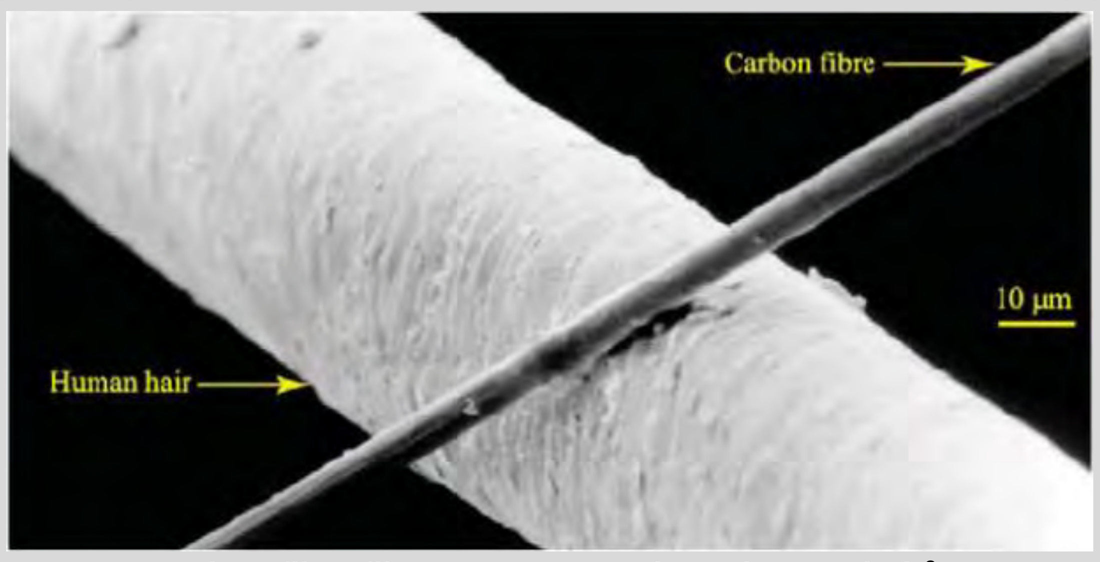
Shale Gas to Carbon Fiber - A Cleaner Pathway from Fossil Fuels to the Hydrogen-Carbon Economy

Bhumika Sule and Razi Nalim

ELEMENTAL CARBON: VERSATILE AND VARIABLE VALUE

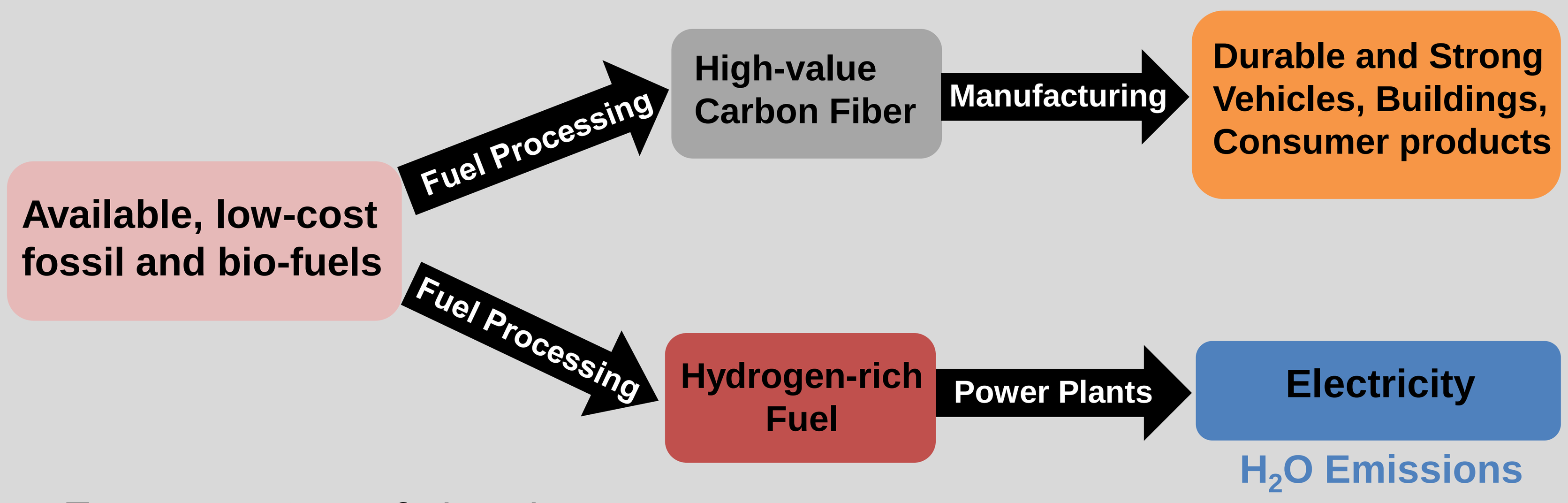
Elemental carbon form (and comparables)	Bulk Price in ~US$ per kg	Global Consumption (metric tons /year)	Global CO2 emissions from fuel combustion (metric tons /year)
Coal	$0.04	7,900,000,000	***33,000,000,000***
Carbon black	$1	13,200,000	***Total CO_2 emissions from fossil fuel** (coal, oil and natural gas) **combustion***
Natural graphite	$0.9	1,100,000	
Carbon fiber[1]	**$22-30**	**110,000**	
Graphene	$100,000	~20,000	
C nanotubes	$400,000	2,300	
Diamond ½ carat	$7,000,000	~20	
Steel	*$0.6*	*1,800,000,000*	
Natural gas	*$0.2*	*3,000,000,000*	
Crude oil	*$0.4*	*4,000,000,000*	

Great potential to expand market for structural materials based on Carbon Fibers (CFs) to replace steel and aluminum for large-volume applications

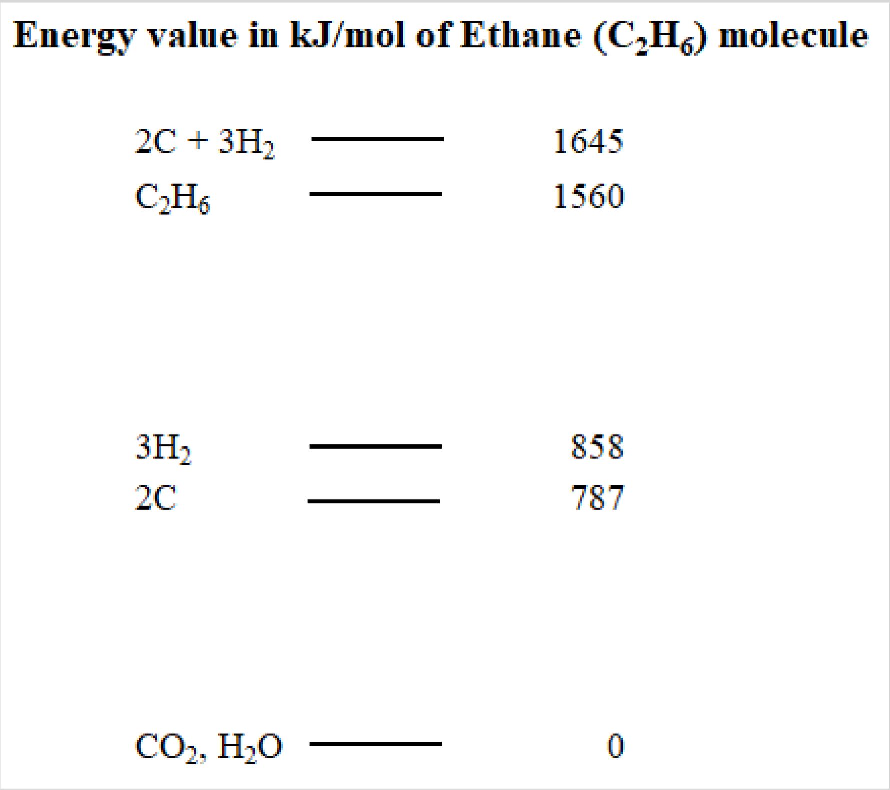


Carbon fiber filament compared to a human hair[2]

CARBON is too valuable to oxidize
CARBON is too dangerous when oxidized
The Hydrogen – Carbon Economy



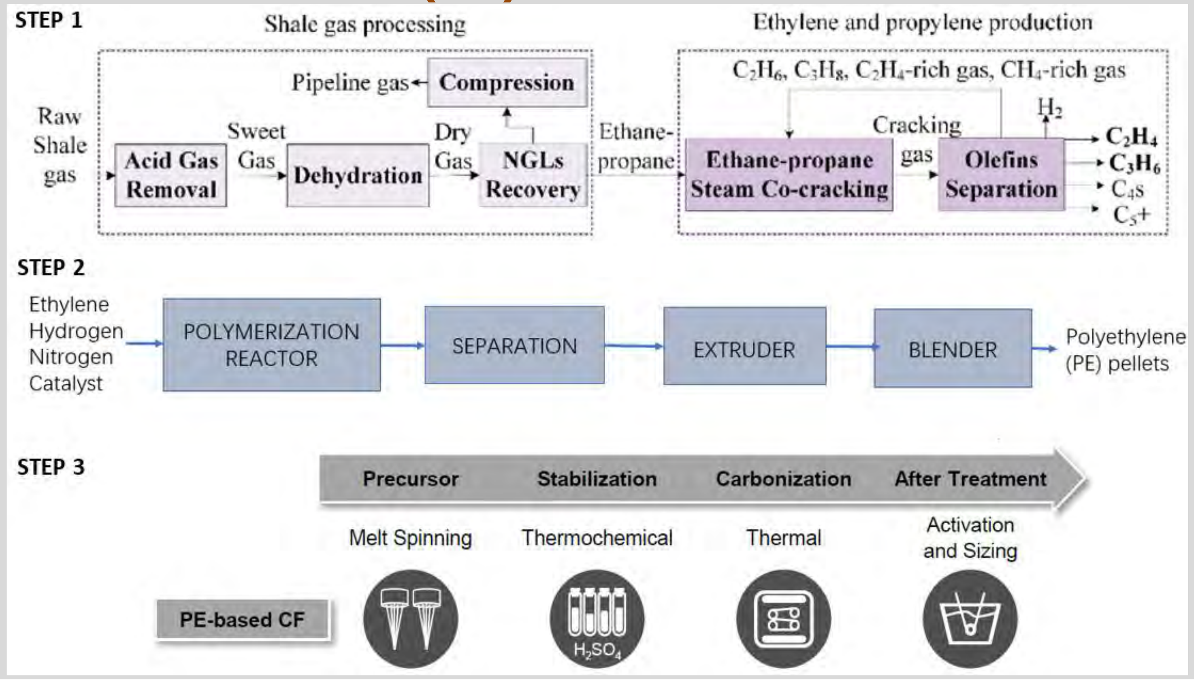
- Energy content of abundant gaseous fuels (natural gas/shale gas) is shared by its hydrogen and carbon constituents
- Ideally, ~50% of the energy of hydrocarbon feedstocks can be converted to H_2, sequestering C as **high-value carbon products**, minimizing CO_2 emissions
- **CO_2, like H_2O has no useful energy content**
- *Capturing and converting CO_2 to fuel or something useful takes more energy than obtained by burning C*
- **Stop burning CARBON**



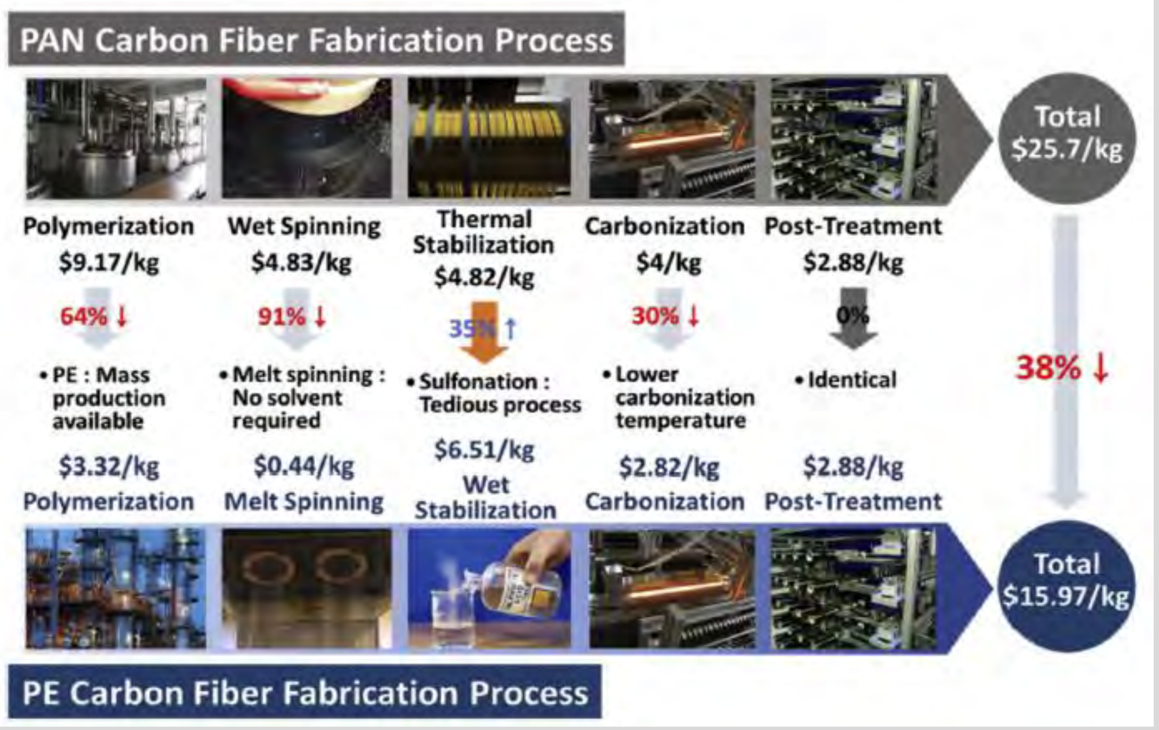
POLYETHYLENE AS CARBON FIBER PRECURSOR

- PE - Low price and abundant supply
- PE is ~$0.6/lb compared to ~$5/lb for PAN precursor
- Carbon content of PE is ~86% and exhibits high carbonization yield of ~70% after sulfonation[5]

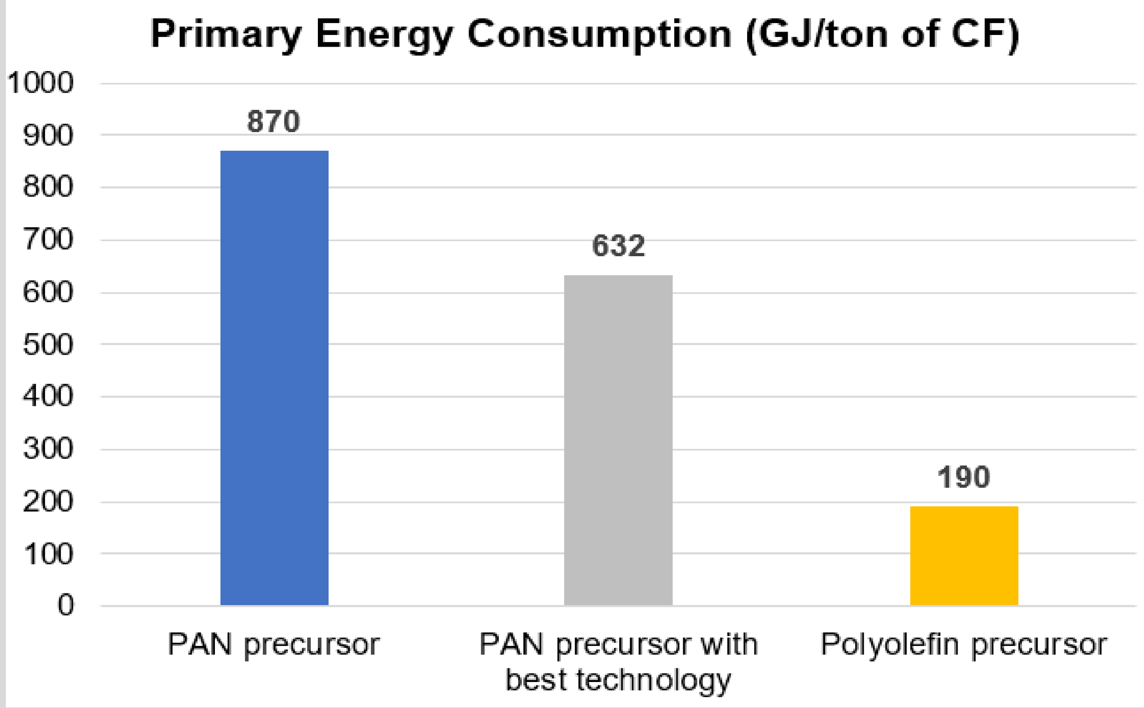
SHALE GAS → ETHANE → ETHYLENE → POLYETHYLENE(PE) → CARBON FIBER



CF COST WITH PE vs PAN, AT CURRENT PRODUCTION RATES[6]

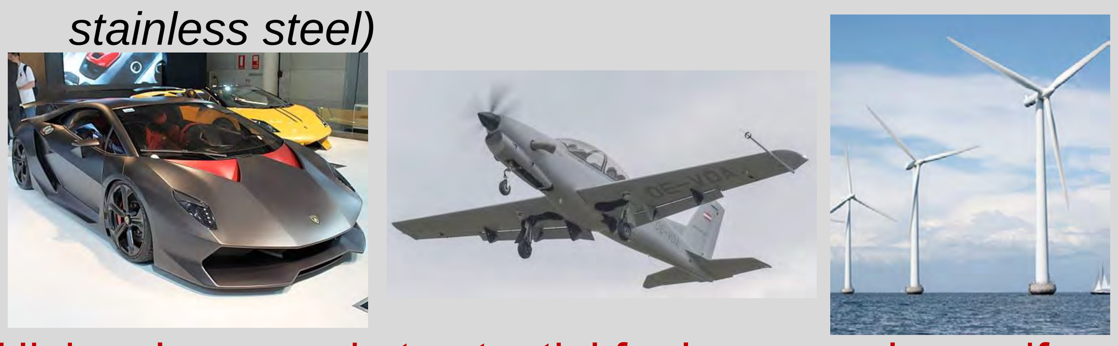


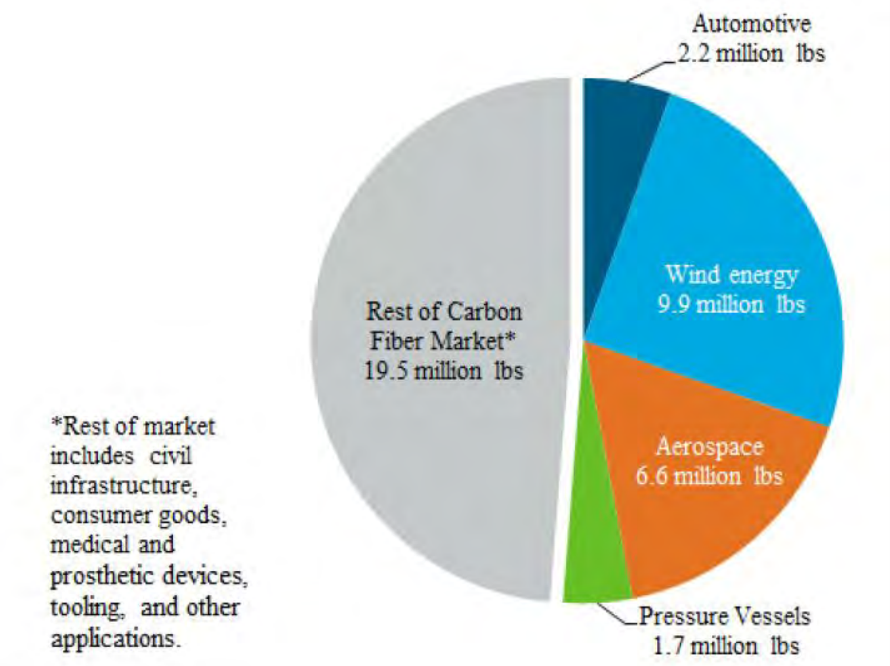
ENERGY INTENSITIES of PAN-based AND PE-based PROCESSES[3]



CARBON FIBER PROPERTIES AND APPLICATIONS

- Exceptional properties as a lightweight structural material
  - **High tensile strength, High tensile modulus**
  - **Low density**
  - High temperature tolerance
  - High chemical/corrosion resistance
- *Tensile specific strength ~2.5 MN-m/kg (30 x stainless steel)*





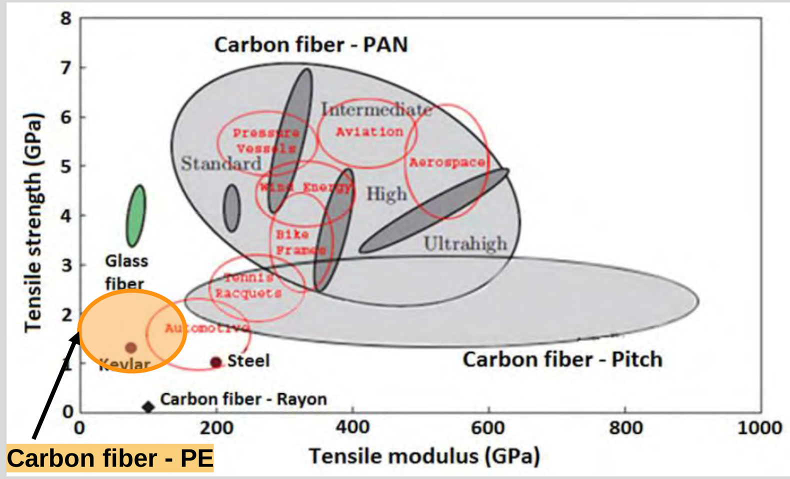
Carbon fiber market in USA in 2010[3]

High-volume market potential for larger-scale use if cost is reduced: **Automotive, Infrastructure, buildings, machines**

CF PROPERTIES WITH PRECURSOR VARIATION

- **PRECURSORS -** Petroleum-derived polyacrylonitrile (PAN), rayon from regenerated wood cellulose, petroleum pitch
- **Greater than 90% CF annual production is PAN-based due to high fiber quality**

Automotive CF requirements could be met with cheaper precursors



Carbon fiber properties for different applications[4]

CHALLENGES IN PRODUCTION OF PE-based CARBON FIBER

- High temperature sulfonation process - Generates toxic SOx fumes
- PE-based CF has inferior properties as compared to PAN-based CF
  - Not suitable for aerospace or pressure vessel applications
  - CF with high tensile strength (~4900 MPa) and moderate modulus (~230 GPa) is required for pressure vessel applications[7]
  - Would be adequate for automotive, construction, other structural applications
- Better design processes required for developing stronger fibers from PE

CONCLUSIONS

- High potential for vastly expanded structural use of CFs in automotive, buildings, infrastructure
- Limited by expense of processes and polymer precursors
- Economic viability of use of PE precursors for CFs is helped by shale gas as an abundant fuel
- Energy intensity for the processes can be reduced by improving process efficiencies and waste energy recovery, use of recycled carbon fiber
- Low weight and high tensile specific strength of CFs would provide net benefit in lifecycle energy use and reduced CO_2 emissions for aircrafts, automobiles
- R&D of PE-based CFs - Potential for a revolution in manufacturing due to the availability of low-cost, light-weight and immensely strong structural material for large volume applications which can also sequester carbon in valuable form

REFERENCES

[1] C. D. Warren, "Carbon Fiber Precursors and Conversion", presentation by Oak Ridge National Laboratory (ORNL)
[2] Liu et al., Polymers 2015,7, 2078–2099
[3] Energetics Incorporated: Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in the Manufacturing of Lightweight Materials: Carbon Fiber Reinforced Polymer Composites, Sept 2017
[4] Adapted from Chung et al., DOE FCTO Annual Progress Report 2018
[5] Liu & Kumar, Polymer Reviews, 52(3), 2012, 234-258
[6] Choi et al., Carbon 142, 2019, 610-649
[7] DOE Office of Energy Efficiency and Renewable Energy, H2@Scale New Markets FOA, DE-FOA-0002229

IUPUI
SCHOOL OF ENGINEERING AND TECHNOLOGY
INDIANA UNIVERSITY–PURDUE UNIVERSITY
Indianapolis