Closing the Loop: Innovations in Waste Valorisation for Circular by Design Materials and Products

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TNO innovation for life

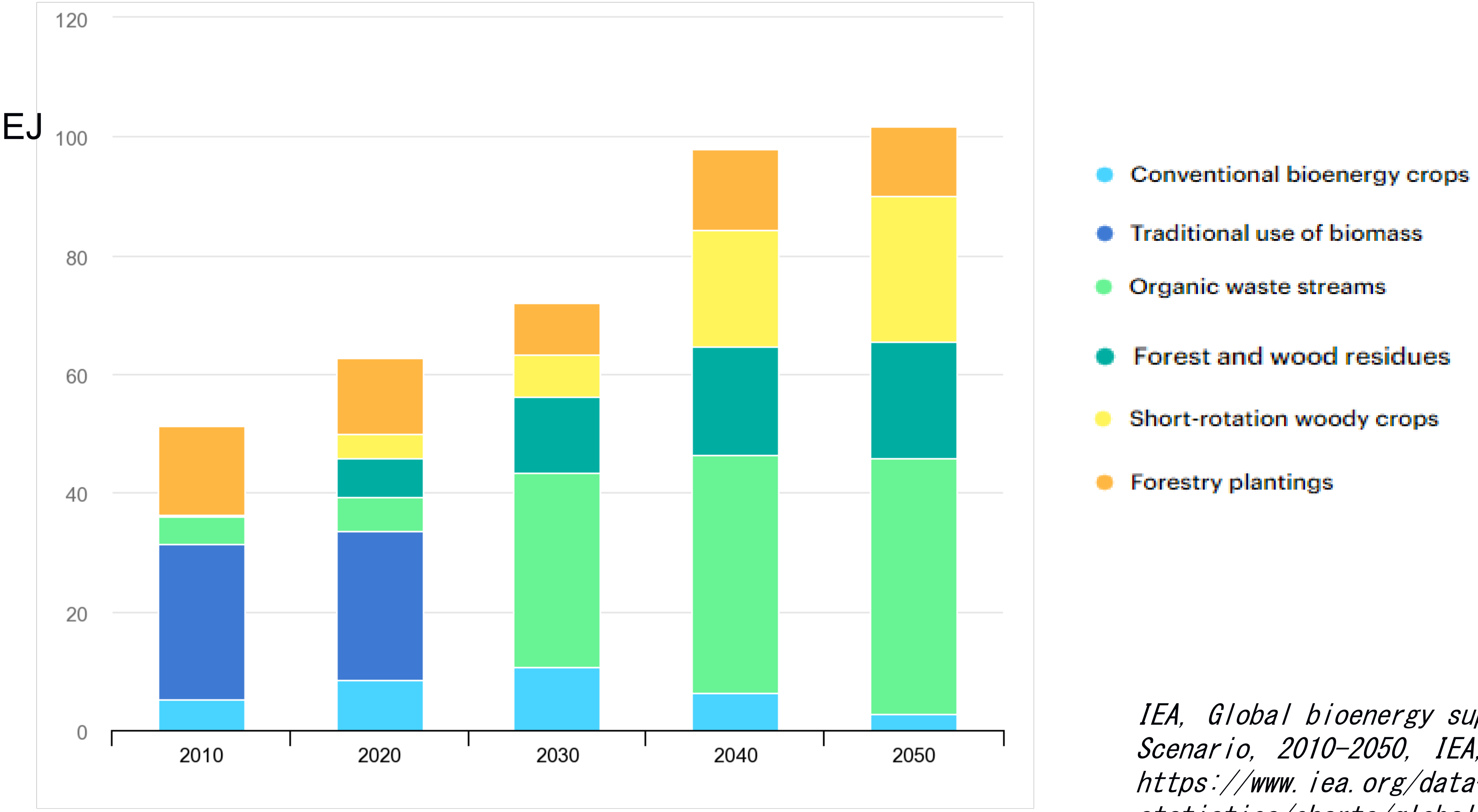
The Energy & Materials Transition

- To achieve climate and sustainability goals, we need to transform energy supply and how we use resources (namely carbon)

- Shift from fossil-based to sustainable, renewable energy
- Shift from fossil-based to sustainable materials, chemicals and products, including re-use and circularity

Photo credit: TNO

Global bioenergy supply in the Net Zero Scenario



IEA, Global bioenergy supply in the Net Zero Scenario, 2010-2050, IEA, Paris https://www.iea.org/data-and-statistics/charts/global-bioenergy-supply-in-the-

Circularity

Materials and Material Combinations Determine:

- Product performance
- Safety and sustainability (SSbD)
- (Multi)functionality
- (Local) sourcing and resource efficiency
- End-of-life scenarios

Design For Circularity:

- Repairability
- Durability
- End-of-Life (recycling, disabling…)

Biomass Resources

- Will be needed for the energy & materials transition
- Must be sustainable
  - Low lifecycle greenhouse gas emissions
  - No harm to ecosystems/biodiversity
  - Not compete with land used for food production
  - Not result in changes to land use that could release CO_2 (e.g., deforestation)

Sustainable Biomass Resources

- **Wastes & Residues**
- Energy crops grown on degraded or marginal lands

- Amount available is limited and unlikely to grow
- Different resources in different areas
- Demand will increase

… so we need to prioritize the best use cases

Image by 1195798 from Pixabay

Image by Michal Jarmoluk from Pixabay

Priorities for biomass (residues)

Energy

- Hard-to-electrify sectors (aviation, shipping)
- Local use cases (especially for heat)
- Balancing fluctuations from wind and solar

Materials and Chemicals

- Biomass as carbon source
- Cascading valorisation (including energy)
- Negative emissions – bio-based products with long lifetimes act as carbon sinks

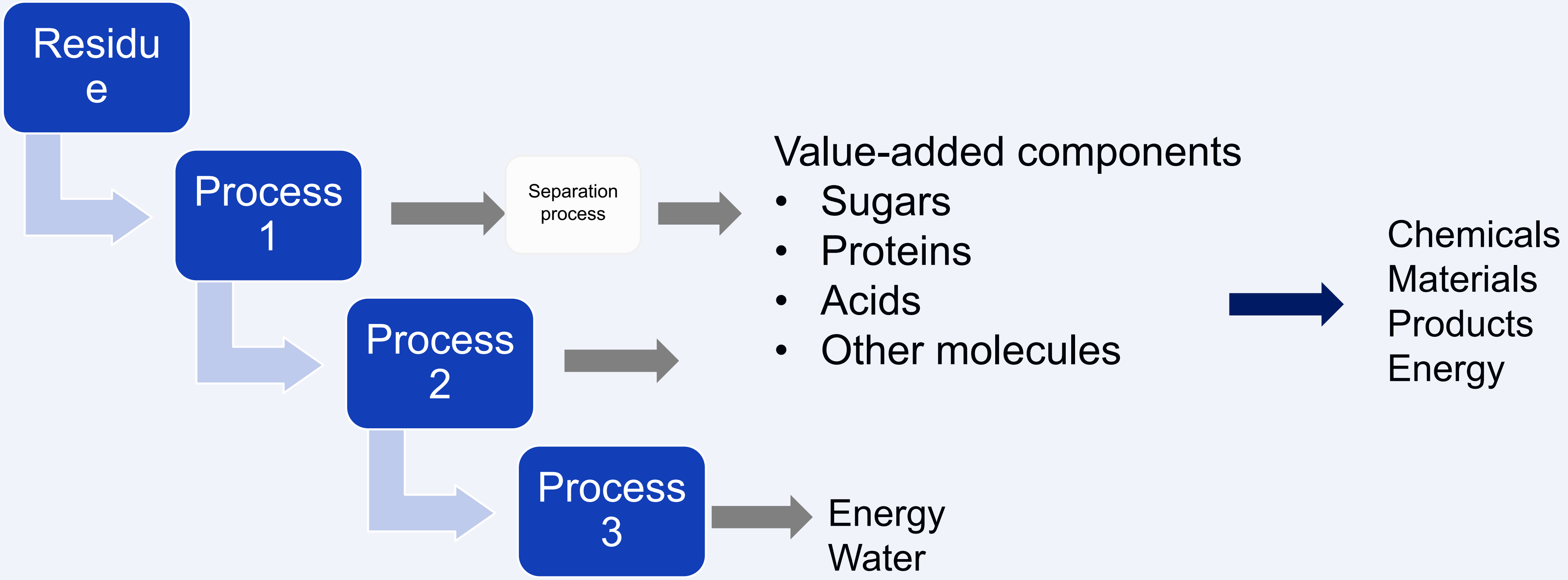
Image by 穿着拖鞋一路小跑 from Pixabay

Pfeiffer & Thran, 2018
Strzalka et al., 2017
Hauser & Wern, 2016

Biomass residues are often challenging

- Wet
- Salty
- Contaminated
- Low energy density
- Seasonal
- Degradable
- Messy
- Complex
- Full of plastic contamination

Cascading valorisation



Further challenges

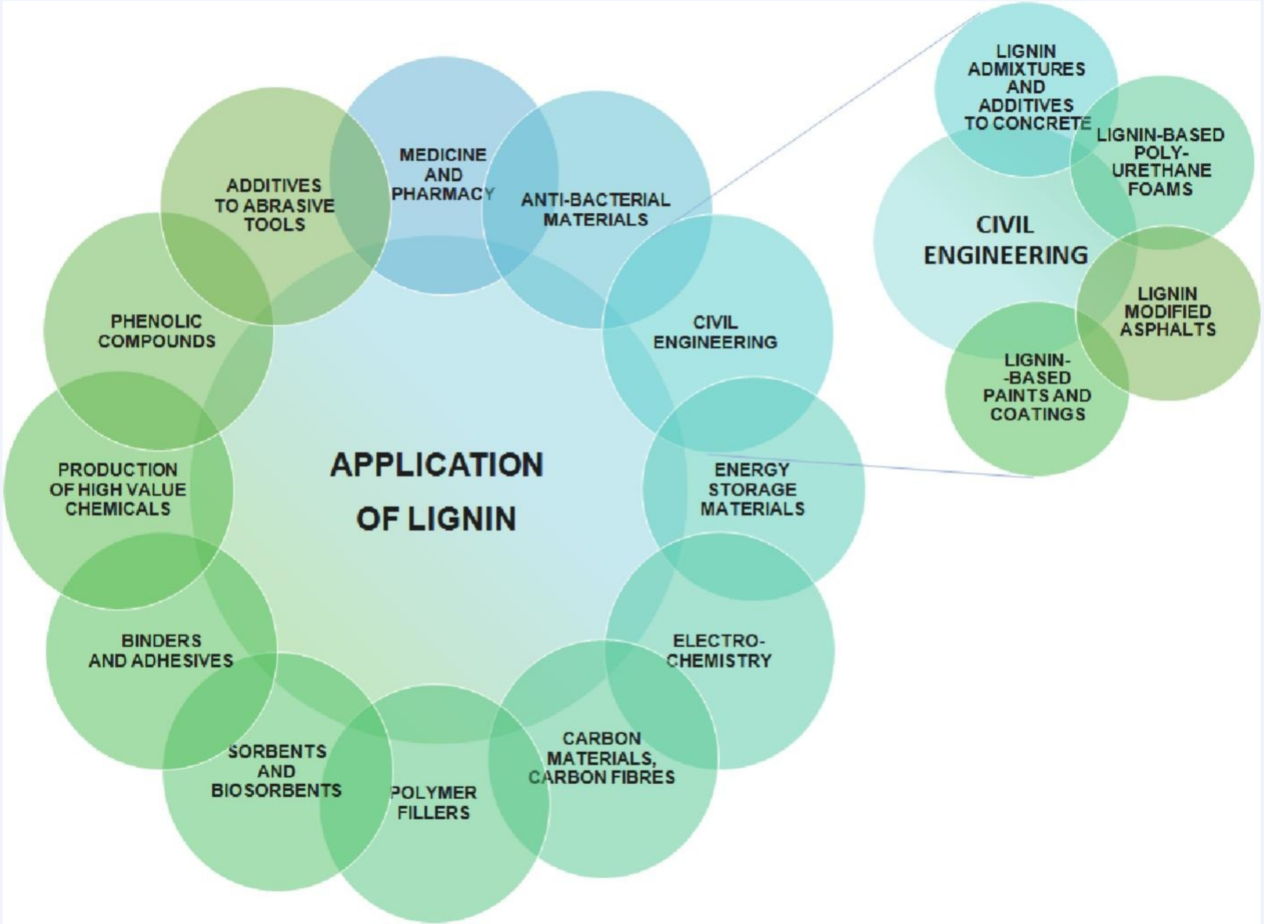
- Need to develop flexible (& continuous) processes
- Cost-competitiveness with fossil-based counterparts
- Scale-up and investment needed to meet demand
  - Most things are still at lab-scale / low TRL
- Lack of policy
- Challenges with recycling

Case Studies

Lignocellulosic Residues

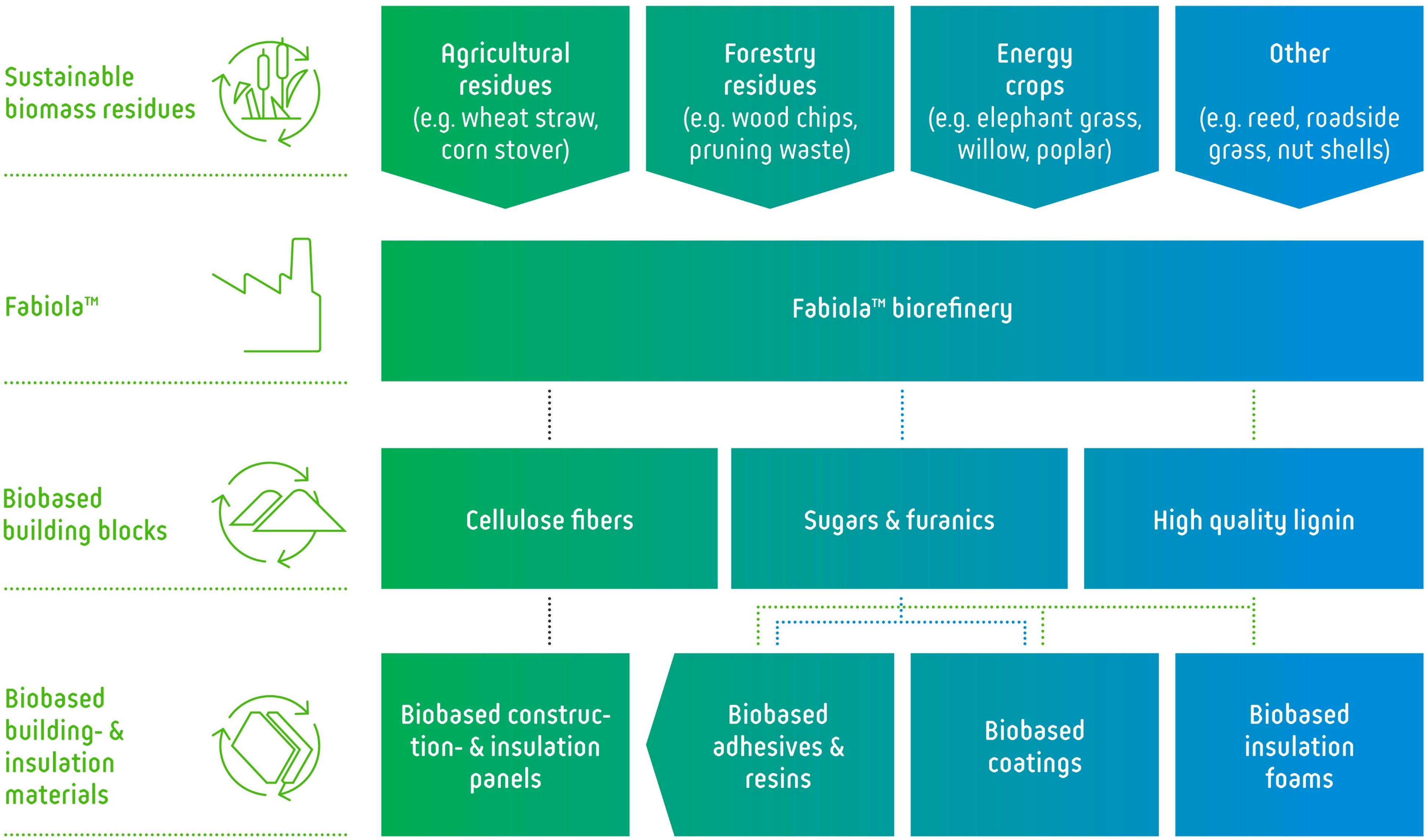
Lignin

- Flame-retardants
- Epoxies
- Resins
- BPA replacement
- Polyurethanes
    - Non-isocyanate PU
    - Foams
    - Insulation
- Coatings (e.g., antioxidant)



Castrillon et al., 2025

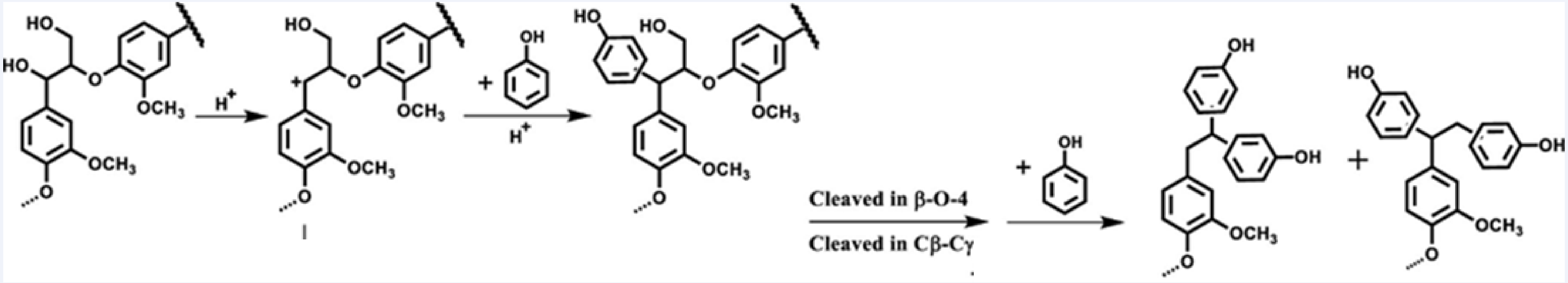
Fabiola™ biorefinery: the feedstock-flexible factory for biobased building blocks



www.biorizon.eu

BPA replacements via polyol modification of lignin

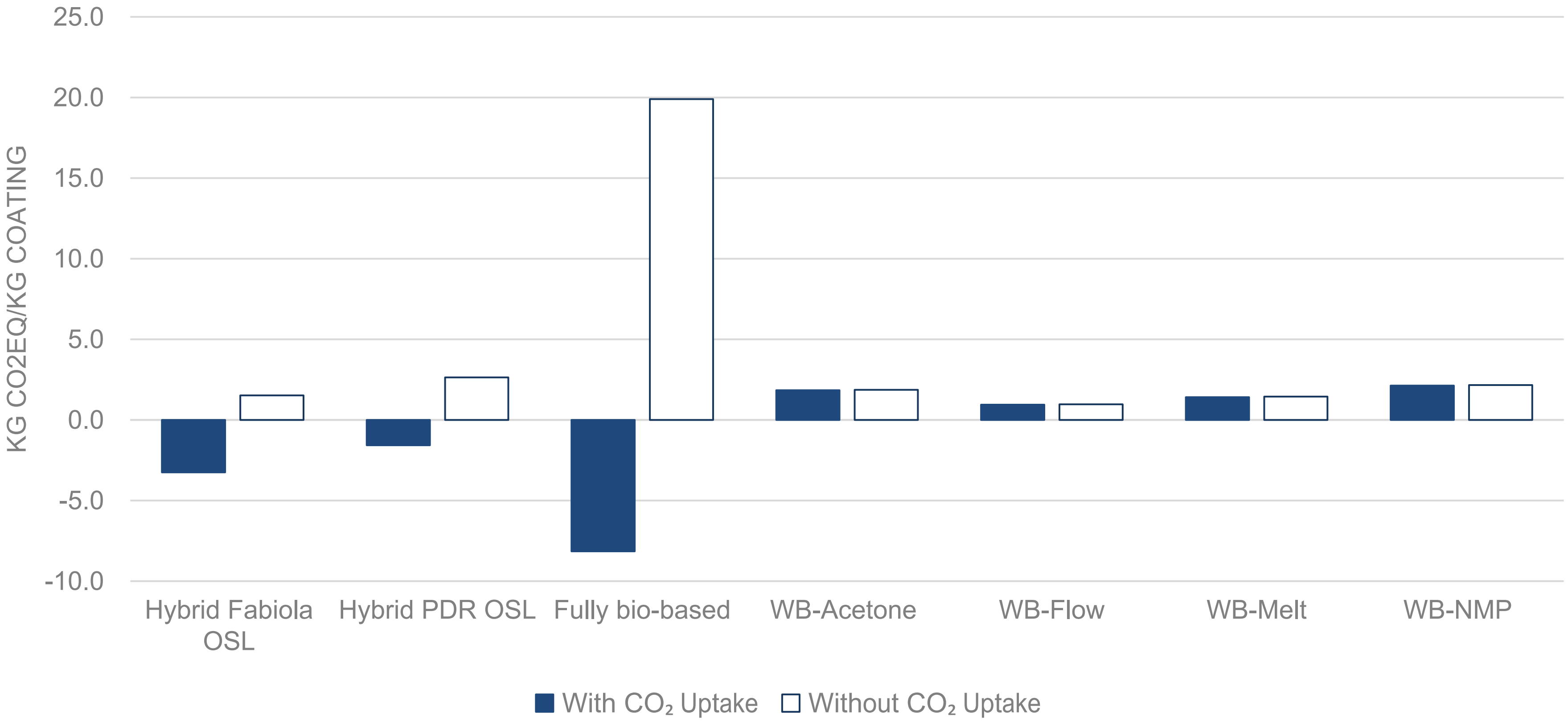
- Bisphenol A is toxic and fossil-based
- EU is moving to ban BPA in various markets
- Substitution of bisphenol A with modified lignin
- Better functionality and use of less toxic building blocks for epoxides
- First PoC of pyrogallol-modified lignin ongoing and epoxide synthesis at lab scale



Innovative value-added materials and products

	Circular carbon feedstocks	Polymer modifications	Value-added materials	Target markets
1	Lignins	Pyrogallol-modification	Polyols replacements	Epoxides for thermosets/ coatings
2	Lignins	Amine-cyclic carbonates	Isocyanate replacements	NIPUs for thermoplastics & resins
3	Lignin/Poly-saccharides	Phosphorylation/ carbamation	Flame retardant additive	Biocomposites & coatings

Bio-based polyurethane coatings



- Lignin as a component of coatings reduces GHG emissions relative to fossil-based coatings
- Bio-based crosslinker associated with higher emissions (needs more research)

- End-of-life scenarios are needed to reduce environmental impacts of bio-based coatings production

Wray et al., 2023

Algae

Macroalgae

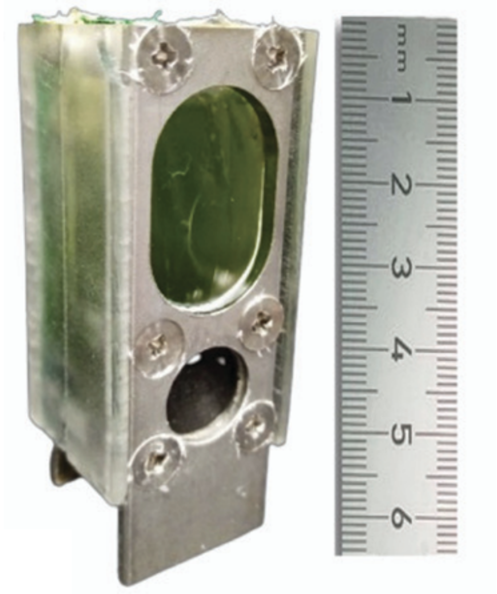
- *Sargassum* biomass from inundations can be used for energy generation (anaerobic digestion) and recovery of high-value products (alginate and fucoidan)
- Most promising business case is for production of high-value products

Microalgae

- Lipids or other extracts as a valuable product and additive to materials (also potential carbon sink)
- Algae-based batteries (Cambridge University)

Dussan et al., 2025 (under review)

Alejandro Granadillo/AP



Bombelli et al., 2022

Wet Residue Streams

Wet residue

Paper sludge

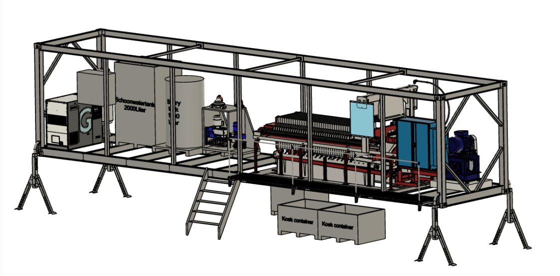
Olive pomace

Orange peels

TORWASH®

Effluent

Mechanical Dewatering



Liquid fraction

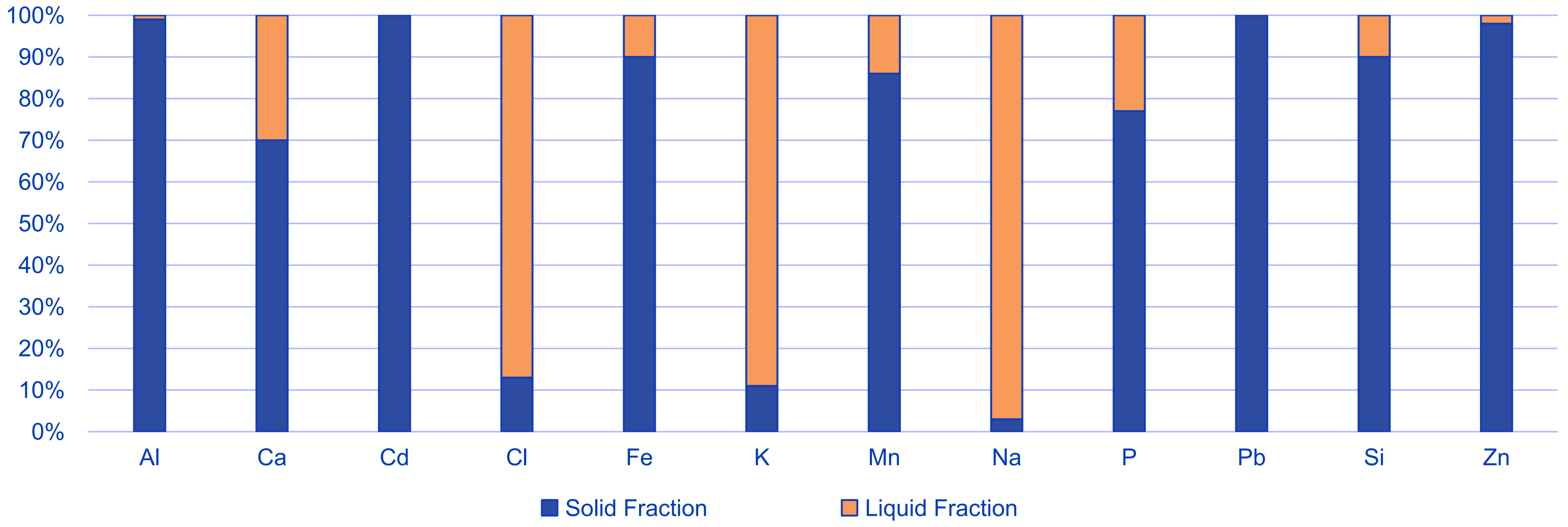
Anaerobic digestion to produce biogas

Nutrient recovery

Solid cakes

Solid fuel for boiler

Hydrothermal Carbonization

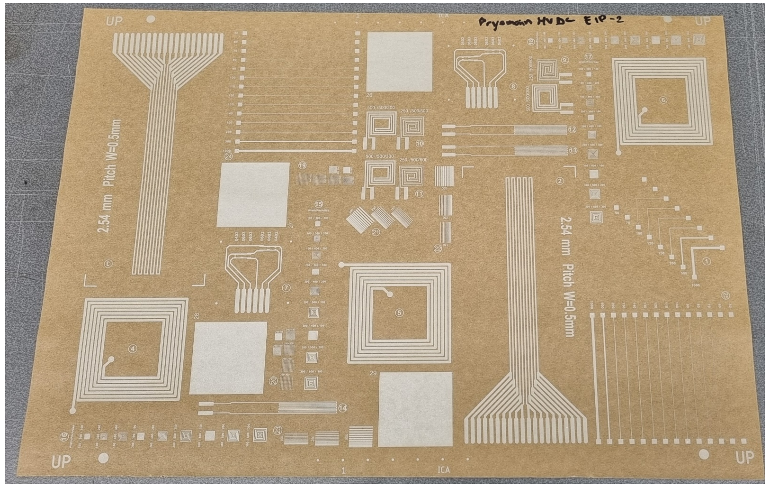


Bio-pellet quality

- Olive pomace pellets most suitable feed for syngas production but pellets were less durable
- Paper sludge pellets had poorer quality (high ash); best suited for direct use on-site
- Lab-scale results better than pilot-scale results

Parameters	ENplus B (ENplus, 2015)	F-CUBED target	Bio-sludge	Olive pomace	Orange peels
Moisture (wt%)	≤10	< 10	7	6	6
N (db) (wt%)	≤1	< 2.5	6.8	2.9	1.6
S (db) (wt%)	≤0.05	< 0.3	2.1	0.2	0.1
Ash (db) (wt%)	≤2	N/A	41	1.1	2.3
LHV (MJ/kg)	≥16.6	> 10	18.2	26.3	22.2

Circular by Design Printed Electronics



Joel Benavides, Margreet de Kok

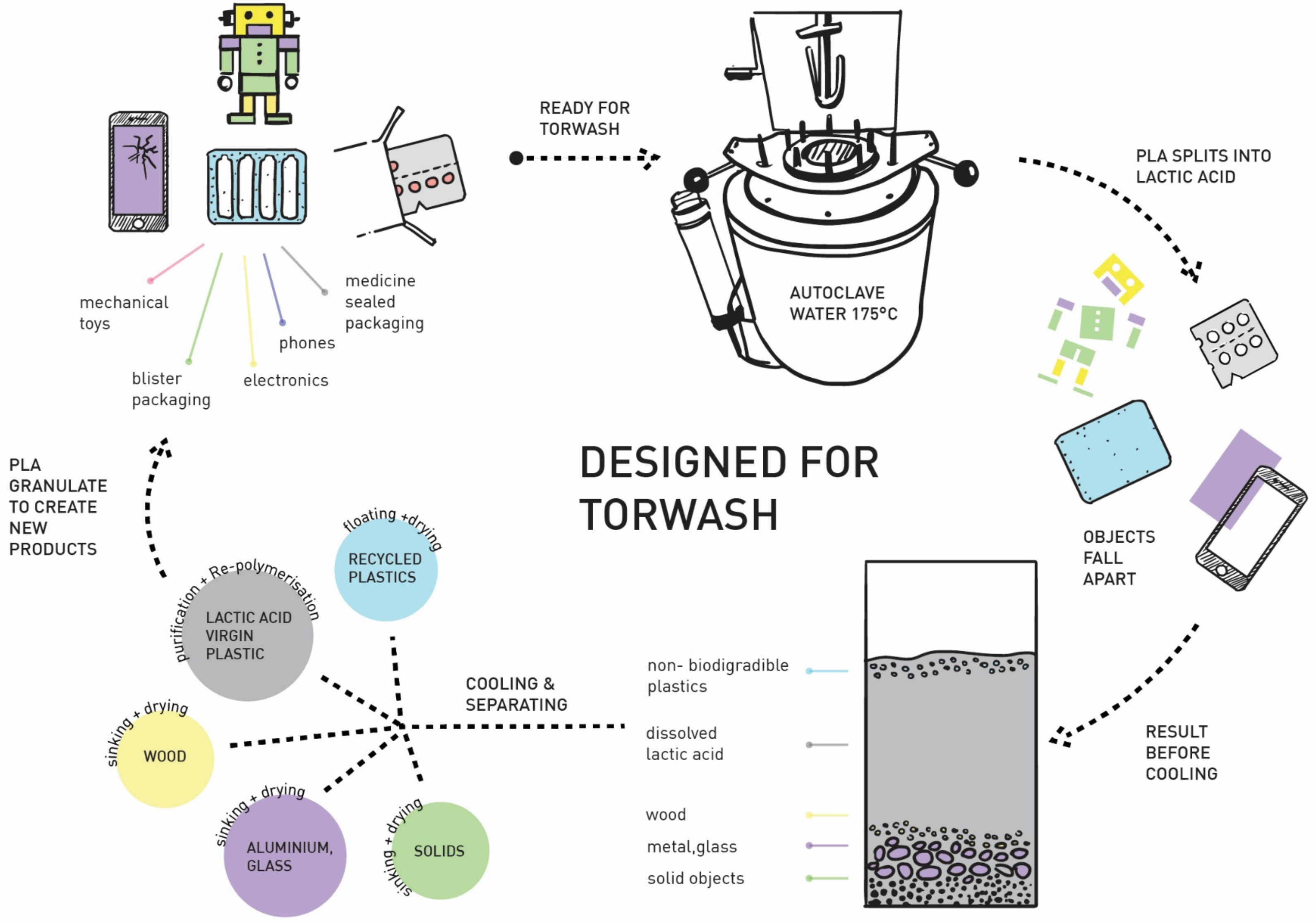
Example EU projects:
Sustronics
Hypelignum

Hypelignum

- Sustainable substrates for printed electronics:
  - Paper substrates
  - Degradable (e.g., hydrothermal dissolution)
  - Biobased plastics

- Biobased materials and building blocks for materials to make electronic components:
  - Lignin as matrix for nanometals in printed electronics
  - Biocarbons as conductors in low-current applications

Design for End-of-Life



Reality Check

- Adoption of circularity by design is slow
  - Cost** and financial risk for companies
  - Technology limitations
  - Insufficient product design standards that mandate circularity
  - Unpredictable feedstocks
  - Complex value chains

In space, constraints force circularity and resource efficiency

Waste as Feedstock

- Combine biomass fractionation/biorefinery + upgrading + design for end-of-life
- Produce circular, SSbD materials

Gaps:

- Feedstock predictability and uniformity
- Valorisation routes at scale (flexible, cascading)
- Product design that considers end-of-life from day 1

What's Next? What should we aim for?

- Prioritize the uses for biomass wastes
  - Difficult-to-electrify sectors
  - Local applications
  - Opportunities for negative emissions (C-storage)
  - Bio-based materials from waste feedstocks
  - Balancing the energy grid from wind and solar fluctuations
- Choose the right feedstock (wastes)
- Develop technologies and processes that allow for more than one product
- Design bio-based products & materials for end-of-life scenarios

Thank you!

Questions?

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