THE SCRAP TIRE RESEARCH AND EDUCATION FOUNDATION, INC.

Pyrolysis State-of-the-Art Market

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Prepared by Weibold for Tire Recycling Conference, Atlanta, 16-17 May 2024

Vienna, 22 May 2024

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Agenda

A quick cross section of the global status of ELT chemical recycling – ***why pyrolysis is a game-changer technology***

- Global view by region – processing volumes, output products
- Major technology developers
- Major processing facilities – now and in 2-3 years
- Demand / supply, output product pricing directions
- Conditions prevailing in the US
- Conclusions and Q&A

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Global View: Status quo & near-future ELT pyrolysis processing volumes

The total amount of finished rCB on the global market is set to exceed 500,000 tons / year in the near future

C. Actual current processing volumes (w! Judgement)

w! JUDGED ACTUAL CURRENT PRODUCTION VOLUMES					
MAP ID		M0	M3	M4	M6 (rCB1+2)
SUMMARY BY REGION	NUMBER OF OPERATORS OR OPERATOR & TECHNOLOGY SUPPLIERS	ELT EQUIVALENT WHOLE TIRE PROCESSING VOLUME	TPO OUTPUT VOLUME	TOTAL CARBON CHAR PRODUCED	Finished rCB1 & rCB 2 OUTPUT VOLUME
Applies to -->	All production facilities known to be in pilot, operating, or restarted.				
EUR	30	224,427 t	81,920 t	59,847 t	28,274 t
APAC	76 *)	4,094,453 t	1,526,804 t	1,095,374 t	124,811 t
North Amer	5	26,463 t	9,880 t	7,057 t	6,067 t
Latin Amer	4	47,781 t	17,838 t	12,742 t	9,542 t
MEA	9	93,500 t	34,907 t	24,933 t	10,133 t
TOTAL	124	4,486,624 t	1,671,348 t	**1,199,953 t**	**178,826 t**

*) Note: The number of operators in APAC is actually larger. There are summary entries for facilites producing only char.

D. Projected real processing volumes in ~2-3 years (w! Judgement)

w! JUDGED FUTURE PRODUCTION VOLUMES					
MAP ID		M0	M3	M4	M6 (rCB1+2)
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Applies to -->	All production facilities known to currently be in planning, construction, pilot, operating, or restarted.				
EUR	67	1,036,962 t	387,132 t	276,523 t	203,709 t
APAC	91 *)	4,459,371 t	1,663,040 t	1,192,686 t	202,388 t
North Amer	14	173,821 t	64,893 t	46,352 t	32,642 t
Latin Amer	5	114,450 t	42,728 t	30,520 t	27,320 t
MEA	19	342,138 t	127,731 t	91,237 t	68,667 t
TOTAL	196	6,126,742 t	2,285,525 t	1,637,318 t	**534,727 t**

*) Note: The number of operators in APAC is actually larger. There are summary entries for facilites producing only char.

1. 2. 3. 4. 5.

w! Observation

1. Out of 1.2 m tons of char, only 178 kt of finished rCB is produced.
2. Due to new pyrolysis operations coming online in 2-3 years, that number increases to 534 kt.
3. Europe will experience a huge upswing
4. North America lags behind
5. APAC does much bigger volumes

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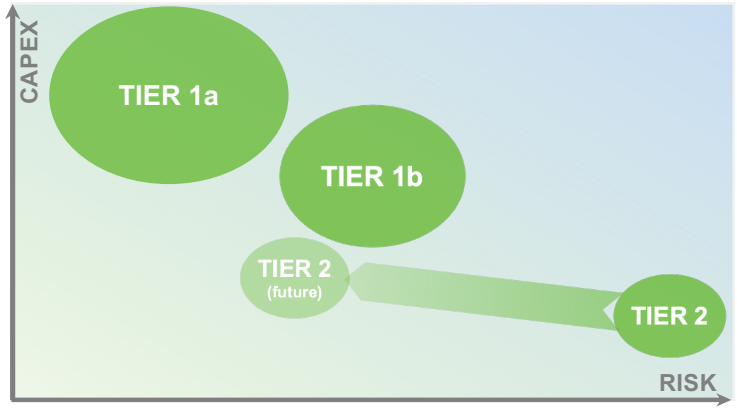
Tiers of technology and project developers

Project size, technology sophistication and different investment risk profiles dictate total project CAPEX

PARAMETER	TIER 1a	TIER 1b	TIER 2 (current) Western country	TIER 2 (current) Developing country
Description	Large facility in **Western** country Full suite ELT --> rCB pellets Technology TRL= 9	Median facility in **Western** country Full suite ELT --> rCB pellets Technology TRL= 9	Smaller facility in **Western** country Full suite ELT --> rCB pellets Technology TRL= 8 or 9	Smaller facility in **developing** country Full suite ELT --> rCB pellets Technology TRL= 8 or 9
Most likely ELT throughput	**80,000 MT / yr**	**60,000 MT / yr**	**20,000 MT / yr**	**20,000 MT / yr**
CAPEX				
Total facility CAPEX	100% **USD 200,000,000**	100% **USD 120,000,000**	100% **USD 10,000,000**	100% **USD 8,000,000**
Normalized CAPEX Metrics				
Facility CAPEX / MT throughput	**USD 2,500 / MT**	**USD 2,000 / MT**	**USD 500 / MT**	**USD 400 / MT**
Equipment CAPEX / MT throughput	USD 875 / MT	USD 800 / MT	USD 135 / MT	USD 135 / MT
Infrastructure CAPEX / MT throughput	USD 550 / MT	USD 500 / MT	USD 235 / MT	USD 185 / MT



- **There is a wide disparity in total facility CAPEX per unit of capacity**

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Tier 1 Technology supplier pioneers (TRL = 9)

Developers and facility operators with track-records in selling & delivering TPO & rCB at industrial scale

PARAMETER
Location
Cumulative Experience
Partners / Off-takers
Expansion Plans
Business Position

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Profiles of selected significant players

Player criteria	APAC		EUR										North America	
	Ecostar	Enrestec	Circtec	L4T	Reoil	Black Bear Carbon	New Energy	Waste-front	Pyrum	Enviro	Ahlat	Contec	Bolder	Ecolo-mondo
	CN	TW	NL	ES	PL	NL	HU	UK	DE	SE	TR	PL	US	CA/US

Global current supply / demand dynamics

Demand outstrips supply for most of the TPO and rCB produced

Current global TPO supply/demand

MASS-FLOW ID	MATERIAL	to OFF-TAKER SECTOR		CURRENT SUPPLY (2023): SUPPLY SPLIT ASSMPTNS	CURRENT SUPPLY (2023): % ELT ARISINGS	CURRENT SUPPLY (2023): JUDGED ACTUAL PRODUCTION VOLUME	ESTIMATED CURRENT DEMAND	TENDENCY	DEMAND / SUPPLY RATIO
M0	ELT arisings		all		100.00%	30,900,000 t **)	30,900,000 t	▶	1.0 x
M1b	Whole Tires for Pyr	S2	ELT Pyrolysis Ops	14.5%	14.52%	4,486,624 t ***)	26,436,451 t *)	▲	5.9 x
M3	TPO (crude)		*Internal to operators*	100.0%	5.42%	1,671,348 t ***)	20,400,000 t *)	▲	12.2 x
M3a, M3c, M3d	TPO remix for Fuel	S3a	Oil Refineries	13.00%	0.70%	217,275 t ***)	10,000,000 t *)	▲	46.0 x
		S3a	Local fuel consumption	85.00%	1.84%	1,420,646 t ***)	10,000,000 t *)	▲	7.0 x
M3b, M3e	TPO remix for circular mtrls.	S3b	Chemical & Petrochem.	1.00%	0.03%	16,713 t	200,000 t *)	▲	12.0 x
M3f	TPO Heavy for sCB	S4	Carbon Black Industry	1.00%	0.03%	16,713 t	200,000 t *)	▲	12.0 x
M4	Char		*Internal to operators*	100.0%	3.87%	1,199,953 t ***)	4,421,127 t *)	▲	3.7 x
M4a	Char for Incineration	S7	Cement and others	85.1%	3.30%	1,021,127 t	1,021,127 t *)	▶	1.0 x
M6	rCB, finished		Manufacturers & Blenders	14.9%	0.58%	178,826 t ***)	3,400,000 t *)	▲	19.0 x
M6a	rCB for tire manufacturers	S6	- Tire Manufacturers	30.00%	0.17%	53,648 t	1,600,000 t *)	▲	29.8 x
M6b	rCB for other rubber goods	S13	- Other Manufacturers	70.00%	0.41%	125,178 t	1,800,000 t *)	▲	14.4 x

Source: Weibold, 2024

Observation

1. Globally, an estimated 1.4 m tons of TPO goes to local fuel applications (mostly APAC).
2. Demand for TPO from the oil sector is virtually infinite.
3. Only a small fraction of the carbon char produced (est. 15%) is used for production of finished rCB. Even less goes to tires.

*) Order of magnitude assumptions by Weibold

**) from Global ELT Management Report WBCSD, Dec 2019

***) From Weibold Database

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Global near-future supply / demand dynamics

Due to new pyrolysis facilities world-wide going online, rCB supplies will improve, although demand remains higher.

Future global ELT pyrolysis supply/demand

MASS-FLOW ID	MATERIAL	to OFF-TAKER SECTOR		FUTURE SUPPLY: SUPPLY SPLIT ASSMPTNS	FUTURE SUPPLY: % ELT ARISINGS	FUTURE SUPPLY: JUDGED ACTUAL PRODUCTION VOLUME	ESTIMATED FUTURE DEMAND	TENDENCY	DEMAND / SUPPLY RATIO
M0	ELT arisings		all		100.00%	30,900,000 t **)	30,900,000 t	▶	1.0 x
M1b	Whole Tires for Pyr	S2	ELT Pyrolysis Ops	19.8%	19.83%	6,126,742 t ***)	27,106,490 t *)	▲	4.4 x
M3	TPO (crude)		*Internal to operators*	100.0%	7.40%	2,285,525 t ***)	20,400,000 t *)	▲	8.9 x
M3a, M3c, M3d	TPO remix for Fuel	S3a	Oil Refineries	13.00%	0.96%	297,118 t ***)	10,000,000 t *)	▲	33.7 x
		S3a	Local fuel consumption	85.00%	2.51%	1,942,696 t	10,000,000 t *)	▲	5.1 x
M3e	TPO remix for circular mtrls.	S3b	Chemical & Petrochem.	1.00%	0.04%	22,855 t	200,000 t *)	▲	8.8 x
M3f	TPO Heavy for sCB	S4	Carbon Black Industry	1.00%	0.04%	22,855 t	200,000 t *)	▲	8.8 x
M4	Char		*Internal to operators*	100.0%	5.29%	1,637,318 t ***)	4,502,591 t *)	▲	2.7 x
M4a	Char for Incineration	S7	Cement and others	67.3%	3.57%	1,102,591 t	1,102,591 t *)	▶	1.0 x
M6	rCB, finished		Manufacturers & Blender	32.7%	1.73%	534,727 t ***)	3,400,000 t *)	▲	6.4 x
M6a	rCB for tire manufacturers	S6	- Tire Manufacturers	60.00%	1.04%	320,836 t	1,600,000 t *)	▲	5.0 x
M6b	rCB for other rubber goods	S13	- Other Manufacturers	40.00%	0.69%	213,891 t	1,800,000 t *)	▲	8.4 x

Source: Weibold, 2024

Observation

1. TPO and rCB production are expected to experience an upswing.
2. Tire manufacturers' share of rCB supply could improve in the competition against MRG producers.

▶ Aggressive uptake policies are required.

*) Order of magnitude assumptions by Weibold

**) from Global ELT Management Report WBCSD, Dec 2019

***) From Weibold Database

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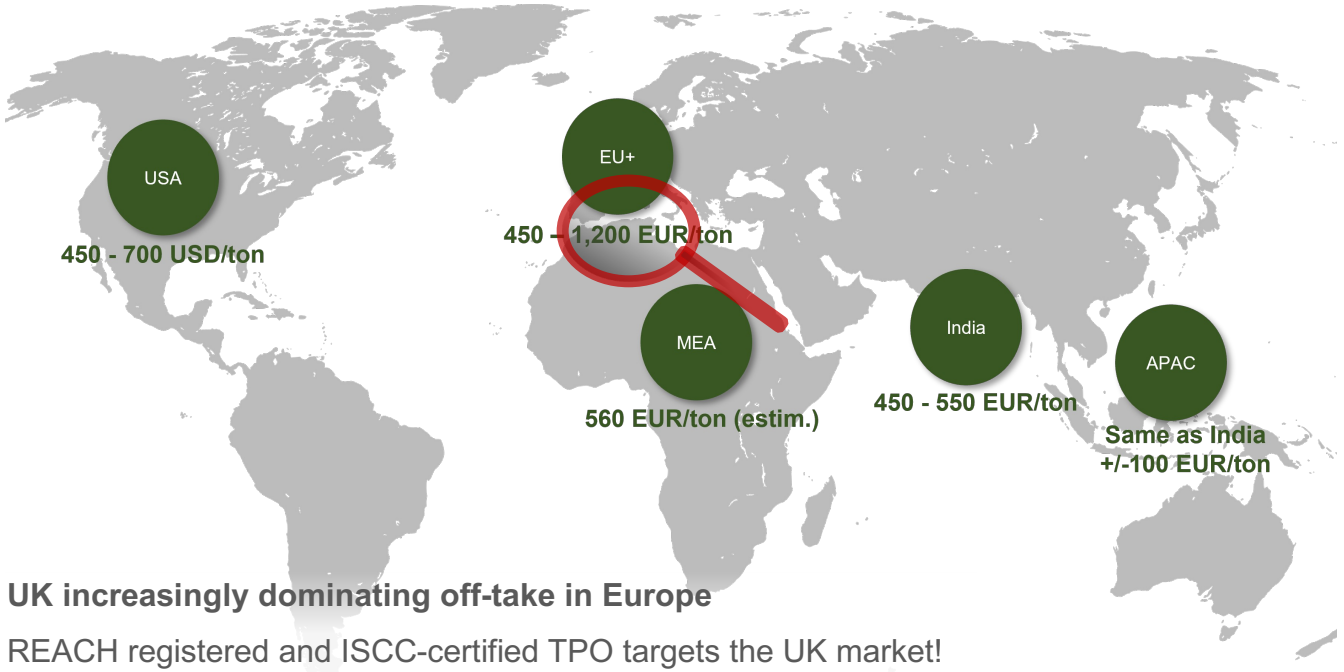
Demand and price level drivers for TPO

Legal obligations or the associated fines (buy-out prices) are increasingly leading to "environmental premiums"



UK increasingly dominating off-take in Europe

REACH registered and ISCC-certified TPO targets the UK market!

Biogenic content of TPO (38-55%) is recognized as development fuel (**RTFO**)

Off-takers in the UK pay high sustainability premiums on top of the base price.

Sustainability premium accounts for up to 100% of the buy-out price for dRTFCs (£1.60 per liter biogenic content) in the UK, resulting in premiums of USD 600 to 1,000 per ton.

GOV.UK RTFO Program

Development Renewable Transport Fuel Certificates

Demand generated in **2025:**
~ 800,000 MT or 900 million liters

Premiums generated **2025**:
~ USD 1.2 billion

w! Observations & Opinion

- **Prices are largely based on the crude oil price** (e.g., Fuel Oil 1% (Platts) FOB Rotterdam Barges)
- Visible trend towards **decoupling crude oil prices and paying "environmental premiums"** for ISCC-certified TPO
- **UK Renewable Transport Fuel Obligations (RTFO) impose high "buy-out prices"** for those who are not fulfilling the obligation
- **The EU and the US could follow** (RED III, and RFS programs)

▶ **The chemical and carbon black industries will have to pay comparably high prices to secure this resource!**

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Conditions prevailing in the US

Intertwined historical, awareness, regulatory and financing reasons are behind the US failure to lead.

+ Environmental policy and regulatory framework

- On the books the environment is good:
  - **No real obstacles** in the regulatory framework. ELT pyrolysis was assessed positively by the EPA in the 1980s and 1990s. But not updated**.**
  - **24 states** have passed bills to **support chemical recycling** facilities. 14 more to follow.
  - The EPA is planning to **exclude pyrolysis** from the classification as Other Solid Waste Incineration (OSWI). ELT pyrolysis facilities are ***already*** explicitly excluded from the municipal waste combustion unit definition in current federal law (40 CFR 60.1465).

- Perceptions

- "Pyrolysis **does not work**!" (false)
- "Pyrolysis **is combustion or incineration**!" (false!)
- "Pyrolysis operations are **dangerous and dirty**!" (false!)

- Landfill practices

- **Loopholes** allow landfill in many states.
- **Landfilling** of cut or shredded ELTs is **still allowed** in 37 US states!
- USTMA: **1.4 million tons** are **un-utilized** or go to **landfill** (2021). Tendency ⇧.

- Lack of Alternative fuel incentives

- **No precedent is known** if the biogenic content of TPO qualifies as renewable / advanced biofuel according the US Renewable Fuel Standard (RFS).

- Collection

- **Lack of uniform rules and competition** in the collection sector.

- Capital

- **High interest rates** and business-as-usual **risk mitigation requirements** make financing almost impossible.

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Conclusion

What the tire industry should know and what you can do to accelerate availability of rCB and sCB

Status Quo

- The tire **pyrolysis** sector is experiencing a **boom** world-wide
- Pyrolysis is proven the **most effective in GHG reductions** of all tire recovery paths
- The **technology** has **matured**, there are multiple successful players
- **Standards** for rCB are solidifying
- A large volume of **new capacity** comes online in the next 2-3 years
- **Demand** far outstrips supply for all pyrolysis output products
- A **second tier of projects** is on its way
- The US lags behind

What can be done?

- Stronger **active involvement by tire manufacturers**. Involve the car industry, too. **Publicly announce rCB demand targets**!
- Initiate **Incubation** practices (through the TRF?)
- Enforce **landfill bans** rigorously nationwide. No federal EPR needed.
- **Material Purchasing** departments:
  - Devise new, **sustainability oriented terms**.
  - **Decouple rCB and TPO prices** from rCB & Oil price indices.
  - **Adapt specifications**, focus on consistency.
  - Be ready to buy **smaller quantities.**
- Develop and adopt **standard terms for investment in securing** sustainable supply.

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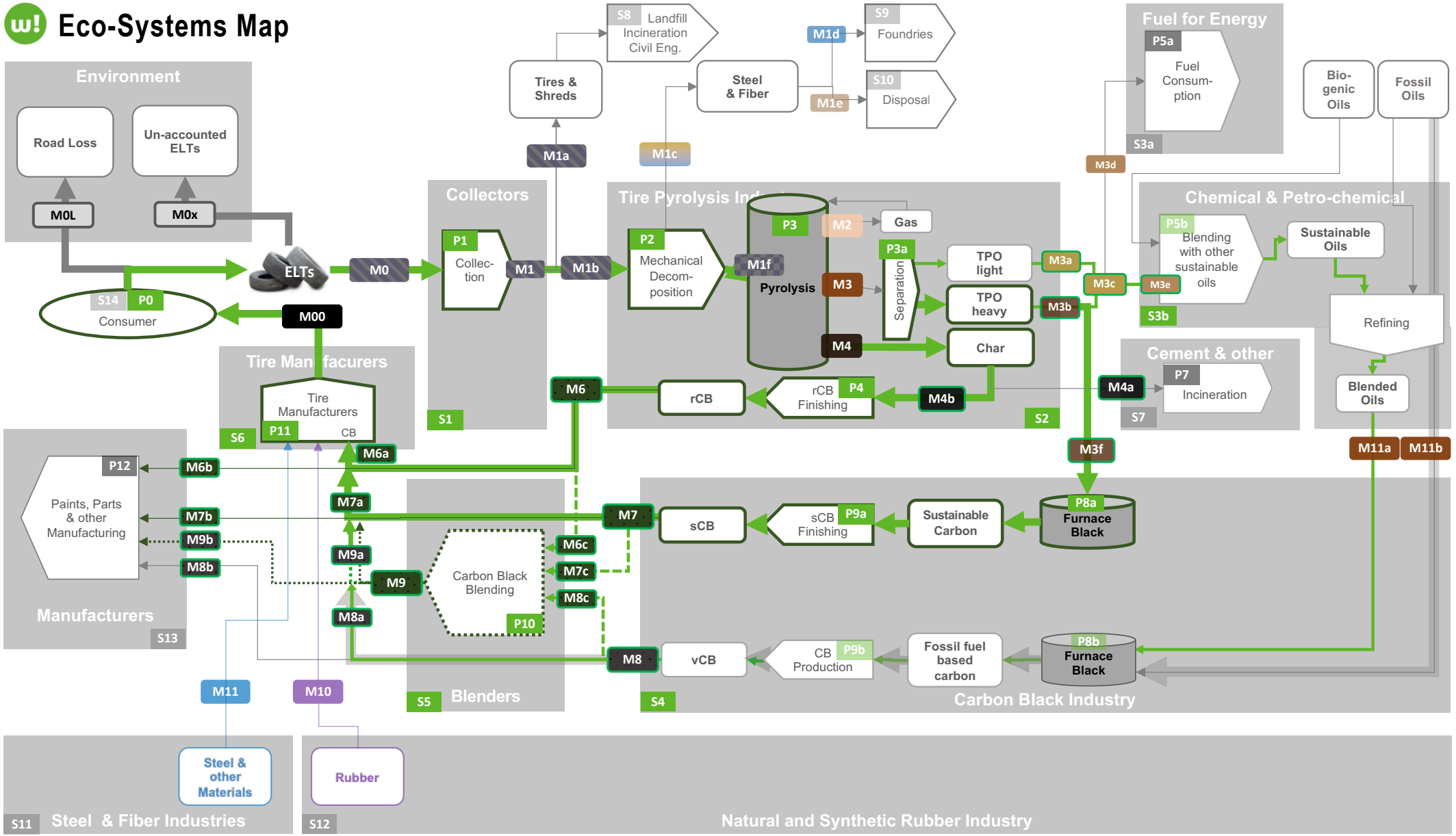
Eco-Systems Map



Tire Pyrolysis Industry

Industry Sector Stakeholders: Groups of companies

P1 Collection

Processes or groups of processes

rCB

Materials (products) that are output of the Processes

M3c

Material Flows at major Nodes between Sectors

Closed Loop Path

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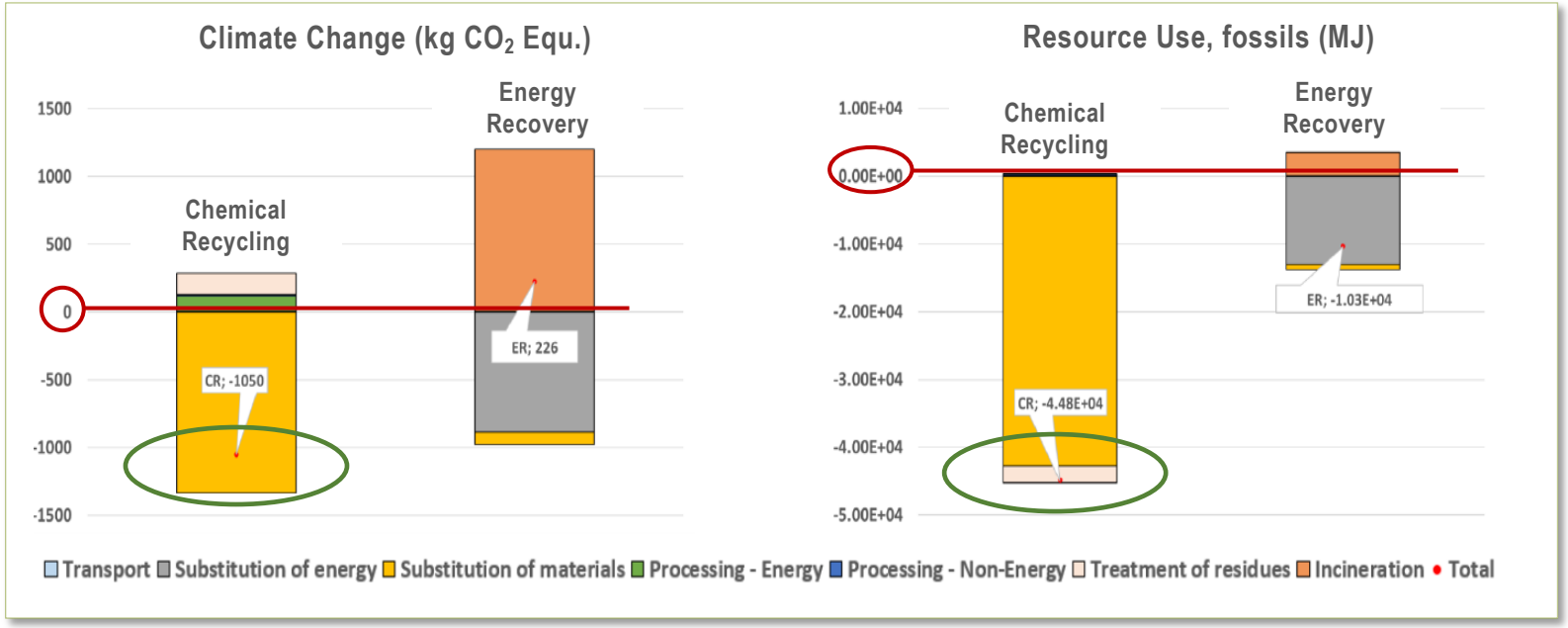
Tire Pyrolysis Fundamentally Creates Highly Sustainable Materials

EU Joint Research Council (JRC, 2023): chemical recycling of ELTs (CR) protects the environment and saves resources

Management of 1 ton of used tire waste through chemical recycling (CR; pyrolysis) and energy recovery (ER; incineration)



Source: EU Joint Research Council (JRC) in 2023, assessment on chemical recycling (CR) and energy recovery (ER) of ELTs

w! Analysis & Observation

Numerous LCA studies unequivocally show the benefits of ELT pyrolysis.

- **Significant net CO_2 savings for climate change (1,050 kg / tone of tires)**
- **Avoids using fossil fuels to produce virgin material (44,800 MJ / ton of tires)**

ELT pyrolysis has been defined as environmentally sound management (ESM) since 2011. (Basel Convention)

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Overview over US ELT Pyrolysis Status

	SUBJECT	UNITED STATES
1	Number of facilties	very few
2	Drivers for historical development of pyrolysis	- little need - easy to land-fill ELTs - low-priced products - expensive to operate - prominent failures
3	Energy supply / demand	- large oil reserves engender neglect for developing alternative sources
4	Culture	Dycotomy: + aggressive environmental policies (shore states) - wasteful consumer practices are common - high labor costs
5	Regulatory	- lacking harmonization by federal oversight + When not discarded, tire derived products are not considered solid waste (EPA 530-F-20-008) - Landfill loophole (in many states landfill is allowed if ELTs are quartered or shredded) - many state and local regulators still lump ELT pryrolysis in with "incineration"
6	Land-fill practices	- verly lax control regime
7	Latest developments	- fires and bankruptcies + rising demand by manufacturers
8	Availability of capital	- High interest rates and stringent risk mitigation criteria by PE and debt funds make projects prohibitively expensive

w! Observations

- The reasons for lack of activity are complex and intertwined.
- The US regulatory landscape per se does not pre-empt or make difficult the generation of ELT chem-recycling facilities.
- **24 states have already classified chemical recycling (pyrolysis) plants as manufacturing facilities** rather than waste management operations.
- The tire waste stream control practices vary across the country and only *one* state enforces an Extended Producer Responsibility EPR system.
- Low dependence on important fossil fuels result in low sense of urgency.
- The image of tire pyrolysis has been marred by recent failures (both at regulatory authorities and in the public eye)

w! Hypothesis

- The **primary inhibitors** are deemed to be the following aspects:
  - Landfill is still the largest competitor in feedstock supply
  - Perceptions dominate reluctance to finance and permit new facilities.
  - Business-as-usual funding practices place inhibiting burdens on investments

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The Renewable Fuel Standard (RFS)

The biogenic content of tire-derived-pyrolysis oil (TPO) should be compliant with the Renewable Fuel Standard (RFS)

Congressional Research Service
Informing the legislative debate since 1914

The Renewable Fuel Standard (RFS) compliance framework (https://www.epa.gov/renewable-fuel-standard-program/overview-renewable-fuel-standard) overseen by the EPA operates through a **tradable credit system**, where obligated entities (mainly refiners and importers) must submit renewable identification numbers (RINs) to match their annual renewable volume obligations (RVOs).

Targets set have not been met since 2014 because of under-production of advanced biofuels.

In the context of the RFS, the **biogenic content of TPO would need to meet the standards set by the EPA for renewable fuels**, ensuring that it contributes to reducing greenhouse gas emissions (e.g.by 50%).

For Contrast: The UK RTFO program increasingly dominates off-take in Europe

REACH registered and ISCC-certified TPO targets the UK market!

Biogenic content of TPO (38-55%) is recognized as “Development Fuel” (**RTFO**)

Off-takers in the UK pay sustainability premiums on top of the base price.

They account for up to 100% of the buy-out price.

dRTFCs are £1.60 per liter biogenic content, resulting in premiums of **USD 600 to 1,000 per ton.**

GOV.UK **RTFO Program**

Development Renewable Transport Fuel Certificates

Demand generated in **2025:**
~ 800,000 MT or 900 million liters

Premiums generated **2025**:
~ USD 1.2 billion

Observation

- **The RFS program appears to have low adherence with little consequence.**
- **There are no precedence cases for successful participation in the RFS program by US pyrolysis operations**
- **In contrast, the biogenic content of TPO has already been recognized as Development Fuel compliant with the RTFO in the UK, and as Renewable Fuel according to RED III in Europe.**
- **Since demand is much higher than supply, this represent a huge opportunity for TPO.**

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rCB classification is well on its way to becoming standardized

Clear classification schemes will provide clarity about rCB qualities

ASTM proposal for rCB classification

Particle Size, D97 [µm] WK71958	<7.5 1	>7.5 2	>12.5 3	>17.5 4	>22.5 5
Toluene Transmittance [%] D1618	<60 **1**	>60 **2**	>80 **3**		>95 **4**
Ash Content [%] D8474 or D1506	<12 **1**	12 to 17 **2**	17 to 25 **3**		>25 **4**
In-Rubber Surface Activity [-] D8491	< N660 **7**	N660 to N550 **6**			>N550 **5**

Example for a common rCB2 used in closed-loop applications.

According to the ASTM proposal, the classification number for rCB2 would be as follows:

P10T85A22-660 → P2T3A3S6 → R2336

Terminology currently in use

Char: often not intended to be upgraded for closed-loop applications

Raw rCB (rCB3*): a precursor for grinded rCB acc. ASTM 8178

rCB: freed from metals (steel) and properly milled, with typically semi-reinforcing properties (acc. ASTM 8178)

- **rCB1***: pelletized rCB class (free of contaminants, ash <22%)
- **rCB2***: same as rCB1 with one or more in-compliances
- **rCB0***: specialty rCB (post-treated, de-ashed)

rCB grade A, B, C, D: proposed classification by Michelin & Bridgestone

* Wolfersdorff Consulting, rCB classification scheme (Berlin, 2020)

Observations

The terms rCB2 and rCB are synonyms used for milled and pelletized rCBs that have proven their industrial suitability in tire rubber and MRG (etc.).

3 min

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Weibold at-a-glance

Weibold's unique position

weibold! at-a-glance

- 100% independent pure consultancy, no affiliation with any commercial entity
- Exclusive focus on tire waste stream since 1999
- Multilingual representation and clients in all major regions
- Team with broad skill level and hands-on experience in tire pyrolysis
- Consulting experience covers all aspects: technical, commercial, financial, environmental, regulatory, marketing, research, strategy development, macro-analysis, brokering, staffing, funding.
- Clients are from all supply chain stakeholders:
  - Entrepreneurs · private and public funding institutions · operators · manufacturers · intellectual property holders · technology suppliers · major off-takers · associations · regulatory agencies.
- Close and friendly cooperation with other (few) consultants in tire pyrolysis
- Trusted shepherd of deep proprietary and confidential trade information

Observation

We are uniquely positioned, because we

- are a truly global consultancy with offices on all continents
- have detailed quantitative data
- continuously provide technical, economic, and commercial analysis
- have access to real-time anecdotal information
- have been studying global environmental aspects and regulatory conditions

▶ **Our analysis and recommendations do not rely on publicly available market data.**

rCB is already substituting vCB in various applications, including tire rubber

ASTM standardization will accelerate this trend even further

Source: Enrestec Inc. - Presentation at Smither's Recovered Carbon Black Conference (2021 in Amsterdam)

Where does rCB go

- **rCB is compatible with various rubber types (EPDM, SBR, NR, NBR) matching the reinforcing properties of N550 and N660.**
- **Non-tire market**

  up to 100% vCB in MRG, plastic products, fiber threads, paints, and inks
- **Tire market**

  20-60% vCB in butyl liner, liner backing, sidewall, and cap tread with demonstrated benefits, such as:
  - lower modulus, higher fatigue resistance, and reduced hysteresis
  - maintains wear properties in treads
  - improves flex fatigue and sidewall performance
  - reduces the Payne effect and gas permeability in inner liners

Observation

Competition for rCB is growing sharply!

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Tire Upcycling Consulting Since 1999

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