From the Sugar Platform to biofuels and biochemicals

Study for the European Commission DG ENER

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1. Objectives
2. Pathways
3. Development status
4. Market size
5. Case studies
6. EU competitiveness
7. Barriers and research gaps
8. Policy development
Objectives

- Very large number of possible pathway combinations of feedstock, pre-treatment options, sugars, conversion and downstream processes exist
- **Study objective** was to review the most promising value chains to biofuels and biochemicals via sugars – assessing technology options, development status, market potential, sustainability, economics and barriers to deployment
- Industry input gathered via two **workshops** covering the competiveness of the EU industry vs. other world regions, the key research gaps and possible policy developments
- Report is to act as an **evidence base** for policymakers & stakeholders to identify opportunities, their key benefits and development needs
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High-level summary of the 94 pathways considered
Ethanol pathways – detailed example
C3 pathways – detailed example
3. Development status
### TRL progression and the “valley of death” for 25 products

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<th>TRL</th>
<th>1-3</th>
<th>4</th>
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<th>7</th>
<th>8</th>
<th>9</th>
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</thead>
<tbody>
<tr>
<td><strong>Research</strong></td>
<td>3-HPA</td>
<td>Acrylic acid</td>
<td>BDO via succinic acid</td>
<td>LC ethanol</td>
<td>1G ethanol</td>
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<tr>
<td></td>
<td>5-HMF</td>
<td>FDCA</td>
<td>Iso-butene</td>
<td>Sorbitol</td>
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<td></td>
<td>Isoprene</td>
<td></td>
<td></td>
<td>Xylitol</td>
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<td><strong>Pilot</strong></td>
<td></td>
<td></td>
<td>BDO direct</td>
<td>Succinic acid</td>
<td>Lactic acid</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>LC butanol</td>
<td>Acetic acid</td>
<td>ABE</td>
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<td></td>
<td></td>
<td></td>
<td>n-butanol</td>
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<td><strong>Demonstration</strong></td>
<td></td>
<td></td>
<td>Iso-butanol</td>
<td>Farnesene</td>
<td>PDO</td>
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<tr>
<td><strong>Commercial</strong></td>
<td></td>
<td></td>
<td>PHAs</td>
<td>Levulinic acid</td>
<td>Itaconic acid</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Algal lipids</td>
<td>Ethylene</td>
<td>Ethylene glycol</td>
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</table>

**Key**
- Biological
- Intracellular
- Chemical
- Thermo-chemical
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<th>Section</th>
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<td>7. Barriers and research gaps</td>
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<tr>
<td>8. Policy development</td>
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Ethanol is by far the largest sugar platform product

• We collected indicative prices and global production volumes for the selected 25 products, along with their fossil counterparts (where applicable):
  • Dominant (~$58bn/yr): bio-ethanol
  • Big (~$1bn/yr): n-butanol, acetic acid and lactic acid
  • No fossil alternatives, >$100m/yr for chemical routes to xylitol, sorbitol and furfural
  • Smallest markets are for earliest TRL products (<$1m/yr): 3-HPA, acrylic acid, isoprene, adipic acid and 5-HMF
  • If economically competitive, many bio-based markets could grow to exceed the current demand for the fossil-based product, and expand into new markets, replacing other products. But the crude oil price crash of late 2014 leaves many sugar platform products extremely challenged
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10 case studies selected to highlight EU actors active in attractive markets

- Case studies exist as standalone ~4 page documents containing a large number of references. Most have been industry reviewed.
  - **Review** of the bio-based product (description and pathways)
  - **Actors** involved in its production (EU and ROW, discussing plants and partnerships)
  - **Value proposition** (production economics, GHG savings and physical properties)
  - **Market** outlook (expected growth rates, new volumes and markets opened up)
- All 10 case studies **claim** “viable economic production costs” once at scale (unlikely now except for niche applications)
- All have modest GHG savings on 1G sugars, high GHG savings on 2G sugars
- All have either equal quality (drop-in) or enhanced properties (non drop-in)
## Case studies (1-5)

<table>
<thead>
<tr>
<th>Product</th>
<th>Actors</th>
<th>Key markets and value proposition</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Acrylic acid</strong></td>
<td>BASF-Cargill-Novozymes (EU) OPXBio-Dow (USA). Both partnerships focusing on 3-HPA route</td>
<td>Drop-in replacement for a widely used chemical intermediate</td>
</tr>
<tr>
<td><strong>Adipic acid (ADA)</strong></td>
<td>Biochemtex and DSM (EU) Some US projects have reached pilot scale (Rennovia, Verdezyne).</td>
<td>Drop-in replacement meeting demand for nylon 6,6 and polyurethanes</td>
</tr>
<tr>
<td><strong>1,4-Butanediol (BDO)</strong></td>
<td>Genomatica (USA) main actor. BASF, Novamont, DSM, Biochemtex making BDO and PBT based on Genomatica technology. JM-Davy BDO is via Myriant’s succinic acid</td>
<td>Drop-in replacement for fossil BDO. BDO is used to make GBL, THF and PBT</td>
</tr>
<tr>
<td><strong>Farnesene</strong></td>
<td>Only one market player, US-based Amyris. There are no major European players, other partners such as Total</td>
<td>Moisturiser emollients, durable easy-cast tyres, and jet fuel properties consistent with C15 iso-paraffin</td>
</tr>
<tr>
<td><strong>2,5-furan-dicarboxylic acid (FDCA)</strong></td>
<td>Development led by Avantium in the EU. Corbion Purac, AVA Biochem and Novozymes also active in this space in Europe</td>
<td>Substitute for TPA to make new class of polyethylene furanoate (PEF) polymers. Application in drinks bottles as superior gas barrier vs PET</td>
</tr>
</tbody>
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## Case studies (6-10)

<table>
<thead>
<tr>
<th>Product</th>
<th>Actors</th>
<th>Key markets and value proposition</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Isobutene</strong></td>
<td>Small number of players, only Global Bioenergies and Lanxess in EU. Gevo and Butamax are main isobutanol developers</td>
<td>Rubber for automotive, and as a precursor for fuel &amp; lubricant additives and biofuels</td>
</tr>
<tr>
<td><strong>Poly-hydroxy-alkanoates</strong></td>
<td>Modest EU activity compared with China and the Americas. Biomer and Bio-on are the key EU players. Metabolix the largest US player</td>
<td>Fully biodegradable, niche use in sutures. Tuneable properties means could be used in most aspects of plastics industry</td>
</tr>
<tr>
<td><strong>Poly-ethylene</strong></td>
<td>Braskem in Brazil is the only commercial scale producer</td>
<td>Drop-in replacement for fossil PE (most common plastic) – main application in packaging</td>
</tr>
<tr>
<td><strong>Polylactic acid</strong></td>
<td>A few large industrials; NatureWorks (USA) and Corbion Purac (NL) dominate PLA and LA production respectively. ~9 other EU producers of PLA and LA.</td>
<td>Bio routes preferred to fossil. PLA suitable for packaging, insulation, automotive and fibres. Durable, degradable/compostable, low toxicity</td>
</tr>
<tr>
<td><strong>Succinic acid</strong></td>
<td>2 main actors in Europe (Reverdia, Succinity) and a further 2 globally (BioAmber, Myriant)</td>
<td>Drop-in replacement for fossil, and near-drop-in for adipic acid in resins, plasticisers, and polyester polyols. Downstream to BDO, PBT, PBS</td>
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EU competitiveness assessed based on 7 criteria vs. US, Brazil and China

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<thead>
<tr>
<th>Criteria</th>
<th>EU</th>
<th>US</th>
<th>Brazil</th>
<th>China</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Policy</td>
<td>C</td>
<td>A</td>
<td>B</td>
<td>B</td>
<td>US has RFS and BioPreferred. Brazil and China have biofuel mandates, but EU lacks long-term policy</td>
</tr>
<tr>
<td>Financing</td>
<td>B</td>
<td>A</td>
<td>B</td>
<td>A</td>
<td>Interest rates lowest in China, highest in Brazil. DOE and BNDES provide loan guarantees</td>
</tr>
<tr>
<td>Public perception &amp; consumer demand</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>Biochemicals yet to suffer biofuel ILUC backlash, no sustainability requirements exist yet</td>
</tr>
<tr>
<td>Level of R&amp;D activity</td>
<td>A</td>
<td>A</td>
<td>B</td>
<td>B</td>
<td>EU &amp; US have best researchers, hence top locations for labs &amp; pilots</td>
</tr>
<tr>
<td>Level of commercial activity</td>
<td>C</td>
<td>B</td>
<td>C</td>
<td>A</td>
<td>Strongest in China. US leader on demonstration, and LC ethanol. EU focused downstream, Brazil limited projects</td>
</tr>
<tr>
<td>Feedstock availability &amp; cost</td>
<td>B</td>
<td>A</td>
<td>A</td>
<td>B</td>
<td>All regions have significant 1G crops. US and Brazil cheapest LC residues and forestry, China yet to mechanise</td>
</tr>
<tr>
<td>Other production costs</td>
<td>C</td>
<td>B</td>
<td>B</td>
<td>A</td>
<td>US highest wages, Brazil highest energy costs, but EU second on both counts. US lowest energy and China lowest wages</td>
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Feedstock availability & cost, plus labour and energy costs vary widely between regions
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Lignocellulosic pre-treatment is vital to unlocking sugar platform potential, but remains expensive

- **Pre-treatment** technical obstacles include insufficient separation of cellulose and lignin, formation of by-products that inhibit downstream fermentation, high use of chemicals and/or energy, high costs for enzymes (although falling rapidly), and high capital costs

- Pros and cons of 11 technologies discussed, ranging from TRL 2 to 8, along with potential mitigating actions
Downstream barriers for converting sugars vary by application

- **Alcohol** production needs to lower energy/economic cost of product separation, and overcome micro-organism toxicity effects in order to improve concentrations of end-products in the fermentation broth.

- **Organic acid** production is more heavily focused on purities, reducing unwanted by-products and the need to improve selectivity of the processes (particularly chemical catalytic routes).

- **Biopolymer** developments are particularly focused on monomer purity, production cost vs. the fossil counterfactual, as well as the ability to use drop-in molecules and/or improve product properties.

- **Process integration** along whole technology chain (feedstock to product) is often poor, due to different disciplines (particularly biological vs. chemical) working in silos and not understanding component interfaces. Also need to develop consolidated processing.
Non-technical barriers examined by Bio-TIC project

• Bio-TIC project has done considerable work in understanding this area and preparing recommendations for improvement

• Categories of non-technical barriers have been prioritised into their importance to the sugar platform as follows:
  1. Demand side policy (most important)
  2. Public perception & communication
  3. Investment & financing
  4. Feedstock
  5. Other barriers (least important)
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Stakeholder suggestions for potential policy improvements

- Longer-term **stability** of mandates
- Setting biomass use between fuels and chemicals on a **level playing field**
- Incentivising **biomass** production
- Creating a clear Europe-wide **communication** campaign
- Dis-incentivising **fossil**-derived products
- **Improving access** to capital and loan guarantees
- **Simplifying** available funding mechanisms
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Thank you for your attention!

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## Technology Readiness Level (TRL) definitions

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<th>TRL</th>
<th>Plant stage</th>
<th>Definition</th>
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<tbody>
<tr>
<td>1</td>
<td>Basic research</td>
<td>Principles postulated &amp; observed but no experimental proof available</td>
</tr>
<tr>
<td>2</td>
<td>Technology formulation</td>
<td>Concept and application have been formulated</td>
</tr>
<tr>
<td>3</td>
<td>Applied research</td>
<td>First laboratory tests completed; proof of concept</td>
</tr>
<tr>
<td>4</td>
<td>Small scale prototype</td>
<td>Built in a laboratory environment (&quot;ugly&quot; prototype)</td>
</tr>
<tr>
<td>5</td>
<td>Large scale prototype</td>
<td>Tested in intended environment</td>
</tr>
<tr>
<td>6</td>
<td>Prototype system</td>
<td>Tested in intended environment close to expected performance</td>
</tr>
<tr>
<td>7</td>
<td>Demonstration system</td>
<td>Operating in operational environment at pre-commercial scale</td>
</tr>
<tr>
<td>8</td>
<td>First of a kind commercial system</td>
<td>Manufacturing issues solved</td>
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<tr>
<td>9</td>
<td>Full commercial application</td>
<td>Technology available for consumers</td>
</tr>
</tbody>
</table>
EU technology is being deployed abroad....

- **Easier/safer to invest** in plants, and products cheaper to make, in the US, Brazil and China:
  - US guaranteeing $1.4bn in loans, $2.5bn more to come
  - Brazil $0.4bn low interest loans + $0.6bn more by 2018
- EU still focusing on R&D
- NER300 funds (€127m) awarded to LC ethanol, none deployed yet
- **BBI** set up with €3.7bn for demo and flagships – could make a significant difference