Sustainable Composites for Hydrogen Delivery and Storage

Kevin L Simmons
Chief Materials Scientist, Pacific Northwest National Laboratory

Wenbin Kuang
Material Scientist, Pacific Northwest National Laboratory

Jinwen Zhang
Joint Appointee WSU/PNNL

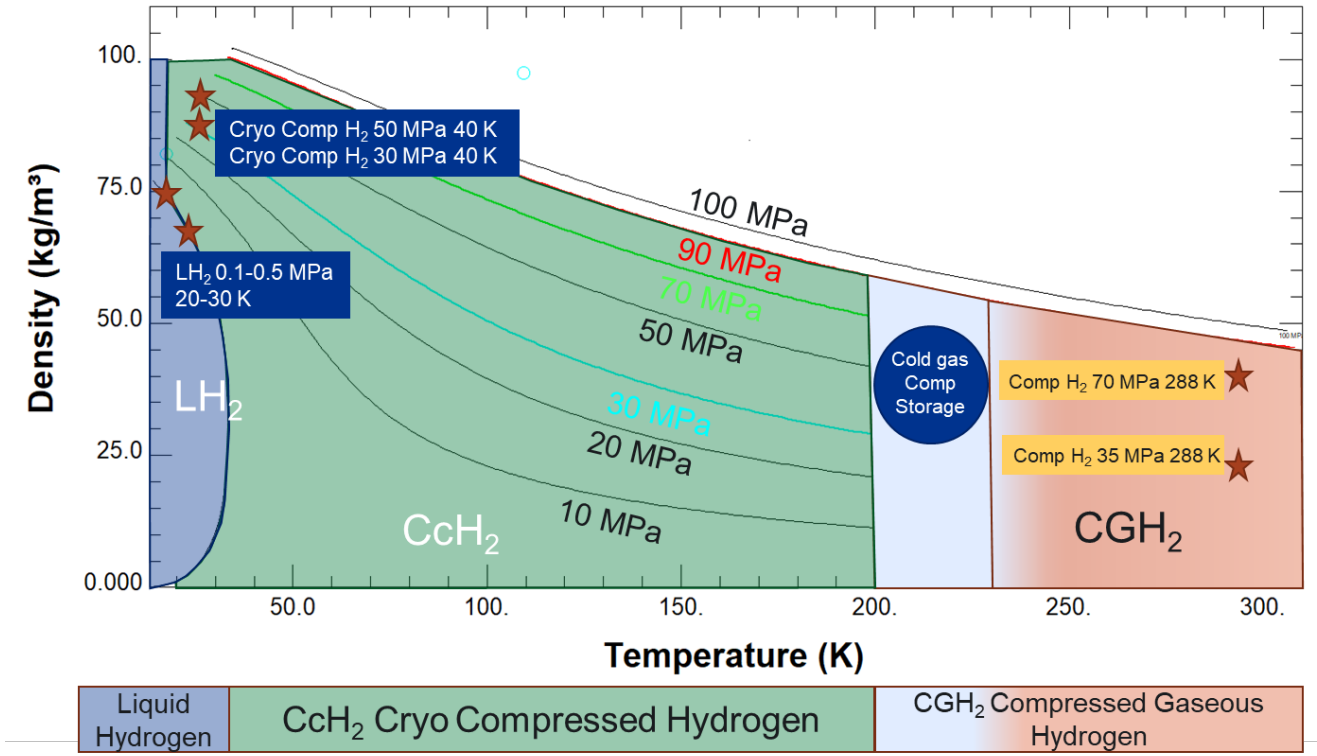
May 20-23, 2024
Long Beach, CA

sampe
Conference & Exhibition

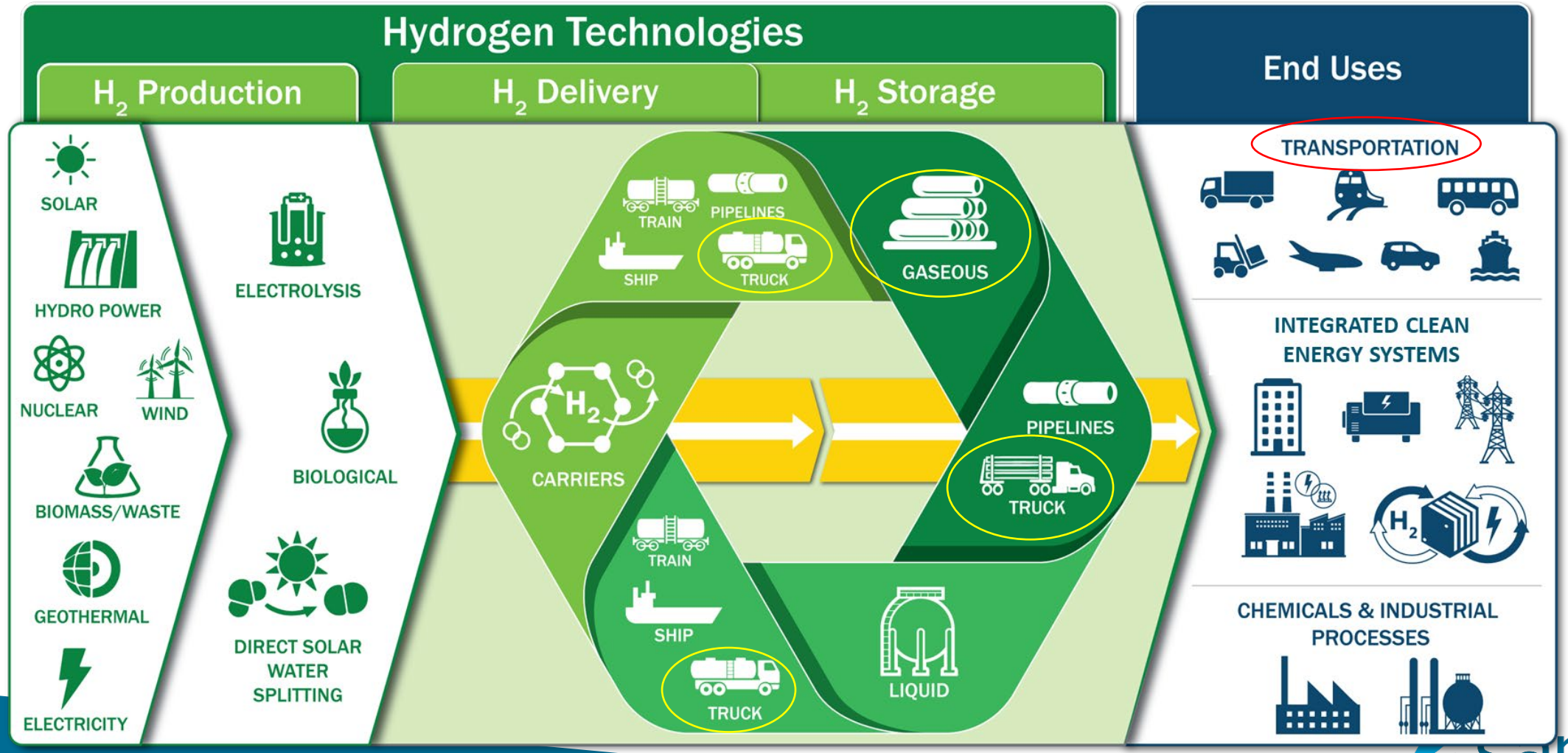
PNNL-SA-198495

Overview

- Hydrogen delivery, storage, and end use
  - Gaseous
  - Liquid carriers
  - Cryocompressed
  - Liquid hydrogen
- MD/HD on-board H_2 truck capacities
- Carbon fiber requirements for MD/HD storage
- Carbon fiber consumption for MD/HD
- Global carbon fiber supply
- Sustainability

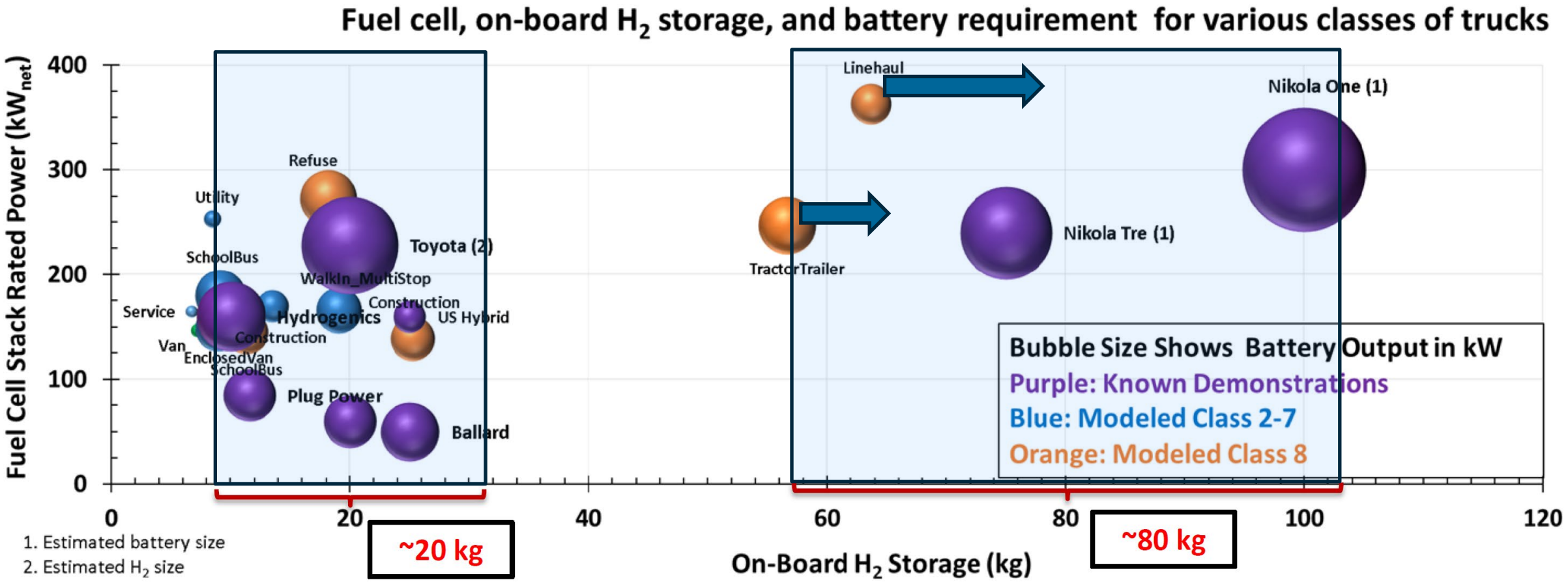


On-board Hydrogen Storage Overview



Source: Ned Stetson 2021 Annual Merit Review HFTO

MD/HD On-board Storage Capacities



https://www.hydrogen.energy.gov/pdfs/review19/st100_james_2019_o.pdf

Kenworth T680 FCEV

Current Tank Geometry
20” OD
80” Length
10 kg H2, 700 bar

Netting Analysis for Composite Calculations

Tank Internal Volume =	229.5	liters
Tank Composite Volume =	101.0	liters
Tank Composite Mass =	159.5	kg
Carbon Fiber Mass =	109.0	kg
Matrix Mass =	50.5	kg
Liner Mass =	12.2	kg
Total Mass =	171.7	kg

Next Gen Tank Geometry
27” OD
80” Length
21 kg H2, 700 bar

Netting Analysis for Composite Calculations

Tank Internal Volume =	513.8	liters
Tank Composite Volume =	223.2	liters
Tank Composite Mass =	352.6	kg
Carbon Fiber Mass =	241.0	kg
Matrix Mass =	111.6	kg
Liner Mass =	19.0	kg
Total Mass =	371.6	kg

Annual Truck Production Levels

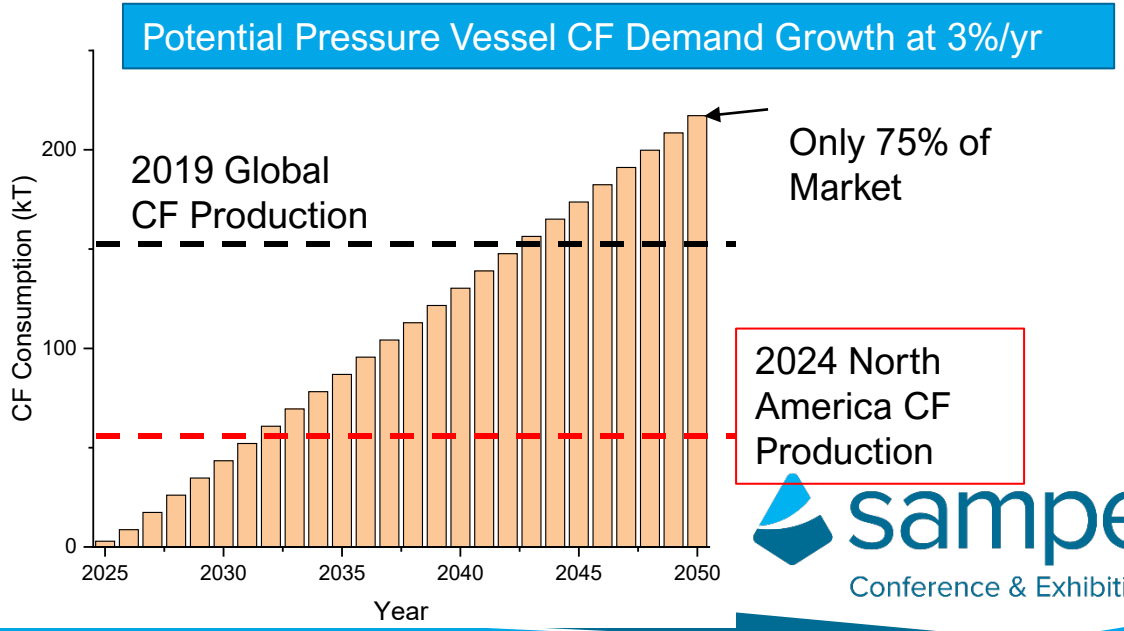
https://www.nada.org/media/5008/download?inline

Year	Class 4		Class 5	Class 6	Class 7		Class 8		Total
2019	21,892		84,754	77,629	66,469		276,348		527,092
2020	21,783		93,081	52,213	50,676		191,900		409,653
2021	28,428		101,770	61,487	48,018		221,889		461,592
2022	24,003		79,960	71,998	45,873		254,206		476,040
On-board req per Max Range	24 kg		19 kg	31 kg	25 kg		60-100 kg based on vocation		
Number of tanks (based on 10 kg/tank at 700 bar) assume 1 kg CF/kg H2	2	3	2	3	2	3	6	8	
Composite requirement (kg)	319	478.5	319	478.5	319	478.5	1343	1652	
Carbon Fiber (kg)	218	327	218	327	218	327	918	1136	
Ave. annual CF production requirement (kT)	5	8	17	26	10	15	233	289	
Annual resin requirement (kg)	2	4	8	7	5	7	26	39	
Number of tanks annually									
1% penetration	480	720	1,599	2,160	917	1,376	15,252	20,336	
3%	1,440	2,160	4,798	6,480	2,752	4,129	45,757	61,009	
6%	2,880	4,321	9,595	12,960	5,505	8,257	91,514	122,019	

CF Consumption Impact on the Market

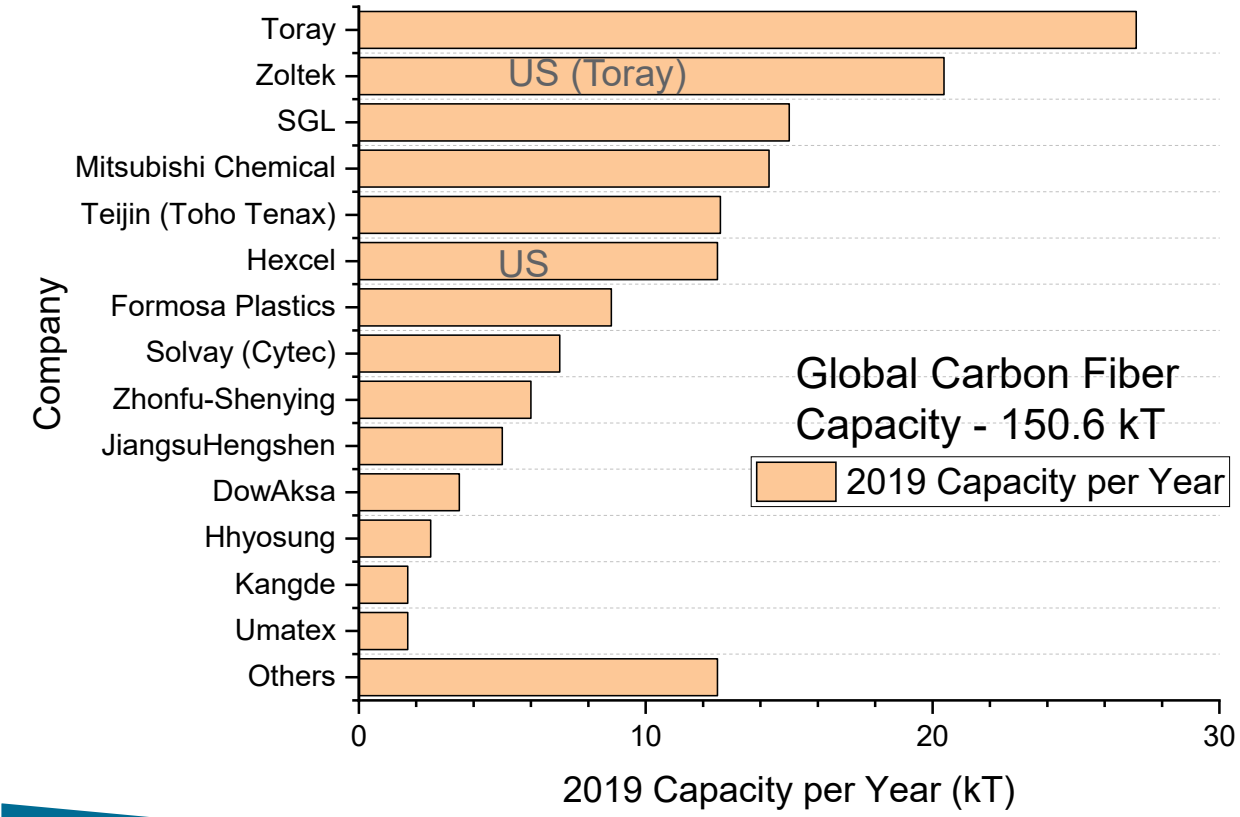
		Market Penetration/yr	Class 4 2 tank (kg)	Class 5 2 tank (kg)	Class 6 3 tank (kg)	Class 7 2 tank (kg)	Class 8 6 tank (kg)	Total CF Production Required (kg)	T/yr	kT/yr
2025	Year 1	1%	52,327	174,313	235,433	100,003	2,333,611	2,895,687	2,896	3
2026	Year 2	3%	156,980	522,938	706,300	300,009	7,000,833	8,687,061	8,687	9
2027	Year 3	6%	313,959	1,045,877	1,412,601	600,019	14,001,666	17,374,122	17,374	17
2030	Year 5	15%	784,898	2,614,692	3,531,502	1,500,047	35,004,166	43,435,305	43,435	43
2035	Year 10	30%	1,569,796	5,229,384	7,063,004	3,000,094	70,008,332	86,870,611	86,871	87

COMPANY	COUNTRY	PRODUCTION CAPACITY (KT/YEAR)	MARKET SHARE (%)
Toray	Japan	27,1	17,99
Zoltek (Toray)	USA	20,4	13,55
SGL Carbon	Germany	15	9,96
Mitsubishi Chemical	Japan	14,3	9,50
Teijin (TohoTenax)	Japan	12,6	8,37
Hexcel	USA	12,5	8,30
Formosa Plastics	China	8,8	5,84
Solvay (Cytec)	Belgium	7	4,65
Zhongfu-Shenying	China	6	3,98
JiangsuHengshen	China	5	3,32
DowAksa	Turkey	3,5	2,32
Hhyosung	South Korea	2,5	1,66
Kangde	China	1,7	1,13
Umatex	Russia	1,7	1,13
Others - total	----	12,5	8,30
Total		**150,6**	

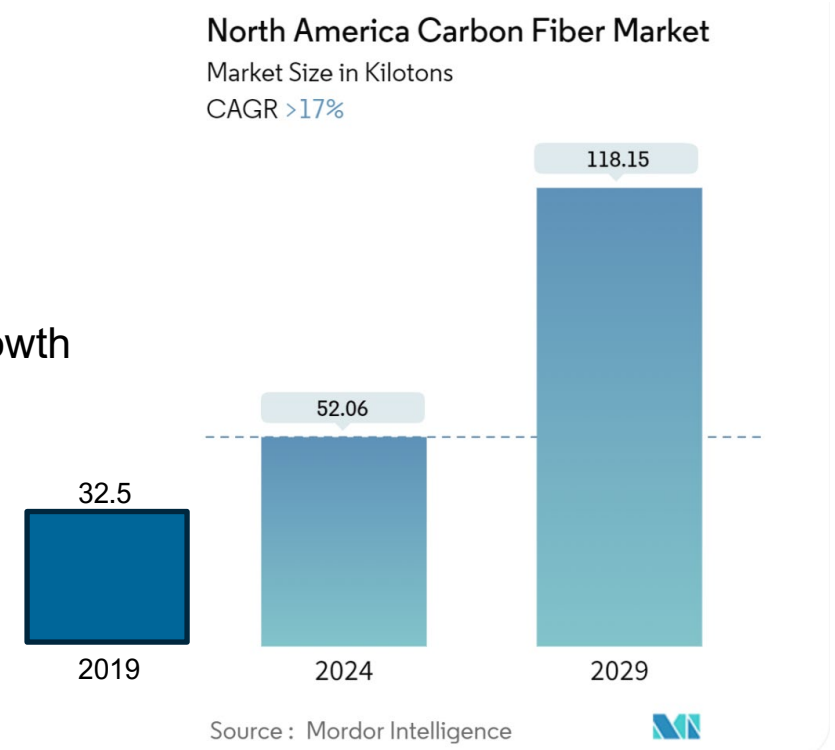


sampe Conference & Exhibition

Global Carbon Fiber Capacity by Company



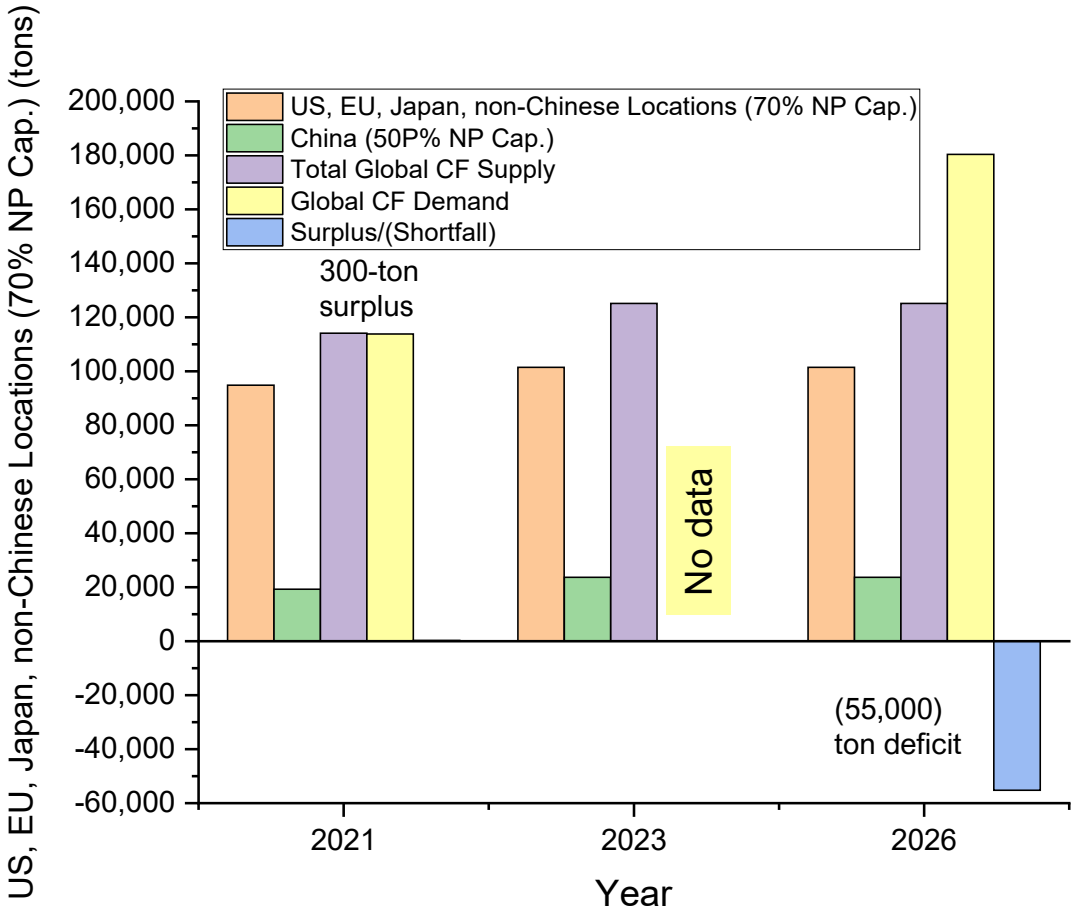
Projected Growth

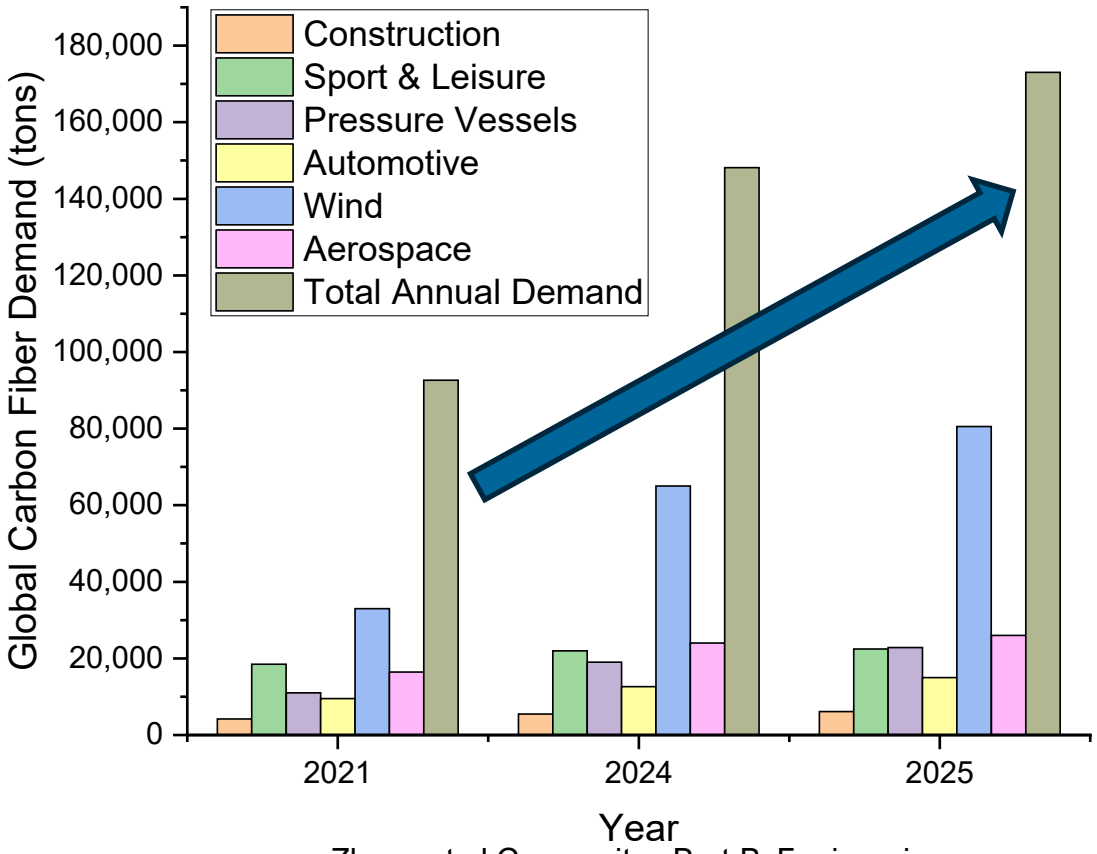


Data from https://www.igtpan.com/Ingles/mercado-carbono.asp

sampe Conference & Exhibition

Global CF Supply





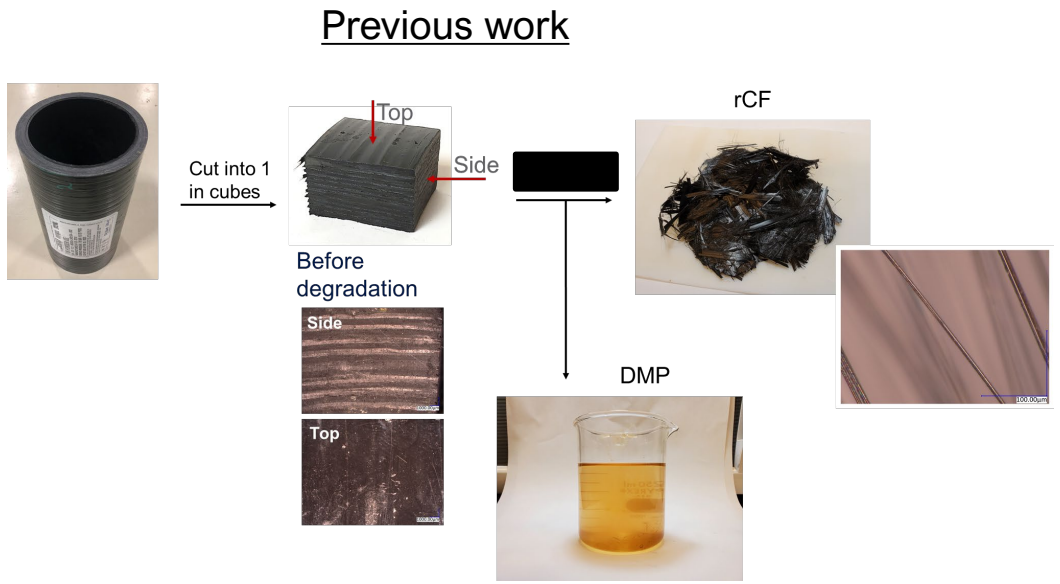
CF Shortfall due to growing demand

Zhang et al Composites Part B: Engineering Volume 250, 1 February 2023, 110463

https://www.compositesworld.com/articles/the-outlook-for-carbon-fiber-supply-and-demand

The Need for End-of-Life Recycling

- **Objectives:**
  - Develop a scalable solution to addressing the needs for effective recycling of COPV at EOL.
  - Retain >90% mechanical properties and original length of the reclaimed carbon fibers
  - Recover >90 wt.% resin from COPV and study the practicality of reusing the resin for new composites/pressure vessels



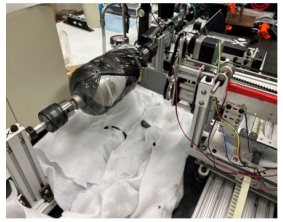
Targets	Embodied Energy (MJ/kg)	Green-house-gas Emission (CO2/kg)	Mechanical property retention	Fiber length retention	Resin recovery (composite)	Resin reuse (composite)
Virgin CF	286-704	24-31	-	-	0% (pyrolysis)	0%
Reclaimed CF	52.48	3.1	>90%	>90%	>90%	>15%

Demonstration of COPV Recycling

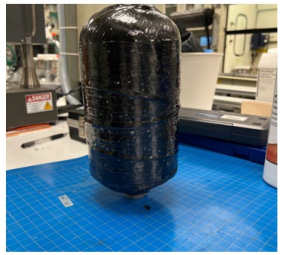
Continuous CF opens up new reuse opportunities and prolongs the value of CF

Tank winding using X-winder

Winding Process




Post Cure




Solvolysis process to degrade resin

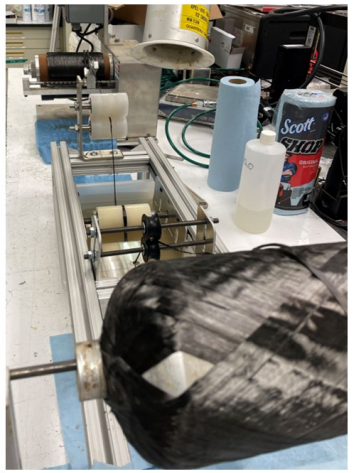
Vessel Removed from Chamber

End of Vessel After Removal

Minimal Fiber Fraying on Vessel

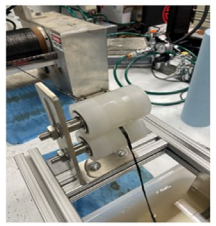
Vessel Soaking after Resin Removal

Unwind and reclaim CF



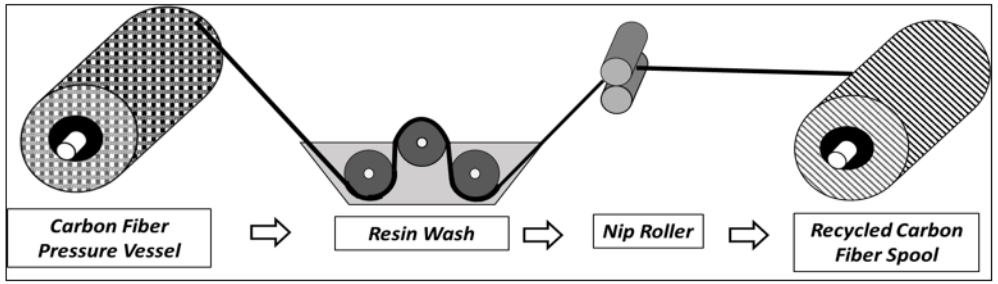
Overview of Functional Unwinding Process





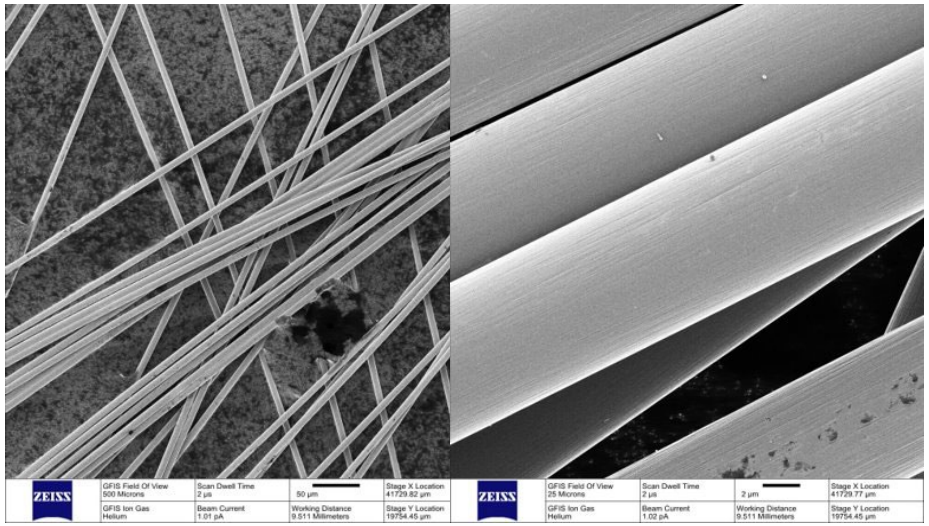
Pressure Vessel Mounted → Resin Wash → Nip Rollers → Rewound Recycled Fibers → Recycled Carbon Fiber Spool

Carbon Fiber Pressure Vessel Unwinding Process

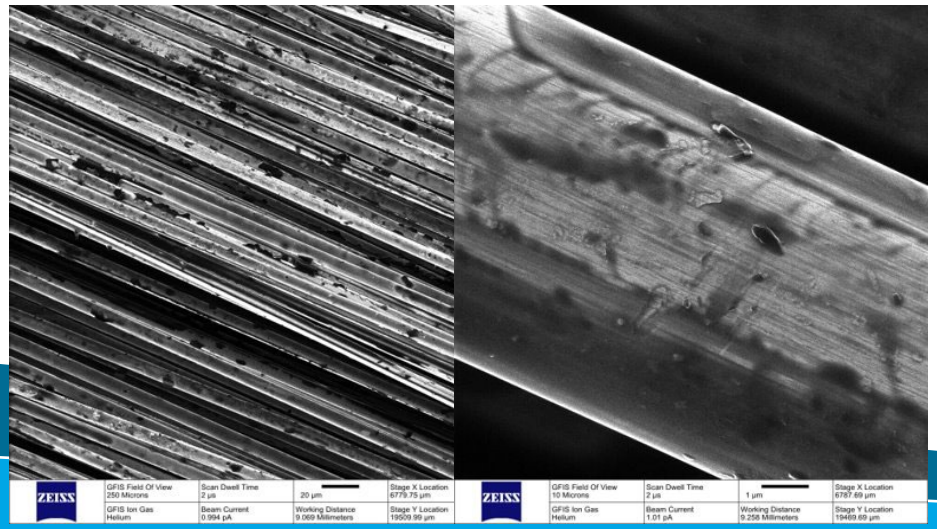


Fiber Surface Characterization and Strand Tests

Virgin CF



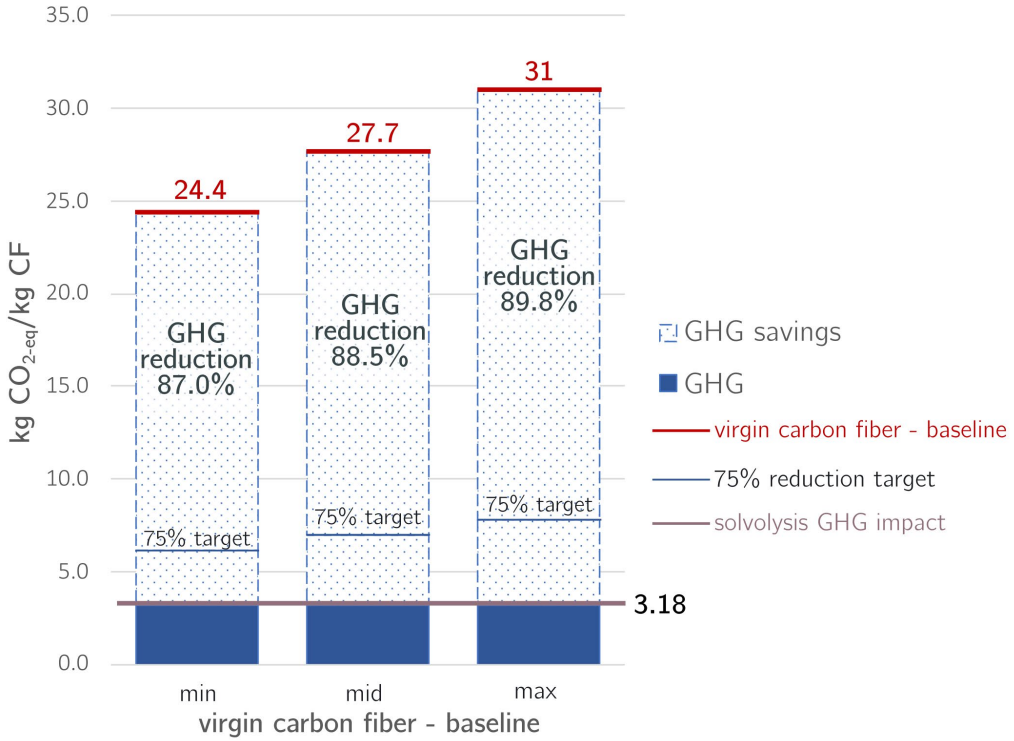
Reclaimed CF



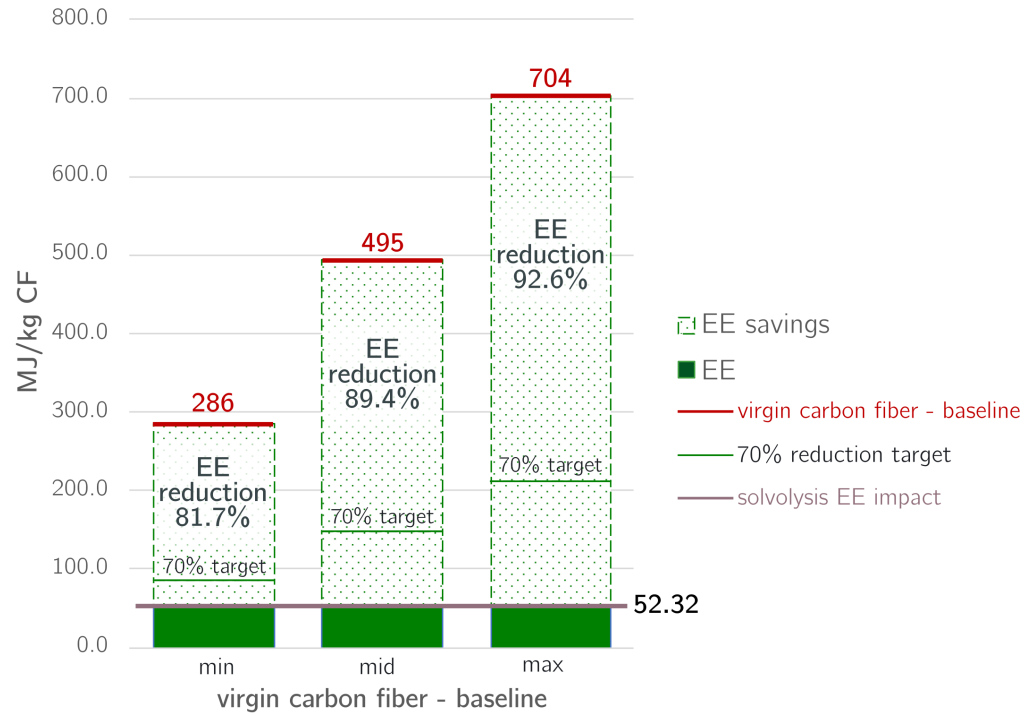
- No surface damages imparted on CF during recycling
  - Post-process washing improvement
- Reclaimed fibers retained ~90% tensile strength
  - 10% loss likely resulted from post-process handling
- Reclaimed fiber modulus shows no loss

Life Cycle Analysis of Solvolysis Recycling

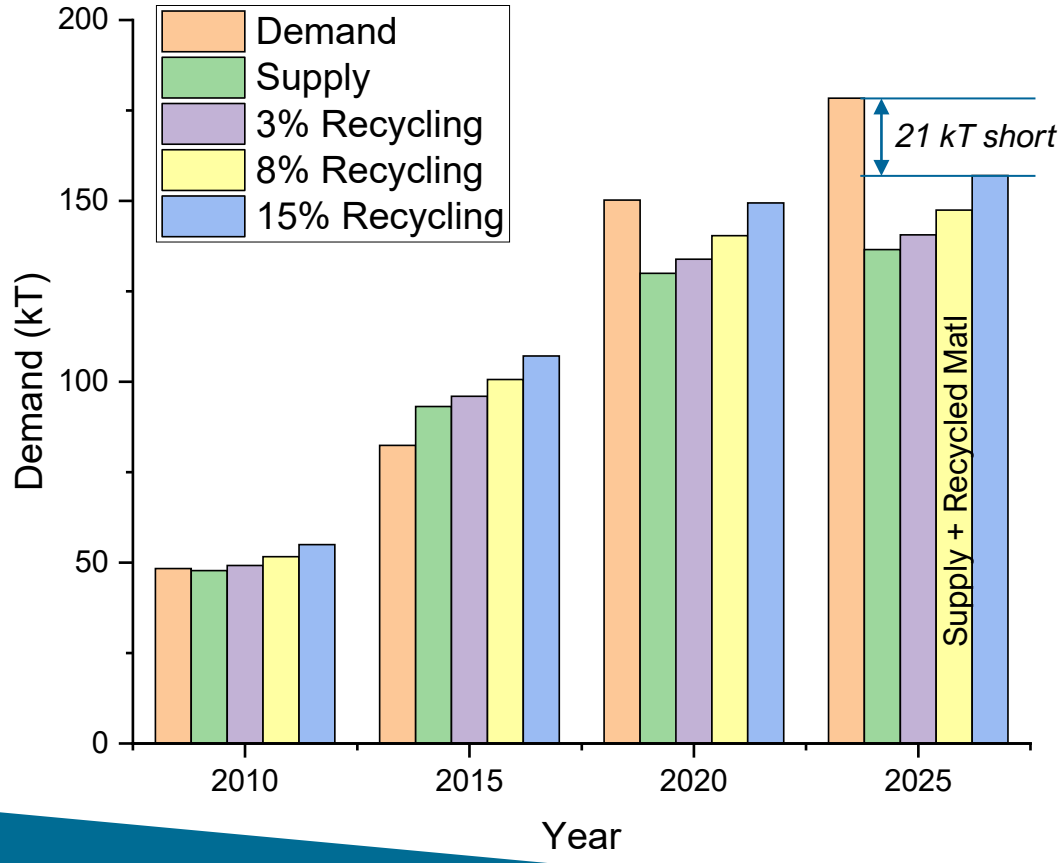
- ***75% GHG emission reduction target***
- GHG emissions from recycled process:
  - 3.18 kg CO2-eq/kg CF
  - reductions: 87.0% to 89.8% via solvolysis



- ***70% EE reduction target***
- Embodied energy from recycled process:
  - 52.32 MJ/kg CF
  - reductions: 81.7% to 92.6% via solvolysis

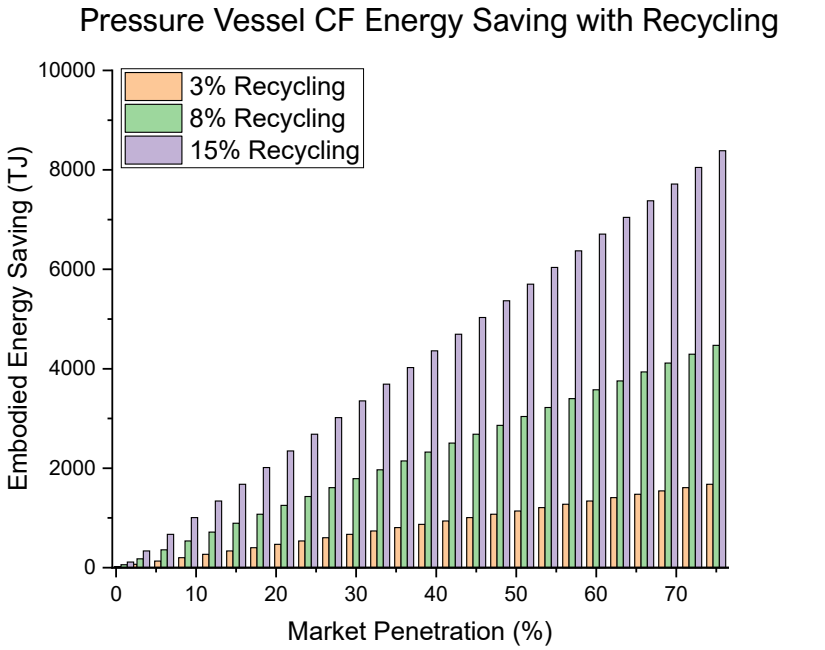


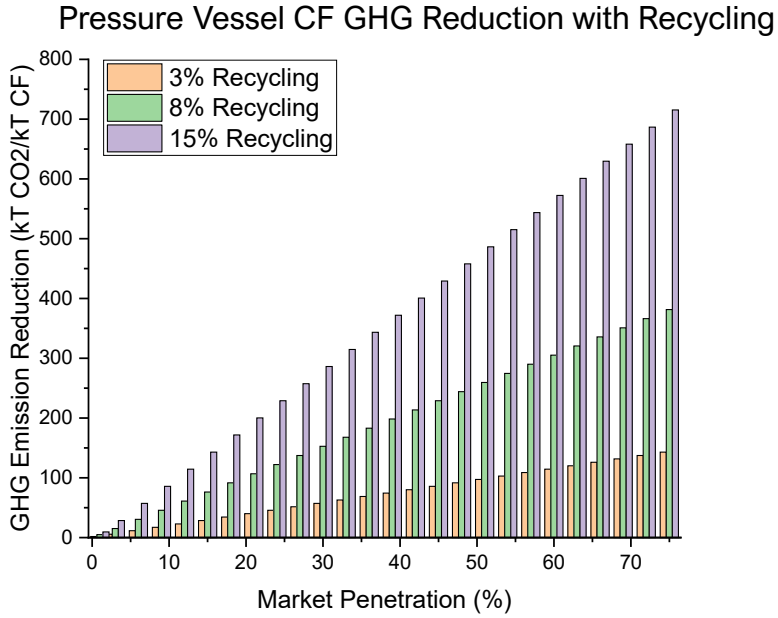
Recycling Impact on Pressure Vessel Energy and GHG



A 15% market penetration and a 15% recycling rate of global supply saves:

- 1800 TJ of Energy savings
- 150 kT CO2/kT CF





Summary

- Class 4 – 7 ranges of 20-30 kg of on-board storage requiring two to three 10 kg storage tanks with 220 to 330 kg of CF per vehicle
- Class 4-7 truck sales in 2022 were ~ 220K and with an 8.2 kT/yr demand at a 15% market penetration in 5 years
- Class 8 trucks require storage for up to 100 kg depending on vocation
- Class 8 trucks require six to eight tanks with a total 920 to 1140 kg of CF per vehicle
- Class 8 truck sales in 2022 were ~ 254K and with an 35 kT/yr demand at a 15% market penetration in 5 years with a six tank configuration
- Global carbon fiber supply in a 2019 was 150.6 kT/yr and 2024 North America production was only 52 kT in 2024 and with a growth of 17% is expected to reach 118 kT/yr
- With current supply and future demand, there is anticipated to be a 55 kT shortfall
- Future outlook with pressure vessel growth potential for MD/HD truck out paces the global and North America supply
- Sustainability in carbon fiber recovery allows for offsetting virgin CF demand and reduces energy consumption and green house gas emissions by nearly 90%

Acknowledgements

This work was fully supported by the U.S. Department of Energy (USDOE), Office of Energy Efficiency and Renewable Energy (EERE), Fuel Cell Technologies Office (FCTO) under Contract Number DE-AC05-76RL01830. We also acknowledge support from the Environmental Molecular Sciences Laboratory (EMSL). EMSL is a national scientific user facility sponsored by the Department of Energy's Office of Science, Biological and Environmental Research program that is located at Pacific Northwest National Laboratory.

A special thank you to Dilara Goreke and Francesca Pierobon for the Life-Cycle Analysis.