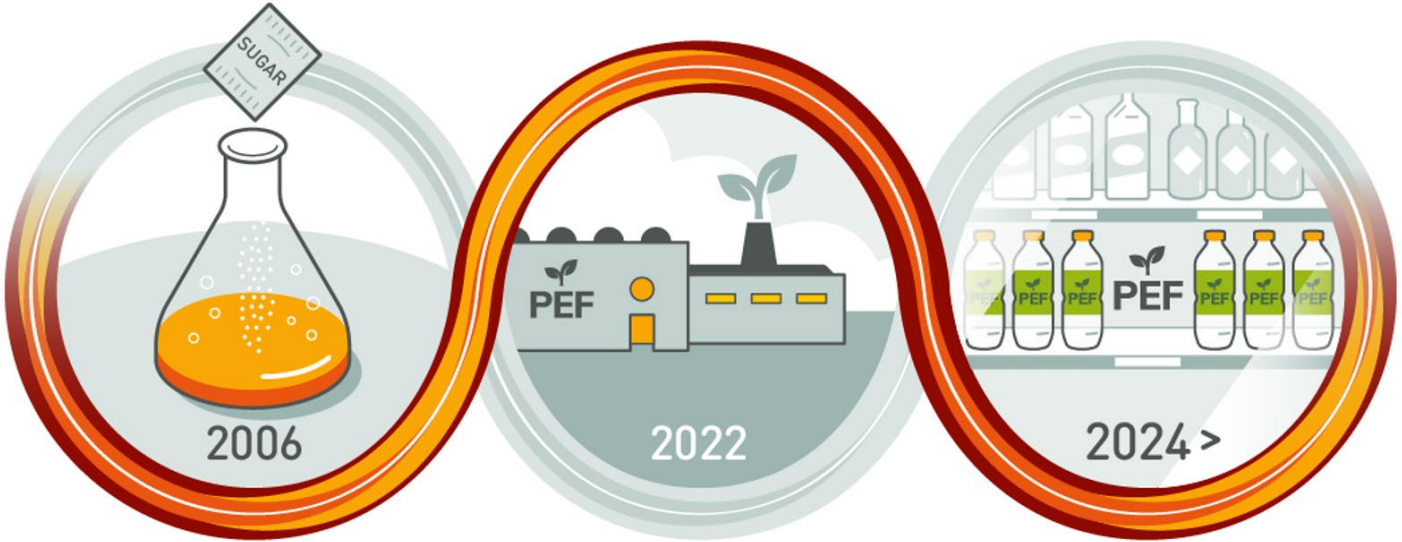


New developments on PEF and Avantium's flagship factory

Ed de Jong

Avantium

Avantium vision

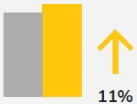
We create **disruptive technologies** and bring them to the world **with partners** to accelerate the transition towards **renewable and circular** products.

Avantium at a glance

Number of FTEs
(end of year)

213
2020: 218
↓ -2%

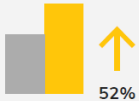
Revenue
(in € million)

10.9
2020: 9.9

↑ 11%

Number of government grants

20
2020: 20
→

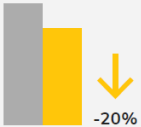
Investments
(in € million)

5.3
2020: 3.5

↑ 52%

Nationalities employed

20
2020: 21
↓ -5%

Grant recognition
(in € million)

6.7
2020: 8.4

↓ -20%

Newly granted patents

17
2020: 18
↓ -6%

Cash outflow[1]
(in € million)

18.1
2020: 18.8

↓ -4%

Gender balance
(% of total workforce)

26.1 women
2020: 24.5
↑ 7%

Newly reported inventions

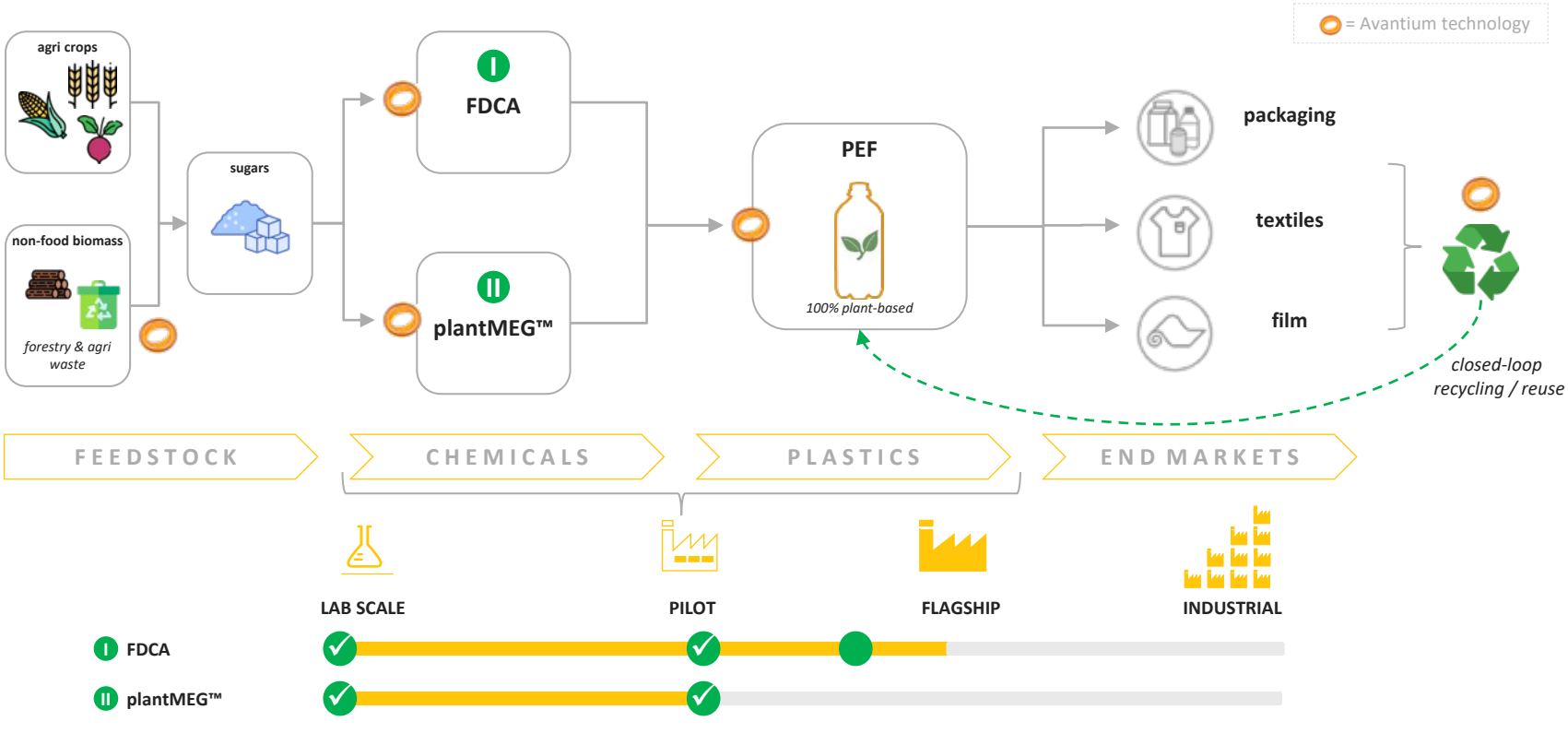
39
2020: 41
↓ -5%

3 Business units:

1. Catalysis
2. Renewable Chemistries
3. Renewable Polymers

A coherent portfolio of renewable products

focused on plant-based plastics, advancing towards commercialization



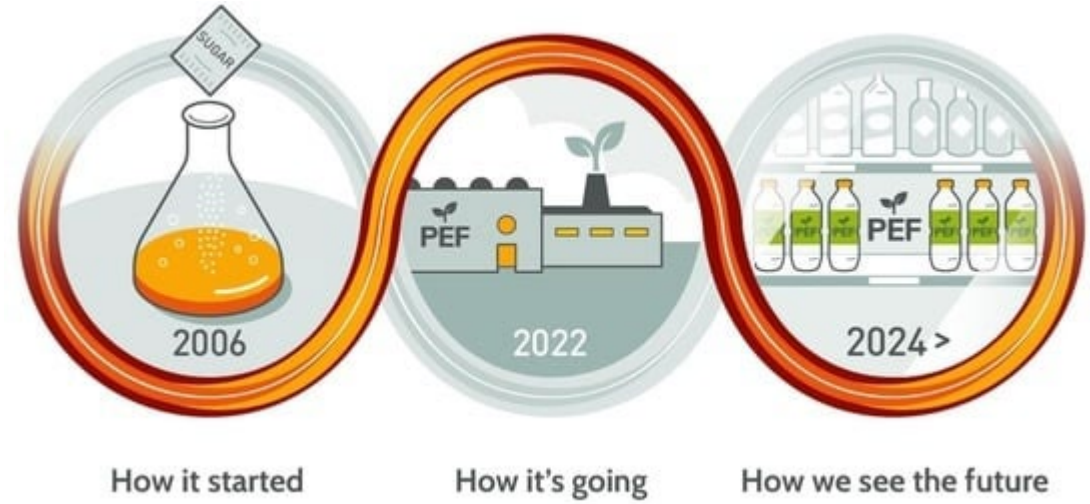
Objective and content

Objective

Give a high-level overview into the evolution of the FDCA and PEF development at Avantium and aspects that have and will influence the road to commercialization.

Content

1. Evolution of the endeavor
2. Strategic route to valorize
3. Intellectual property
4. Application development
5. Drive to circularity
6. Regulations
7. Partners
8. Take away messages



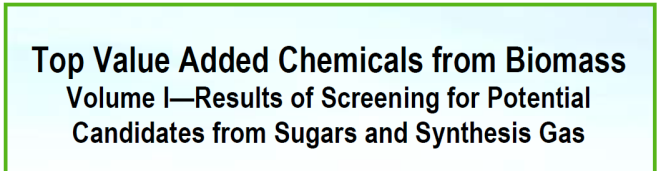
1

The evolution of the endeavor

The spark of an idea

Our FDCA journey started with a Friday afternoon experiment

- Avantium started as a spin-out of Shell in 2000
- Avantium started to explore the use of chemical catalytic conversion processes on biobased feedstock
- In 2005 a first Friday afternoon experiment was carried out dehydrating sugar using ethanol as solvent.
- The technology later branded as YXY® was validated in 2006



The first prototypes: golden bottles

The initiation of the bottle consortium

In 2008 Avantium and NatureWorks started a development collaboration. It led to the first PEF prototypes in collaboration with NatureWorks LLC.

These bottles, and particularly their performance attracted direct attention from the packaging world, leading to the partnership with TCCC, Danone and ALPLA.

AVANTIUM

NatureWorks LLC

The start of the pilot plant

SDH and oxidation promoted to larger scale

Thanks to the bottle consortium Avantium was able to raise capital to construct a pilot plant (or actually two: SDH and oxidation) in Geleen.

The pilot plant became operational in 2011.

In September 2016 the pilot plant was re-opened at a new location and a purification plant was included.

Purposes of the plant:

-process development/demonstration

-FDCA production

In 2015 FDCA was added to the safe list of EU for the use in PEF.

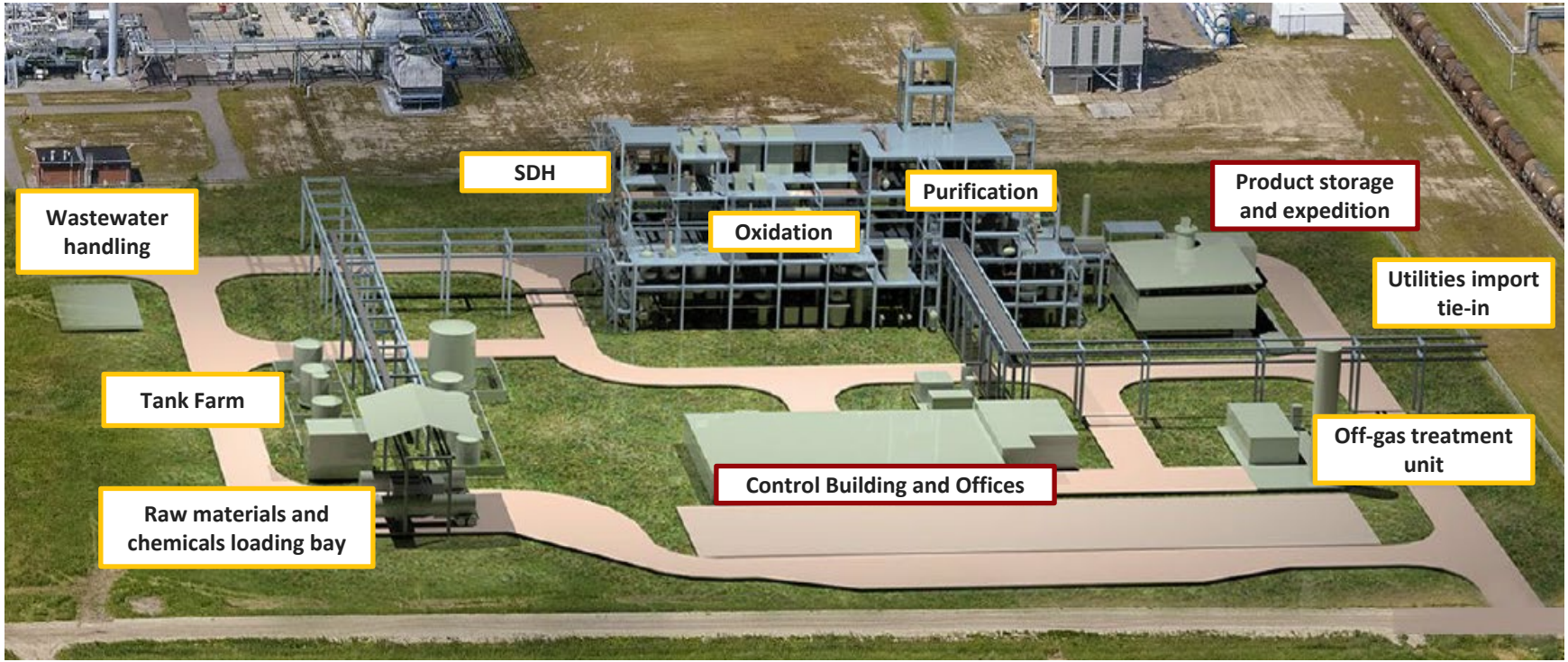
Where we are now: the first piles are in the ground

FDCA will become commercial reality

- In April 2021 it was half of the flagship capacity was already reserved with conditional off-take agreements.
- On December 9th 2021 a positive final investment decision was made to construct the flagship plant in Delfzijl.
- In April 2022 the first pile ceremony took place.

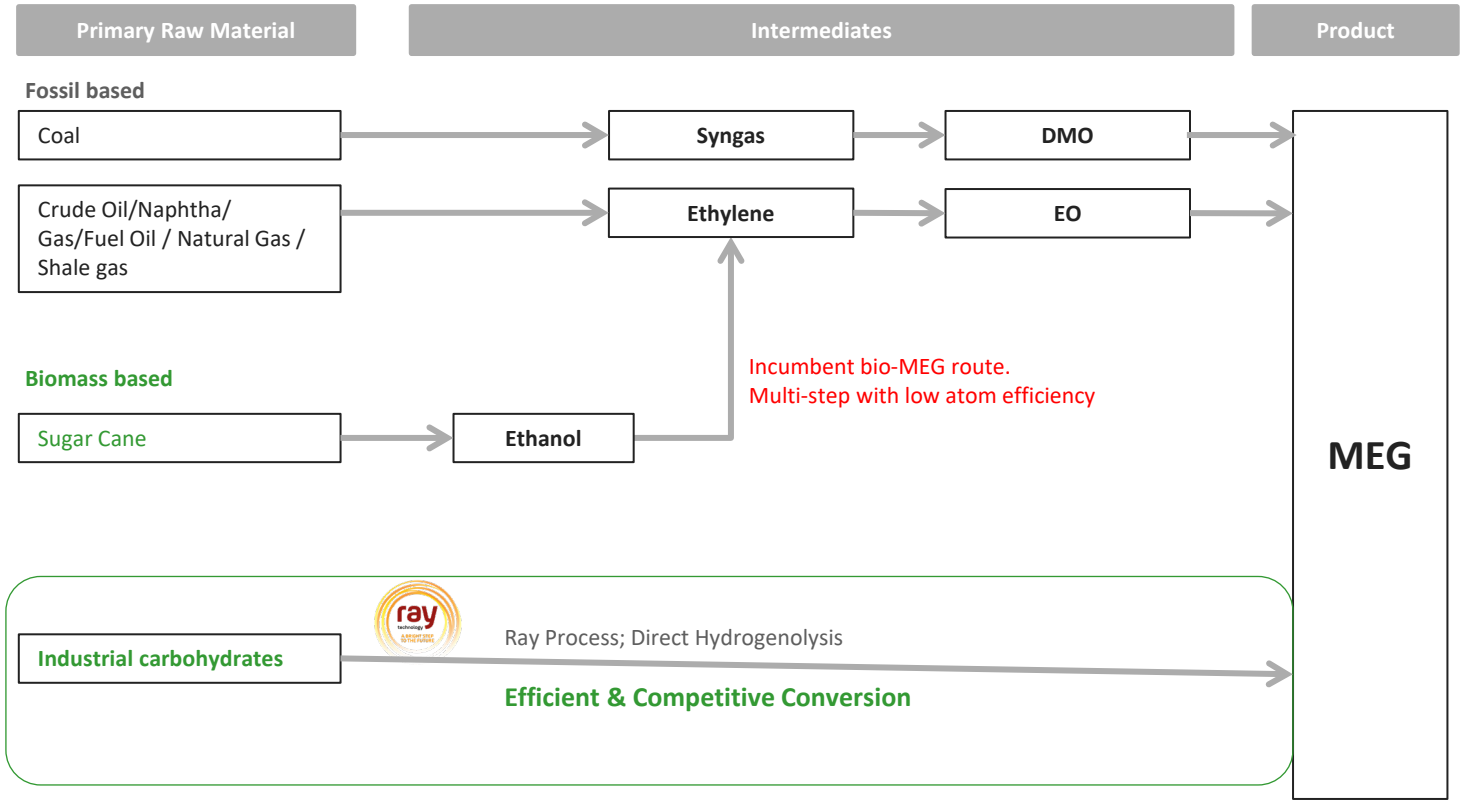
Avantium

Layout of the flagship plant



Ray Technology™ - Plant-based glycols

Routes to MEG

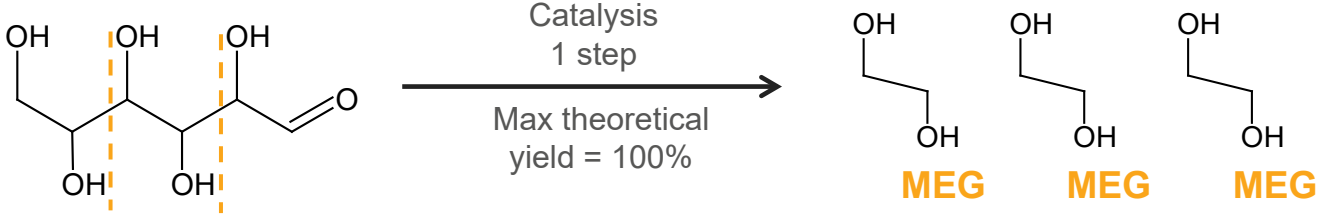


Avantium's Ray Technology™ in a nutshell

- Production process: convert sugars to plant-based MEG (monoethylene glycol)
- Chemical catalytic process
- Superior carbon efficiency
- Aims to help fulfilling the growing MEG demand; >70 million ton in 2045

Hydrogenolysis

E.g. Glucose



- Ray Technology converts industrial carbohydrates from first and second generation sources (wheat, corn, beet and cane etc.) into valuable glycols
- High selectivity of **MEG** with **MPG (1,2-propanediol)** as main co-product.

Ray Demonstration Plant

- Located in Delfzijl, the Netherlands
- Demonstration Plant: >10t/a capacity
- ~ €10m capital investment
- 10-20 employees
- Opened: Q4 2019

CHEMPORT EUROPE

Chemie Park DELFZIJL

- **End-to-end process: Sugars to distilled Glycols**

- **Producing plant-based glycols for qualifications**
- **Preparing technology for commercial scale-up**

Avantium's Ray demonstration plant is being supported by the European Investment Council (EIC) under SME Instrument (Phase2): EGgPLANT; by the European Regional Development Fund through SNN; by a grant from the Bio Based Industries Joint Undertaking (BBI JU) under the European Union's Horizon 2020 program: VEHICLE; and by a SPIRE grant, part of Horizon 2020: IMPRESS.

2

Strategic route to valorize

Drop-in vs new building block

Challenges depend on the nature of the building block

drop-in like MEG (RAY)

+ Only validation and limited application development required
+ Customers well trained to use the product

- Only value proposition is the plant-based origin. Price difference with incumbent can only be carried with a green premium.

new building block like FDCA (YXY)

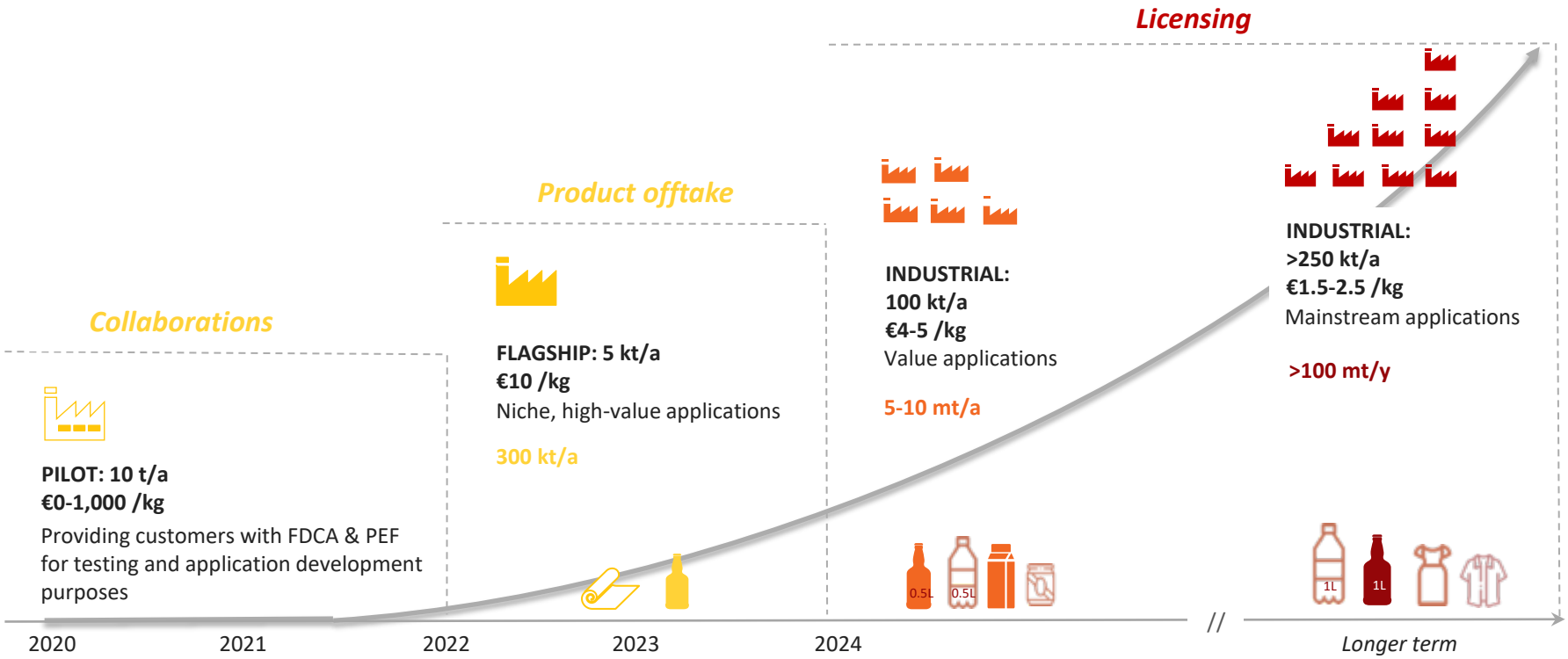
+ Besides a green premium the properties of the product can lead to additional value propositions.

- Extensive fundamental studies and application development are required
- Customers require support when using the product.

Despite being “new” FDCA and PEF have the advantage that they have a well know fossil-based counterpart and can be processed in existing assets.

Avantium

FDCA/PEF: focus on (high-)value applications



Price/kg: market price estimates to be competitive in that particular market segment

Sources: Report Global Multilayer PET bottles Industry 2019 -2020; The Future of High Barrier Packaging Films to 2024; Soft drink database 2015; Packaging master database 2015

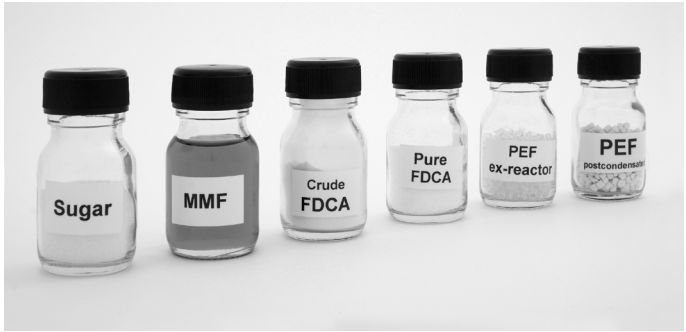
3

Intellectual property

Avantium's approach to IP protection

Building attractive licensing package while keeping end market open

- Avantium Renewable Polymers has a broad patent portfolio with >55 patent families representing >450 patent rights.
- The patents cover topics through the value chain:
  - Sugar dehydration
  - Oxidation
  - Purification
  - Side streams (e.g. humins)
  - Polymerization
  - Resin modification
  - Applications (bottles, films, thermoforming, fibers)

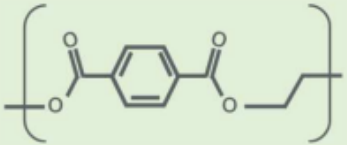
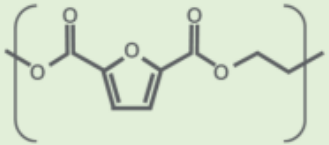


After basic protection on applications ARNP follows an open innovation approach

4

Application development

Comparison of some of the major characteristics of the polyesters PET and PEF[#]

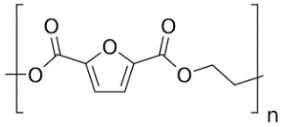
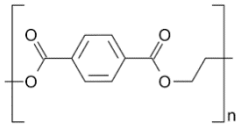
Property	PET (Amorphous)	PEF (Amorphous)	References
Molecule			
Density (amorphous)	1.36 g/cm^3	1.434 g/cm^3	[129,130,133,141]
Density (crystalline, calculated)	1.455 g/cm^3	1.565 g/cm^3	[129,130,142–144]
Melting temperature (T_m)	250–270 °C	210–230 °C	[56,109]
Glass transition temperature (T_g)	~76 °C	~88 °C	[145,146]
Crystallization time	2–3 min	20–30 min	[128,133–135,147]
E-modulus (ISO 527/1A, 1 mm/min)	2.1–2.2 GPa	3.6 GPa	[146]
Yield strength (ISO 527/1A, 10 mm/min)	50–60 MPa	90–100 MPa	[146]
O_2 permeability * (@23 °C, 65% RH)	2.5 cm^3·mm/(m^2·24 h·bar)	0.23 cm^3·mm/(m^2·24 h·bar)	[146]
CO_2 permeability * (@23 °C, 0% RH)	23.6 cm^3·mm/(m^2·24 h·bar)	1.6 cm^3·mm/(m^2·24 h·bar)	[146]
H_2O permeability * (@38 °C, 90% RH)	0.9 g·mm/(m^2·24 h)	0.36 g·mm/(m^2·24 h)	[146]

[#] de Jong, et al. *Polymers* **2022**, *14*, 943.

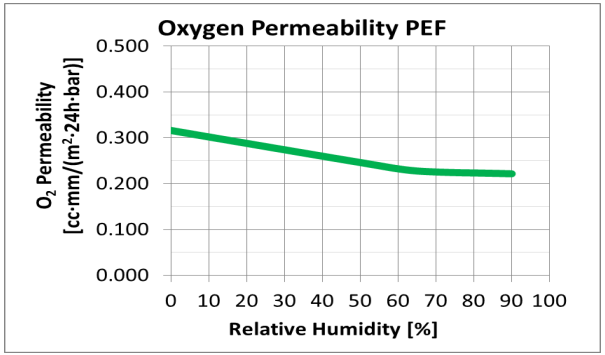
* All permeability experiments were carried out by an independent laboratory on 45 µm thick cast films in accordance with ASTM: ASTM F1927-14 (O_2), ASTM F2476-13 (CO_2) and ASTM F1249-13 (H_2O). For PET a commercial bottle grade PET was used with an IV of 0.80 dL/g and the PEF resin used had an IV of 0.89 dL/g as measured according to ASTM D4603 (0.4 g/L).

PEF: part of the polyester family, with excellent barrier performance

Great candidate as barrier material

	PEF	PET
		
O_2 permeability (23 ºC 65%RH) [cc·mm/(m²·24h·bar)]	0.23	2.5 (~11x)
CO_2 permeability (23 ºC 0%RH) [cc·mm/(m²·24h·bar)]	1.6	24 (~15x)
WVTR (38 ºC 90%RH) [g·mm/(m²·24h)]	0.36	0.9 (~2.5x)

Source: data measured at independent lab in accordance with ASTM F1927-14, ASTM F2476-13, ASTM F1249-13.
Values reported here refer to amorphous (non biaxially oriented) materials.



Values reported here refer to amorphous (non biaxially oriented) PEF

PEF is a polyester, same chemical family as PET, but with much better barrier performance which show little dependency on ambient conditions (i.e. relative humidity)

Addressing an extensive number of end-markets over time

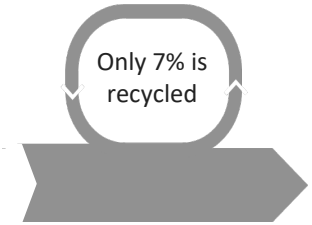
Today	Tomorrow	Longer-term
High-value applications	*Value applications*	*Mainstream applications*
	 	
Specialty bottles: • Multi-layer • Monolayer	PEF bottles to replace • Glass bottles • Aluminium cans	PEF bottles to replace • PET bottles (beverages, personal care)
		 
Specialty films: • Barrier • Optical	Films & Fibers: • Technical fibers • Flexible films (shrink films and skin layer)	Other • Fiber – Apparel • Automotive • Thermoforming

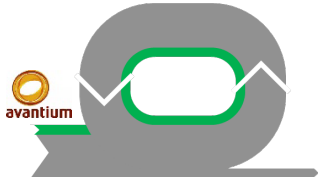
5

Drive to circularity

Tomorrow's solutions have to facilitate the transition today

… driving the change through compatibility, partners & leadership





Today

- Low collection rates
- Low recycling rates

↓

- Insufficient availability of food approved recycled material
- High dependency on virgin
- High waste

>2025

- Light-weighting
- Full-polyester packaging solutions
- Enhance collection schemes

↓

- Improved circularity
- Reduced dependency on virgin
- Reduced waste.

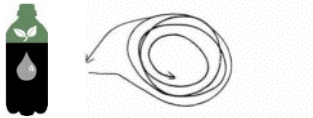
>2035

- Transfer from fossil to renewable through upscaling of technologies
- Keep existing material pool alive and only use virgin for market growth and minor losses in cycle.

↓

Linear + Fossil based

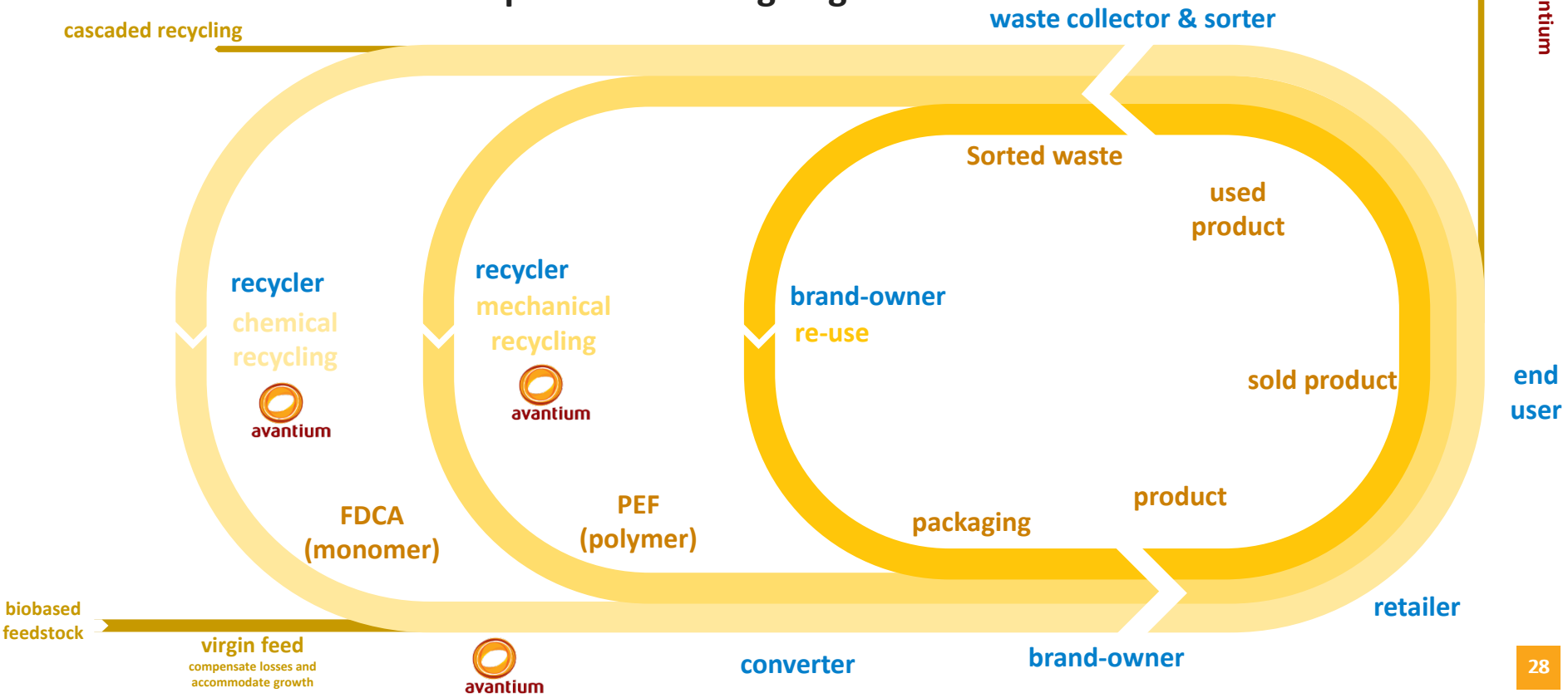
Circular, but mostly Fossil based



Circular + Fossil-free

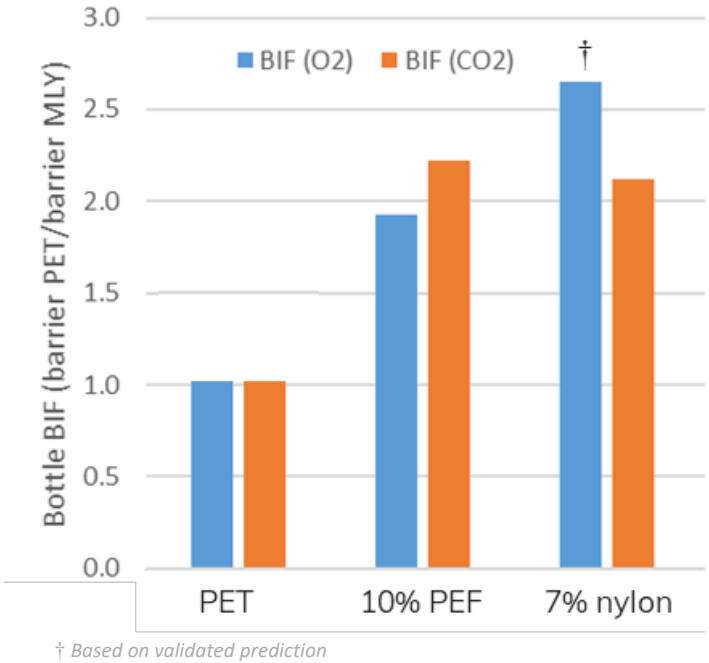
Circularity has multiple routes

Avantium has development work ongoing on each route

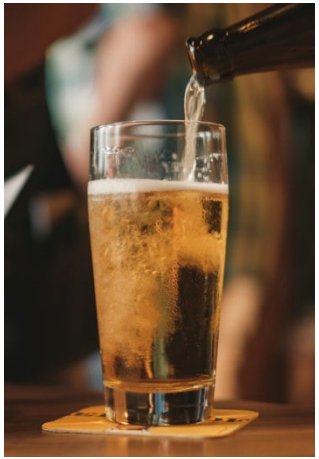


Example on recycling studies: Multilayer bottles

Performance in-use: PEF barrier performance proven

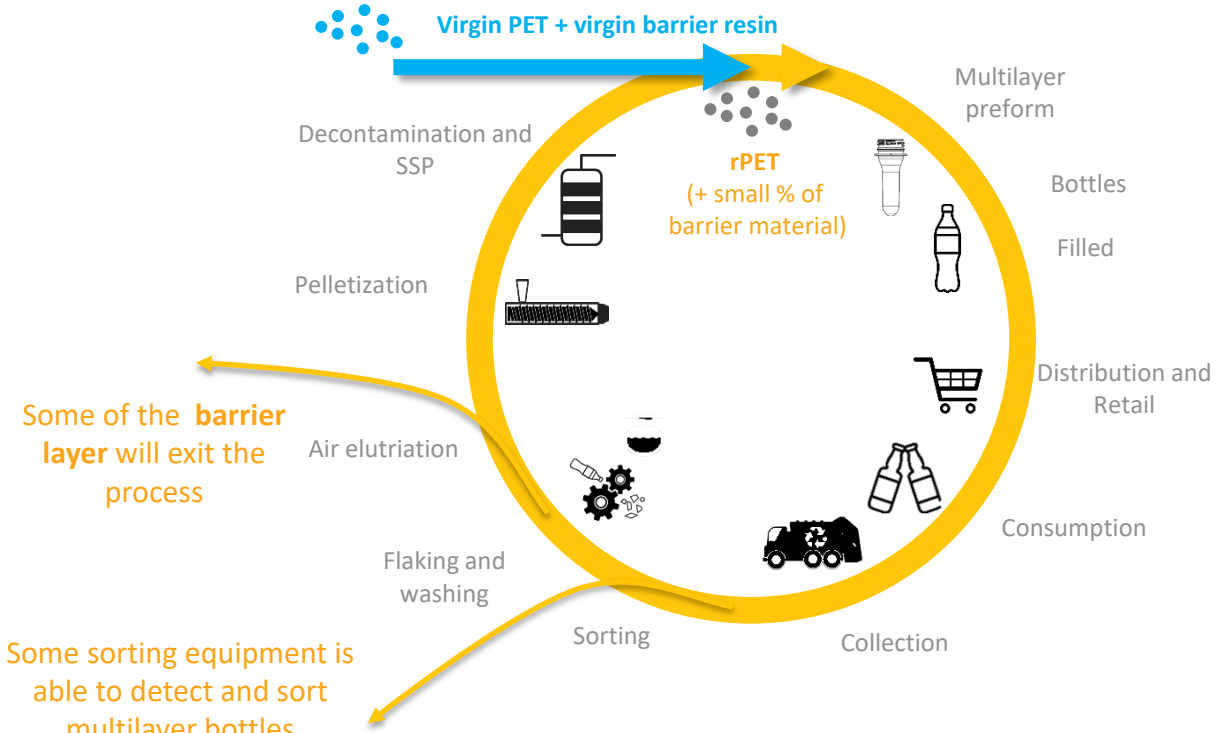


† *Based on validated prediction*



How are (multilayer) bottles currently recycled?

The need for recycling assessments



Depending on sorting efficiency on bottles and layer level, some barrier material can enter the recycling stream.

Avantium Renewable Polymers is assessing the impact of PEF multilayer bottles can have on the existing PET stream:

In EU (EPBP)
In US (APR)
In Japan (CPBR)

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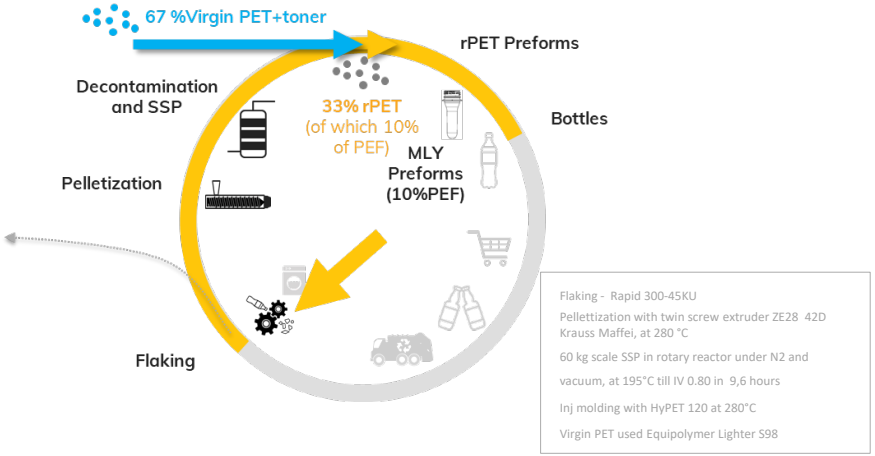
Recycling multilayer PET/PEF pre-assessment



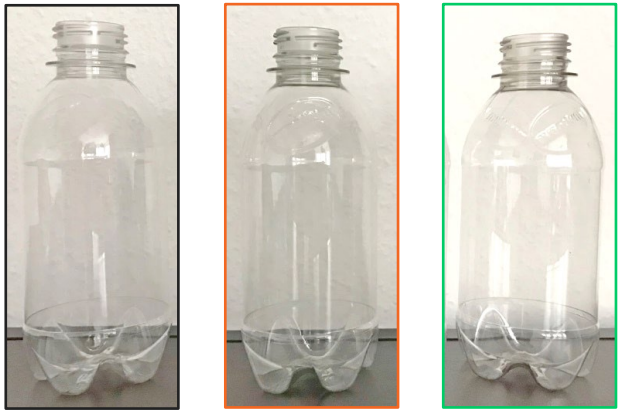
Flaking - Rapid 300-45KU

Pellettization with twin screw extruder ZE28 42D Krauss Maffei, at 280 °C

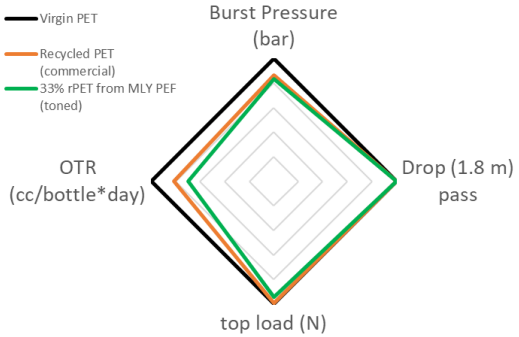
60 kg scale SSP in rotary reactor under N2 and vacuum, at 195°C till IV 0.80 in 9,6 hours

Inj molding with HyPET 120 at 280°C

Virgin PET used Equipolymer Lighter S98



	Virgin PET	Recycled PET (commercial)	33% rPET from Multilayer PET/PEF
L*	95	95	95
a*	0	-0.4	-0.2
b*	0.6	1.1	0.8
Haze % D65/10	2	2.9	1.8



Mechanical properties comparable with commercial recycled PET (from deposit scheme)

Color, haze and general appearance comparable if not better

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EPBP PEF as barrier: Preform and bottle design

Worst case scenario design was selected

Preform

- Selected 10 wt% barrier layer: highest relevant percentage for nylon barrier replacement.
- Barrier layer was positioned towards the core: a worst case (air elutriation more difficult) and therefore most robust results.
- The barrier layer starts just below the neck, down to the gate (closed dome). This is also worst case as it is more difficult to remove barrier material from the base.

Bottle

- 500 mL generic CSD bottle shape was selected

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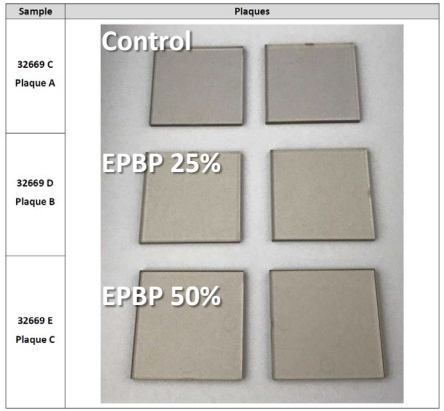
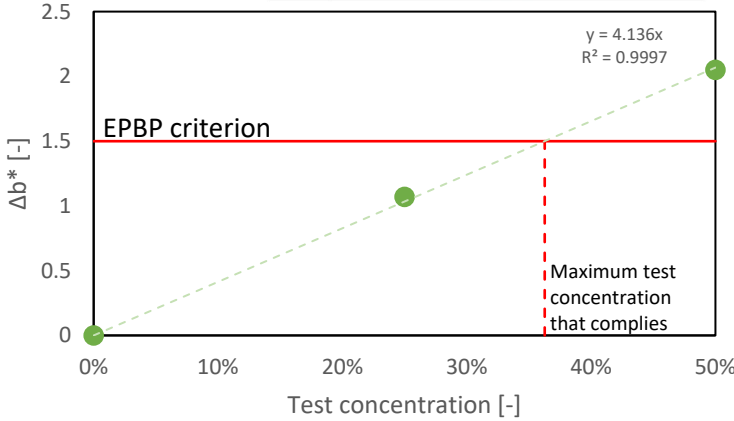
EPBP 3rd party assessment of PEF as barrier

At 25% test concentration all criteria are passed

- The 3 mm plaques were injected according to protocol.
- No significant differences in the injection molding conditions.
- **Both test concentrations pass ALL criteria except for the colour increase of the plaque.**
- The color on the plaques reveals that a 36 % test concentration will pass on the Δb* criterion of max 1.5.
- According to the EPBP conversion table a 36% test concentration correlates to an allowed market penetration of 12%.





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EPBP PEF as barrier: interim endorsement

- Based on the assessment results, EPBP has awarded an interim endorsement for PEF as a barrier material up to a market penetration level of 5% (taking local accumulation into account).

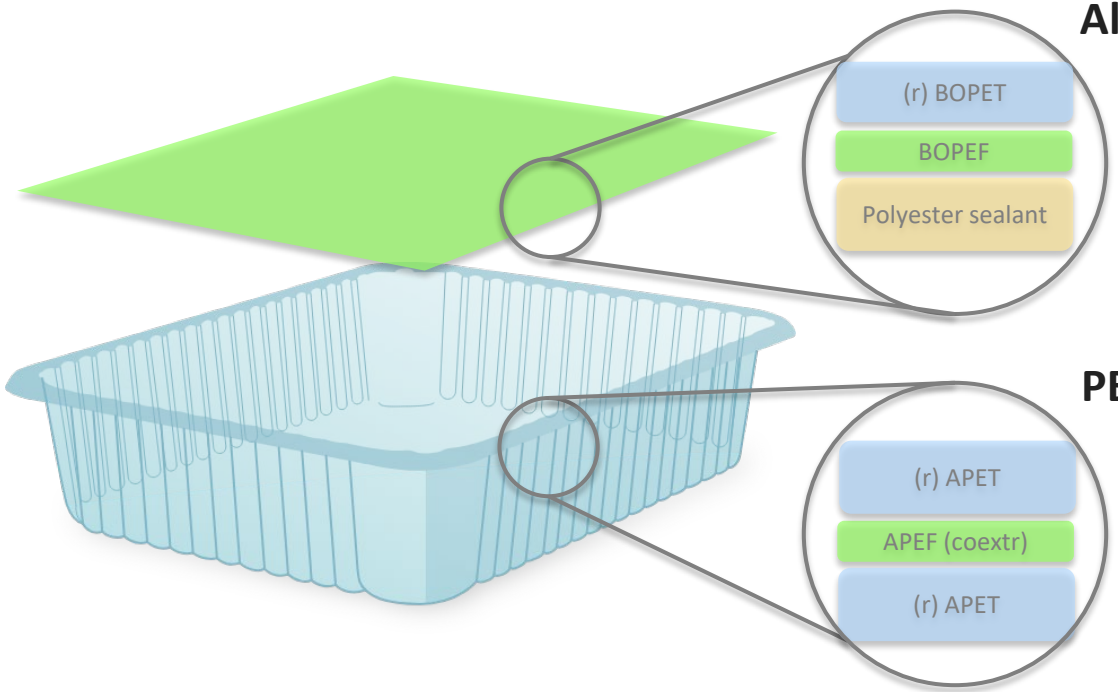
- The endorsement will expire on 30th of June 2025 but can be converted into a permanent endorsement if the conditions are met.

- Once the endorsement is permanent the EPBP can include PEF into their design guidelines, which trickle down to the Recyclass guidelines.

Work on APR (US) and CPBR (Japan) ongoing

Concept, PEF barrier for trays

A (barrier) material that meets (1) shelf life requirements, (2) enables the incorporation of recycled material(s) in the tray and (3) results in a tray that can be recycled into food approved resin



All polyester lidding film

- Take benefit of PEF barrier
- Polyester sealant, eventually developed based on FDCA
- Once PEF price comes down a full PEF solution will be more beneficial

PET tray

- If needed, extra barrier achieved with A-B-A structure with PEF
- Other structure possible incorporating rPET content
- Polyester sealant layer can be added for improved sealing.

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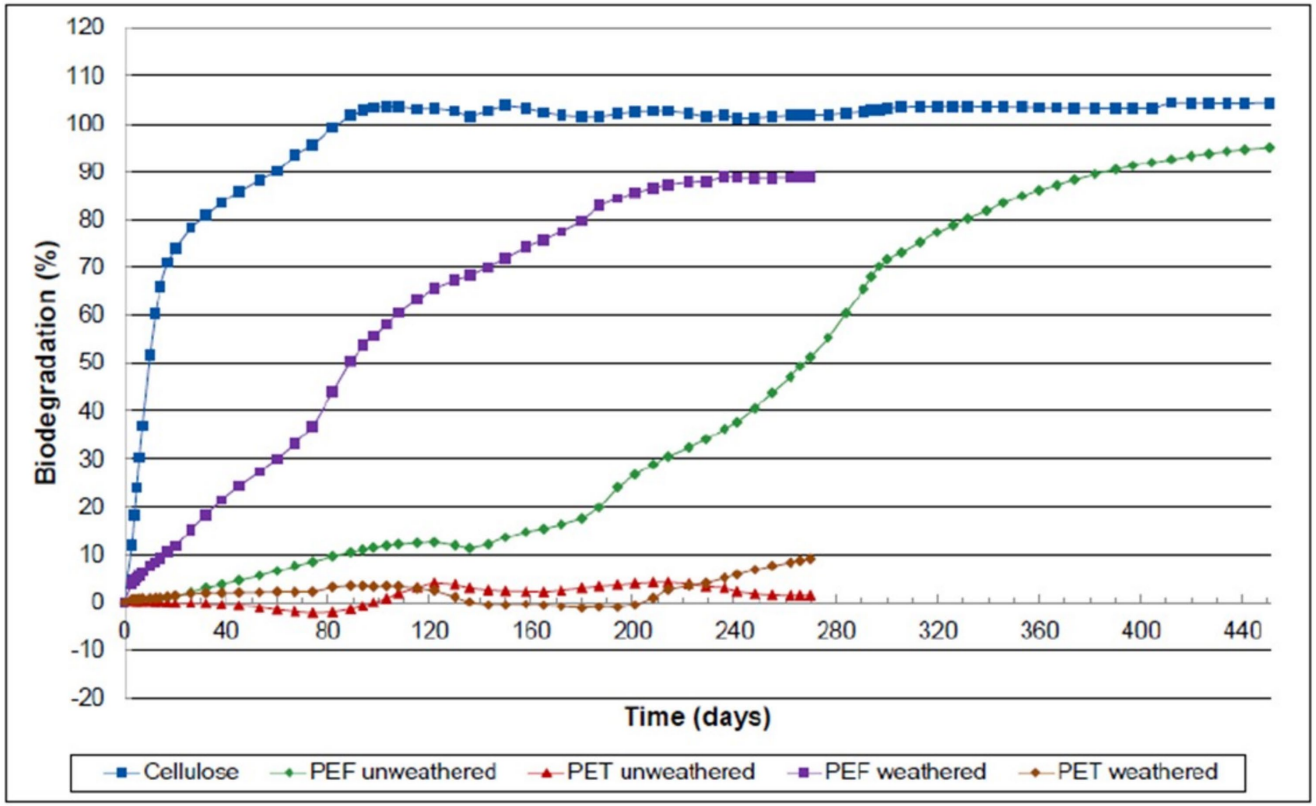
Other circularity studies

- **Re-use packaging solutions**
  - Pilot scale development activities ongoing
- **PEF to PEF recycling**
  - Demonstrated at lab scale for 12 loops
  - Pilot scale (~100 kg) assessment ongoing in collaboration with commercial partner
- **De- and repolymerization**
  - Different routes are being compared on lab scale
- **Environmental degradation kinetics**
  - Reaction routes and kinetics studied in collaboration with University of Amsterdam.
  - Real life testing ongoing on the roof-top of the Avantium headquarters

Degradation of PEF (OWS and UvA work)



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6

Regulations

Some examples of regulations

Stricter and evolving regulations challenges new market entry

- REACH- FDCA is registered by ECHA (EU) up to 1000 tons per annum, with Avantium as lead applicant and owner of the toxicity studies. FDCA Is also registered in the US and Japan.

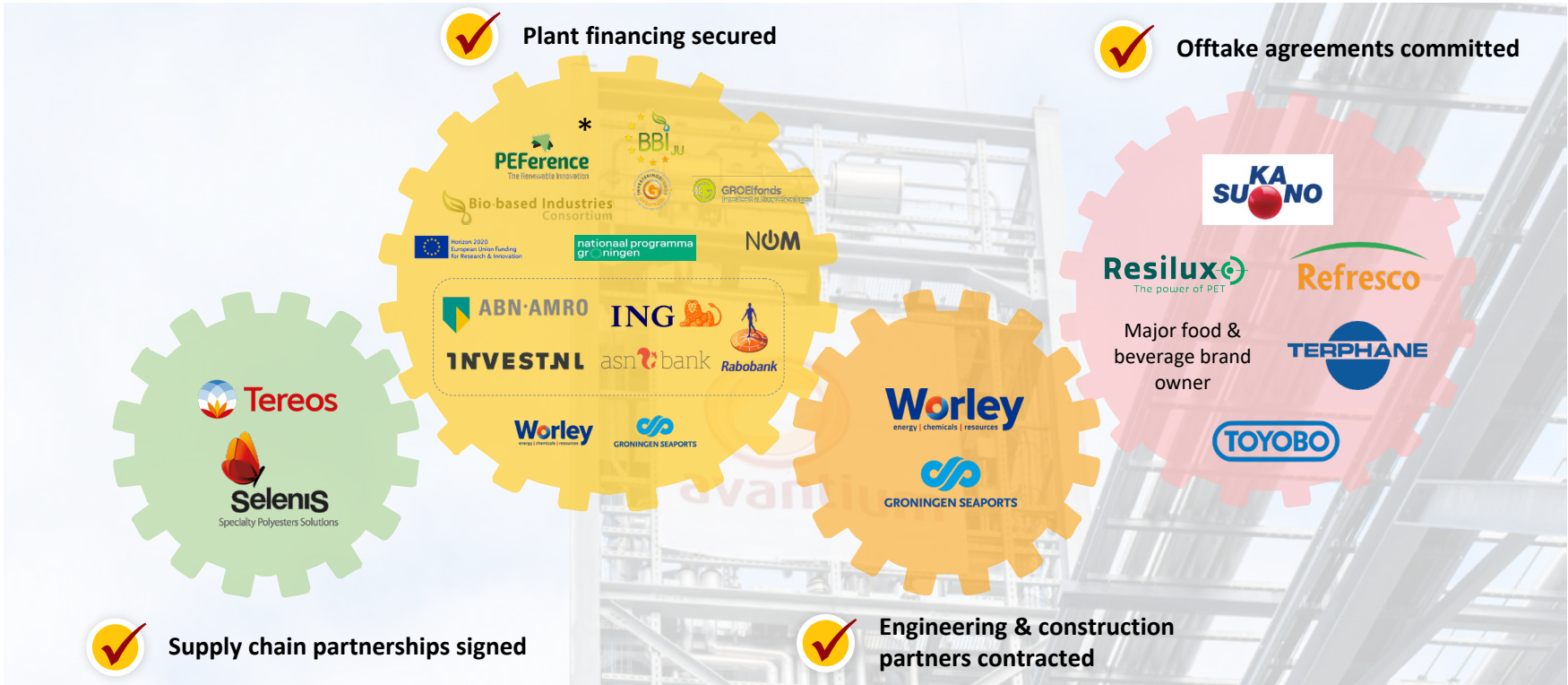
- Food approval-FDCA was added in 2015 to the Union list as a safe substance to be used in the manufacturing of PEF. Avantium recently developed a PEF resin grade (RP90Nx) that is safe to be in direct contact with acetic foods, alcoholic drinks (<20 %vol alcohol) and clear and cloudy drinks in compliance with European Regulations.

- Food approval recycled PEF- Avantium is performing the assessments required for the existing regulations. However, the EU regulations for recycled resins are currently under revision, challenging the choice on best route to follow.

7

Partners

Important partners throughout the PEF value chain



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Take away message

Take away messages

- Avantium is well under way to bring FDCA, plantMEG and PEF into the market.
- Bringing a new building block into the market takes effort and perseverance by many parties throughout the value chain.
- A detailed review paper on our journey has recently been published:

  Ed de Jong et al. *The Road to Bring FDCA and PEF to the Market* **Polymers** 2022, 14, 943
  https://doi.org/10.3390/polym14050943

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Thank you!
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