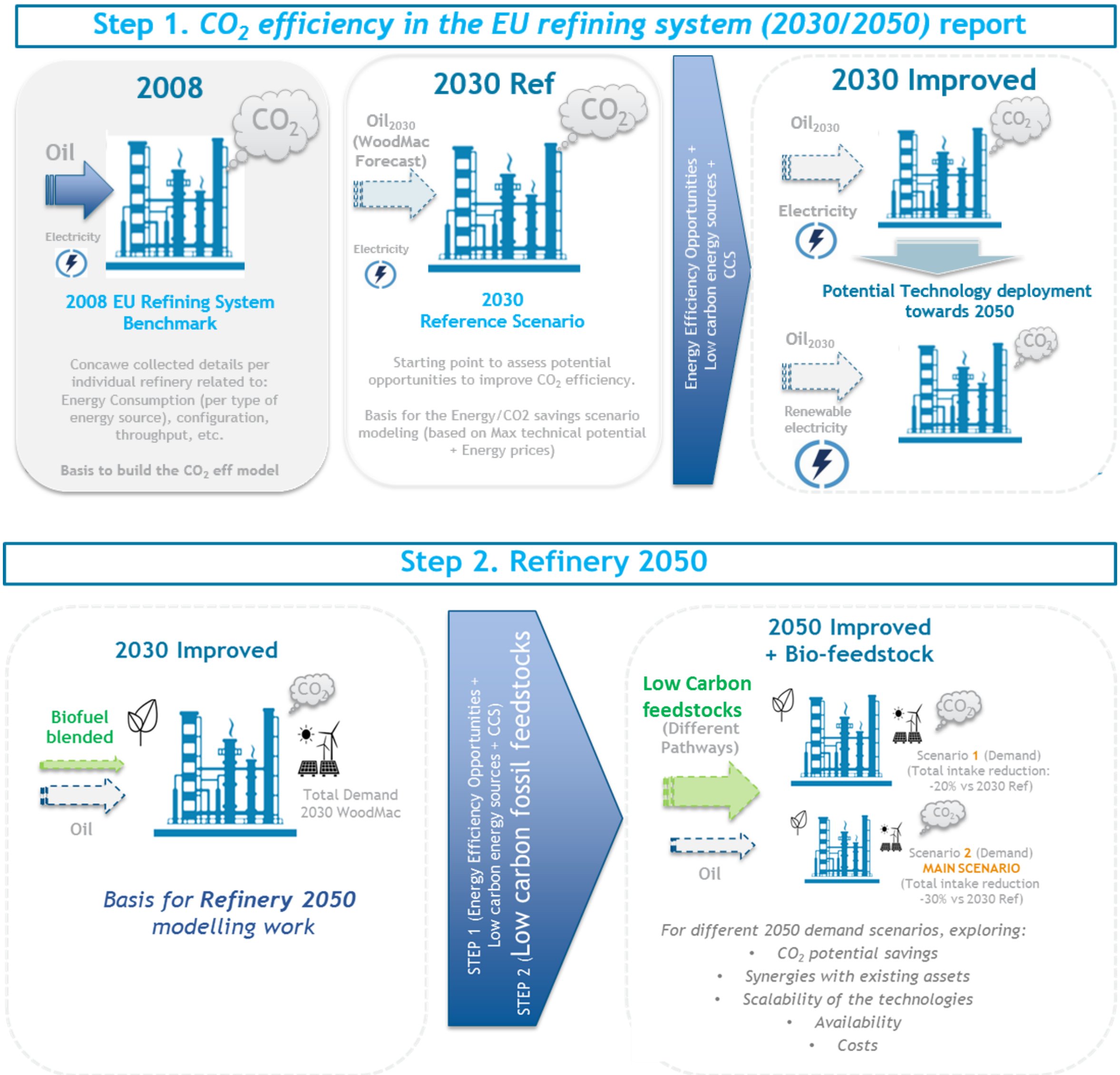
APPENDIX A1 CONCAWE LOW CARBON PATHWAYS. REFINING RELATED REPORTS. SUMMARY OF SCOPE COVERED UNDER STEP 1 & 2.

Figure A.1 Summary of scope covered under both Concawe Low Fossil Carbon Pathways refinery-related reports



APPENDIX A2 A LOOK INTO SAFETY AND AIR QUALITY POTENTIAL IMPLICATIONS

The Low carbon technologies covered in this report are examples of different pathways which deem to have significant positive effects on reducing CO_2 emissions associated to the refining system by 2050. Additional impacts in terms of safety, air quality or water are even more uncertain. Some preliminary ideas related to both Safety and Air Quality are presented in this section and, when needed, will be subject to a more detailed assessment within Concawe (not included in the scope of this report).

The evolution of the refinery assets as low carbon technologies are implemented may have a potential impact on safety issues within the refinery battery limits (on-site through co-processing or co-located conversion technologies described in previous sections of this report) as well as the ones associated to the production of alternative feedstocks (upstream) and final end-product use (*downstream*).

A2.1 SAFETY

The refinery related (on site) technologies for the Low Carbon Pathways are all known as activities by the Refining industry and the associated risks are studied, known and controlled. All of these activities (except CCS) are already in place but most of the time not on a large scale. Scalability is therefore the main potential source of risk and passing from small scale to a larger scale would require a proper *Management Of Change* (MOC), following the same risk management procedures as the refineries to ensure that the risks are not underestimated. During that MOC, the risks related to the upscaling will be studied and the ad-hoc safety studies would need to verify that the inherent risk of the new low CO_2-intensive product or activities would be lower than the risk of the previous product of activity when looking to the entire value chain (from upstream to downstream).

Overall, the implementation of the low carbon technologies across the whole value chain including transportation are not envisaged to increase safety risks compared with conventional activities as long as the change is effectively managed and risk management procedures are properly followed and implemented.

A2.2 AIR QUALITY

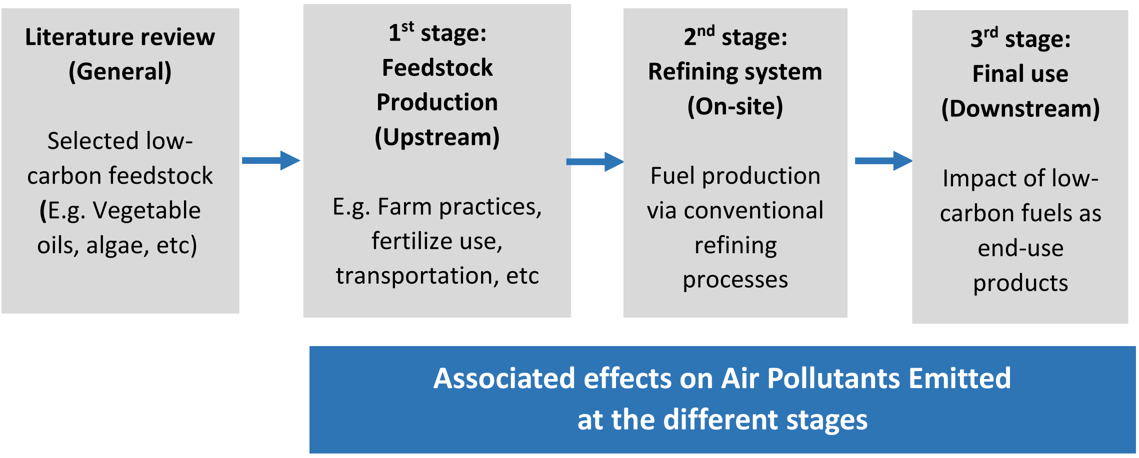
In order to better understand how the different Low-carbon pathways (LCP) technologies related to bio-feedstocks might impact the emissions of air pollutants, a qualitative assessment has initially been performed based on an extensive literature review. The air pollutants considered include SO_2, NOx, O3, PMs, VOCs, NH3, PAH, Benzene, HCN, and CO.

As a first step, different bio-feedstock routes were considered and the associated effects on the emissions of various air pollutants at the various process stages (e.g., production of the bio-feedstock, production of the relative bio-fuel through the refining process, and finally use of bio-fuel as end-use product), were evaluated. To illustrate the potential impacts, the following bio-feedstock routes have been chosen:

a) Vegetable oils (including algae)
b) Gasification of biomass
c) Waste-plastics
d) E-fuels

The following graph presents schematically the approach that has been followed:

Figure A2-1 Schematic presentation of the qualitative approach to assess the potential impacts of LCP technologies to air pollutants emissions



It should be noted that this qualitative assessment is a starting point for the Concawe work aiming to improve our understanding regarding the potential associated effects of different low fossil carbon feedstocks to air pollutants emissions, as well as to highlight the uncertainties and the knowledge gaps existing so far which would trigger new areas of future research on the subject.

Summary findings

The literature review shows that there is a lack of detailed information regarding the impact of the different routes considered in this initial assessment on Air Quality (AQ), more or less severe depending on the technology selected. Although the initial tests/analyses give an indication in terms of the role of these technologies to mitigate air pollutants when the whole value chain is considered, more robust Life-Cycle Analysis would need to be conducted to better inform the subject. At this stage, some initial findings worthy of noting:

a) Vegetable oils

a1) Non-algae

- General: At the moment, the effects of using vegetable oils as bio-feedstock to air pollutants emissions, seem to be better understood compared to other bio-feedstock routes examined in the assessment, mainly during the feedstock production and bio-fuels end-use products stages.
- Upstream / Final use: The examined literature reports variable changes on air pollutant emissions (and other environmental parameters) during the feedstock production and bio-fuels end-use product stages. The trend and the magnitude of the changes might differ among the pollutants.

  Most of the studies in the examined literature suggest that higher NH_3 and NO_x emissions are expected during the production of the vegetable oils, with possible associated increases of O_3 and acidification problems. This increases may reach up to 40% for NO_x as it is suggested from the literature. The production of vegetables oils may also result in changes to biogenic NMVOCs emissions, with a general trend for lower emissions (up to 55%), however, the type of crop grown will determine the trend and the magnitude of biogenic VOC emissions. In terms of PMs, variable changes are reported in the examined literature, ranging from -55% reduction to more than +100% increase. CO emissions are generally expected to be lower up to 30%, as suggested by the examined literature.

At the end-use product stage, most of the studies examined here suggest likely lower PM (up to 60%), NMVOCs (up to 7%), and CO emissions (up to 40%), while NO_x emissions are likely to be higher (up to 20%). However, it is mentioned in the examined literature that these changes depend on various factors (e.g., type of vegetable oil use for the bio-fuel, engine type, engine conditions, etc.) and that further work is needed to better quantify the magnitude as well as the trend of those changes.

- On-site: Further research is needed to complement the modelling work conducted by Concawe as described in the present report to assess the impact of vegetable oils when processed in the refining scheme defined in the Refinery 2050 (next steps of the work). In general, less utilisation of FCC and Coker is expected which we believe, will result in lower air pollutant emissions. However, none of the examined studies focuses on the associated air quality effects on that stage.

a2) Algae

- Upstream: Using algae as a bio-feedstock is believed to have positive environmental impacts during the production stage. However, none of the examined studies focus on specific air pollutants and further research is needed.
- On-site: The associated effects on Air Quality (AQ) during the refining process stage is uncertain based on the examined literature. Similar to vegetable oils, less utilisation of FCC and Coker is expected which we believe will result in lower air pollutants emissions. However, further research is needed.
- Final use: Variable changes on air pollutant emissions have been reported using bio-fuels from algae as end-use products. The trend and the magnitude of the changes might differ among the pollutants. From the literature examined in our review, higher NO_x emissions (up to 50%), and lower hydrocarbons (up to 60%) and PAHs (from 20% to 50%) have been reported using bio-fuels from algae as end-use products. In terms of PMs, PM mass emissions will probably decrease, while PM number emissions will increase. Based on the existing literature, both changes can reach up to 50%.

b) Gasification of biomass

- Upstream: The examined literature reports that the use of gasification of biomass as a bio-feedstock route might have a positive environmental impact during the feedstock production stage. A few studies for example, indicate that collection and use of straw as a feedstock will replace open field burning activities and probably reduce the associated emissions (e.g., Non-Methane Volatile Organic Compounds (NMVOCs), Elemental Carbon (EC), Particulate Matter (PMs). However, further research is needed to quantify the associated air quality effects.
- On-site: In the production stage of the bio-fuel, variable changes on air pollutant emissions have been reported in the examined literature. The trend and the magnitude of the changes might differ among the pollutants. The studies examined in our review, showed generally lower SO_2 and NO_x emissions, while Hydrogen Cyanide (HCN), H_2S, Polycyclic aromatic hydrocarbon (PAHs) will probably increase. Further work is needed to quantify the magnitude of these changes.
- Final use: Only two studies were found in our review that examine the effects of using GTL (gasification to liquids) fuels as end-use products to air pollutants emissions. Both studies examine GTL fuels produced in the same facility and report lower NO_x and PM emissions up to 40%. Other studies suggest generally lower emissions from biofuels produced via gasification as end-use products than those generated from coal-gasification, due to the inherently low sulphur and ash content of most biomass. None of them although, gives a direct comparison between biofuels from gasification of biomass and conventional fuels and their effects on air pollutants emissions. Further research is needed to quantify the magnitude of the changes.

c) Waste-Plastics

- Upstream: The waste-plastics bio-feedstock routes might have a positive impact on AQ during their production stage. However, none of the examined studies focus on specific air pollutants and further research is needed.
- On-site: In the production stage of the bio-fuel, the examined literature reports that changes in air pollutants emissions heavily depend on the conversion route chosen. A few studies for example, suggest that slow pyrolysis may produce elevated PAH, PMs, and NO_x emissions, while hydrothermal liquefaction of wastes could produce high NO_x emissions. On the contrary, pyrolysis using SCW (super critical water) system is expected to produce negligible amounts of NO_x, SO_x, and PMs. In general, most of the studies suggest possible negative impacts on air pollutant emissions although, it is suggested that further research is needed to quantify them in more accuracy.
- Final use: Variable changes on air pollutant emissions have been reported using bio-fuels from wastes and plastics as end-use products. The trend and the magnitude of the changes might differ among the pollutants. From the literature examined in our review, it was found that using bio-fuels from pyrolysis of waste plastic oil could result in higher NO_x (10-100%) and unburned HC (5-25%) emissions, and lower soot emissions (~50%). In addition, bio-fuels from HTL of waste plastics may lead to lower NOx emissions than diesel (e.g., -15% of NO_x emissions with HTL20 blend). HTL bio-fuels can be mainly used as transportation fuel for marine applications however, are less examined than those resulting from pyrolysis.

d) E-fuels

- Upstream: It was generally found in the literature that the feedstock production stage of e-fuels will possibly have positive environmental impacts. However, none of the examined studies focus on specific air pollutants and further research is needed.
- On-site: No information regarding the impacts on air pollutant emissions during the production stage of e-fuels was found in the literature and further research is needed. However, considering the structure and composition of e-fuels (less aromatics/ less heavy HC chains), we believe that e-fuels are expected to have lower emissions on-site.
- Final use: The studies examined in our review, generally suggest that using e-fuels as end-use products is expected to result in lower emissions. However, no information regarding the impact of using e-fuels as end-use products on specific air pollutants emissions was found in the literature. Further research would be needed.

The following graph summarises the main findings from the performed literature review regarding the effects of different bio-feedstock routes on AQ. Detailed information for each bio-feedstock route can be found in the Appendix 3. It should be noted that this analysis is indicative only and subject to change as further research becomes available.

Figure A2-2 Summary of findings of the effects of different bio-feedstock routes on AQ as reported in the examined literature (comparison vs conventional oil-based diesel).

APPENDIX 3 AIR QUALITY - LITERATURE REVIEW - DETAILS

A3.1 VEGETABLE OILS

Table A3-1 Summary information currently reported in the examined literature regarding the effects of using vegetable oils as bio-feedstock on air pollutant emissions.

	Feedstock Production - General Information	**Feedstock Production - Feedstock specific information** (Comparison with ULSD)	**Refining System**	**End-use products**	**Comments**
Vegetable Oils	- Potential land use changes - Potential increase of biomass burning emissions - Changes to biogenic VOCs (+/-). Heavility dependent on crop used. - Changes in soil deposition. - Changes in eutrophication - Increased use of fertilisers • Higher NOx, NH_3 emissions • Possible acidification problems • Possible increases of O_3 production • Higher N_2O emissions	**Canola** – N_2O: > +1000% – CO: Up to -17% – NMVOC: Up to -43% – NOx: Up to +37% – PM: Up to +135% **Palm Oil** – N_2O: > +1000% – CO: Up to -8% – NMVOC: Up to -55% – NOx: Up to +19% – PM: Up to -28% **Tallow** – N_2O: > +1000% – CO: Up to -5% – NMVOC: Up to -55% – NOx: Up to +6% – PM: Up to -30% **Cooking Oil** – N_2O: ~ 0% – CO: Up to -30% – NMVOC: Up to -55% – NOx: Up to +14% – PM: Up to -57%	– No study found to deal with the associated changes in air pollutant emissions at refinery level from the production of bio-fuels from vegetable oils. – In general, as less utilisation of FCC and Coker is expected, we feel that this will probably result in lower air pollutants emissions.	**General** – Variable changes – Likely Lower PM, NMVOCs, Benzene, PAHs, – Likely higher NOx – Changes depend on various parameters (feedstock type, engine type, engine conditions, etc.) **Feedstock Specific (Examples)** **Canola** – N_2O: Up to -6% – CO: Up to -36% – NMVOC: Up to -4% – NOx: Up to +17% – PM: Up to -58% **Palm Oil** – N_2O: Up to -6% – CO: Up to -36% – NMVOC: Up to -4% – NOx: Up to +19% – PM: -58% **Tallow** – N_2O: up to -6% – CO: up to -38% – NMVOC: up to -7% – NOx: up to +13% – PM: up to -59% **Cooking Oil** – N_2O: ~ 6% – CO: up to -38% – NMVOC: up to -7% – NOx: up to +13% – PM: up to -59%	– Changes in deposition, acidification not well quantified – Info for **“Feedstock production - Feedstock Specific”** has been taken from the report *“The greenhouse and air quality emissions of biodiesel blends in Australia”*. The different biodiesel were compared to ULSD – A summary of performance, combustion and emission characteristics of diesel engines fuelled with various biodiesel fuels and their blends can be found in Tamilselvan et al., 2017 (Table 3).

A3.2 ALGAE

Table A3-2 Summary information currently reported in the examined literature regarding the effects of using algae as bio-feedstock on air pollutant emissions.

	Feedstock Production	Refining System	End-use products	Comments
Algae	- In general, positive environmental impacts. - Algae grown has less impact on land-use for food production compared with grain and other lignocellulosic biomass. - No competition between food and energy uses. - Growth of microalgae can effectively remove phosphates and nitrates from wastewater.	– No study found to deal with the associated changes in air pollutant emissions at refinery level from the production of bio-fuels from algae. – In general, as less utilisation of FCC and Coker is expected, we feel that this will probably result in lower air pollutants emissions.	General – Lower PM mass emissions: up to 50%. – Higher PM number emissions: 25-50% – Lower HC: Up to 60% – Higher NOx: Up to 50% – Lower PAHs: 20-50%	– HTL bio-crude oil from algae (micro and macro) might be a potential promising pathway. – Although, HTL is at a very early stage of development. – A few studies have shown NOx reductions in the downstream. – Useful summary information in the following paper (see Table 6): Islam et al. 2017.

A3.3 GASIFICATION OF BIOMASS

Table A3-3 Summary information currently reported in the examined literature regarding the effects of using gasification of biomass as bio-feedstock on air pollutant emissions.

	Feedstock Production	Refining System	End-use products	Comments
Gasification of biomass (e.g. straw, wood, corn, pulp)	- Possible positive environmental impact E.g., collection and use of straw replaces open field burning and reduces the associated emissions. (changes in soil under debate)	– Co-gasification process: – lower SO_2, NOx emissions – Syngas may contain increased NH_3, HCN (NOx precursors), H_2S and HCL. – High ash concentrations. Large amounts of PAHs (especially when straw is used).	– Emissions from biofuels produced via gasification as end-use products are generally lower than those generated from coal-gasification, due to the inherently low sulphur and ash content of most biomass. – Lower PM: up to 40% – Lower NOx: up to 40%	– Only two studies assess the magnitude of the effects of using GTL fuels as end-use products on air pollutants emissions. Both studies use GTL fuels produced in the same facility. – No direct comparison between biofuels and conventional fuels in terms of AQ pollutants (as end-use products) was found in all other studies.

A3.4 WASTE-PLASTICS

Table A3-4 Summary information currently reported in the examined literature regarding the effects of using wasted-plastics as bio-feedstock on air pollutant emissions.

	Feedstock Production	Refining System	End-use products	Comments
Waste-Plastics	- Reduction of CH_4 emissions from landfills (due to utilization/conversion processes). - Reduction of Nitrogen and Phosphorous deposited in the soil and water. - Reduction of pollutants emitted during incineration.	– Slow Pyrolysis may produce emissions of PAHs, PMs, and NOx. – Pyrolysis using SCW (Super Critical Water) system produces negligible NOx, SOx, and PM emissions. – HTL in general, doesn't generate significant amounts of hazardous products of combustion such as NOx. – HTL bio-crude for garbage may have high levels of nitrogen. This may cause high NOx emissions from combustion. – It has been reported that further research is needed on that topic.	– Higher NOx (10-100%) and unburned HC (5-25%) emissions from pyrolysis waste plastic oil. – Lower Soot emissions from pyrolysis waste plastic oils (~50%). – HTL blends may lead to lower NOx emissions than diesel (-15% NOx with HTL20).	– It is mentioned that HTL is preferred over pyrolysis for processing feedstock with significant moisture content. – It has been also mentioned that HTL bio-crude is difficulty to be used as transportation fuel apart from marine applications. – However HTL is less examined than pyrolysis.

A3.5 E-FUELS

Table A3-5 Summary information currently reported in the examined literature regarding the effects of e-fuels on air pollutant emissions at the different stages.

	Feedstock Production	Refining System	End-use products	Comments
E-fuels	- Possible positive environmental impact.	– No study found to deal with the associated changes in air pollutant emissions at refinery level from the production of e-fuels – Considering the structure and composition of e-fuels (less aromatics/ less heavy HC chains), we feel that e-fuels are expected to have lower emissions on-site	– No direct comparison between e-fuels and conventional fuels in terms of AQ pollutants (as end-use products) was found in the literature. – It is only mentioned that emissions may be lower using e-fuels.	– It has been mentioned in several studies the need of further research on that topic.

APPENDIX 4 A LOOK INTO MID AND LONG TERM MAXIMUM POTENTIAL AVAILABILITY AND DEMAND FOR LOW CARBON FEEDSTOCKS/ FUELS IN EUROPE (2020-2050) – LITERATURE REVIEW

A4.1 INTRODUCTION. SCOPE

The EU Commission has recently published its long-term strategic vision in Europe: "*A Clean Planet for all*". Recognising that climate change represents an urgent threat to societies and the planet, the Commission sets the goal, in accordance with the 2015 Paris Agreement targets of keeping global warming well below 2°C above pre-industrial levels, and pursuing efforts to limit it to 1.5°C by 2050.

The EU transport sector accounts for nearly a quarter of the EU's greenhouse gas emissions and so reductions in emissions will be crucial to achieving these EU's goals. Such reductions can only be achieved if we look at the whole system. Within this context, technologies for the production of low fossil carbon fuels.

Sustainable biofuels, subject to the updated sustainability criteria currently proposed by the European Commission, are one of the main low fossil carbon liquid alternatives to petroleum based fuels for transport, as they are easily deployable using existing transport infrastructure.

The Renewable Energy Directive (RED), the Fuels Quality Directive (FQD) and the 'ILUC Directive' set out biofuels sustainability criteria for all biofuels produced or consumed in the EU to ensure that they are produced in a sustainable and environmentally friendly manner.

Current legislation (RED I and RED II) requires a 7% cap on the contribution of conventional biofuels, including biofuels produced from energy crops, to count towards the renewable energy directive targets regarding final consumption of energy in transport in 2020 and in 2030.

Secondly, the RED II directive (that entered into force on 24 December 2018) sets as a binding minimum a 0.5% target for advanced biofuels by 2021 and 3.5% by 2030. Thirdly, the directives harmonized the list of feedstocks (Annex IX) for the production of advanced biofuels across the EU. Those can be considered to count double (i.e. to be twice their energy content) in terms of their contribution towards the 2030 target of 14% for renewable energy in transport.

These directives require that biofuels produced in new installations—starting after 1 January 2021— emit at least 65 % fewer greenhouse gases than fossil fuels.

The Fuels Quality Directive allows gasoline fuels in Europe to contain up to 10% bio-derived oxygenates, usually in the form of ethanol, while diesel fuels can contain up to 7% fatty acid methyl ester, although other bio-derived components are also allowed.

This Appendix addresses the potential availability of low fossil carbon feedstocks and offers a look into different demand scenarios providing an outlook on biofuel potential for the 2020, 2030 and 2050 time-horizons in Europe and Worldwide covering the following scope:

- ✓ Current situation
- ✓ Potential Biomass availability for 2020, 2030 and 2050 time-horizons
- ✓ Potential Demand for the 2020, 2030 and 2050 time-horizons
- ✓ Technologies conversion routes and TRL
- ✓ Potential Production Costs for the 2020, 2030 and 2050 time-horizons
- ✓ Challenges: Barriers and potential enabling-conditions

It is based on a literature review process of some selected external sources and highlights the uncertainty associated with the maximum potential availability, heavily dependent on some key enabling framework conditions which would be required to unleash the full potential in Europe.

The main references are summarized below, each of them following a specific approach:

Table A4-1 Approach followed by each reference to develop their estimates

	Main references	**Main approach followed by the sources**
BIOFUELS[1]	SETIS	Based on renewable EU targets and installed capacity
	DG R&I Ecorys	Based considering extensive R&I efforts across agriculture, mobilization of resources and development of conversion technologies, and feedstock availability on what the agricultural/transport sectors can provide
	SGAB	Based on what the industry can deliver from the conversion facilities point of view, given the appropriate policy framework and financing structure
	IEA	Based on renewable EU targets and future demand scenarios
	IRENA	Based on assumptions about policies and biofuel availability and cost
	ICCT	Based on the availability of sustainable biomass
EFUELS[2]	AGORA	Based on importation from regions with cheap and full load hours electricity
	LBST and DENA	Based on demand scenarios competing with other technologies
	ICCT	Based on future electricity prices and financial parameters

Note: IEA and IRENA provides a worldwide scope meanwhile SETIS, Ecorys, SGAB, ICCT, AGORA and DENA focus on a European framework.

Most of the studies only cover the potential availability and demand for advanced sustainable biofuels, not assessing the 1G biofuel potential by 2030/2050.

[1] Biofuel references used in the study:
(1) **ICCT (2018).** https://www.theicct.org/blog/staff/bioenergy-solve-some-climate-problems-not-all-once
(2) **SETIS (2018).** SET Plan Implementation Plan. Action 8: Bionergy and Renewable Fuels for Sustainable Transport
(3) **DG R&I. Ecorys (2017).** Research and Innovation perspective of the mid-and long-term potential for advanced biofuels in Europe
(4) **SGAB (2017).** Sustainable Transport Forum. Building up the future
(5) **IEA (2017).** Technology Roadmap. Delivering Sustainable Bioenergy
(6) **IPIECA (2017).** GHG emissions and the cost of carbon abatement for light-duty road vehicles
(7) **IRENA (2016).** Innovation Outlook. Advanced Liquid Biofuels
(8) **ICCT (2016).** Beyond the Biofrontier: Balancing competing uses for the Biomass Resource
(9) **ENERGY BIOSCIENCES INSTITUTE (2014).** Biomass in the energy industry
(10) **CE (2011).** Energy Roadmap 2050
(11) **IEA (2011).** Technology Roadmap. Biofuels for transport http://www.ieabioenergy.com/wp-content/uploads/2013/10/IEA-Biofuel-Roadmap.pdf
(12) **Matthew S.Orosz, David Forney (2008).** A comparison of algae to biofuel conversion pathways for energy storage off-grid

[2] Efuels references used in the study:
- **Frontier Economics / AGORA (2018).** The Future cost of electricity-based synthetic fuels
- **LBST and DENA (2017).** The potential of electricity-based fuels for low-emission transport in the EU
- **ICCT (2018).** Decarbonization potential of electrofuels in the European Union

A4.2 POTENTIAL BIOMASS AVAILABILITY FOR 2020, 2030 AND 2050 TIME-HORIZONS

Potential biomass availability is analyzed worldwide and across Europe. Across Europe, it is split between the whole European bioenergy availability and that part allocated to the transport sector (as a subgroup of the bioenergy system). The whole bioenergy system covers all sectors, such as electricity, heat, chemical industry and transport; all these sectors compete for same biomass sustainable resources; therefore even maximizing sustainable bioenergy production, cross-sectorial competition is high.

a) Worldwide biomass availability

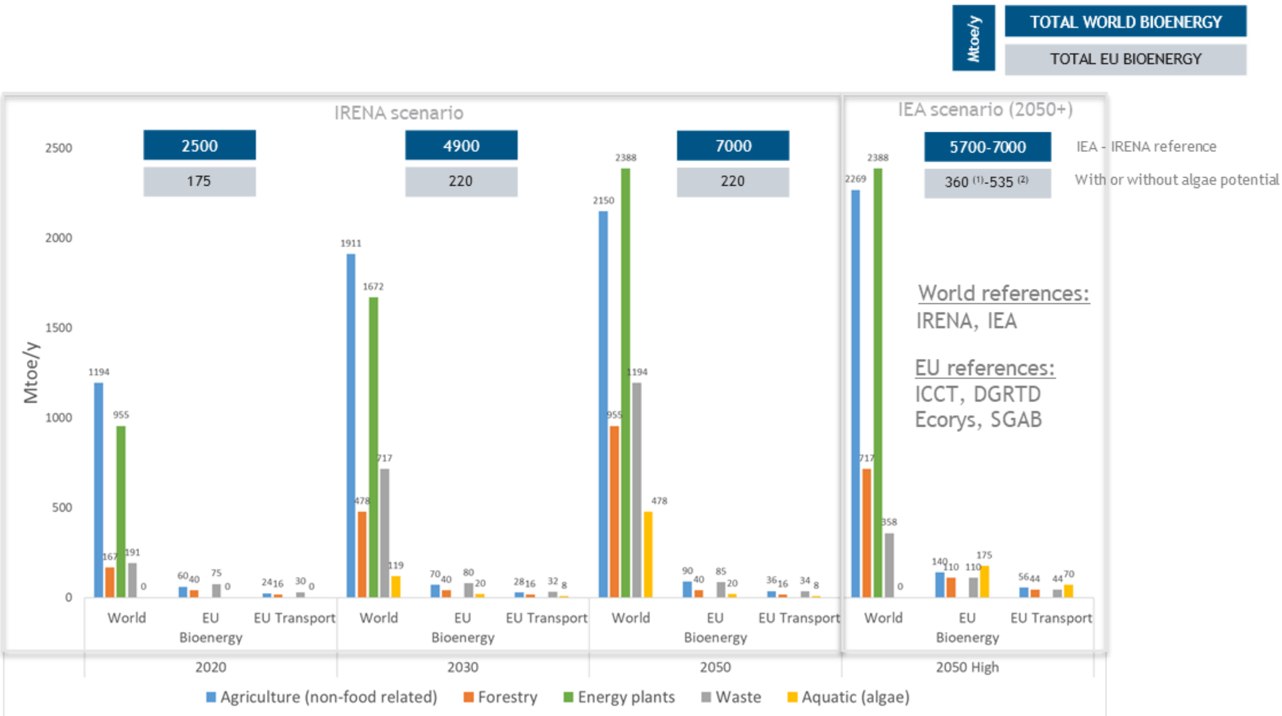
World sustainable biomass availability is generally expected to increase continuously from a total of **2500 Mtoe/a by 2020** (IRENA reference) **to 5700-7000 Mtoe/a by 2050 in the max scenario** (IEA-IRENA reference) mainly based on agricultural residues and energy crops (>70%).

IEA 2050+ scenario forecasts a lower potential availability as defined by IRENA in their 2050 base scenario, with the main difference being the envisaged potential for algae. Indeed, the potential deployment for algae is uncertain (mainly due to the current efficiencies and high cost). While several sources recognize algae in their 2050 scenario (e.g. According to IRENA, algae could reach 478 Mtoe/a by 2050), other sources such as IEA are more conservative in this regard and do not consider any relevant penetration of algae within the 2030-2050 timeframe.

Some references, such as ICCT[3], claim that there is not enough bioenergy to decarbonize all sectors together. They have a more conservative view, assuming that the maximum global amount of biomass that could be supplied for energy by 2050 is around 2150 Mtoe/a.

[3] *https://www.theicct.org/blog/staff/bioenergy-solve-some-climate-problems-not-all-once*

Figure A4-2 World Maximum Biomass Availability (2020-2050), Mtoe/year of biomass



(1) ICCT has a more conservative view, assuming that the maximum global biomass availability 2050 is around 2150 Mtoe/a.
(2) Biomass availability if the full potential for algae is realised

Source: Concawe own assessment based on data from IRENA and IEA for World Availability. ICCT, DGR&I Ecorys and SGAB for EU Availability. Note that the figure is expressed in Mtoe/a of biomass, not final energy demand

Note: Energy contents: (1 toe = 41,868 GJ)
Conversion factors[4] used by Concawe for comparison purposes (Simplified approach):

Agriculture residues energy content	0.56	toe / t
Forestry energy content	0.21	toe / t
Waste energy content	0.76	toe / t
Aquatic (algae) energy content	0.48	toe / t

b) European Biomass Availability

Zooming into European sustainable biomass availability, the whole of bioenergy system is estimated to grow **from 175 Mtoe/a (2020) to approximately ≈350-535 Mtoe/a by 2050.**

Biomass to satisfy the demand for bioenergy is expected to be 360 Mtoe/a according to DG R&I Ecorys. As 15 Mtoe/a should be imported, approximately ≈350 Mtoe/a could be the maximum biomass availability in Europe. In case of fully realised algae potential, biomass availability could increase from around ≈350 up to 535 Mtoe/a, although Ecorys do not consider the full potential for algae will be exploited because of its high cost.

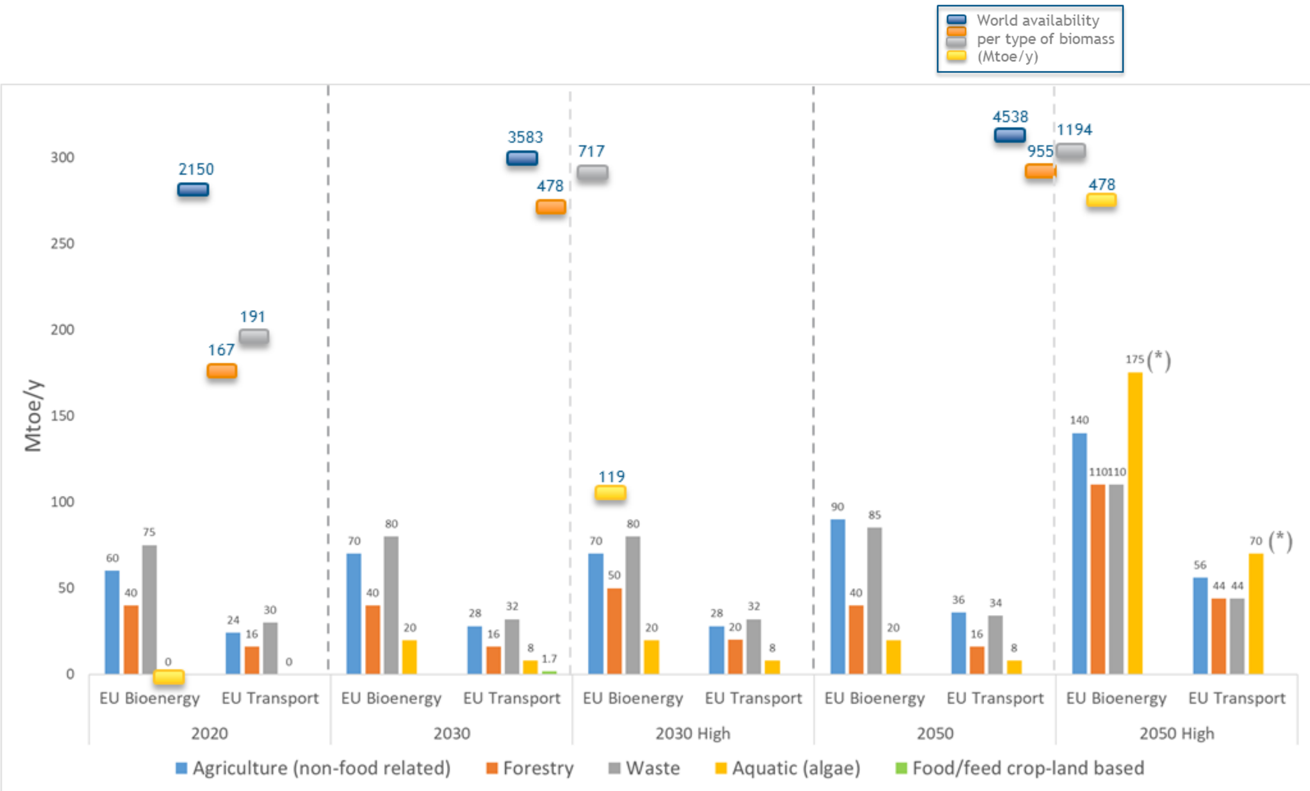
[4] *References: ENERGY BIOSCIENCES INSTITUTE (2014). Biomass in the energy industry*
Matthew S.Orosz, David Forney (2008). A comparison of algae to biofuel conversion pathways for energy storage off-grid

According to the EU Commission strategy "A Clean Planet for all", the production of bio-feedstock in Europe will be lower by 2050. Their estimates range from 210 to 320 Mtoe/a (majority coming from waste sector), and assume that most of the biomass used in the EU economy will be produced within Europe (imports of sustainable solid biomass are limited to 4% to 6% of the solid biomass used for bioenergy by 2050).

In the transport sector, different sources estimate that biomass availability contribution could range **from a total of 70 Mtoe/a(2020) to 140-210 Mtoe/a by 2050.**

Expressed in energy content, agricultural residues and wastes are expected to contribute more followed by forestry residues and algae.

Figure A4-3 European Biomass Availability (2020-2050), Mtoe/a of biomass



<u>Source:</u> Concawe own assessment based on data from IRENA and IEA for World Availability. DG R&I Ecorys for EU Availability (*) Algae uncertainty in 2050 High Ecorys scenario. High scenario considers high learning rates for all technologies.

<u>Notes:</u>

(1) For the purpose of this assessment, it is assumed that a percentage of 40% from total bioenergy could be allocated to transport (based on Ecorys demand scenarios).
(2) Energy contents: Same as previous figure.
(3) As a general reference, energy content of one hectare of miscanthus is 12 toe/ha
(4) ICCT provides a more conservative EU Availability by 2030 (only a total of 84 Mtoe/a for Bioenergy meanwhile SGAB provides a more optimistic view (350-400 Mtoe/a).
(5) IRENA worldwide values based on average data. High variability in extreme data (e.g. energy plants by 2050 could vary from 10 to 1000 EJ).

A4.3 POTENTIAL DEMAND FOR THE 2020, 2030 AND 2050 TIME-HORIZONS

The previous section assesses the maximum potential for R&I to enable secure, low-cost and sustainable biomass feedstock for energy (and transport sector). This following chapter, in contrast, focuses on the potential contribution of biofuels towards achieving the EU's ambitious climate change objectives from the perspective of what possible demand from different bioenergy sectors (demand scenarios).

The maximum potential usage (*demand*) for advanced biofuels in the EU, whilst limited by availability, is estimated to grow **from close to ≈ 0 Mtoe/a in 2015 to 70-140 Mtoe/a by 2050.**

According to the EU Commission strategy "A Clean Planet for all", advanced biofuels could represent a smaller contribution to transport sector by 2050 (up to 50 Mtoe/a). Power and industrial sectors would absorb most of the biomass (< 20% allocated to transport).

Based on resource availability and allocation across the whole European Bioenergy sectors, there could be a significant variability of potential demand according to different references. DG R&I Ecorys 2050 high scenario is significantly higher than the rest, followed by IEA.

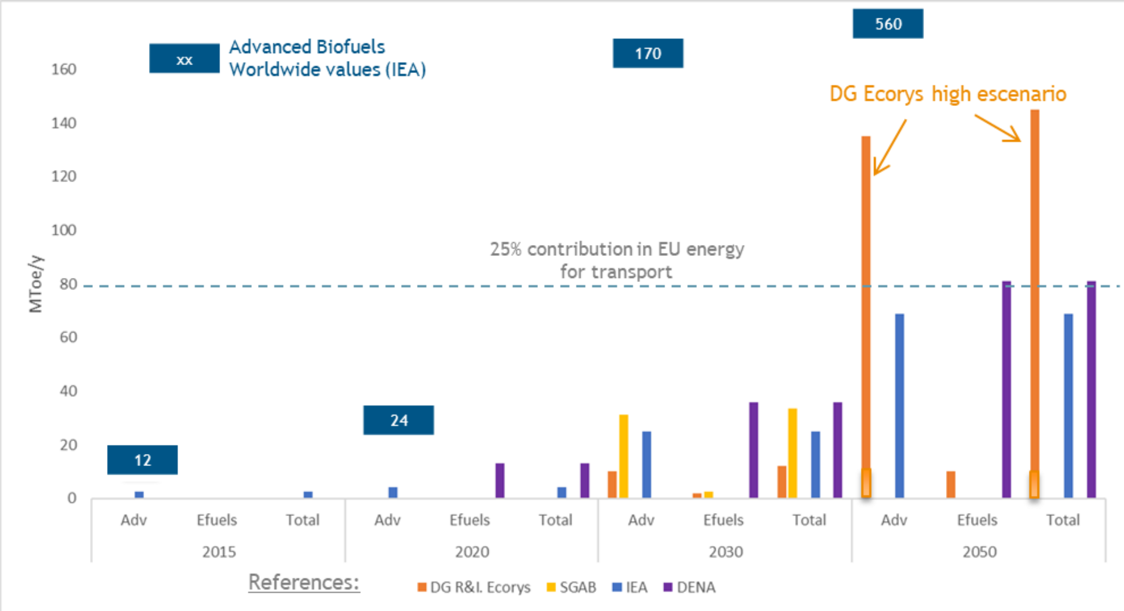
There is also a big variability regarding e-fuels. According to DENA reference, e-fuels play also a role by 2030 (36 Mtoe/a) and 2050 (80 Mtoe/a). However, DG R&I Ecorys has a more conservative view: they estimate a potential e-fuel production of 10 Mtoe/a (~10 Mt/a) by 2050 high scenario.

On the contrary, according to ICCT, e-fuels are not expected to play a role unless there is policy support.

According to the EU Commission strategy "A Clean Planet for all", e-fuels could represent from 0 to 71 Mtoe/a of the energy demand in transport in 2050, and it assumes they would all be produced within Europe.

The following chart summarizes these aspects comparing to the worldwide potential availability (in the most optimistic scenarios, European demand of advanced biofuels would be equivalent to 16% of what could become available in the rest of the world. Future demand scenarios out of Europe have not included in this comparison).

Figure A4-4 Maximum Potential Demand (2020-2050)



Source: IEA and IRENA for World Demand. DG R&D Ecorys, SGAB, IEA, ICCT and DENA for EU Demand

Note:

As a general reference, the energy content in a typical road tanker full of gasoline assumed as the conversion factor is 23 toe.

In 2050, wider and shorter orange columns refer to DG R&D Ecorys base scenario.

In 2030, IRENA worldwide value is 100 Mtoe/a (below IEA 170 Mtoe/a estimation), considering a LHV of 44MJ/kg (100% HVO/FT Diesel).

Ecorys highest projections see an increase, in terms of bio-energy consumption, by around 80% by 2050 compared to today.

DG R&I Ecorys study examines the **Research and Innovation** (R&I) **potential** for advanced biofuels, under future scenarios where EU targets are met.

They develop a base, medium and high scenario, assessed under assumptions of different R&I efforts levels. The key factors to release the whole potential in Europe are:

1) **Improvements in feedstock supply.** As an example,
   - **Yield increase** of conventional (food/feed) crops due to plant breeding. Plant Breeding aims to build up the resistance of crop varieties to biotic and abiotic stresses (drought, pests and diseases) as well as to increase residue to crop ratios (straw/grain ratio). This should result in absolute increase of main crop biomass and crop residues and potentially provide more space for growing energy crops (if demand for food/feed can be satisfied with less land);
   - Yield increase of dedicated energy crops from the development of hybrids of; development of more robust - stress resistant energy crops as a result of prebreeding and breeding activities; and domestication of new energy crop species.
   - Enhanced production by growing **dedicated energy crops** on un-used agricultural lands. Further expansion of energy crops on non-agricultural areas (marginal lands) is anticipated in the future. Expansion on marginal lands will be possible due to breeding efforts targeted to developing more robust plants, which are able to grow in less suitable conditions;
   - Effects of further development in **genetic research** are considered in the long term;
   - **Fertilisation** of forests growing on poor soils.

2) **Improvements in the efficiency of the whole biomass to biofuel process chain.** As an example,
   - Improved agricultural management practices (e.g. selection of varieties, crop rotation and intercropping, plant nutrition, water management, adoption of precision agriculture practices) to bridge the current gaps of yields among EU member states.
   - Improved harvesting practices and machinery (development of new equipment for both – conventional and dedicated energy crop harvesting, improving harvesting practices, development of precision farming);
   - Increased **mobilisation** of agricultural biomass by optimised supply chain logistics (mobilization of so far unexploited biomass by using cleaner, more efficient and more cost-effective technologies, technology transfer, streamlining biomass supply chains with existing practices, development of new supply chains for dedicated energy crops);
   - Trees are harvested more efficiently, which results in a reduction of harvest losses

3) **Decrease in conversion costs.**
   - As a result of improvements in the efficiency chain (mentioned before)

4) **High potential of algae**
   - Increased R&I efforts for the development of Photo-Bioreactor (PBR) systems;
   - Targeted R&I efforts on algae strains with high productivity rate and lipid content such as chorella
   - Adaption of harvesting methods that are commercially available for the food and feed sector such as flocculation, sedimentation, filtration as well as centrifugation to microalgae-to biofuel value chains;
   - R&I efforts on direct conversion of microalgae to biofuels via the HTL route at pilot scale
   - Increased R&I efforts in the field of aquaculture production of macroalgae while wild harvest of seaweeds is decreased;

5) **High learning rates for all technologies**
   - The learning rates represent the effect of R&I in the learning-by-doing mechanism which reduces the capital costs of the conversion technologies as capacity accumulates.

6) **Significant investments in advanced biofuels capacity**
   - To achieve the 2020 targets, the currently installed capacity for advanced biofuels must increase from 0,2 GW to close to 1,1 GW, at an estimated cost of € 4,5-5 billion. Advanced biofuels also have the potential to reach the 2030 and 2050 targets if capacity is increased to 30 GW in 2030 and to 250 GW in 2050.

7) **Substantial efforts and coordination between stakeholders**
   - Increased awareness and capacity of various actors involved in the biomass supply chain.

8) **R&I policies**
   - Targeted policies, for instance R&I for feedstock and conversion technology, are crucial to unlocking this potential. Such policies should also address the substantial investments needed for the market transition to large-scale advanced biofuels production, which could otherwise become the greatest threat for the development of advanced biofuels.

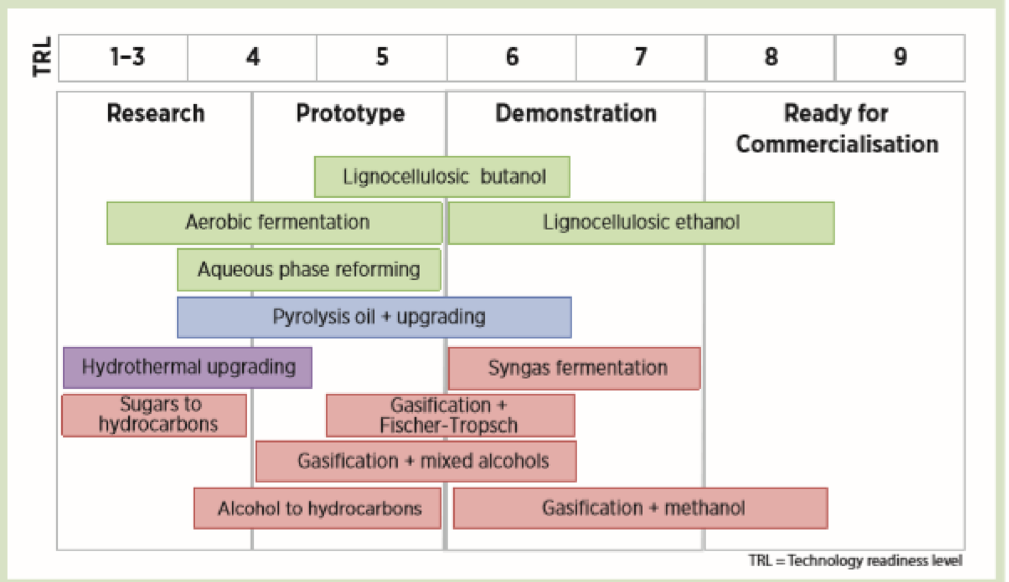
These policies may include efforts to attract foreign capital. Whereas most of the EU countries (apart from Finland, France, Germany, Italy, Poland, the Netherlands, Spain, Sweden, and the UK) do not yet produce advanced biofuels, they also have some future potential in sustainable feedstock and advanced biofuels production.

A4.4 TECHNOLOGIES CONVERSION ROUTES AND TECHNICAL READINESS LEVELS (TRL)

Currently, there are several conversion and upgrading technologies, with different technology readiness level (TRL), from research status (TRL 1) to commercialization (TRL 9).

A high level overview is shown in this section. Regarding different conversion technologies, feedstocks and TRL, different biofuels costs are expected.

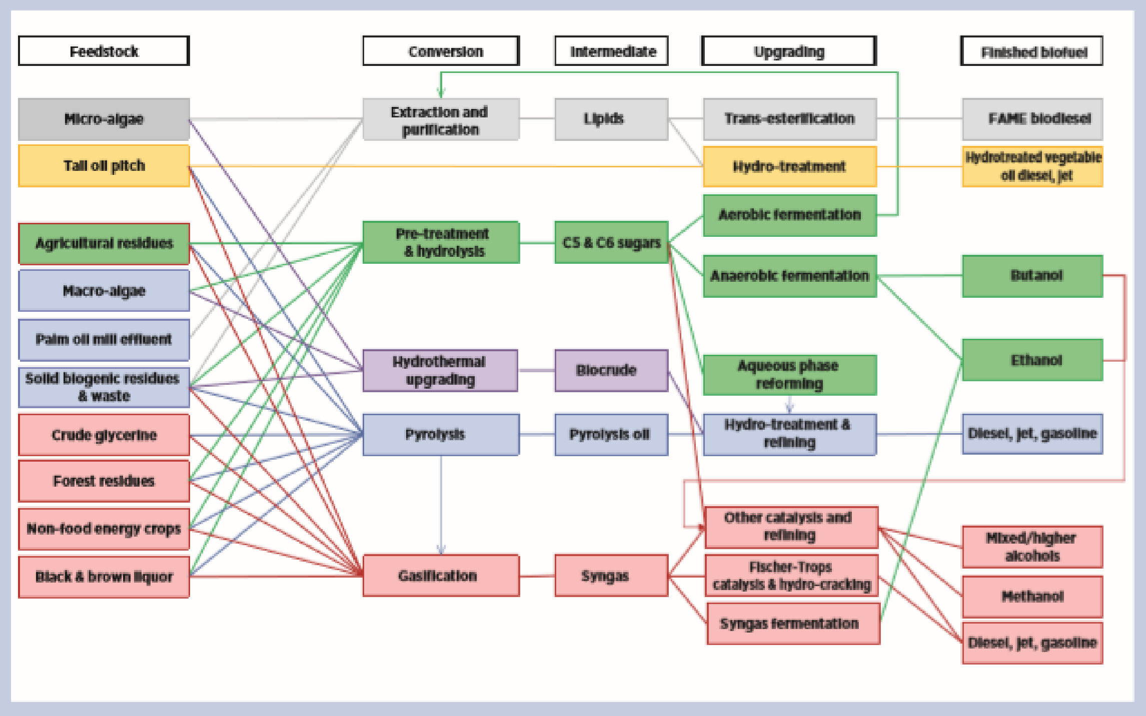
Figure A4-5 Commercialization status of advanced fuels conversion technologies



Note: Colours represent the principal conversion process, hydrolysis (green), pyrolysis (blue), hydrothermal upgrading (purple) and gasification (red).

Source: IRENA

Figure A4-6 Advanced biofuels pathways



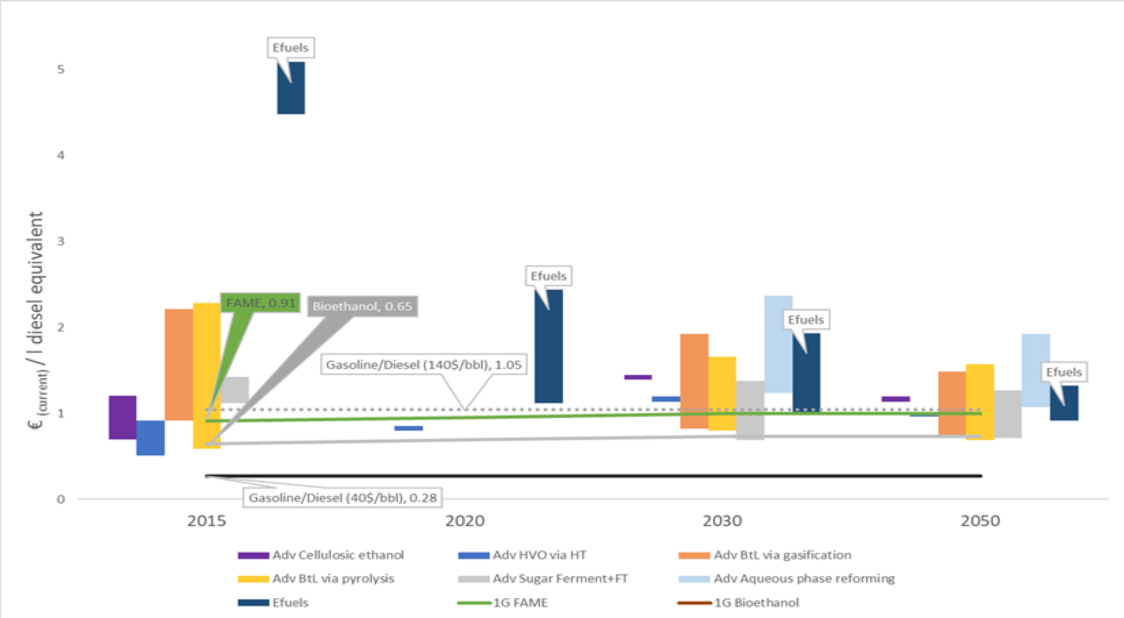
Source: IRENA

A4.5 POTENTIAL PRODUCTION COSTS FOR THE 2020, 2030 AND 2050 TIME-HORIZONS

Currenlty, production costs for advanced biofuels and e-fuels are prohibitively higher in comparision with the equivalent oil-based gasoline or diesel. Different references suggest there is significant potential for the production costs of both feed crop-land based biofuels and conventional gasoline/ to be reduce by 2050 (< 2 €/l diesel equivalent) with different levels of variability depending on the conversion technology used.

IRENA claims that based on potential improvements in conversion efficiency, capital cost reduction, scaling up, learning rates and efforts to reduce the costs of feedstock supply, the production costs for advanced biofuels could become competitive with fossil fuel at above around 100 $/bbl. At below 80 $/bbl, advanced biofuels pathways are very unlikely to be able to compete directly with gasoline and diesel over the next three decades unless very low or negative cost feedstocks are available.

Figure A4-7 Potential Production Costs (2015-2050)



References: DG R&D Ecorys, SGAB, IRENA, IEA, ICCT, IPIECA, CEFIC, DENA and Frontier Economics (AGORA)

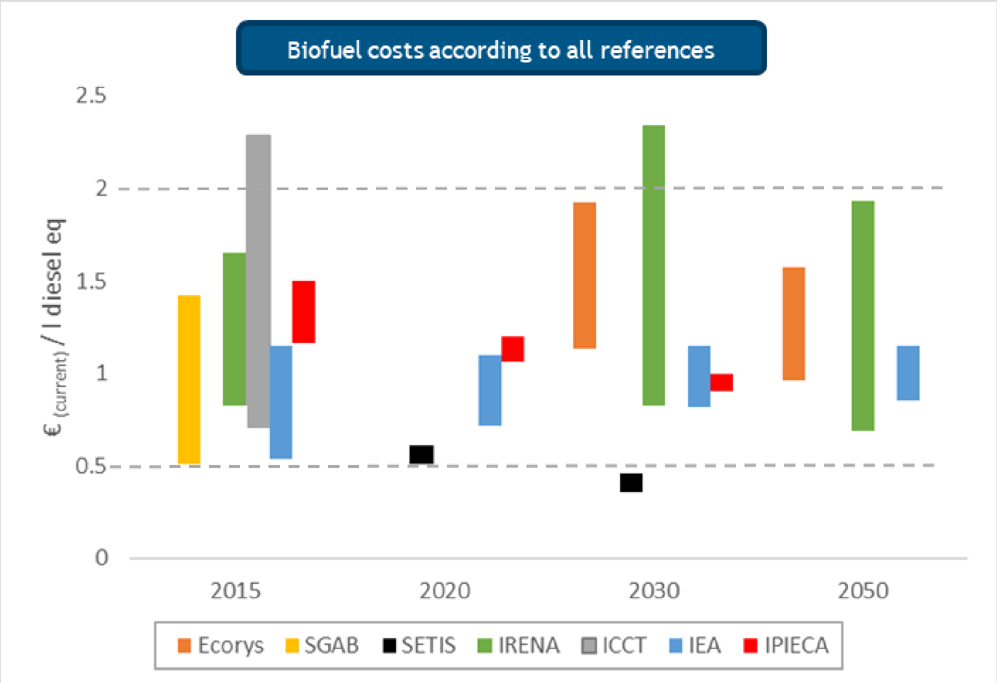
Key data: 1 toe = 41,868 GJ; Cost expressed as €/l of diesel equivalent: Diesel LHV: 44 MJ/kg: Diesel density: 0.832 kg/l. Gasoline/diesel production costs, reported without taxes

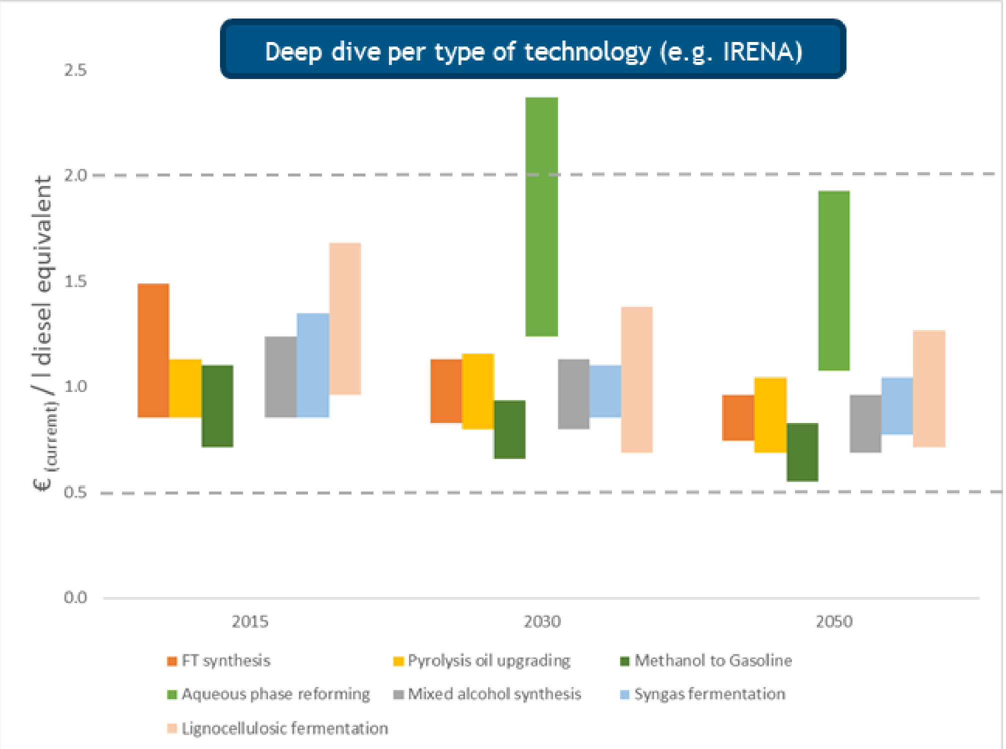
Note. Production costs of land based biofuels originating from feed crops (FAME and bioethanol) are expected to be in the same range as conventional gasoline or diesel when the crude oil price is around 100 $/, according to IEA.

A look into future costs associated with both feedstock prices and conversion technologies will follow showing the high uncertainty around the projections developed by the different sources consulted.

a) A look into different conversion processes and technologies

Figure A4-8 Potential Production Costs according to different references and technologies (2015-2050)





Source: DG R&D Ecorys, SGAB, SETIS, IRENA, IEA, ICCT, IPIECA
Key data: 1 toe = 41,868 GJ; Diesel LHV: 44 MJ/kg: Diesel density: 0.832 kg/l; Change $/€ $_{2014}$: 1.329

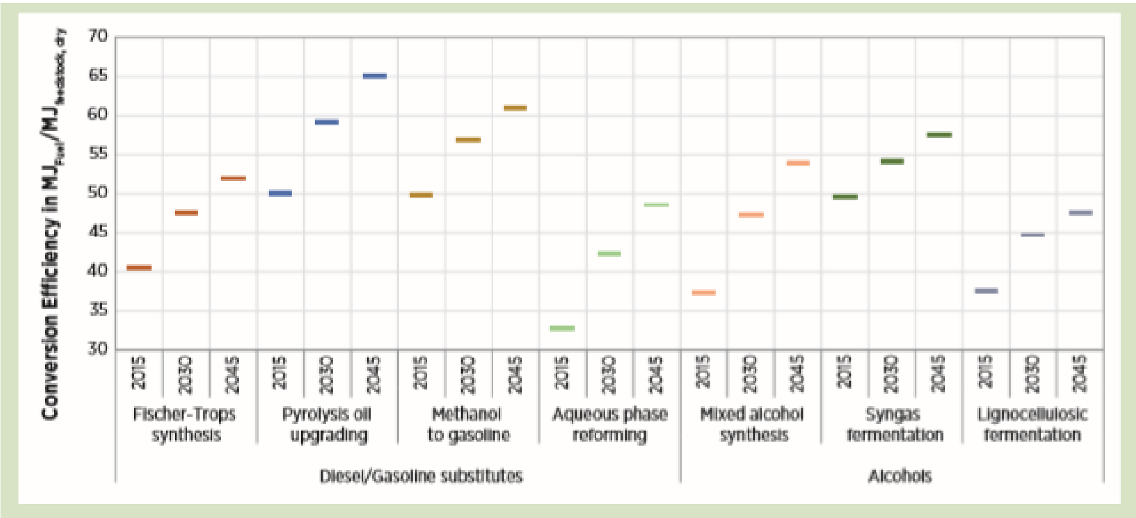
The average costs are expected to remain from 0,5 to 2 €/l diesel equivalent although the variability among different references define a quite uncertain future for the development of the technologies as they scale-up. Aqueous phase reforming biofuels costs are claimed to be higher than the average (max of 2,4 €/l by 2030 to 1,9 €/l by 2050, according to IRENA) and cost reduction and yield increase are the main challenges to become the technology available for their widely use in the transport sector.

According to IRENA, gasification (FT synthesis), pyrolysis pathways and methanol to gasoline show higher maximum theoretical conversion efficiencies when compared with other pathways. The majority of these pathways may still achieve significant improvements in overall conversion efficiency, with the exception of fermentation. This fact allows these technologies to achieve a potential lower production cost in the next decades.

Lignocellulosic fermentation and syngas fermentation pathways to ethanol are currently operating closer to their maximum theoretical yields. There is thus less scope to increase yields.

The following figure shows the forecasted process efficiencies improvement in the next decades

Figure A4-9 Comparison of process efficiencies



<u>*Source:*</u> IRENA

b) Biomass Supply Costs

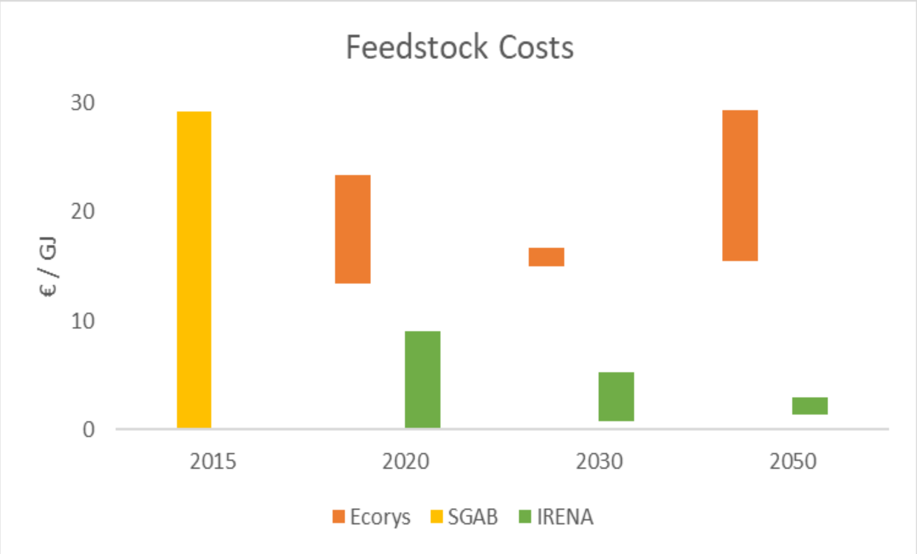
The forecast for biomass cost is one of the main uncertainties due to future competition for resources among different bioenergy sectors (including transport).

According to e.g. IRENA, the biomass cost ranges could potentially vary from -2 to 8 €/GJ depending on origin: Energy plants feedstock costs are claimed to be higher than waste, followed by agriculture residues and finally, forest residues.

Cost of biomass supply is expected to increase from 2020 to 2050 according to DG R&I Ecorys but expected to decrease according to IRENA.

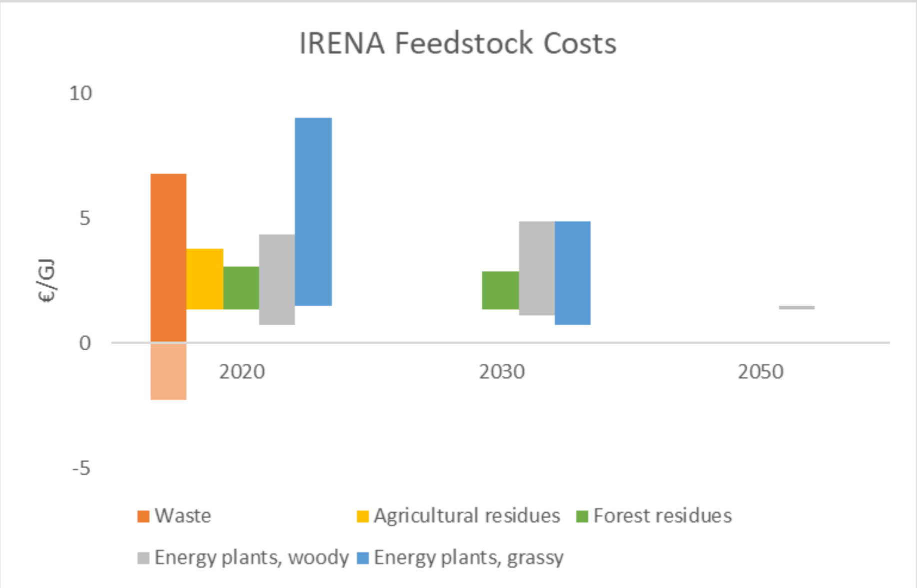
IRENA claims that feedstock accounts for 40-70% of production costs in most pathways, using typical wood or agricultural residue cost assumptions. As learning rates increase and efficiencies improve, the contribution of feedstock cost to the overall costs may increase over time. Reducing the feedstock supply cost is key to reducing production costs.

Figure A4-10 Biomass Supply Costs according different references (2015-2050)



Source: DG R&D Ecorys, SGAB, IRENA

Figure A4.11 Biomass Supply Costs according different sources, e.g. IRENA (2020-2050)



Source: IRENA

A4.6 CHALLENGES: BARRIERS AND POTENTIAL ENABLING-CONDITIONS

Some of the main challenges identified by several sources, including for example SETIS, to release the full potential of biofuels across all sectors are summarized below:

- Support for emerging technologies at low TRL to increase efficiency as well as continued R&I efforts in high TRL technologies to comply with reduced cost projections, GHG emissions goals and deployment.

  Currently, the main reasons behind the slow technology uptake are claimed to be:

  - High barriers to entry including long investment cycles, capital intensive nature, and high fuel certification standards;
  - High production costs compared to fossil fuels and conventional biofuels are one

- Support for sustainable feedstock mobilization is perceived as a key enabler to boost availability and minimize supply chain risks.

- Development of infrastructure and logistics across the whole value chain from the production step to the transport and conversion steps to produce the final standard fuel to end-use or intermediate customers.

- As widely covered in the present report, the transformation of the EU refining system and its develop as a hub for new feedstock supply chains, producing consistent, high quality low carbon fuels to end customers through its established distribution infrastructure is a critical enabler.

Environmental Science for European Refining

Concawe
Boulevard du Souverain 165
B-1160 Brussels
Belgium

Tel: +32-2-566 91 60
Fax: +32-2-566 91 81
e-mail: info@concawe.eu
http://www.concawe.eu

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