# Symbiotic Systems for The Future of Energy, Water, and Food


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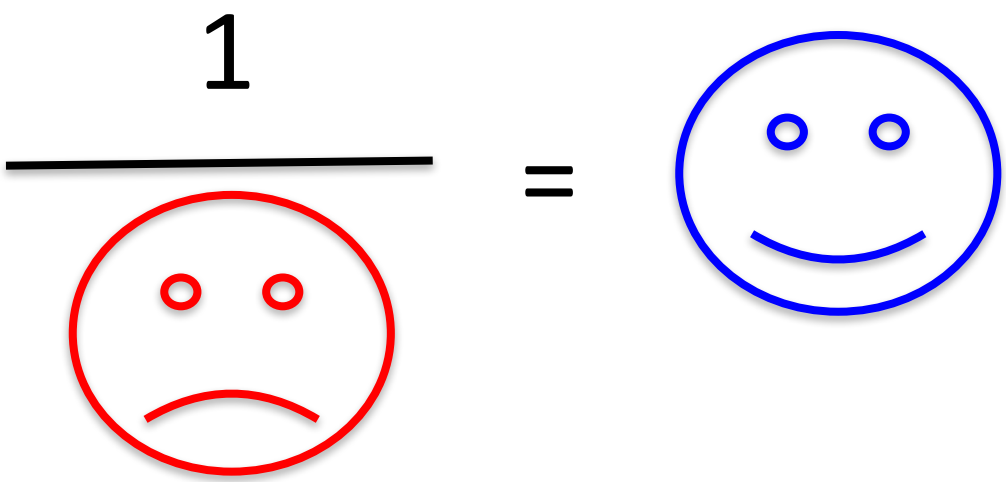


# Overall Theme of this Presentation:
## Energy is *KEY* to EVERYTHING
## Everything is the *KEY* to energy

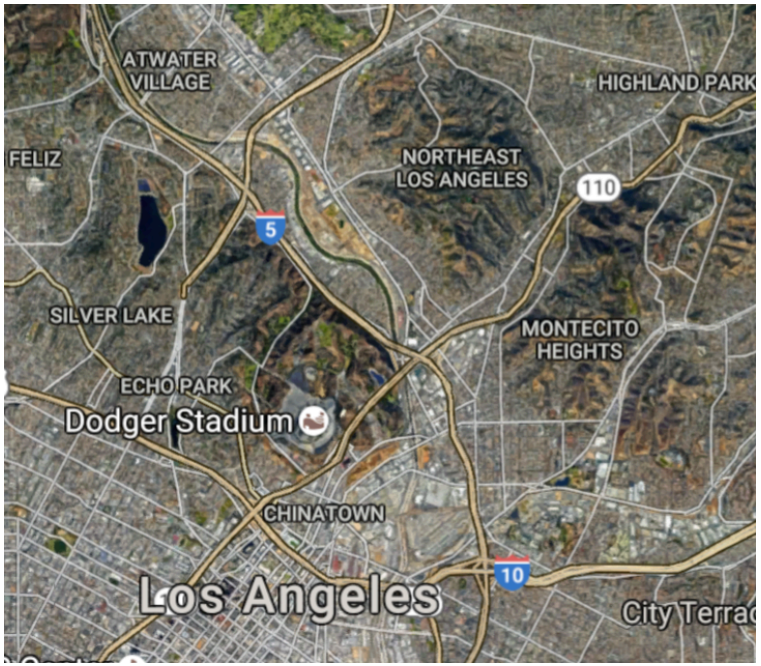
- Materials can catalyze *BIG* Changes in humanity
- Automation drives down cost of renewables and storage
  - Just as cell phones enabled bypassing land lines…
  - Incremental advances will creep us to the tipping point…
- Symbiotic relationships will help create tipping points
  - Solar energy farms *with* energy storage, hydroponic farming
  - Offshore wind *with* fish farms, energy storage, uranium mining
  - Hydrocarbons *with* nuclear (spent fuel disposal)
  - Seawater pumped hydroelectric *with* reverse osmosis
  - Saving Planet *with* Education

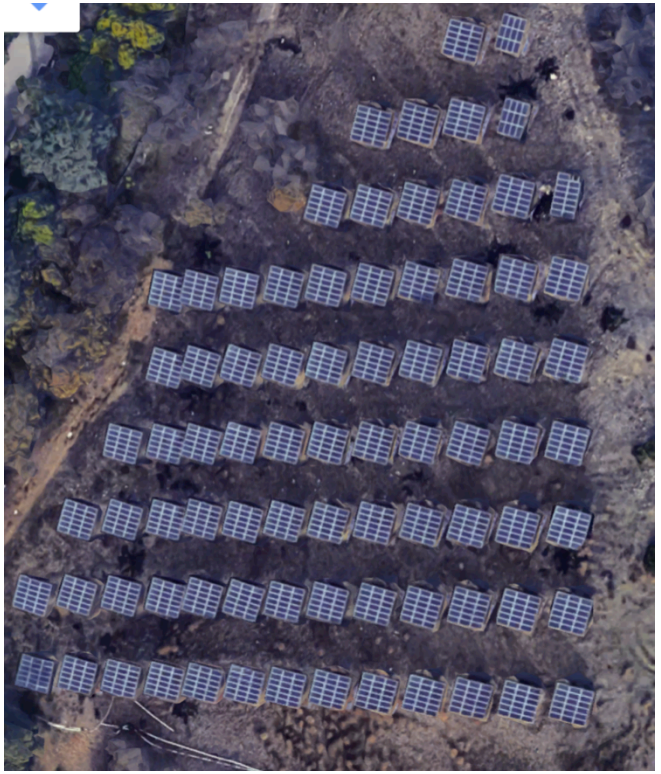
# Topics (*Opportunities!*)

- PV: its not just for flat planes and rooftops
  - Hillsides
- Offshore wind
  - + Aquaculture
  - + Mineral harvesting from seawater
  - + Energy Storage
- Reducing cost of wind energy
  - Tapered spiral welded towers
- Integrated Pumped Hydro Reverse Osmosis System

# Hillsides are great for PV!

- Less shading means potential for closer spacing and lower cost mounts
  - There are a lot more unused steep hillsides facing south than flatlands



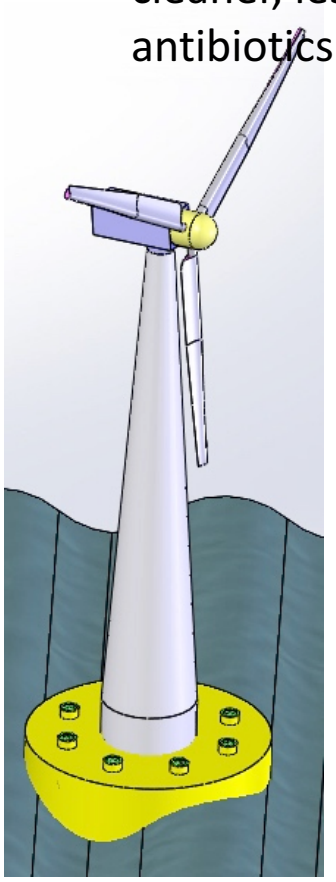
# Hillside Solar in Asia

## A great opportunity for innovation!

Autonomous deployment and maintenance machines will be needed

# Offshore Wind *with* Aquaculture

- Wind and Aquaculture can go hand in hand
  - Far offshore water is cleaner, less need for antibiotics



| Symbiotic System Requirements | | |
|---|---|---|
| population served | 10,000,000 | |
| kg of fish per person per day | 0.2 | |
| average electric power per person (includes industry needs) (kW) | 2 | |
| average net electric power per offshore wind turbine (MW) | 2 | |
| Percentage of population to be covered by grand challenge | 50% | |
| **Wind Farm Parameters** | | |
| People served per wind turbine | 1000 | |
| number of wind turbines required | 5,000 | |
| ocean area per turbine (km^2) | 1 | |
| rectangle ratio (length/width) | 1.6 | 10 |
| ocean rectangle width (km) | 56 | 22 |
| ocean rectangle length (km) | 89 | 224 |
| wind turbines installed per day | 4 | |
| years to full installation | 4 | |
| **Aquaculture System** | | |
| years to mature fish from fry to harvest | 1 | |
| kg/fish | 1 | |
| fish per person per wind turbine based pen | 73 | |
| total fish to be contained in a pen supported by a wind turbine | 73000 | |
| water volume per fish (m^3) | 2 | 1 |
| total volume water to be encased by wind turbine based pen (m^3) | 146000 | 73000 |
| diameter of spherical pen to contain fish | 65 | 52 |
| diameter of cylindrical tank (diameter = height) (m) | 57 | 45 |
| **Comparison with Nuclear Power** | | |
| nuclear power plant size (MW) | 2000 | |
| equivelant number of nuclear power plants | 5 | |

See for example: Buck, Bela H., Gesche Krause, and Harald Rosenthal. "Extensive open ocean aquaculture development within wind farms in Germany: the prospect of offshore co-management and legal constraints." Ocean & Coastal Management 47 (2004): 95-122

# A Planetary Grand Challenge?

## Symbiotic *Energy and Food from the Sea*

- Why a grand challenge?
  - Romans challenged their legions to compete with each other to most rapidly build the highest quality sections of roads and other structures, such as Hadrian's Wall.
- Overall System Requirements: How many people are to be served, and how much fish and power do they need will be the primary system configuration drivers.
  - Wind Farm: How many turbines are needed? How big the wind farm needs to be? How many years will be required to complete the system?
  - Aquaculture: Size and type of confinement zones around each turbine? Feeding? Waste management?

# Asia Could Catalyze the World

- Challenge its cities to compete to create offshore wind energy and aquaculture farms:
  - "as long ago as the 12th Century B.C., there were fish rearing records in the Chinese Classics of early Chou Dynasty (1112–221 B.C.)."
  - 'The Chinese Fish Culture Classic' was originally written by Fan Lee, a politician turned fish culturist, in ancient China during the 5th Century B.C." .

# Example

| **Symbiotic System Requirements** | | |
|---|---|---|
| population served | **10,000,000** | |
| kg of fish per person per day | **0.2** | |
| average electric power per person (includes industry needs) (kW) | **2** | |
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| People served per wind turbine | **1000** | |
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| ocean area per turbine (km^2) | **1** | |
| rectangle ratio (length/width) | **1.6** | **10** |
| ocean rectangle width (km) | **56** | **22** |
| ocean rectangle length (km) | **89** | **224** |
| wind turbines installed per day | **4** | |
| years to full installation | **4** | |
| **Aquaculture System** | | |
| years to mature fish from fry to harvest | **1** | |
| kg/fish | **1** | |
| fish per person per wind turbine based pen | **73** | |
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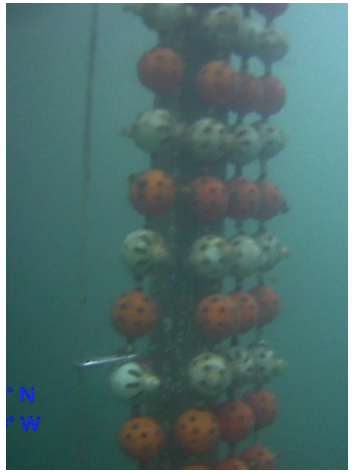
| total volume water to be encased by wind turbine based pen (m^3) | **146000** | **73000** |
| diameter of spherical pen to contain fish | **65** | **52** |
| diameter of cylindrical tank (diameter = height) (m) | **57** | **45** |
| **Comparison with Nuclear Power** | | |
| nuclear power plant size (MW) | **2000** | |
| equivelant number of nuclear power plants | **5** | |

# Harvesting Minerals From Seawater

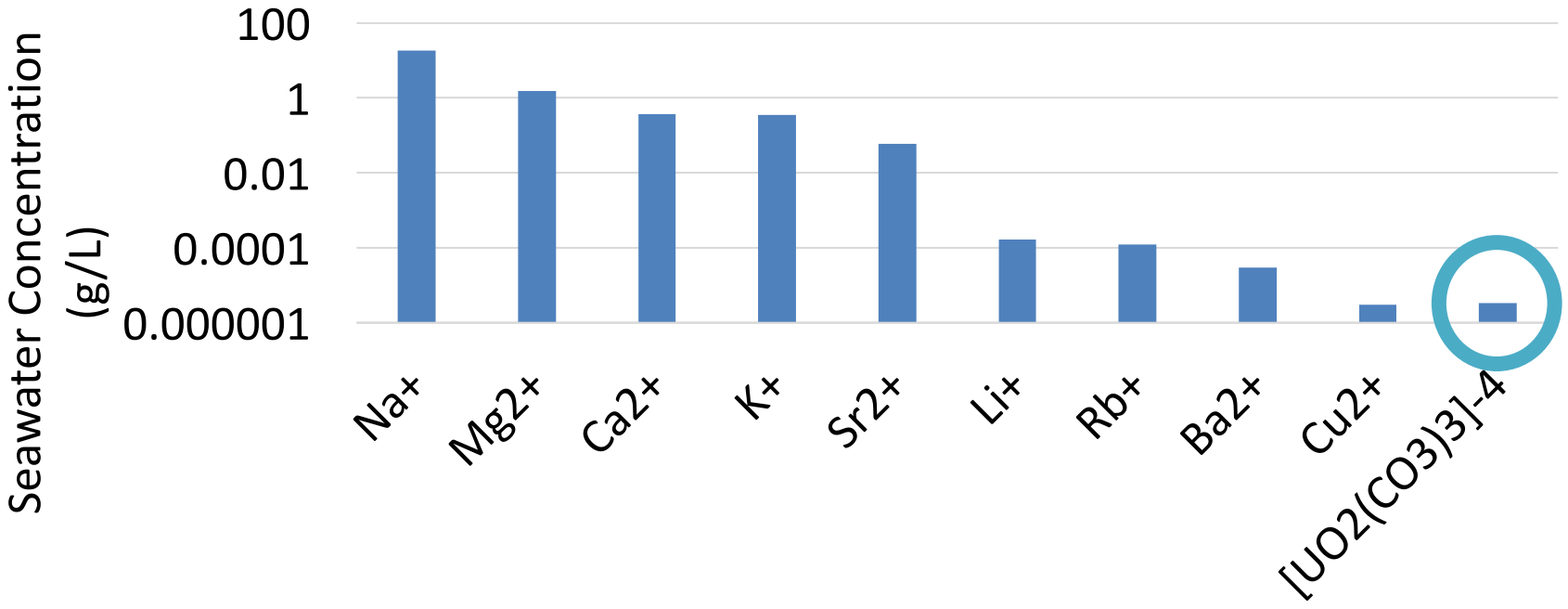
- Initial focus: System to harvest uranium from seawater
  - Shell enclosure for uranium adsorbing polymer decouples chemical & mechanical requirements:
    - Ocean tested two 1/10th physical scale prototypes.
    - Achieved >30% cost-reduction in seawater uranium production cost.
- Longer term: “strategic” minerals could be harvested
  - E.g., Cobalt will be needed in vast quantities for battery Gigafactories!
- ***Great potential to reduce conflicts between countries***
  - ***Its time to put the World First!***
  - ***http://www.untoldrecords.com/marcgrahamphd/worldfirst3.mp3***



# Minerals in Seawater

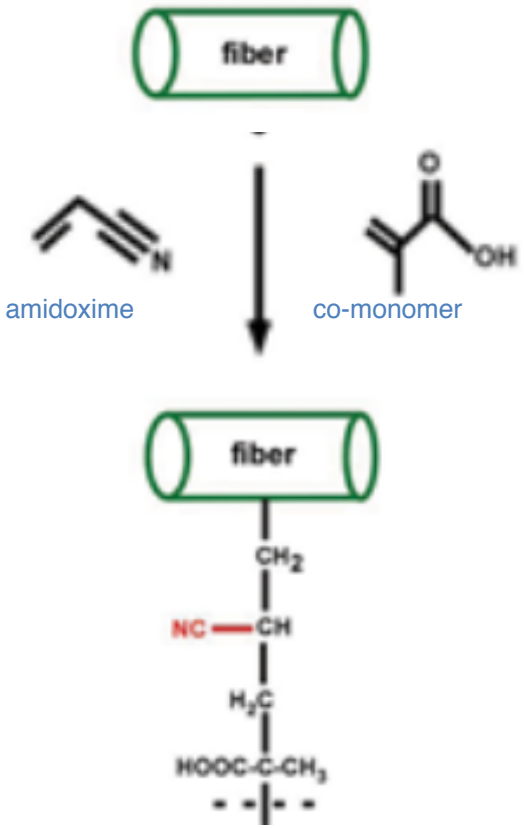
## *Especially Uranium*

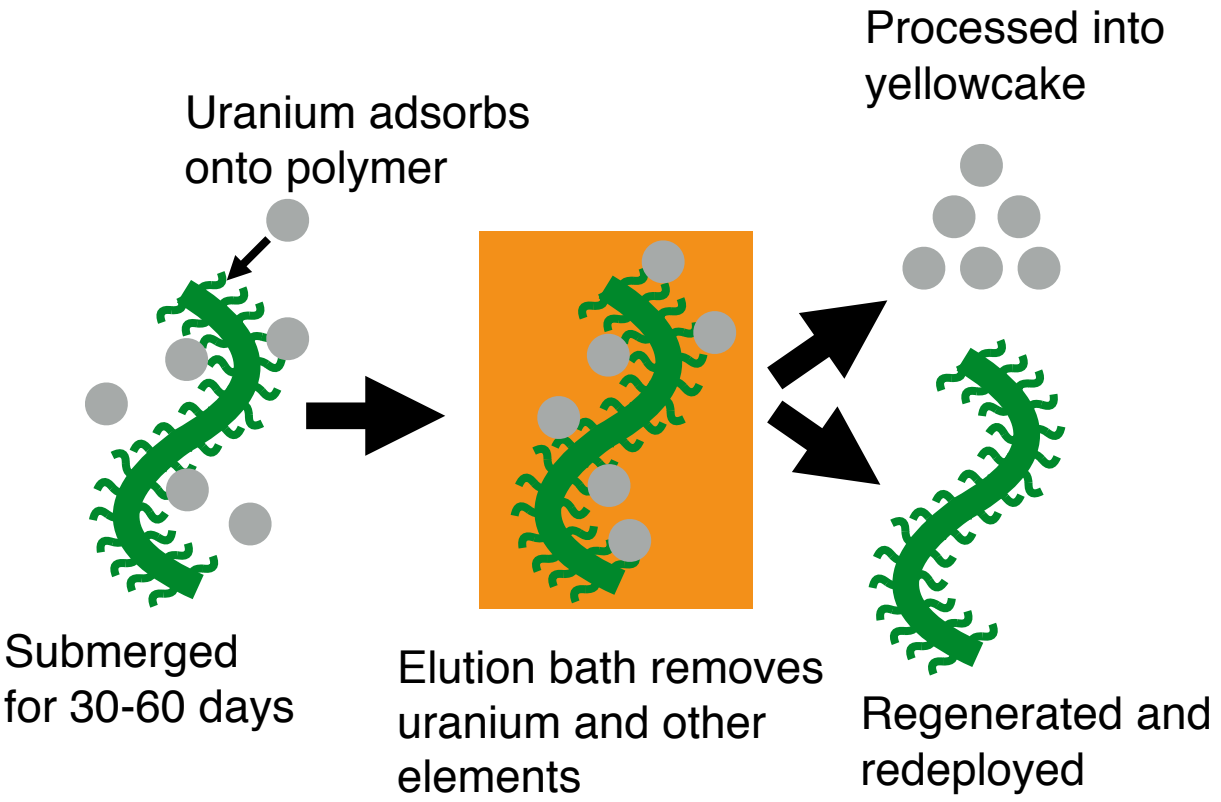
- Uranium exists in stable tricarbonate complex [UO2(CO3)3]-4
- Must dissociate into uranly ions UO2+ to bind as other cations.
- Uranium is not the dominant cation in seawater
- Near the surface: (deeper, e.g., cobalt, others are also abundant)



# Materials: Keys to Our Future

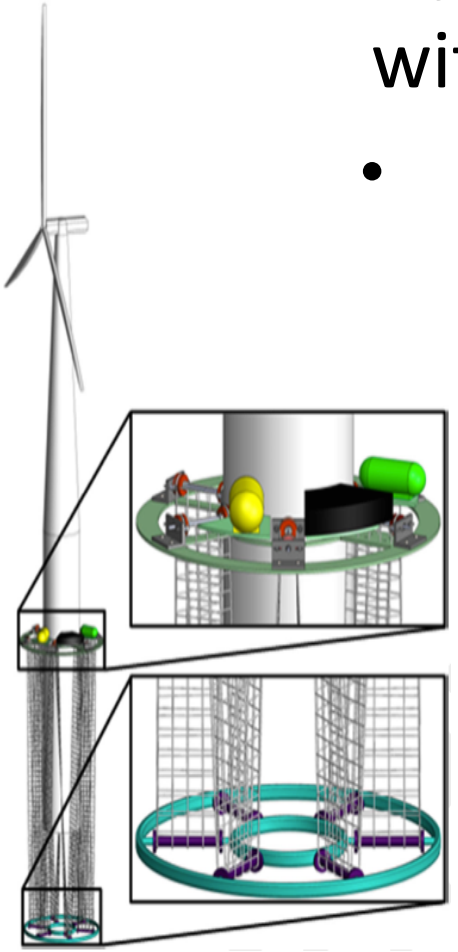
- Passive uranium adsorption by chelating polymers most promising in terms of cost, adsorption capacity, & environmental footprint [Kim et al., 2013]



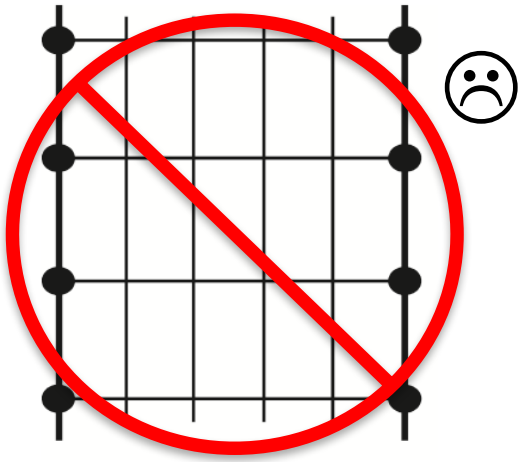
# Hypothesis: Symbiotic System

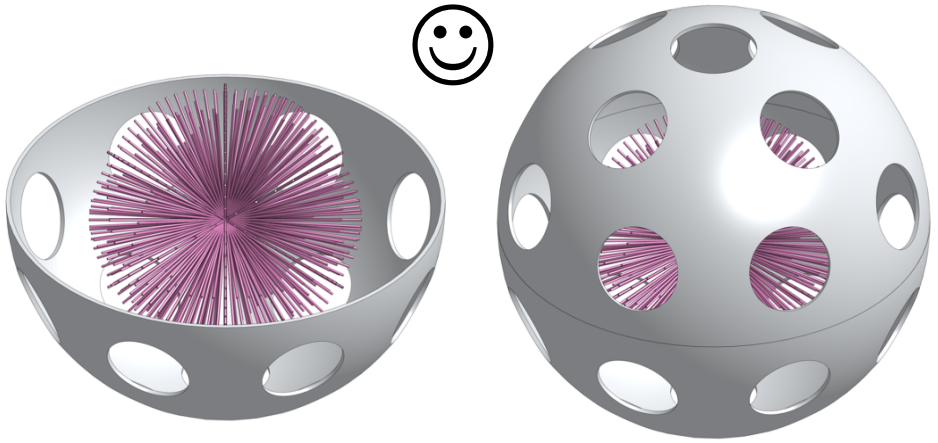
- Hypothesis: An offshore symbiotic system with on-site elution could reduce $/kg-U
  - Picard et al. (2014) designed uranium harvesting system attached to OC3-Hywind offshore wind turbine tower
    - Reduces mooring and deployment costs
    - Would harvest 1.2 tonnes of uranium per year, enough for 5 MW nuclear power plant



# *The BIG Idea:* Shell Enclosure

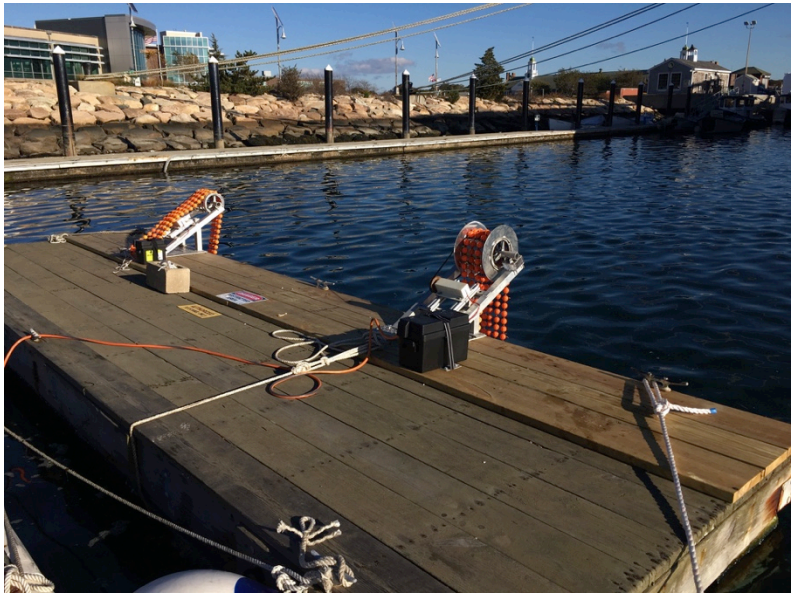
- Protective outer sphere with large holes for water passage.
  - Allows chemists to investigate adsorbents that do not require polyethylene trunk for strength.
  - Decouples chemical & mechanical requirements

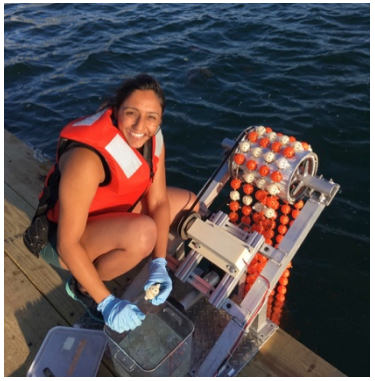


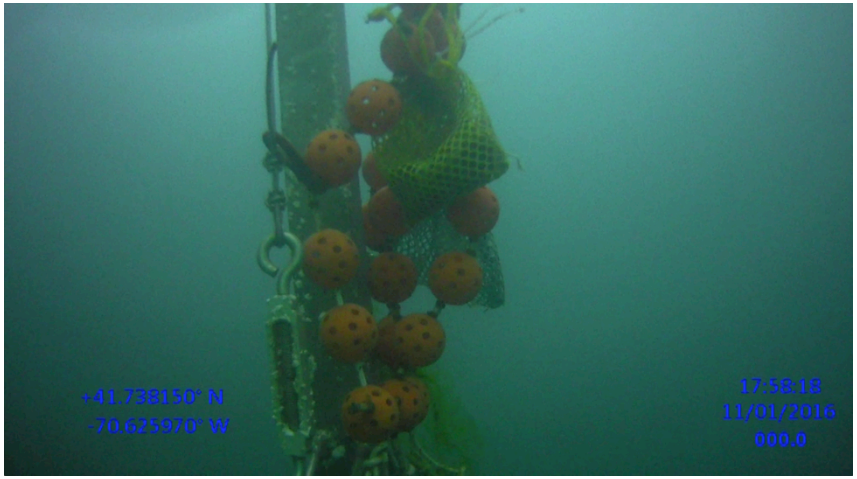


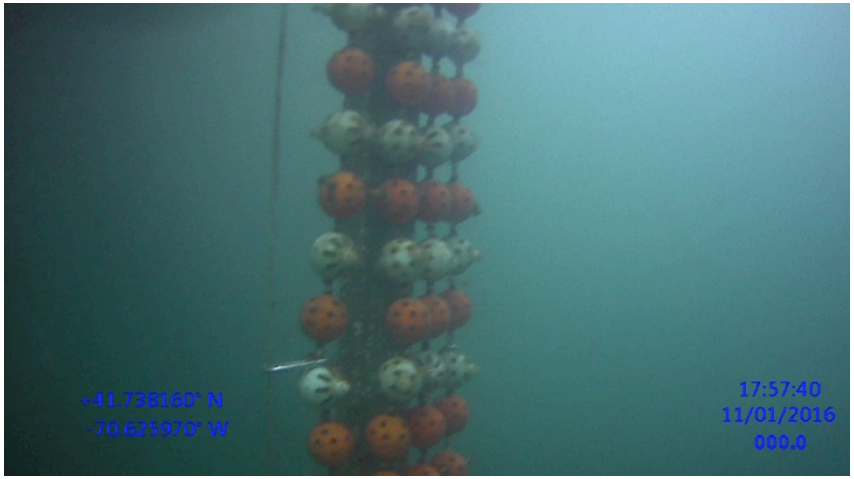
[Haji et al., 2015]

# 1/10th Prototype: Adsorbent Deployment

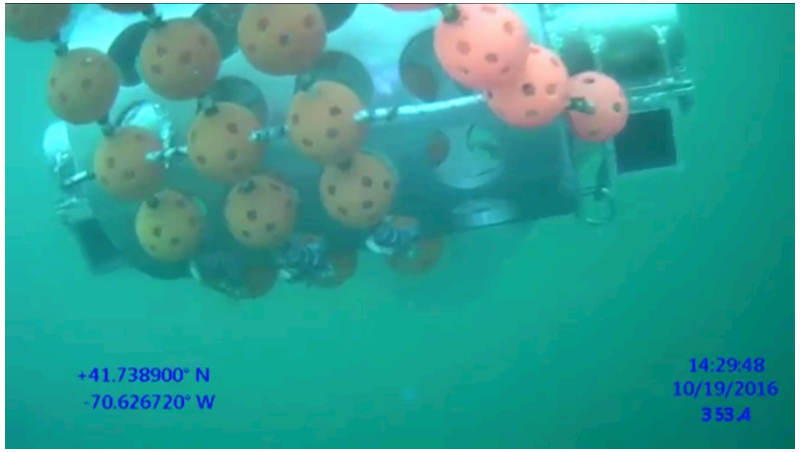


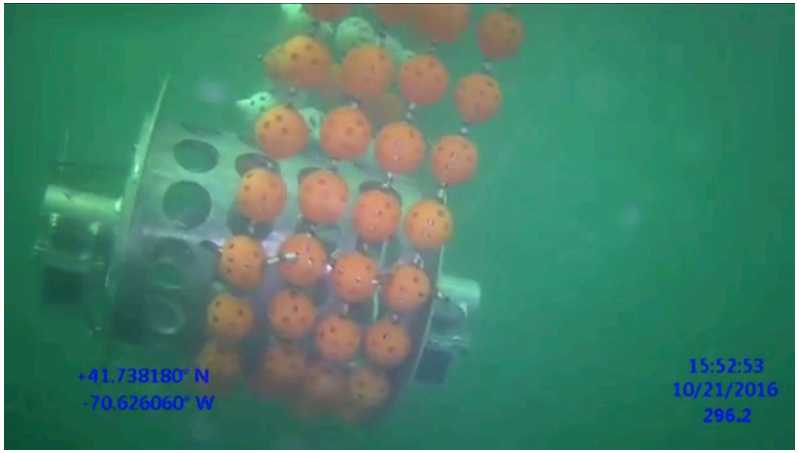


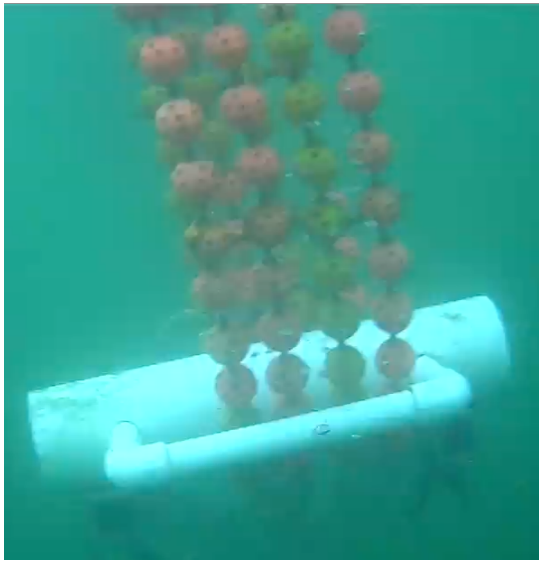


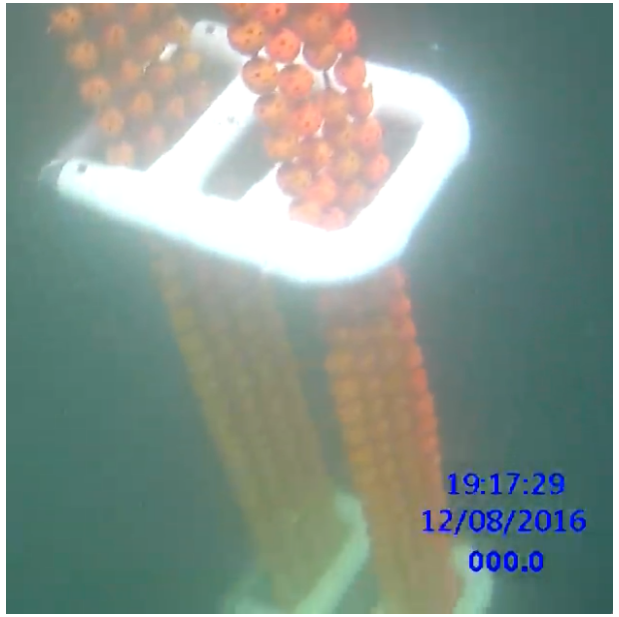



# Ocean Test: It Works!



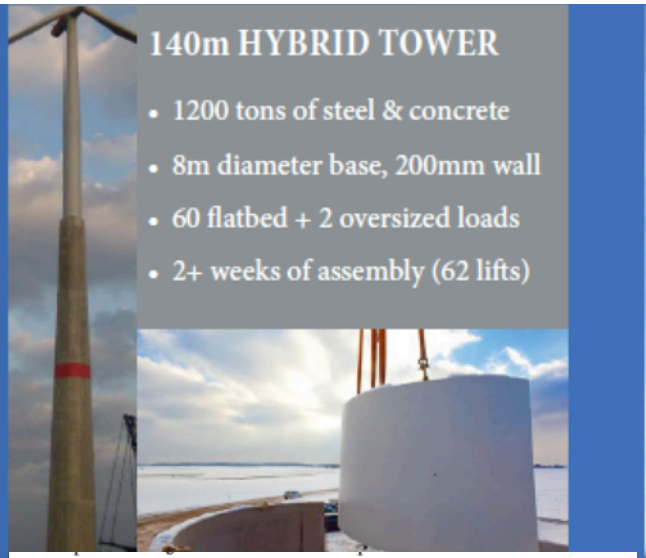



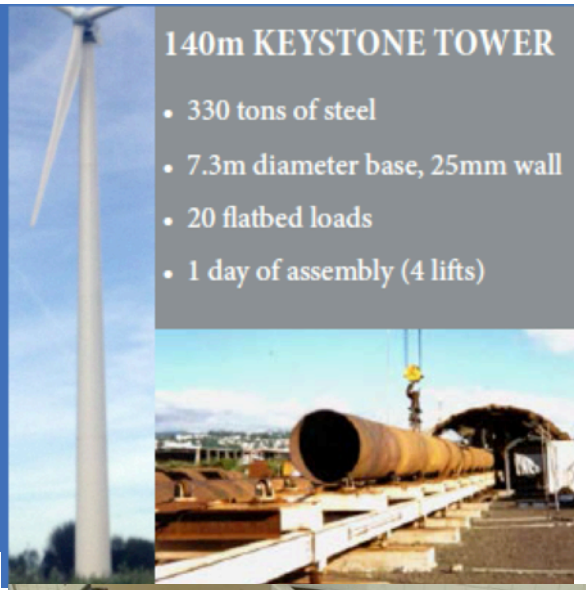



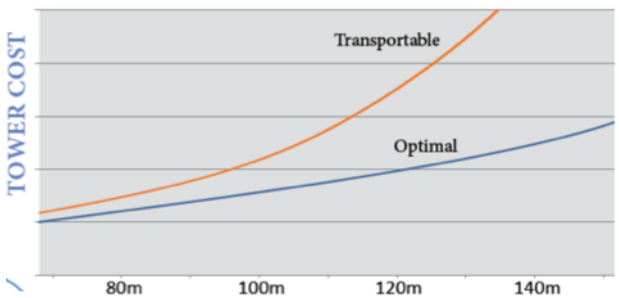


# Lowering the Cost of Wind Energy by 10%

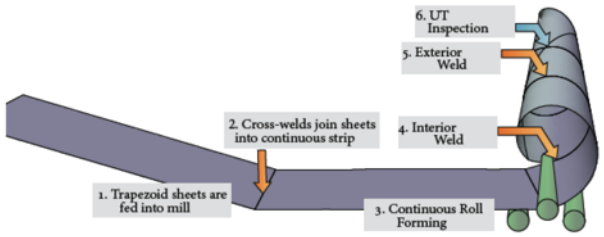
- Tall towers make class III @ 80 m sites into Class 4 sites @ 120-140m
  - Maine goes from 6 GW potential to 60 GW potential!
- Keystone Tower Systems, Inc. in-situ tapered tower manufacturing

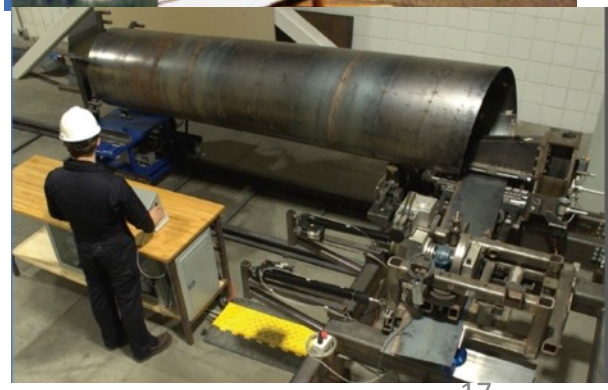




DELIVERED AND INSTALLED TOWER COST VS. HUB HEIGHT



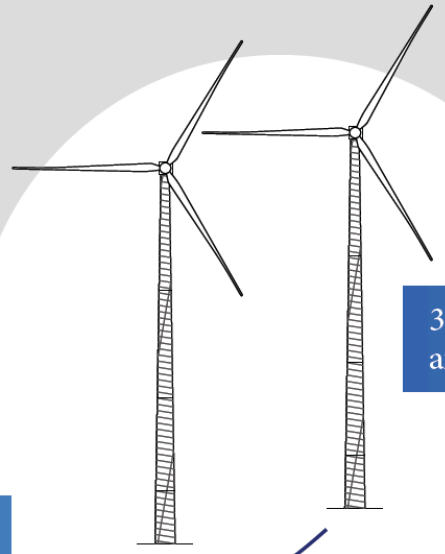



# ON SITE SPIRAL WELDING

The pipe industry has already shown that on-site spiral welding is an attractive way to get around transportation limits. Keystone's innovations bring this technology into the wind industry, unlocking the potential of much taller towers.

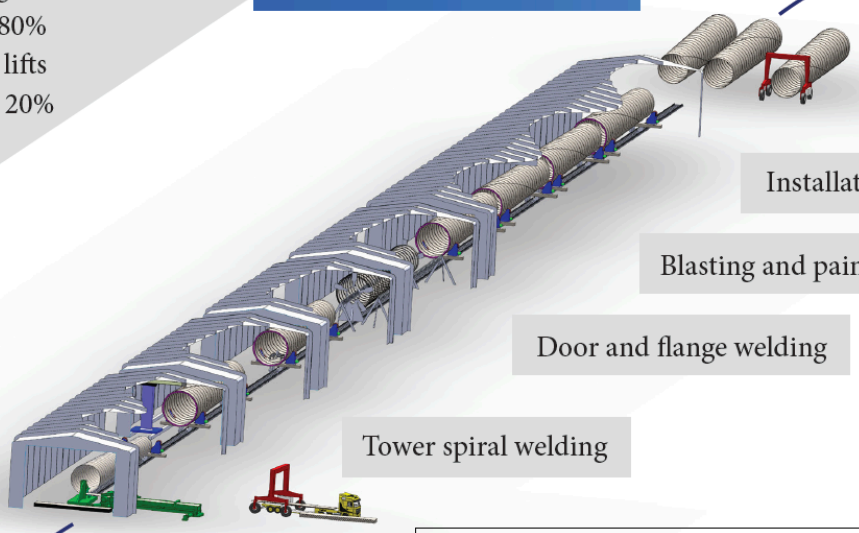
## ON SITE SPIRAL WELDING ENABLES LARGE DIAMETER TALL TOWERS

- 100+ tons of steel saved per tower by increasing diameter
- Standard trucks reduce shipping costs by over 80%
- Larger tower sections enable fewer flanges and lifts
- Larger base flange reduces foundation costs by 20%
- Thinner walls allow use of lower cost steel coil rather than plate
- Locally manufactured towers may satisfy local content requirements



3. Tall towers are erected

2. Towers are spiral welded at the wind farm



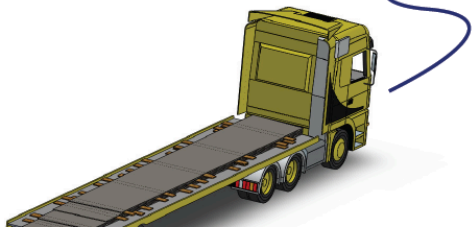
Installation of internals

Blasting and painting

Door and flange welding

Tower spiral welding

1. Steel is shipped as flat sheets



## ON-SITE SPIRAL WELDING BY THE NUMBERS

- Can be deployed at a new site in just three weeks
- Deployment justified for projects with as few as 5 towers
- Only 2 acres (1 ha) required for setup (smaller than a laydown yard)
- The mobile facility is staffed by a crew of just 30
- Towers can be produced and erected at a rate of one a day

# Premium Spiral Tower Mill

September 2017

# Keystone Tower Systems and SMS Group partnership

KEYSTONE TOWER SYSTEMS

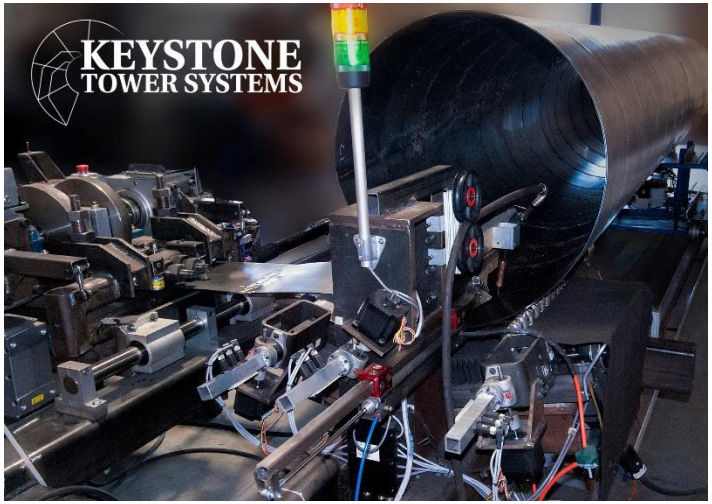
**Innovative Tower Technology Producer**

Inventor of Spiral tower mill technology for high throughput, automated wind tower production.

SMS group

**Leading Partner in the World of Metals**

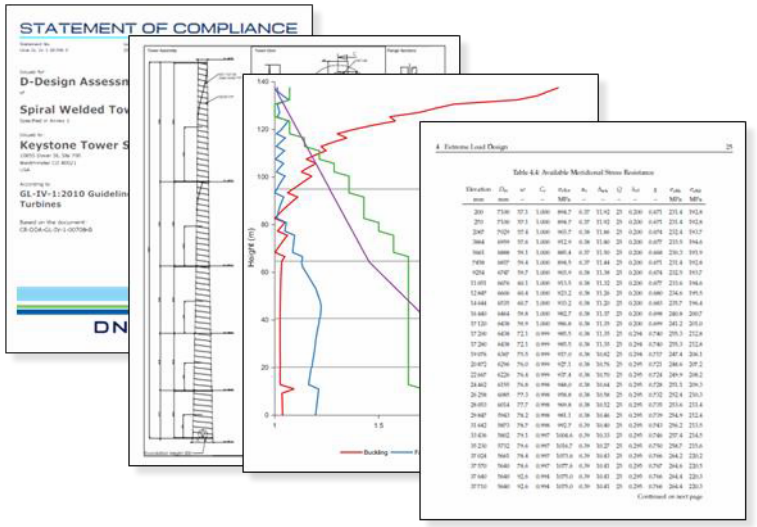
Global player in plant construction and mechanical engineering for the steel and nonferrous metals processing industry. 50 years of experience in pipe mill technology

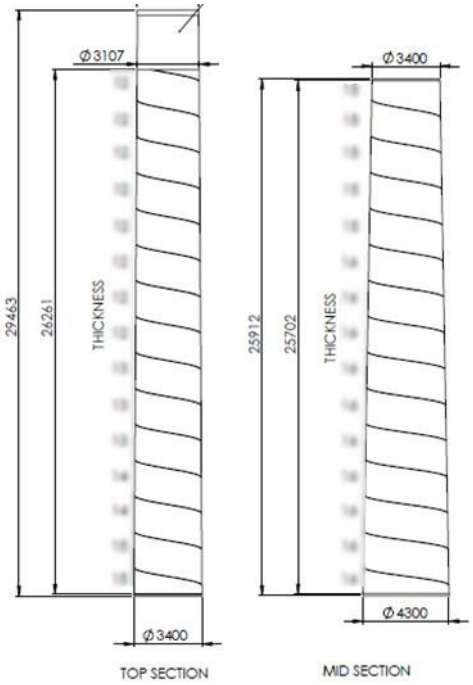



KEYSTONE TOWER SYSTEMS

# Spiral towers designed for leading OEMs

- Potential penetration:
  - 95%+ of US market share
  - 40%+ of EU market share
- New designs require minimal time



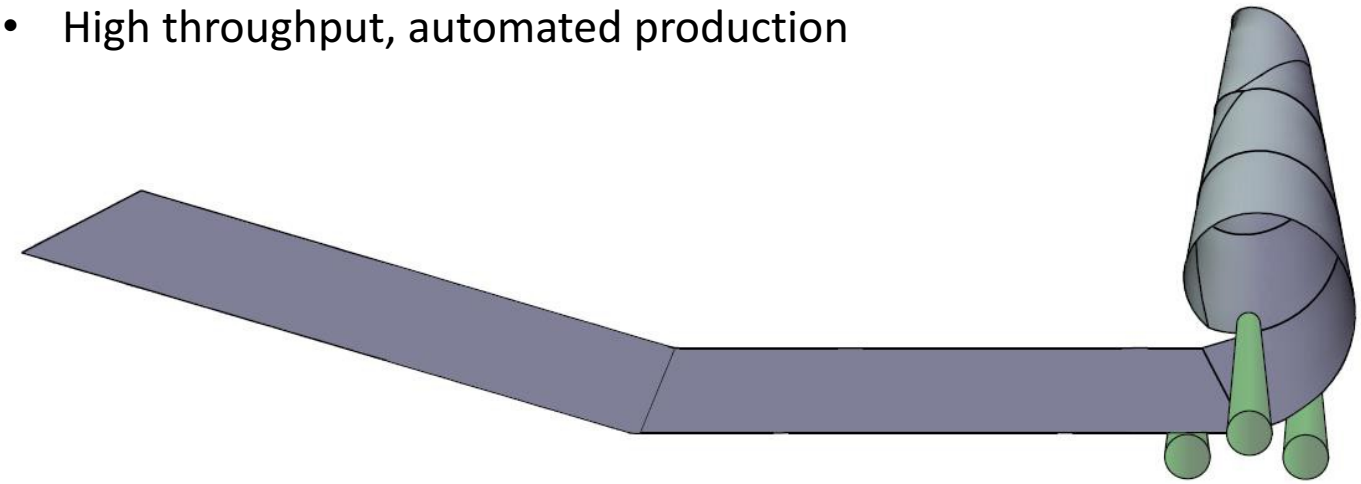
# Premium Spiral Tower Mill

Straight, fixed width steel stock

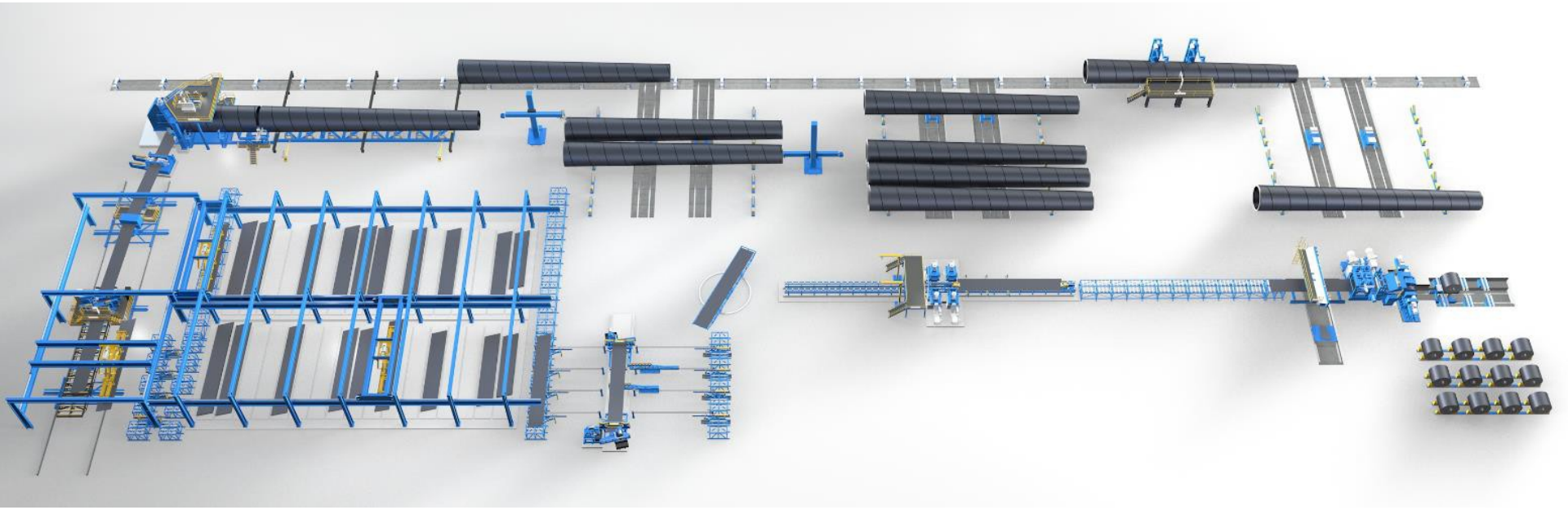
Tapered Spiral Welding

variable diameter, variable thickness, large diameter steel tubes

- In-situ manufacturing using proprietary process and machines:
  - 30% less steel and potentially no flange joints
  - Simultaneous rolling & welding
  - High throughput, automated production



# Layout for black shell production

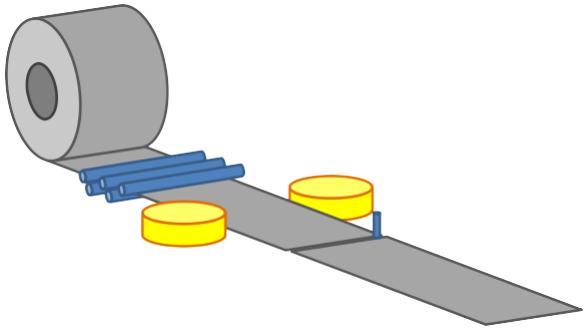


At a glance:

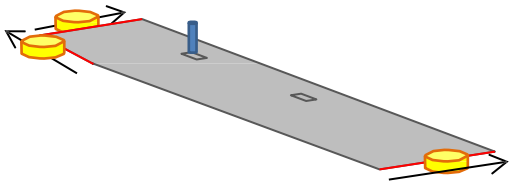
- 600 tower/year
- 50% labor savings
- 30-50% smaller footprint

# Production sequence for black shell production

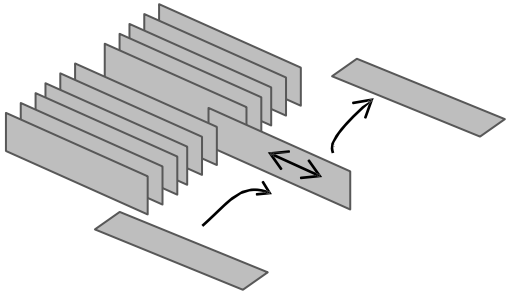
1. Unroll and edge mill

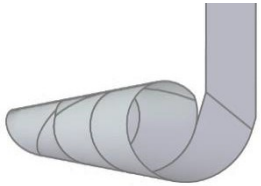


2. Short edge mill and etch

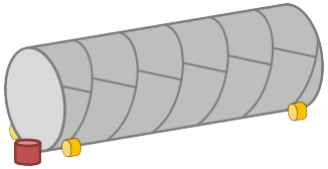


3. Sort and store

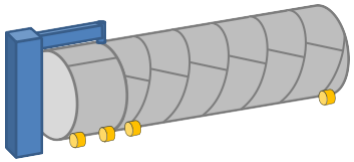




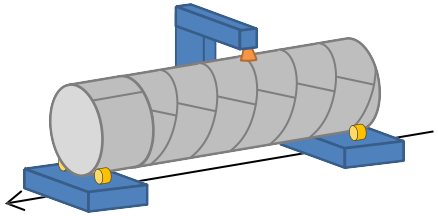
4. Spiral weld



5. End bevel



6. Flange install



7. NDT and repair

# KTS Proven technology

KTS 1/7 scale working machine
to produce test towers

KTS tower segment undergoing
certification testing (successful!)

# Scale up KTS system using SMS conventional spiral pipe equipment expertise

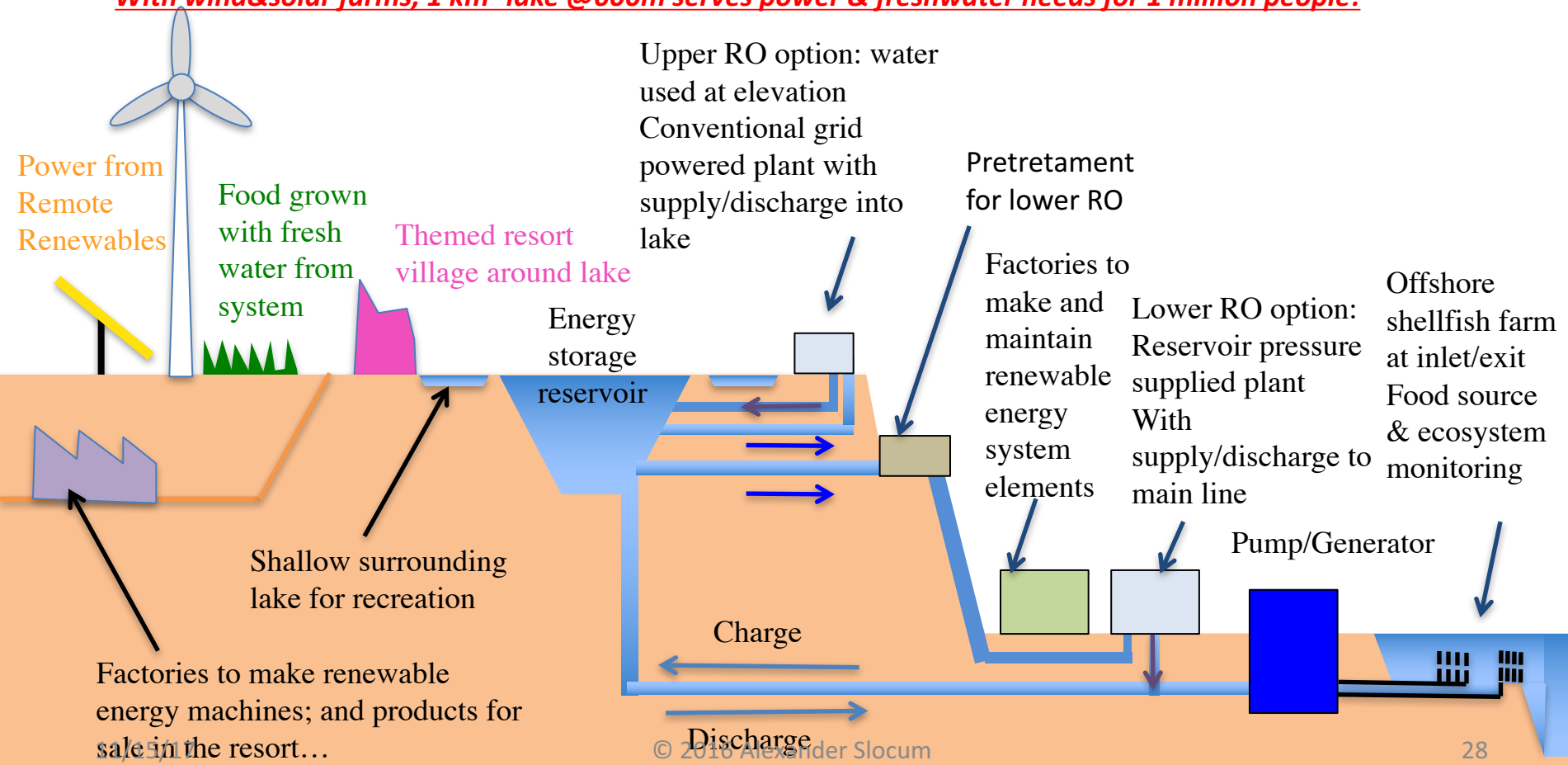
# Key benefits:

- Increased throughput
  - 600 towers per year from each system
  - 30-50% smaller manufacturing footprint
- Reduced labor
  - 50% labor savings
- Lower cost materials
  - Able to use coil or plate steel
- Superior quality
  - Fully automated process

# *IPHROS:* Integrated Pumped Hydro Reverse Osmosis System

## *Supplying renewable energy, fresh water, and jobs for an entire region*

- Many drought stricken coastal regions have mountains near coast
- Intelligent design ☺: Pumped Hydro Head = 500-700 m, = RO desal head
  - http://www.sciencedirect.com/science/article/pii/S2213138816300492
- 20m^3 water => 2kWe, 1 m^3 => 500l freshwater
  - Brine out-flow from RO plant is readily diluted by the output from the turbine
- ***With wind&solar farms, 1 km² lake @600m serves power & freshwater needs for 1 million people!***

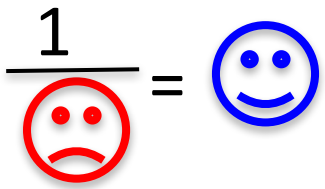


*Summary:*

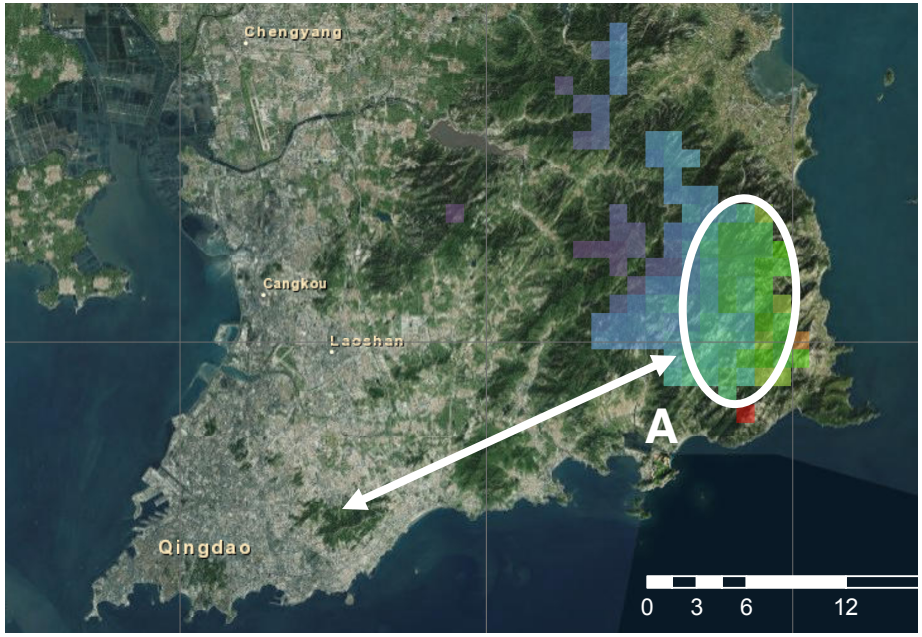
# IPHROS: Key Parameters

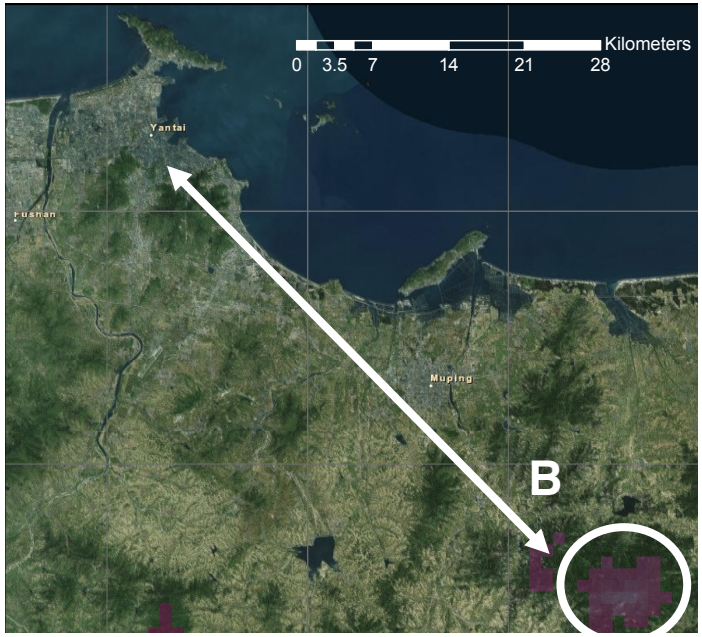
*Summary:*

- One million people can be served by every 1 $km^2$ of pumped seawater lake at > 500m asl
- To provide the ideal daily power (2 kW) and freshwater (500l) needs of a person requires:
  - 20 $m^3$ seawater for storing energy from solar and wind farms
  - 1 $m^3$ of seawater for RO plant
    - Brine gets diluted 30:1 by seawater output from power turbine
- Energy system needed: Peak (6000 MW solar & wind + 3000 MW pumped storage) => 2000 MW 24/7
- New economy <=> good jobs!:
  - Solar and wind farms
    - Factories to make solar and wind energy machines, installation, maintenance
      - Jordan's Ma'an region has world's best silica for making solar cells!
  - PHROS system: Tunnels, earthworks, pumped hydro plant, grid
  - Resort & theme park: Construction, operation, supporting infrastructure
    - Hotels, restaurants, shops, manufacturing (souvenirs!), agriculture, transportation…
- Cost: $5 / Watt installed power for the renewable energy, storage, RO systems
  - 1 million people @ 2kW/person => $10 billion
    - Much of the tech equipment can be bought from hi tech economies that could finance the project
  - Amount Germany will spend on refugees in 2016-17: $50 billion
  - Amount US will spend on armaments in 2016-2017: > $100 billion



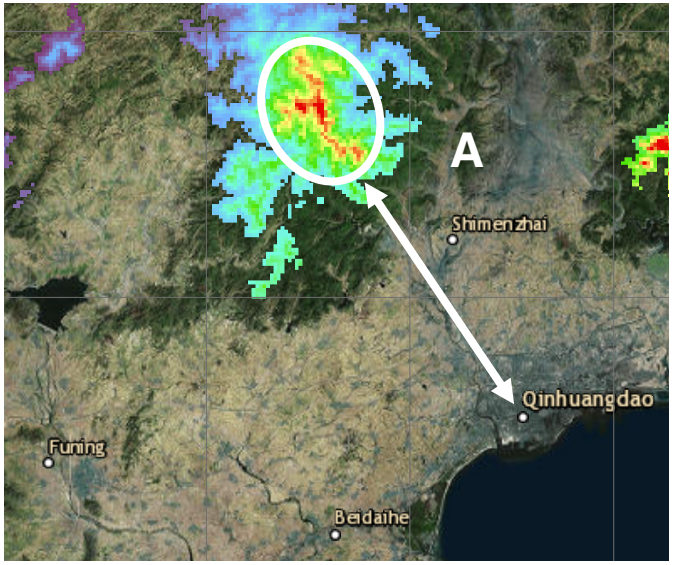
# Where? Peninsulas with Qingdao and Yantai

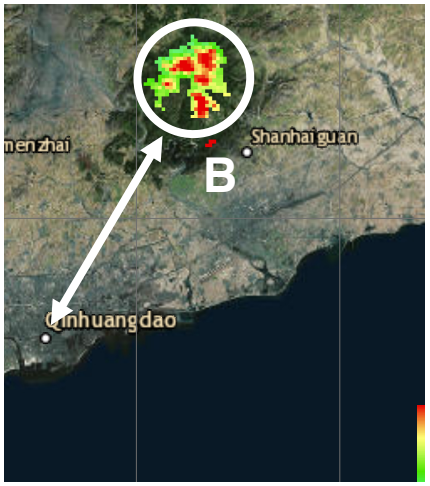



| Region | Head (m) | Surface area ($km^2$) | Distance from coast (km) | A-Index | Nearest major city (NMC) | Distance to to NMC | Energy potential (GWh) |
|---|---|---|---|---|---|---|---|
| A | 720 | 46 | 4.4 | 0.165 | Qingdao | 18.6 | 2236 |
| B | 620 | 43 | 23.6 | 0.026 | Yantai | 43.3 | 1811 |

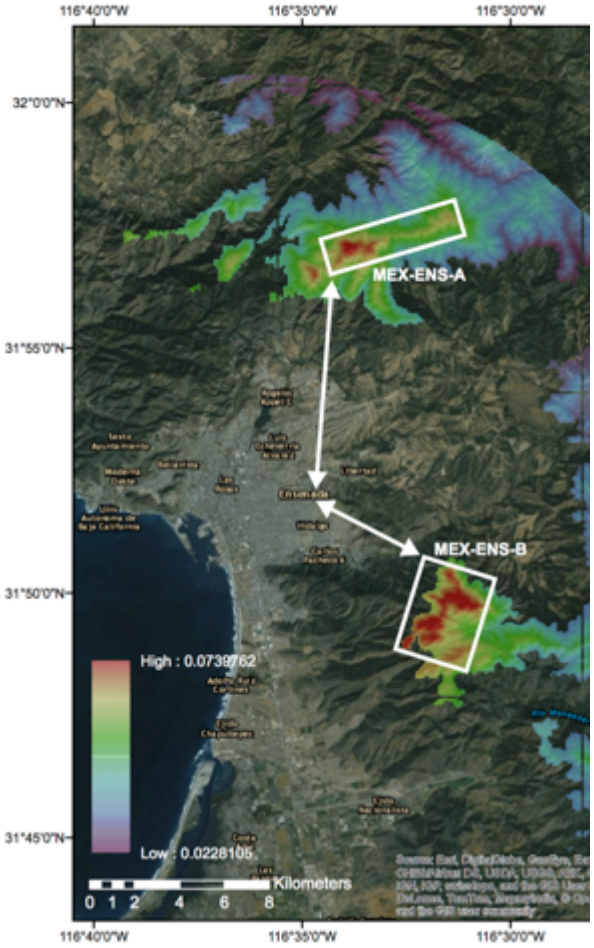
# Where? Mountains north of Qinhuangdao

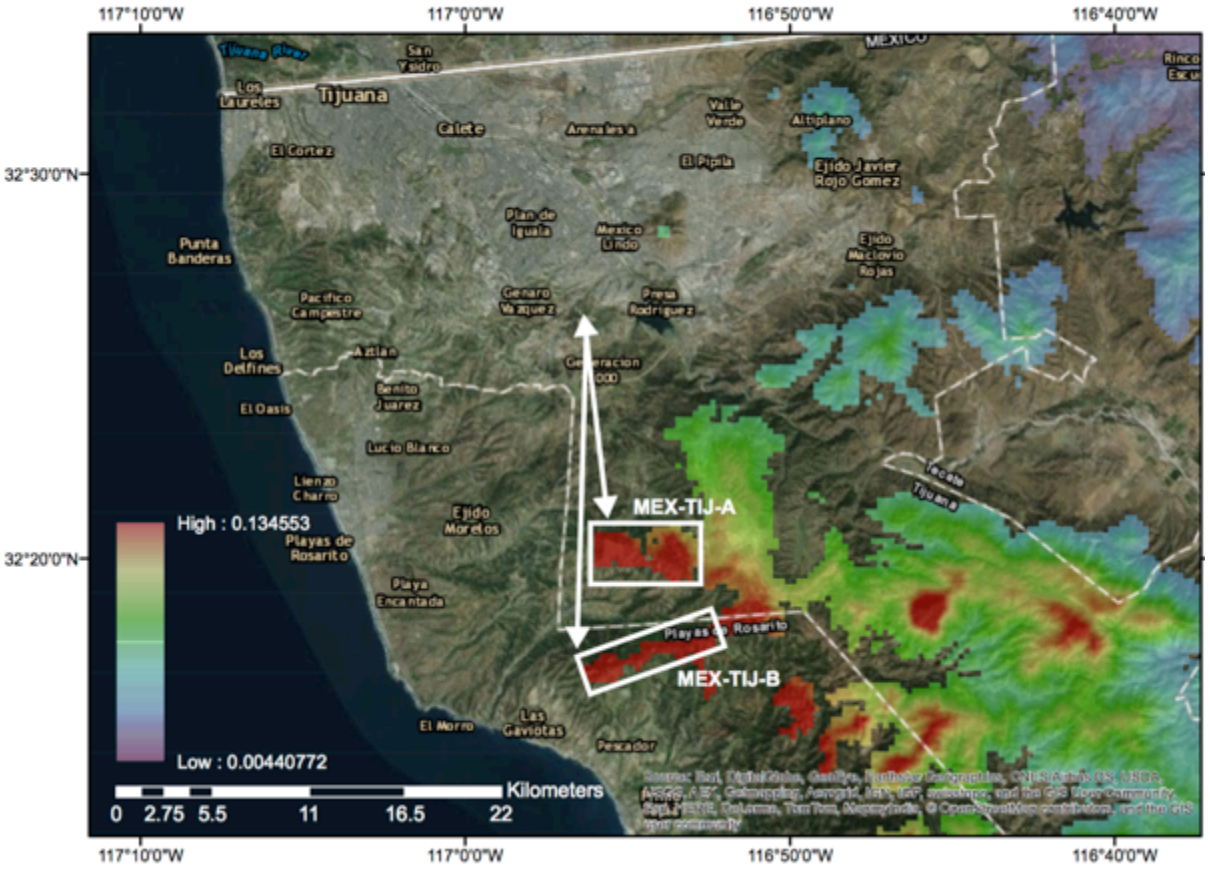



| Region | Head (m) | Surface area ($km^2$) | Distance from coast (km) | A-Index | Nearest major city (NMC) | Distance to to NMC (km) | Energy potential (GWh) |
|---|---|---|---|---|---|---|---|
| A | 1129 | 20.7 | 33.5 | 0.034 | Qinhungdao | 25 | 15667 |
| B | 676 | 17.2 | 19 | 0.036 | Qinhungdao | 25 | 782 |

# *Where?* Mexico: Ensenada & Tijuana



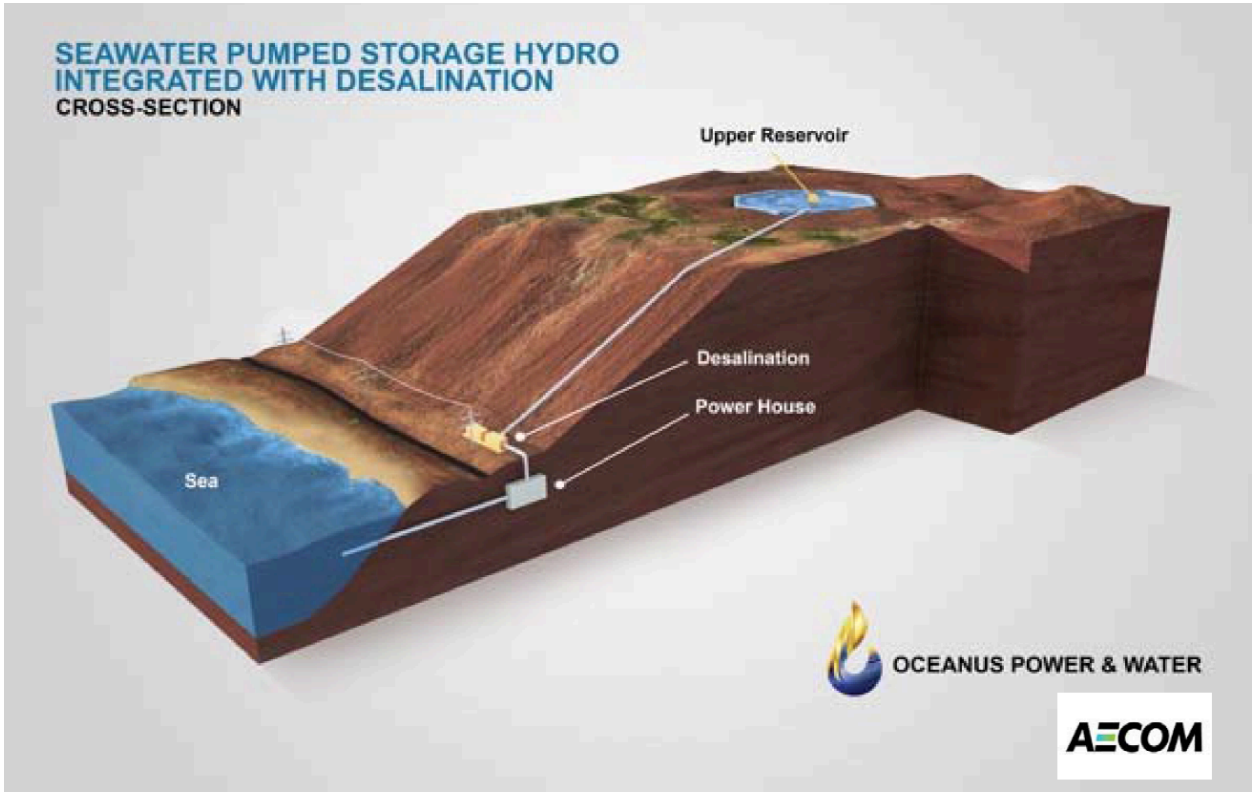



# Symbiotic Catalyst…

- IPHROS needs energy from solar and wind
  - Electricity and fresh water produced
  - Wind Turbines could act as center pivot for sprinklers that irrigate using water from IPHROS…

# Oceanus Inc. Formed to Design IPHRO Systems

- Independently formed of Prof. Slocum's research
  - They have identified sites in Mexico and obtained permits
  - Contact Neal Aronson:  neal@oceanus.pw



# Automated Symbiotic Agriculture Systems

*("As Soon As Sensible" ☺)*

## Research Goals

- Combine MIT deterministic engineering with bottom line approach to automated symbiotic food production
  - Partner with Little Leaf Lettuce farms in Ft. Devens Mass
- Develop operation review methods to identify and model symbiotic opportunities
  - Rockwool plant media and plant stems, to chicken farmers instead of landfill
    - Chickens eat the plant material and scratch the rockwool to dust
- Precision engineering audit to increase system robustness and efficiency (yield)
  - Precise seed planting & cutting
  - Alignment of mechanisms
- Create deterministic design process for automated greenhouses as a function of the type of crop to be grown and the location of the greenhouse.
  - Minimize energy & water consumption, maximize health, safety and symbiotic "reuse" of materials.
  - Investigate if such systems be implemented in schools
    - Better nutrition
    - Automation vocational education

# Example: Little Leaf Greenhouse

*Little Leaf designed & built perhaps the most advanced greenhouse in the world to consistently & economically produce year round the highest quality & best tasting baby greens*

- High-efficiency LED lights maximizes growing cycle
- Symbiotic heating and cooling system:
  - Natural gas power with CO2 “pure” exhaust enhances plant growth
- Automated growing system— ”Clean from the Start”
  - No human hands touches product – seeding through packaging
  - Continuous 28 day growing process, seeding and harvesting 6 days/week
  - 5 acres of production grows enough to continually supply 30,000 people with their lettuce greens needs per year
- A “precision engineering assessment” of “problem areas that need fixing” was able to suggest rational simple economical fixes
  - Hence was born the idea of collaborating to combine MIT deterministic engineering with bottom line approach to automated symbiotic food production

# Why a “Little Leaf Farms” approach for the world’s food supply?

## *Quality*

We supply our “close to home” product year-round, giving consumers the longest shelf life

## *Food Safety*

Greens are never touched by humans, to reduce possible pathogen exposure

## *Scale*

Our large, advanced operation can meet urban volume requirements


***Clean from the Start™***

***Millions of bags per year***

Little Leaf Farms
BORN LOCAL. RAISED RIGHT.

Little Leaf Farms
BORN LOCAL. RAISED RIGHT.

# Target Consumer and Product Mix

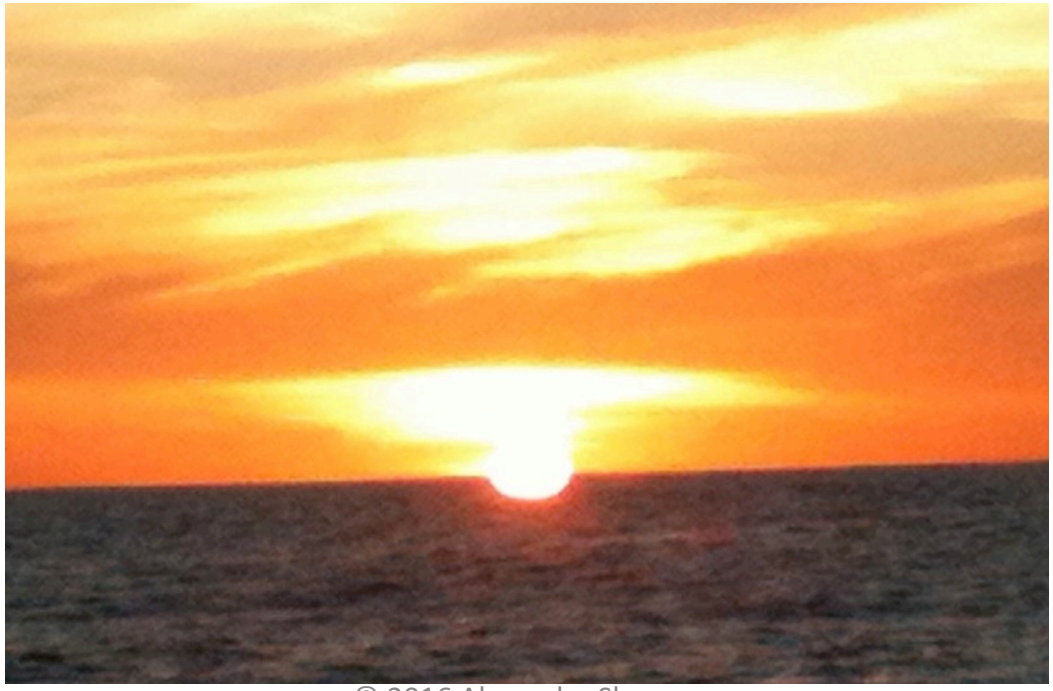
- Target consumer: Age 25-50, educated, salad lovers, health conscious, shops to support values
- Billion dollar market opportunity for local lettuce production in Northeast US
- True baby leaf lettuces: 3 week growing cycle
- Two initial SKUs:
  - Red & Green Mix:  50/50 blend of green and red Leaf
  - Spring Mix: green, red, and blond leaf, and chard and arugula

# Results: Inputs and Outputs

- Rockwool growing media
  - 0.18 kg rock wool per kg lettuce
  - Use 20 cubic meters of fresh water per day
  - Produces 1246 kg of lettuce per day
  - Byproduct is “Waste” rockwool
    - Full of lettuce plant roots AND chickens love to eat it all!
- Growth media
  - Fertilizers are water soluble nutrients consisting of N-P-K and micro nutrients. Can use organic or conventional fertilizer
- 500 tonnes lettuce per year
  - 450,000 cubic meters of natural gas
  - 10,000 $M^2$ greenhouse area produces

# The Future Is Ours!

- Engineering is a blend of science and statistics with which managers and politicians paint our future
- We are all responsible for the canvas of life
  - We CAN work together to create a beautiful future for the planet and all its lifeforms



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Focus on how to design robust, high quality products that efficiently balance **precision** and cost. Learn more and register at:

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***"Life is a bowl of springs"*** - A

Slocum