Faculty Members

TEAM HYGROSCIENCE

Faculty Name	Expertise Critical in Project (up to 2)
Dr. Xi Chen (Team Lead)	A. Vision for the Technology; B. Water-Responsive Materials.
Dr. Ahu Aydogan	A. Design; B. Prototype Implementation.
Dr. Daniel DiSalvo	A. Public Communications; B. Energy/Public Policy.
Dr. Raymond Tu	A. Polymer Science; B. Natural Materials.
Dr. Charles Vörösmarty	A. Scalability of Energy Production Process; B. Water Cycle Analysis at Regional and National Scales

Framing Question

TEAM HYGROSCIENCE

What would it look like if we could create a NEW form of sustainable energy?

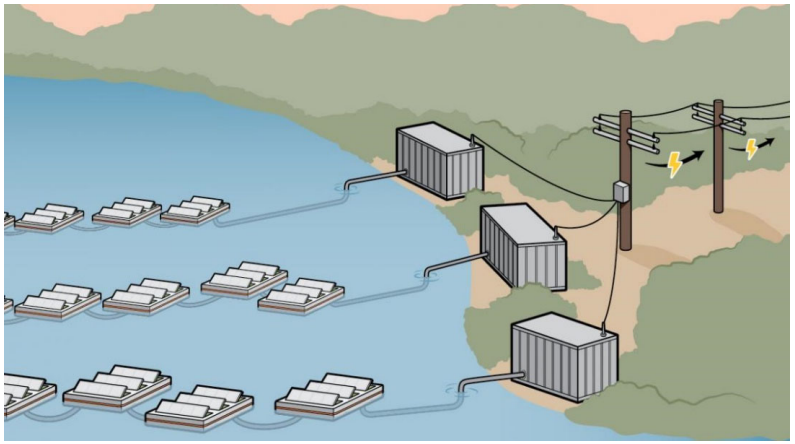


Illustration of an upscaled system that continuously harvests evaporation from an open water reservoir to produce electricity. (Credit: P. Bethge, E. Strickland).

“Hygroscience” for Evaporation Energy Harvesting

Problem Statement:

Scientists are urgently seeking to develop cheaper, cleaner, and more sustainable energy sources. While great progress has been achieved in renewable energy technologies, we are unlikely to simultaneously solve the climate crisis and address challenges to the nation’s economic health without adopting a more diverse mix of renewables.

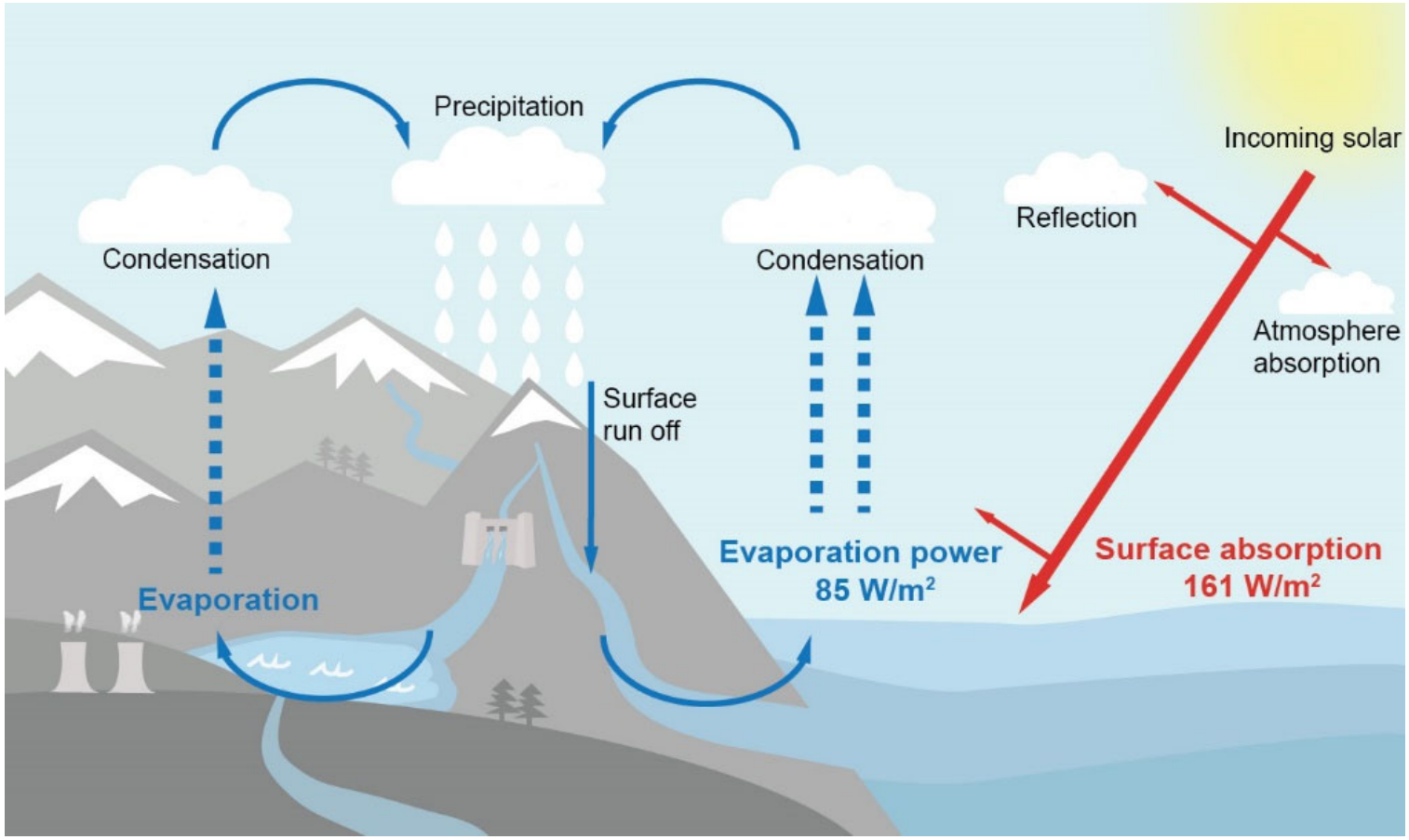
Reneable energy (Solar) has problems:

1)Silicon is $$$

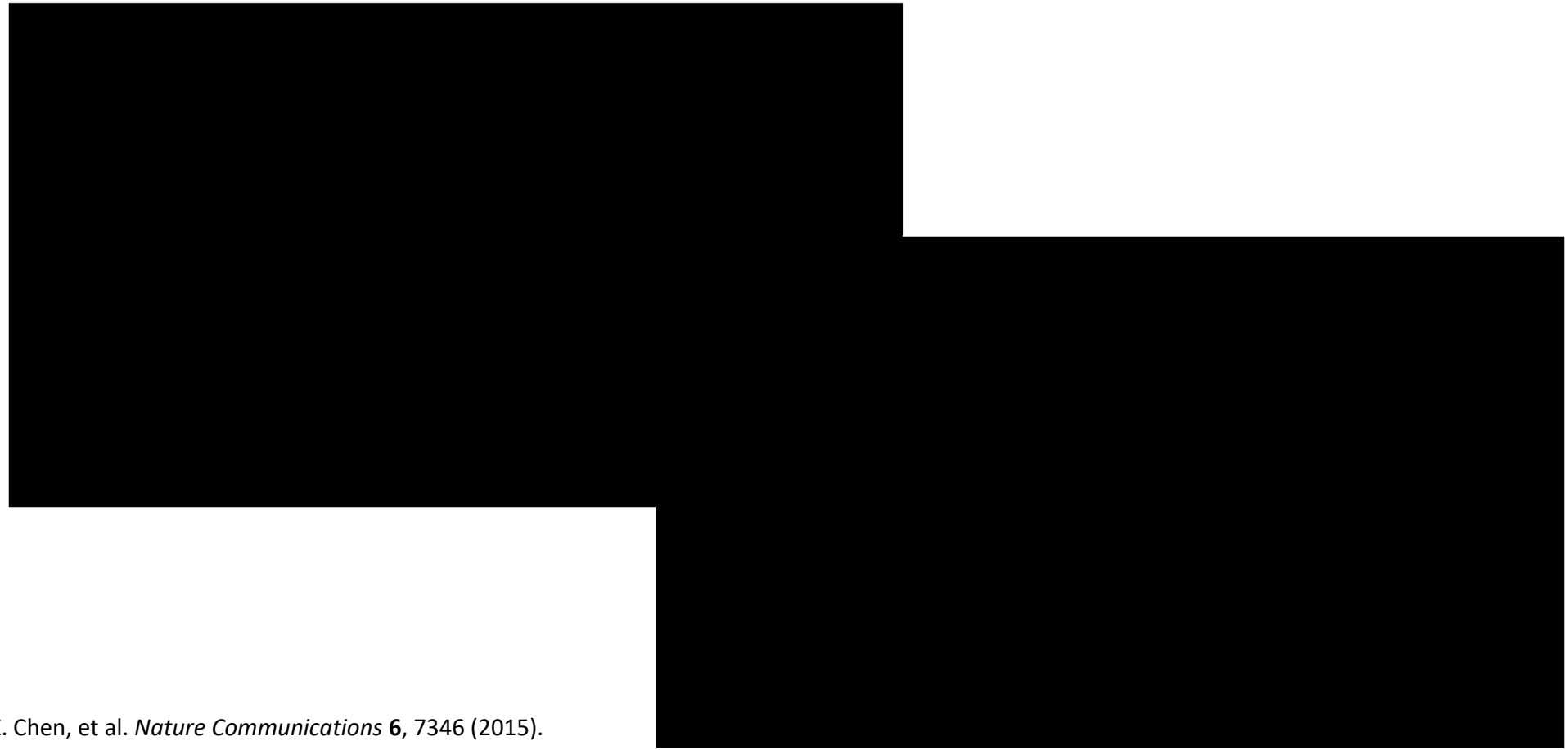
2)Batteries are $$$

3)Intermittency

Evaporation is a Major Control of the Water Cycle



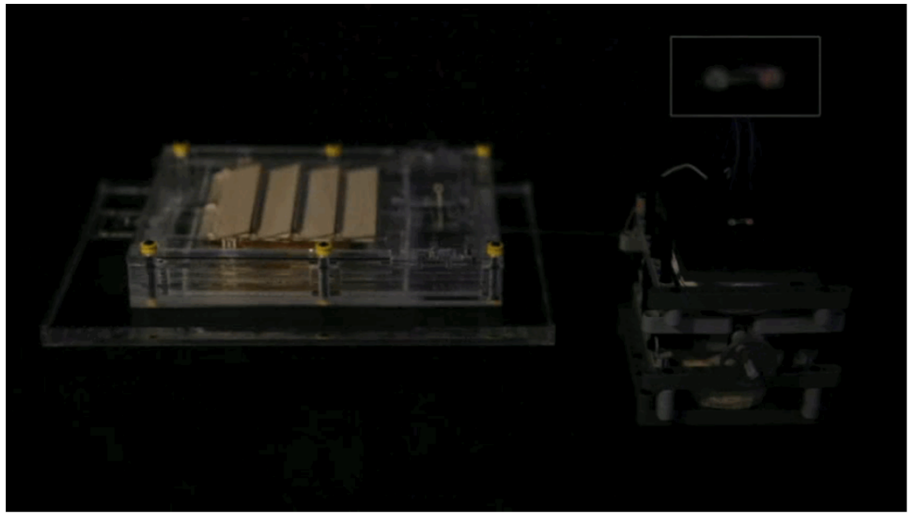
Our Solution



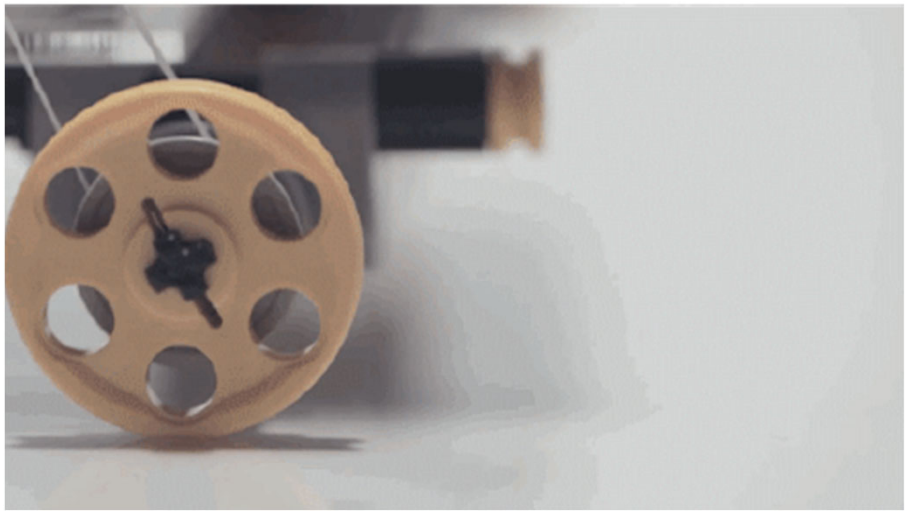
X. Chen, et al. *Nature Communications* **6**, 7346 (2015).

Our Solution

Evaporation Generator



Evaporation-driven Car



BBC NBC NEWS SCIENTIFIC AMERICAN The New York Times Vox

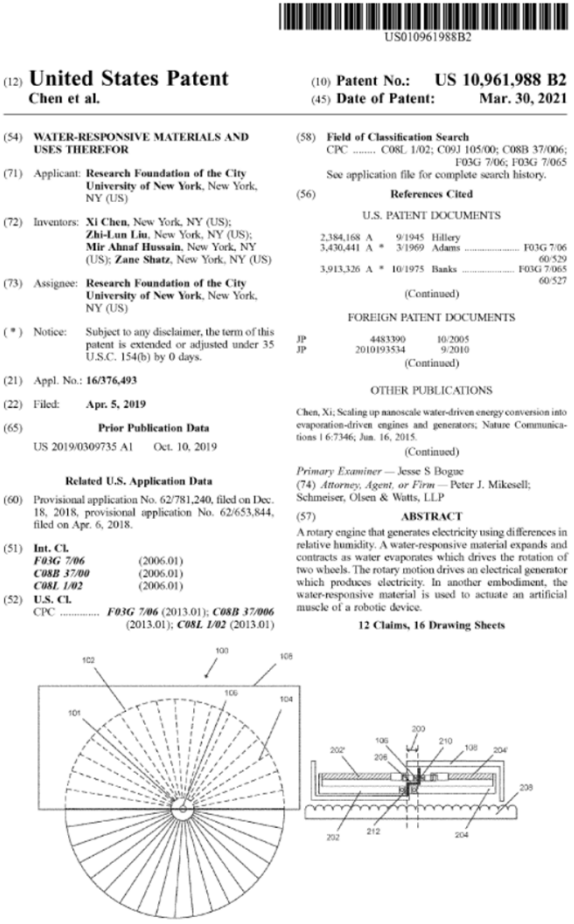
The Washington Post theguardian DER SPIEGEL BUSINESS INSIDER

Our Solution

Solar energy **drives evaporation**
(Evaporation **~ 50% solar**)

Evaporation occurs **day** & **night**
(Occurs **95% of the time**)

Much **cheaper** than silicon
(~100 - 1000x cheaper!)



US010961988B2

(12) **United States Patent**
Chen et al.

(10) **Patent No.: US 10,961,988 B2**
(45) **Date of Patent: Mar. 30, 2021**

(54) **WATER-RESPONSIVE MATERIALS AND USES THEREFOR**

(71) Applicant: **Research Foundation of the City University of New York**, New York, NY (US)

(72) Inventors: **Xi Chen**, New York, NY (US); **Zhi-Lun Liu**, New York, NY (US); **Mir Ahnaf Hussain**, New York, NY (US); **Zane Shatz**, New York, NY (US)

(73) Assignee: **Research Foundation of the City University of New York**, New York, NY (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **16/376,493**

(22) Filed: **Apr. 5, 2019**

(65) **Prior Publication Data**

US 2019/0309735 A1 Oct. 10, 2019

Related U.S. Application Data

(60) Provisional application No. 62/781,240, filed on Dec. 18, 2018, provisional application No. 62/653,844, filed on Apr. 6, 2018.

(51) **Int. Cl.**
F03G 7/06 (2006.01)
C08B 37/00 (2006.01)
C08L 1/02 (2006.01)

(52) **U.S. Cl.**
CPC ***F03G 7/06*** (2013.01); ***C08B 37/006*** (2013.01); ***C08L 1/02*** (2013.01)

(58) **Field of Classification Search**
CPC C08L 1/02; C09J 105/00; C08B 37/006; F03G 7/06; F03G 7/065
See application file for complete search history.

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(Continued)

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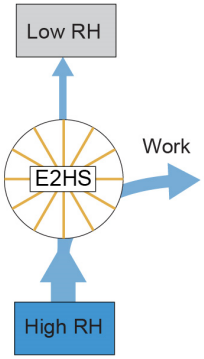
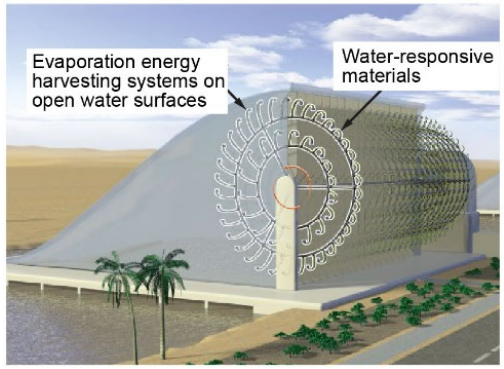
(57) **ABSTRACT**

A rotary engine that generates electricity using differences in relative humidity. A water-responsive material expands and contracts as water evaporates which drives the rotation of two wheels. The rotary motion drives an electrical generator which produces electricity. In another embodiment, the water-responsive material is used to actuate an artificial muscle of a robotic device.

12 Claims, 16 Drawing Sheets

Objectives





- **Technical objective 1**

  Develop high-scalability WR materials (Tu and Chen).

- **Technical objective 2**

  Develop and test laboratory- and meso-scale evaporation energy harvesting devices (Chen and Aydogan).

- **Political/marketing objective 3**

  Feasibility studies: theoretical potential, intermittency, environmental impacts, cost-effectiveness, and scalability (Vörösmarty and Chen).

- **Political/marketing objective 4**

  Marketing strategies for policymakers and the general public (DiSalvo and Chen).

Intellectual Merits and Broader Impacts

- **Intellectual Merits**
  1. Physical aspects: power production and material efficiency.
  2. Techno-economic parameters to inform deployment and opportunities across the nation.
- **Broader Impacts**
  1. Provide pioneering methods to harness the ubiquitous, untapped energy source of natural evaporation for actuation, energy conversion, and environmental protection.
  2. Lead to a new source of clean energy whose power density and production is comparable to current solar and wind farms, but at a much lower economic and resource cost.

	Evaporation	Solar PV	Wind Turbine
Power Density	**~10 W/m^2**	~6-9 W/m^2	2-4 W/m^2
Aggregate Capacity (% US 2020 Electricity Generation)	**~325 GW (70%)**	48 GW (2.25%)	118 GW (8.4%)
Average Production Cost	**~ 2 ¢/kWh**	~ 10 ¢/kWh	~ 5 ¢/kWh

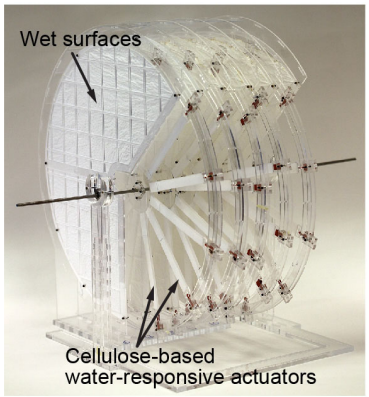
Technical Approach

- **Technical objective 1** (**Tu** and **Chen**)
  1. Reduce the parameter space of potential materials by focusing on critical benchmarks of WR power density (>50 kW/m^3), efficiency (>10%) and scalability.
  2. Material processing to define a set of silk-based films where a different degree of crosslinking or welding defines WR properties for different operating conditions.

  Contingency plan: We will use spores, peptidoglycan, cellulose and copolypeptides as backups if silk-based WR materials failed to reach the performance targets.

- **Technical objective 2** (**Chen** and **Aydogan**)
  1. Build a series of testbeds from laboratory- (0.2 to 1 meter) to meso-scale (1 to 10 meters) that are easy to reconfigure for different WR materials and adjust for optimizing power output.
  2. Create a plant-based, evaporation-powered air filtering system.

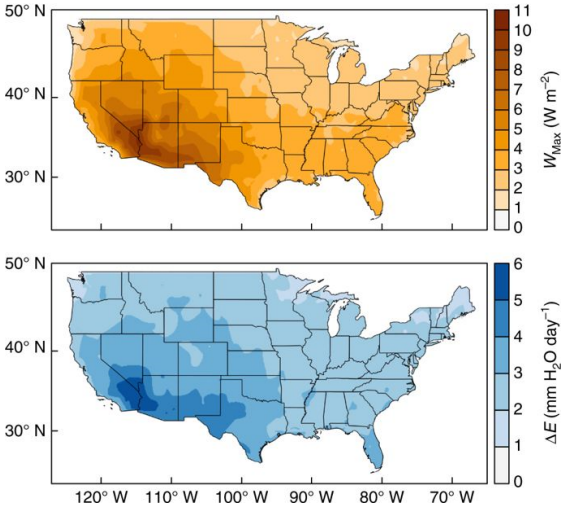
  Contingency plan: Three other recently patented device configurations, including a horizontally rotary engine and an oscillatory engine, will be used as backups.



Technical Approach

- **Political/marketing objective 3** (**Vörösmarty** and **Chen**)
  1. Develop theory and simulations that describe the whole energy conversion and transfer processes.
  2. Determine the theoretical potential of the system and its management for application in electricity generation scenarios in a variety of environments.

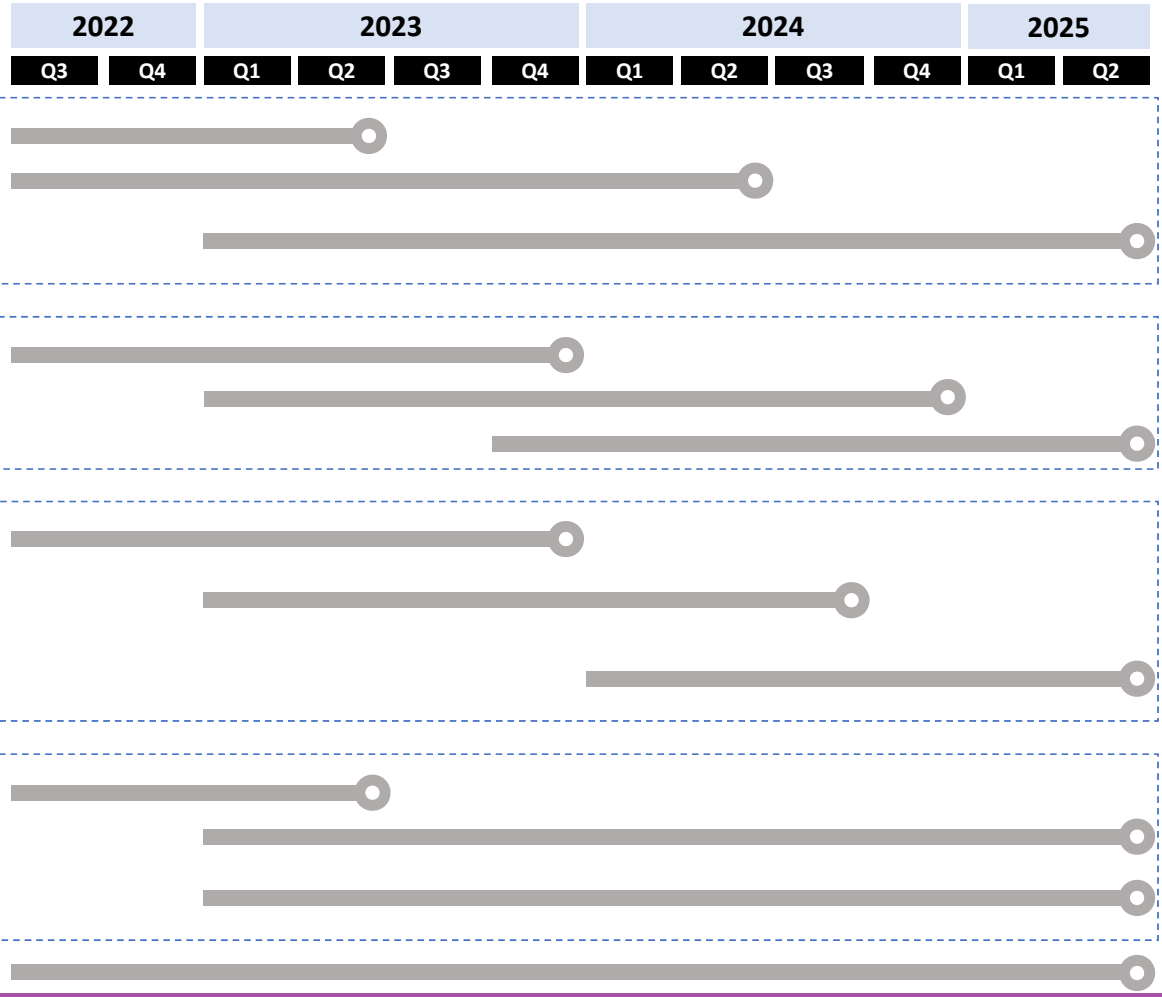
  Contingency plan: The system dynamics simulations are flexible enough to accommodate any changes under Obj.1&2 as they potentially materialize.



- **Political/marketing objective 4** (**DiSalvo** and **Chen**)
  1. Develop marking materials, where the evaporation energy harvesting technique will be compared to existing renewable energy to show the potential of our technique.
  2. Gather information and create a contact list of these relevant agencies.

  Contingency plan: DiSalvo and Chen, together with other team members, will closely work together to accommodate any changes under Obj.1-3.

Team Milestones



Obj. 1 High-scalability WR materials (*Tu & Chen*)

- Fabrication systems for high-scalability WR materials.
- Crosslinking dependent WR characteristics of silk and its composites.
- A series of centimeter scale, silk-based WR materials with tunable WR characteristics.

Obj. 2 Evaporation energy harvesting devices (*Chen & Aydogan*)

- Lab-scale (~ 0.2 to 1 meter) rotary devices.
- Self-powered indoor purification systems.
- Meso-scale (~ 1 to 10 meter) rotary devices.

Obj. 3 Feasibility studies (*Vörösmarty & Chen*)

- Models to simulate the performance of rotary devices
- Models that predicts the potential of evaporation energy harvesting as a function of climate and geographic conditions.
- The theoretical potential of the system for application in electricity generation in a variety of environments.

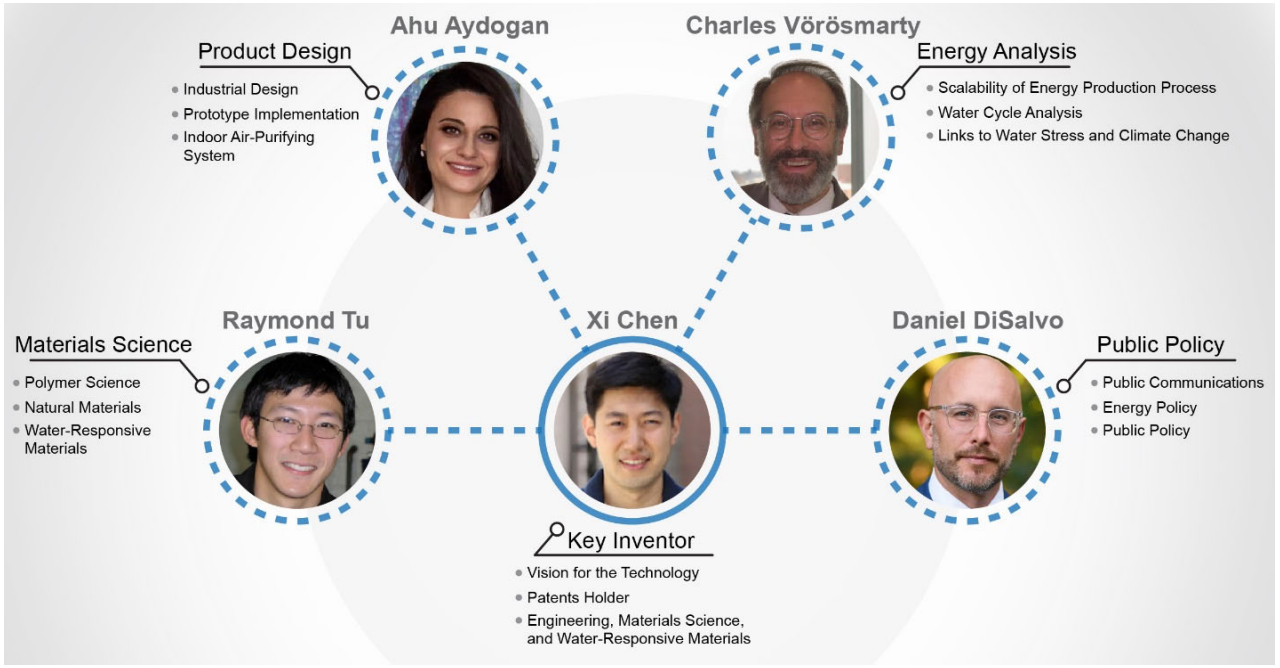
Obj. 4 Marketing strategies (*DiSalvo & Chen*)

- Information collection and analysis of existing renewable energy.
- Contacts and materials to pitch evaporation energy.
- Conference presentations, videos, media coverage, on-site visits, publications in major newspapers, and business plans.

Project Meetings, Proposal Development, Annual Reports and Retreats

Annual Technical Reports and Project Retreats on every Q2.

Team Qualifications

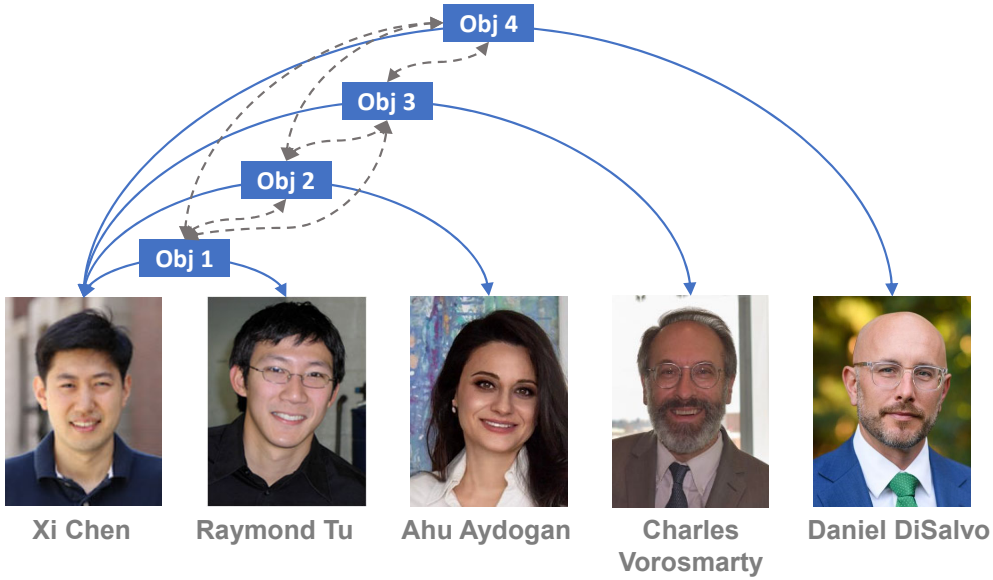


Research Funding: ~$ **7.1 M** in the last **3** years

Team Qualifications

- **High-scalability WR materials**
  - **Biomaterials –** Dr. Tu and his team explore new biomolecular architectures that self-assemble to yield nanostructured materials with rationally designed bioinspired properties.
  - **Scalable silk-based WR materials –** Drs. Tu and Chen have co-developed silk-based WR materials.
- **Evaporation energy harvesting devices**
  - **Rotary devices –** Dr. Chen invented a series of evaporation energy harvesting devices.
  - **Plant-based purification systems –** Dr. Aydogan has completed significant work in plant-based air purifying systems.
- **Feasibility studies**
  - **Energy analysis –** Dr. Vörösmarty has led several energy analysis projects, focusing on regional and national electrical energy systems and their sensitivity to climate change, water stress, and affiliated extremes.
  - **Modeling of the evaporation energy harvesting technique –** Dr. Chen has published a preliminary model that predicts the potential.
- **Marketing strategies**
  - **Public Communications and Energy/Public Policy –** Dr. DiSalvo has conducted extensive research on public policy processes and political communications in the United States.

Management Plan



Tu and **Chen** will provide WR materials and WR characteristics to efforts in the device development and modeling. **Chen** and **Aydogan** will provide the device properties to efforts in modeling, feasibility studies, and marking strategies. **Vörösmarty** and **Chen** will provide simulated device performance metrics to support device development and marketing strategies. **DiSalvo** and **Chen** will collect information from Obj. 1-3 and develop marketing strategies. **Chen** will coordinate all proposed efforts.

Project Meetings: The team will arrange meetings every month to share results, seek input, and provide opportunities to trainees to present and hear about research in other project groups. The teams gather once a year for a day-long, in-person project retreat to promote interactions.

Future Funding Prospects and Self-Sustaining Plan

- **CRV efforts**
  1. Make the first transformative progress.
  2. Position CCNY at the center of this emerging field of “Hygroscience.”
  3. Inform the scientific community, policymakers, and the general public about the potential of evaporation energy.
- **Funding support**
  1. Current supports:
  2. Potential funding agencies: DoE, DoD, NSF, and Alfred P. Sloan Foundation.
- **Opportunities for “Hygroscience” in 5-10 years**
  1. Find applications in other fields and in new technologies.
  2. Consolidate the new research field of “Hygroscience.”
  3. Different funding sources can propel the future progress of the field.

Image credit: Simi Luft