Recycling of Carbon Dioxide – A Green Chemistry

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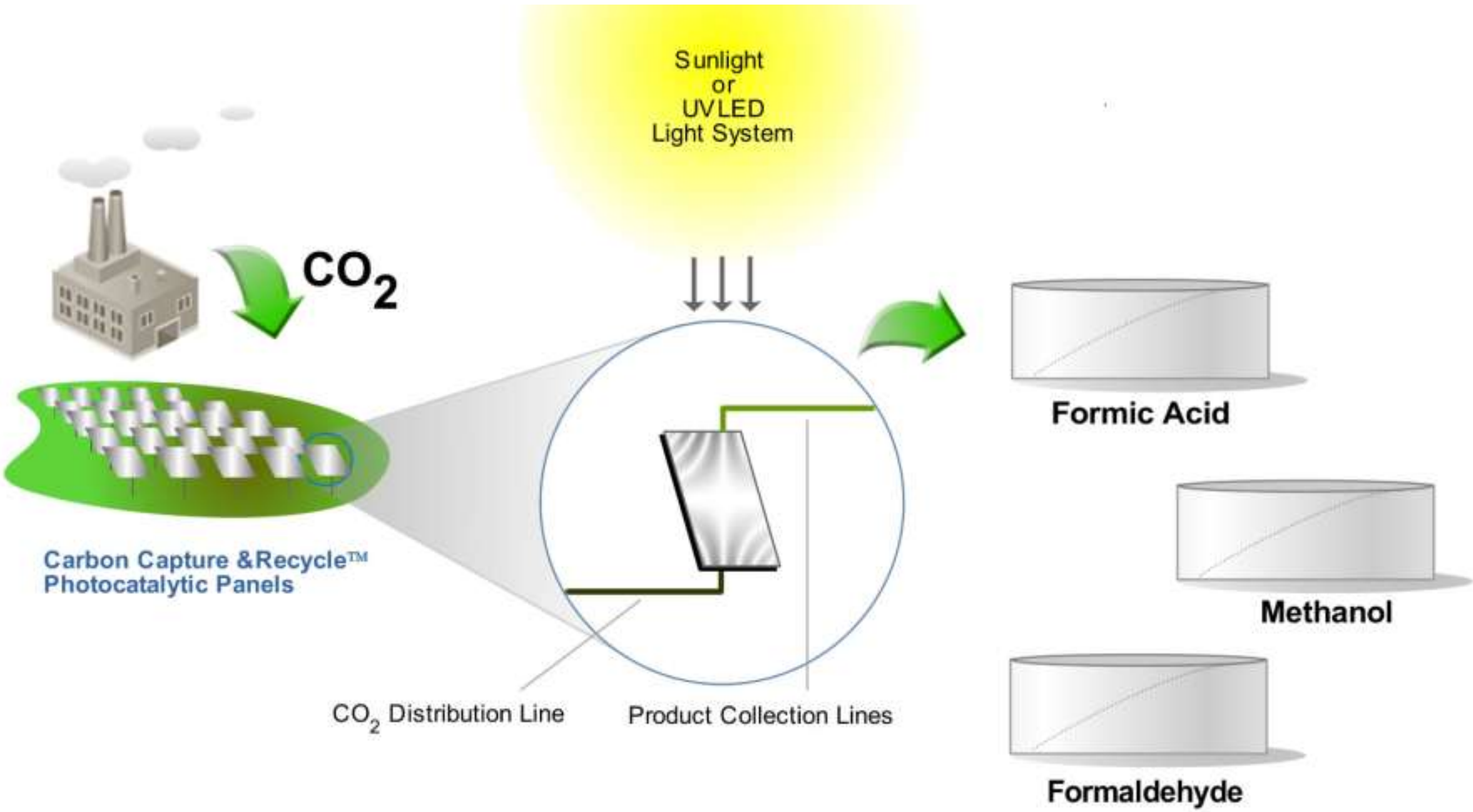
Concept – "Green" Synthesis



CO_2 + H_2O + UV light + photocatalyst = valuable product

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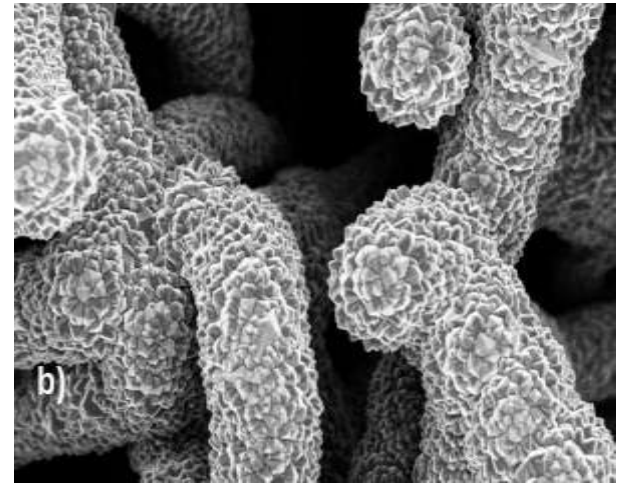
Advantages

- Continuous flow process
- Tunable byproducts
  - Formic acid
  - Formaldehyde
  - Methanol
- Utilization of solar power
- Lower parasitic load
- Reduce storage burden
- Fewer CO_2 pipelines



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Opportunity

Chemical	Production (million metric tons)	Price per metric ton (U.S. $)	Revenues (Million $)
Methanol	46.0	345	15,870
Formic Acid	0.6	1,450	870
Formaldehyde	32.5	350	11,375

2012 Predictions: Global Industry Analysts, Inc

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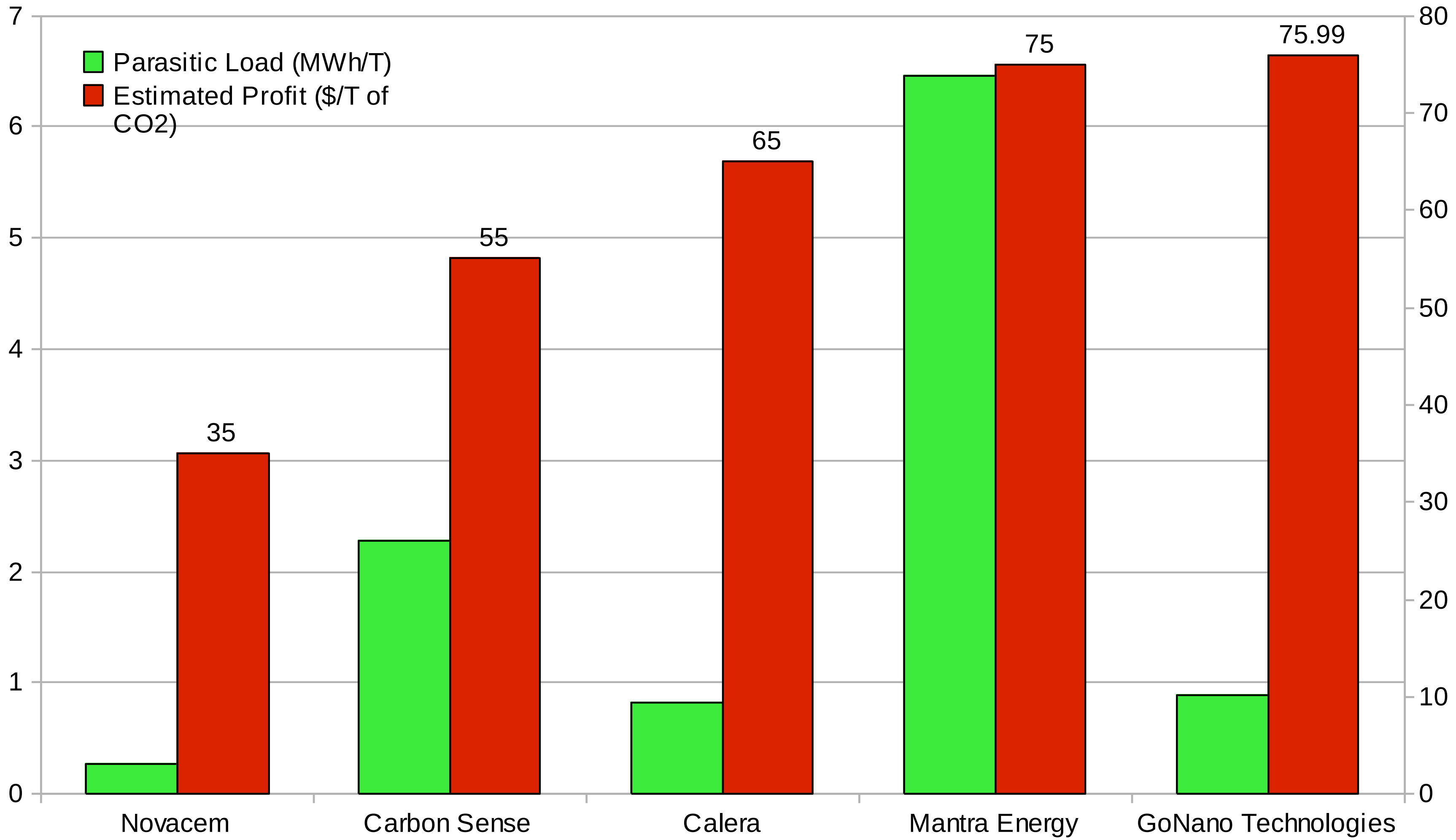
A Compelling Approach



Carbon Utilization Technologies Comparison

15% conversion ; 20 sccm flow rate; tuning 52% formaldehyde, 44% formic acid and 4% methanol

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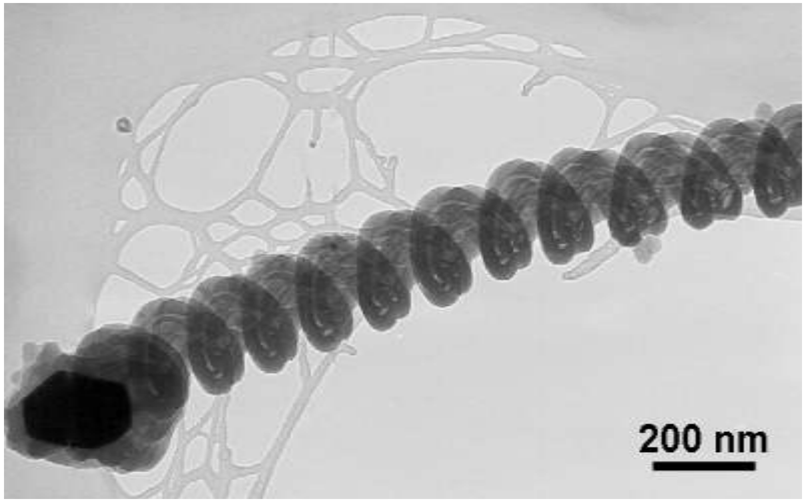
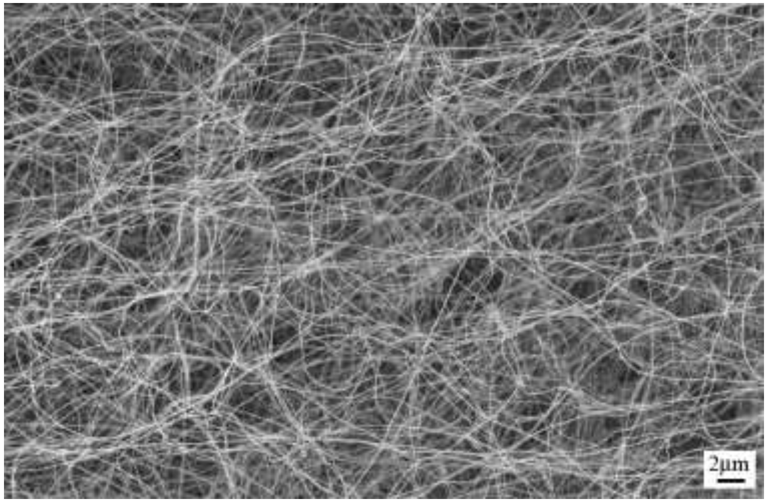
Technology Platform

Silica Nanosprings™



An individual SiO_2 Nanospring



A mat of Nanosprings

Advantages of Nanosprings:
- Low growth temperature (< 350° C)
- Atmospheric pressure process
- Mat thickness 3 – 300μm
- Hydrophilic
- 100% accessible surface area (>350m^2/g)
- Easy to functionalize, e.g., using silane chemistry

Substrate Flexibility:
- Aluminum foil
- Glass (including Pyrex®)
- Ceramics
- Fiberglass
- Silica beads
- Stainless steel
- High T_g polymers

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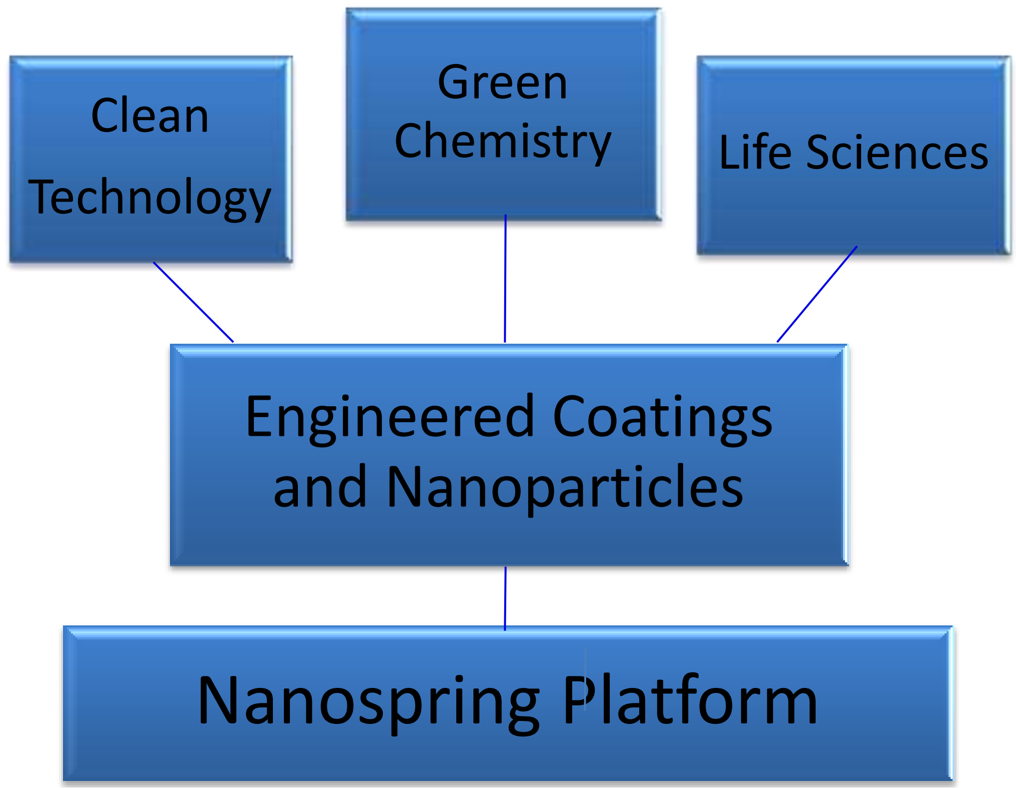
Multiple Applications

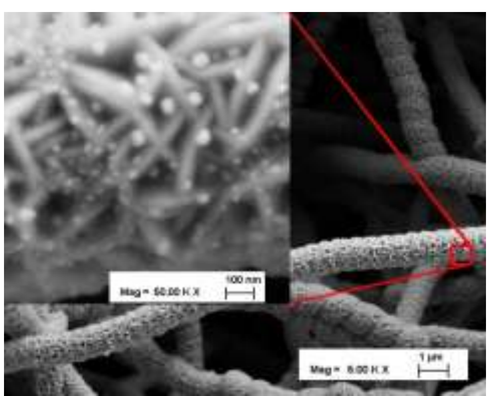
Emerging Opportunities with Partners

- Advanced Composites
- Hydrogen Storage
- Ultracapacitors
- Biological and Chemical Sensors
- Energy Generation and Storage



Internal Focus Areas

- Continuous Flow Chemistry
- Catalytic Converters
- Carbon Capture & Recycle



Cu-ZnO nanoparticle catalyst on Nanospring

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High Efficiency Photocatalyst

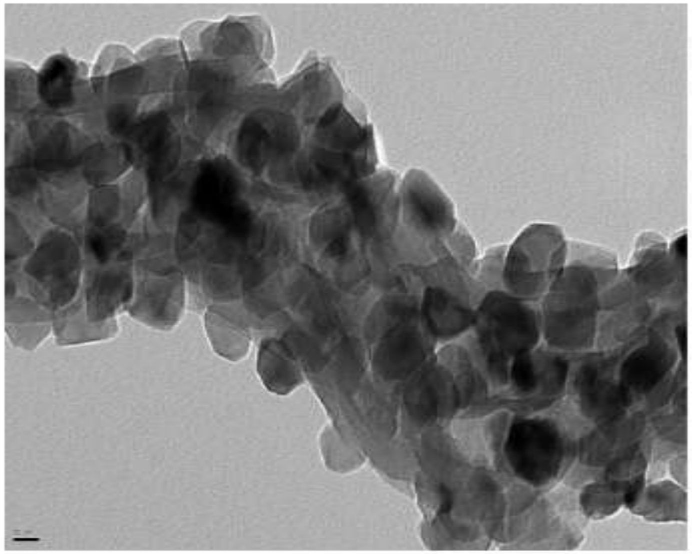
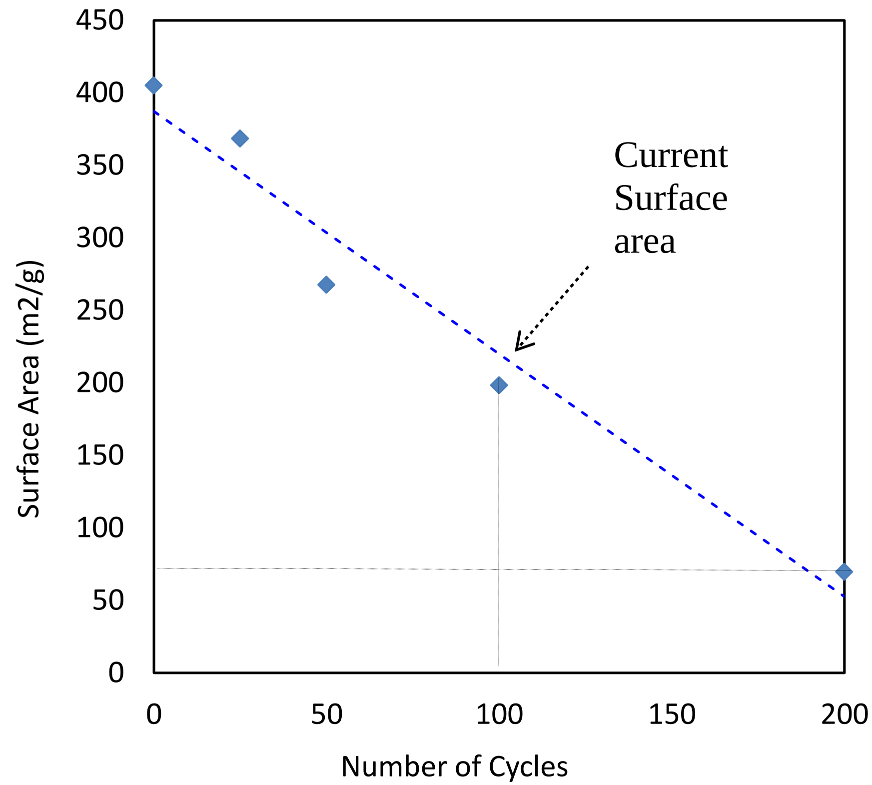


Image of TiO_2 particles on a Nanospring



BET surface area measurements

- High surface area (350 m^2/g) catalyst support
- Controlled TiO_2 particle size by ALD coating
- Four times the surface area of Degussa P25 particles
- 100% accessible surface area due to inverse porosity
- Conversion efficiencies up to 30% (to date)
- Product yields about 1,000 greater than P25

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A Green Chemistry Approach for Hydrogen

$CO_2 \rightarrow$ Formic Acid $\rightarrow H_2$

FA to H_2 see: Boddien, A., *et al* (2011) *Science* **333**, 1733

$CH_4 + CO_2 \rightarrow CO + H_2$

Photocatalytic conversion using Ga_2O_3 at mild conditions, see:
Yuliati, L., *et al* (2008) *Chem. Phys. Lett.* **452**, 178