IEA Bioenergy, also known as the Implementing Agreement for a Programme of Research, Development and Demonstration on Bioenergy, functions within a Framework created by the International Energy Agency (IEA). Views, findings and publications of IEA Bioenergy do not necessarily represent the views or policies of the IEA Secretariat or of its individual Member countries.
Content

- IEA Bioenergy Task 42 Biorefining
- Introduction on Biobased Chemicals
- Market size and potential GHG savings
- Technology push or market pull?
- List of Bio-based chemicals and producers
- Dilemma: Drop-in versus novel building blocks
- Avantium examples
- Conclusions
Task Framework – Biorefining

Definition IEA Bioenergy Task42

Sustainable processing of biomass into a portfolio of marketable biobased products (food and feed ingredients, chemicals, materials, fuels, energy, minerals, CO₂) and bioenergy (fuels, power, heat)
Setting the Scene
Biorefining in a Future Circular (Bio)Economy
Renewable Carbon

A Fossil-Free World

There are only three renewable carbon sources available in this world...

- Plant-Based
  - Rediscover

- Air-Based
  - Reroute

- Man-Made
  - Repurpose

Glucose as Building Block

CO₂ Conversions

Chemical Recycling

...that enable a circular economy

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Task 42 - Biorefining in a Future BioEconomy
The Chemical Industry: A Key to Mitigating Climate Change

6 years until the carbon budget to limit global warming to 1.5 degrees is used (extrapolating current CO₂ emissions)

90% of the chemical products we use are derived from fossil carbon (this excludes fuels)

4x is the expected growth of the plastic market from 2014-2050

This represents 11% of global primary demand for oil and 8% for natural gas

plastics are expected to make up 15% of carbon budget in 2050

1-2% of current plastics are made from renewable feedstock

Source: Carbon Brief 2017, IPCC – Figures correspond to a 50% chance to limit global warming to 1.5 or 2 degrees; IEA, July 2018; Ellen McArthur Foundation ‘The new plastics economy’, 2016
IEA Bioenergy Task42
Deliverables 2016 - 2018

- Biorefinery Factsheets
- Monitoring of international standardisation/certification activities biomass-use
- Monitoring international BioEconomy developments
- Joint Tasks Projects (bioenergy supply chains)
- Strategic Reports on
  - Proteins for Food and Non-food (2016)
  - Biobased Fibrous Materials
  - **Biobased Chemicals (2018)**
- Updates of National BR Country Reports
- (Thematic) Stakeholder Workshops
- Conference & training contributions
- Biannual newsletters
Why producing Biobased Chemicals (in conjunction with Bioenergy) in a Biorefinery

- To supply the market with sustainable/renewable chemicals
- To improve the economics of bioenergy production
- To partly make use of existing industrial (energy) infrastructure potentially decreasing initial investments and shorten time-to-market
- To make scaling up easier (makes plant already commercial viable at smaller scales)
- Unique functionality
- Medium term CO2 storage (depending on chemical)
- Reduction of non renewable energy usage (NREU) usage (both because of renewable product and less fossil fuel used in production)
Current Market Size

Fossil based Chemicals:  
330 million tonnes

Main molecules:  
methanol, ethylene, propylene, butadiene, 
benzene, toluene and xylene

Biobased Chemicals & Materials:  
50 million tonnes

Main molecules:  
Non-food starch, cellulose fibres/derivatives, 
tall oils, fatty acids and fermentation products
### Potential for GHG savings

<table>
<thead>
<tr>
<th>Product</th>
<th>GHG savings (t CO$_2$/t of product)</th>
<th>Installed world capacity (million t/year)</th>
<th>Annual GHG savings (million tonne CO$_2$/year)$^4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acetic acid</td>
<td>1.2</td>
<td>8.3</td>
<td>9.6</td>
</tr>
<tr>
<td>Acrylic acid</td>
<td>1.5</td>
<td>2.9</td>
<td>4.4</td>
</tr>
<tr>
<td>Adipic acid</td>
<td>3.3</td>
<td>2.4</td>
<td>7.9</td>
</tr>
<tr>
<td>Butanol</td>
<td>3.9</td>
<td>2.5</td>
<td>9.6</td>
</tr>
<tr>
<td>Caprolactam</td>
<td>5.2</td>
<td>3.9</td>
<td>20.0</td>
</tr>
<tr>
<td>Ethanol</td>
<td>2.7</td>
<td></td>
<td>7.1</td>
</tr>
<tr>
<td>Ethyl lactate</td>
<td>1.9</td>
<td>1.2</td>
<td>2.2</td>
</tr>
<tr>
<td>Ethylene</td>
<td>2.5</td>
<td>100.0</td>
<td>246</td>
</tr>
<tr>
<td>Lysine</td>
<td>3.6</td>
<td>0.6</td>
<td>2.3</td>
</tr>
<tr>
<td>Succinic acid</td>
<td>5.0</td>
<td>1.4</td>
<td>6.8</td>
</tr>
<tr>
<td>1,3-propanediol</td>
<td>2.9</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PHA</td>
<td>2.8</td>
<td>57.0</td>
<td>160</td>
</tr>
<tr>
<td>PLA</td>
<td>3.3</td>
<td>11.1</td>
<td>36.5</td>
</tr>
</tbody>
</table>

Pull or Push?

- Governmental – Legislative push
  - Sustainability
  - Green House Gas savings / Non Renewable Energy Usage
  - Security of supply

- Technological push
  - Biochemical / Chemical
  - Concepts versus applicability

- Market pull
  - Brand owners
  - Consumers
The Biobased Transition has started, Companies look for Bio-Based Alternatives

Apple believes that improving the environmental performance of our business starts with our products. The careful environmental management of our products includes controlling the types of materials used: plastics used in the display frame are made with 28% bio-based content.

The best-known example of how we rethink our packaging is our breakthrough bio-based, low-carbon, Green Fibre Bottle. It continues to attract attention and spark discussion.

Lego invests 1 billion DKK in R&D and implementation of new, sustainable, raw materials to manufacture LEGO elements as well as packaging materials; “This is a major step for the LEGO Group on our way towards achieving our 2030 ambition on sustainable materials”.

We envision a transition from linear to circular business models and a world that demands closed-loop products...”. “We are re-imagining waste streams as value streams”. “...and encourage broader adoption of renewables as part of our effort to control absolute emissions”.

The new Biolage R.A.W. haircare line was sustainably designed and developed, in response to consumers’ growing expectations in this area. Raw materials of natural origin are preferred, with percentages of natural ingredients between 70% and 100%

There are about 400 pounds of plastic on a typical car, our job is to find the right place for a green composite to help our impact on the planet.
Also Chemical Companies are increasingly Diversifying into Bio-Based Materials

"I'm very pleased with this joint venture (...) This investment is consistent with our One Total ambition of expanding in biofuels and bioplastics, in addition to our more traditional oil- and gas-based products."
Bernard Pinatel, President of Total Refining & Chemicals, on the JV with Corbion to produce bio-PLA

Synvina: BASF and Avantium join forces

“2015-2020: To be recognized as a leader in the production of chemical products and thermoplastic resins from raw renewable materials.”
Braskem Sustainable Strategy
Global production capacities of Bioplastics 2017 (by material type)

Total: 2.05 million tonnes

- Other (bio-based/non-biodegradable): 9.2%
- PBAT: 5.0%
- PBS: 4.9%
- PLA: 10.3%
- PHA: 2.4%
- Starch blends: 18.8%
- Other (biodegradable): 1.5%
- PET: 26.3%
- PA: 11.9%
- PEF*: 0.0%
- PE: 9.7%
- PP*: 0.0%

Bio-based/non-biodegradable: 57.1%
Biodegradable: 42.9%

*Bio-based PP and PEF are currently in development and predicted to be available in commercial scale in 2020.


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Task42 – Biorefining in a Future BioEconomy
Global Production Capacities of Bioplastics (2017 – 2022)

Overview of IEA Bioenergy T42
Biorefinery Classification system
Dominant Platforms

Syngas Platform
Biogas Platform
C6 sugar platform*
C6/C5 sugar platform
Plant-based Oil Platform*
Algae Oil Platform
Organic Solutions Platform
Lignin Platform
Pyrolysis Oil Platform

* Currently the dominant platforms for biobased chemicals
Biobased Chemicals Table

- Gives an overview of the biobased chemicals status in two categories
  - High growth potential
  - In the pipeline (demonstration or pilot facility running)
- Organized from C1 (methanol, formic acid etc) to Cn (all molecules with more than 6 C atoms)
- Exhaustive list but certainly not complete
- Biobased Chemicals Field is very dynamic at the moment so probably already some new changes / additions needed
## Biobased Chemicals

<table>
<thead>
<tr>
<th>Cn</th>
<th>Products with strong growth potential</th>
<th>Bio-Based Chemicals in the pipeline</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Chemical</td>
<td>Company</td>
</tr>
<tr>
<td>1</td>
<td>Methanol</td>
<td>BioMCN, Sodra, AkzoNobel/Enerkem</td>
</tr>
<tr>
<td></td>
<td>Methane</td>
<td>Many</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Ethylene</td>
<td>Braskem</td>
</tr>
<tr>
<td></td>
<td>Ethanol</td>
<td>Many</td>
</tr>
<tr>
<td></td>
<td>Ethyleneglycol (MEG)</td>
<td>India Glycols Ltd, HaldorTopsoe, UPM, Avantium</td>
</tr>
<tr>
<td></td>
<td>Ethylene Oxide</td>
<td>Croda, Biokim</td>
</tr>
<tr>
<td>Cn</td>
<td>Products with strong growth potential</td>
<td>Bio-Based Chemicals in the pipeline</td>
</tr>
<tr>
<td>----</td>
<td>--------------------------------------</td>
<td>-------------------------------------</td>
</tr>
<tr>
<td></td>
<td>Chemical</td>
<td>Company</td>
</tr>
<tr>
<td>3</td>
<td>Lactic acid (many)</td>
<td>Corbion, NatureWorks, Anhui, Galactic, Henan, Jindan</td>
</tr>
<tr>
<td></td>
<td>Propane</td>
<td>Neste</td>
</tr>
<tr>
<td></td>
<td>Glycerol</td>
<td>Many</td>
</tr>
<tr>
<td></td>
<td>Epichlorohydrin (many)</td>
<td>Yihai Kerry Group, Jiangsu Yangnong, Advance Biochemical Thailand</td>
</tr>
<tr>
<td></td>
<td>1,3-Propanediol</td>
<td>DuPont/Tate&amp;Lyle, <em>Metabolic Explorer</em></td>
</tr>
<tr>
<td></td>
<td>Ethyl lactate</td>
<td>Vertec BioSolvents</td>
</tr>
<tr>
<td></td>
<td>Propylene Glycol (1,2-Propanediol)</td>
<td>ADM, Oleon, <em>BASF</em></td>
</tr>
<tr>
<td></td>
<td>Acetone</td>
<td>Green Biologics</td>
</tr>
<tr>
<td>Cn</td>
<td>Products with strong growth potential</td>
<td>Bio-Based Chemicals in the pipeline</td>
</tr>
<tr>
<td>----</td>
<td>--------------------------------------</td>
<td>-----------------------------------</td>
</tr>
<tr>
<td></td>
<td>Chemical</td>
<td>Company</td>
</tr>
<tr>
<td>4</td>
<td>n-Butanol</td>
<td>Green Biologics</td>
</tr>
<tr>
<td></td>
<td>iso-Butanol</td>
<td>Butamax, Gevo</td>
</tr>
<tr>
<td></td>
<td>Succinic acid</td>
<td>Reverdia, Myriant, Succinity</td>
</tr>
<tr>
<td></td>
<td>1,4-Butanediol</td>
<td>Genomatica, Novamont, GBL</td>
</tr>
<tr>
<td>5</td>
<td>Furfural</td>
<td>Many</td>
</tr>
<tr>
<td></td>
<td>Xylitol</td>
<td>a.o. Danisco/ Lenzing, S2G Biochem</td>
</tr>
<tr>
<td></td>
<td>Glutamic acid</td>
<td>a.o. Global Biotech, Meihua, Fufeng, Juhua</td>
</tr>
<tr>
<td></td>
<td>1,5-pentanediamine</td>
<td></td>
</tr>
</tbody>
</table>
# Biobased Chemicals

<table>
<thead>
<tr>
<th>Cn</th>
<th>Products with strong growth potential</th>
<th>Bio-Based Chemicals in the pipeline</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Chemical</td>
<td>Company</td>
</tr>
<tr>
<td>6</td>
<td>Sorbitol</td>
<td>a.o. Roquette, ADM</td>
</tr>
<tr>
<td></td>
<td>Isosorbide</td>
<td>Roquette</td>
</tr>
<tr>
<td></td>
<td>Aniline</td>
<td>Covestro</td>
</tr>
<tr>
<td></td>
<td>Citric acid</td>
<td>a.o. Cargill, DSM, BBCA, Ensign, TTCA, RZBC</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>n</td>
<td>PHA</td>
<td>Telles, Meridian plastics</td>
</tr>
<tr>
<td></td>
<td>Dicarboxylic acids</td>
<td>Cathay Biotech, Evonik</td>
</tr>
<tr>
<td></td>
<td>Fatty Acid derivatives</td>
<td>Croda, Elevance</td>
</tr>
</tbody>
</table>
Product Commercialization

Key Criteria

Market assessment

- Market fundamentals (local, regional, global)
- Feedstock availability & price
- Utilities (steam, gas, electricity etc) availability & price
- Product profitability
- Bankability
- Competitive nature of market
- Need for partnerships
- Downstream development opportunities

Technology assessment

- Commercial experience
- Necessary capital investment
- Process complexity
- Access to technology
- Environmental considerations
## Drop-in versus New Functionality

<table>
<thead>
<tr>
<th>Bio-based chemical</th>
<th>Reference Petrochemical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acetic acid</td>
<td>Acetic acid</td>
</tr>
<tr>
<td>Adipic acid</td>
<td>Adipic acid</td>
</tr>
<tr>
<td>n-Butanol</td>
<td>n-Butanol</td>
</tr>
<tr>
<td>Ethylene</td>
<td>Ethylene</td>
</tr>
<tr>
<td>Bio-MEG</td>
<td>MEG (mono-Ethleneglycol)</td>
</tr>
<tr>
<td>Ethyl lactate</td>
<td>Ethyl acetate</td>
</tr>
<tr>
<td>FDCA</td>
<td>Terephthalic acid</td>
</tr>
<tr>
<td>PHA</td>
<td>HDPE</td>
</tr>
<tr>
<td>PLA</td>
<td>PET and PS</td>
</tr>
<tr>
<td>Succinic acid</td>
<td>Maleic anhydride</td>
</tr>
</tbody>
</table>
# Drop-in versus Unique Functionality

<table>
<thead>
<tr>
<th></th>
<th>Drop-in</th>
<th>Unique molecule</th>
</tr>
</thead>
<tbody>
<tr>
<td>Market acceptance</td>
<td>↑↑</td>
<td>↓↓</td>
</tr>
<tr>
<td>Speed of introduction</td>
<td>↑↑</td>
<td>↓↓</td>
</tr>
<tr>
<td>Fit with existing infrastructure</td>
<td>↑↑ ↔</td>
<td>↔ ↓</td>
</tr>
<tr>
<td>Oil/Feedstock price sensitivity</td>
<td>↑↑↑↑</td>
<td>↑</td>
</tr>
<tr>
<td>Sustainability</td>
<td>↑ ↔ ↓</td>
<td>↑↑↑ ↔</td>
</tr>
<tr>
<td>Unique market space</td>
<td>↓↓↓↓</td>
<td>↑↑↑↑</td>
</tr>
<tr>
<td>Scalability</td>
<td>↑↑↑</td>
<td>↑ ↔ ↓</td>
</tr>
<tr>
<td>Legislation (e.g., REACH)</td>
<td>↑↑↑</td>
<td>↑↑↑ ↓↓↓↓</td>
</tr>
</tbody>
</table>
Avantium example: PEF from lignocellulosic feedstocks
Mixture of Novel Functionality & Drop-in

Dawn Technology™
Biorefinery: Woody Biomass To 2G Industrial Sugars and Lignin

About
- A radically improved proven process, through proprietary inventions; reduction of water consumption by 70%
- Unlocks the glucose available in non-food agricultural and forestry residues

Diagram:
- Non-food, plant-based feedstock
- Acid
- Mixed sugars are separated from the feedstock
- Mixed sugars (C₅/C₆)
- Acid
- High purity glucose is separated from the feedstock
- High purity glucose
- Acid
- The remaining product is lignin
- Lignin
- The vessel is emptied and the process is repeated

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Benefits of Drop-ins

**Mekong**
Industrial Sugars to MEG

**About**
- Superior carbon efficiency
- Aims to help fulfilling the growing MEG demand (2017-2035 CAGR = 3.5%)^A^

**Value proposition**
- Drop-in
- Competitive
- Bio-based
- Versatile
- Scalable
- Sustainable
- Same quality as fossil-MEG
- Competes with fossil-MEG cost
- Utilize 1G or 2G resources
- Worldwide feedstock options
- Common unit operations
- Significant CO₂-eq reduction

---

**Mekong Process**

**Hydrogenolysis**

Glucose:

\[
\begin{align*}
\text{OH} & \quad \text{OH} & \quad \text{OH} \\
\text{OH} & \quad \text{OH} & \quad \text{OH} \\
\text{OH} & \quad \text{OH} & \quad \text{CO} \\
\end{align*}
\]

Catalysis 1 step

Max theoretical yield = 100%

\[
\begin{align*}
\text{OH} & \quad \text{OH} & \quad \text{OH} \\
\text{OH} & \quad \text{OH} & \quad \text{OH} \\
\text{OH} & \quad \text{OH} & \quad \text{OH} \\
\end{align*}
\]

EG

EG

EG

---

^A^ CAGR 2017-2025: 3.9% (Nexant Petrochemical Market Dynamics, Polyester & Intermediates, 2017); CAGR 2025-2032: 3.0%

B= Compared to traditional fossil-MEG plant. Data to be verified by third party environmental life-cycle assessment (LCA) based on to be collected demonstration plant data.

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Task 42 – Biorefining in a Future BioEconomy
A New Value Chain: From Sugars to PEF

Naptha → p-xylene (Catalytic reforming) → Oxidation & Purification → PTA (Terephthalic acid) → PET resin (Polyethylene-terephthalate) → Plastic processing

→ Building on existing PET know-how
→ Fitting with existing PET assets

C6 Sugars (Fructose) → Sugar DeHydration → Oxidation & Purification → RMF (5-methoxyMethylFurfural) → pFDCA (FuranDiCarboxylicAcid) → PEF resin (Polyethylene-Furanoate)

Catalytic processes, developed with high throughput screening technology

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Benefits of Unique Functionality

Synvina: What can PEF do?

- **Sustainability**: 100% biobased polymer
- **BIOBASED**
- **Lightweighting**: 60% higher modulus vs PET
- **MECHANICS**
- **Superior Heat Resistance**
- **RECyclability**
- **Hot Filling**: 12°C higher glass transition vs PET
- **100% recyclable**
- **Shelf Life**: improved transfer rates vs PET:
  - $O_2$: 10x
  - $CO_2$: 6-10x
  - $H_2O$: 3x
Conclusions

- **Strong Market Pull Biobased Chemicals**
- Production is currently expanding at decent pace
- In several cases products are market competitive without subsidies
- No winner between drop-in versus new functionality

Dissemination

- Updated report will be available in 2019
- Pdf version will be available on IEA Bioenergy Task 42 website ([http://task42.ieabioenergy.com/](http://task42.ieabioenergy.com/))
- Feedback: Ed de Jong (ed.dejong@avantium.com)