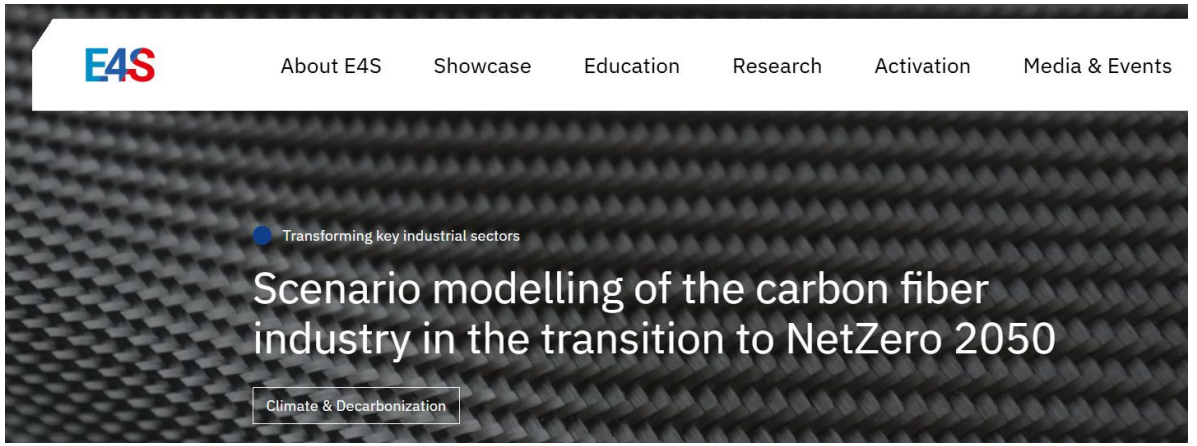
Re-wiring CAPEX and Finance in Circular Value Chains: A Case Study of Advanced Materials

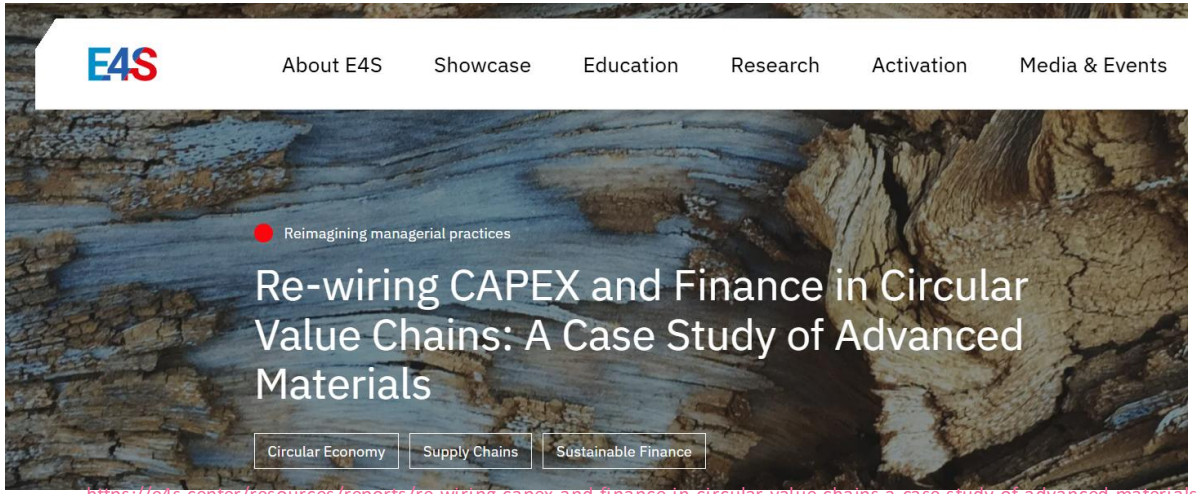
Dr. M.D. Wakeman, EPFL
F. Doukouré, EPFL
R. Ramezani, EPFL
Prof. K. Schmedders, IMD
Prof. V. Michaud, EPFL

martyn.wakeman@epfl.ch

Overview – interim results (draft data, known model inconstancies)

- Industrial decarbonization
- Historical MFA of carbon fiber
- Mass-based market growth
- Decarbonization enablers
- CF $kgCO_2e/kg$ predictions to 2050
- MFA predictions to 2050
- Interim conclusions





https://e4s.center/resources/reports/re-wiring-capex-and-finance-in-circular-value-chains-a-case-study-of-advanced-materials/

https://e4s.center/resources/reports/scenario-modelling-of-the-carbon-fiber-industry-in-the-transition-to-netzero-2050/

Preliminary data subject to revision

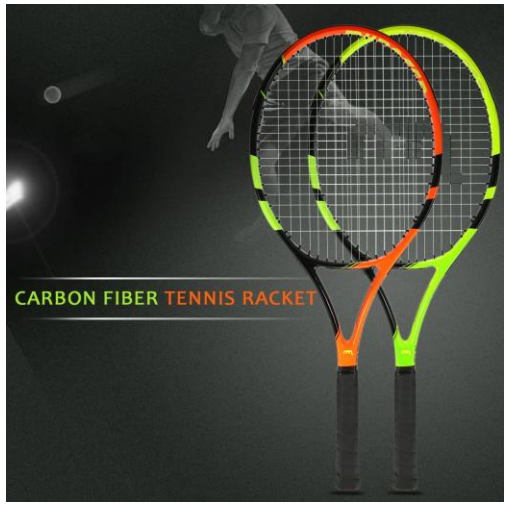
Fire side chat

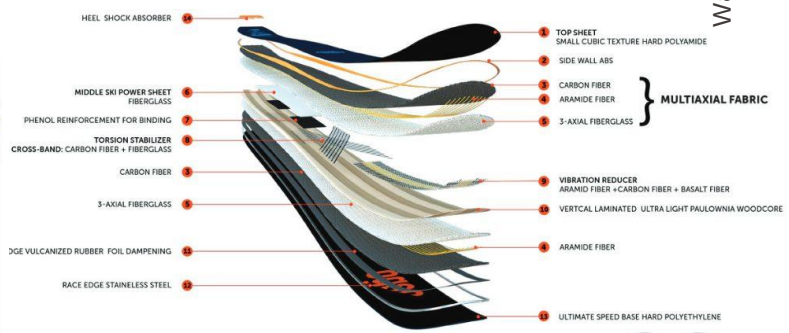
- What flows in our economy?
  - Energy
  - Mass
  - CO_2e
  - $
  - People
  - Information
- Need a systemic approach

Who owns something made of advanced composites?

- Skis / poles
- Bike
- Tennis
- Tripod
- RC

- Fishing rod
- iPhone/pad
- Car

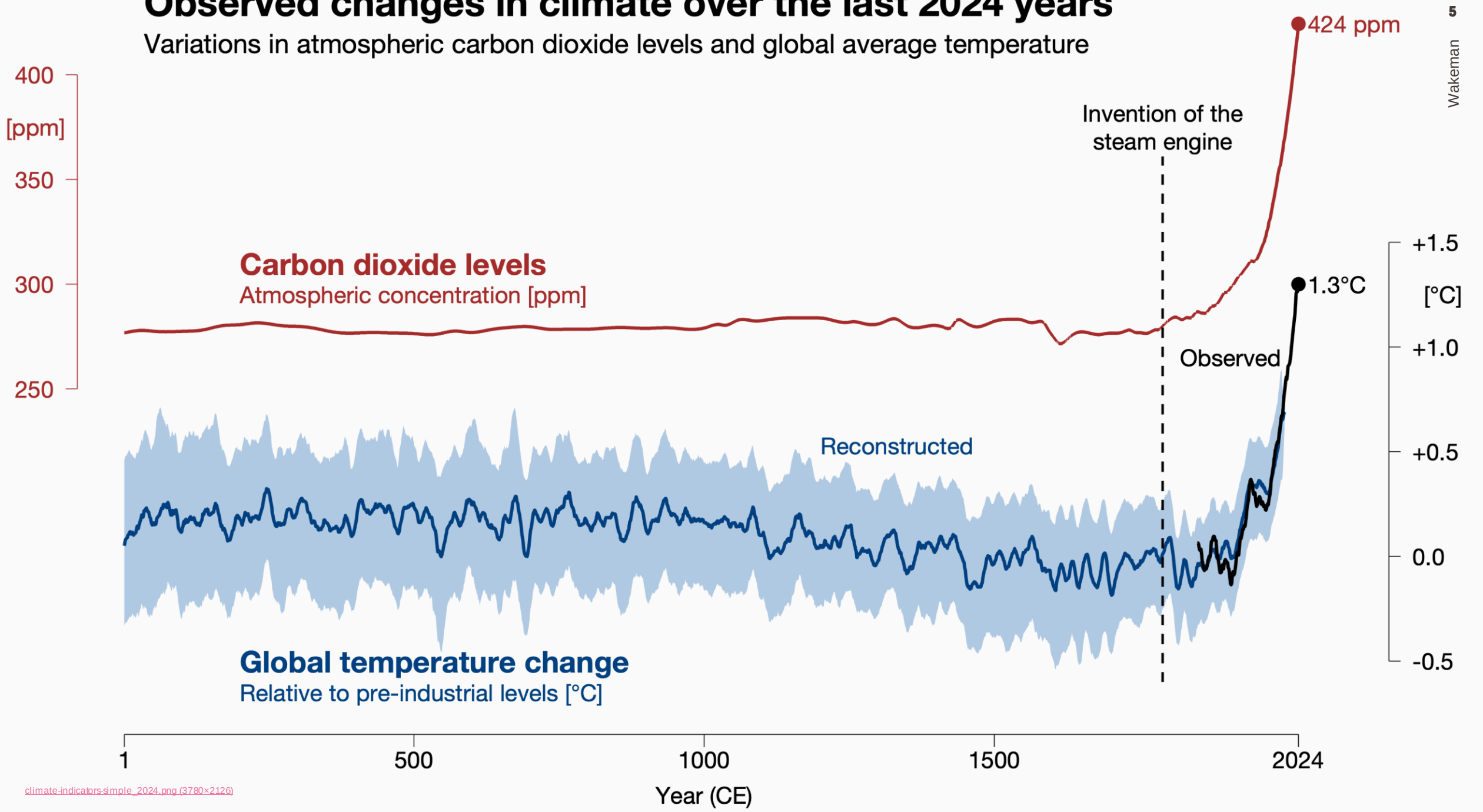




Wakeman

Observed changes in climate over the last 2024 years

Variations in atmospheric carbon dioxide levels and global average temperature



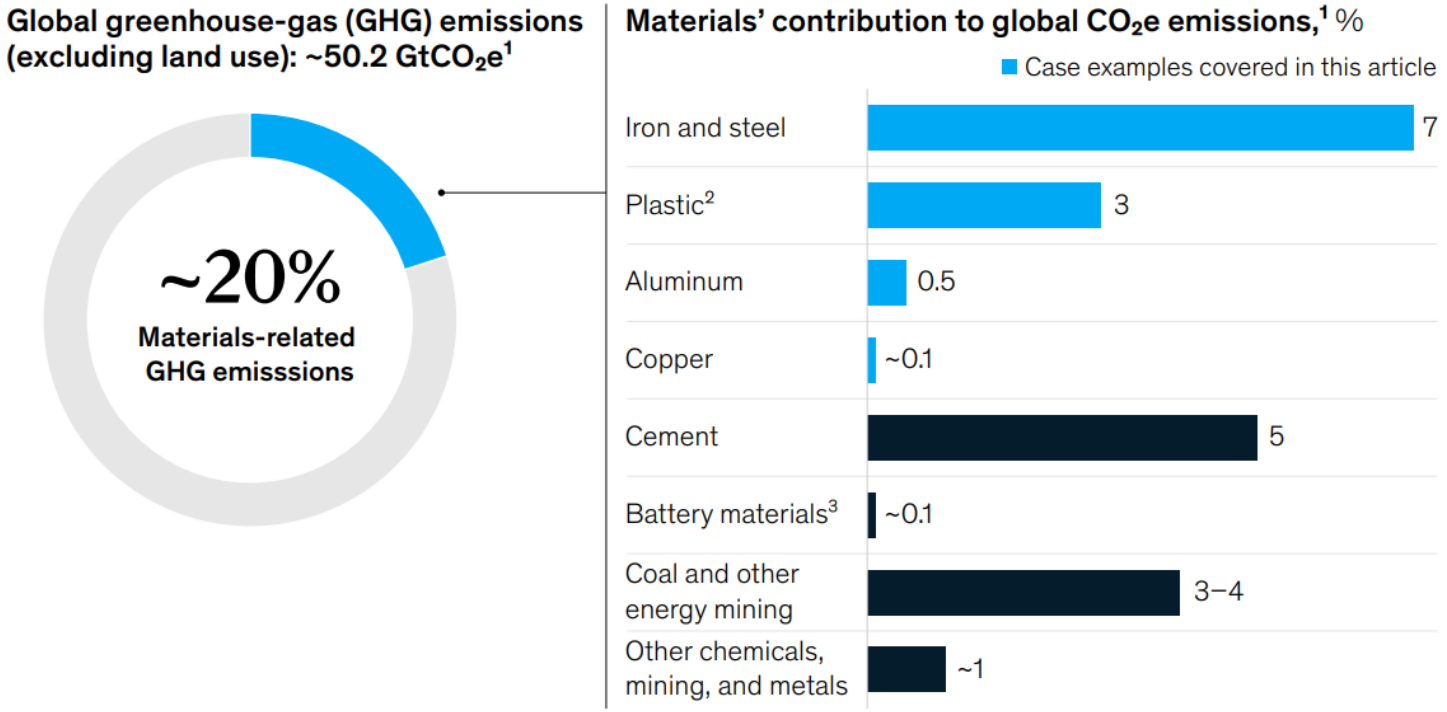
5

Wakeman

climate-indicators-simple_2024.png (3780×2126)

Materials value chains contribution to global CO2 emissions

Materials value chains account for 20 percent of greenhouse-gas emissions, a large portion of which are generated by just a few commodities.

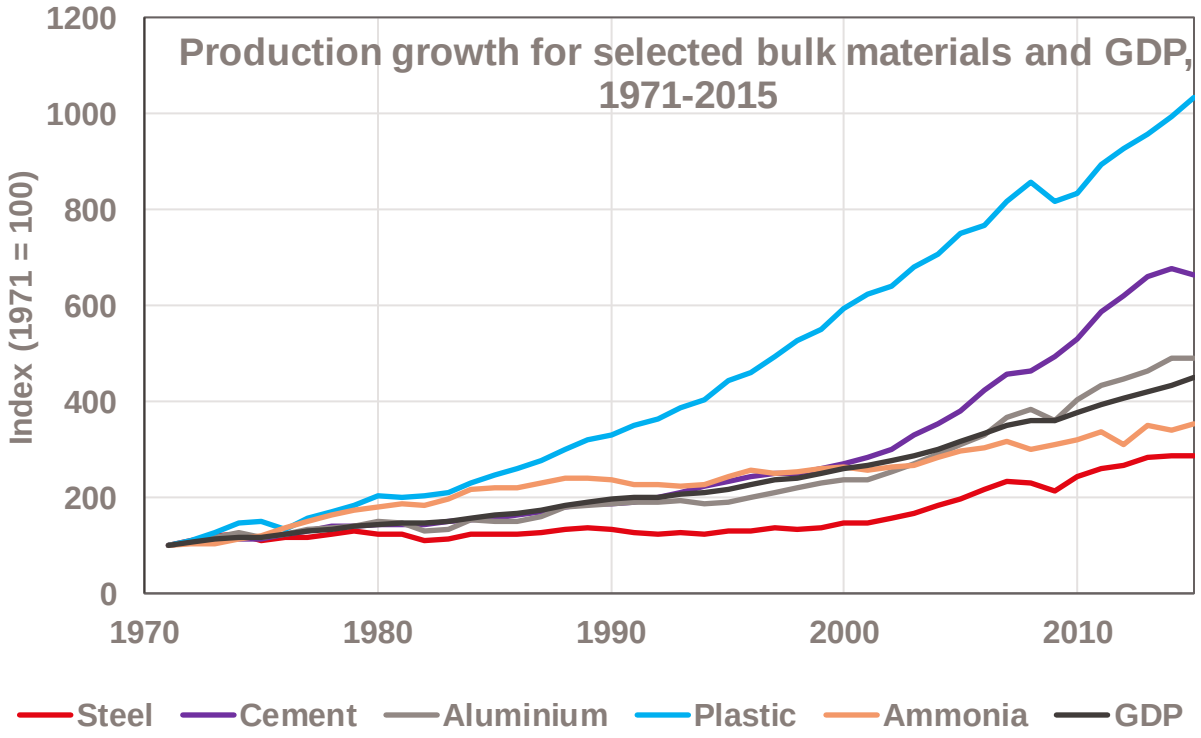


[1]CO_2 equivalent; Scope 1 in 2019, excluding any captive electricity emissions.
[2]Polyethylene terephthalate (PET), polypropylene (PP), polyethylene (PE), polyvinyl chloride (PVC), polystyrene (PS), and others.
[3]Lithium, nickel, cobalt, and other residual metals used in batteries.
Source: McKinsey MineSpans; McKinsey Sustainability Insights EMIT database

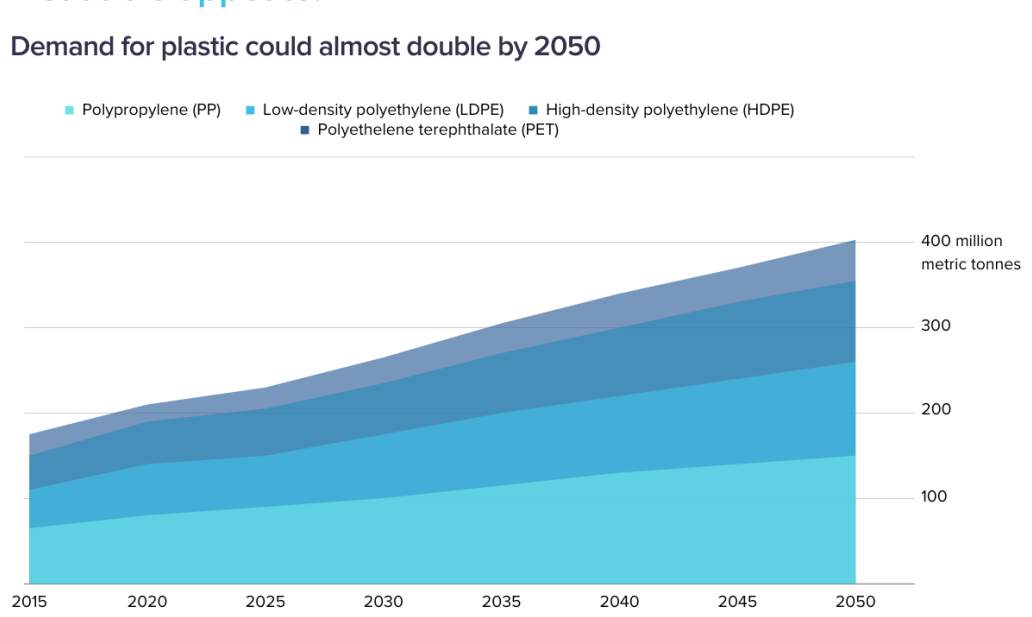
Reuters_Unlocking_Decarbonisation_Whitepaper

capturing-the-green-premium-value-from-sustainable-materials-vf.pdf (mckinsey.com)

What are hard to abate materials?

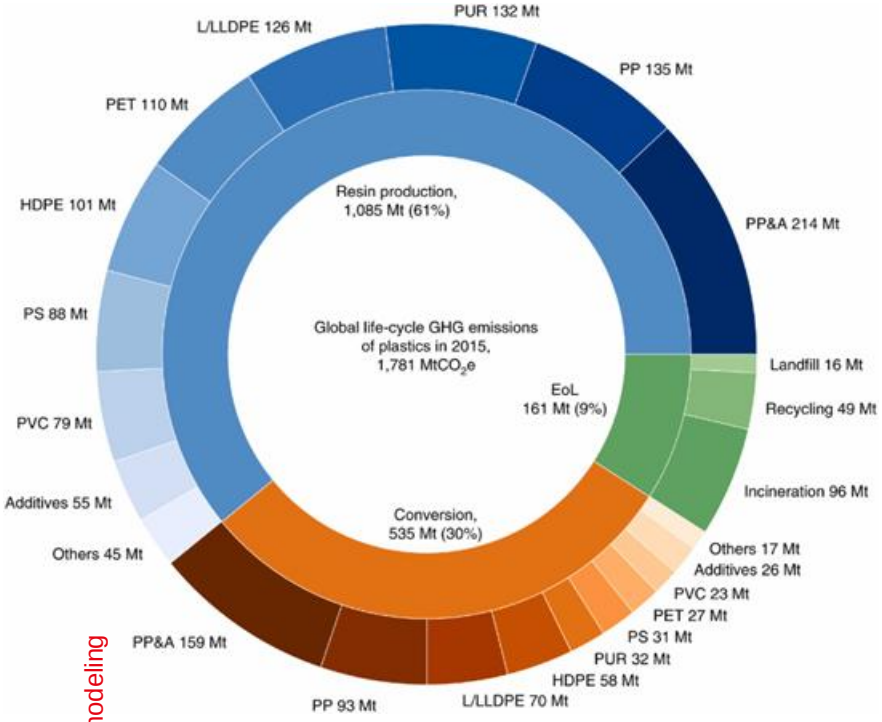


Production growth for selected bulk materials and GDP, 1971-2015 – Charts – Data & Statistics - IEA



Source: BloombergNEF, Nexant. Shows outlook in BNEF's Economic Transition Scenario.

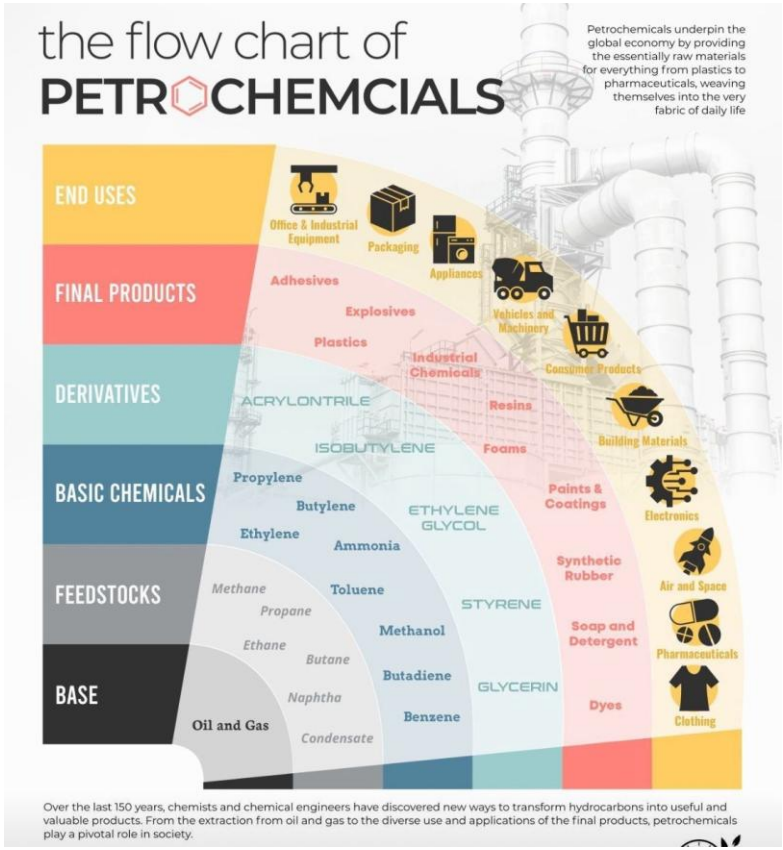
Plastics emissions



Resin production = 61%

PP kg 1.7 CO2e/kg

Carbon dioxide-focused greenhouse gas emissions from petrochemical plants and associated industries: Critical overview, recent advances and future prospects of mitigation strategies - ScienceDirect



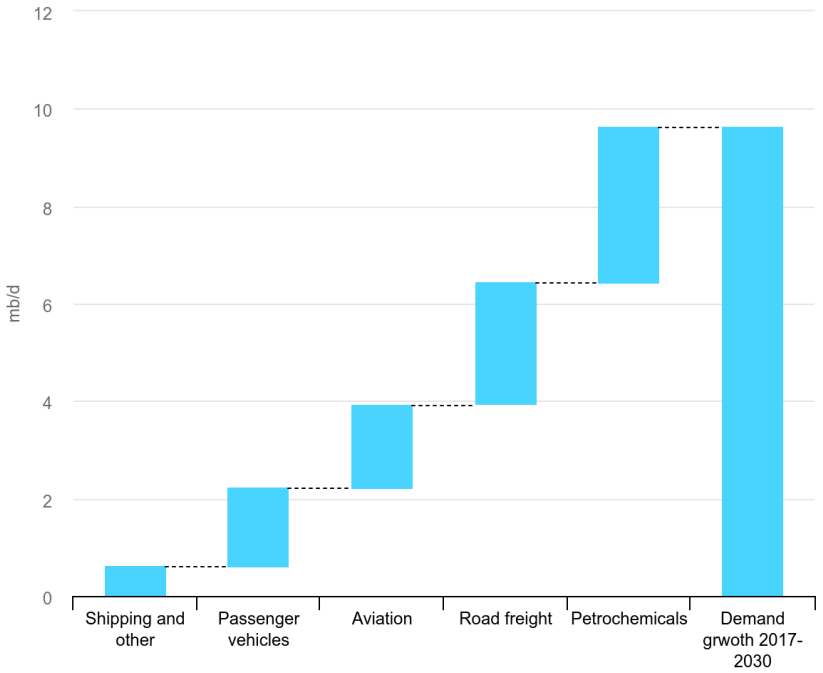
The chemical industry uses a small set of raw materials or feedstocks to produce tens of thousands of products, …

EllenMacArthur_White_Paper_2019.pdf

CAS Content | CAS

Chemicals in Commerce - International Council of Chemical Associations (ICCA) (icca-chem.org)

Oil demand growth by sector, 2017-2030



Petrochemicals forecast to be third of the growth in oil demand to 2030, and nearly half to 2050, ahead of trucks, aviation and shipping.

The Future of Petrochemicals – Analysis - IEA

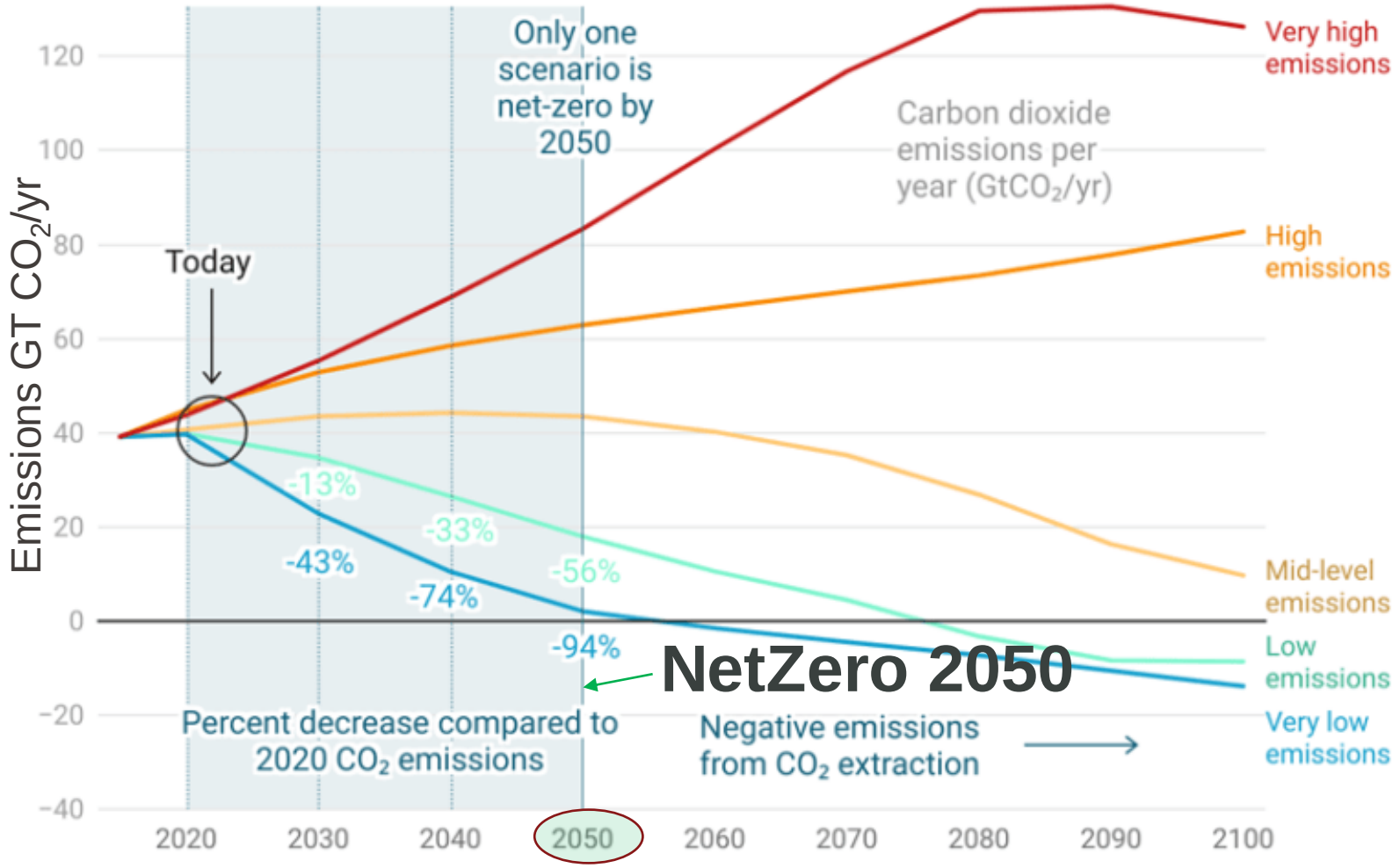
CO_2 emissions reduction scenarios

90 case, 2.7°C (STEPs policies and actions)

50 case, 2.1°C (APS pledges & targets)

10 case, 1.5°C (NZ Paris agreement)

P90 P50 P10



SSPs

[What Five Graphs from the U.N. Climate Report Reveal About Our Path to Halting Climate Change - Eos](#) Credit: Jenessa Duncombe. Source: *IPCC* [2021]

Reduce scope 3 upstream (raws), scope 2 (energy), scope 3 downstream (EL)

Decarbonization – battle of high school math

If we multiply a linearly increasing function (market demand) by a linear decreasing function (kgCO2e/kg) of the same gradient what is the resulting function?

Linearly increasing function
Market demand (parts)

$f(x) = mx + b$

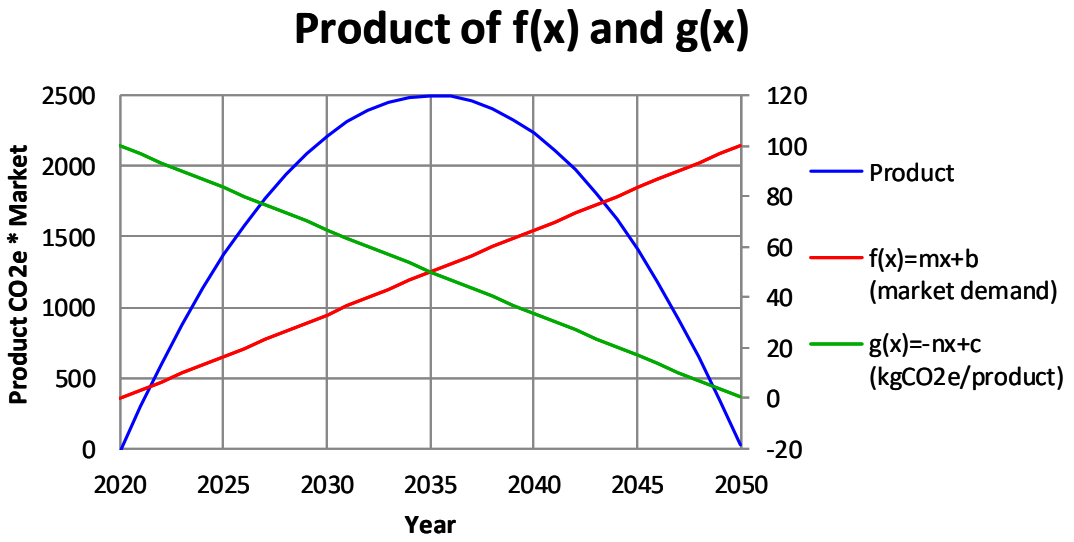
Linearly decreasing function
Product kgCO2e

$g(x) = -mx + c$

$$h(x) = f(x) \cdot g(x) = (mx+b)(-mx+c)$$

h(x) = Market demand (parts) * Product kgCO2e
h(x) = MTCO2e emitted by total products in market

NetZero



Constraints
Market demand
2020 = ~ 0
2050 = 100

CO2e
2020 = 100
2050 = ~ 0
Ideal case

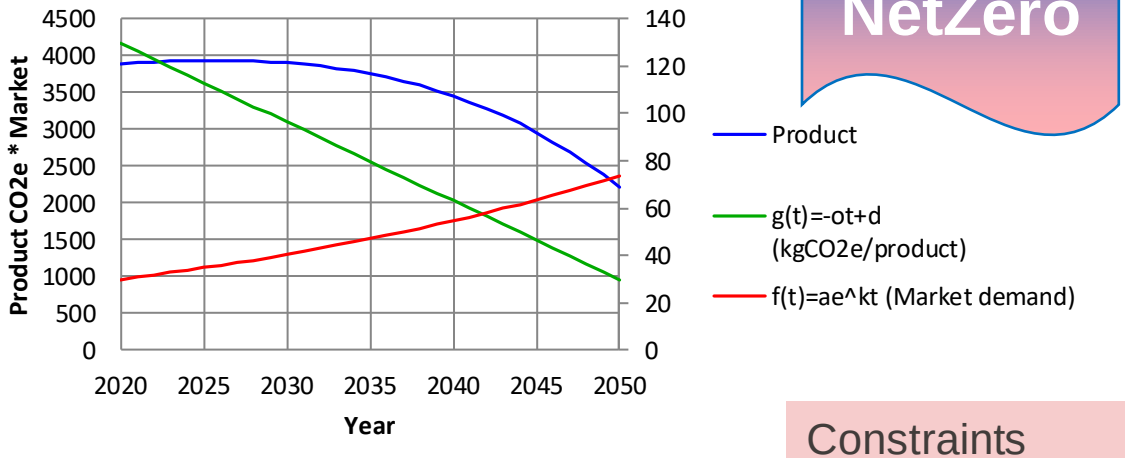
Decarbonization – battle of high school math

$$h(t) = f(t) \cdot g(t) = (ae^{kt}(-mt+b) = abe^{kt} - amte^{kt}$$

h(t) = Market demand (parts) * Product kgCO2e

h(t) = MTCO2e emitted by total products in market

Expected GDP 3% to 2030 (IEA)

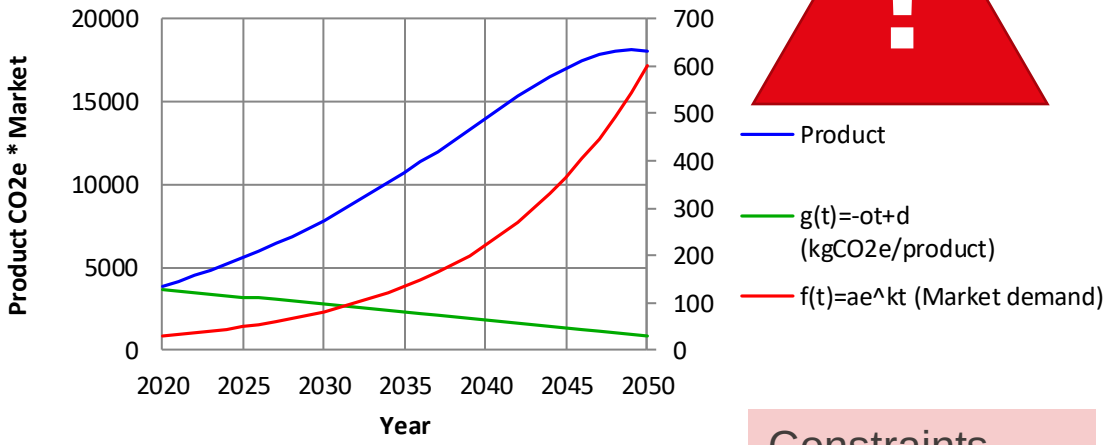


NetZero

A linear reduction in hypothetical product CO2e can flatten a 3% GDP curve but not bring it to zero
- We need dematerialization, societal adaptation, and a circular economy to shift the curve

Constraints
Market demand
2020 = 30
k = 0.03 (CAGR 3.05%)

CO2e
2020 ~130
2050 = 30



A linear reduction in product CO2e cannot mathematically control k=0.1(e.g. CAGR 10.5%) exponential market growth in selected market sectors

Constraints
Market demand
2020 = 30
k = 0.1 (10.5% CAGR)

CO2e
2020 ~ 130
2050 = 30

Net Zero by 2050 – Analysis - IEA

Monte Carlo model schematic

Model specific pathways / scenarios

Socio-economic pathways

Enablers vs. time

Enabler(s) [1-10]

- Each with 10-50-90 assumptions
- Each tracking vs. time
  - •Needed CAPEX, $
  - **•Mass flow (MFA)**
  - •CO_2e/kg

Market evolution vs. time

by sector(s) [1-10]

- Each with:

  P10, P50, P90 assumptions connected to SSPs
- Product durability / life time (by sector) for circularity
- **Calculate mass-based percentage circularity**
- Pricing $

Output vs. time

Evolution vs. time

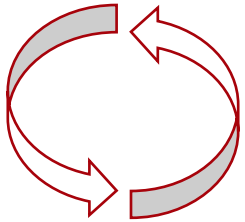
- Product CO_2e/kg
- Industry GT CO_2e
- **MFA, MT**
- CAPEX, $
- Revenue, $

Road maps

Quantified

- **Strategies**
- **Initiatives**
- **Discussion**
- **Engagement**
- **Change**

P90 P50 P10



Python script
Excel input & output

Preliminary data subject to revision

P10-50-90 definitions

90, proved

- Established technology
- Incremental innovation
- Continuous improvement R&D only
- Current market sectors with organic growth
- Low risk?
- Business as usual

P90

50, median

- Some technological innovation needed
- Pilot scale facilities
- Industry patents
- Medium to long term R&D activity
- New investment in manufacturing (beyond incremental capacity expansion using known technology)
- Expansion of current market sectors / limited opening of new sectors previously not possible
- Improved sustainability position

P50

10, possible

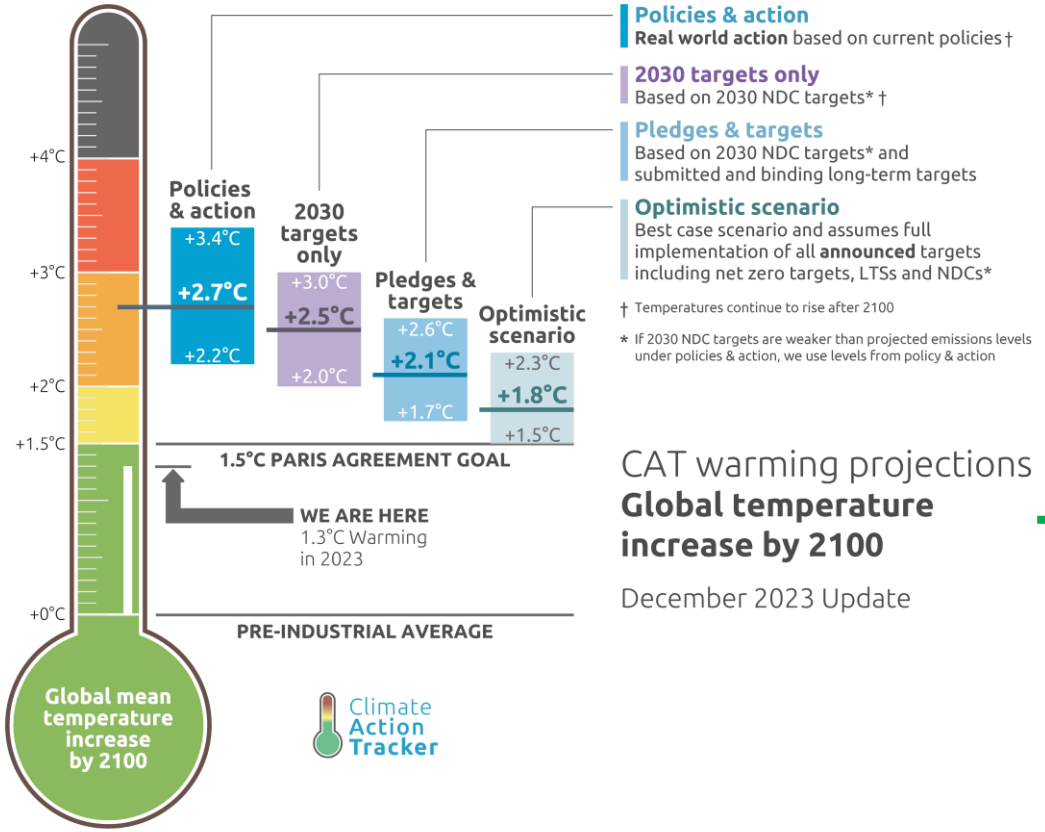
- Needs significant break throughs in technological innovation (e.g. at University research stage today) or generally not possible today
- CAPEX investments to lower costs
- Enable significant market growth in current sectors and expansion into new sectors previously not possible
- Significantly improved sustainability

P10

Preliminary data subject to revision

Wakeman

SSP scenarios to 2050



No change to warming as fossil fuel endgame brings focus onto false solutions | Climate Action Tracker

COP30: pledges and targets = +2.1°C; policies and actions = +2.7°C

90 case, 2.7°C (policies and actions)

- Climate considerations subordinate to economic development and societal wellbeing
- 35% clean energy
- Increased conflict and military expenditure
- Limited circularity

50 case, 2.1°C (pledges & targets)

- Environmental problems are recognized
- Some companies invest in the green transition
- > 50% renewable energy
- Poor cooperation worldwide

10 case, 1.5°C (Paris agreement)

- Production and consumption are intrinsically linked to the natural environment
- > 92% clean energy
- Green Hydrogen
- > 85% EVs
- Cooperation between EU, US, China and India
- Circularity is part of everyday-life

Preliminary data subject to revision

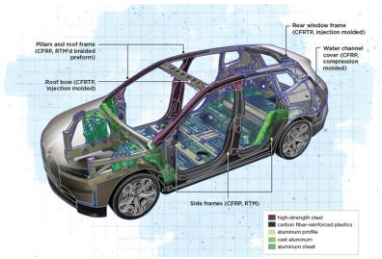
Composites will see rapid growth as enablers towards 2050 SSPs

Wakeman

Main sectors

Sub sectors

Aerospace	Wind	Automotive	Hydrogen	Infrastructure	Consumer
☐ Civil wide body	☐ Wind on-shore	☐ Super cars	☐ CNG tanks	☐ Concrete rebar	☐ Bicycles
☐ Civil narrow body	☐ Wind off-shore	☐ Premium	☐ Auto Hydrogen	☐ Buildings	☐ Marine
☐ Evtol/drones	☐ Tidal	☐ EVs	☐ Aero Hydrogen	☐ Train	☐ Consumer
☐ Military	☐ Fuel cells	☐ Other	☐ Ground Hydrogen	☐ Other	☐ Other
☐ Other	☐ Other		☐ Rail Hydrogen		
			☐ Other		



Industrial sector segmentation 1980-2050 in EPFL model

P90 P50 P10

Preliminary data subject to revision

Monte Carlo simulation

NetZero 2050 Transition strategy modeling

SSP
10x Market demand & sub-sectors

	P90 (2.7 °C)	P50 (2.1 °C)	P10 (1.5 °C)
Chemical industry electrification			
Bio-based precursor			
Microwave carbonization			
Grid energy mix			
PIW / Automation & weight			
Durability Recycling & re-use			

Monetary $
Pricing by CF grade

Revenue to CAPEX ratio

Years

CO_2e

Years

D-MFA
% circularity

Years

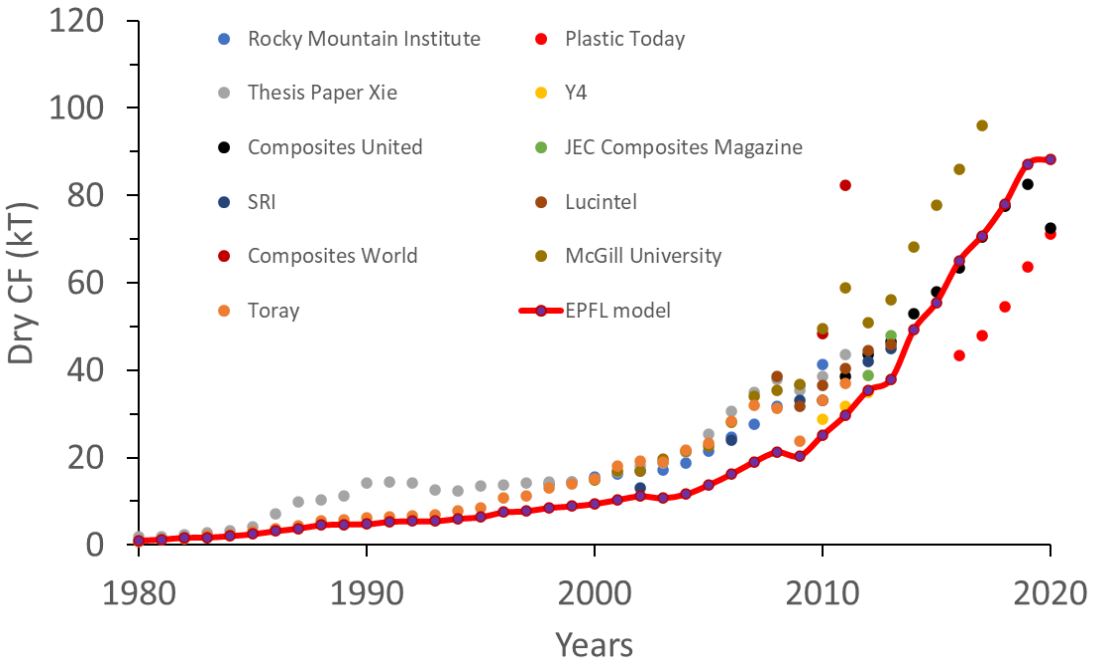
ON
OFF
Durability switch On/Off

Python script
Excel input & output

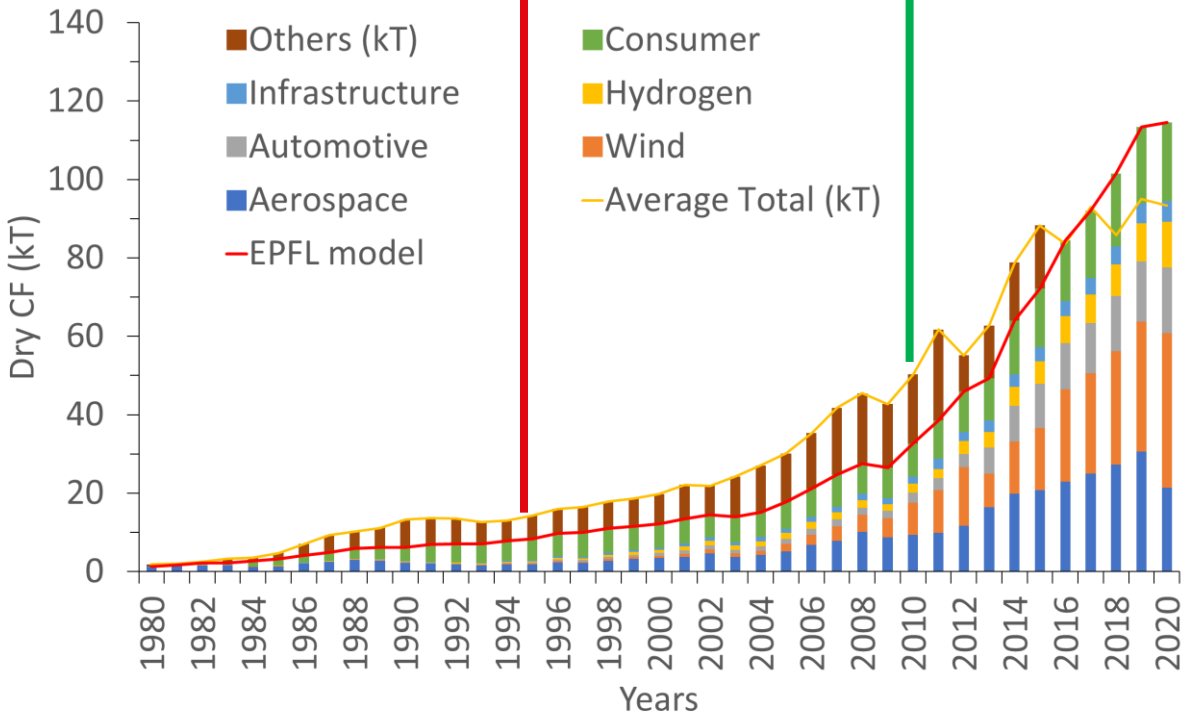
Wakeman Wakeman

EPFL model of dry carbon fiber historical demand 1980-2020

Durability is the delay to reach end of life and enter recycling / disposal scenarios



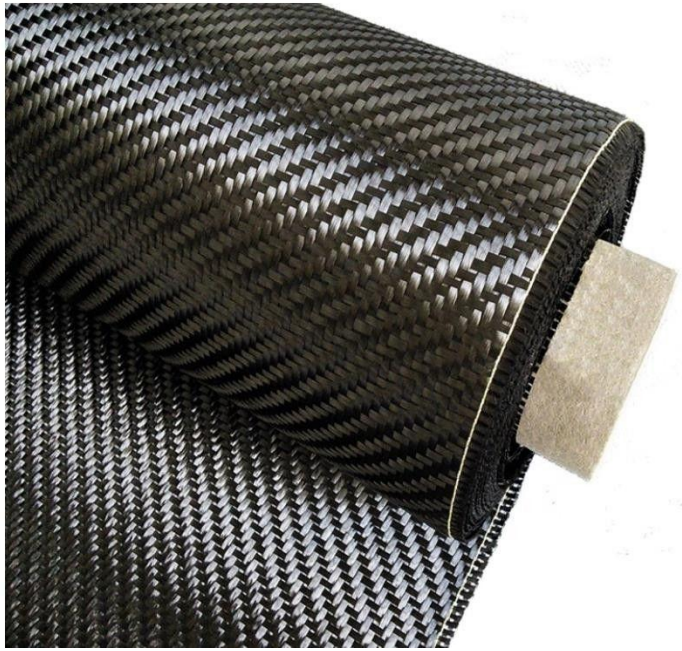
Durability by sector and sub-sector

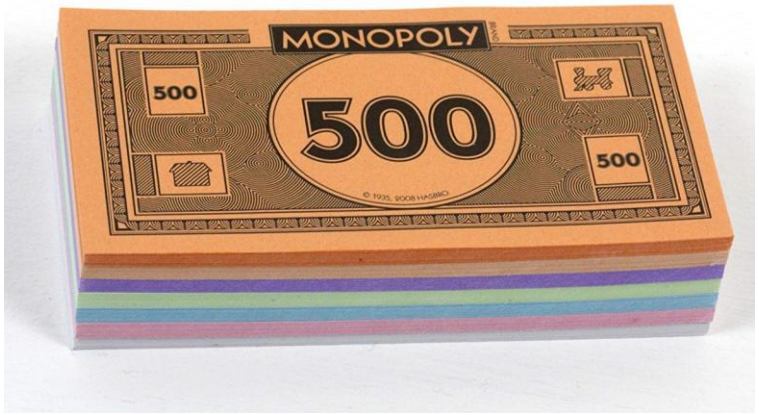


Data used in MFA (circularity versus time)

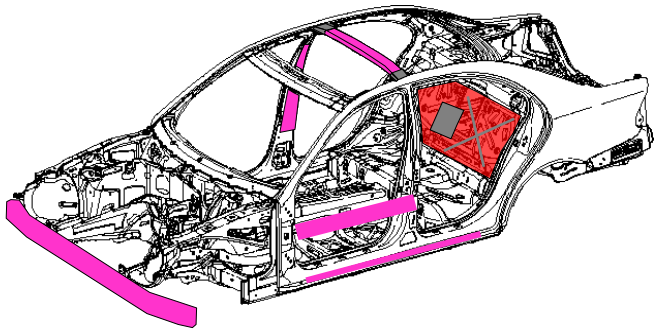
Preliminary data subject to revision

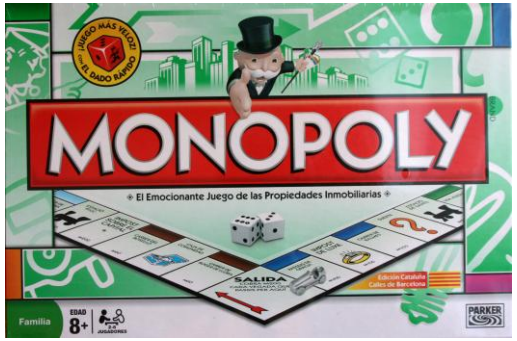
Enablers: reduce PIW





Wakeman

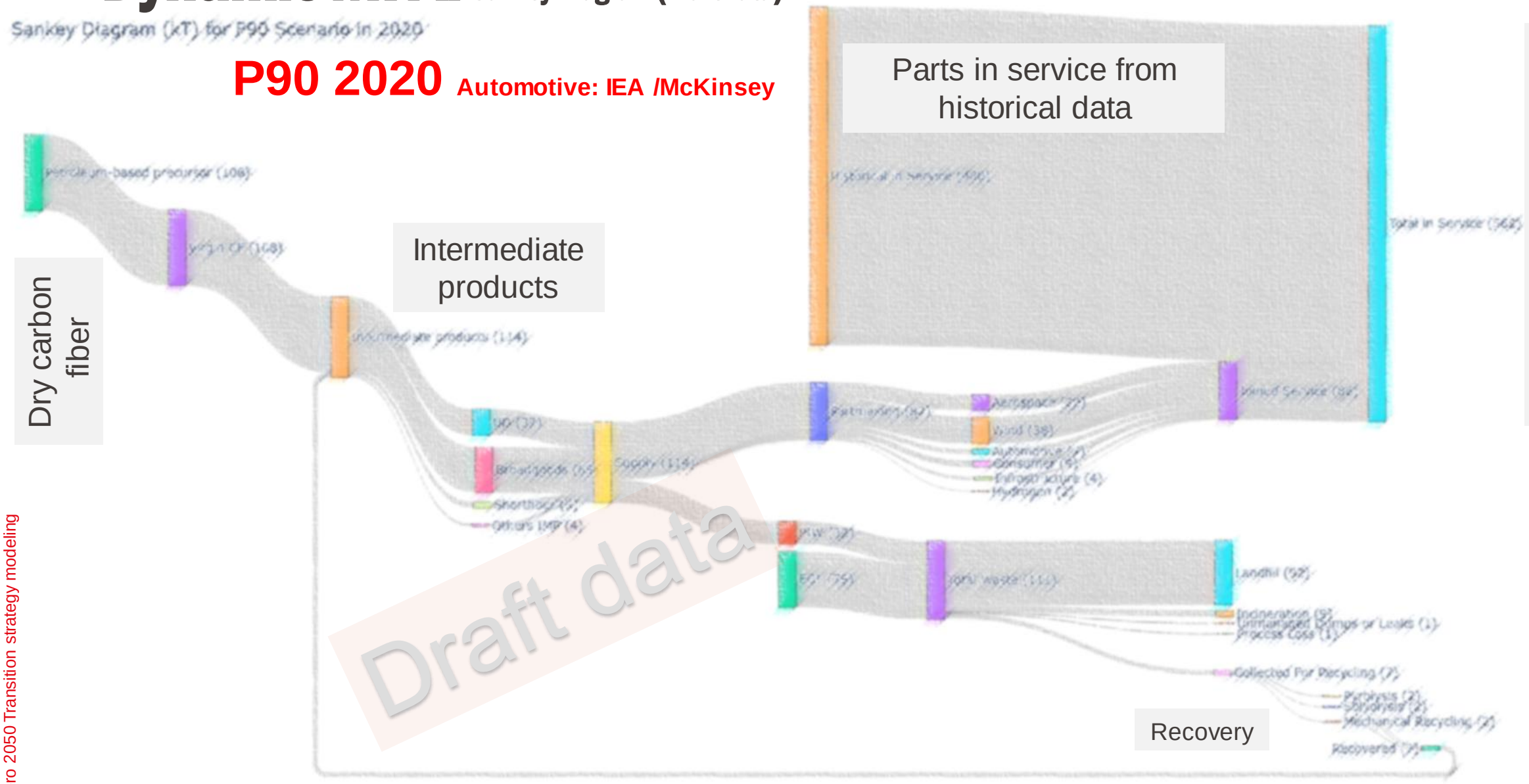




Dynamic MFA: Sankey Diagram (draft data)

Wakeman

P90 2020 Automotive: IEA /McKinsey

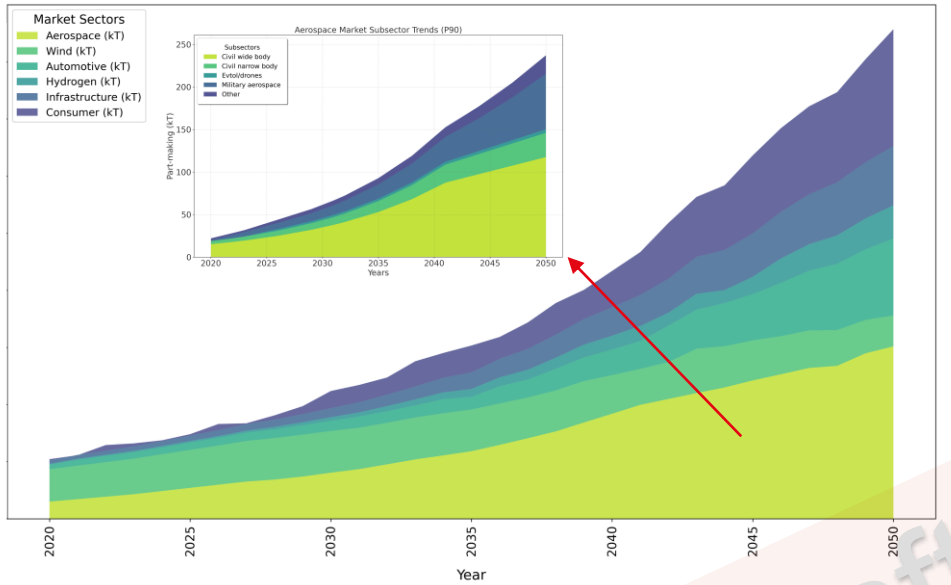


<10% recycling rate

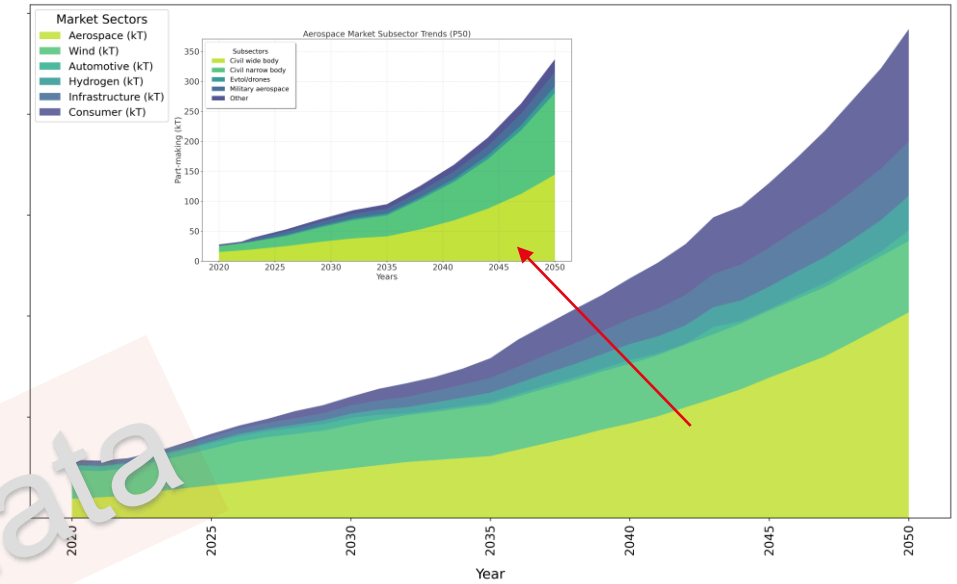
Preliminary data subject to revision

Carbon fiber demand models 2020-2050

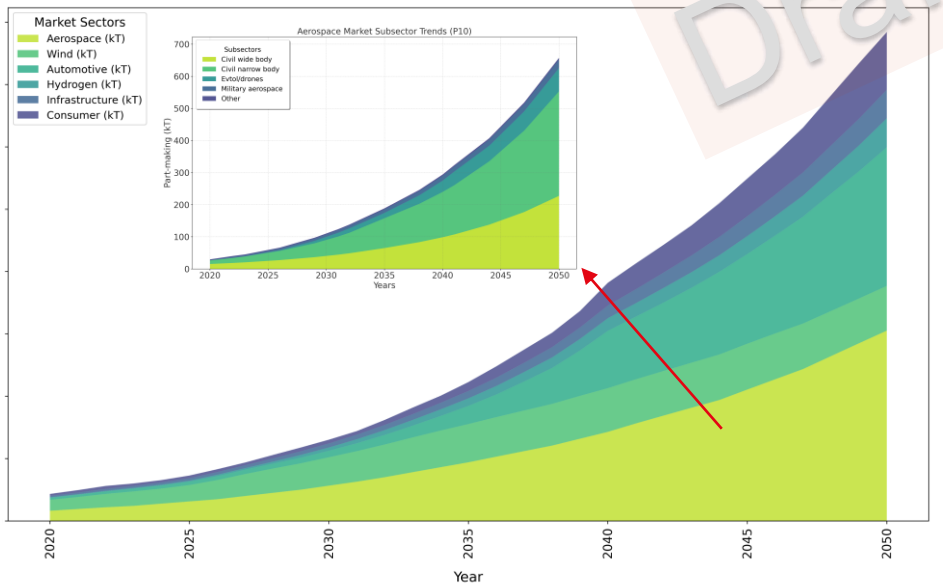
P90 Supply Area Chart



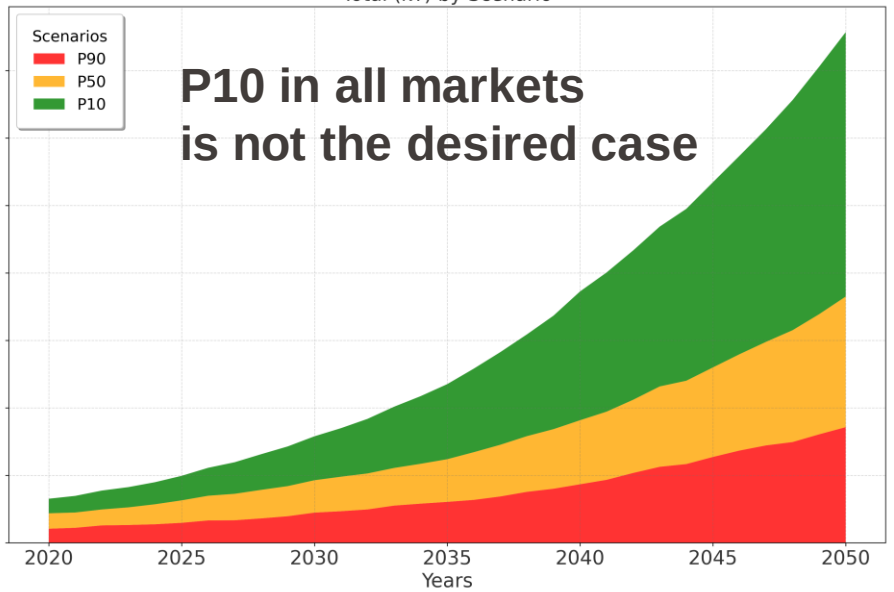
P50 Supply Area Chart



P10 Supply Area Chart



Total (kT) by Scenario



Preliminary data subject to revision

Example for automotive

Current automotive use of CFRP (2018-2024)

All vehicles with CF!	Sales in units (sold / year)	CF parts in each car

Weight estimation of CFRP parts / then dry CF

Mass of CFRP in powertrain, BIW, closures/panels, interior and additional features, and battery tray

Define CAGR according to IEA, EU, and McKinsey models for supercars, premium, consumer, and EV

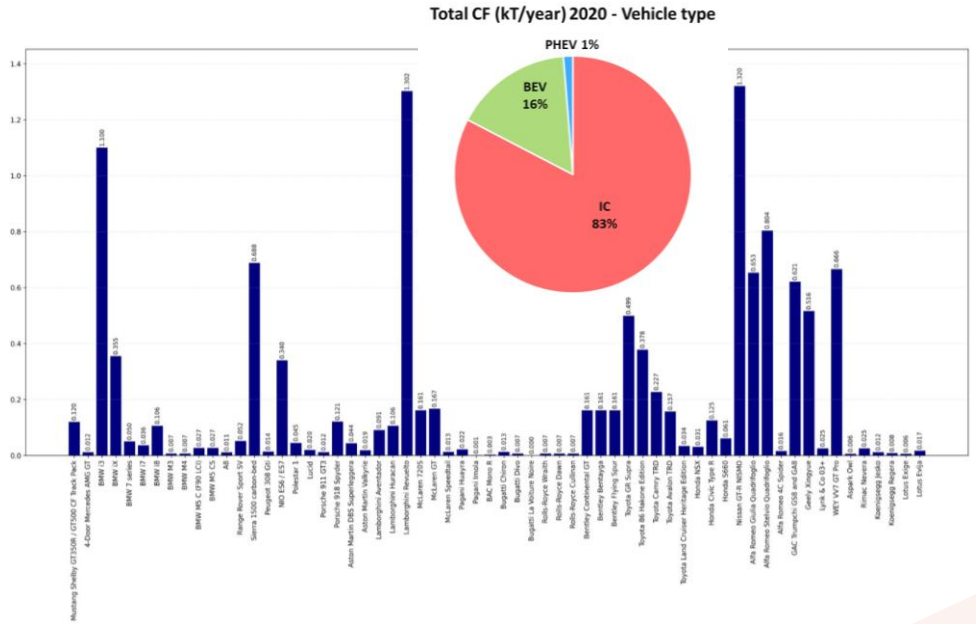
P90, P50, P10, and P50 prime EPFL assumptions	CFRP data collection according to STEPS, APS, and NZE

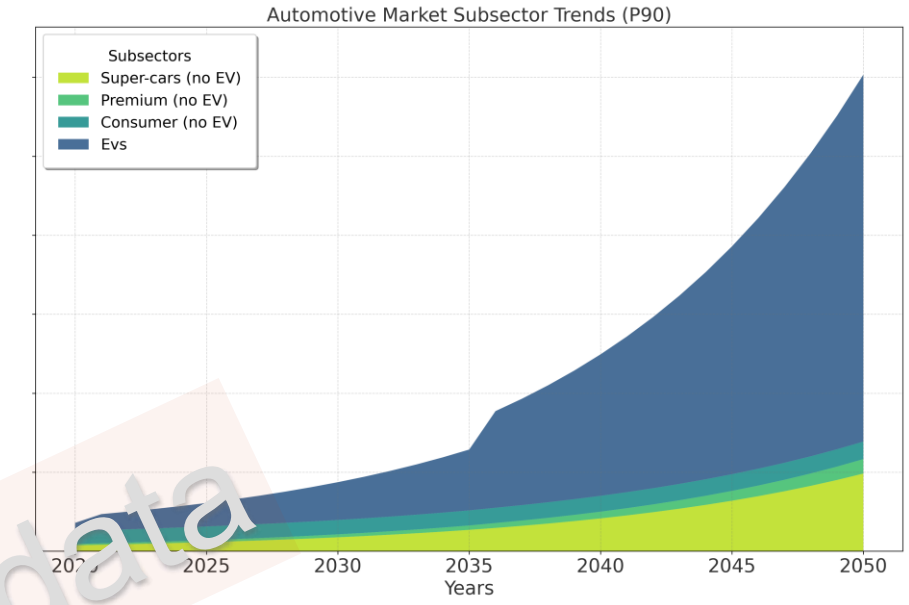
Projection

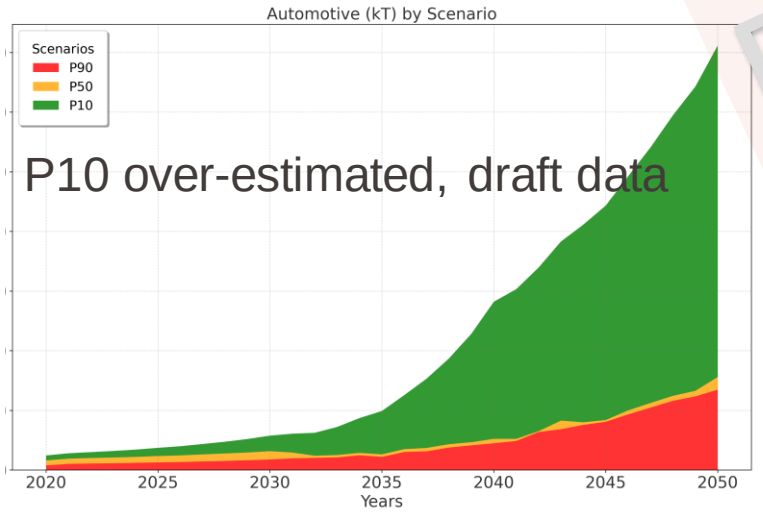
Projecting 2020 data to 2050 year by year (P10, P50, P90)

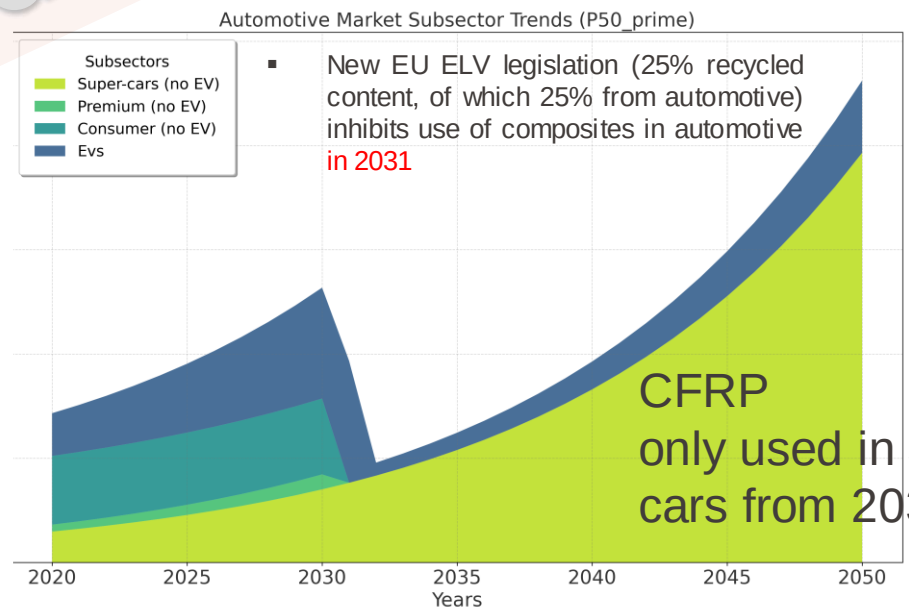
Preliminary data subject to revision

Example for automotive (from IEA and McKinsey models)









- NetZero 2050 Transition strategy modeling

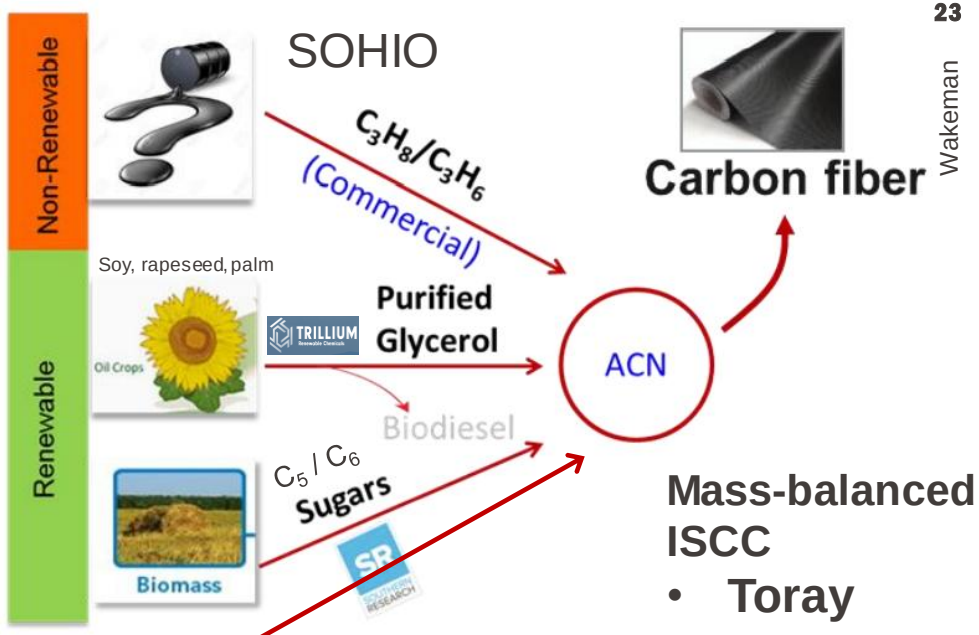
Preliminary data subject to revision

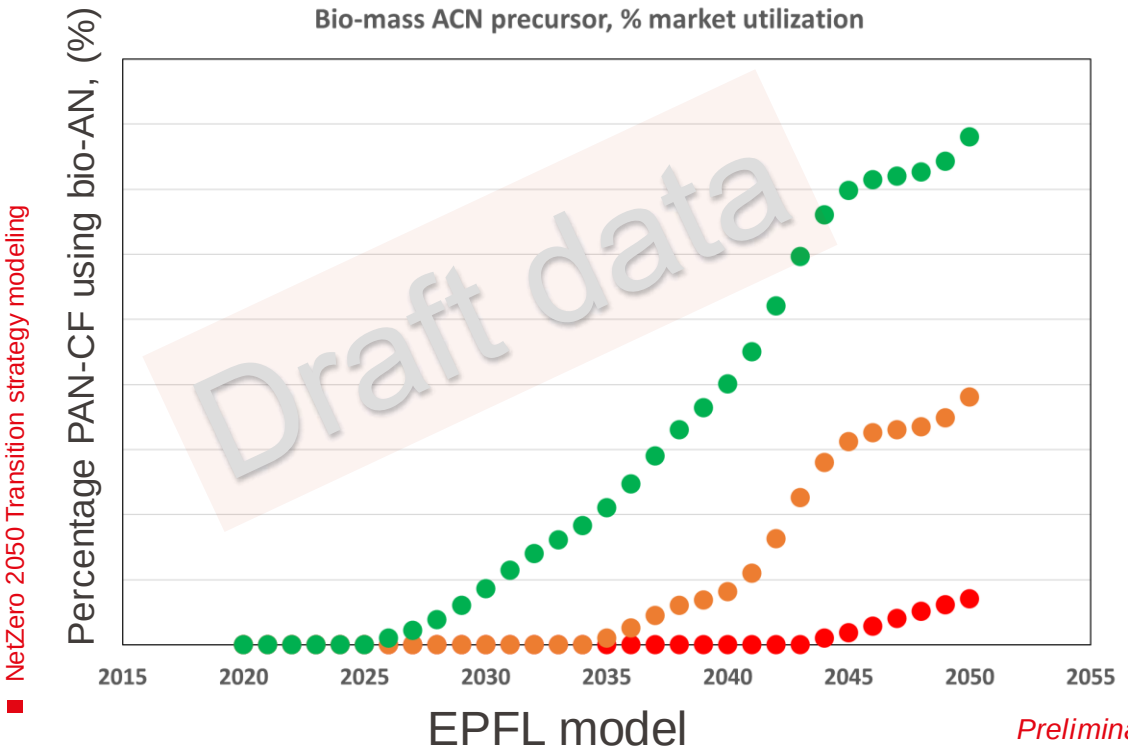
Carbon fiber manufacture

Block A
- Stage 1: AN precursor (propylene & ammonia)

Block B
- Stage 2: PAN polymerization
- Stage 3: Solution spinning

Block C
- Stage 4: Stabilization / oxidation
- Stage 5: Carbonization



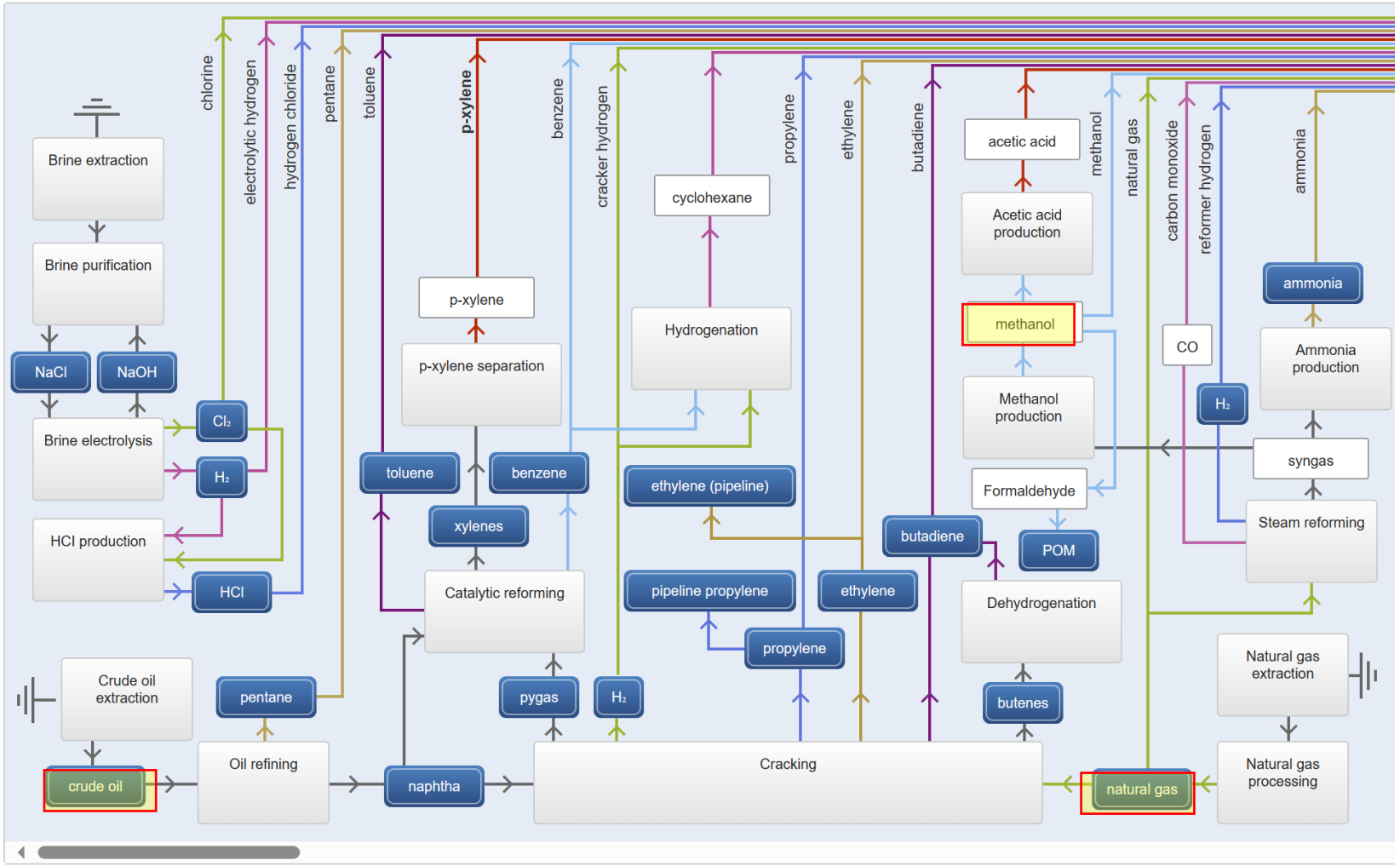


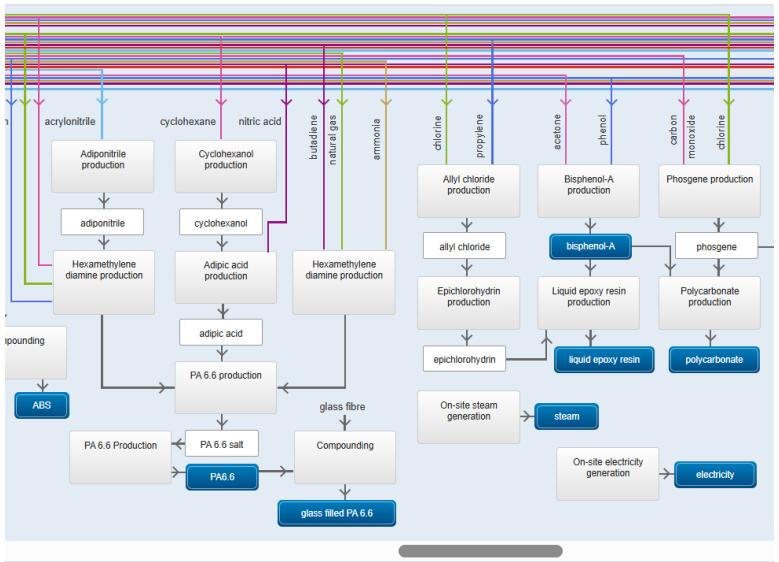
SYENSQO

"Syensqo to Showcase Sustainable Mobility and Technology Collaborations at JEC 2024." Accessed: May 14, 2024. [Online]. Available: https://polymer-additives.specialchem.com/news/product-news/syensqo-jec-world-2024-carbon-fiber-applications-000233226

Preliminary data subject to revision

Bio-methane and bio-methanol for bio-attributed polymeric products





CAS data base covers more than 400'000 different substances but not all are produced regularly …
Number of chemicals regularly produced at industrial scale = 30'000 to 40-50'000

Produced from a small number of Petro-chemical feedstocks and basic chemicals and derivatives

Need to operate upstream on few derivatives to impact many products

CAS Content | CAS


nature portfolio

ADVERTISEMENT FEATURE Advertiser retains sole responsibility for the content of this article

Synthetic methane could smooth the path to net zero

Researchers explore ways to sustainably synthesize methane to reduce a reliance on natural gas.

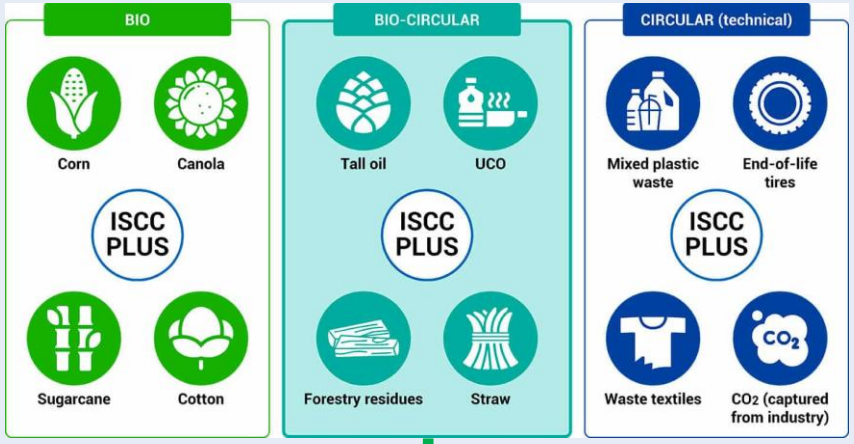
" The chemical industry uses a small set of raw materials or feedstocks to produce tens of thousands of products,…
Synthetic methane could smooth the path to net zero (nature.com)

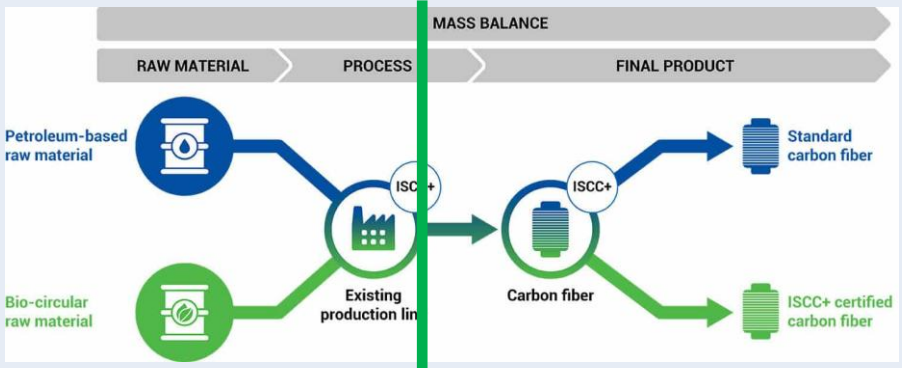
Eco-profiles (plasticseurope.org)

Bio-circular or DACC Methane to Acrylonitrile to mass-balanced PAN and carbon fiber

Reset

Wakeman





ISCC oils

- ISCC mass balanced certified, traceable
- Forestry residue, tall oil and used cooking oils (UCO).
- The Toray Group chose to use bio-circular AN as this category of materials does not compete with animal or human food supply chains.

Bio-propylene

propylene

Bio-naphtha

Oil refining

naphtha

Cracking

Bio-methane

natural gas

Natural gas processing

Natural gas extraction

Bio-ammonia

ammonia

Ammonia production

syngas

Steam reforming

Bio-AN

Acrylonitrile production

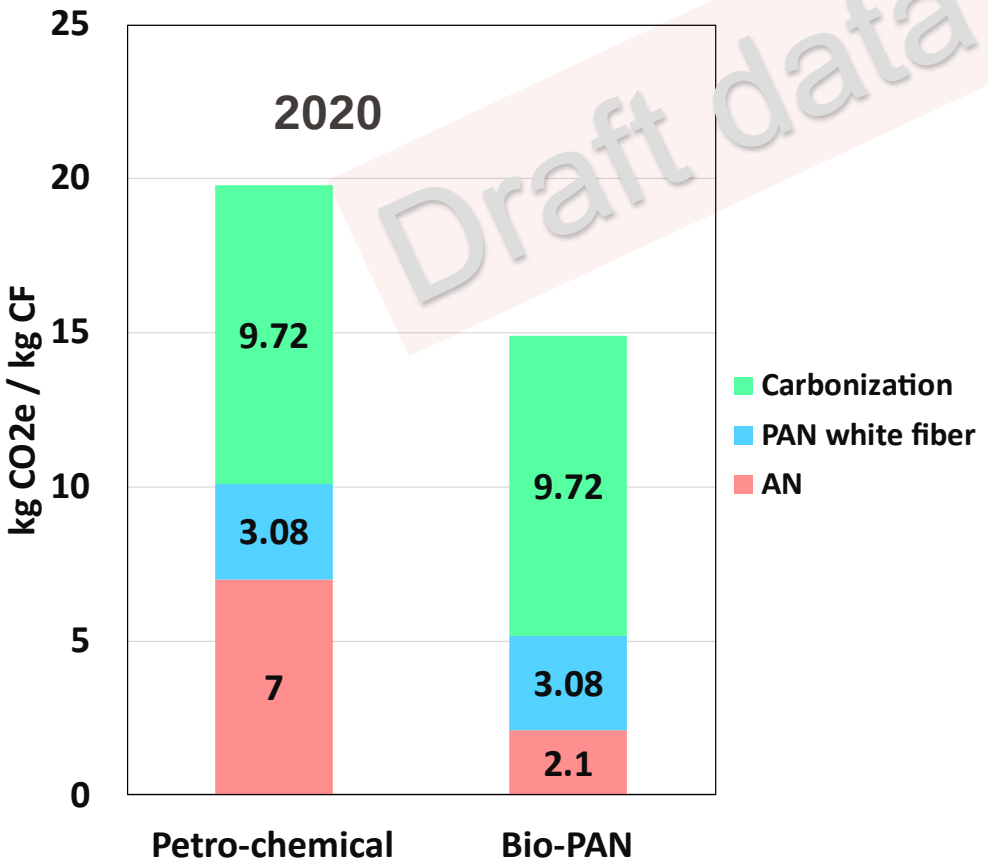
acrylonitrile

Bio-circular Carbon Fiber - Toray

kg CO2e/kg AN or CF: Effect of bio-mass / bio-attributed AN

- Traditional AN (SOHIO)
  3.5 to 6.6 $kgCO_2e/kg$ AN (1)
- Bio-based AN
  - 70% reduction (Trillium)
  - Assumed here as 1.05 $kgCO_2e/kg$ AN
- PAN white fiber (2)
  - 5.04 - 3.5 kg = 1.54 $kgCO_2e/kg$ PAN
- Carbonization (3)
  - 9.72 $kgCO_2e/kg$ CF

JCMA 19.8 $kgCO_2e/kg$ CF (4)



(4)carbonfiber.gr.jp/english/tech/pdf/lci2022_en.pdfcarbonfiber.gr.jp/english/tech/pdf/lci2022_en.pdf

(1) M. A. Morales-Mora, E. Rosa-Dominguez, N. Suppen-Reynaga, and S. A. Martinez-Delgadillo, "Environmental and eco-costs life cycle assessment of an acrylonitrile process by capacity enlargement in Mexico," *Process Safety and Environmental Protection*, vol. 90, no. 1, pp. 27–37, Jan. 2012, doi: 10.1016/j.psep.2011.10.002.
(2) K. Kawajiri and K. Sakamoto, "Environmental impact of carbon fibers fabricated by an innovative manufacturing process on life cycle greenhouse gas emissions," *Sustainable Materials and Technologies*, vol. 31, p. e00365, Apr. 2022, doi: 10.1016/j.susmat.2021.e00365.
(3) https://www.harperintl.com/wp-content/uploads/2011/09/JEC-Draft-20120323-Post-Presentation-Edits.pdf

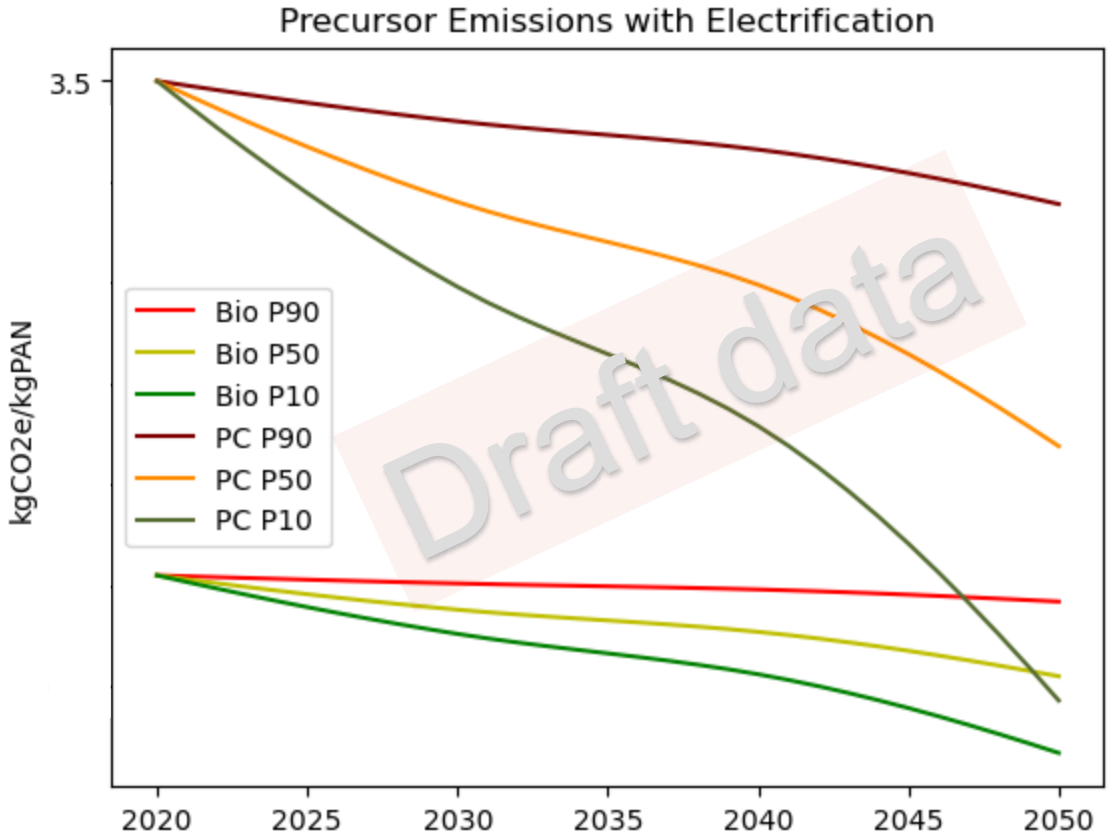
Preliminary data subject to revision

AN emissions

- Evolution from 2020 to 2050 of the $kgCO_2e/kg$ of:
- i) conventional petrochemical AN
  3.5kgCO2e/kg AN Morales-Moras et al,
- ii) Bio-Attributed AN

Recent developments in low-carbon footprint AN:

- INEOS's Invireo™ bio-based acrylonitrile, 90% reduction in GHG emissions through the use of bio-attributed propylene via a mass balance approach.
- Trillium Renewable Chemicals, partnership with INEOS, developing world's first demonstration plant at INEOS's Green Lake facility in Texas, set to begin operations in early 2025.

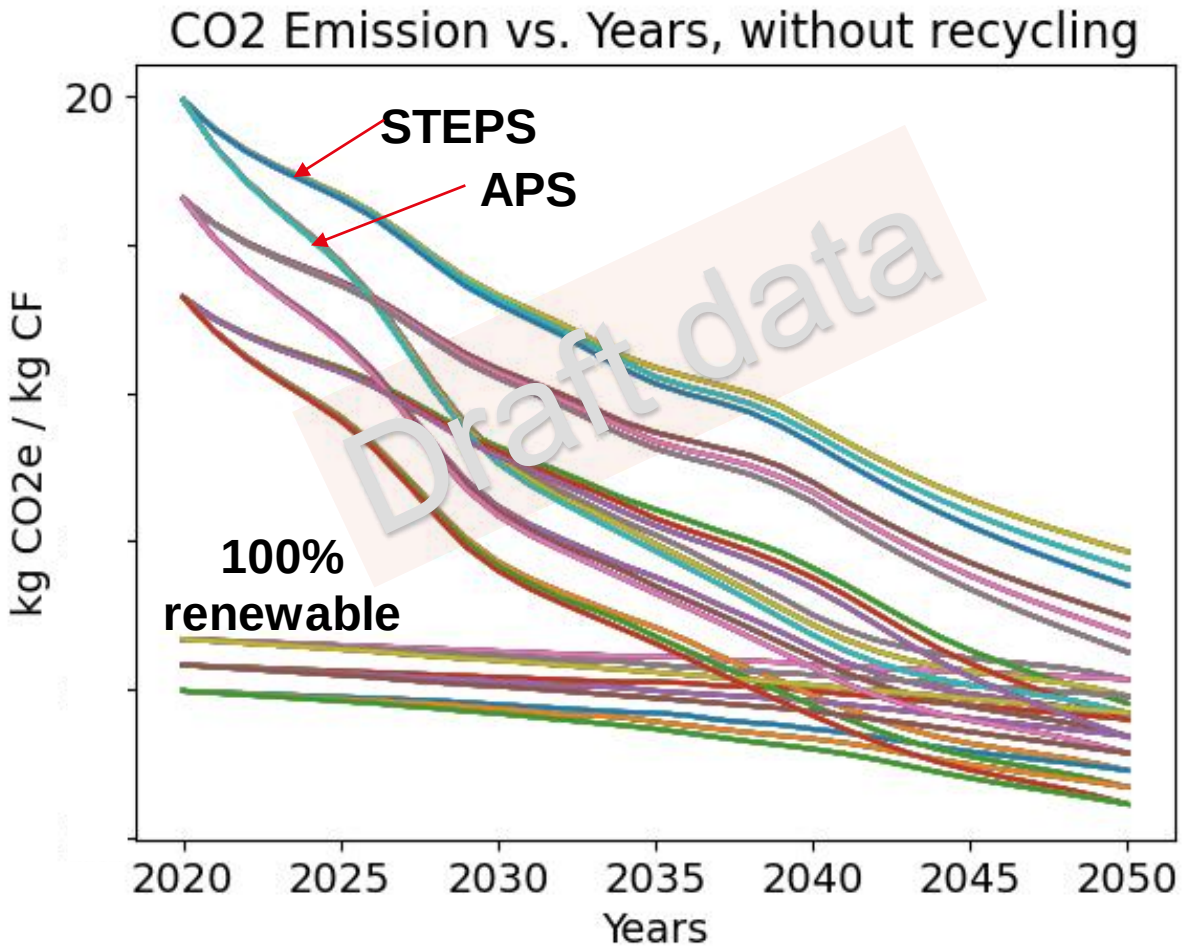


Preliminary data subject to revision

kg CO2e/kg CFv predicted to 2050

- Precursor (bio-AN vs. PC-AN)
- Lower energy carbonization (microwave, 50%)
- Grid energy mix on carbonization
  - IEA models vs. time
    - STEPS
    - APS
    - 100% renewable
- Carbonization energy
  - Harper = 20.6 to 28.2 kW.hr / kg
  - Translated to new grid mix ($kgCO_2e/kW.hr$) scenarios vs. time

JCMA 19.8 $kgCO_2e/kg$ CF



processing-advancements-within-reach.pdf (harperintl.com)

Preliminary data subject to revision

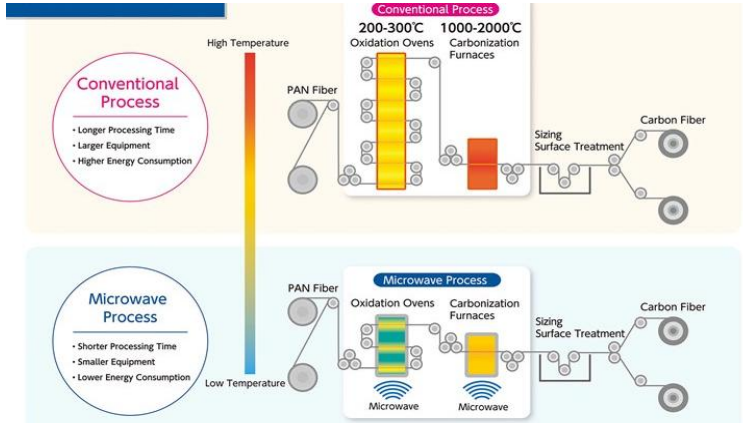
Enabler: Microwave Carbonization

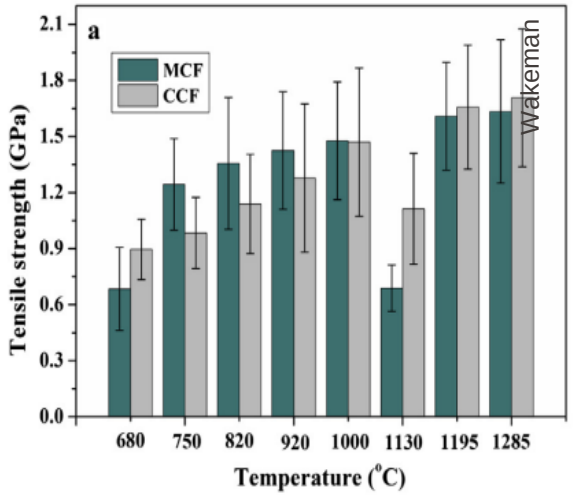
↓ energy consumption by **+70%**

↓ heating time by **+90%**

↓ CO2e by **+90%**

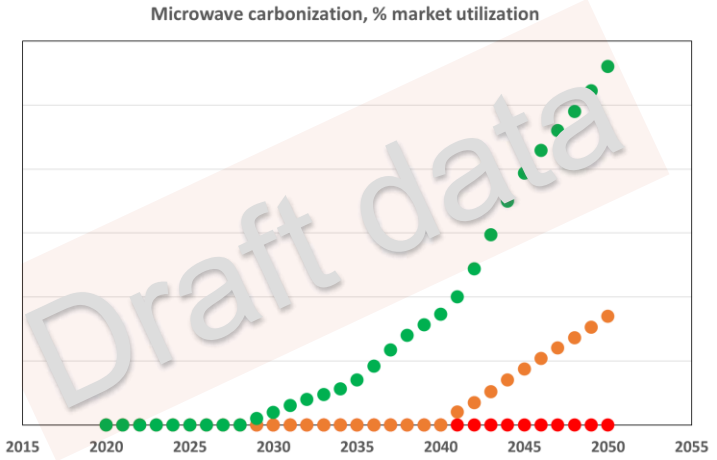
- Carbonization is highly energy intensive
- Conversion of electromagnetic energy into heat
- Hot-spots in the middle of the fibers?
- Properties are not affected





Seong Yun Kim, *Two step microwave plasma carbonization including low plasma power pre-carbonization for polyacrylonitrile based carbon fiber,* Polymer, 2015

- $35 – 60 million per line



First line	% tot. demand in 2050
-	
2040	
2030	

NetZero 2050 Transition strategy modeling

Mitsui Chemicals, Microwave Chemical Set to Install Demonstration Facility at Nagoya Works to Advance Innovative Microwave-Based Production Technology for Carbon Fiber | 2022 | Press Release | MITSUI CHEMICALS AMERICA, INC.

Microwave Chemical co.(MWCC)

2014: Building **microwave chemical plant**

December 2023: **Pilot production line ($14M)** in Mitsui Chemicals (#11)

Conventional carbonization line capacity = 3kT ($33-50 million/line) (same versus time for now)
Microwave = 14 million $ invest,

Preliminary data subject to revision

Enabler: Energy Mix

IEA, Global Energy and Climate Model

IEA STEPS (stated policies)

- -5% energy use in advanced economies
- +50% in emerging markets
- Natural gas demand increase
- Renewables delayed

IEA APS (announced pledges)

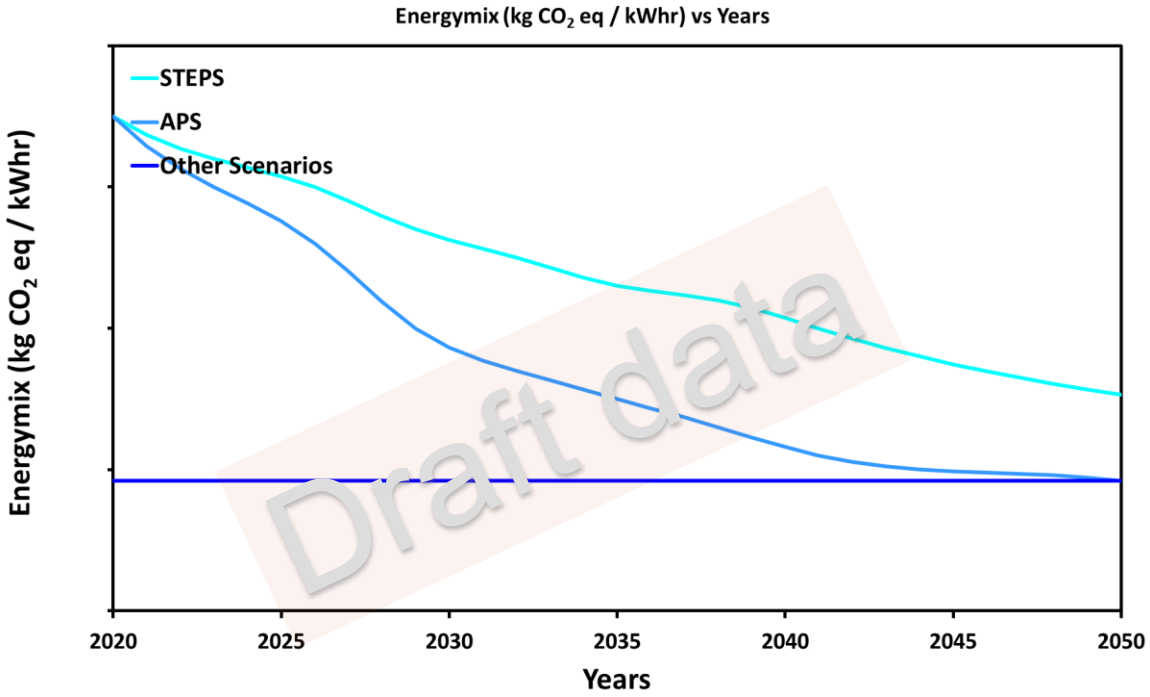
- 70% renewables, led by wind and PV
- Natural gas declines
- Coal plants must have CCUS
- +85% hydropower capacity

IEA NetZero model

- Some companies committed
- Lack of grid capacity

10' case: 100% renewables

- Some companies committed
- Lack of grid capacity

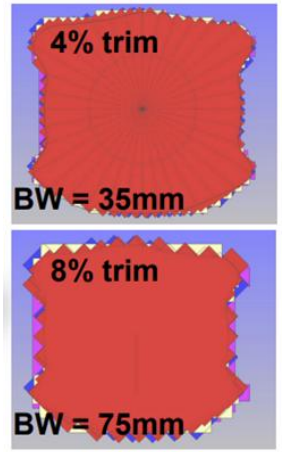


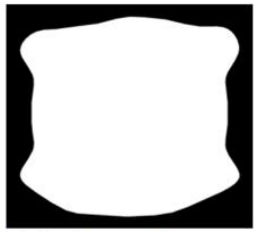
NetZero 2050 Transition strategy modeling

Preliminary data subject to revision

Enablers: Manufacturing Automation

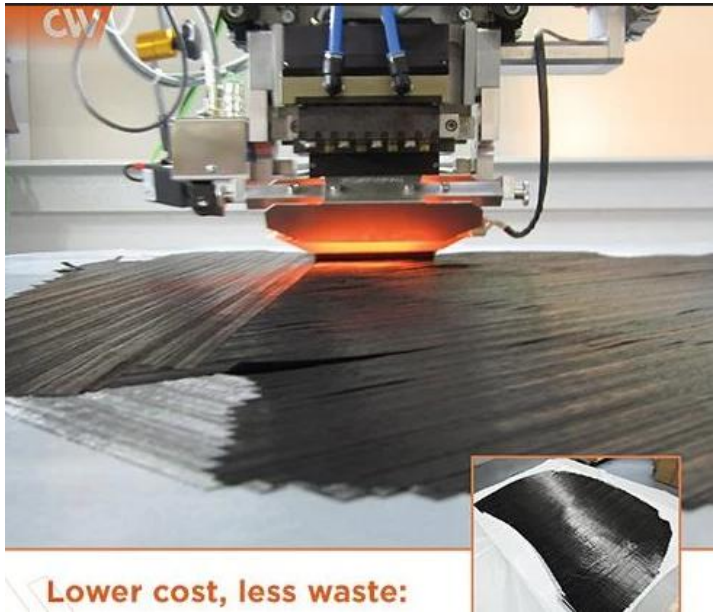
- 30-40% loss between CF line and end parts
- Switch from “broad-goods” to near-net shape UD via automation
- 20% weight saving
- Block chain to identify parts





Fabric preform versus net shape (33% trim)

Wakeman



https://d2n4wh9np1vta.cloudfront.net/cms/0516CW_Prepregging_Page52_opening.jpg:width=860:format=webp

% of the UD Aerospace production in 2050

“Composites Waste - How to Track and Reduce Waste?” https://www.addcomposites.com/post/composites-manufacturing-tracking-and-reducing-waste

Coriolis Composites - IFS DEMONSTRATION - YouTube

Preliminary data subject to revision

Enablers: Manufacturing Automation

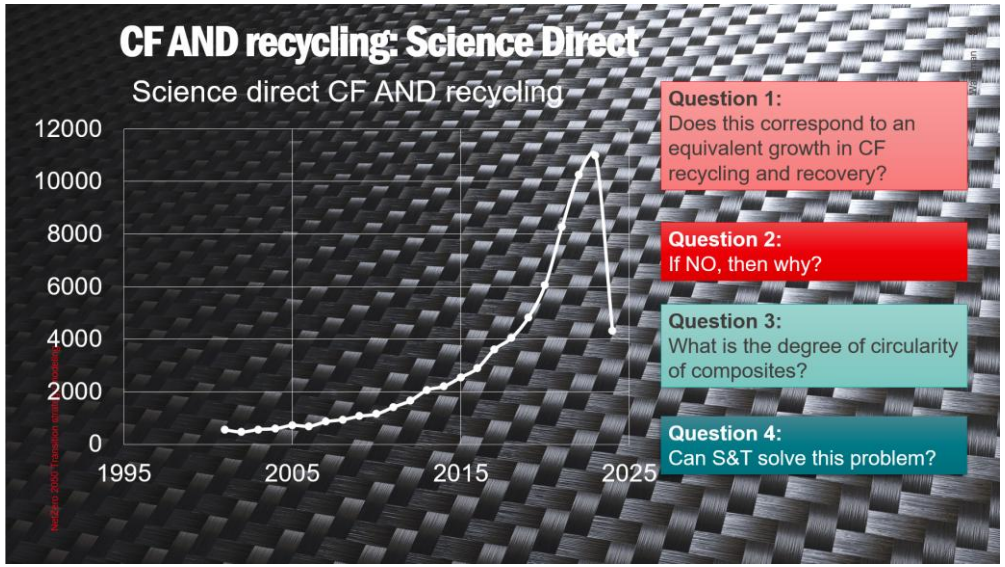
- Modify in-efficient **mass flows**
- 1) Reduce waste, reduce supply, modify MFA
- 2) Reduce mass via tailored ply lay-ups vs. quasi-isotropic

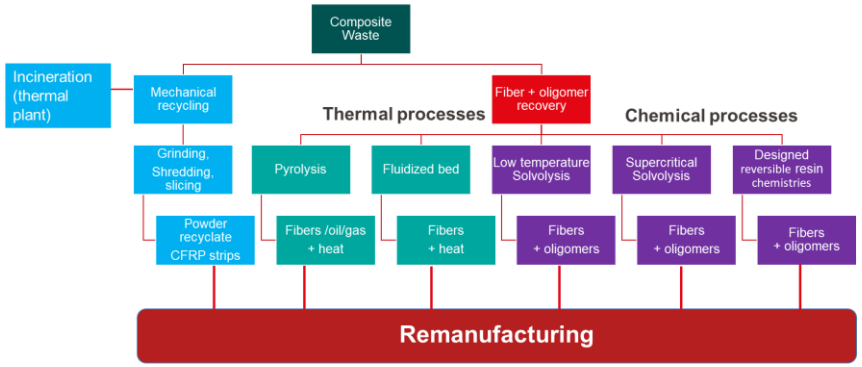
- Reduce post industrial waste for UD materials used in aerospace

Preliminary data subject to revision

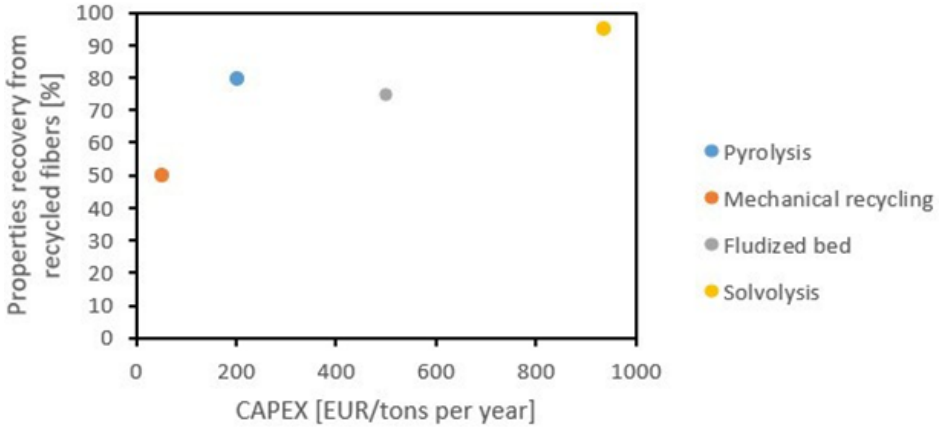
Enabler - Recycling

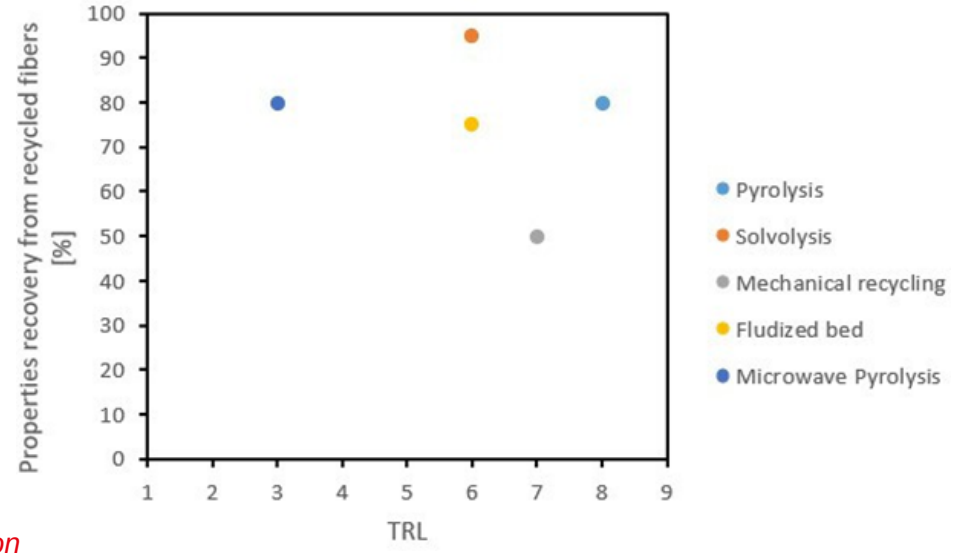
- Barriers to recycling are not CAPEX intensity or TRL





Aim for >65% mass based CF recycling by 2050





Preliminary data subject to revision

THE WORLD'S MOST ADVANCED MATERIAL HAS A DIRTY WASTE PROBLEM

- Over **90%** of carbon fibre ends up in landfill
- **20x** more CO_2 emitted than steel
- Expected **500,000,000 kg** of carbon fibre waste by 2035

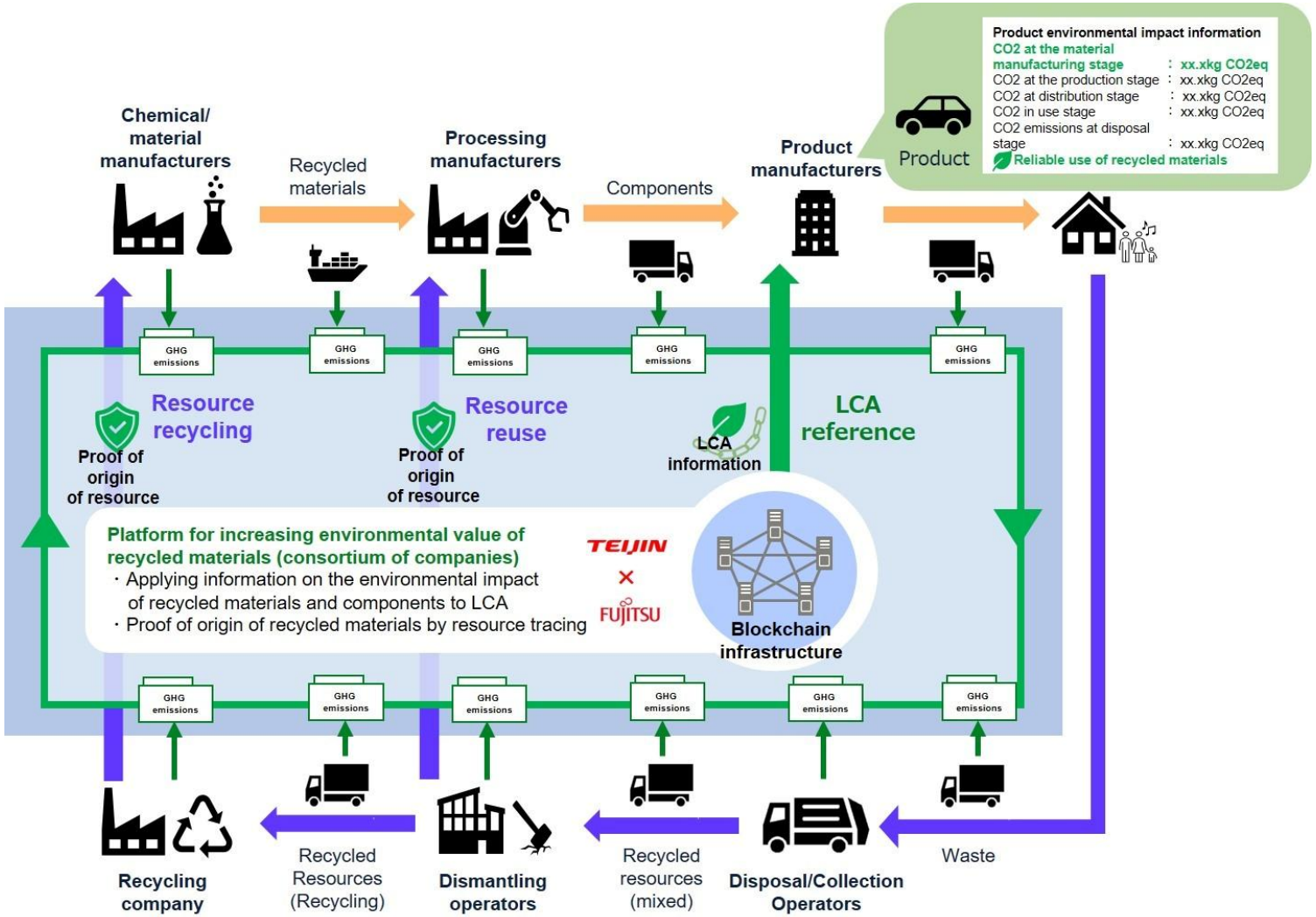
15.5 Mt CO_2e

NetZero 2050 Transition strategy modeling

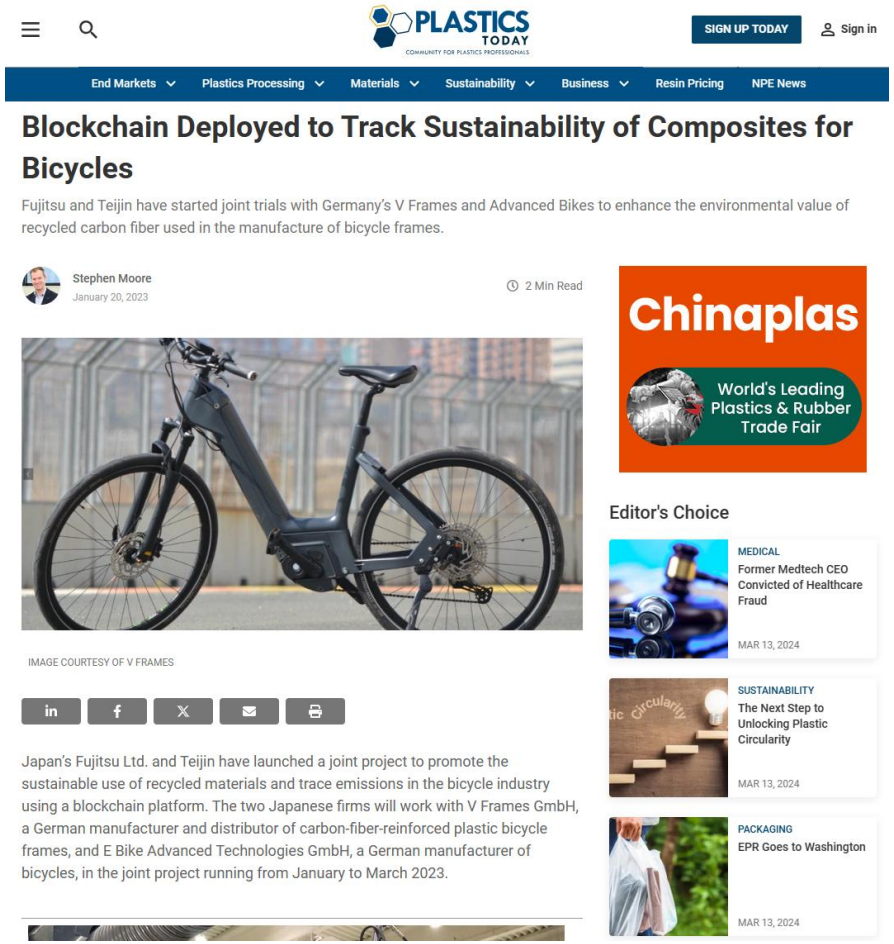
Enablers: block chain enabled reverse supply chains

- How to go from non-standardized waste to standardized raw materials?
- Traceability / supply chain …

Block chain enabled carbon fiber composite recycling



Teijin, Fujitsu to develop blockchain-based commercial platform for recycled materials manufacturing | CompositesWorld



PLASTICS TODAY
SIGN UP TODAY
Sign in
End Markets | Plastics Processing | Materials | Sustainability | Business | Resin Pricing | NPE News

Blockchain Deployed to Track Sustainability of Composites for Bicycles

Fujitsu and Teijin have started joint trials with Germany's V Frames and Advanced Bikes to enhance the environmental value of recycled carbon fiber used in the manufacture of bicycle frames.

Stephen Moore
January 20, 2023
2 Min Read

IMAGE COURTESY OF V FRAMES

Japan's Fujitsu Ltd. and Teijin have launched a joint project to promote the sustainable use of recycled materials and trace emissions in the bicycle industry using a blockchain platform. The two Japanese firms will work with V Frames GmbH, a German manufacturer and distributor of carbon-fiber-reinforced plastic bicycle frames, and E Bike Advanced Technologies GmbH, a German manufacturer of bicycles, in the joint project running from January to March 2023.

Chinaplas
World's Leading Plastics & Rubber Trade Fair

Editor's Choice

MEDICAL
Former Medtech CEO Convicted of Healthcare Fraud
MAR 13, 2024

SUSTAINABILITY
The Next Step to Unlocking Plastic Circularity
MAR 13, 2024

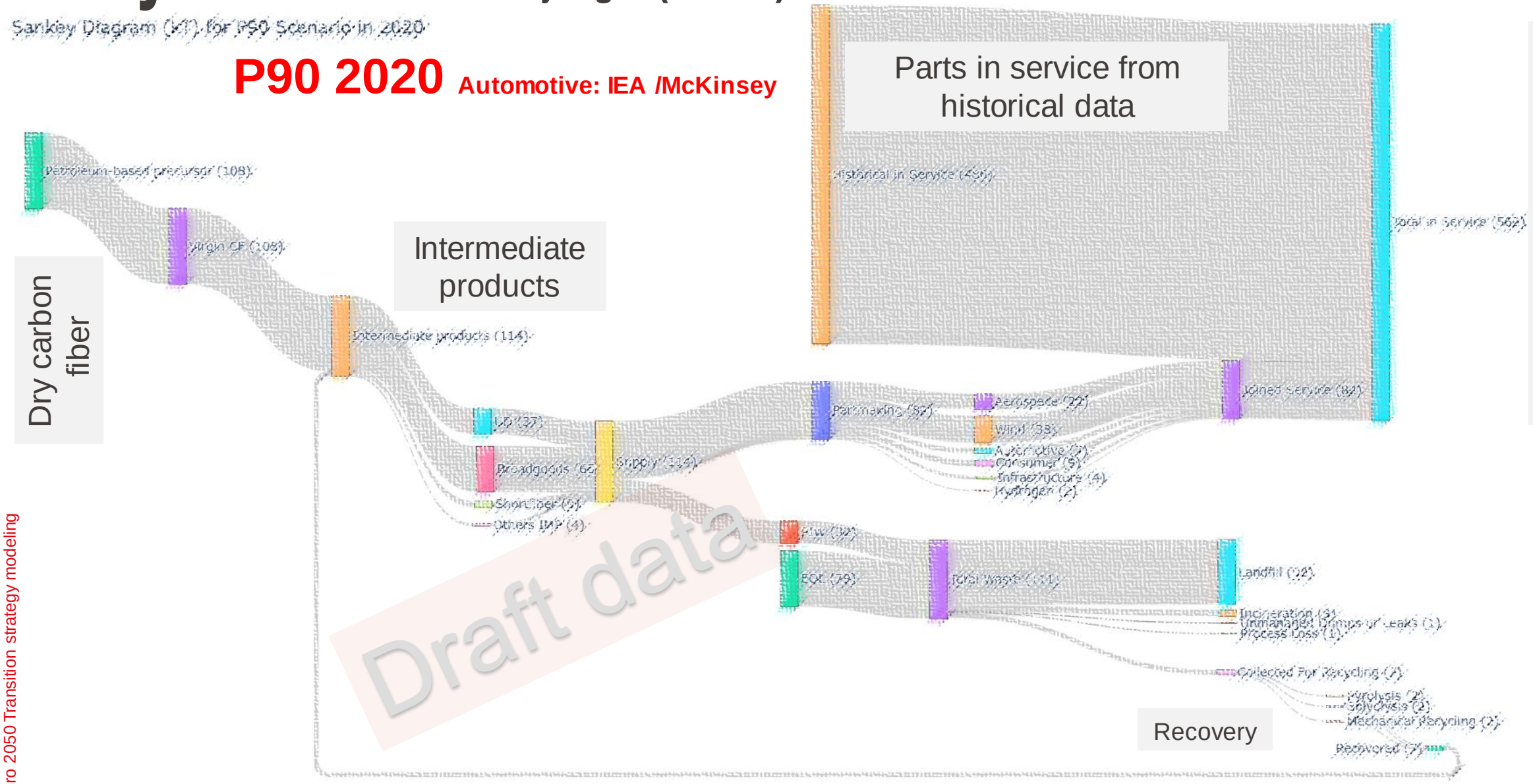
PACKAGING
EPR Goes to Washington
MAR 13, 2024

Blockchain Deployed to Track Sustainability of Composites for Bicycles (plasticstoday.com)

Dynamic MFA: Sankey Diagram (draft data)

Sankey Diagram (v1) for P90 Scenario in 2020

P90 2020 Automotive: IEA /McKinsey



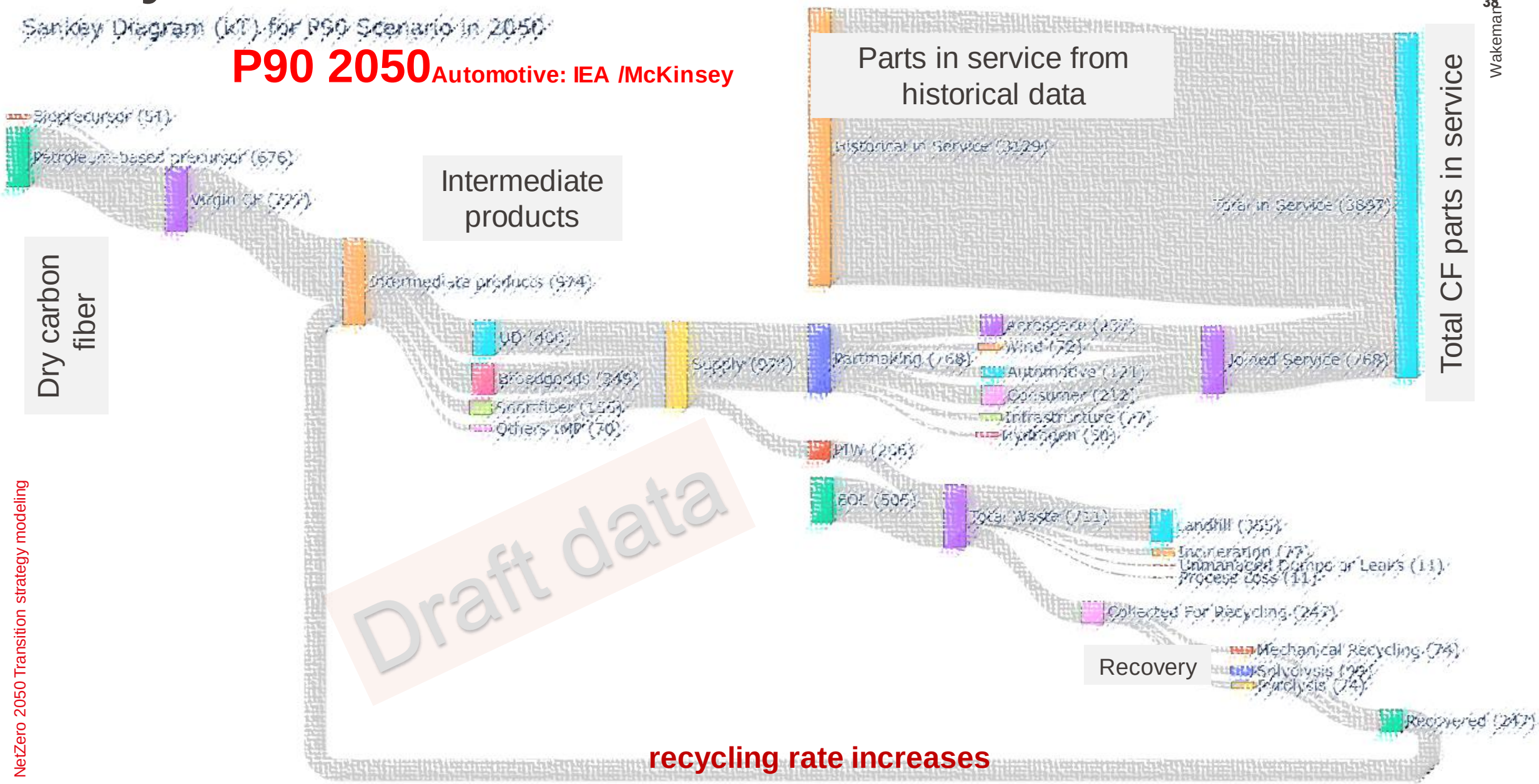
<10% recycling rate

Preliminary data subject to revision

Wakeman

Dynamic MFA: Sankey Diagram (draft data)

Wakeman

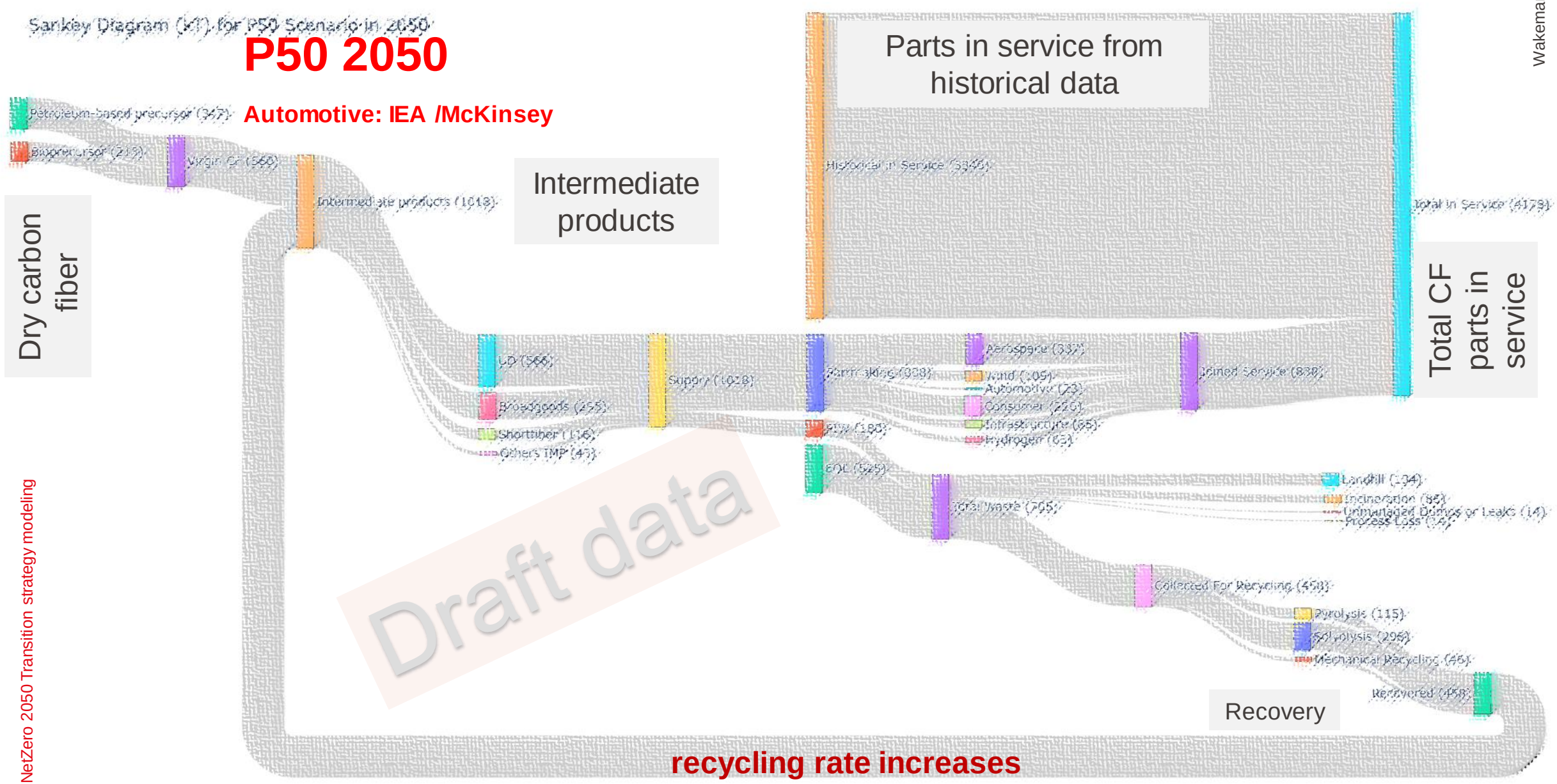


NetZero 2050 Transition strategy modeling

recycling rate increases

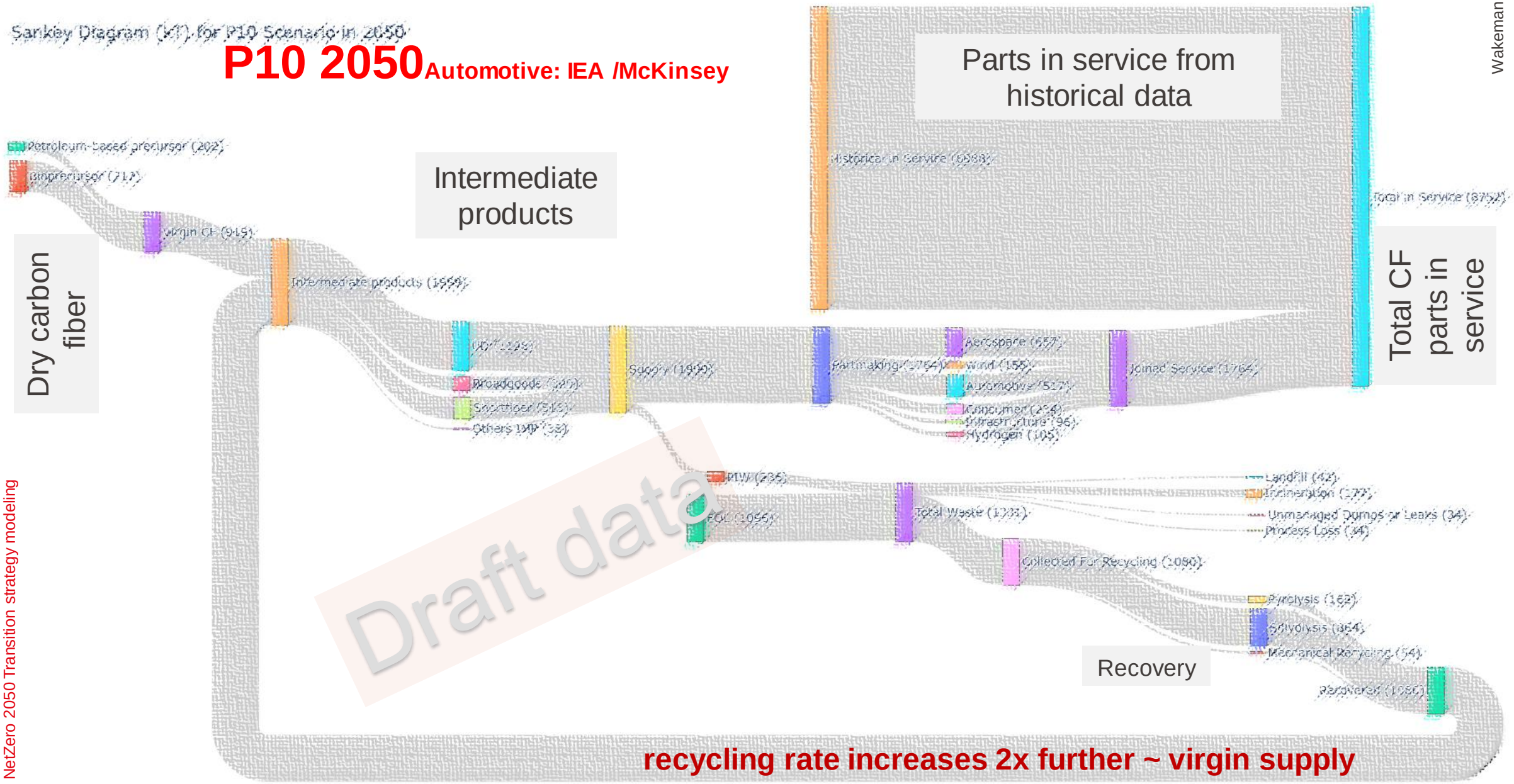
Preliminary data subject to revision

Dynamic MFA: Sankey Diagram (draft data)



Preliminary data subject to revision

Dynamic MFA: Sankey Diagram (draft data)



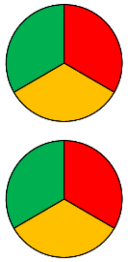
Preliminary data subject to revision

41

Dynamic MFA: Sankey Diagram (draft data)

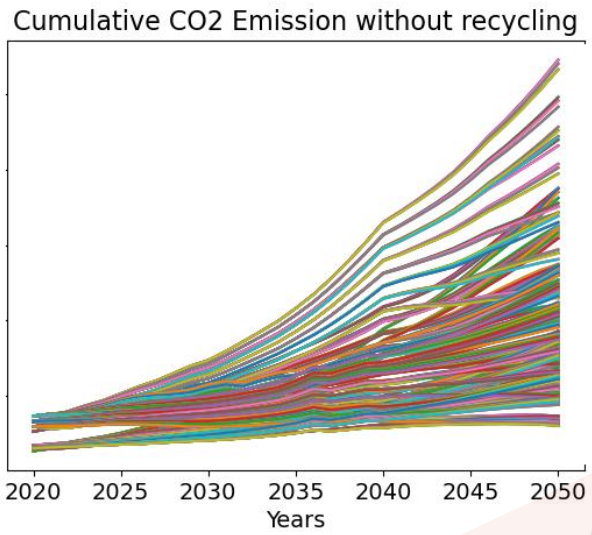
- Currently MFA models ALL parameters in 3 sets
  - i) Market sectors
  - ii) Enablers
- As P90, P50, P10 

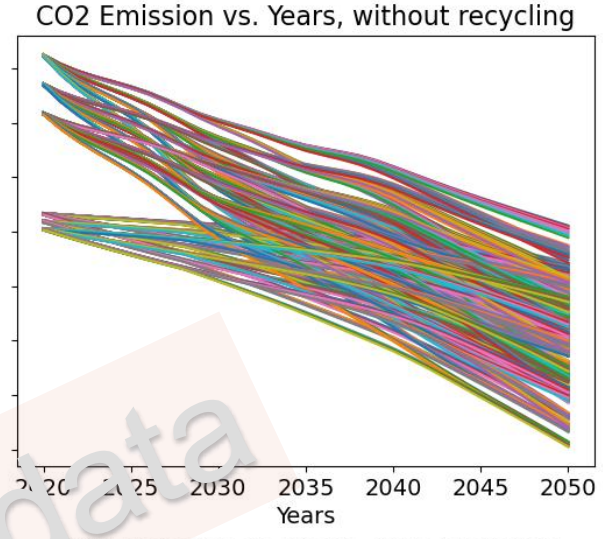
- Next stage
  - Independently set scenarios
  - i) Market sectors
  - ii) Enablers

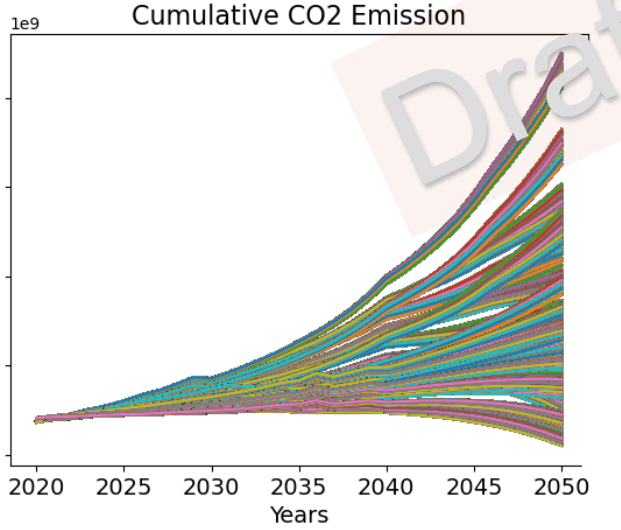


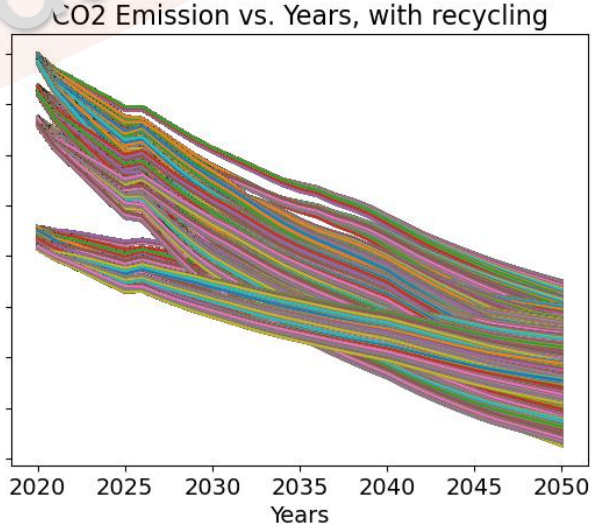
Preliminary data subject to revision

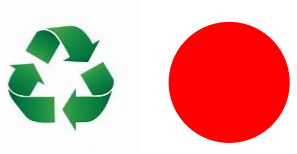
P10 everything and P90 recycling - How important is recycling?

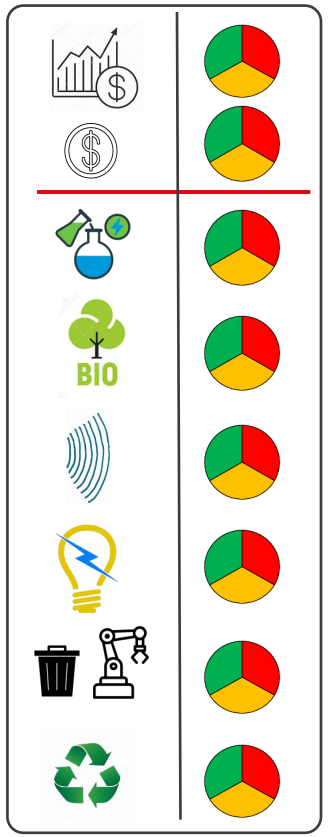








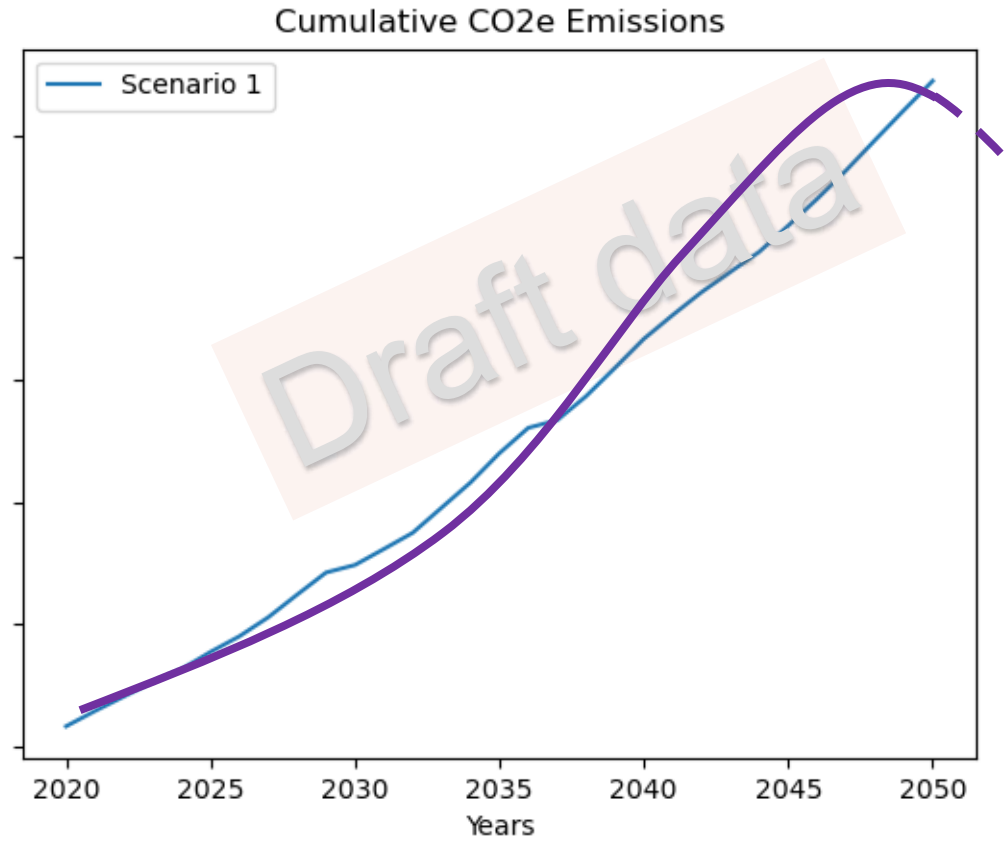


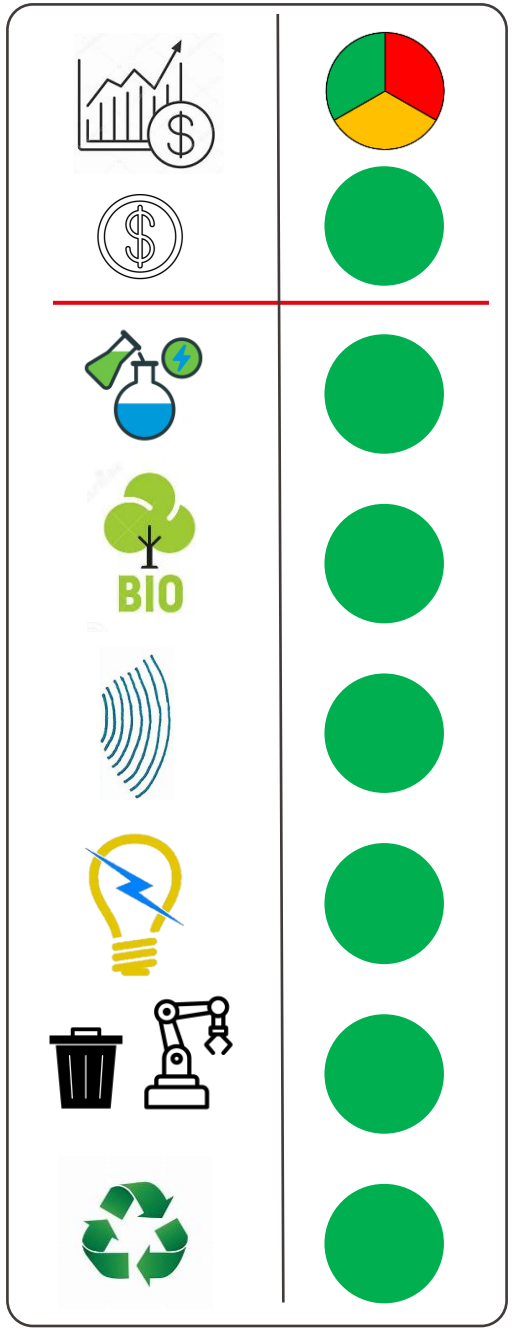


Preliminary data subject to revision

Selected high growth, high enablers?

- Markets
  - Wind p10, Hydrogen p10, Lowest case for consumer so p90, Auto p50 prime (not widely used), Aero p10 prime (societal adaptation so lower version), Infrastructure p10
- All enablers at P10
- Durability switch off (still being coded)



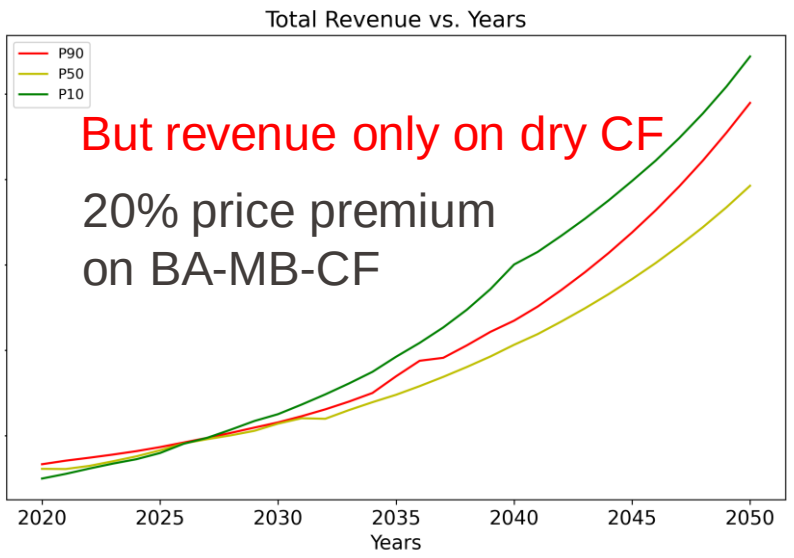


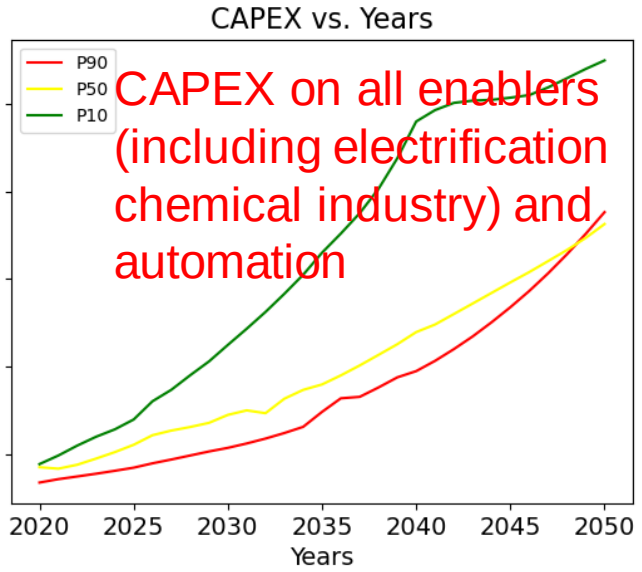
OFF

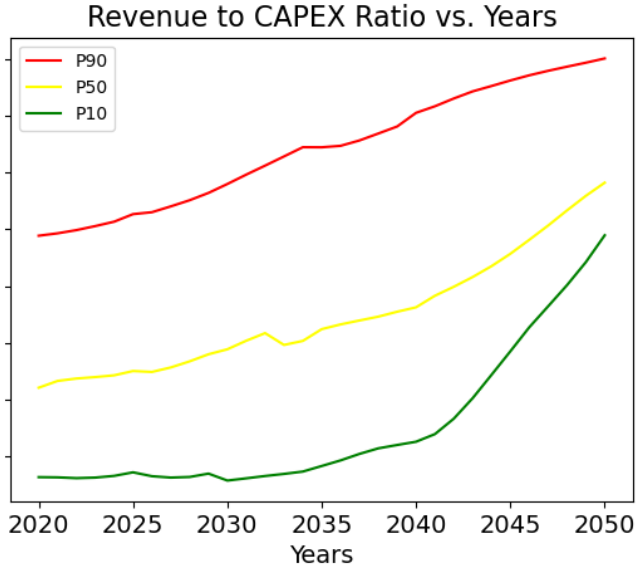
Preliminary data subject to revision

Revenue to CAPEX ratios

- What effect does the additional investment & higher prices have on monetary flows?





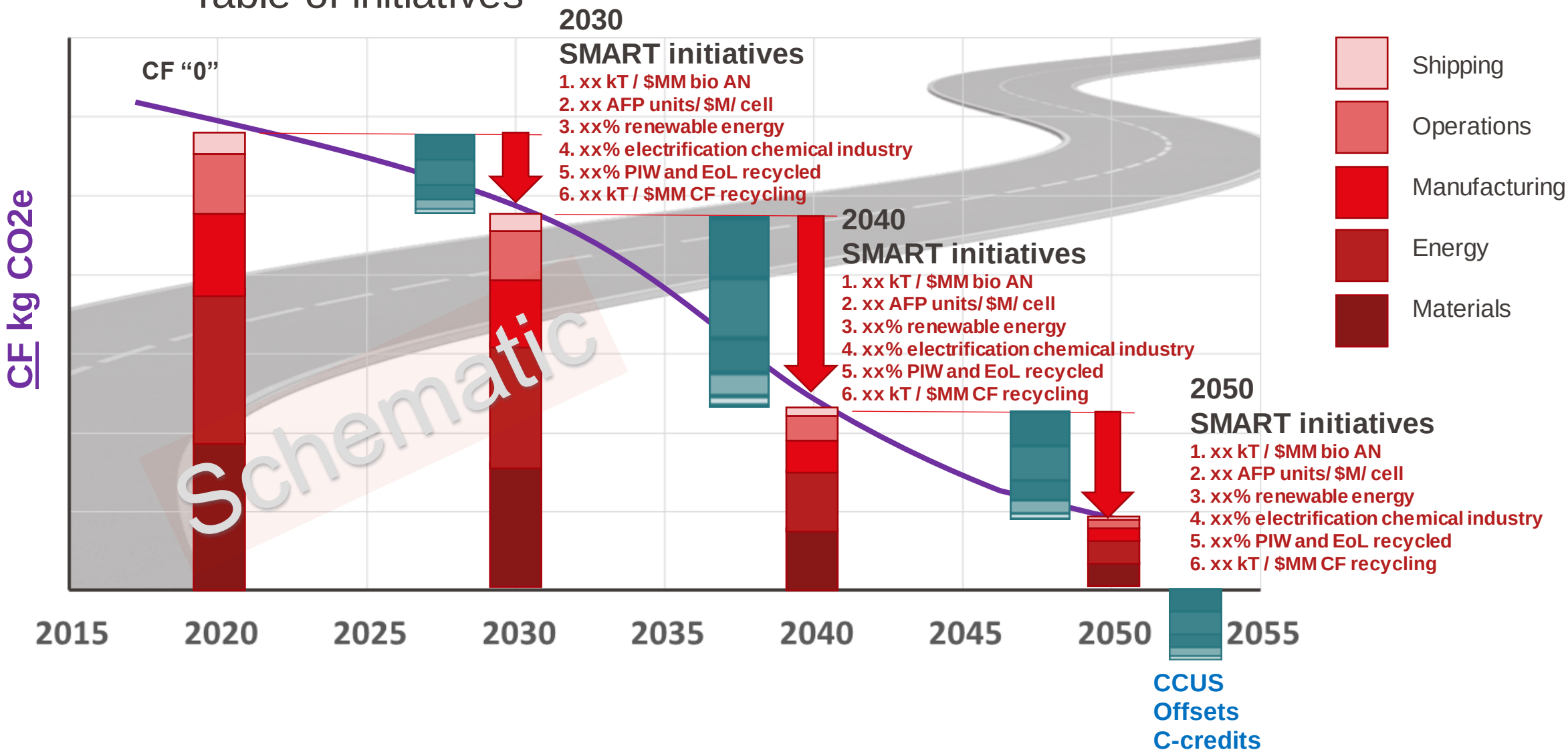


Revenue calculation section						
2022 data	P50	Pricing selection				
CF grade selling price ($/kg) by grade	choose scenario	CF Bio-mass grade s	Low cost PAN suitable	Recycled CF gardes suitable	P90	P50	P10
Bio-mass PAN CF: 1-12k	28				40.0	32.0	26.0
Bio-mass PAN CF: 24k	36				46.0	34.3	32.4
Bio-mass PAN CF: >48k	24				34.0	31.6	29.2
T300-T700: 1-12k	30	yes		yes	50.0	35.0	30.0
T300-T700: 24k	30	yes	no	yes	50.0	38.6	27.0
heavy tow: >48k	20	yes		yes	34.0	28.0	18.0
T800-T1100: 1-12k	60				55.0	60.0	55.0
T800-T1100: 24k	60				50.0	50.0	50.0
M35-M60: 1-12k	200				200.0	150.0	100.0
Pitch	300				500.0	300.0	200.0
other / low cost T700s	30				40.0	34.0	32.0
Recycled carbon fiber	16				18.0	14.0	12.0

Preliminary data subject to revision

CF decarbonization roadmap

- Table of initiatives



Preliminary data subject to revision

Key sustainability initiatives for the carbon fiber industry

- ✓Electrification of the chemical industry
- ✓Develop bio-attributed / bio-circular CF (and resins)
- ✓Reduce manufacturing trim (PIW), automation, reduce part mass
- ✓Use renewable energy for all plant operations
- ✓Societal adaptation (P10 prime: aerospace, rail, automotive, P90 consumer)
- ✓Enhance product durability
- ✓Eliminate landfill, reduce incineration
- ✓Increase degree of circularity (legislation)
- ✓Invest in recycling infrastructure ahead of waste streams to recover CF / resins
- ✓Labelling of products and waste streams, reverse logistics, blockchain
- ✓Convert recycled CF into semi-finished products

The CF market is growing so strongly we need to adopt all measures to the maximum extent in a compressed time frame.

Preliminary data subject to revision

Next steps

- Complete durability switch 

- Model de-bugging
- Automotive model completion
- D-MFA for mixed scenarios
- Finalize data set for first complete run
- CAPEX to revenue plots
- Monetary flow diagram
- JMP statistical analysis ML model from Monte Carlo results
- Trade-off analysis: CAPEX allocation vs. decarbonization
- Re-wired supply chains and CAPEX distribution
- Waterfall decarbonization plot
- Road map of CAPEX investments and legislation vs. time

Preliminary data subject to revision

Acknowledgements

- An approach and modelling tool to quantify strategies and initiatives
  - Case study: Carbon fiber industry: 10-50-90 scenario Monte-Carlo simulation


Gabrielle Rossi


Ramezani Reyhaneh


Sierro Maxime Edouard


Lefevre Iléane Tiphaine Françoise Marie


Yacine Belgacem M'Hamdi


Nanda Surya Fahrizal


Binta Doukouré

SYENSQO
TRILLIUM Renewable Chemicals
CORIOLIS
HUNTSMAN Enriching lives through innovation
for pressure testing data and assumption

E4S Enterprise for Society
Seed funding


https://e4s.center/resources/reports/re-wiring-capex-and-finance-in-circular-value-chains-a-case-study-of-advanced-materials/

https://e4s.center/resources/reports/scenario-modelling-of-the-carbon-fiber-industry-in-the-transition-to-netzero-2050/

Preliminary data subject to revision