# Business cases

## Case studies on potentially attractive opportunities for bio-based chemicals in Europe

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Consortium:

DECHEMA Gesellschaft für Chemische Technik und Biotechnologie e.V. | btg biomass technology group | E4tech Strategy | Energy | Sustainability | nova Institute for Ecology and Innovation

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# Executive Summary

This report provides an analysis of **nine potentially attractive business opportunities ("sweet spots")** for the European bio-biobased industry. The "sweet spots" have been chosen by analysing the current landscape of bio-based chemicals and those that have reached an advanced development stage, and hence may represent a **potential business opportunity for the European chemical industry** (more details in an upcoming Deliverable). The selected "sweet spots" cover a range of biogenic feedstocks and represent different categories of bio-based chemicals.

| **Bio-based chemicals categories** | **Feedstock** | | |
|---|---|---|---|
| | Sugar/Starch | Vegetable oil | Syngas & other |
| Drop-in | | **Ethylene** | **Methanol** |
| Smart drop-in | **1,4-Butanediol** | | |
| Dedicated | **PHA, Lactic acid, PEF, Furfural*** | **Dodecanedioic Acid, Glycerol** | |

* C5 sugars

The case studies were analysed using an in-depth assessment of the value chains, markets, potential and barriers of nine potentially attractive opportunities compared to their fossil-based equivalents.

The analyses show that there are a number of potentially viable opportunities to replace fossil with bio-based chemicals. **Cost competitiveness**, **sustainability impact** and **advanced functionality** are the *key factors* in determining the displacement of fossil derived chemicals.

The focus of future development will be on the production of bio-based chemicals from cheaper and more sustainable feedstock, economically viable commercial scale production and new and innovative products which outperform traditional fossil-based products.

The bio-based chemicals business case studies will be useful in informing and illustrating the 2030 target of the European bio-based industry Roadmap and its related opportunities and barriers.

# Approach to selecting "sweet spots" for business case studies

A sweet spot in RoadToBio is defined as an attractive business opportunity. Nine sweet spots were selected by analysing a long list of bio-based chemicals across  the product groups: Adhesives, Agrochemicals, Cosmetics, Lubricants, Man-made fibres, Paints/Coatings/Dyes, Plastics/Polymers, Solvents and Surfactants. The bio-based opportunities have been ranked by evaluating the **market potential criteria** (market volume, market price and market growth) and **ease of implementation** which is measured by the TRLs of bio-based chemicals.

The sweet spots for business cases have then been chosen from the top of the list of the ranked bio-based opportunities  by taking into consideration:

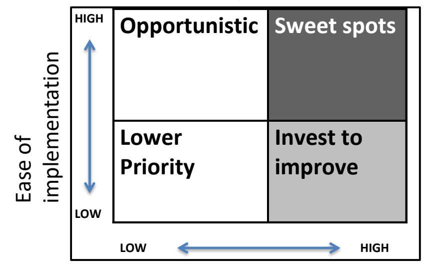
a. Priorities of the chemical industry when selecting the business cases
b. Representation of each of the three classifications of bio-based chemicals (drop-in, smart drop-in, and dedicated chemicals)
c. Representation of different product groups

In this way, the selected  sweet spots will represent a wide variety of bio-based chemicals which will provide learnings and inform the Roadmap about opportunities and issues of different types of bio-based within different product groups.

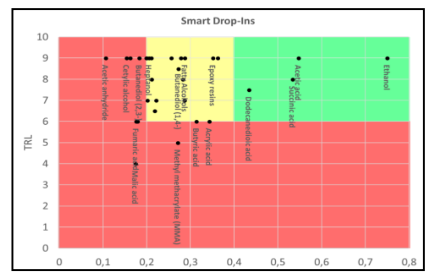
You will find a detailed description of the approach in the upcoming Deliverable on the methodology of RoadToBio.

Analysis of the bio-based opportunities for the chemical industry
[Del 1.1]

Ranking for `market potential´ and `ease of implementation´




Creating and ranking long list
For each kind of chemical group
→ **Sweet spots**




Priorities of the chemical industry for selection of business cases

| Criteria |
|---|
| Improvement in resource efficiency |
| Bio-based product has improved functionality |
| High margin can be obtained |
| Low risk for political or ethical disputes |
| Savings in GHG emissions |
| Availability of biomass in the EU |
| Decrease in use of toxic /harmful substances |
| Potential for green premium |
| EU has competitive advantages |

Workshop 02.07.17
Phone interviews

| Product group | Feedstock | | |
|---|---|---|---|
| | Sugar/Starch | Vegetable oil | Rest streams/other |
| Platform chemical | Lactic acid<br>1,4-Butanediol | Ethylene<br>Glycerol | Furfural<br>Methanol |
| Solvent | | | |
| Adhesive | | | |
| Agrochemical | | | |
| Lubricant | | | |
| Plastic | PEF | | PHA |
| Man-made fiber | | | |
| Coatings | | Dodecanedioic Acid | |
| Surfactant | | | |

Dedicated, Drop-in, Smart drop-in

9 business case studies

Workshop 19.06.18

# Contents

# 1. Introduction

**1. About RoadToBio**

This report was prepared as part of RoadToBio, a European Union funded project to explore the opportunities to increase the share of bio-based chemicals in the European chemicals industry. The project will deliver a roadmap and an action plan to exploit "sweet spots" (potentially attractive business opportunities) for Europe's chemical industry in the bioeconomy space from present day to 2030.[1]

The roadmap developed in RoadToBio will be based on an analysis of the most promising opportunities for the chemical industry to increase its bio-based portfolio as well as the technological, commercial, regulatory and public acceptance barriers to these opportunities. The roadmap will include an action plan and engagement guide to support the sustainable growth of the sector.

**2. Goal and scope of this report**

This report presents the business case studies for nine potentially attractive opportunities that were identified during the course of the RoadToBio project. These opportunities are spread over **three groups of chemicals** (defined on subsequent pages), namely:

- Drop-in chemicals
- Smart drop-in chemicals
- Dedicated chemicals

**Notes:**
1. More information about the project, its goals and plans, and how you can contribute to this roadmap for the chemical industry can be found on www.RoadToBio.eu

Horizon 2020
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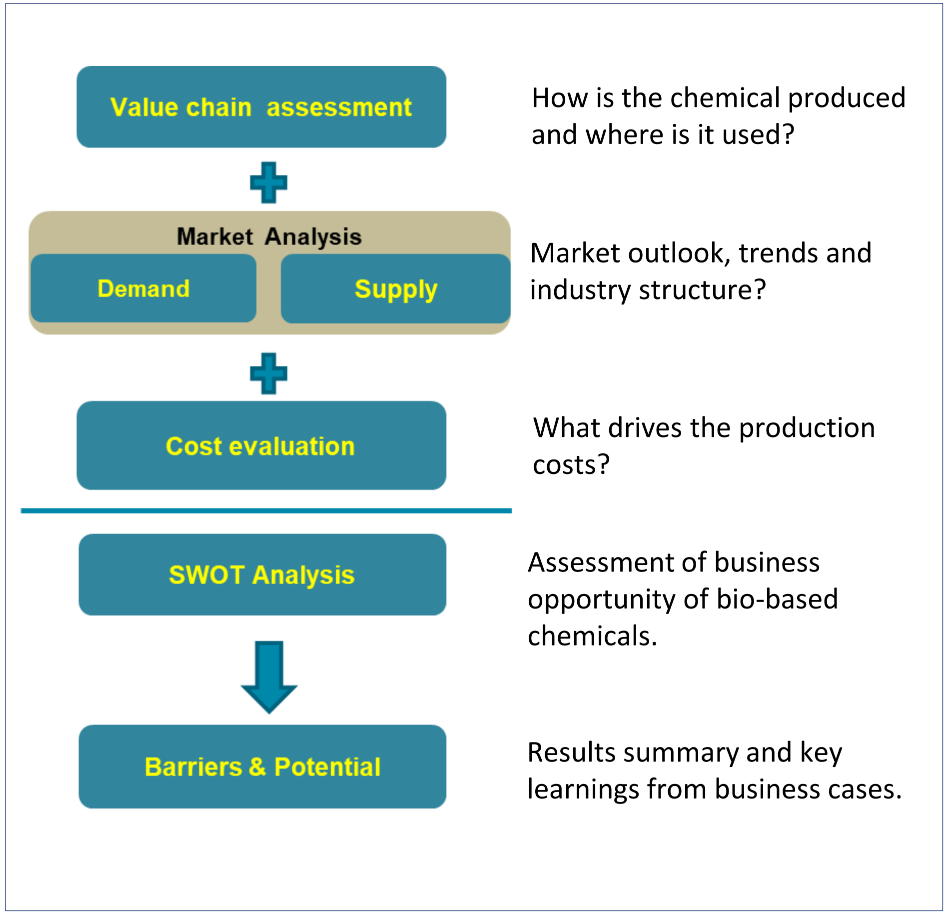
# 2. Framework for developing business case studies

The main objective of this task is to identify representative opportunities and barriers associated with potentially attractive bio-based chemicals across different product groups. The analysis of nine case studies was completed in three stages:

**Stage 1. Development of case studies:** for the nine "sweet spots" key information about the bio-based chemicals value chains, markets (supply & demand) and production costs was collected, analysed and benchmarked against the fossil equivalents.

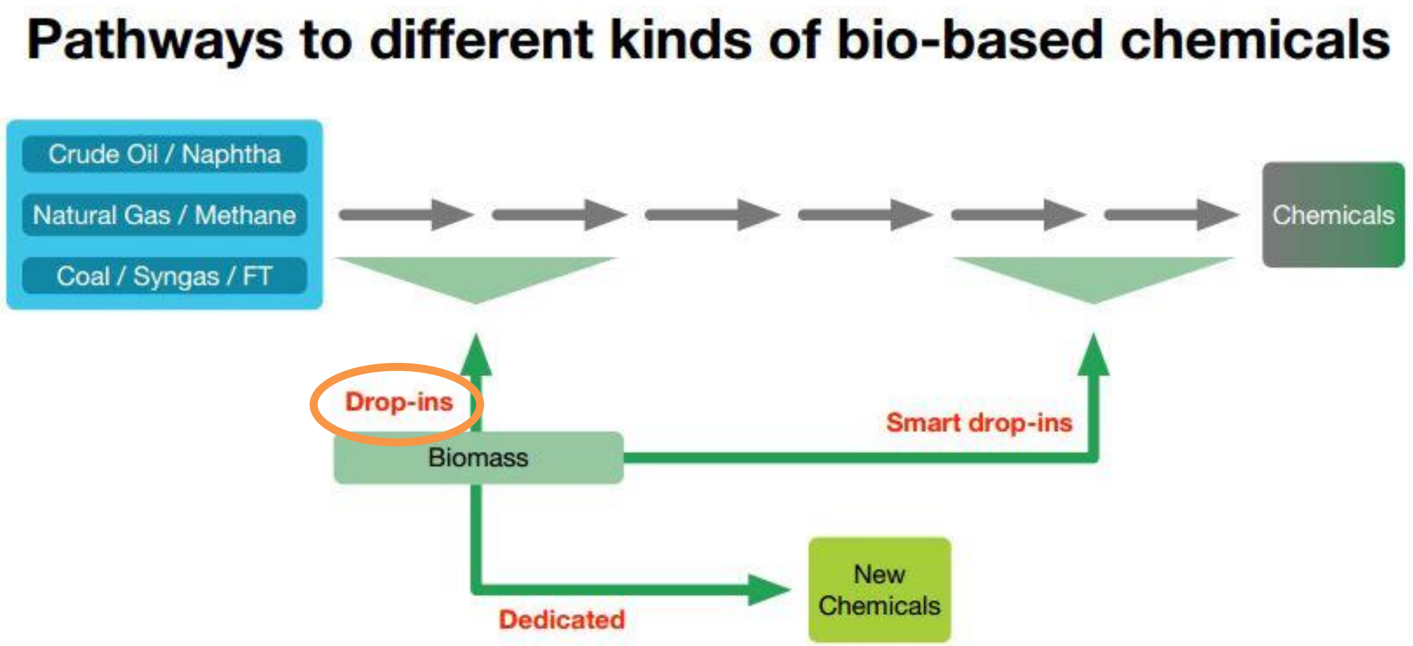
**Stage 2. SWOT analysis:** the strength of the opportunity for the nine case studies was illustrated by a SWOT analysis, which was discussed with industry stakeholders at a dedicated workshop organized by the RoadToBio consortium.

**Stage 3. Analysis of potential and barriers:** the results of the case studies have been summarized into opportunities and issues. Learnings from these opportunities and issues will provide valuable input for the 2030 RoadToBio roadmap and action plan for the European bio-based industry.



# 3. Drop-in chemicals

Bio-based drop-in chemicals are bio-based versions of existing petrochemicals that already have established markets. They are chemically identical to existing fossil-based chemicals and are produced using a similar pathway.[1]



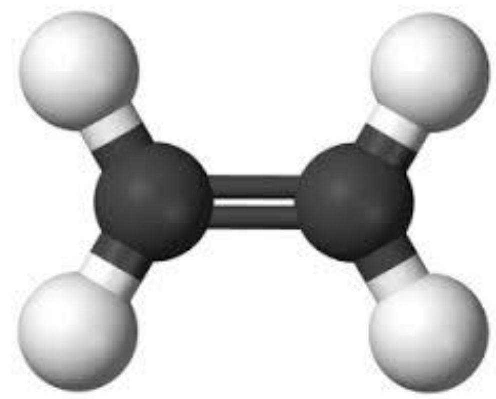

Business case studies for the following drop-in chemicals are presented in this report:

1. Ethylene
2. Methanol

**Notes:**
1. Carus et al. (2017). Bio-based drop-in, smart drop-in and dedicated chemicals https://www.roadtobio.eu/uploads/publications/articles/17-12-18-RoadToBio-Drop-in-paper.pdf

# 3.1 Ethylene

**Ethylene** or ethene is a hydrocarbon that belongs to the family of alkenes (olefins), being the most simple one ($CH_2=CH_2$). Ethylene is one of the basic organic chemicals serving as feedstock for a number of downstream chemical products. With a current global production exceeding 150 million tonnes per year, it is by far the largest bulk chemical used for the production of around half of the plastics. It is used for direct or indirect production of most important synthetic polymers, including high- and low-density polyethylene (HDPE and LDPE), polyvinyl chloride (PVC), polystyrene (PS) and polyethylene terephthalate (PET).

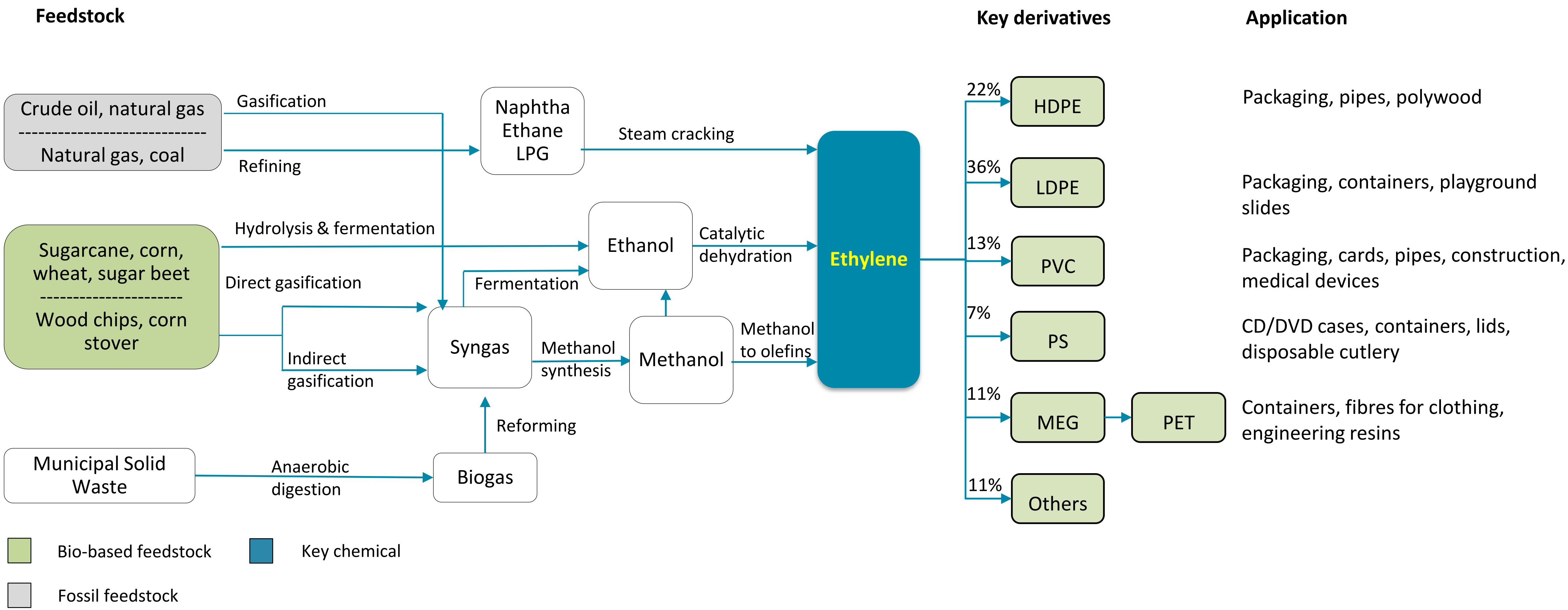


Today, almost all ethylene is produced from petroleum derivatives, including naphtha (mostly Europe and Asia), ethane and, to a lesser extent, propane and butane in the Middle East and North America. However, increasing concerns over greenhouse gas (GHG) emissions have now focused the attention on renewable feedstocks for bio-ethylene production.

The first step in bio-ethylene production is the production of bio-ethanol, by the fermentation of a variety of sucrose, starchy and lignocellulosic biomass, followed by the use of commercially available or demonstrated technologies such as catalytic dehydration of ethanol or methanol-to-olefins. In Brazil, the availability of low-cost sugarcane and bio-ethanol production has led to investments in facilities for production of bio-ethylene and its downstream products (e.g. bio-PE) [11].

The potential for bio-ethylene production is large, but its implementation will depend on the future availability and price of the biomass feedstocks, which are linked to developments in food demand and the use of biomass for other industrial uses.

# Value chain



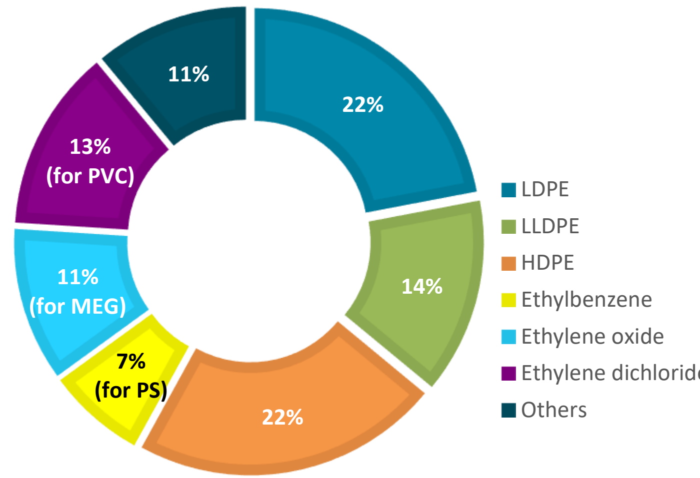
Feedstock
Key derivatives
Application
Crude oil, natural gas
Natural gas, coal
Gasification
Refining
Naphtha
Ethane
LPG
Steam cracking
Sugarcane, corn, wheat, sugar beet
Wood chips, corn stover
Hydrolysis & fermentation
Direct gasification
Indirect gasification
Fermentation
Ethanol
Catalytic dehydration
Syngas
Methanol synthesis
Methanol
Methanol to olefins
Reforming
Municipal Solid Waste
Anaerobic digestion
Biogas
Ethylene
22%
HDPE
36%
LDPE
13%
PVC
7%
PS
11%
MEG
PET
11%
Others
Packaging, pipes, polywood
Packaging, containers, playground slides
Packaging, cards, pipes, construction, medical devices
CD/DVD cases, containers, lids, disposable cutlery
Containers, fibres for clothing, engineering resins
Bio-based feedstock
Key chemical
Fossil feedstock

# Demand

The current annual global production volume of ethylene is about 150 million tonnes, of which about 21 million tonnes is produced in Europe. The global demand for ethylene is forecast to grow at a 1.05% rate (2016-2030). Growth in world ethylene consumption will be driven by growth in the use of polyethylene for consumables; ethylene oxide/glycol for polyethylene (PET), resins for polyester fibre, bottles and other packaging; and ethylene dichloride for PVC uses in construction and pipes. Together, these end uses represent about 72% of world ethylene consumption.

The most important regions in terms of ethylene consumption are Asia (40%) and America (30%). Western Europe is expected to consume and produce less ethylene in the next five years, as the regional markets are mature and the production is based on less-economic feedstock (naphtha), making it increasingly difficult to compete in the global ethylene derivative export market [5].

**Ethylene consumption by derivatives in EU-15* (2016)**

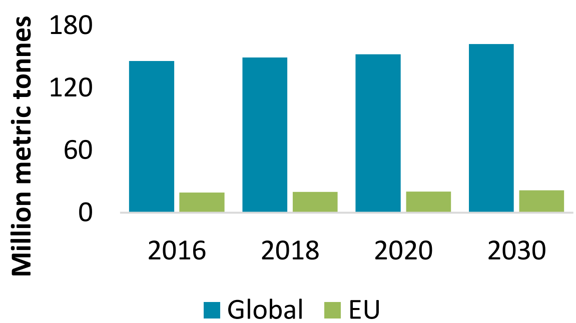



*EU-15 + Norway + Turkey

Others: ethanol, acetaldehyde, ethylene propylene diene monomer (EPDM), ethylene-vinyl acetate (EVA), vinyl acetate monomer (VAM) and other derivatives

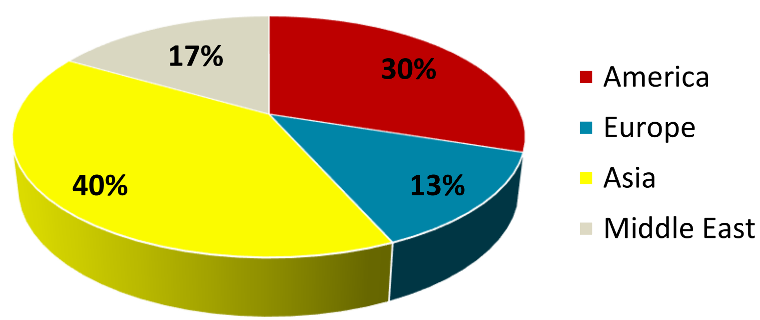
Based on ref. [4]

**Market Volume**




Based on ref. [4 and 5]

**Regional Demand (2016)**




Based on ref. [5]

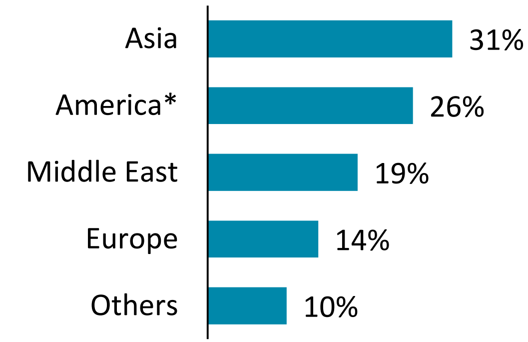
# Supply

Global production of ethylene in 2016 was dominated by fossil feedstock with naphtha making up the highest share (>42%). Asia leads global ethylene production (31%), while 14% of the supply is Europe based.

Industrial plants based on ethanol dehydration have been developed by different companies and technology providers, including Braskem, Chematur, British Petroleum (BP), Dow, and Axens-Total-IFPEN. There are commercial facilities producing bio-ethylene located in Brazil and also several production plants are under construction or planned (*e.g.* in China). Since 2010, **Braskem (Brazil)**, the largest bio-ethylene producer, produces about **200 kta** of ethylene from sugar-cane-based feedstock in an ethanol-to-ethylene plant [1]. There is no commercial bio-ethylene production in Europe [3].

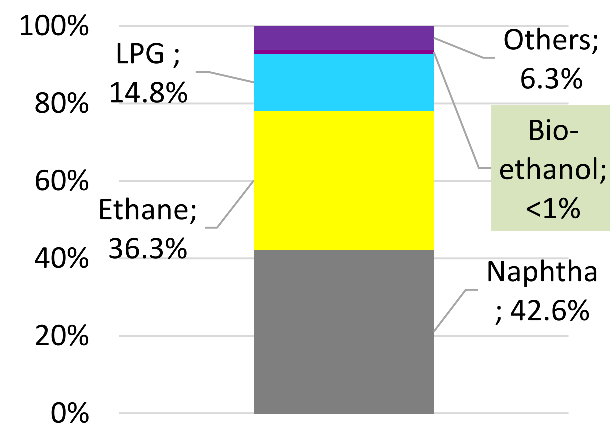
**Neste (Finland)/IKEA** recently announced a partnership to deliver renewable bio-based plastics. The announcement specifies that bio-based plastics will be compatible with existing recycling streams, which implies they are looking for **drop-in products** to replace oil derived polyethylene (PE) and polypropylene (PP). Neste's source of bio-based feedstock are by-products from the biodiesel production from waste oils and fats at their refineries in Finland and elsewhere, which can be fed to an existing cracker together with fossil oil derived feedstock which is processed at the same time. However, crackers and polymerisation reactors are built at large scale and so the bio-feedstock is diluted with fossil oil derived feedstock based on hydrocarbon (*e.g.* naphtha) cracking method, which is processed at the same time. Further dilution occurs in the polymerisation reactor so any batch of PE or PP has a very low bio-based content [13].

**Global supply of ethylene (2016)**




* Including < 1% Bio-ethylene from Braskem
Based on ref. [5]

**Ethylene global production by feedstock (2016)**




Others = Coal , shale gas

# Cost and environmental performance

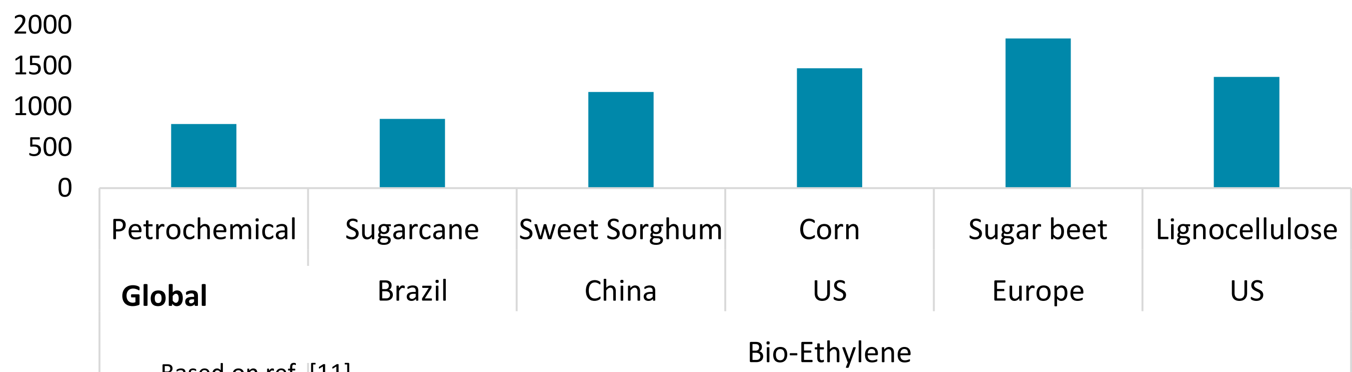
For bio-ethylene, bio-ethanol accounts for almost 90% of the production costs. Consequently, the region of ethanol production and feedstock source dictate total production costs. The acid-catalysed dehydration of ethanol has become attractive because of the large volume of sugarcane and corn bio-ethanol produced.

In Brazil, the availability of low-cost, low direct GHG emissions sugarcane-driven bio-ethanol has led to investments in facilities for production of bio-ethylene (bio-PE) and its downstream products.

The current production cost of bio-ethylene (sugar-cane case) is ∼ 1650 €/kg which is between 1.1 and 2.3 times higher than the global average petrochemical ethylene cost of production. In the EU, this gap would be bigger but lignocellulosic bio-ethylene could reduce the gap.

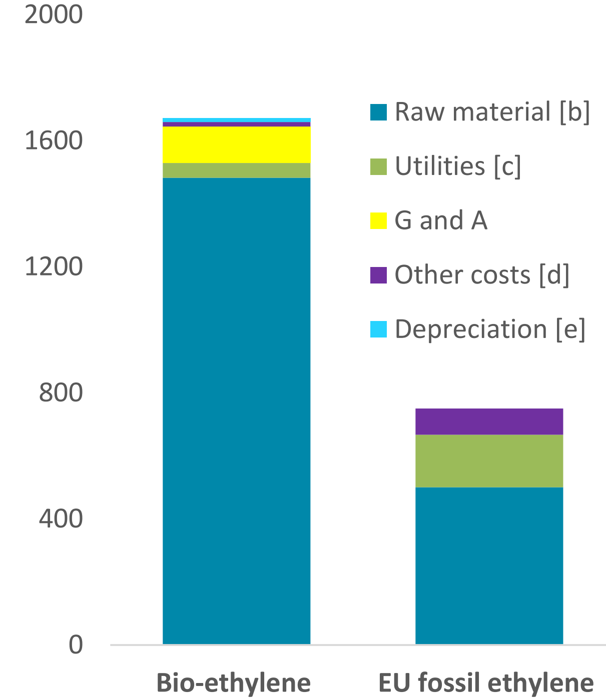
Producing bio-based ethylene from sugarcane is estimated to use 60% less energy compared to the fossil-based method (crude oil > naphtha > ethylene)[11] because of the integrated heat- and power-generation in burning bagasse. GHG emissions are also cut by 40%.

**Cost of production per feedstock (2009)**




Based on ref. [11]

**Production costs, Euro/tonne[a]**




[a] Years 2014-2015; [b] Bio-ethanol for bio-ethylene (estimated for EU) and naphtha for fossil ethylene; [c] Heat, steam, electricity; [d] Labour, maintenance, plant overhead. NOTE: for fossil ethylene depreciation is also included in other costs; [e] Estimated as 5% of the capital costs (20 years operating plant)

Based on ref. [14, 15]

# SWOT analysis

| Strengths | Weaknesses |
| --- | --- |
| • Large market volume<br>• High GHG emission saving compared to fossil ethylene<br>• Less energy demand compared to fossil ethylene<br>• Bio-ethanol catalytic dehydration technology commercially available and competitive | • Price gap with fossil ethylene<br>• The Brazilian production conditions (from sugarcane) are difficult to replicate in EU, making the EU uncompetitive |
| **Threats** | **Opportunities** |
| • Bio-ethanol used for bio-ethylene will compete with fuel sector<br>• Strong competition with fossil ethylene from shale gas feedstock<br>• Fossil fuel subsidies<br>• Low biomass availability in EU | • $CO_2$-tax and other policy measures<br>• Development of bio-ethanol production from lignocellulosic feedstock<br>• Global bio-based polymer production is expected to grow at 4% by 2022, which could drive the production of bio-ethylene |

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# Potential and Barriers

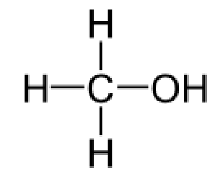
| Opportunities | Issues |
| --- | --- |
| **Techno-economic factors**<br>• Bio-based ethylene is easily produced by catalytic dehydration of bio-ethanol which has become increasingly efficient and competitive. Nowadays, 90% of the ethanol on the market is biomass-derived.<br>• Bio-ethylene from sugarcane-based bioethanol appears to be the most cost-competitive. In Brazil and US ethanol costs have come down significantly and this trend is expected to continue with increasing yields.<br>• Bio-ethylene production from ethanol *via* indirect synthesis from syngas could be an option, especially carbon capture and storage is considered. | **Techno-economic factors**<br>• Bio-ethylene is still more costly than fossil-based ethylene, particularly in light of the cheap feedstock opportunities presented by shale gas developments in the United States.<br>• The Brazilian production conditions (from sugarcane) are difficult to replicate in other areas. For example, production of sugars from starchy feedstock large enough to supply bio-ethanol for large scale bio-ethylene production is difficult to obtain in other areas.<br>• There is still no commercial process producing ethylene from second generation feedstocks. |
| **Environmental factors**<br>• Producing bio-based ethylene from sugarcane is estimated to use 60% less energy compared to the fossil-based method because of the integrated heat- and power-generation in burning bagasse. GHG emissions are also cut by 40%.<br>• Lignocellulosic biomass, if cheap and competitive, could enlarge the feedstock availability with minor impact on food production. | **Environmental factors**<br>• Careful consideration of sustainability of biomass feedstocks used |

# Potential and Barriers *(continued)*

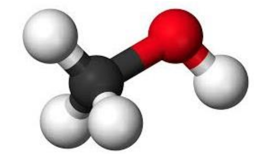
| Opportunities | Issues |
|---|---|
| **Market factors**<br>• More than 67% of the bioethanol is used as biofuel, but its high-volume production at relatively low cost offers an opportunity for its valorisation as a raw material for the production of various renewable chemicals.<br>• Commercial projects on lignocellulosic biomass are currently supported by policy incentives and government loans in many countries.<br>• Removing subsidies to fossil fuels and carbon taxes will help close the price gap between petrochemical and bio-based products.<br>• The current market for bio-based polymers is small but global bio-based polymer production is expected to grow at 4% by 2022.<br>• Bio-based plastics can attract premium prices on the market, which could make them a competitive business in regions with abundant and cheap biomass feedstock. | **Market factors**<br>• A higher demand for bio-based fuels and materials might lead to the conversion of food plantations to bio-ethanol production and increasing food prices with uncertain impacts in developing countries.<br>• The current increase in the production of bioethanol is mainly due to its use as a biofuel to substitute for the fossil fuels.<br>• Several industry sectors (e.g. transportation fuels, power generation and the chemical industry) might compete for biomass feedstock. |

# 3.2 Methanol

Methanol is a liquid chemical with the formula $CH_3OH$ (often abbreviated MeOH). It is colourless, volatile, flammable, and poisonous.



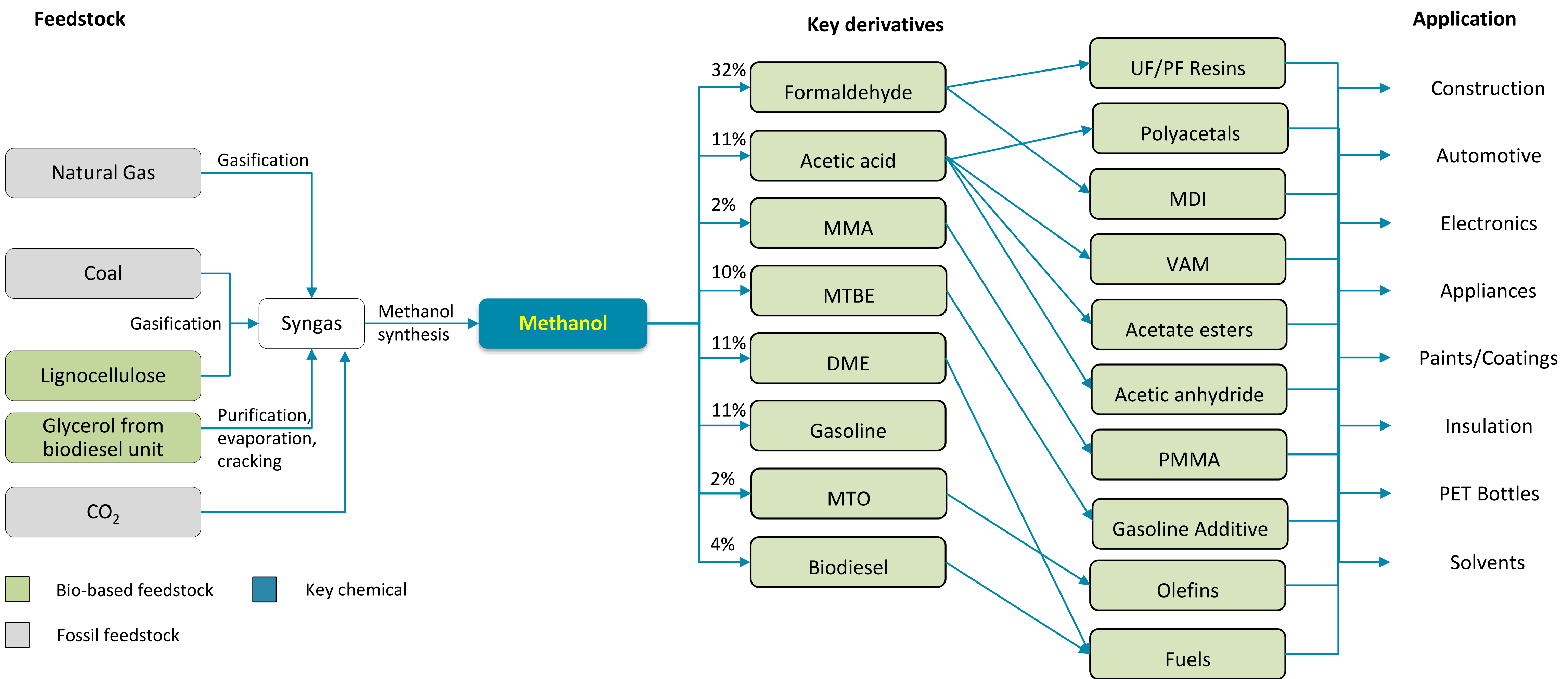

Methanol can be made from a variety of feedstocks. The first step involves production of *synthesis gas*, which is a mixture of CO, $CO_2$ and $H_2$. While natural gas is most often used, methanol can be made from any resource that can be converted into synthesis gas. This includes coal and oil, but also biomass, including agricultural and municipal waste, and wood. Methanol could be central to the development of biorefineries as an intermediate in the conversion of biomass to useful products.



Synthesis gas can also be produced by combining waste $CO_2$ from manufacturing or power plants with hydrogen produced from the electrolysis of water using renewable electricity. And methanol can be manufactured from small-scale units, producing a few hundred gallons or litres per day, to large plants making 1.6 million gallons/6 million litres each day.

Based on [1,13]

# Value chain




Based on [2]

# Value chain *(continued)*

**Methanol value chain**

**Methanol Producers** → **Direct** / **Distributor** → **End users** Construction, Automotive, Electronics, Appliances, Paints, PET bottles, Solvents; **Fuel producers**

- **Methanol producers**
  - Methanex
  - Helm
  - Sabic
  - Zagros
  - Yankuang
  - MGC
  - Sinopec
  - Mitsubishi
  - Petronas
- **Distributors**
  - Brenntag
  - Univar
  - Helm
- **Intermediates for end-uses**
  - Celanese
  - Evonik
  - DuPont
  - BASF
  - Chemanol
  - SAFCO
  - Kothari
  - Kuraray
  - Changchun PC
- **Fuels**
  - Exxon Mobil
  - Shell
  - Sabic
  - IOCL

*Non-exhaustive list*

# Demand

Methanol is one of the chemicals/fuels with the largest growth rate in the last decade, with its demand increasing from ~ 5  in 2005 to >70 Mt in 2015. The CAGR nearly doubled in the last five years compared to the average in the decade before. A significant increase is seen for:

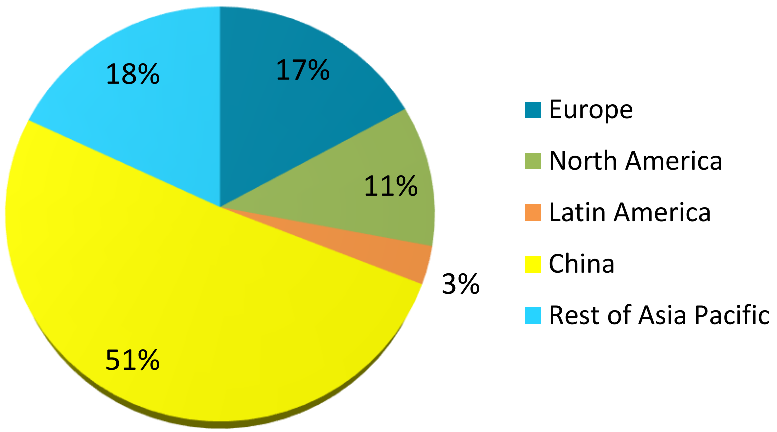
- Formaldehyde, driven by the expansion in polymers and resins particular in Asian markets.
- Olefins (methanol-to-olefin (MTO)/methanol-to-propylene (MTP) processes) in the last few years, particularly in China.
- Dimethyl ether (DME), also especially in China.
- Gasoline/fuel/biodiesel, especially in Europe.

In terms of end use, the formaldehyde segment is predicted to witness substantial demand in the global methanol market over the period between 2017 and 2026. The application of methanol and its derivatives in the construction and automotive sectors has increased significantly over the past few years.

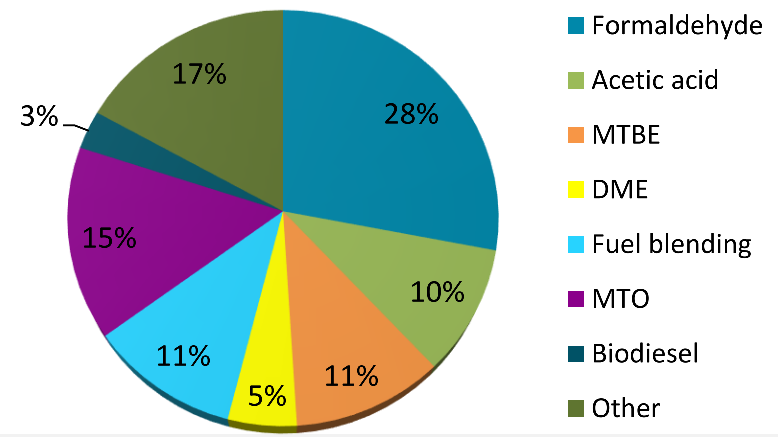
Asia Pacific, except Japan, is anticipated to continue to remain the most lucrative market for methanol during the period between 2017 and 2026.  The growth of this market is attributed to the growing demand for methanol and its derivatives in several industry sectors, such as automotive, textile, construction and furniture.

Based on [3,4,11,13]

**Global methanol demand by region (2016)**




**Global methanol demand by derivative (2016)**



# Supply

Major producers with large-capacity plants (up to 5,000-6,750 metric tonnes/day) are found in China, the Middle East, Russia. Worldwide, there is an estimated annual production capacity of 110 million tonnes.

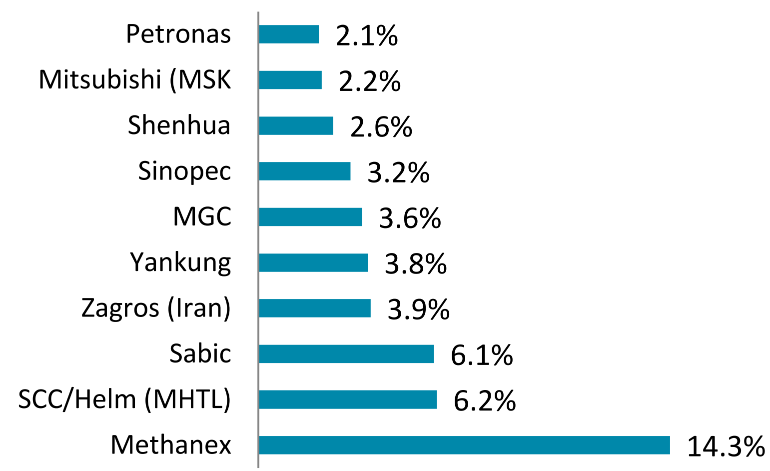
About 80% of methanol production is based on natural gas, the rest is based on coal (17%) and in small amounts on oil and biomass. Natural gas is likely to witness most growth as a feedstock. But, particularly in China, where large coal reserves are available, coal-based methanol capacity (i.e. currently about 9 Mt/year) is rapidly increasing, with applications as a fuel for transport and in the MTO (Methanol-to-Olefins) process.

The increasing oil and natural gas prices in recent years, as well as concerns about greenhouse gas (GHG) emissions, have sparked growing interest in alternative processes for methanol production based on renewable sources. Alternative feedstock includes biomass, waste and by-products from various sectors (including biogas from landfill, sewage, solid waste treatment; glycerine (glycerol) from biodiesel production; and black liquor from the pulp and paper industry). $CO_2$ is expected to become a feedstock in the future – one of the main drivers in Europe will be policy incentives.

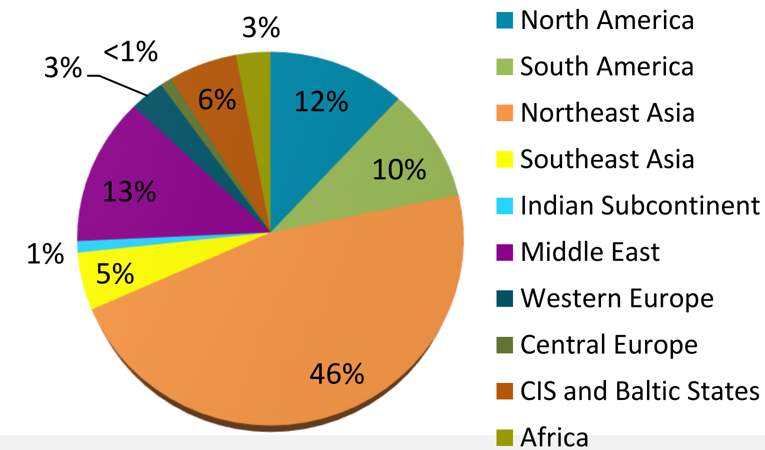
There are advanced pilots (small demos), which have shown that conversion of cellulosic material to synthesized products is feasible and that heat and material balances are in line with results of simulation work. On that basis, the first commercial scale plants based on municipal solid waste gasification are being built.

Based on [2,3,5,6,7,13 14]

**Market share of top producers of methanol (2016)**




**Global capacity for methanol (2018)** ***(projection)***



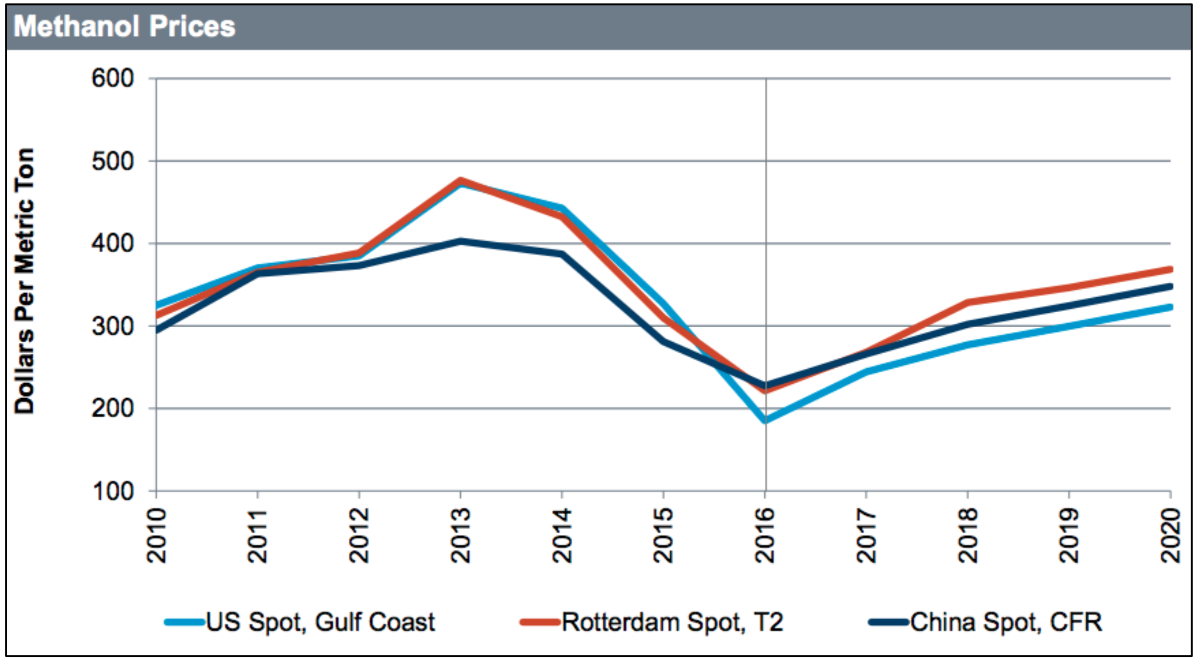
# Cost and environmental performance

Methanol prices have fluctuated between 200-450 US$ per tonne in recent years. The consensus in the European market is that global methanol markets are set for an oversupply in 2018. Large plants in the US and Iran have the potential to flood the global markets.

The methanol market in Europe is expected to follow global growth trends since 2016. The demand is driven mainly from the demand for biodiesel, formaldehyde and acetic acid derivatives. The increase in capacities in Asia ensures sufficient supplies worldwide. However, incremental demand from Asia coming from methanol conversion to olefins might increase the prices for methanol in the long run.

Expectations of supply length have already manifested themselves in greater contractual discounts in Europe for 2018.

But uncertainty remains around the timing and extent of the new production volumes as well as potential mothballing of older plants and feedstock gas shortages in other regions.




Based on [8,9]

# Cost and environmental performance *(Continued)*

The costs of methanol production from fossil fuels range from 75-250 €/t for natural gas and from 150-300 € /t for coal. The cost of wood-based bio-methanol production is estimated to range from 160 to 940 € /t.

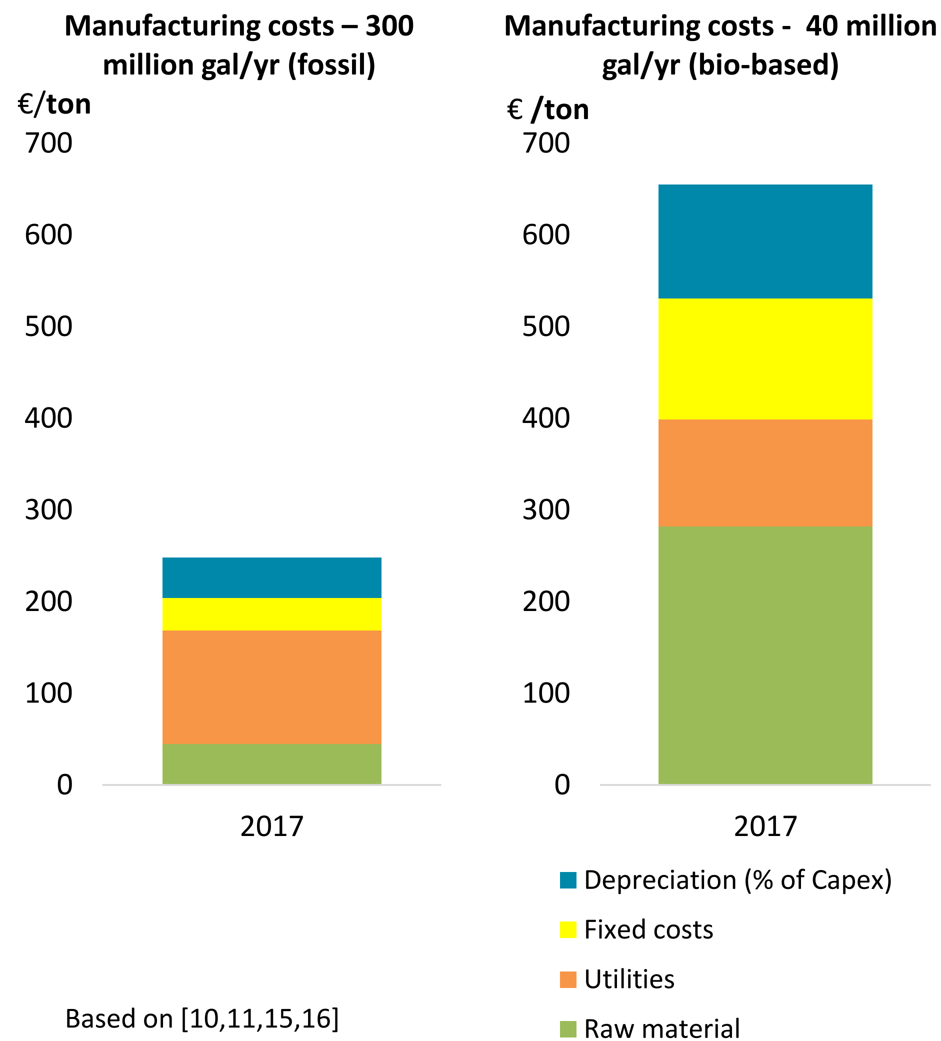
The production costs of bio-methanol are highly sensitive to local conditions. Key factors that influence the currently available estimates are feedstock types and prices, electricity generation fuel mix and prices, scale of production capacity, technology choice and investment costs and the desired grade of the final product. Electrolysis requires a lot of electricity, but if the price of electricity is very low, a bio-methanol facility using electrolysis can become an economically attractive option.

The capital cost per unit of capacity for wood-based bio-methanol is at least 3.4 times higher than the capital cost of plants based on natural gas. A bio-methanol production facility based on $CO_2$ is estimated to be about 15 times as expensive as the most economical natural gas-based facility.

Larger plants (*e.g.* 30-40 kt/yr capacity) are estimated to have a significantly lower cost per unit of capacity. For a 300 MTPD methanol plant, a ROI of 29% is expected. For a 150 t/d For a plant based on biomass which is normally  150 t/d capacity, the ROI is reduced to 18%.

Overall, for the same energy output, bio-methanol plants are about 1.8 times more expensive than bio-ethanol facilities.

In terms of environmental performance, bio-methanol can offer GHG emissions savings of 19%.




Based on [10,11,15,16]

# SWOT analysis

## Strengths

- Methanol has a large market volume and is a flexible platform chemical with many downstream uses
- Since it is a drop-in no, change in processing is necessary at customers side

## Weaknesses

- Bio-based methanol production in most cases is not cost-competitive with today's hydrocarbon price
- Competition with natural gas and future possible competition with $CO_2$ routes, which are both considered relatively clean options

## Threats

- OECD mentioned that fossil fuel subsidies are damaging bio-based markets
- Larger plants similar to natural gas-based methanol might not be possible due to biomass availability constraint
- High cost of biomass in Europe

## Opportunities

- More carbon efficient gasification of methane ($CH_4 \rightarrow C + 2H_2$) not releasing $CO_2$, could be an opportunity to produce bio-based methanol more efficiently
- A $CO_2$ emission tax could make bio-based methanol more cost competitive
- Due to the low energy content of biomass and its low density (e.g. straw), processing of biomass could be divided into a decentralized (pyrolysis) step and an centralized gasification and synthesis step

# Potential and Barriers

| Opportunities | Issues |
| --- | --- |
| **Techno-economic factors**<br>• Methanol is a highly useful solvent for the synthesis of a huge portfolio of chemicals<br>• Methanol can follow the acetic acid, the formaldehyde or the DME/olefin branch for chemicals in the value chain on page 17 and can also be used for fuels.<br>• Biomethanol is interchangeable with standard methanol and can benefit from the existing infrastructure.<br>• The technologies used in the production of methanol from biomass are relatively well known since they are similar to the coal gasification technology.<br>• There is a gradually increasing demand for methanol in chemical industry<br>• A potentially economical option is to mix renewable and fossil feedstocks (co-feeding). This can gradually make methanol production environmentally friendly and increase the expertise in biomass-based methanol production. | **Techno-economic factors**<br>• In the short run, biomethanol suffers from the same problems as many renewables in that it is more expensive than other sources of methanol. In other words, making biomass gasification cost-competitive has proven to be difficult.<br>• Production costs of biomethanol are highly sensitive to local conditions, such as feedstock type and price, electricity mix and prices, scale of production capacity.<br>• Energy density (by weight or volume) is one half of that of gasoline and 24% less than ethanol.<br>• Strong competition by natural gas (fossil but better than crude oil) and $CO_2$-based methanol.<br>• Production process is complex. |
| **Environmental factors**<br>• The main environmental advantage of methanol from biomass is the uptake of atmospheric $CO_2$ in the plant growth phase.<br>• Conversion of $CO_2$ to methanol provides a possible route for using waste $CO_2$ from industrial processes that is attractive to both government and industry. | **Environmental factors**<br>• Current policies for $CO_2$ accounting only consider the on-site emissions for the chemical sector and do not accurately reflect environmental advantages of bio-based chemicals.<br>• Careful consideration of sustainability of biomass feedstocks used<br>Based on [11,12] |

# Potential and Barriers *(continued)*

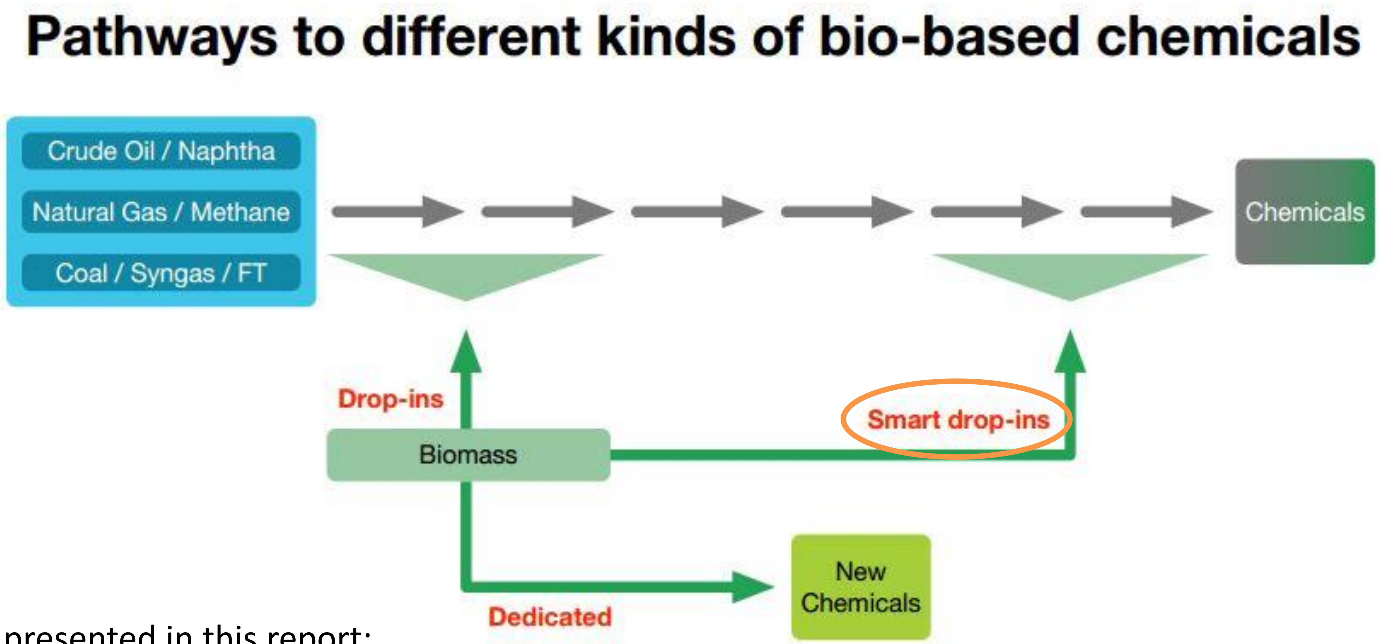
| Opportunities | Issues |
|---|---|
| **Market factors**<br>• Chemicals coproduction can also improve economics and energy efficiency. Bio-methanol can be co-produced along with hydrogen, bioethanol and urea.<br>• A significant increase is expected in the production of:<br>    • Formaldehyde, driven by the expansion in polymers and resins particular in Asian markets.<br>    • Olefins (methanol-to-olefins (MTO)/methanol-to-propylene (MTP) processes) in the last few years, particularly in China (coal-based).<br>    • Dimethyl ether (DME), also especially in China.<br>    • Gasoline/fuel/biodiesel, especially in Europe. | **Market factors**<br>• A higher demand for bio-based fuels and materials could lead to the conversion of food plantations to bio-ethanol production with increasing food prices. This risks negative environmental and social impacts on developing countries.<br>• Several industry sectors (*e.g.* transportation fuels, power generation and the chemical industry) might compete for the availability of biomass feedstock. |

Based on [11,12]

# 4. Smart drop-in chemicals

Smart drop-in chemicals are a sub-group of drop-in chemicals. They are also chemically identical to existing chemicals based on fossil hydrocarbons, but their bio-based pathways provide advantages compared to the conventional pathways. Drop-in chemicals are considered to be 'smart drop-ins' if at least two of the following criteria apply:

- The Biomass Utilization Efficiency from feedstock to product is significantly higher compared to other drop-ins.
- Their production requires significantly less energy compared to other production alternatives.
- Time-to-product is shorter due to shorter and less complex production pathways compared to the fossil-based counterpart or other drop-ins.
- Less toxic or harsh chemicals are used or occur as by-products during their production process compared to the fossil-based counterpart or other drop-ins.[1]



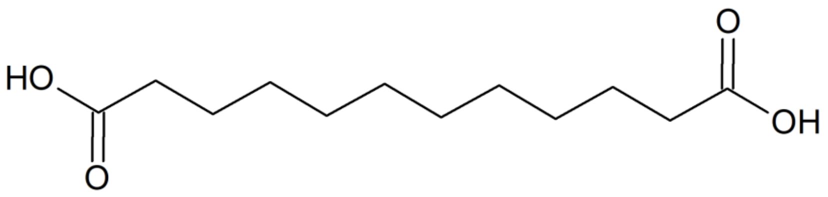

Business cases for the following smart drop-in chemicals are presented in this report:

1. Dodecanedioic acid (DDDA)
2. 1,4-Butanediol

**Notes:**
1. Carus et al. (2017). Bio-based drop-in, smart drop-in and dedicated chemicals https://www.roadtobio.eu/uploads/publications/articles/17-12-18-RoadToBio-Drop-in-paper.pdf

# 4.1 Dodecanedioic acid (DDDA)

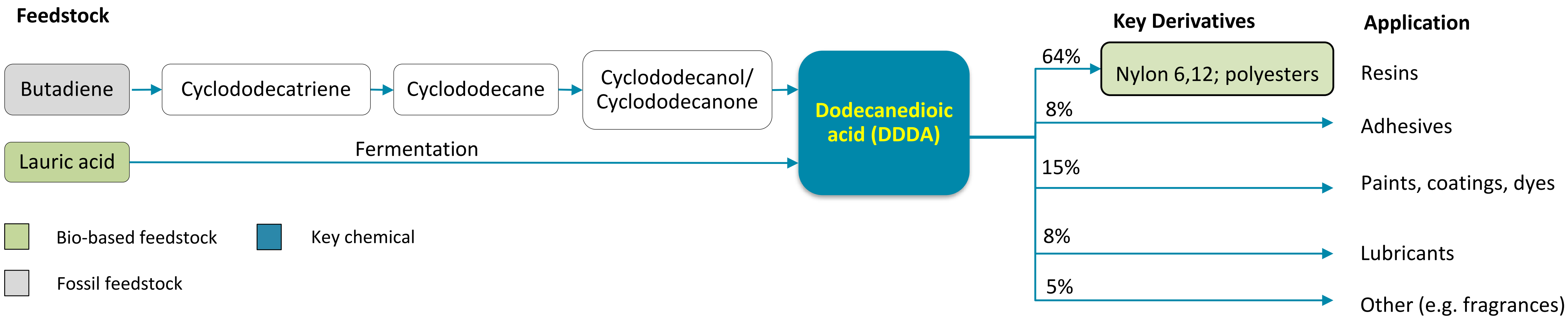
Dodecanedioic acid (DDDA) is a long chain diacid, with twelve carbon atoms and a carboxylic acid group on both sides. It is mainly used for the production of precursors of polymers, such as polyamide 6,12 (nylon 6,12) or polyesters. It also finds applications in molding resins, adhesives, and lubricants.




The traditional production of DDDA is a multi step process from butadiene, which has several steps that require high pressures, temperatures and catalysts. Moreover, the fossil-based production produces 0.2 kg $NO_x$ per kg of DDDA. However, DDDA can also be obtained from bio-based sources, such as lauric acid (from palm kernel oil), using yeast to convert lauric acid into DDDA in a single step.

With the bio-based process only requiring two steps from the palm kernel oil, compared to the four steps required to obtain DDDA from fossil-based butadiene, DDDA can be classified as a smart drop-in chemical. Moreover, the production of DDDA poses no health issues due to its low vapour pressure (no VOC emissions) and is not genotoxic or mutagenic. The only potential VOC emissions from the process originates from the ethyl acetate used for the purification.

# Value chain




The main application of DDDA is in polymer resins (60%). Next to this, it finds applications in powder coatings, such as anti-corrosion coatings in the automobile industry, lubricants and adhesives.

**Fossil-based DDDA**

Fossil-based DDDA is commonly produced in four steps starting from butadiene. In the first process, two equivalents of butadiene enter a cyclisation reaction to form cyclododecatriene. A catalyst is needed to prevent the polymerisation of butadiene. The first commercial scale plant reached 90% selectivity in this step at a 18 kton/y scale. The cyclic alkene is then hydrogenated with $H_2$ at 200 °C under 10 to 15 bar to form cyclododecane. The cyclododecane is then oxidized with boric acid to form a mixture of the cyclic alcohol and ketone. Oxidation to the diacid is performed with $HNO_3$ in a final step.

**Bio-based DDDA**:

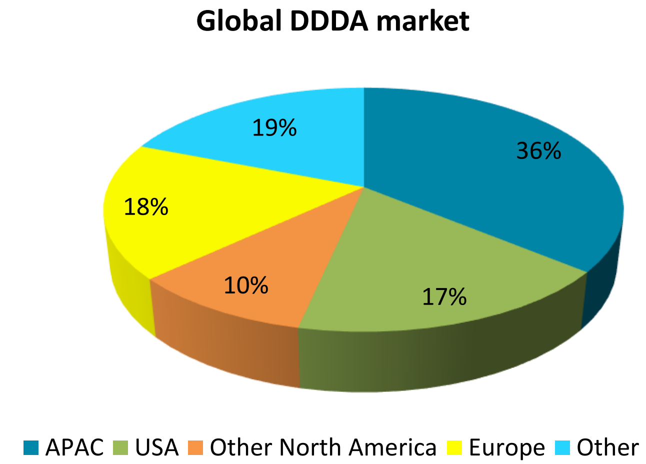
The starting material for bio-based DDDA is lauric acid, which is obtained from palm kernel oil. The lauric acid is fermented to obtain DDDA. The fermentation has been performed by Verdezyne as an aerobic fed batch process with a co-feed of dextrose. The produced DDDA is insoluble in the fermentation broth and thereby easy to separate and purify.

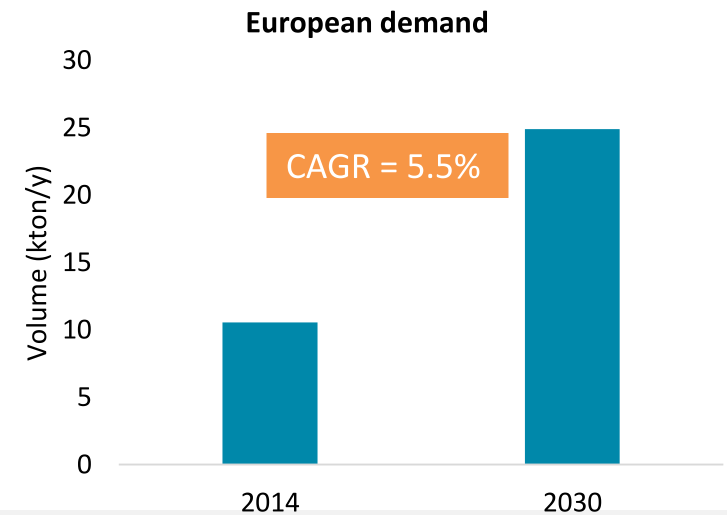
# Demand

The demand for DDDA in Europe was >10 ktonnes/yr (2014) and is expected to continue to grow, due to the expected growth in its applications sectors (such as adhesives, nylon 6,12, paints and powder coatings). Pressure on the paint industry to reduce the amount of volatile compounds is an opportunity for DDDA.

Resins are the most important use of DDDA, accounting for 64% of DDDA demand. This is also the market where bio-based DDDA is expected to have the largest appeal. It is expected that bio-based DDDA will contribute 30% to the total DDDA market.

The growth in DDDA markets is strongest in APAC and North America. The DDDA market in the EU is only expected to see a modest growth, due to the small growth of nylon in the EU. Overall, there is an established DDDA market with a lot of room for growth.

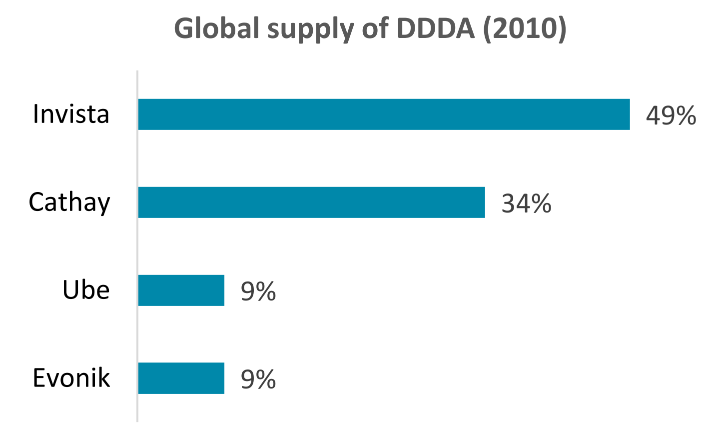


# Supply

The currently installed fossil-based DDDA production capacity is unclear. However, numbers from 2010 give an indication of the top players for the fossil-based DDDA supply. Most producers (e.g. Invista, Ube, Evonik) use the multi step process from butadiene, whereas Cathay uses biotechnology processes with fossil-based starting materials. It should be noted that since the publication of these numbers Invista closed their DDDA plant in Texas in March 2016.

The bio-based production of DDDA is currently at TRL 8, with the first bio-based plant under construction in Malaysia by Verdezyne. However, with the withdrawal of one of the investors, Sime Darby, Verdezyne had to stop operations in May 2018. Their plant would be the first large scale bio-based production of DDDA with a capacity of 6 ktonnes/year, which was expected to be expanded to over 10 ktonnes/year. Cathay is involved in bio-based DDDA as well, aiming to convert their fossil-based bioprocess to one based on bio-based feedstocks.



# Cost and environmental performance

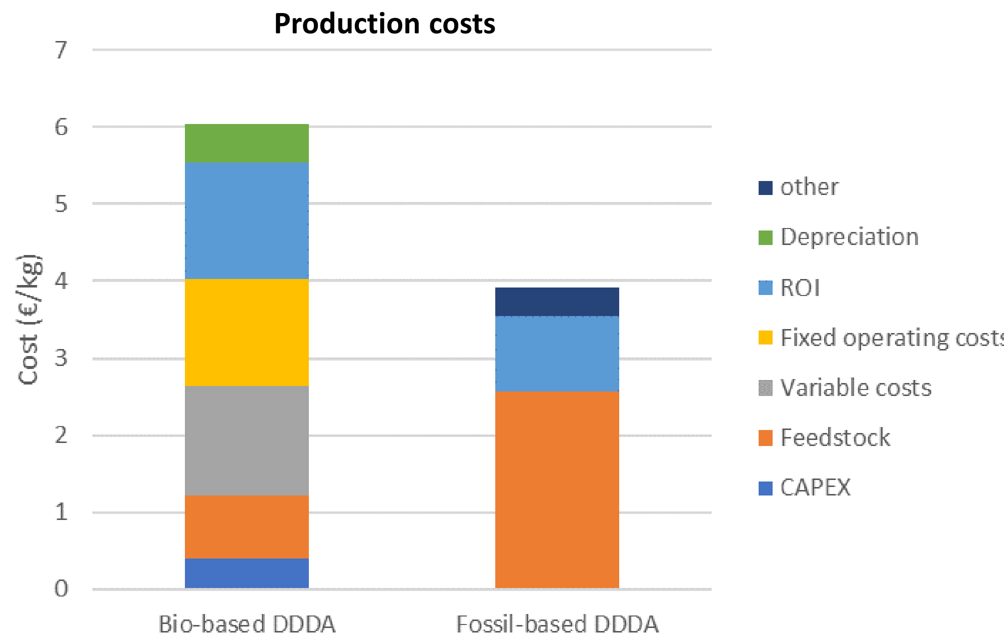
There is still a large price gap between fossil-based and bio-based DDDA. Where fossil-based DDDA costs 3.5 to 4 €/kg (estimation from Cathay in 2011), bio-based DDDA costs more than 5 €/kg (according to Verdezyne in 2017 and Mills 2018).

Using palm kernel oil reduces the costs for feedstock. This feedstock only costs around 0.6 €/kg, whereas the butadiene required to produce DDDA from fossil feedstocks has a price of nearly 3 €/kg.

The breakdown of the bio-based DDDA costs is based on Mills 2018, who estimates that a minimum price of DDDA of 4.9 €/kg is required in order to break-even. Assuming a life-time of the plant of 15 years with a production capacity of 14 kton/year.

The breakdown of the costs of fossil-based production of DDDA is based on the estimations from Cathay on both butadiene price and the price of butadiene based DDDA. Assuming the ROI is 25% of the total DDDA cost.

In terms of environmental performance, there is no reliable evidence in the literature about GHG emissions savings from bio-based DDDA. However, the bio-based route to DDDA takes place in only one fermentation step from its feedstock, and thereby has a much lower environmental impact (for example, in terms of NOx emissions) than the fossil production, which requires four conversion steps.



# SWOT analysis

| Strengths | Weaknesses |
| --- | --- |
| • Well known fermentation process ready for scale up.<br>• DDDA is used in household and consumer goods, for which there could be a demand for bio-based products. | • DDDA is a small market (total demand of 10 ktonnes/yr in 2014), which does not have a high impact on the total $CO_2$ emissions. |
| **Threats** | **Opportunities** |
| • The social acceptance of products that originate from (a co-product stream of) palm oil is low. | • 18% of the DDDA market is in Europe.<br>• The markets where DDDA is used are expected to grow. |

# Potential and Barriers

| Opportunities | Issues |
| --- | --- |
| **Techno-economic factors**<br>• The market for bio-based nylons is expected to grow rapidly. This growth in demand is expected to be challenging to meet with fossil supply. The gap could be bridged with bio-based feedstocks, such as bio-based DDDA.<br>• The technology of bio-based DDDA production is well known and is ready for scale up to large production facilities.<br>• The successful production of long carbon chain diacids opens the possibility to produce other long chain diacids via fermentation. This clears the way for new products with new properties and applications. | **Techno-economic factors**<br>• The scale up to multiple ktonne scale has proven difficult (too expensive and uses palm oil), which is exemplified by the recent attempt by Verdezyne. The construction of the plant was interrupted when one of the investors backed out of the project in May 2018. |
| **Environmental factors**<br>• As a smart drop-in, the bio-based route to DDDA takes place in only one fermentation step from its feedstock. This saves many steps, and thereby has a much lower environmental impact (for example, in terms of NOx emissions) than the fossil production, which requires four conversion steps. | **Environmental factors**<br>• The use of palm kernel oil, even though it is often presented as a waste stream from the palm oil production, is associated with deforestation by unsustainable palm oil production. |

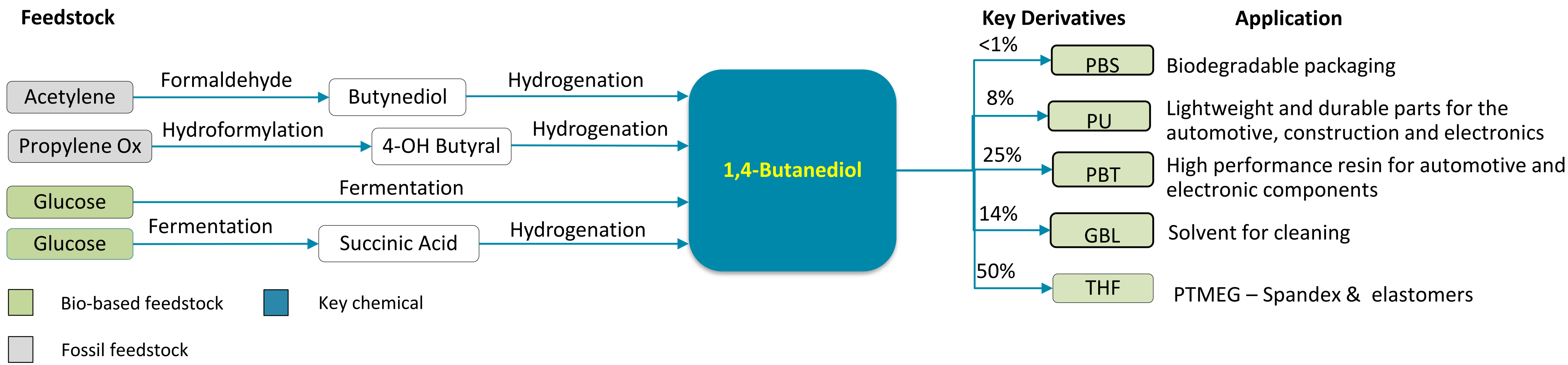
# 4.2 1,4-Butanediol (BDO)

**1,4-Butanediol** (BDO) is today commercially produced from fossil feedstock and from renewable (bio) feedstock. Fossil based production remains dominant on the market although new capacities of bio-based 1,4-BDO are planned in Europe, North America and Asia.

The largest consumption of BDO is for tetrahydrofuran (THF) used as a monomer in the production of polytetramethylene ether glycol (PTMEG), which is used in the manufacture of polyurethane fibres (Spandex), cast and TPU elastomers, and high-performance copolyester-polyether elastomers. These materials are used in various sectors such as clothes, sportswear, automotive, aviation, etc.

Other important derivatives of BDO are: gamma-butyrolactone (GBL) used as solvent in paint strippers, circuit board cleaning products, and the production of herbicides and pharmaceutical products; polybutylene terephthalate (PBT) used for production of electrical and automotive components and polybutylene succinate (PBS) used for biodegradable packaging [1].

# Value chain




**Fossil based BDO**

BDO is produced from different fossil feedstock including acetylene, butadiene, maleic anhydride, propylene and propylene oxide. Historically acetylene-based production (Reppe process) is the most embedded into the BDO industry. Over 40% of fossil-based BDO is produced via Reppe process where acetylene is reacted with formaldehyde to form butynediol which then undergoes high-pressure hydrogenation to form BDO. Acetylene, maleic anhydride and propylene routes are popular in China and Middle East, while in Europe and the US the most popular route is propylene oxide. [2]

**Bio-based BDO**

BDO can be produced from renewable feedstocks, either via a one-step direct fermentation of glucose, or a two-step process consisting of the initial glucose fermentation into bio-based succinic acid and subsequent conversion to BDO through conventional hydrogenation. Both processes are commercially available.

# Demand

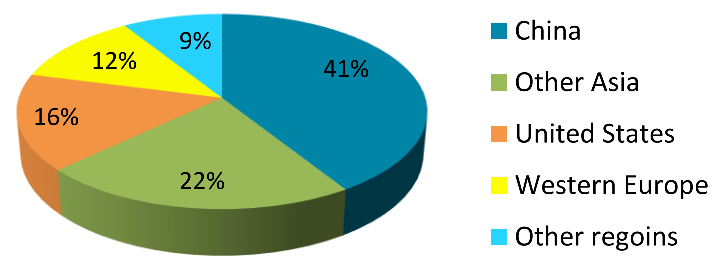
In 2016 the global market for BDO was at about 2,000 kta. Relatively little BDO is sold on the merchant market and most is consumed as intermediate. BDO demand is mainly driven by textile, construction and automotive industry for growing China and developing market consumption. Rising health, fitness, and sports awareness has driven the demand for flexible, yet comfortable athletic & sportswear, contributing positively to BDO consumption for spandex fiber application. With the rising consumption of lightweight and durable parts for the automotive, construction and electronics sectors, polyurethane (PU) emerged as another fast-growing application.[1]

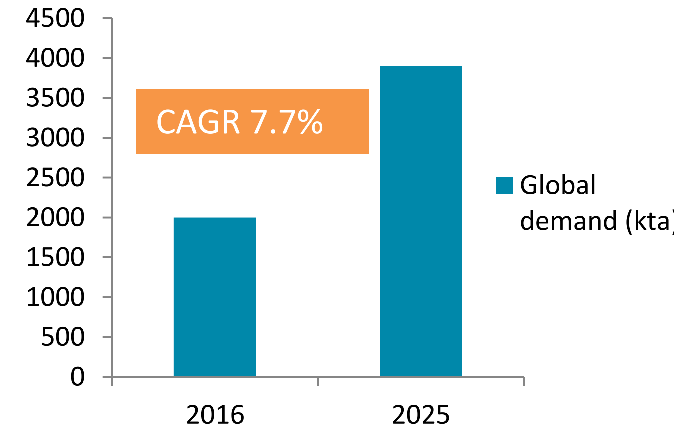
The highest demand growth is expected in China and South-East Asia which is mainly driven by the rapid growth of spandex, PBT and PU production. Developed regions such as North America and Europe may grow at lower rates, owing to end-use industry saturation and downward revision of GDP.[6]

Increasing environmental concerns, especially in Europe and United States are likely to favour bio-based BDO demand in these regions. Growing use of sustainable fibers and reducing carbon footprint of clothing is a major opportunity and driver for bio-based BDO. Oher factors which may favour bio-based BDO include price volatility and high manufacturing cost of fossil derived BDO.

The pricing trends for 1,4-butanediol basically follow raw material prices such as for propylene, butadiene, n-butane, or maleic anhydride, which in turn are related to feedstock costs for crude oil, natural gas, or coal. However, the supply/demand balance also plays a role in pricing; 1,4-butanediol prices were lower in 2015 because of significant world overcapacity. [5]

**1,4-Butanediol regional demand (2016)**

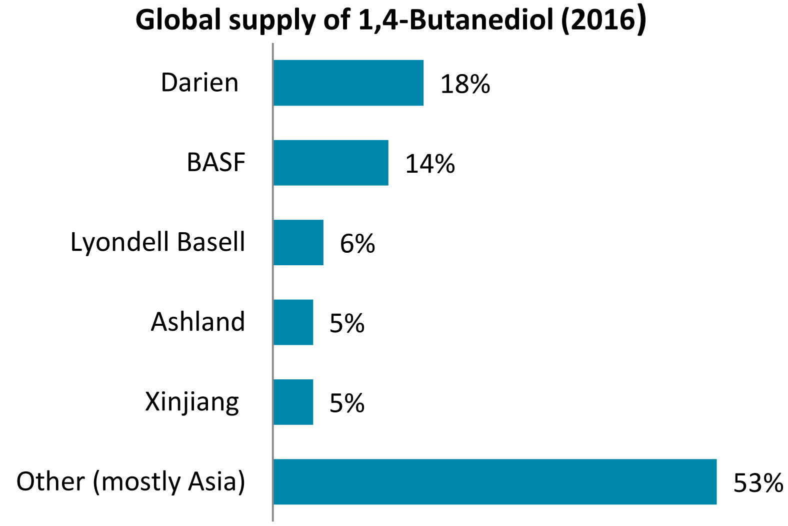


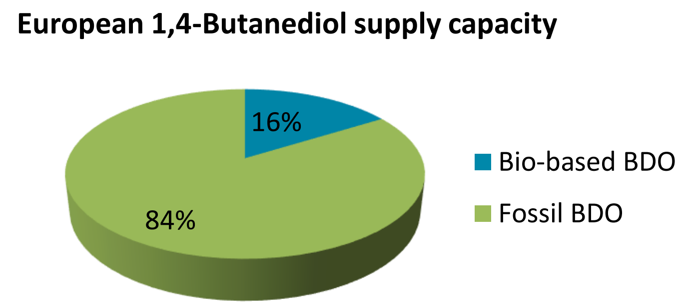



# Supply

BDO industry is moderately consolidated. In 2016 about 50% of total BDO was supplied by 5 top players, almost entirely produced from fossil feedstock. [7] The most important producers in Europe are BASF, in Ludwigshafen, Germany; LyondellBasell in Botlek, Netherlands, and Ashland in Marl Chemical Park, Germany, in total supplying about 415 kta of BDO. BASF and Ashland produce BDO *via* acetylene route while LyondellBasell used propylene oxide feedstock.

Production of bio-based BDO is commercially proven and currently available at TRL 8-9. Since 2016, Novamont is producing in Italy about 30 kta of bio-based BDO by direct glucose fermentation route developed and licensed by Genomatica. BASF has licensed Genomatica's bio-BDO technology and plans for a commercial production if market demand is present. BASF consider building a 50 kta bio-based BDO. Other companies working on the development of bio-based BDO are Bio Amber and Myriant, both technologies are based on conversion of bio-based succinic acid to BDO.



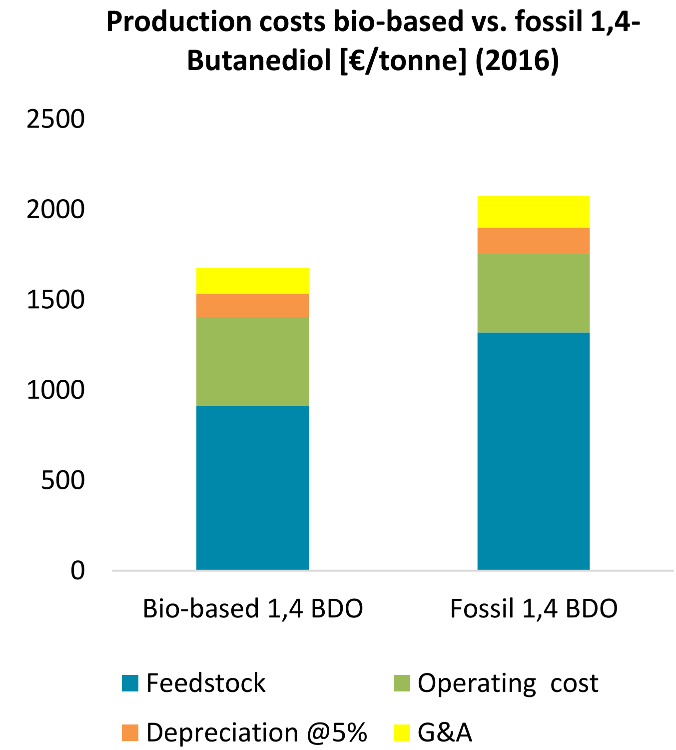
# Cost and environmental performance

Cost of production via fermentation is 15-30% lower than fossil and competitive at low oil prices of $45/bbl range. Once fermentation route technology achieves scale, significant cost-advantages relative to petroleum-based BDO are expected. [8]

In 2016, Novamont reported investing €100 million to build the bio-based BDO plant of 30 kta capacity in Italy. This sum is generally considered to be low compared to plants that produce chemicals from fossil fuels, even more so since it is a first-of-its-kind plant. [10]
The fermentation process is energy-intensive and there is likely to be an opportunity to improve efficiency and further cut costs through process optimization and innovation, further improving the competitive edge of the bio-based BDO.

Furthermore, development of new and higher value downstream products, such as polyurethanes for lightweight and durable parts for the automotive, construction and electronics sectors, which could outperform conventional plastic, is another opportunity where bio-based BDO could potentially feature and grow.

In terms of environmental performance, bio-based BDO can offer significant GHG emissions savings compared to fossil route - > 70%




Estimated production cost are for fossil and bio-based 1,4 butanediol plant of about 60 kta.

# SWOT analysis

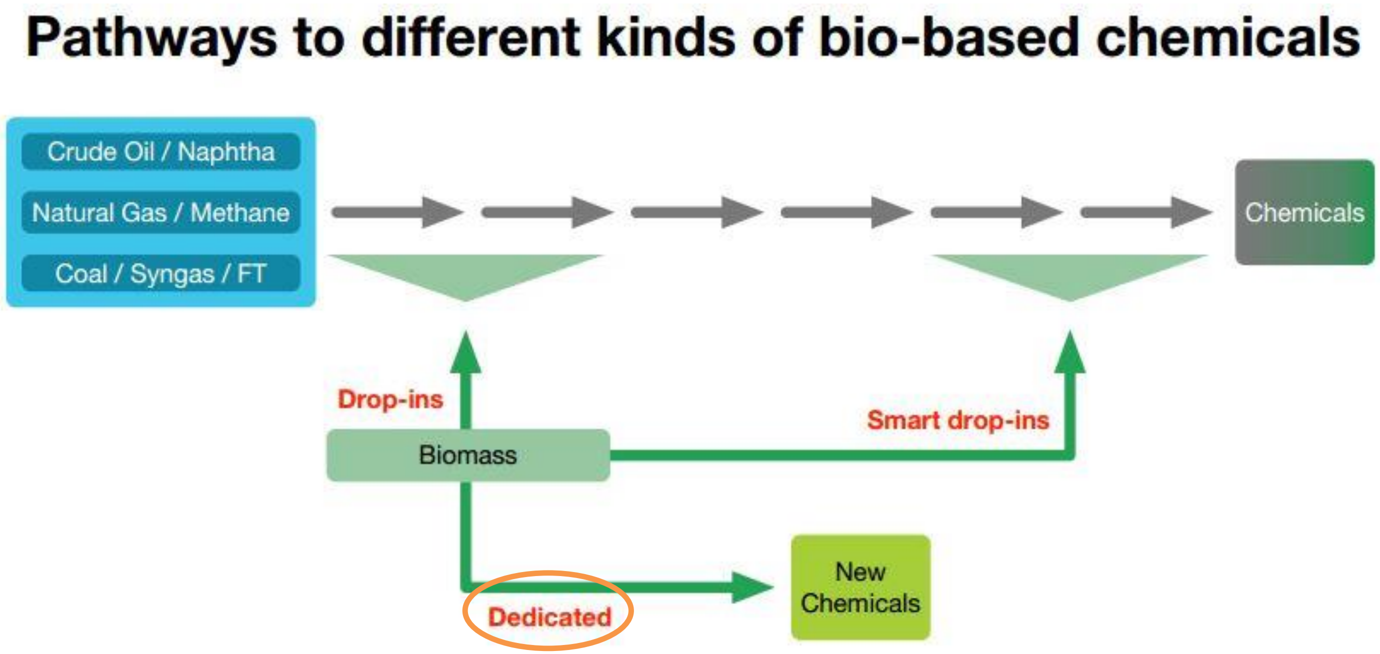
| Strengths | Weaknesses |
| --- | --- |
| • Bio-based 1,4-BDO has potentially lower production costs than fossil 1,4-BDO<br>• Bio-based 1,4-BDO offers potential to be more sustainable than fossil 1,4-BDO | • The relative small market in the EU |
| **Threats** | **Opportunities** |
| • Glycol market is very competitive<br>• Succinic acid has a high value, so it may not make economic sense to go further than succinic acid<br>• THF (the main product from BDO) is under pressure due to health and safety (of the THF compound) | • There might be an opportunity in the packaging industry if bio-based PBS takes off. Expected growth in PBS market should be investigated (no knowledge of this in the audience)<br>• There are also routes *via* benzene and butane to make BDO |

# Potential and Barriers

| Opportunities | Issues |
|---|---|
| **Techno-economic factors**<br>• Bio-based 1,4-BDO is cost competitive at industrial scale<br>• Growing demand for sustainable fibre in Europe and US are like to favour the production of bio-based 1,4-BDO<br>• Looking into other feedstock options which are more sustainable such as sugars from lignocellulosic biomass may represent the opportunity to further improve cost competitiveness of 1,4-BDO | **Techno-economic factors**<br>• For European production of bio-based 1,4-BDO the biggest challenges are end-use industry saturation and low oil price. New capacities of fossil and bio-based 1,4-BDO are built mainly in Asia which is also home to most of the end-use industries e.g. textile, automotive, footwear.<br>• Lack of downstream integration with the end-use industry particularly with textile and footwear industries which are mainly outside Europe, are likely to limit the demand of bio-based and fossil 1,4-BDO in EU.<br>• 1,4-BDO price is still affected by supply/demand balance<br>• Bio-based 1,4-BDO is not produced at commercial scale |
| **Environmental factors**<br>• Bio-based route has significant reduction of GHG emissions compared to fossil route - above 70% | **Environmental factors**<br>• The 30,000 tonnes of bio-BDO produced by Novamont requires 100,000 tonnes of glucose syrup, which is used in the food industry and needs agricultural land to be produced. Although the volumes of bio-based BDO and other chemicals are still small, risks associated with an increase in demand in feedstock need to be considered. |

# 5. Dedicated chemicals

Dedicated bio-based chemicals are chemicals which are produced via a dedicated pathway and do not have an identical fossil-based counterpart.[1]




Business cases for the following dedicated chemicals are presented in this report:

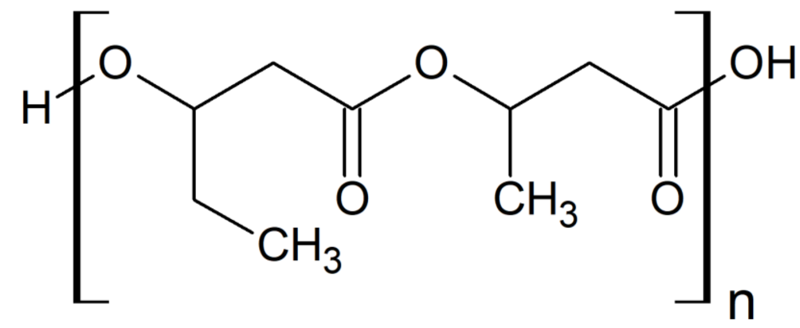
1. Polyhydroxyalkanoate - PHA
2. Polyethylene furanoate - PEF
3. Lactic acid
4. Furfural
5. Glycerol

**Notes:**

1. Carus et al. (2017). Bio-based drop-in, smart drop-in and dedicated chemicals https://www.roadtobio.eu/uploads/publications/articles/17-12-18-RoadToBio-Drop-in-paper.pdf

# 5.1 Polyhydroxyalkanoates (PHA)

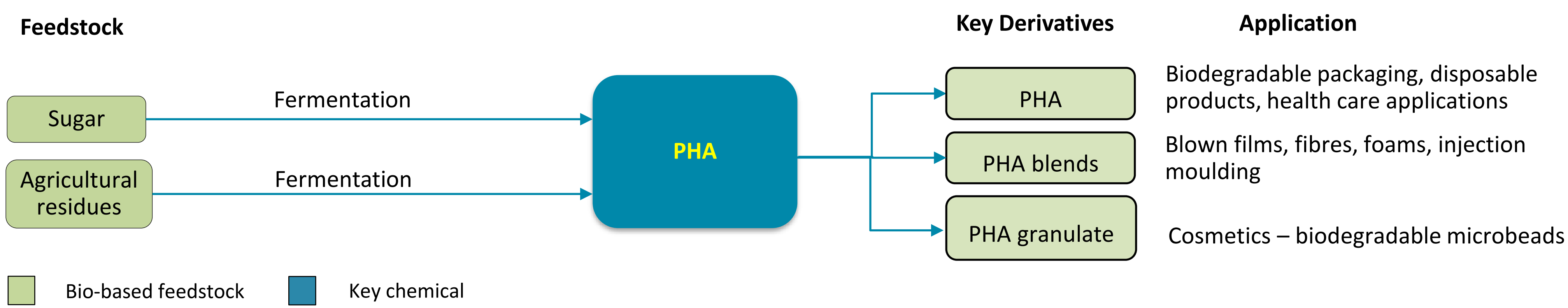
Polyhydroxyalkanoates (PHA) are a family of linear polyesters that are naturally produced by numerous microorganisms. Microorganisms produce PHA when excess of carbon is available as a buffer for periods with less available resources. There are many types of PHAs, depending on the monomer that the PHA is built of. Common forms of PHA are polymers of hydroxybutyrate (PHB) and hydroxyvalerate (PHV) or a mixture of the two in PHBV. The properties of PHA are dependent on the type of PHA being produced, where the ratio in monomers determines the final polymer properties.



The material was first commercialised in the 1980s. However, many companies quit production in the 90s as the oil price went down. The struggle in the early development of PHA is a result of its high price. Especially for early applications, which were mostly aimed at packaging, PHA could not compete in price with the commonly used fossil-based polymers such as polypropylene, polyethylene, polystyrene and polyethylene terephthalate.

Since the mechanical and physical properties of PHA can be tuned, and because of the excellent biodegradability, PHA is still seen as a promising bio-based polymer that can replace a large share of fossil-based polymers currently used. It is expected that, potentially with a shift to cheaper feedstocks, the polymer will grow from niche applications, such as bio-implants, use in tissue engineering, and cosmetics to larger scale applications, such as packaging and, in the form of blends, in foams and fibres.

# Value chain




**Value chain summary**

PHA is originally produced by fermentation of glucose. However, current trend in the production of PHA is to move towards lower cost starting materials, such as agricultural residues. The range of potential feedstock for PHA production is huge, where sugars, such as glucose and fructose, can be used as well as fatty acids. Waste streams from the pulp and paper industry, municipal waste streams, methane, and genetically modified plants have been used as well for PHA production on pilot scale. A difference with other fermentations is that PHA resides inside the cells of the bacteria, which means that the down-stream processing is more challenging and costly.

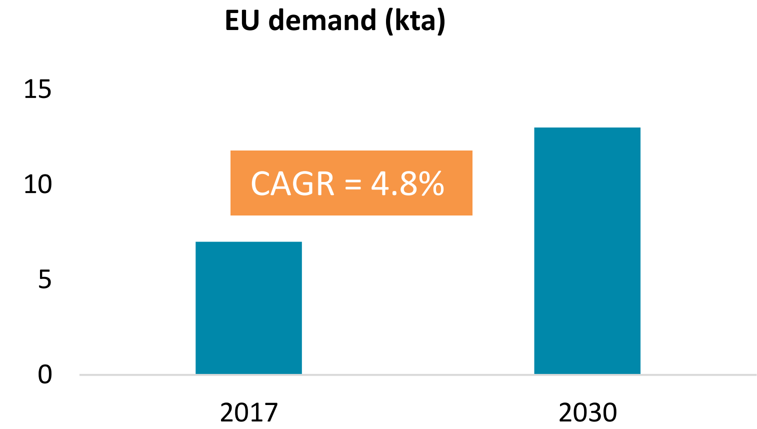
**Fossil based plastics**

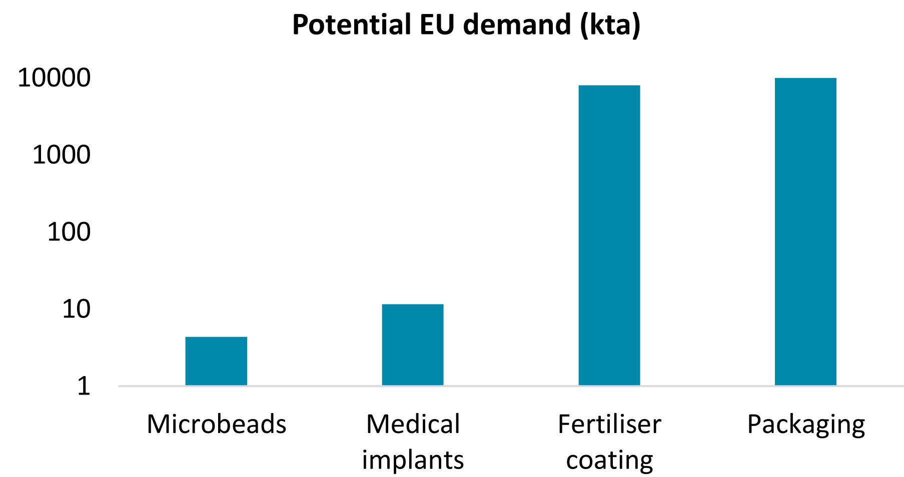
Early versions of PHA were expected to compete with polypropylene, especially for use in packaging and disposable products. The targeted applications for PHA shifted towards more high-end applications such as cosmetics (micro-beads) and health care (tissue engineering, bio-implants).

# Demand

PHA constitutes a small share of the total bio-based plastics market. Currently, PHA is used in food packaging on a small scale. The targeted high-end uses, such as microbeads in cosmetics (EU demand 4 ktonnes/yr) and medical implants (EU demand 12 ktonnes/yr) have relatively small production numbers as well.

Applications that open up larger markets include coatings for fertilisers that enable controlled urea release (PHA market demand of 2 to 8 million tonnes/yr). With a decrease in production cost, PHA is believed to potentially replace 50% of the fossil packaging market due to its biodegradable nature. This would enable PHA to replace part of the polyethylene and polypropylene market, with a potential demand of 10 million tonnes/yr.



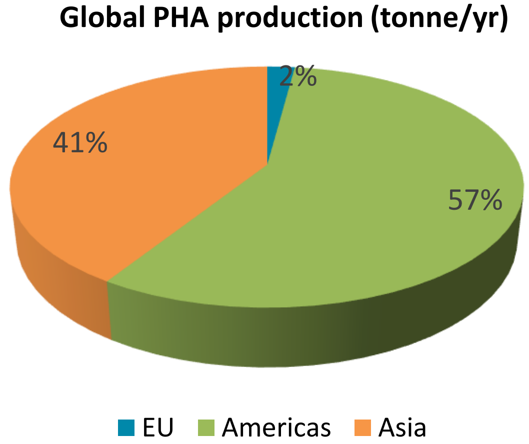



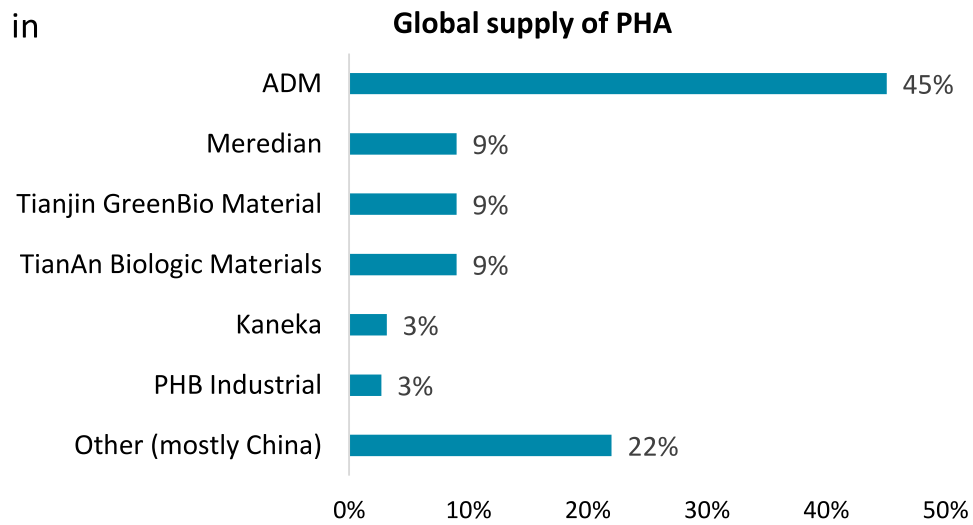
# Supply

The current supply of 2.3 kton/y PHA in the EU is provided by Kaneka and Newlight. This is only a small part of the global PHA production, which takes place mostly in the US and China. Examples of major global players are ADM, Meridian and Tianjin Green Bioscience.

Production capacity for PHA is growing rapidly using the available waste streams from sugar beet agriculture. The capacity of Kaneka is expected to grow from 3.5 kton/y to 12 kton/y in 2020. Moreover, Bio-on is constructing a plant with a potential capacity of 2 kton/y in Italy.

PHA production based on sugar is well-known, but had many unsuccessful start ups in the 90s. Other systems, that use alternative feedstocks, processes and/or purification techniques, are still being developed (TRL 6 - 8) and many pilot projects can be found in the EU.



# Cost and environmental performance

Current PHA production has feedstock cost and downstream processing (DSP) costs as major downsides. The sugar feed contributes 40 to 50% of the total PHA cost of €4 to €5 per kg. Switching to other feedstocks can significantly bring down the production cost of PHA.

Several cost estimations show the opportunities in cost reduction by switching to

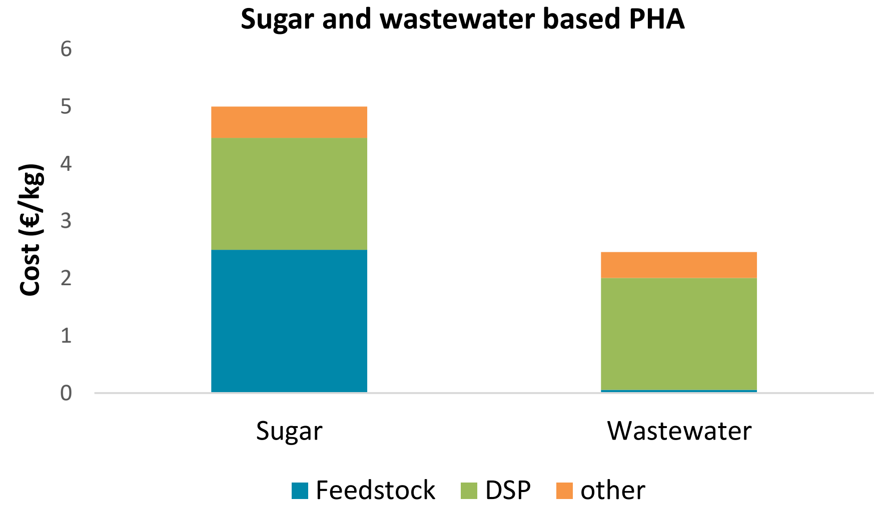
- Wastewater (estimated cost of €1.99 to €2.46 per kg): Major cuts in production cost are achieved by using cheap feedstock such as wastewater rather than sugar.
- Biogas (estimated cost of €0.95 per kg): Major cuts in production cost can be achieved via lower utility costs.

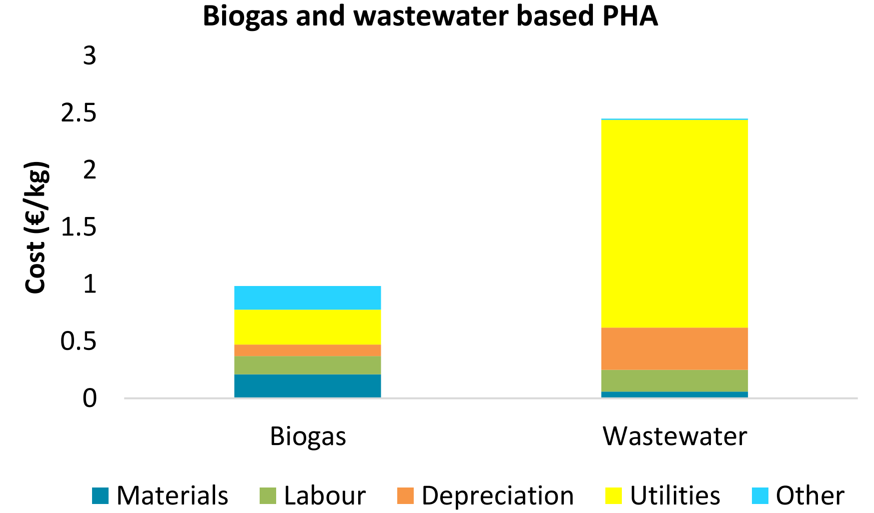
In summary, the biogas route compared to both sugar-based and wastewater-based PHA routes appears to be the most attractive in terms of cost competitiveness.

Expensive DSP remains a bottleneck for cost efficient PHA production. However, price ranges in the order of fossil plastics (€1 to €2 per kg) are within reach.

In terms of environmental performance, PHA are biodegradable polymers that can offer GHG savings from 20% with starch feedstocks to 80% with sugarcane and 90% with lignocellulosic feedstocks.

- Sugar case based on Kootstra 2017, with DSP calculation from Dacosta 2015
- Wastewater case based on Dacosta 2015, DSP with halogenated solvent, no cost reduction for prevented wastewater treatment
- Biogas case based on Criddle 2014, DSP with SDS-hypochlorite, 10 kton/y scale



# SWOT analysis

| Strengths | Weaknesses |
| --- | --- |
| • Marine biodegradability | • Specialised equipment required for processing<br>• High production costs due to the expensive downstream processing<br>• Competes with PEF |
| **Threats** | **Opportunities** |
| • Introduction of a product produced from waste is challenging due to regulations (e.g. Waste Framework Directive)<br>• Unsuccessful history of sugar-based PHA | • Many large or high value potential markets for biodegradable polymers (packaging, medical implants, cosmetics, fertilizer coatings, mulch films)<br>• Use of waste streams as feedstock could result in cheaper production |

# Potential and Barriers

| Opportunities | Issues |
| --- | --- |
| **Techno-economic factors**<br>• PHA can be obtained from many biomass feedstocks, as long as they contain carbon that can be used by microorganisms. This means that PHA could potentially be produced from waste streams that have no or little value, such as municipal waste or agricultural residues.<br>• Many PHA-processes from waste streams are currently tested at pilot scale (e.g. BioBarr and P4SB in Horizon 2020, AFTERLIFE within BBI).<br>• There are many potential markets for PHA that can take advantage of its biodegradability. Examples include the use in medicine as implants, the use in cosmetics as a replacement for microbeads, or as coating for fertiliser that enable a slow release of the fertiliser.<br>• The properties of PHA can be tuned by controlling the ratio of butyrate and valerate monomers. | **Techno-economic factors**<br>• PHA produced by microorganisms ends up inside the cells as polymer granules. Together with the low concentration of the product, this makes the downstream processing difficult and expensive.<br>• The melting point of PHA is close to its degradation temperature. This gives a very narrow processing window that requires specialised knowledge and equipment.<br>• The properties of PHA are dictated by the ratio of butyrate and valerate. By utilising waste streams, this parameter is difficult to control and constant quality can not be guaranteed.<br>• There is still no commercial process for the production of PHA from waste streams and the current production is done on fermentation from sugars.<br>• The biodegradable and brittle nature of PHA makes them unsuitable for applications with long-term use. |
| **Environmental factors**<br>• PHAs are receiving a lot of attention due to excellent biodegradability. It is one of the few materials that are fully marine biodegradable, which is an important quality for tackling the plastics issue. | **Environmental factors**<br>• Careful consideration of sustainability of biomass feedstocks used |

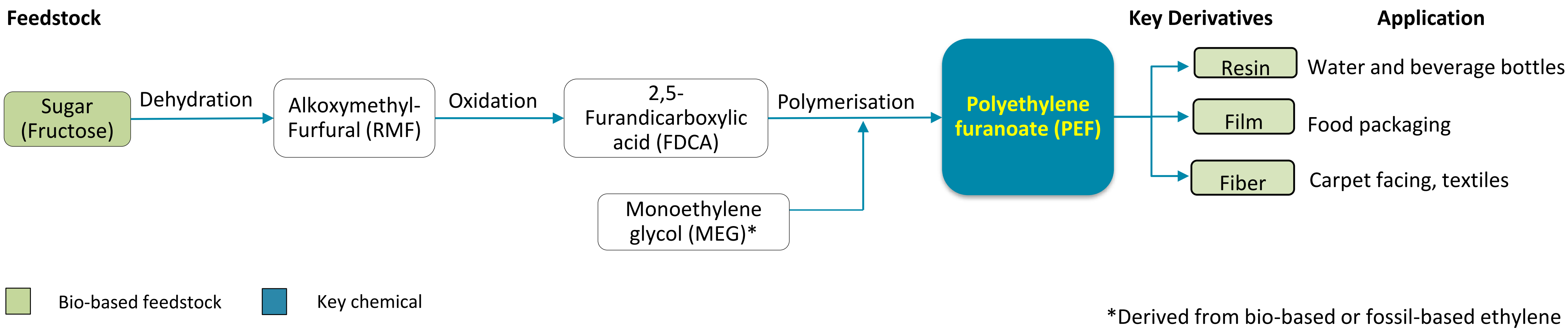
# 5.2 Polyethylene furanoate and terephthalate (PEF, PET)

**Polyethylene furanoate** (PEF) is an aromatic polyester formed by the polymerisation of FDCA (2,5-Furandicarboxylic acid) and MEG (monoethylene glycol). PEF is recyclable and is a 100% bio-based alternative to PET (Polyethylene terephthalate). [1,2]

The current focus is on using PEF as a replacement resin for PET beverage bottles. However, PEF film and fibre can also be used in applications such as food packaging, and carpets, textiles. PEF production is still at pilot scale but has garnered interest from key customers such as Coca-Cola, Danone, and ALPLA. [1,4]

**Polyethylene terephthalate** (PET) is a thermoplastic polymer resin and the most commonly used polyester. It is produced from MEG (monoethylene glycol) and either purified terephthalic acid (PTA) or dimethyl terephthalate (DMT). PET can be made into a resin, fibre or film and has good processability allowing it to be recycled repeatedly into many new products, as well as returned to its constituent monomers. The largest application of PET is for the production of polyester fibre (filament and staple), followed by packaging resin production. Currently PET film is mainly used in packaging applications. It is also used in magnetic or adhesive tapes, and a new application in PV (photovoltaic) cells is growing rapidly. [3]

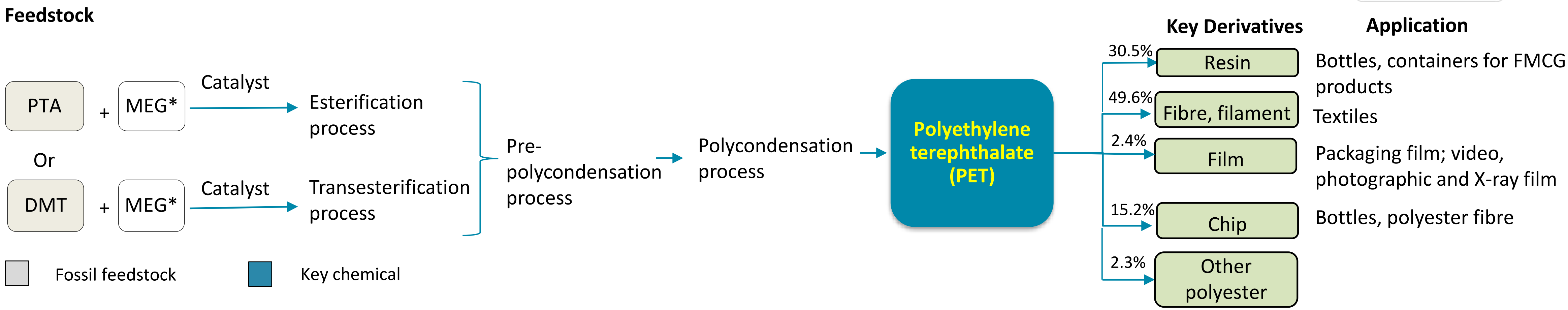
# Value chain




**PEF**

PEF can be produced from renewable feedstocks by a multistep process that involves catalytic dehydration of carbohydrate feedstock in an alcohol (*e.g.* methanol) to make alkoxymethyl furfural (RMF). This is followed by catalytic oxidation of RMF in acetic acid to make FDCA. Finally, polymerisation of FDCA and MEG is carried out to form PEF. This is a patented process by Avantium, known as the YXY technology, and has been tested at pilot scale. [5]

# Value chain *(continued)*




*Derived from bio-based or fossil-based ethylene

**PET**

PET can be produced from MEG (monoethylene glycol) and either purified terephthalic acid (PTA) or dimethyl terephthalate (DMT). The main process steps are raw material preparation, esterification/transesterification, pre-polycondensation and polycondensation.

PTA is preferred to DMT as the PTA process eliminates the need to recover methanol while having the added advantage that esterification to the pre-polymer step is faster that the transesterification reaction using DMT. However, DMT may be favoured in polyester film applications due its adhesion addition quality. [3, 6]

# Demand

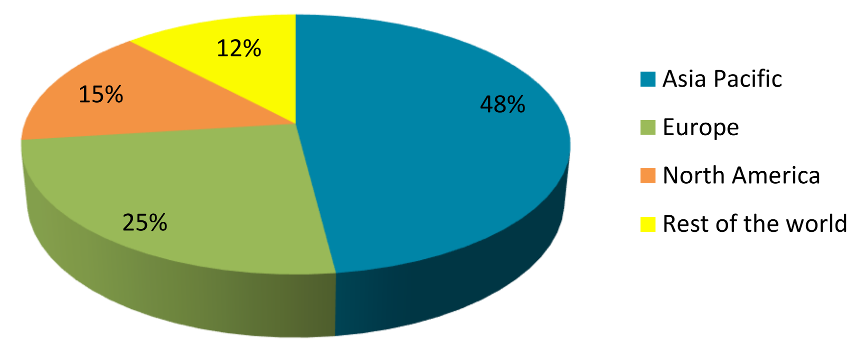
**PEF**

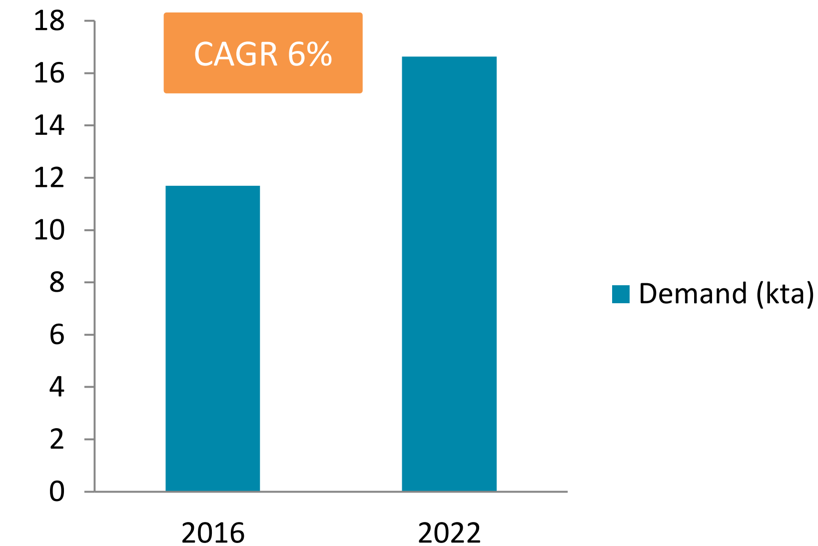
Global PEF market is at a nascent stage of development. Global demand was close to 12 kta in 2016 and is expected to grow to nearly 17 kta in 2022. [9,10] The PEF market in the Netherlands was around 223 tons in 2016 and is expected to expand at a CAGR of 8.8% in the 2016-2022 period. [10] Although PEF market volume was led by the Asia Pacific region in 2016, Europe is likely to emerge as the most promising region (CAGR of 7%) in terms of volume. Stringent regulatory standards and increasing demand for sustainable packaging are anticipated to accelerate PEF market growth over the forecast period. Demand for PEF is mainly in the packaging of beverages, that is, PEF-based bottles as an alternative to fossil-based PET bottles.

PEF faces strong competition from bio-based PET. A recent study suggests that of 6.1 million tons of bioplastics that could be produced in 2021, 1.1% will be PEF while 28.2% will be PET. [11] Coca Cola has been supporting Virent since 2011 for R&D in producing p-Xylene from sugarcane residue, which in turn can be oxidized to PTA for use in the conventional production of PET.[4] The fully recyclable and 100% bio-based plastic bottle has been marketed as PlantBottle™. Prior to the partnership with Virent, the PlantBottles were made of 30% bio-based material (bio-MEG). As of 2017, PlantBottle™ packaging is used in 6 billion bottles every year worldwide.[7,8]

PEF also competes with polytrimethylene furandicarboxylate (PTF) polymer. DuPont is focusing on the production of the PTF which is similar to PEF. PTF can be used for the manufacture of beverage bottles and other applications currently served by PET. The monomer they plan to use is furan dicarboxylic methyl ester (FDME), a derivative of FDCA. The process was developed in partnership with ADM (US-based agricultural processor). [15] DuPont and ADM opened a 60 tpa pilot plant for producing FDME in 2018. [16]

**PEF regional market volume (2016)**



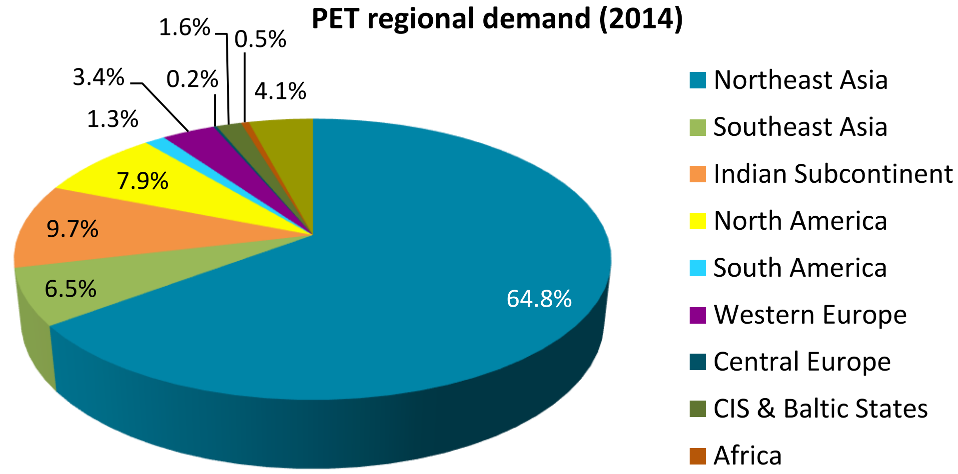



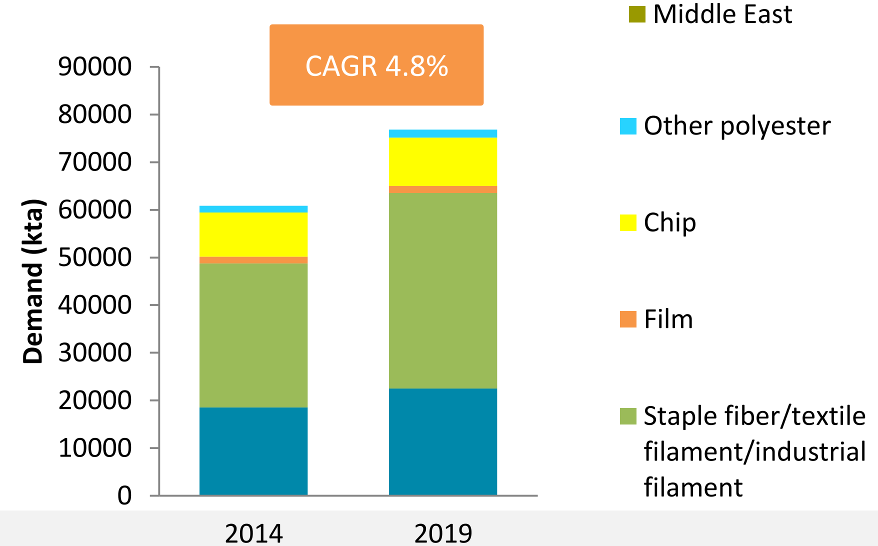
# Demand *(continued)*

**PET**

Global consumption of PET reached 60,828 kta in 2014 and is expected to be well over 76,000 kta by 2019, with the market expanding at a CAGR of 4.8% in the forecast period. Demand for PET is highest in Asia. The staple fibre *(used for fillings in pillows and sofa)*, textile filament *(used in producing fabrics and textiles)* and industrial filament *(used in making tyre cord, car safety belts, conveyor belts)* segments together make up more than half the demand for PET globally. Solid state resin, which is used to make bottles and containers, is the next segment that is in high demand. [4]

The solid state resin segment is of interest for PEF producers such as Avantium who intend to produce a PEF bottle-grade resin that can substitute PET bottle-grade resin. Global consumption of PET bottle resin was estimated at 19.4 million tons in 2015, and is expected to grow at a rate of 5% per annum. [4]



# Supply

**PEF** production is at a nascent stage and involves the following companies:

Avantium, Corbion, Toyo Seikan Kaisha, AVALON Industries, Origin Materials *(not an exhaustive list)*

**Synvina** is a Joint Venture of **Avantium** and **BASF**, located in Amsterdam, and operates a pilot plant in Geleen (in the Netherlands). Synvina produces and markets furandicarboxylic acid (FDCA) from renewable resources on pilot plant scale and markets the new polymer polyethylene furanoate (PEF). [12] The pilot phase has been extended in order to improve the production process. [13]

**Coca Cola**, **Danone** and **ALPLA** have Joint Development Agreements with Avantium for development of PEF bottles based on Avantium's 'YXY technology'. [17] Further, **Wifag-Polytype** and Avantium are collaborating on producing 100% bio-based PEF thermoformed products such as cups, containers and trays. [18] In 2016, Avantium established a partnership with **Toyobo** for PEF polymerization and PEF films. [21]

**Corbion** is developing 100% biobased FDCA for PEF. [19] The process is at pilot scale and a toll manufacturer has produced several tonnes of HMF using this process. [20] This HMF has been used to produce FDCA at the Bioprocess Pilot Facility in Delft. [20]

**AVALON** Industries' 5-HMF (5-Hydroxymethylfurfural) platform chemical is the key molecule for bio-based plastics like PEF. The AVALON HTP technology uses C6 sugars to produce 5-HMF in crystalline form or in aqueous solution. [22]

US-based **Origin Materials** aims to make competitively priced FDCA from lignocellulosic feedstocks. It acquired technology from Eastman Chemical for making FDCA from sugar, and also purchased an Eastman oxidation pilot plant. The company has partnerships with Danone and Nestlé to develop biobased monomers for bottles. [15]

In 2017, the European Joint Undertaking on Bio-Based Industries (BBI) granted €25 mn to "**PEFerence**", a consortium of eleven companies including Synvina, BASF and Croda*. The grant supports the establishment of an innovative value chain for bio-based raw materials as well as chemicals and materials based on polyethylenefuranoate (PEF). It includes the intended construction of a 50 kta FDCA reference plant, the main chemical building block for PEF. Synvina will be coordinating the "PEFerence" project. [14, 23]

# Supply *(continued)*

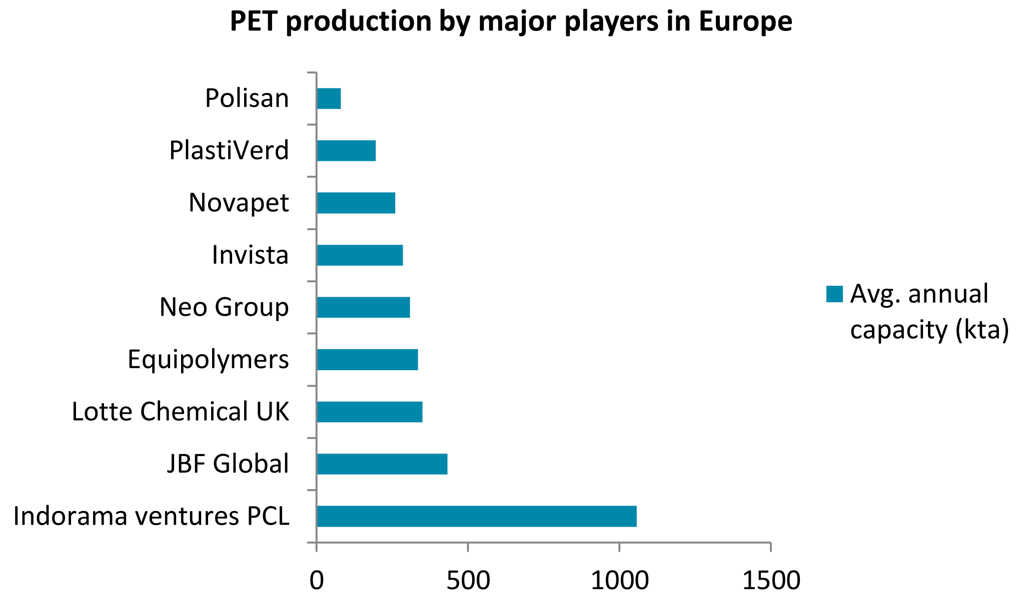
**PET**

As of 2014, the total capacity for PET polymer production in Europe was >3.6 million metric tons, which represented > 4% of the total global capacity. [4]

The most important producers in Europe are Indorama Ventures *(PTA production in the Netherlands, Spain, and Portugal; PET production at 6 locations*), Neo Group *(PET production: Lithuania)*, Novapet *(PET production: Spain)*, Invista *(PET production: Germany)*, Equipolymers *(PET production: Germany)*, Lotte Chemical UK Ltd *(PET production: UK)*, PlastiVerd *(PET production: Spain)*, JBF Global *(PET production: Belgium)*, and Polisan Hellas SA *(PET production: Greece)*. [24]

As of 2015, over 360 kta of PET was being imported from South Korea, Indonesia and Turkey. [25]

PET recycling has been given priority in the EU, and as of 2016 nearly 60% of all PET bottles and containers placed in the European market were collected (1,880.9 kt) and 1,773.2 kt were mechanically recycled. [26]



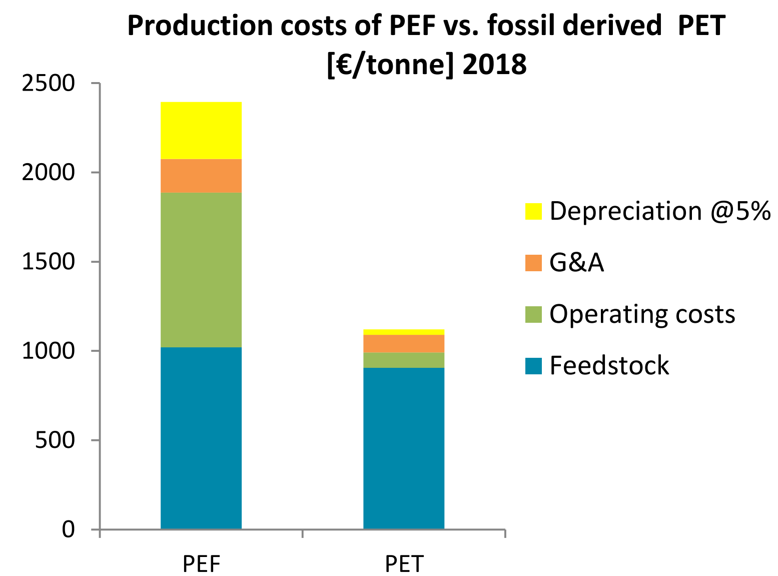
# Cost and environmental performance

Currently PEF production costs are more than double those of PET, which is mainly because of high operating and capital expenditures of PEF manufacturing. PEF is still produced on a small scale and it has not gone through the decades of learning that PET production has. Gradual increase in PEF production capacities is likely to create an opportunity to improve process efficiency and bring down capital and operating costs.

Higher value applications where consumers are prepared to pay extra for advanced performance of PEF over PET are likely to drive the initial demand growth and PEF production scale. This will enable PEF to reach the next level of applications at which point the bio-based polymer starts to be produced on a larger scale.

Another opportunity to bring down PEF production cost is to switch to cheaper feedstock. Today PEF is mainly produced from fructose which gives high yields to FDCA. Isomerization of glucose to fructose is economically limited to 42%, requiring additional and expensive separation steps. As a consequence, the final market price of fructose is significantly higher than that of glucose. Single step conversion of glucose to FDCA, which would eliminate expensive separation steps could present an opportunity to reduce PEF feedstock cost. High yield single-step conversion of glucose to FDCA has already been successfully demonstrated on a lab scale. Investments are needed for further development of this technology and demonstration at commercially relevant scales. [32]

Production of PEF from FDCA has environmental advantages, reducing the non-renewable energy use by 51% - 58% compared to PET, and producing GHG emissions of 1.4 – 2.1 $tCO_2$/ t-product compared to fossil PET emissions of 3.8 – 4.4 $tCO_2$/ t-product (a saving of approximately 60%).




PEF is not yet produced at a commercial scale. Presented production cost are estimated for a PEF plant of about 150 kta, which is comparable to a medium size PET plant. PEF production cost are estimated for an integrated production process which includes conversion of fructose to FDCA and polymerization of FDCA and MEG into PEF.

# SWOT analysis - PEF

| Strengths | Weaknesses |
|---|---|
| • Improved functionality vs. PET: better barrier properties and mechanical strength<br>• PEF is entirely made from renewable feedstock and it is more sustainable than fossil PET | • Not easily recyclable<br>• PEF is still not produced on a commercial scale |
| **Threats** | **Opportunities** |
| • Competition with other bio-based polymers *e.g.* PTF and bio-PET<br>• Big focus on recyclability in Europe – circular economy | • Development of fully recyclable products<br>• Easily used in higher volume applications – *e.g.* packaging<br>• Could be used in lesser amount than PET for same product<br>• PEF can be produced in existing PET plants<br>• Switching to cheaper feedstock *e.g.* glucose *vs* fructose could improve PEF's cost competitiveness |

# Potential and Barriers

| Opportunities | Issues |
|---|---|
| **Techno-economic factors**<br>• A major advantage of PEF compared to PET is the technical superiority. PEF offers improved gas barrier properties important for food and drinks packaging as well as tensile strength properties, which makes PEF more than a direct replacement for PET. PEF can in fact be used for applications currently serviced by much more expensive multilayer, aluminium, steel or glass solutions.<br>• Another major opportunity for PEF is that existing PET polymerisation assets can be used with minimal capital investment for retrofitting.<br>• Strong demand for sustainable packaging represents an opportunity for PEF polymer<br>• Due to its superior properties PEF polymer could potentially access large market by replacing PET, aluminium and glass in various applications. | **Techno-economic factors**<br>• PEF is still not produced at commercial scale. Production costs are still too high to compete with fossil derived PET or other materials (aluminum or glass) which this bio-based polymer could replace.<br>• PEF faces strong competition from other bio-based polymers such as PTF and bio-based PET.<br>• To feature in circular economy PEF recyclability must be improved |
| **Environmental factors**<br>• PEF is entirely made from renewable feedstock and it is more sustainable than PET.<br>• Low biodegradability. | **Environmental factors**<br>• Careful consideration of sustainability of biomass feedstocks used |

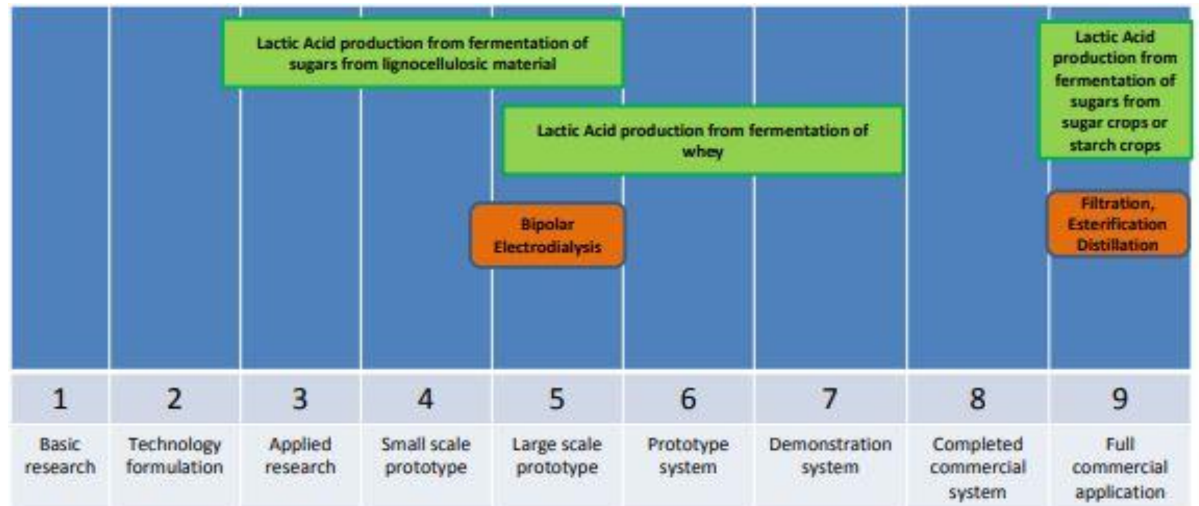
# 5.3 Lactic acid

Lactic acid is used in a wide range of food processing and industrial applications. Lactic acid has the potential of becoming a very large volume, commodity-chemical intermediate produced from renewable carbohydrates for use as feedstocks for biodegradable polymers, oxygenated chemicals, plant growth regulators, environmentally friendly 'green' solvents, and specialty chemical intermediates.[2]

Lactic acid is commercially available today, however, the different production technologies are at different levels of maturity as summarized in the figure to the right. [14]

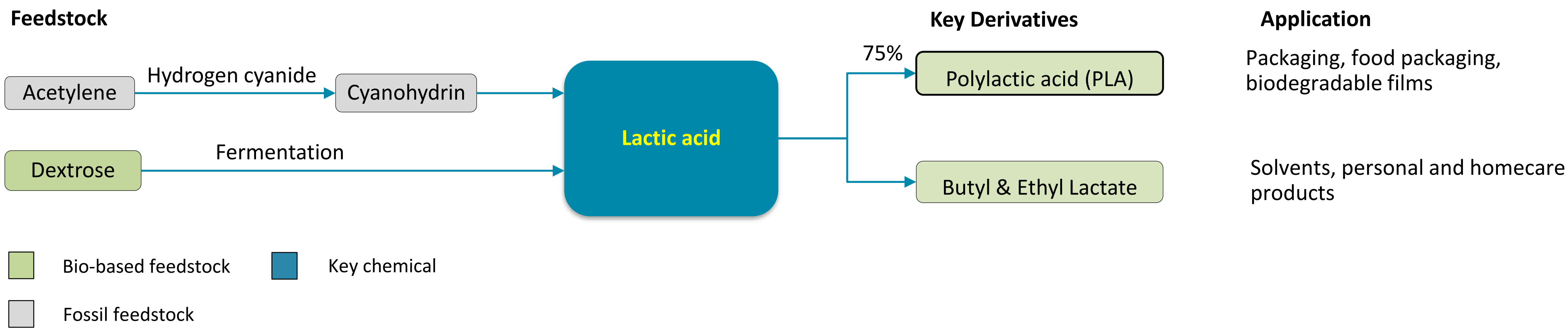
Lactic acid exists as two optically active isomers (enantiomers or stereoisomers) referred to as L (+) lactic acid and D (-) lactic acid. Synthetic *i.e.* petrochemical routes result in a racemic mixture that contains each enantiomer in equal proportions. On the other hand, biological routes (fermentation) are designed to produce an optically pure product.

**Technology readiness levels for lactic acid production**




*Source: European Commission*

# Value chain




**Lactic acid** is commercially produced by bacterial fermentation of carbohydrates (sugar, starch) or by chemical synthesis from acetaldehyde, that is available from coal or crude oil. Today most of the lactic acid is produced by fermentation process rather than chemical synthesis. This is because although synthetic routes produce a high quality product, they use hazardous raw materials (hydrogen cyanide), have high energy intensity due to triple distillation, cannot only make the desired L-lactic acid stereoisomer, and overall suffer high manufacturing costs.[1]

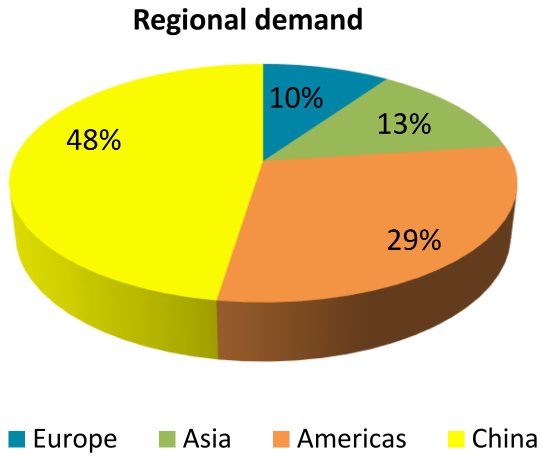
The majority of demand is for L-lactic acid. At the lowest level of purification, L-lactic acid is used in animal fodder, in which the residues from fermentation add value as flavours and nutrients. High purity L-lactic acid is employed as active ingredient for antimicrobial cleaning and personal care formulations. L-lactic acid at the very highest levels of purification is used in cosmetics and pharmaceuticals [11]. D-lactic acid can serve as a building block for PLA polymers used in food serviceware, rigid and flexible packaging, toys, electronics, nonwoven filtration materials, and personal care products. [12]

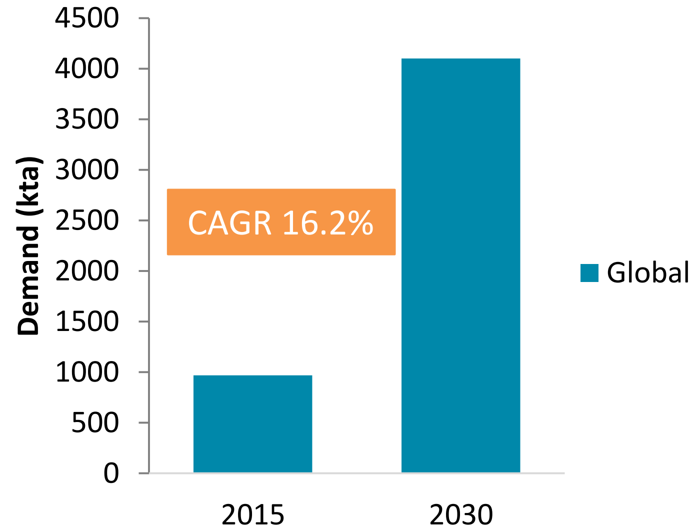
# Demand

Global demand for lactic acid in 2016 was around 1200 kta and it is expected to grow to > 4,000 kta by 2030 at a CAGR of 15.5% [13]. Maximum demand for lactic acid is in Asia, especially China. Demand for lactic acid in Europe was 120 kta in 2016 [13].

The main uses of lactic acid and its derivatives are in the production of food additives, personal care products, and biodegradable plastics. There is also a market for lactic acid in the manufacture of industrial chemicals and products for the medical and pharmaceutical sectors [11,12,13].

In 2015, highest demand for lactic acid was in food and beverage applications. Polylactic acid (PLA) manufacture was the second-largest end use of lactic acid. It is anticipated that PLA manufacture will be the leading application for lactic acid by 2020. [16] Demand for more environmentally-friendly packaging products, and the use of PLA in starch-based plastics is expected to drive demand for PLA over the next few years. [18] Growing application from industrial and personal care may promote lactic acid market size. Lactate ester solvent including butyl lactate and ethyl lactate are biodegradable and non-toxic in nature and provide use in consumer and industrial applications.



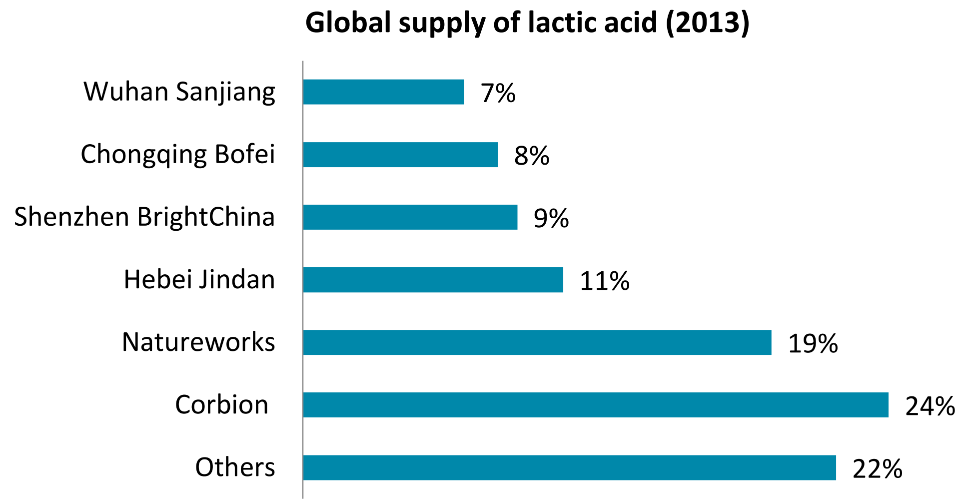
# Supply

Lactic acid industry is consolidated. The global market is dominated by Corbion (225 kta; production in the US, Netherlands, Spain, Thailand, and Brazil) and NatureWorks (180 kta; production in the US). Other producers, which have smaller market share are mainly in Asia.

Technologies for producing bio-based lactic acid and its key derivative PLA, are today available at a commercial scale. Companies which specialize in development and licensing of lactic acid and PLA technology include: ThyssenKrupp, Myriant (licensed to Corbion), Plaxica (Optipure D-lactic acid process technology licensed to NatureWorks), Hitachi Global.

New capacities of lactic acid and PLA are forecasted for Asia region, which expects the fastest growth driven by increasing demand from end user markets. There is no evidence which indicates that new production capacities of Lactic acid or PLA are planned Europe.

However, considering that in Europe there is a growing demand for bio-based and sustainable plastics, and that Europe is becoming more strict on use and release of toxic and non-degradable chemicals in the environment; opportunity could be large for PLA-based polymers and non-toxic lactic acid-based solvents which are biodegradable and non-toxic to the environment. Increasing local supply of lactic acid could potentially meet European market needs and reduce import dependencies in the future.



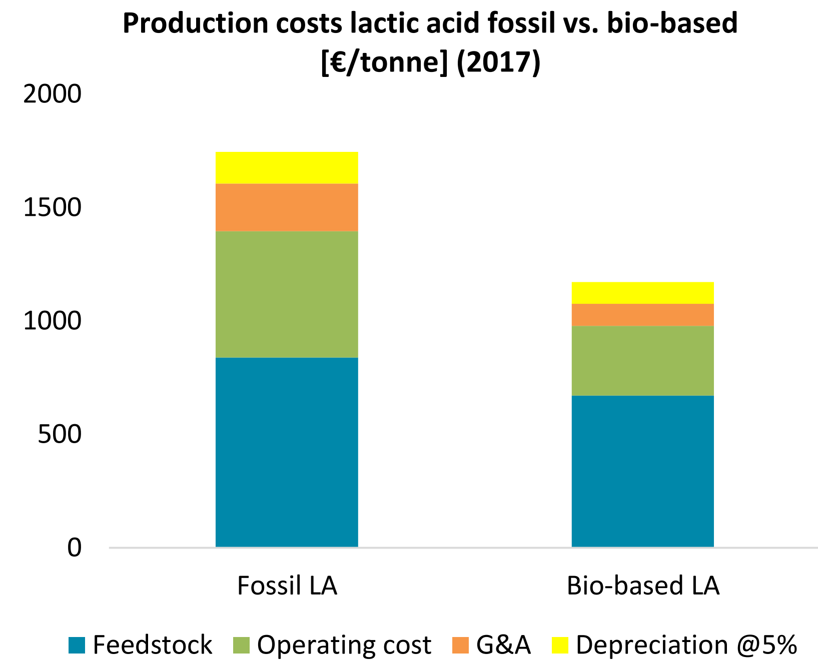
# Cost and environmental performance

Lactic acid is a good example of industry switching from fossil to bio-based. Bio-based production of lactic acid uses cheaper and safer feedstock: glucose vs. acetaldehyde/hydrogen cyanide, uses less energy and produces optically pure product.

Major derivative of lactic acid is polylactic acid (PLA) polymer which is often used for packaging, food packaging, disposable wipes, etc. PLA is biodegradable plastic, it offers a substantial reduction in GHG emissions (30% -70%) and energy use compared to competing fossil equivalents such as polypropylene (PP), polystyrene (PS) and polyethylene terephthalate (PET). However PLA suffers from performance drawbacks as compared to conventional plastics. For example, PLA is brittle, it has poor gas barrier performance and is susceptible to distortion at relatively low temperatures.

Despite mature manufacturing technology PLA is still not cost competitive option for packaging, it is still more expensive than fossil alternatives that serve similar markets. At the end of 2017 polylactic acid was traded at about 2600 €/tonne in Western Europe [17], while PET market price was estimated at about 1100 € /tonne.

To improve cost competitiveness, PLA feedstock costs (bio-based lactic acid) and production costs have to be further reduced. At the same time its performance characteristics have to be improved to be at least comparable to its fossil equivalents PP, PE and PET.




Capital costs are estimated for fossil and bio-based processes of about 100 kta. Bio-based lactic acid process assumes sugar feedstock of 380 Euro/tonne

# SWOT analysis

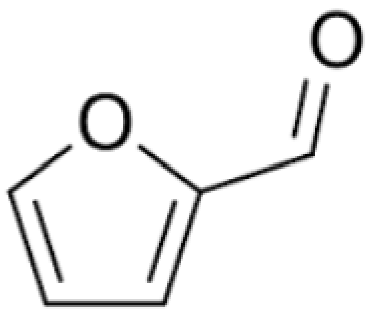
| Strengths | Weaknesses |
| --- | --- |
| • Nontoxic and biodegradable as a solvent<br>• There are several markets<br>• Lower price than other biodegradable polymers | • PLA is brittle polymer<br>• To improve performance PLA requires a lot of additives and plasticizers which can reduce biodegradability and renewability character<br>• Use in applications other than PLA plastic are still fairly low<br>• No established recycling stream |
| **Threats** | **Opportunities** |
| • PLA has no advanced performance characteristics compared to other plastics | • Development of fully recyclable process for PLA<br>• Chemical recycling |

# Potential and Barriers

| Opportunities | Issues |
| --- | --- |
| **Techno-economic factors**<br>• Bio-based production of lactic acid is more cost-effective compared to fossil<br>• Bio-based lactic acid and PLA manufacturing process is mature<br>• PLA could potentially be used in large volume applications replacing fossil plastics in packaging and food packaging<br>• Strong demand for sustainable packaging represents an opportunity for bio-based lactic acid and PLA polymer | **Techno-economic factors**<br>• To feature in circular economy PLA recyclability must be improved<br>• PLA polymer suffers from brittleness, poor gas barrier performance and is susceptible to distortion at relatively low temperatures (i.e. lower heat resistance). Fossil equivalents such as PE, PP and PET outperform PLA in packaging and food packaging applications. |
| **Environmental factors**<br>• Bio-based lactic acid is more sustainable than fossil based – uses less energy and it does not use harmful chemicals in the production process<br>• PLA provides GHG emissions savings of between 30 – 70% compared to its fossil equivalents PE, PP and PET<br>• PLA offers a strong environmental incentive for replacement of fossil equivalents. It has a lower carbon footprint and uses less energy, and offers improved end-of-life options because it is biodegradable and low in toxicity | **Environmental factors**<br>• Careful consideration of sustainability of biomass feedstocks used |

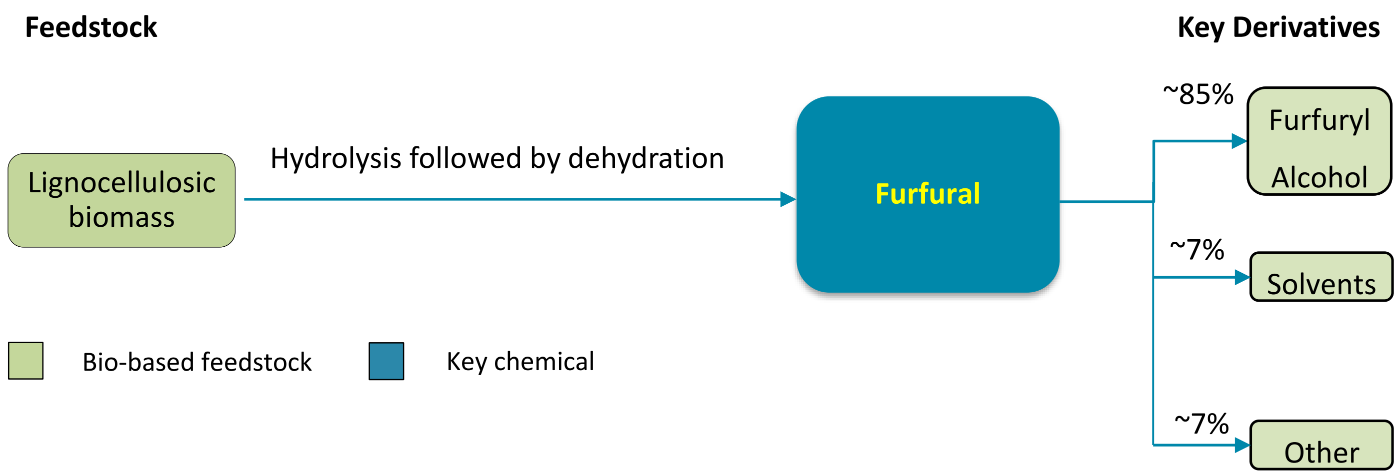
# 5.4 Furfural

Furfural, or furfuraldehyde, is a oily liquid, produced by dehydrating xylose, a monosaccharide found in large quantities in the hemicellulose fraction of biomass. Any material with a sufficient amount of 5-carbon sugars (pentosans) can be used as feedstock for furfural production, though lignocellulosic agricultural waste, such as bagasse, corn cobs, and wheat bran are being used extensively. Furfural is not produced from fossil feedstocks so all current – and presumably future – production is biobased.




Furfural was first produced commercially in 1922 by the Quaker Oats Company. Main reason for their furfural production was the large quantities of surplus oat hulls for which they had no application. Furfural production starts with pre-treatment followed by acid hydrolysis (mainly sulphuric acid) to release the pentoses from the biomass. The next step is dehydration using acid and steam to produce the furfural. The furfural is recovered by steam stripping from the solution. Yields are generally low: about 50% of mono sugars is converted into furfural. The traditional Quaker Oats process consumes large amounts of energy and sulphuric acid. More recently, new processes, like the SupraYield technology, are being developed. Other developments are combinations of furfural production with cellulose ethanol production.

# Value chain




**Application**

Resins for foundry moulds (main application)
Furan fiber-reinforced plastics, Converted to 1-pentanol (coating material for DVD's), Wood modification

Tetrahydrofurfuryl alcohol (THFA) (green solvent used in agriculture, printing ink, cleaners), 2-methyltetrahydrofuran (MTHF) (specialty solvent), Tetrahydrofuran (THF) (solvent for chromatography applications)

2-methylfuran (MF) (feedstock for antimalarial drugs, other intermediate chemicals), Nitro substituted furans are used as biocides or fungicide. Sulphur substituted furans are used as flavouring agent, Cyclopentanone (pharmaceuticals, insecticides, rubber chemicals), Cyclopentanol (perfume, pharmaceutical solvent, intermediate for dyes and pharmaceuticals, Maleic Anhydride (polyester resins used in fiber-reinforced plastics, alkyl resins used in paints and coatings)

**Value chain summary**

Furfural is produced from the pentosans in lignocellulosic biomass. Dedicated production involves hydrolysis with an acid catalyst, followed by dehydration. Furfural can also be produced as a by-product during the production of cellulose ethanol, or cellulose pulp (for paper production). Derivatives like furfuryl alcohol are produced via catalytic hydrogenation.

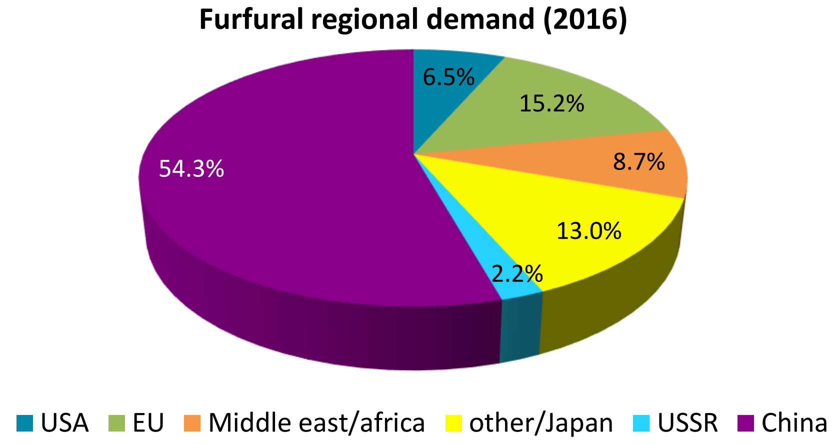
Current (dedicated) furfural production is a process characterised by a low yield (approx. 50%), high steam use (20-50 tonne of steam per tonne of furfural) and high (sulfuric) acid consumption (20% of furfural output). New process developments aim to increase the yield or reduce energy consumption during the purification step.

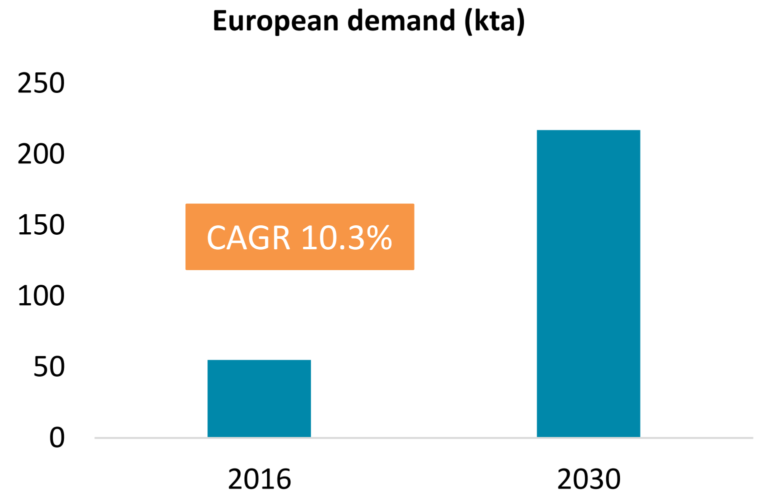
# Demand

Global furfural market demand was 270 ktonne in 2012 and is expected to reach 652.5 ktonne by 2020, growing at a CAGR of 11.9% from 2014 to 2020. The European market has a slightly slower growth with a CAGR of 10.3%. Reasons for this growth forecast are shifts towards minimizing dependence on fossil chemicals, and the recent emergence of more applications for furfural. China is an important market for furfural, mainly because of the many applications of furfuryl alcohol.

Growth in furfural demand in the EU is expected, though from a relatively low base. Total EU demand is estimated to lie between 40– 70 ktonne/year. From 1995 until 2012 there was an anti-dumping regulation in force in the EU. This anti-dumping regulation was aimed at China. In 2012 this anti-dumping regulation was repealed, on the basis that no significant below-price dumping took place anymore.

Historical prices of furfural have shown to be volatile. In 2002 market prices of furfural were reported to be 1874 USD /tonne. In the years up to 2009 prices remained stable between 720 – 1300 USD/tonne. Most recent price information lists 1250 USD/tonne. Chinese conditions as regard to supply of raw material (agricultural waste such as corn cobs) are of prime importance for the global market price.



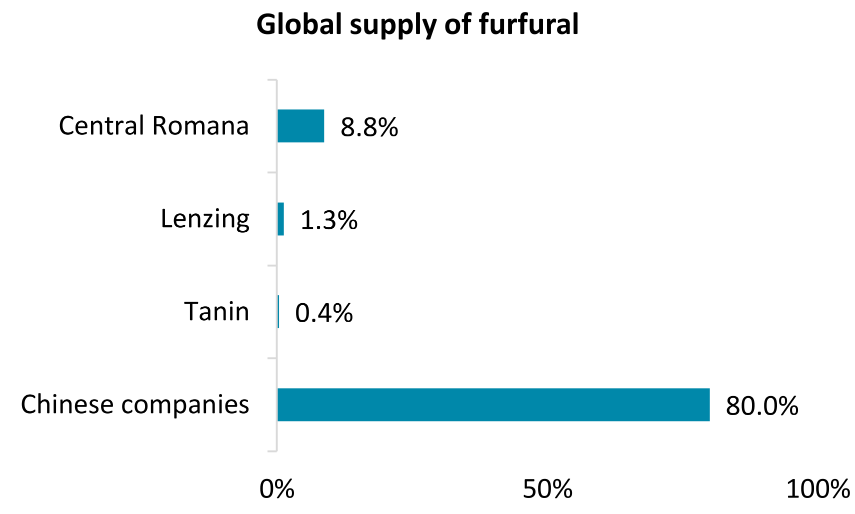
# Supply

Most of the furfural production takes place in China. South Africa and the Dominican Republic are the second and third largest suppliers. The furfural market is reported to be fragmented, with a presence of a large number of small scale manufacturers in China. Major companies operating in the global market include Teiling and Central Romana Corp., and Lenzing and Tanin are the major European players.

In Europe there are two producers of furfural, which hold only a small part of the total production:

- Lenzing AG from Austria produces furfural as a by-product from their wood pulp production. They operate two pulp plants in Europe, with a production capacity of approximately 560,000 tonnes of pulp during 2017. Their furfural production is estimated at 5,000 tonne per year.
- The company Tanin sevnica kemicna industrija of Slovenia produces furfural from wood chips in a dedicated process. Their total production capacity is estimated at 1,500 tonne/year.

A recent development worth mentioning is the planned 300,000 tonne/year biorefinery to be implemented in India by Chempolis, Fortum and Numaligarh Revinery Ltd. The facility is currently expected to begin operations in 2020. The plant will produce annually 60 million liters of bioethanol, 19,000 tons of furfural, 11,000 tons of acetic acid, and 144 gigawatt hours of green energy.



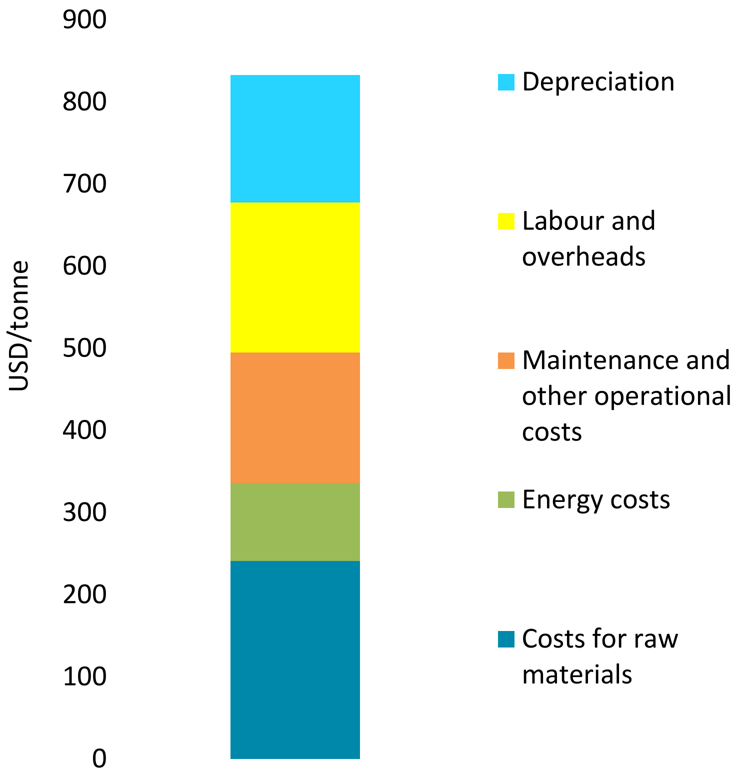
# Cost and environmental performance

The options for producing furfural in the 'traditional' way in Europe are considered limited. The traditional process is inefficient, which means that the raw material costs are high. Furthermore, large quantities of steam – and therefore energy – are required further increasing the costs. There are finally safety issues, such as toxicity and corrosivity, related to the handling of large quantities of aqueous sulphuric acid required for the hydrolysing step. The fact that production in the EU is currently very small is testimony of these concerns.

There are however opportunities for production of furfural in the EU when it can be combined with other processes, such as cellulose ethanol production or wood pulp production. In practice, any large pentosan-rich residue stream can in principle be utilised. Utilising a residue stream also eliminates the need for using large quantities of sulphuric acid.

An estimation of the production cost breakdown is presented to the right (in USD as this is the standard for the global furfural market). In this estimation, it is already assumed that the furfural purification step can be replaced by vacuum recompression, eliminating 95% of the energy costs. Besides that, raw materials – assuming a reasonable price for the pentosans – are the largest production cost factor.

In terms of environmental performance, there is no reliable evidence from literature about GHG emissions savings. However, the use of agricultural waste streams as feedstock for furfural production helps tackle waste accumulation and is an example of waste valorisation.



# SWOT analysis

## Strengths

- Uses non-food biomass as feedstock.
- Established applications that are already economically viable.

## Weaknesses

- The European market is small compared to the global market.
- Limited number of product applications at commercial level.

## Threats

- Furfural production is codependent on the production of other products.
- The resin produced is black, which limits its applications.

## Opportunities

- The European market for furfural is much larger than the European production.
- Chemical routes to FDCA are possible, which could lead to PEF. These routes are currently at very low TRL.
- The furan functionality could enable furfural to establish itself as a platform chemical.

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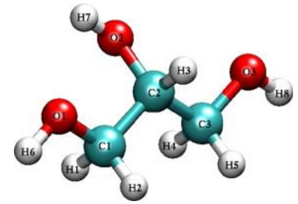
# Potential and Barriers

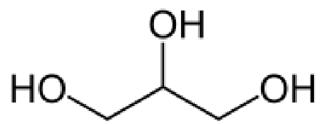
| Opportunities | Issues |
|---|---|
| **Techno-economic factors**<br>• Furfural is already produced and used on a large scale. With the increasing number of applications, the demand for furfural is expected to continue to grow rapidly.<br>• The European market is currently mostly supplied by furfural from the Americas and China. European production is very limited compared to the European market.<br>• It is formed as a by-product in older and established industries. Because of this, the main product may pay for the logistics. However, this can become an issue when larger production volumes are desired, since the volume of furfural production is linked to the volume of the main product produced. | **Techno-economic factors**<br>• Direct, dedicated furfural production is too costly in terms of high energy use and low yields. Such a production would not be feasible within the EU. Improvements are being made in this area, however, none of these techniques have reached higher scale systems yet.<br>• A more feasible production of furfural is therefore linked to the production of other chemicals, where this could be a benefit in some cases, this can also act as a constraint.<br>• Even though European production is much smaller than the European market, the European market is still small compared to the global market. This incentivises companies to build outside of Europe instead. |
| **Environmental factors**<br>• Furfural can be produced from agricultural waste streams, which prevents waste and has a low impact on the environment. | **Environmental factors**<br>• Furfural is toxic.<br>• Careful consideration of sustainability of biomass feedstocks used |

# 5.5 Glycerol

Glycerol is the simplest alcohol and named propane-1,2,3-triol according to IUPAC. It is also commercially known as glycerine or 1,2,3-propanetriol. The term “glycerol” is only applicable to the pure chemical compound 1,2,3-propanetriol, while the term “glycerine” normally applies to purified commercial products with contents of higher than 95% glycerol. This versatile molecule finds broad applications in the pharmaceutical, personal care, food & beverages, and tobacco industries.



Crude glycerol is a by-product of fatty acids and fatty alcohols production. It is not contaminated with methanol and catalyst’s salts, and also has a much lower content of other organic impurities. This glycerol is usually completely converted into refined products, and mostly to those of Pharmaceutical or Kosher/Halal quality.



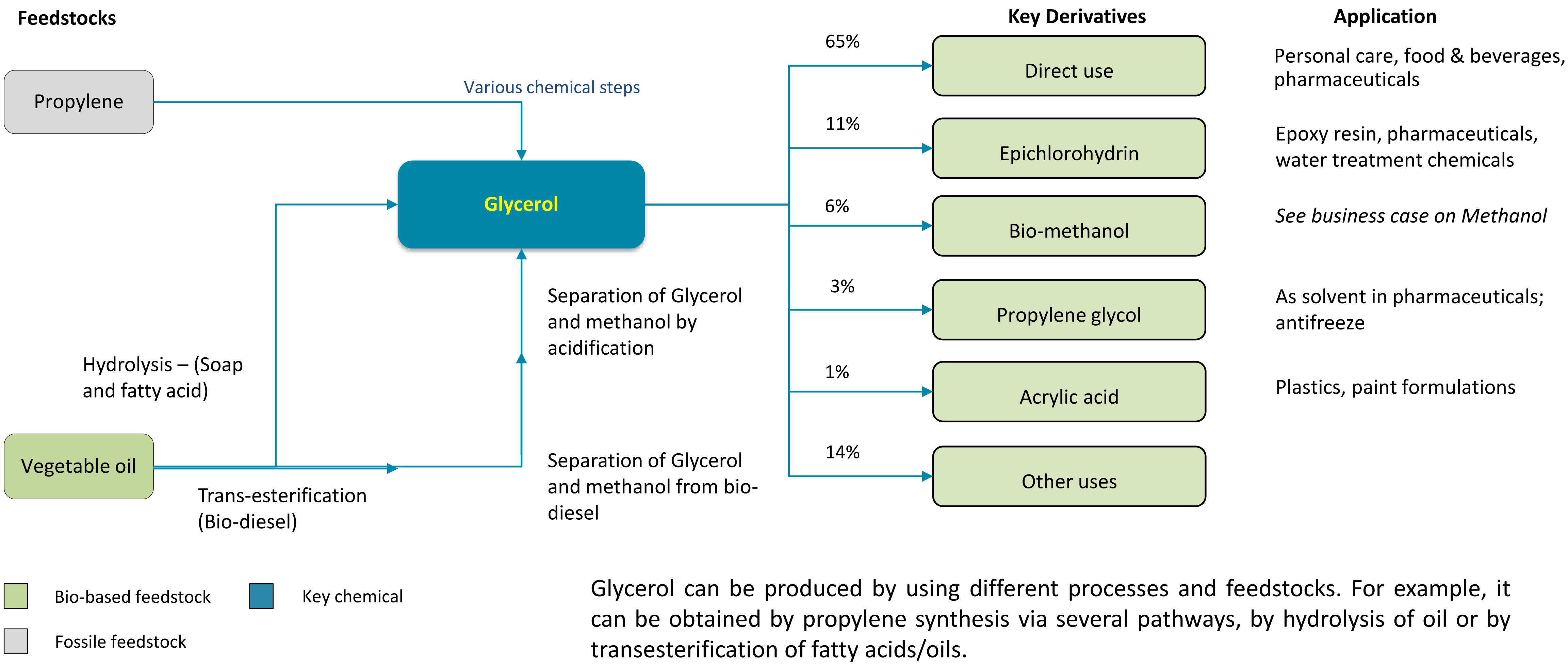

Crude glycerol from biodiesel units is commonly composed of around 80 % glycerol with small amounts of water, fatty acid, ash and methanol. Crude glycerol is not pure enough for direct use in many applications. To overcome this problem, impurities must be removed by an efficient purification process to minimize production costs and waste. It is possible to purify up to Pharmaceutical or Kosher/Halal quality, but it is not economically viable except for large-scale biodiesel factories.

**Refined glycerol** is classified into three main classes, related to glycerol purity:

- Technical grade (95.5% purity) – used as a building block in chemicals, not for food or drug formulation;
- USP glycerol from animal fat or plant oil sources, suitable for food products and pharmaceuticals;
- Kosher glycerol from plant oil sources (99.5-99.7% purity), suitable for use in kosher foods

Based on [1,7]

# Value chain




Glycerol can be produced by using different processes and feedstocks. For example, it can be obtained by propylene synthesis via several pathways, by hydrolysis of oil or by transesterification of fatty acids/oils.

Based on [2,7]

# Value chain *(continued)*

**Glycerol value chain**

**Bio-based glycerol** (Biodiesel producers, Soap producers
Fatty acid producers, Fatty alcohol producer)
**Petro-based glycerol**

**Direct**

**Distributor**

**Intermediate Chemicals (**Epichlorohydrin, Propylene glycol, Alkyd resins, Polyether polyols, Triacetin)

**End users (**Personal care, Food and Beverage, Pharmaceuticals)

- **Biodiesel producers**
  - Bioeton Kyritz
  - Biopetrol Rostock
  - Glencore
  - Biopetrol
- **Fatty acid producers**
  - Croda
  - Oleon
  - IO Oleo
- **Fatty alcohol producers**
  - BASF
  - Ecogen
  - Sasol
- **Distributors**
  - Brenntag
  - Univar
  - Helm
- **Personal care**
  - Henkel
  - L'Oréal
- **Food and Beverage**
  - Nestle
  - Ritter Sport
- **Pharmaceuticals**
  - HEXAL
  - Novartis
- **Epichlorohydrin**
  - Dow
- **Propylene glycol**
  - Oleon
  - Evonik
- **Alkyd resins**
  - BASF
  - Ipox
- **Polyether polyols**
  - Covestro
  - Wanhua chemicals
- **Triacetin**
  - Eastmann
  - Lanxess

*Non-exhaustive list*

# Demand

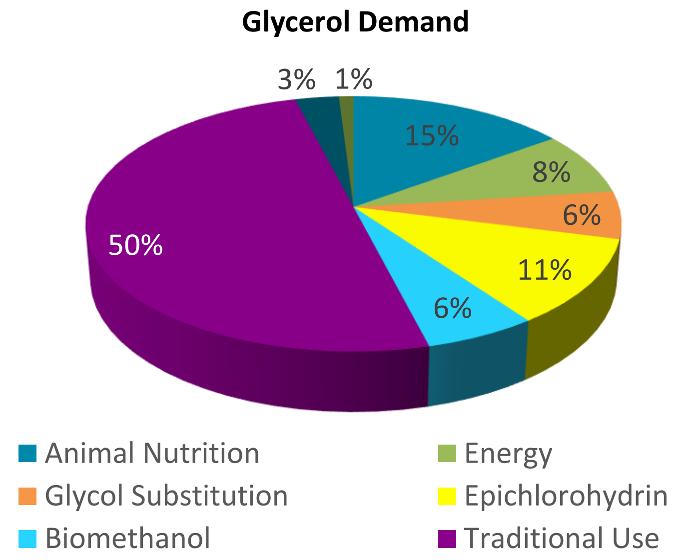
More than 55% of the world's demand for crude glycerol comes from two regions: Europe and South-East Asia. While Europe is the biggest buyer of crude glycerol, Asia is the biggest producer and consumer of refined glycerol, using approximately 35% of world's supply.

Europe consumes 28% of refined glycerol produced annually in the world and North America around 19%.

| Utilisation pathway | Future plant concept | Estimated European glycerol demand *via* biodiesel route (t/a) |
|---|---|---|
| Food supplements | Vitamin B12<br>Beta-carotene<br>DHA<br>Trehalose | 250<br>1,000<br>6,500<br>11,500 |
| Green chemicals | 1,3 PDO - concept 1<br>1,3 PDO - concept 2<br>PHA<br>Polymers | 125,000<br>160,000<br>300,000<br>250,000 |
| Biofuels | Ethanol, butanol, FAGE | 200,000 |

*Brosowski, A., et al., 2017*

** Future plant concept: Currently no one is producing the chemicals/fuels/supplements mentioned in the table using glycerol. The quantities mentioned are a futuristic demand estimate if at all glycerol is used for these applications.*



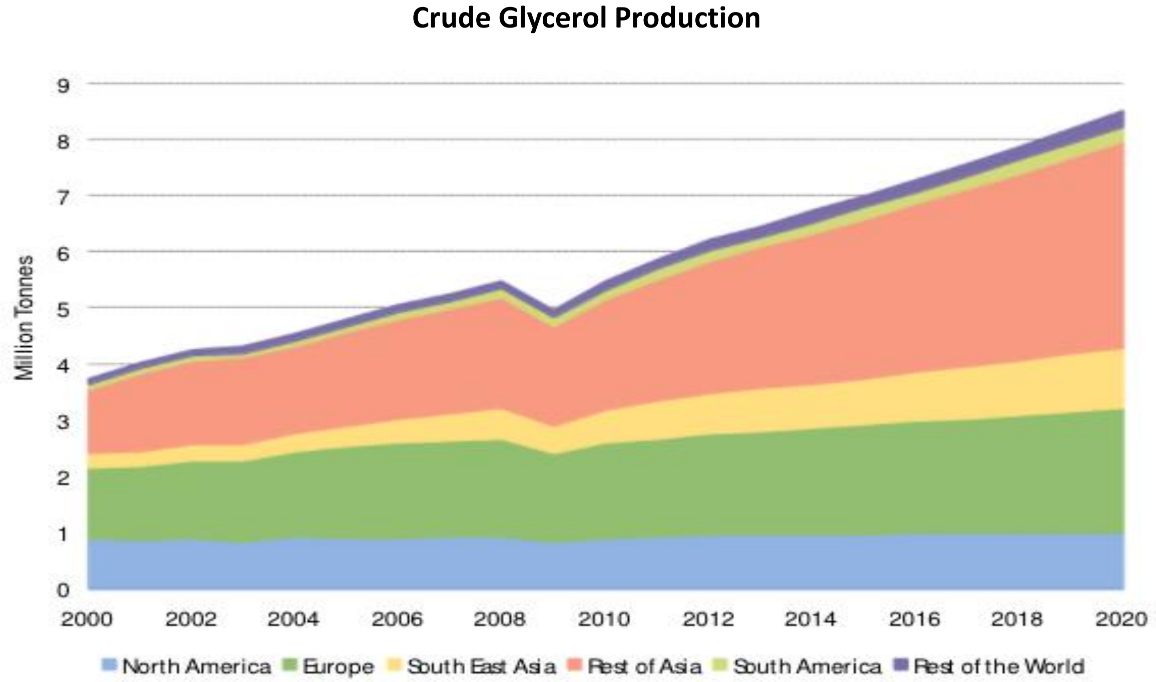

Based on [3,4,5,6]

# Supply

Biodiesel was the largest source for production of glycerol accounting for 62% of the market in 2013. However, fatty alcohols are expected to be the fastest growing source for glycerol production.

In 2013, European biodiesel production implied a technical glycerol potential of 828 kt/a. There are about a total of 203 operational biodiesel plants in 37 European countries. This clearly indicates that there is a high availability of crude glycerol in the market.

The global refined glycerol market is highly concentrated with the top four companies including IOI Group, KL Kepong, Emery Oleochemicals and Wilmar International accounting for more than 65% of market revenue in 2013. Other companies operating in the market include P&G, Kao Corp., Cremer Gruppe and Oleon.




Based on [3]

# Cost (glycols from glycerol) and environmental performance

Since glycerol is a by-product of biodiesel production, the production economics is in line with biodiesel production and thus no direct production costs are depicted. We therefore show production costs of one derivative, glycol from glycerol.

Crude bio-glycerol from FAME plant based on esterification of waste fats or used cooking oil (UCO) is glycerol of the most inferior quality in terms of its further conversion to the refined grades. Due to the high content of saturated fatty acids, this crude bio-glycerol has a high melting point, high viscosity and often even contains solid particles.

An analysis from 2011, aimed to estimate the cost of crude bio-glycerol purification up to 98 wt. % (by combination of evaporation, acidulation, filtration/centrifugation, and column distillation), calculated the lowest OPEX for glycerol purification at level of 0.15 USD per kg. Measured in current prices, it is about 0.16 USD per kg or 136 €/ton.

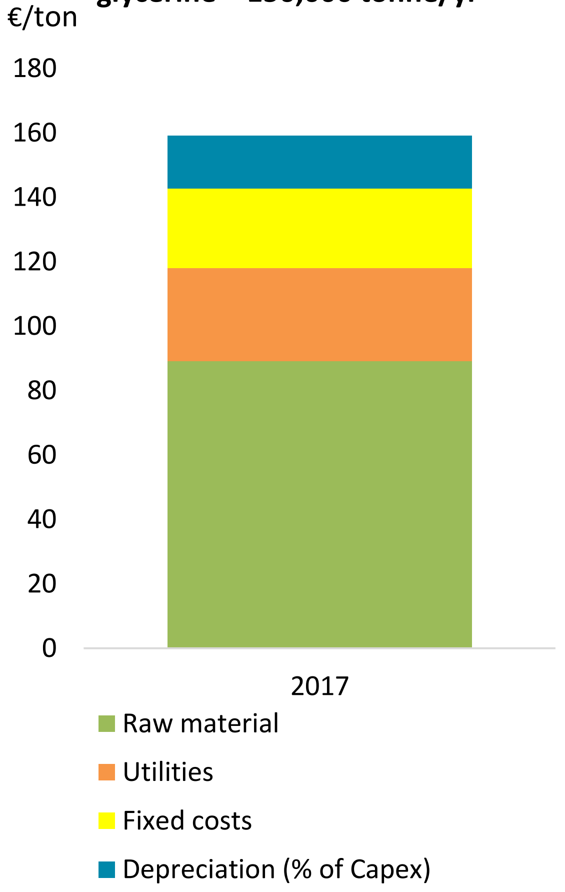
High investment expenditures (CAPEX) effectively minimize the economic viability of construction of process units for glycerol refining within small and medium biodiesel (FAME) factories.

It is estimated that, in general, there is no economic viability for construction of glycerol refinery within biodiesel factory with a capacity < 10,000 t/yr.

Indicative market price for 99.5% technical quality refined glycerol is 600 €/t (mid-2018), while that for 80% crude glycerol is 350 €/t (*for refining*) and 175 €/t (*for disposal*).

In terms of environmental performance, bio-based glycerol can offer GHG emissions savings of 45-94%.

**Manufacturing costs of glycols from crude glycerine – 150,000 tonne/yr**




Based on [8,9]

# SWOT analysis

| Strengths | Weaknesses |
| --- | --- |
| • Cheap C3 platform molecule<br>• Simple logistics<br>• By-product<br>• Some individual conversions are established | • Price volatility<br>• Purification required, leading to higher production costs<br>• Dependant on biodiesel production and thus on biofuel subsidies |
| **Threats** | **Opportunities** |
| • Difficult and expensive (considering smaller market size) to trace feedstock<br>  - Need to ensure no GMO, no pesticides, no palm oil<br>• Epichlorohydrin is still toxic, even if you make it from bio-based resources.<br>• DSM uses different feedstocks for production of bio-based paints. This is direct competition for glycerol-based paint. | • In theory, potential to become a platform chemical for a wide range of bio-based chemicals<br>• Glycerol-based acrylic acid can be used for paints, coatings, diapers, detergents |

# Potential and Barriers

| Opportunities | Issues |
|---|---|
| **Techno-economic factors**<br>• As long as biodiesel is produced, 10% crude glycerol is always produced - thus glycerol is cheap to have in large quantities.<br>• Large applications portfolio already available<br>• Not drop-in as raw material - petrol-based glycerol is only available in small quantities on the market (pharmaglycerine)<br>• Glycerol can - at least theoretically - be used chemically as the basis for a wide range of bio-based chemicals<br>• Glycerol can - at least theoretically - be used biotechnologically as main or secondary raw material.<br>• Lot of R&D for glycerol to glycerol-derived products<br>• Individual conversions are competitive and now established - e.g. epichlorohydrin for epoxy resins<br>• Simple logistics - liquid, non-explosive, low toxicity | **Techno-economic factors**<br>• If biodiesel is no longer produced, the raw material could become expensive and scarce (but not disappear, as it is also produced in oleochemistry)<br>• Crude glycerol must be purified for many uses - higher costs<br>• Existing IP and patents could hinder technical implementation<br>• Prices of glycerol-based products cannot currently compete with petrochemical alternatives |
| **Fuel, Food & Materials**<br>• Price volatility, that once was linked to the volatile demand of a chemical mainly used by the pharmaceutical and personal care industries, today originates from the volatile nature of the glycerol supply, influenced by two main factors: policies (i.e. fiscal incentives to biodiesel oleochemicals) and oil price. | **Environmental factors**<br>• Land use (direct and indirect) if derived from raw vegetable oils |

# 6. Conclusions

The analysis of the nine business case studies shows that there are a number of opportunities to replace fossil-based chemicals with bio-based chemicals. This replacement could lead to more sustainable products on the market, in some cases with improved performance and functionality and relatively lower production costs.

In most of the cases, bio-based chemicals have lower greenhouse gas (GHG) emissions compared to their fossil-derived equivalents. Large volume bio-based drop-ins like ethylene, and dedicated polymers such as PEF or glycerol derivatives could lead to significant displacement of fossil-based feedstock and improve the overall carbon footprint of European chemical industry. However, further technology developments and energy optimization of bio-based process are needed to continue reducing GHG emissions and improve the overall sustainability and cost competitiveness of bio-based chemicals.

A significant driver for dedicated bio-based plastics such as PEF, PLA and PHA is the environmental impact after disposal, where recycling and/or biodegradability are key end-of-life considerations.

Focus should be on development of innovative bio-based products which outperform traditional fossil-based products technically, environmentally and in terms of process efficiency - improved functionality and value will result in a strong end-user drivers.

An important enabler for the development and the market uptake of bio-based chemicals will be improving the cost competitiveness of bio-based chemicals. Cost optimization of the entire value chain of bio-based chemicals is required. Supply of low cost renewable sugars and technology advances in utilization of waste feedstock are major opportunities for cutting the production costs and improving sustainability of bio-based chemicals.

Seizing the opportunities in the bio-based sector will best be achieved through a range of supporting activities including research programmes and funding, the facilitation of networks and collaborations, the establishment of open access piloting and demonstration facilities, support for early stage companies, as well as demand side measures.

The economic value of the markets that could be accessed by these bio-based chemicals is very large. There is therefore a strong rationale for investing in this area, though investments should follow more careful and detailed assessments of the technical and economic prospects of the specific bio-based chemical production pathways.

# Acronyms

bbl – Barrel
BDO – Butanediol
CAGR – Compound annual growth rate
DDDA – Dodecanedioic acid
DMA – Dimethyl terephthalate
€ - Euro
EU – European Union
FDCA – Furan dicarboxylic acid
G&A – General and administrative costs – typically 5 – 10% of plant cash costs
GHG – Greenhouse gases
kt – Kilotonne
kta – Kilotonne per annum
MEG – Monoethylene glycol
PE- Polyethylene
PEF – Polyethylene furanoate
PET – Polyethylene terephthalate
PHA – Polyhydroxyalkanoate
PHB - Polyhydroxybutyrate
PHV – Polyhydroxyvalerate
PLA – Polylactic acid
PP - Polypropylene
PS – Polystyrene
PTA – Terephthalic acid
PVC – Polyvinylchloride
t – Tonne
$ - United States Dollar
USD – United States Dollar
Yr – Year

# Colophon

| | |
|---|---|
| **Project Title: Roadmap for the Chemical Industry in Europe towards a Bioeconomy** | |
| **Acronym: RoadToBio** | |
| **Grant Agreement No: 745623** | |
| **Start Date: 01 May 2017** | |
| **Duration of the Project: 24 Months** | |
| **Deliverable No.** | D1.2 |
| **Deliverable Title** | Business cases: Case studies on potentially attractive opportunities for bio-based chemicals in Europe |
| **Type** | Report |
| **Due Date** | 07 September 2018 |
| **Date Delivered** | 07 September 2018 |
| **Prepared by (Lead Partner)** | E4tech<br>Contact: yamini.panchaksharam@e4tech.com |
| **Dissemination Level** | Public |

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