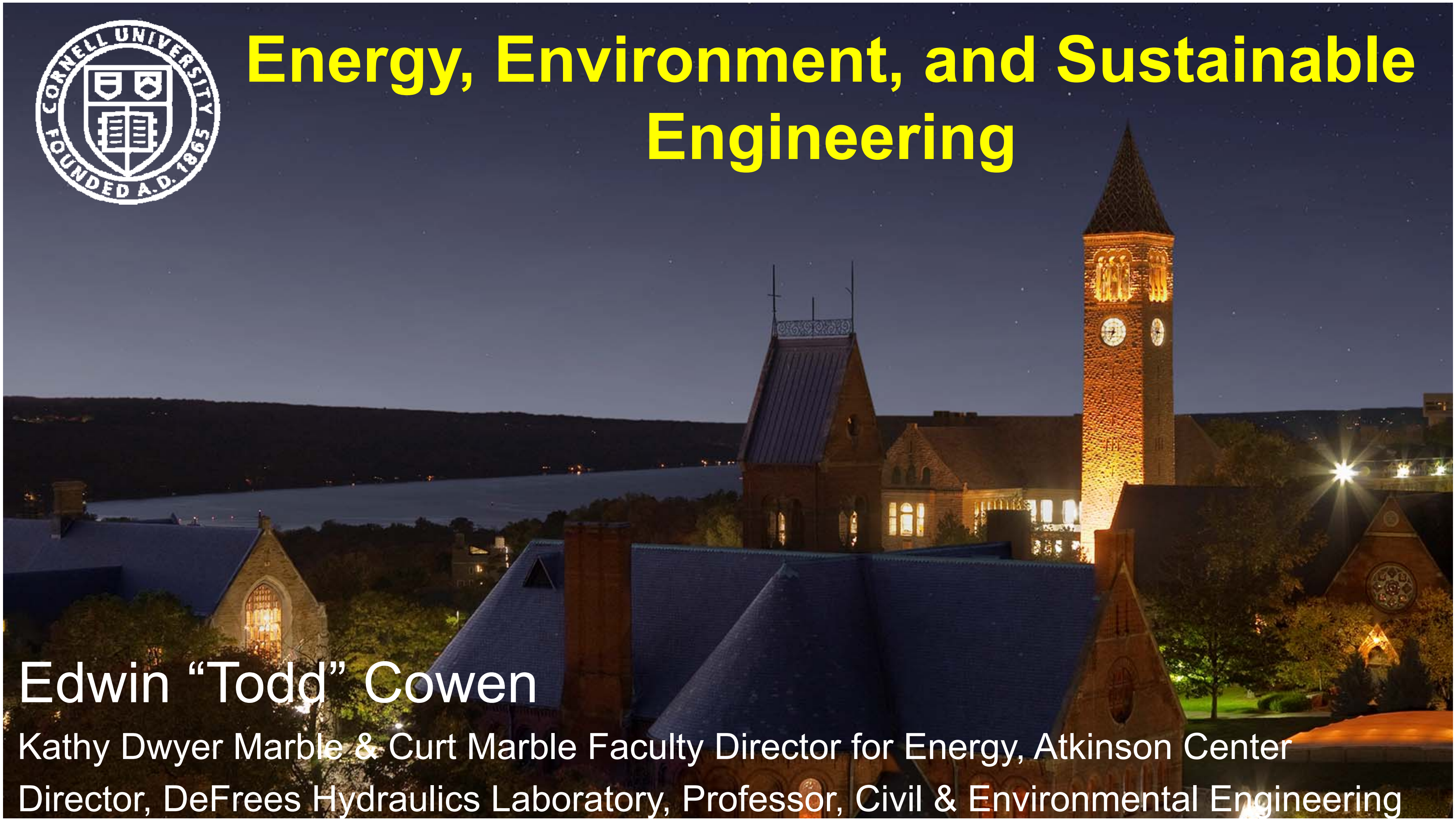


Energy, Environment, and Sustainable Engineering

Edwin “Todd” Cowen
Kathy Dwyer Marble & Curt Marble Faculty Director for Energy, Atkinson Center
Director, DeFrees Hydraulics Laboratory, Professor, Civil & Environmental Engineering

The Cornell Landscape

- *The Climate Action Plan* – a carbon neutral campus by 2035
- *The Living Laboratory* – Our campus is our testbed
- *Radical Collaboration* – target and elevate strategic, radically collaborative discipline areas
- *The Atkinson Center* – seeding cross-disciplinary teams with external partners on a pathway to impact
- *CornellTech* – Dan and Ron wowed us last night

Climate Action Plan: Senior Leaders Climate Action Group

Spurring Innovative Cross-Disciplinary Solutions in 8 areas:

- Campus Engagement
- Energy Efficient Buildings
- Mission-Linked Carbon Offsets
- Greenhouse Gas Inventory Protocol Review
- Electricity
- Heat
- Transportation
- Funding Alternatives

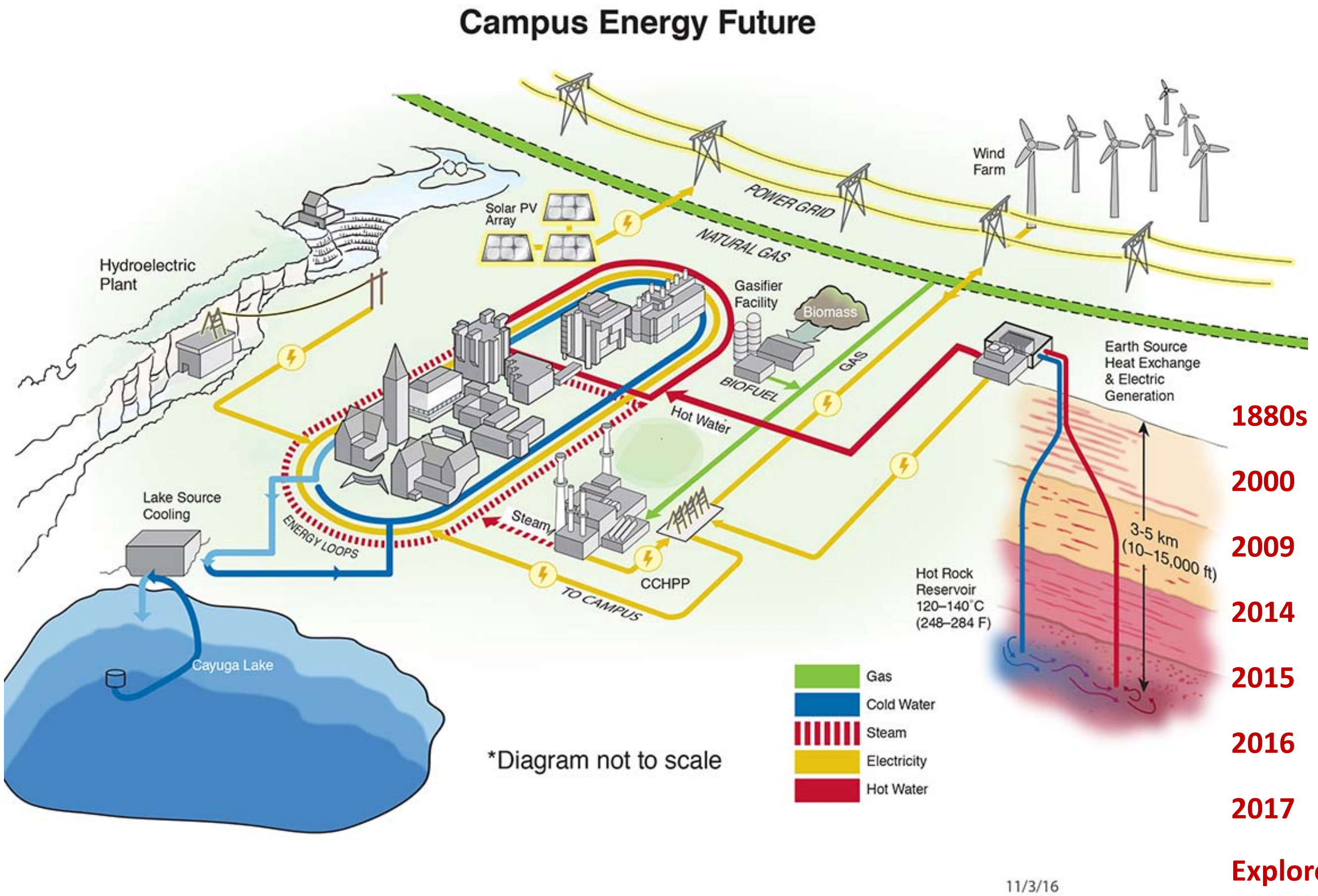
A Living Laboratory for Energy

20%
Campus growth since 2000, flat building energy usage

30%
Reduction in emissions since 2008

7%
Campus electricity supply is generated by solar power

2011
Ithaca campus certified STARS Gold



1880s	Hydro Power
2000	Lake Source Cooling
2009	Combined Heat & Power
2014	Snyder Road Solar Farm
2015	Geneva Solar Farm
2016	Ledyard & Harford Solar Farms
2017	DOE Earth Source Heat grant
Explore	Earth Source Heat

A Smart Community Living Laboratory:
2000 New beds on North Campus

- people + technology = behavior change + impact

Radical Collaboration – *Breaking University Rules*

- Data Science
- Genome Biology
- Humanities and Arts
- Infection Biology
- Nanoscale Science and Molecular Engineering (NEXT Nano)
- Social Sciences
- Sustainability

Sustainability Task Force Recommendations

01

Focus interdisciplinary research on the UN Sustainable Development Goals for 2030

- The initial focus would be on the equitable distribution of food, energy, and water for a growing human population as this focus builds on existing Cornell strengths.

02

Fill critical intellectual gaps & enhance community with coordinated hires of 8 senior faculty

- Bridge disciplines relevant to the system of systems analysis necessary to achieve the SDGs.
- Available across campus

03

Educate the next generation of sustainability professionals: a new PhD program

- Create a university-wide graduate program in Sustainability Studies
- Two years fellowships with cross-disciplinary mentors

04

Create structures to support large, long-term, co-created interdisciplinary research programs

- Work with non-academic orgs to change sustainability products, practices or policies.
- Non-tenure-track faculty hires to provide tactical support

David R. Atkinson Center for a Sustainable Future

2017 Academic Venture Fund awards with CoE faculty

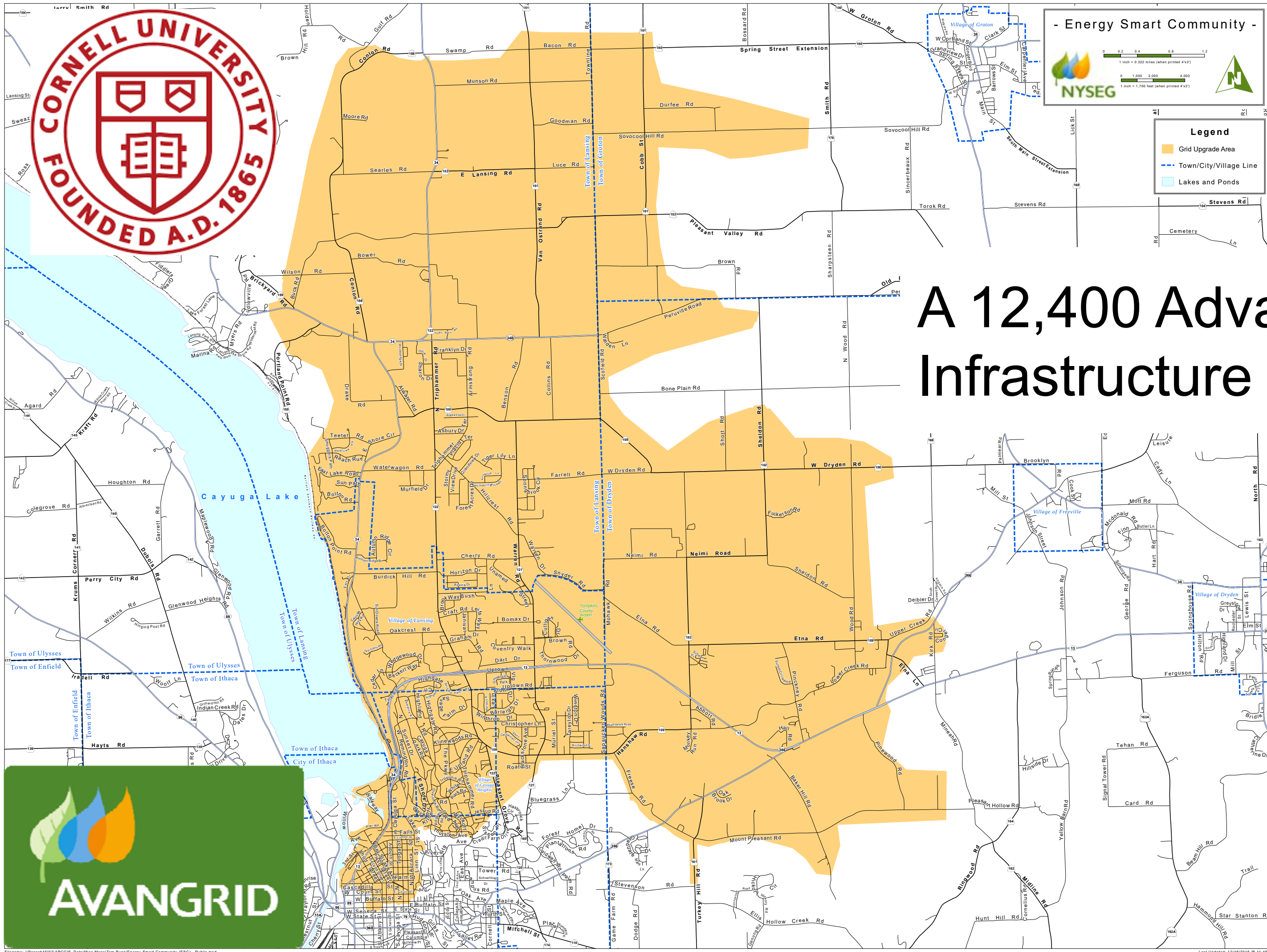
- *Greening the Grid* – ground source heat pumps as distributed energy resources – Jeff Tester
- *Making the Most of Marginal Lands* – suitable for biofuel feedstocks – Abe Strook
- *Taking the Quicksilver out of Gold Mining* – getting the mercury out – Matt Reid
- *Seeding Solar in New York* – energy vs food on agricultural lands – Max Zhang
- *The Future of Pharma is Sustainable* – CO_2 and electricity as drug industry feedstocks – Abe Strook
- *Small Device, Big Results* – hand held antibiotic resistance diagnosis – David Erickson
- *Preparing for Earth Source Heat* – deep fluid flow and seismic risk monitoring – Matt Pritchard, Katie Keranen, Greg McLaskey
- *Green is the Norm* – test public messages that "green" attitudes and behaviors are in fact the norm in minority communities – H. Oliver Gao

Atkinson Center,
Venture Scholars, Adding Value

- Sustainability with an entrepreneurial spirit
- Empowering pioneers at the heart of radical collaboration, creating lasting impact
- Recognizing potential reward in novel or early research where others see only risk
- Hub for sustainability researchers across Cornell's campus
- 490+ Faculty Fellows from 65 departments
- 250 projects funded in 8 years
- $15M invested by the center has contributed to the return of $120M to the university
- Portal to Cornell sustainability for those outside Cornell

Let's Look at Some Examples

Energy Smart Community



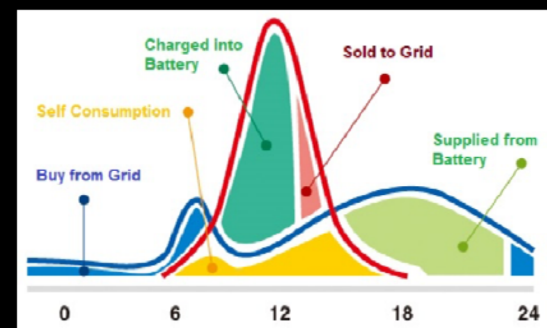
A 12,400 Advanced Metering Infrastructure (AMI) Test Bed

Objective: Accelerate the Electrification of the Built Environment and Transportation Sectors

- Path: Leverage a highly interdisciplinary team assembled at Cornell to collaborate with AVANGRID using their *Energy Smart Community* (ESC) testbed within NYS Reforming the Energy Vision (REV) framework to accelerate integration of Distributed Energy Resources (DER) and Smart Grid Services to extract new value on the grid for customers, utilities, and third-party businesses

PFI:BIC - Energy Smart Community - Leveraging Virtual Storage to Turn Advanced Metering Infrastructure into a Smart Service System

Red line: solar power generated
Blue line: home power use
Alternatively (if no solar), imagine red line shifted to right a few hours is a peak demand charge and green "charge battery" area shifts to overnight hours yet the blue curve remains the same. Battery allows homeowner to avoid peak demand charges



Price ($/kWh)	Deadline (hour)
0.35	1
0.25	2
0.20	3

Our team is exploring multiple pricing signals as inputs into the smart service system being developed. One idea for electric vehicles is pricing energy according to charging deadline (longer deadline = lower price as shown in the bubble above). We call this *deadline differentiated energy services.*

Unlocking Flexibility in Demand – Eilyan Bitar

Demand is largely inflexible (today)…

- Majority of customers pay a flat rate for electricity

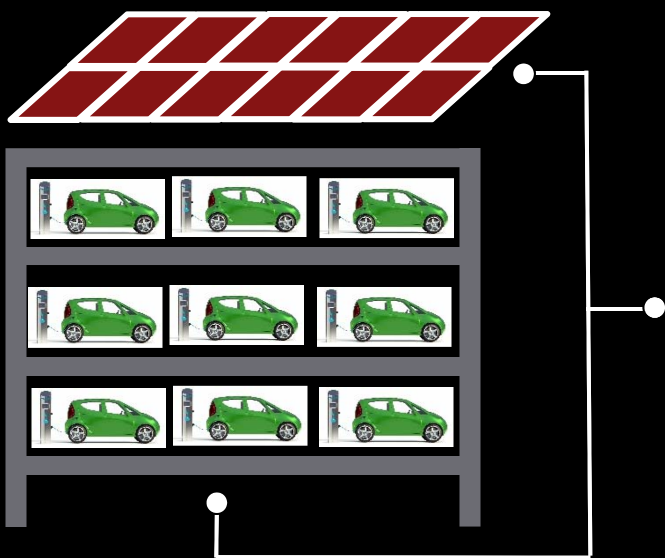
The ability to shape demand has the potential to:

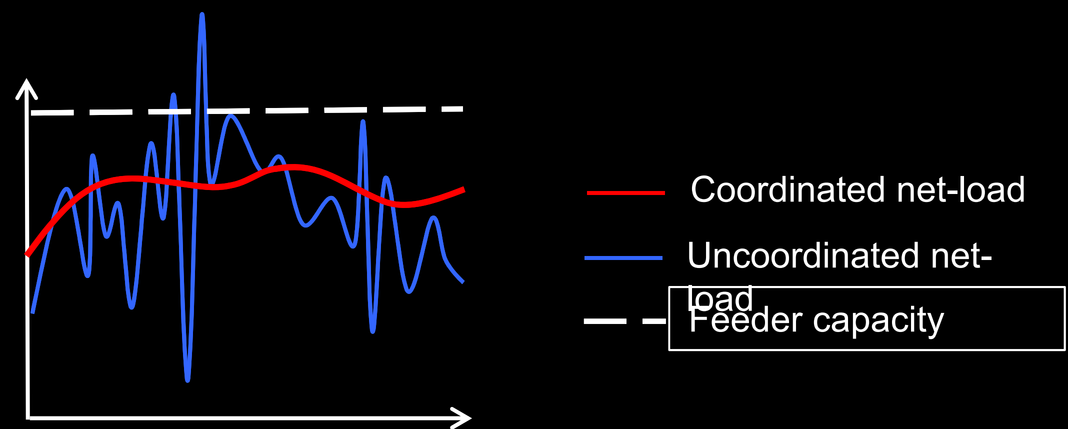
- Balance fluctuations from renewables
- Reduce peak electricity prices
- Mitigate the exercise of market power (by strategic generators)

How to harness (emerging) sources of demand flexibility?

Electric Vehicle Charging Services

Emerging infrastructure of solar + EV garage/charging facilities…





- EVs loads are flexible -- inherently **deferrable** in time
- How to unlock and harness this flexibility for grid services? *Why not treat EV charging as a service?*

HI-LIGHT: Artificial Photosynthesis Reactor

Making solar fuels viable through efficient utilization and even distribution of sunlight in scalable reactor forms with novel functionalized catalysts.

Cornell University
Elvis Cao, PhD Student MAE
Jessica Silva, PhD Student, CBE
Prof. Tobias Hanrath, CBE
Prof. David Erickson, MAE

Dimensional Energy
Jason Salfi, CEO
Clayton Poppe, CTO

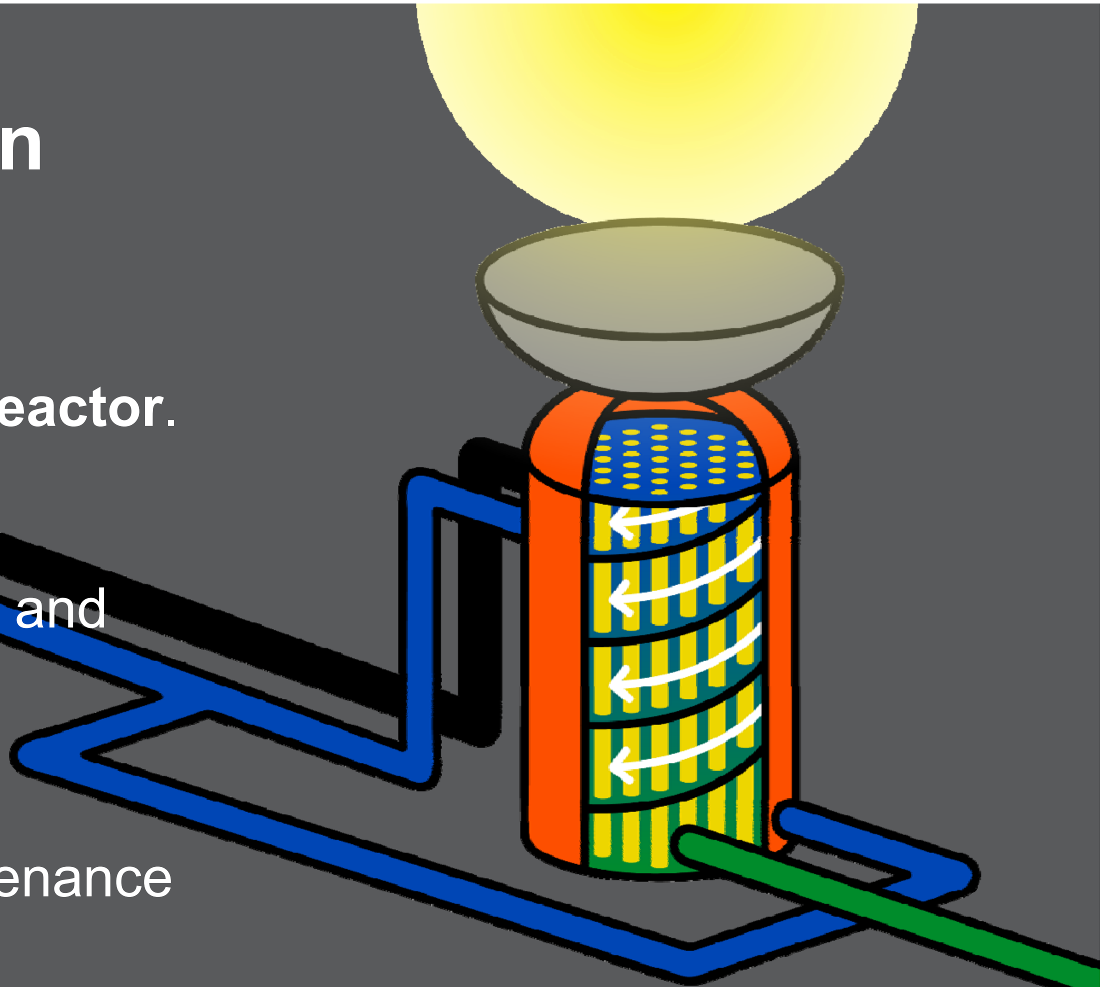
The Hi-Light Solution

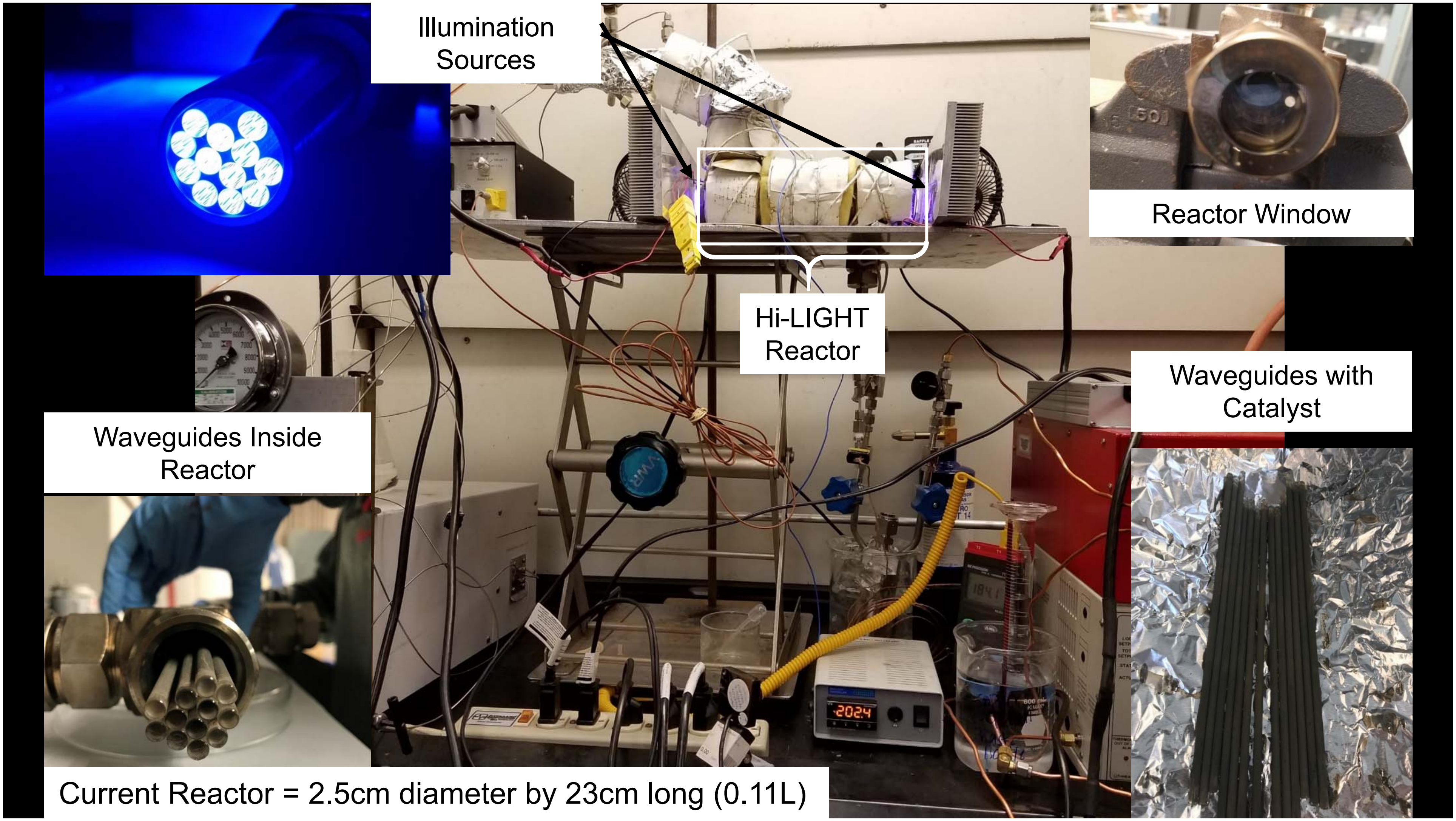
Scalable Industry Standard reactor.
Modified to utilize sunlight.

- Low Cost of Energy
- Fits existing infrastructure and methods to lower CAPEX

Fluidized catalyst

- Increased throughput
- Lower cost catalyst maintenance




Illumination Sources
Reactor Window
Hi-LIGHT Reactor
Waveguides with Catalyst
Waveguides Inside Reactor
VWR
Current Reactor = 2.5cm diameter by 23cm long (0.11L)

Solar Fuels: Barriers to Scale

Customer Problems with Solar Fuel Production:

Custom reactors

- Unproven at scale
- Expensive to fit into existing infrastructure

Sub-optimal light delivery & poor Energy Balance

- Low volumetric productivity
- High Effective Energy Cost
- Inefficient, high cost catalyst usage.

Business Model

LICENSE IP TO CHEMICAL COMPANIES

REACTOR DESIGN
- HI-Light Shell and Tube for Syngas Production.

SMALL REACTOR SALES
- CO2 RR
- SOLAR REFORMING
- RESEARCH

FUNCTIONALIZED CATALYST

WAVEGUIDE SALES

ONGOING REVENUE FROM LICENSORS AND CUSTOMERS

SERVICE CONTRACT for Reactor, Catalyst, Waveguide:

- TECHNICAL SUPPORT
- MONITORING SYSTEMS
- OPTIMIZING OPERATION OF: REACTORS, CATALYSTS, WAVEGUIDES

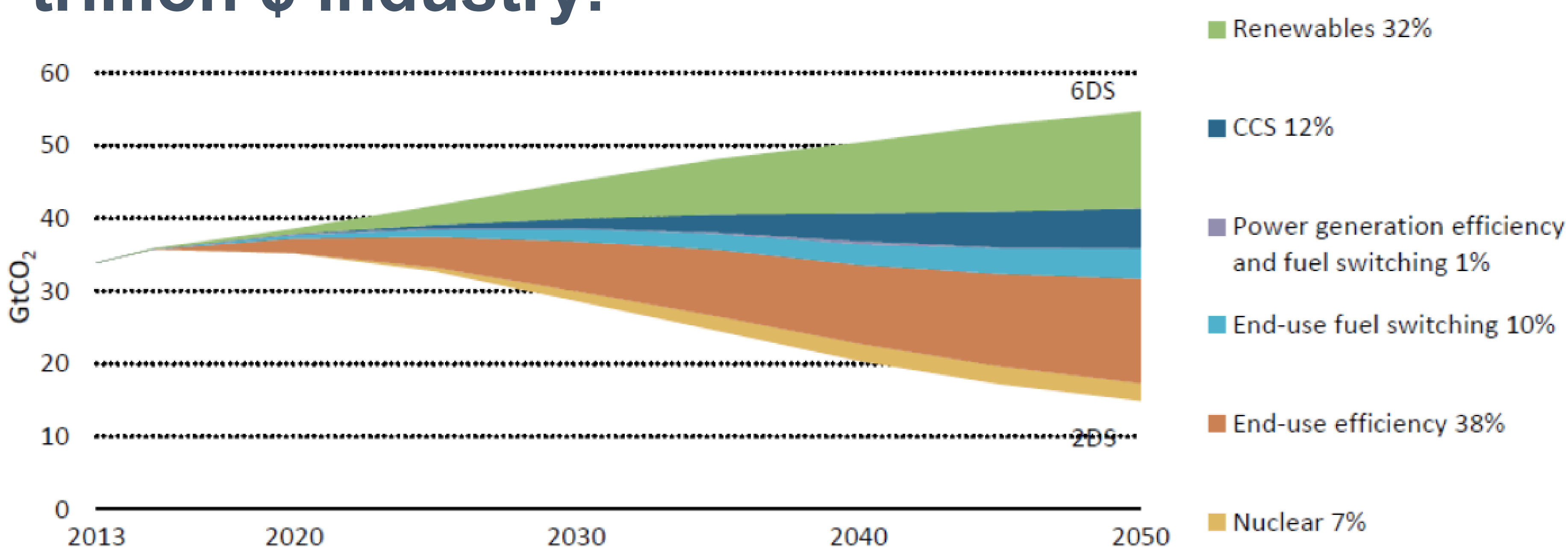
HI-LIGHT SCALE UP

GROW EXISTING SOLAR FUELS MARKET: LICENSE AND SERVICE CONTRACTS

NEW MARKETS

- WATER PURIFICATION
- VOC MITIGATION
- OTHER CHEMICALS

Market Dynamics – A nascent trillion $ industry.

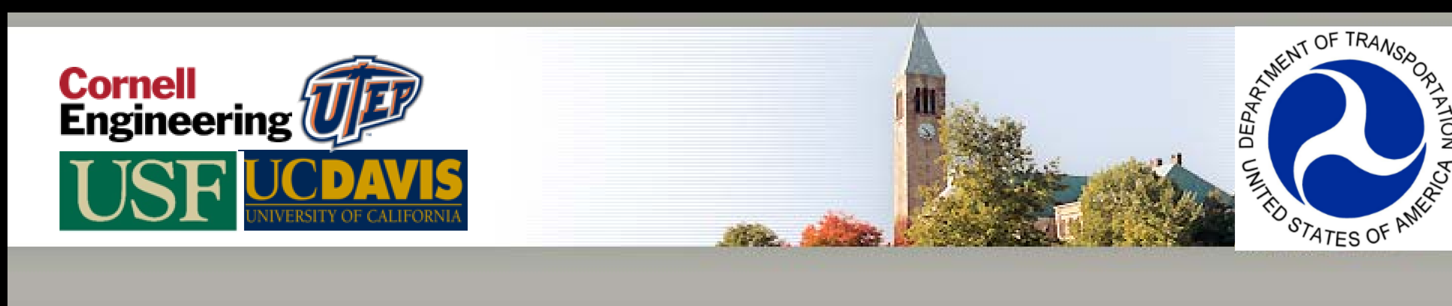


Source: IEA (2016b), *Energy Technology Perspectives 2016.*

Center for Transportation, Environment, and Community Health

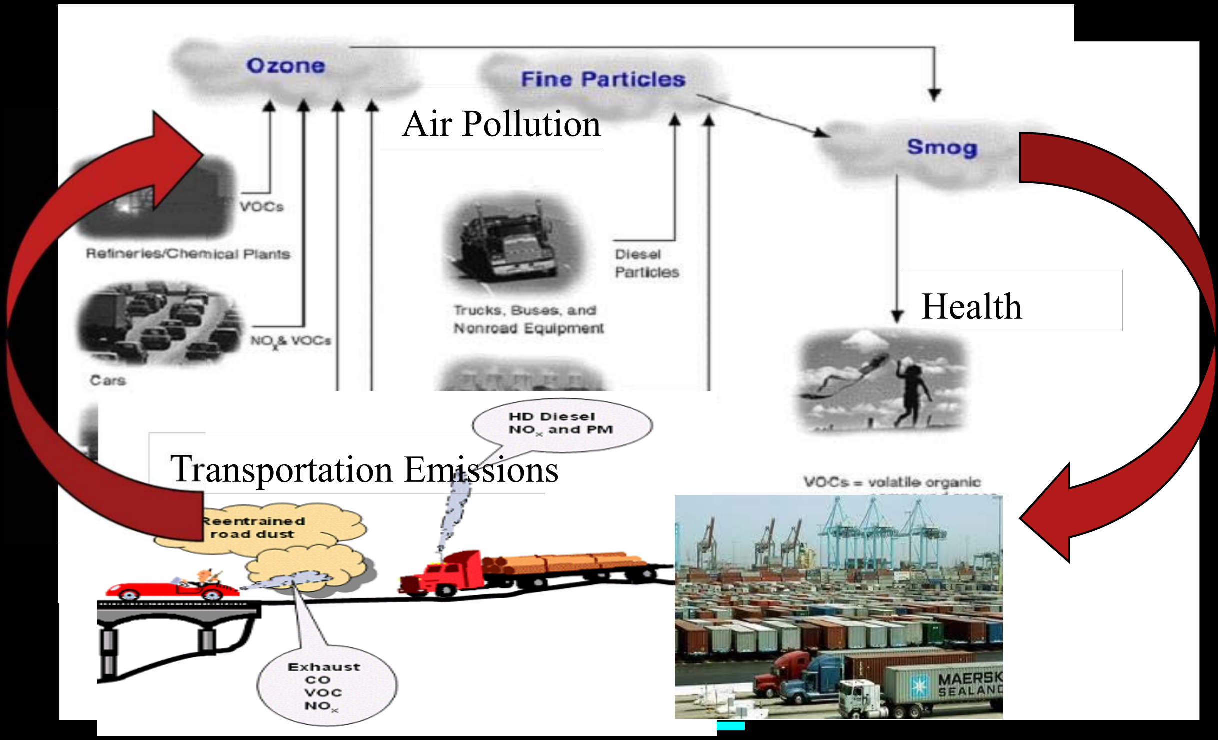
UTC PROGRAM FAST ACT

H. Oliver Gao
Director, CTECH
School of Civil and Environmental Engineering, Cornell University



Cornell University

CTECH—Integrating Transportation, Environment, and Community Health



Vision: Research and education innovations for sustainable mobility of people and goods while preserving the environment and improving community health.

CTECH Research

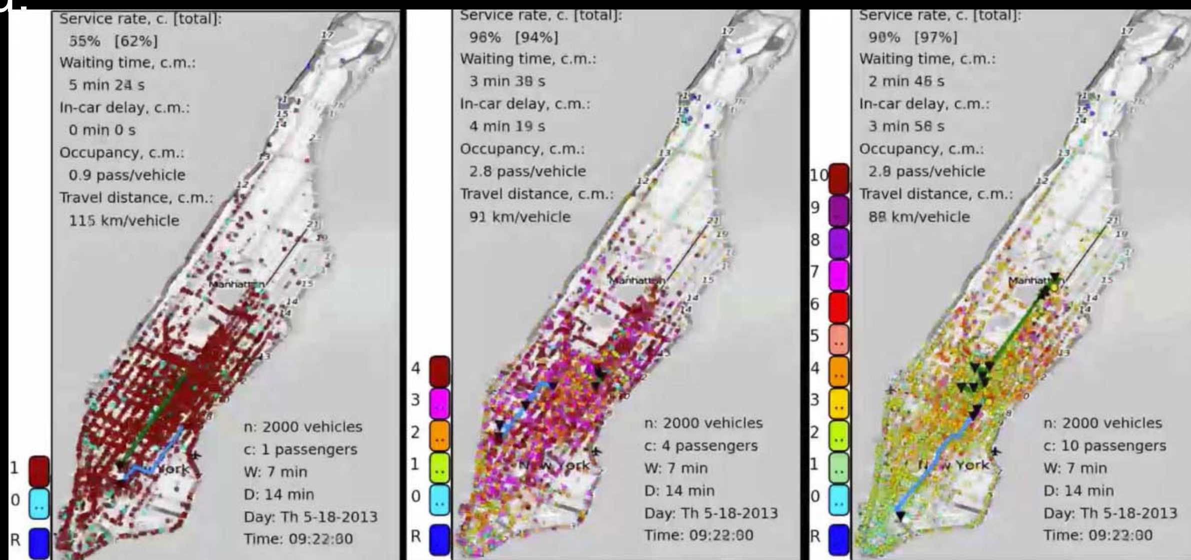
- CTECH organizes its research through six thrusts:
  1. Behavior, Active Transportation, and Community Health;
  2. New Transportation Technologies and Business Models (e.g., mobility-on-demand services);
  3. Green Multimodal Transportation Systems;
  4. Freight Transportation and Community Health;
  5. Data-Driven Transportation-Health Informatics (e.g., Smart City and Internet-of-Things); and
  6. Energy, Technology and Policy Pathways.

Through multi-level, multidisciplinary and institutional collaborations, CTECH will advance transportation sustainability in its broader human and environmental contexts.

High-capacity On-demand Ridesharing

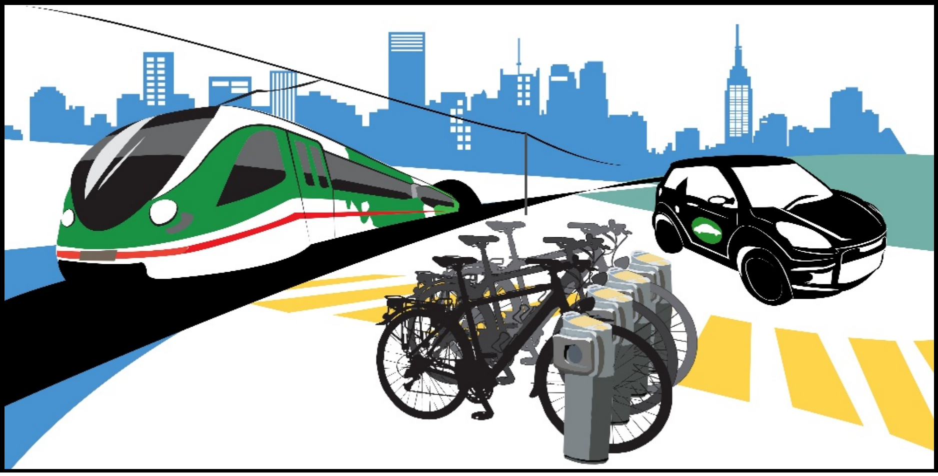
Samitha Samaranayake

- Scalable ILP can process all of the NYC taxi demand (~400 requests per minute) operating at a 30 second time step.
- 2000 vehicles of capacity ten (15% of taxi fleet) can serve 98% of the demand.



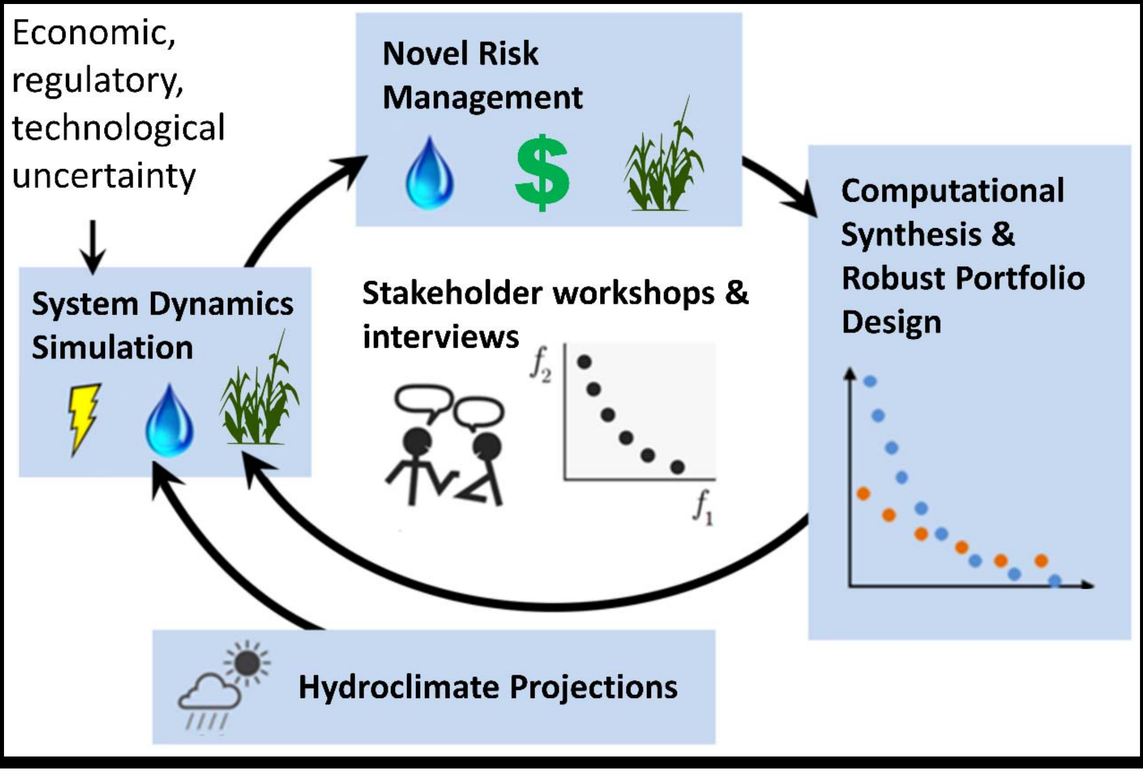
Smart Transit @ Cornell Project

- Working with policymakers and industry partners to create mathematical models and analysis tools that better inform high level decision making
  - Integration across modes
  - Higher capacity sharing (dynamic micro-transit services)
  - Pricing and incentive mechanisms for load balancing
  - Incorporating demand modeling and congestion effects



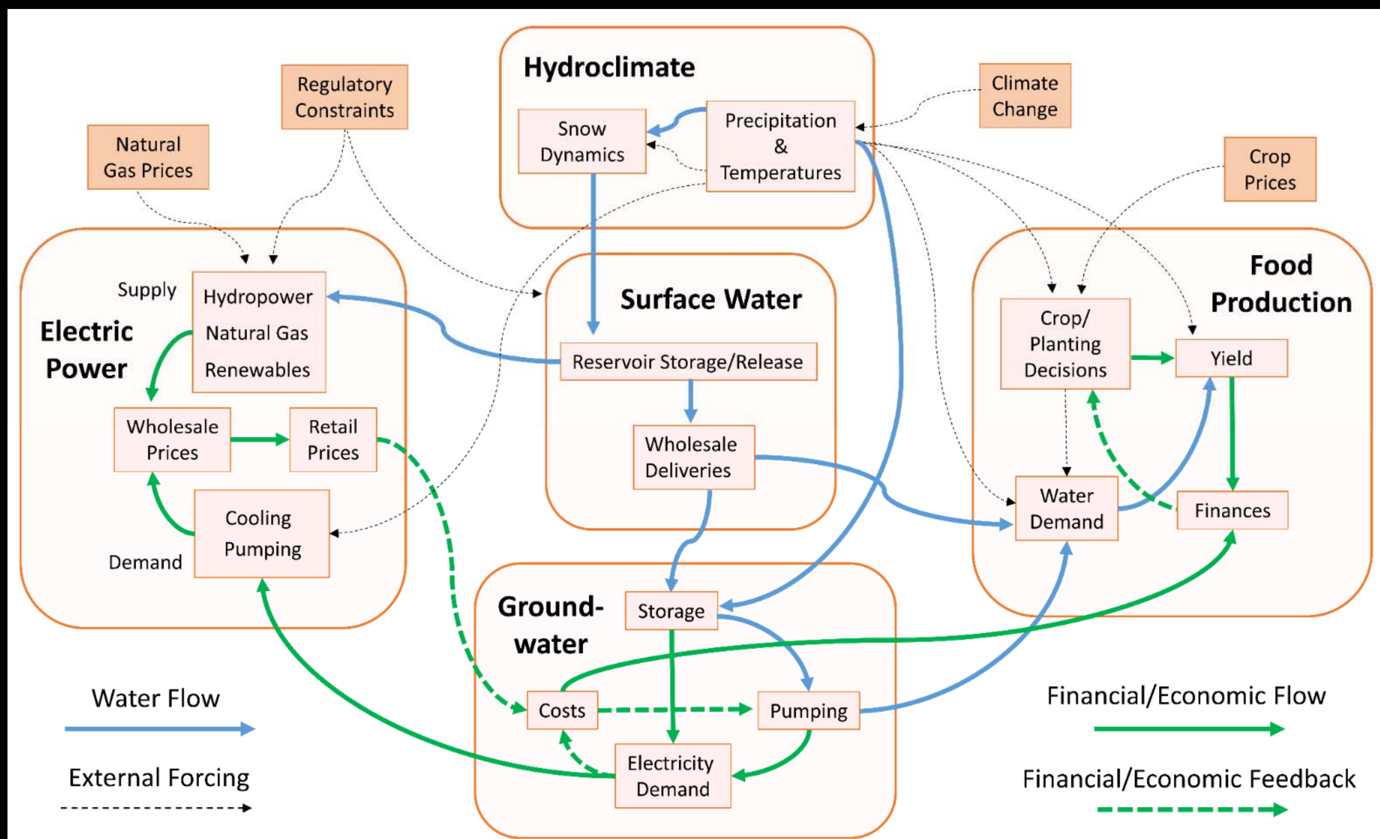
The sustainability-productivity tradeoff:
Water supply vulnerabilities and adaptation opportunities in California's coupled agricultural and energy sectors

- Pat Reed
- Open source tools for cross-sector, multi-objective decision-making under uncertainty



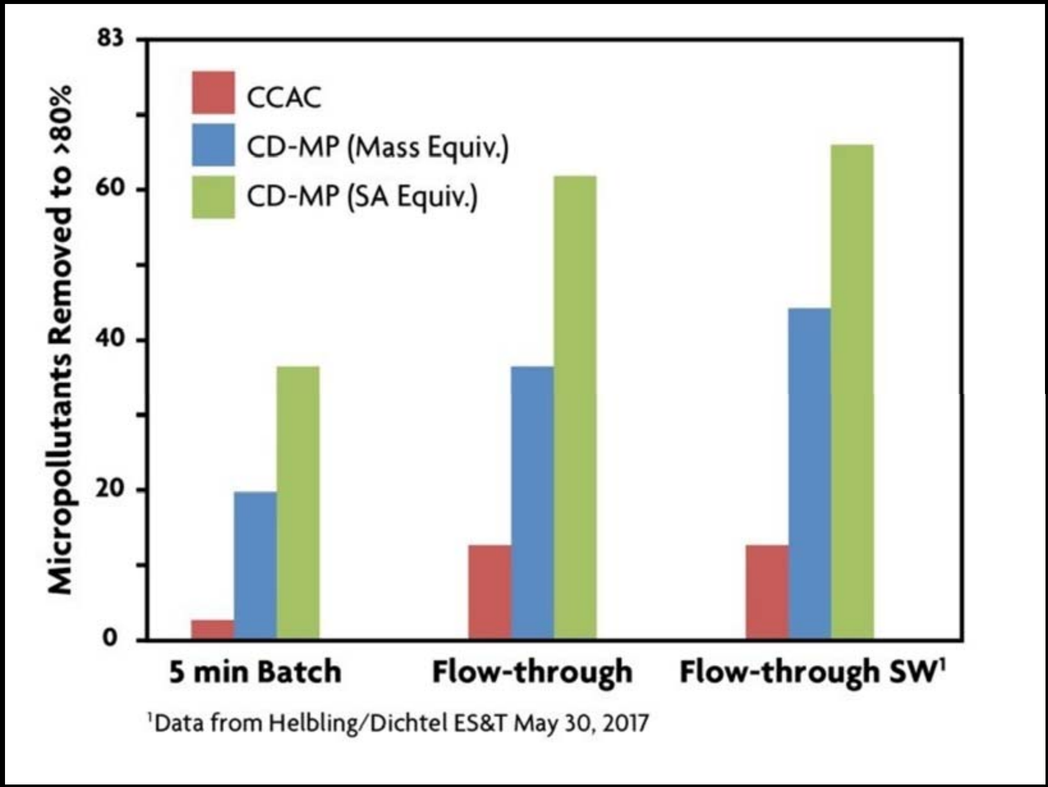
THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

CalFEW Coupled Human-Natural Systems



CycloPure Polymer - Damian Helbling

- Micropollutant polymer
- Outperforms activated carbon
- Washable
- Start-up company

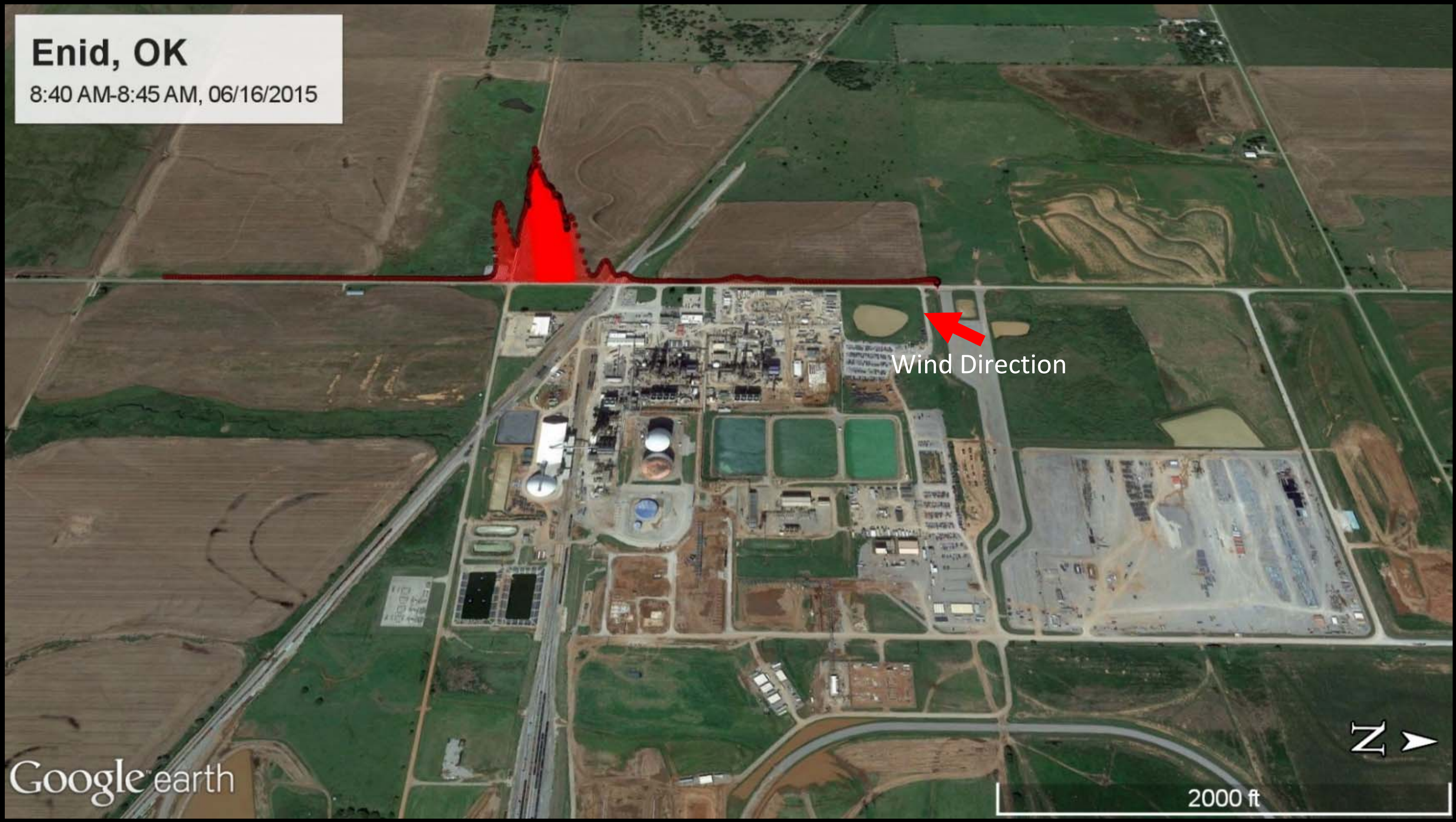


Cornell – EDF Partnership: Looking Downwind for Methane

John Albertson

- A Google street view car
- Fertilizer and Ammonia Plants
  - Selected based on location (rural, open), production capacity.
- Enid, OK (06/15-06/16), Woodward, OK (06/17), Borger, TX (06/18-06/19)
- Sampling procedure:
  - 1. Stationary 3-D sonic wind sensor in a nearby, open place
  - 2. Repeated passes around the targeted facility to identify possible leaks

An example of plume transect (Enid, OK)



Computer Systems and Complexity - José Martínez

Intelligent Resource Management in Multi-Agent Systems

- **Problem:** Allocate resources across agents to optimize computation
  - Network bandwidth;
  - Power budget;
  - Local storage; etc.
- Dynamic: Adapt on the fly
- Transparent: Agent is oblivious
- Retargetable: Maximize aggregate performance vs. energy efficiency vs. fairness …
- **Approach:** Transparent auto-optimizers based on:
  - Machine learning
    - Neural nets to model resource utility
    - Reinforcement learning to schedule tasks with foresight
  - Market mechanisms
    - Agents endowed with "virtual currency;" market adjusts resource "prices" based on demand
    - Quick convergence to Pareto-optimum operating point

Security in the Internet of Things: The Free Rider Problem – Stephen Wicker

- The Mirai Attack (October 2016)
  - Botnet created by hacking IoT devices (cameras, alarm systems, etc.)
  - Subsequent DDOS attack rendered Amazon, Netflix, Twitter, etc. unreachable

- Key Issue: The Free Rider Problem
  - Our code analysis shows that botnets formed through very simple attacks
  - Products providing Internet access with grossly inadequate security

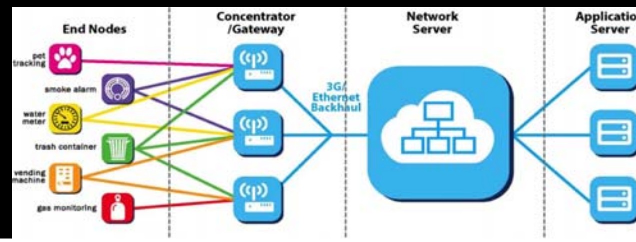
- Research Topics:
  - Game-theoretic models for free rider behavior point to key motivators
    - A little bit will go a long way…
  - Security tools built into the design process
  - Automated verification and certification

Privacy in the Internet of Things: The Radar Problem

- Key Issue: Increased numbers of WiFI devices at higher bandwidths allow for remote imaging of household/corporate behavior
  - The 802.11ay will have bandwidths of up to 8 GHz, providing range resolution of 2 cm
  - Precision passive sensing betrays personal/corporate information while also creating a physical security risk
- Research Topics:
  - Utility of standard radar countermeasures as well as the unique opportunities provided by the 802.11 standard, equipment, and the residential deployment scenario
  - Explore potential for cooperative signaling techniques

IoT-based Energy and Environmental Monitoring – Max Zhang

Maplewood Apartments



IoT Testbed: Maplewood Apartments

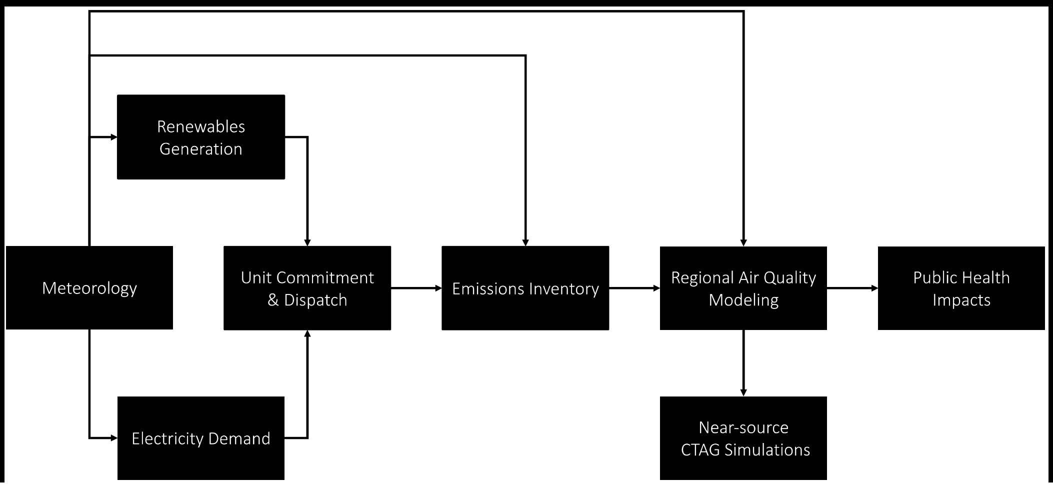
- An all-electric community for 900 Cornell graduate students
- Electrically–driven heating with air-source heat pumps
- To be completed by Fall 2018
- We are working on a wireless energy monitoring network to quantify the real-world performance of heat pumps.

IoT Testbed: Cornell Ithaca campus

- We are working on ubiquitous and granular power and water monitoring at Ithaca campus
- The IoT network will promote individual accountability and promote behavior changes in energy and water usage.
- Potentially, an IoT monitoring network can be deployed in the North Campus Expansion project (dorms for 1000 new beds for Cornell undergraduate students) to be completed by Fall 2020

Quantify the Value of Distributed Energy Resources (VDER)

- New York State Public Service Commission announced in March 2016 the replacement of net energy metering (NEM) by VDER tariffs to take into account locational, environmental, and temporal values of renewable energy projects.
- This marks the most fundamental change in how to incentivize renewable development.
- We are working with state agencies to develop a framework (shown below) to quantify VDER by integrating energy and environmental modeling.



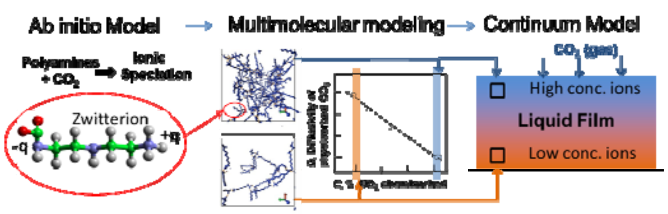
Value Stacks

- Energy
- Distributed Voltage Support
- Capacity
- Reduced Environmental Impacts
- Demand Reduction
- Locational System Relief

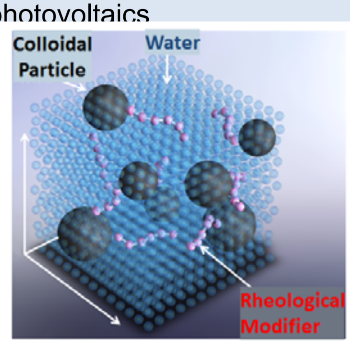
- The results will have direct impact on energy policies in New York State and potential the rest of the U.S.

NEW YORK STATE OF OPPORTUNITY. | NYSERDA Supported

Examples of Cornell's computational multiscale energy modeling

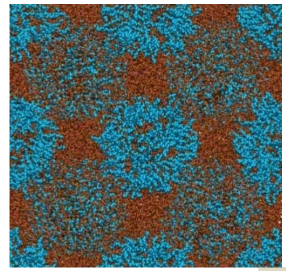


Escobedo-
- CO_2 capture in polyamine thin films
- self-assembly of pure and mixed nanocrystals for photovoltaics

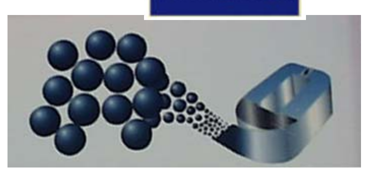


Joo- Slurry transport (nuclear waste, hydrofracking)

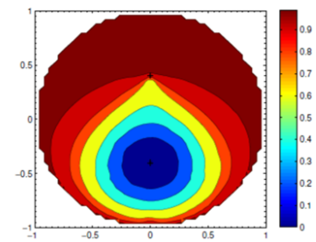
- Energy storage devices (Li ion, Li air batteries)



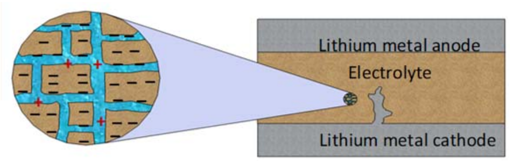
Clancy- Materials design for solar cells
- Quantum dots (w/Hanrath)
- Roll-to-roll processing (w/Bao, Stanford)
- All-organic solar cells (w/Loo, Princeton)



Steen- Energy efficient processing of metals



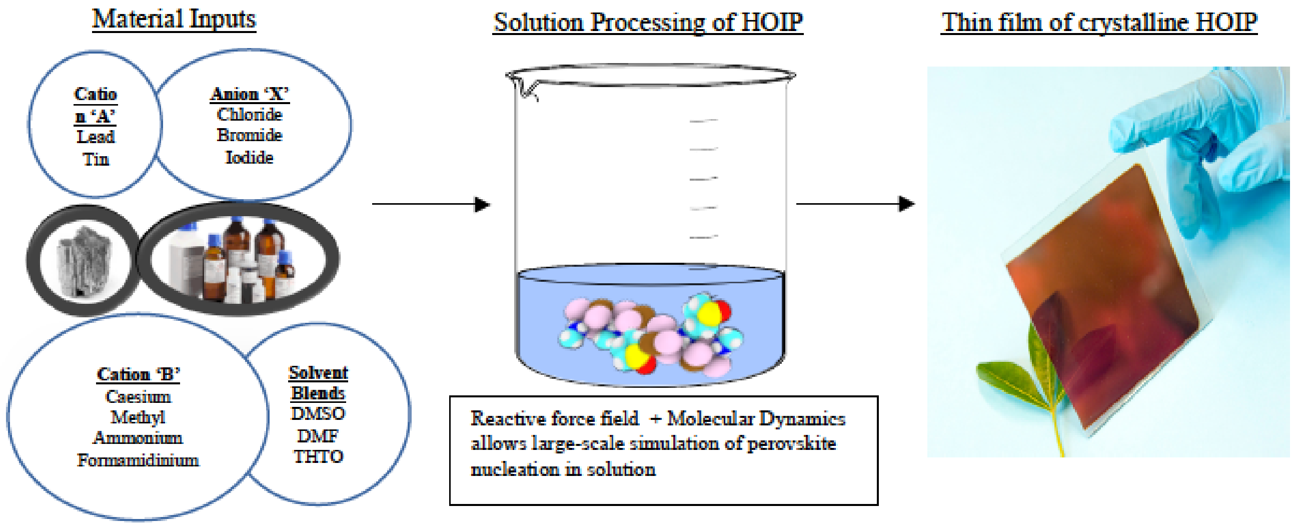
Tester- CFD, thermal hydraulic & reaction modeling for geothermal (w/Koch), thermal energy storage, algal bioenergy



Koch- Modeling transport in porous media:
- Inhibiting dendrite growth in Lithium metal batteries (w/Archer)
- Enhancing CO_2 dissolution in brine for geological sequestration (w/Stroock).

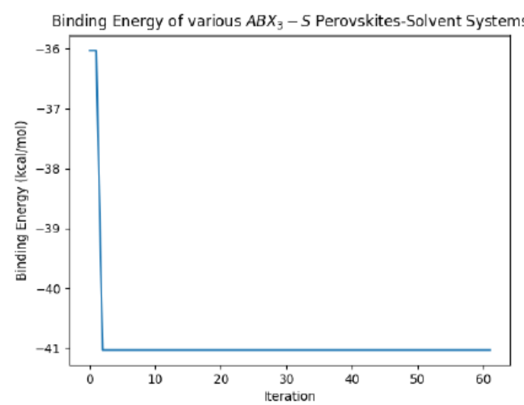
Bayesian optimization to tame the complexity of all the possible choices to make hybrid organic-inorganic perovskites

Paulette Clancy



Bayesian Optimization provides an accelerated search of all those material inputs (different choices of cations, anion, and solvent blends).

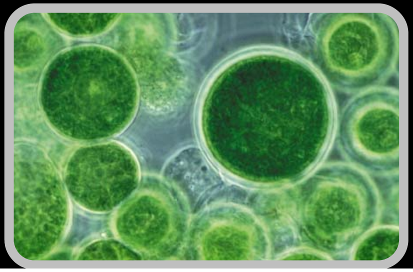
Proof of concept: A Bayesian search finds the optimal choice of $PbAX_3$ in 8 pure solvents in 3 tries (out of 60 possible combinations)

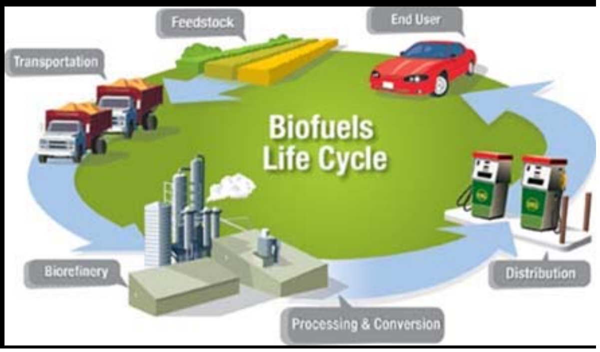


Bioenergy, Biofuels and Bioproducts

Expanding Cornell's biomass portfolio using diverse feedstocks and hybridized bio and thermochemical processing

- Algal feedstocks to biofuels and animal feed
- Life cycle assessment (LCA) and TechnoEconomic analysis (TEA)
- Coupled anaerobic digestion and hydrothermal conversion of dairy and food wastes for energy and nutrient recovery
- Selective willow and switch grass breeding and hydrothermal deconstruction of lignin-cellulosic feeds to sugars in supercritical water





Cornell Energy Institute (CEI): Areas of active energy research

- ❑ Subsurface science and engineering - earth energy systems focused on geothermal energy and unconventional fossil
- ❑ Wind and water power -- Aerodynamic and hydrokinetic energy
- ❑ Solar Energy capture and conversion
- ❑ Advanced materials for energy storage
- ❑ Bioenergy, biofuels, and bio-Products
- ❑ Multiscale computational modeling - molecular to process to LCA /TEA
- ❑ Energy systems for Sustainable Communities
- ❑ Energy Systems Management and Integration -- Verizon data centers and cell tower cooling projects

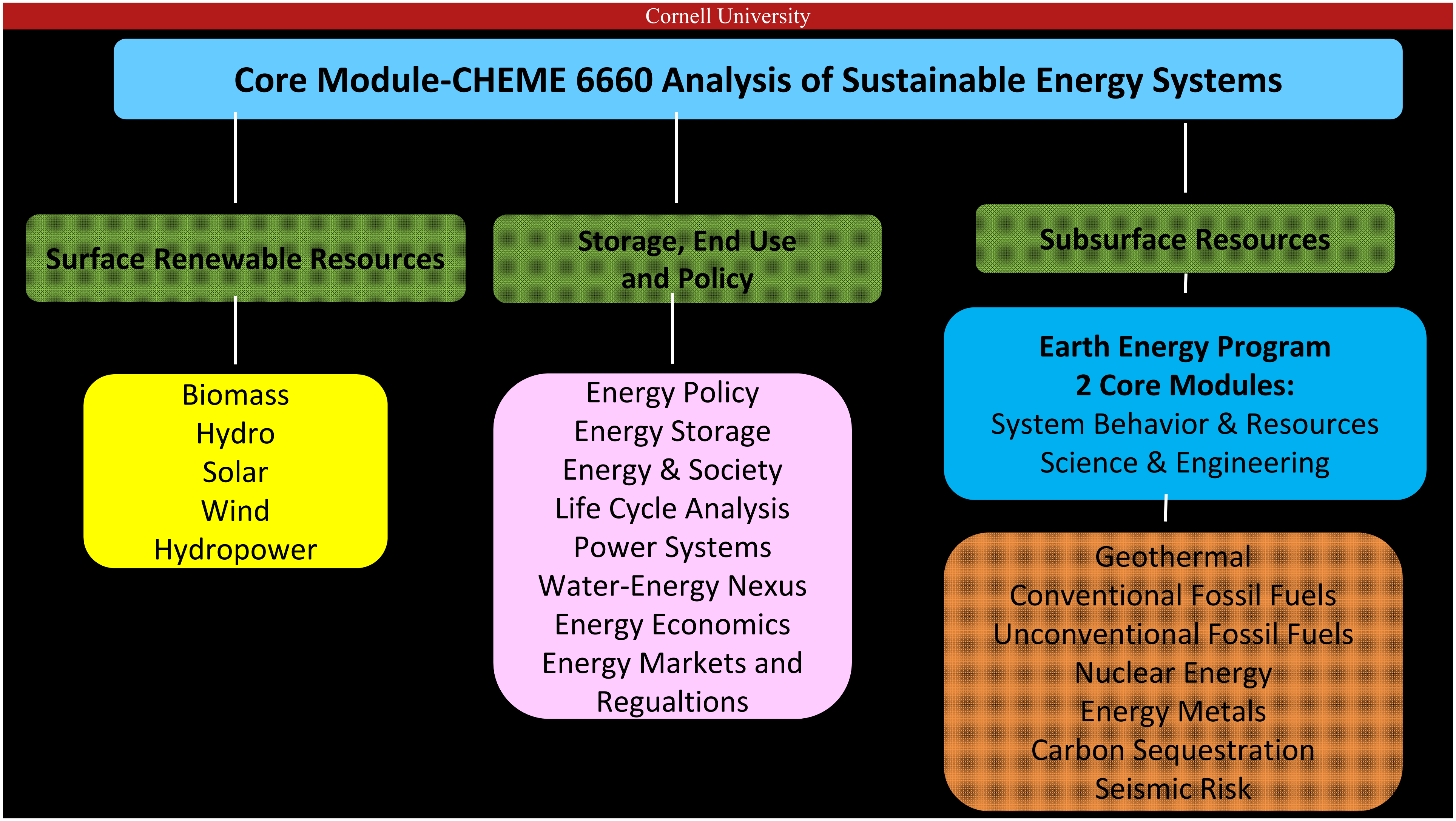
CEI's Role in CoE Energy Education

- ❑ **Sustainable Energy Systems minor for undergrads and grad students**

- ❑ **20 Energy modules**

- ❑ **3 Earth Energy program core courses**
  - Analysis of Sustainable Energy Systems
  - Earth Energy Systems Behavior and Resources
  - Earth Energy Science and Engineering

- ❑ **Weekly Energy seminar program and invited speakers**


Cornell University
Core Module-CHEME 6660 Analysis of Sustainable Energy Systems
Surface Renewable Resources
Storage, End Use and Policy
Subsurface Resources
Biomass
Hydro
Solar
Wind
Hydropower
Energy Policy
Energy Storage
Energy & Society
Life Cycle Analysis
Power Systems
Water-Energy Nexus
Energy Economics
Energy Markets and Regualtions
Earth Energy Program
2 Core Modules:
System Behavior & Resources
Science & Engineering
Geothermal
Conventional Fossil Fuels
Unconventional Fossil Fuels
Nuclear Energy
Energy Metals
Carbon Sequestration
Seismic Risk

Project Teams, an Example - AguaClara

- Puerto Rico Recovery – Resiliency
  - 1 L/s water treatment plant
  - No electricty required
  - Tegucigalpa, Honduras pilot
  - 250 L/day for 300 people
  - Largest component of the plant is a 3 ft diameter PVC pipe
- Connecting with CoE alumnae in Puerto Rico

Cross-Disciplinary Co-Creation with External Partners

- CornellTech & Atkinson Center leading Cornell and arguably universities in this space
- Cornell Energy Institute growing its capacity in this space
- Many in the College of Engineering already doing this

- *Tremendous opportunity in the College – ECC members can serve as connectors between CoE and industry*