SAND2012-1877P

Exceptional service in the national interest

Sandia National Laboratories

ENG 505 - ENERGY SURETY AND SYSTEMS

Water

Energy-Water Nexus
Marine Hydrokinetics
Conventional Hydro
Offshore Wind

Daniel Laird
Manager - 6122
Water Power Technologies
Sandia National Laboratories, New Mexico (USA)

SANDIA REVIEW & APPROVAL NUMBER

U.S. DEPARTMENT OF ENERGY | NNSA National Nuclear Security Administration

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Presenter Bio

Daniel Laird

- University of Illinois at Urbana-Champaign
  - B.S. in General Engineering
- University of Wisconsin – Madison
  - M.S. in Mechanical
  - Ph.D. in Mechanical Engineering (Analysis of Distortion in Patterned Thin Films)
  - Current member of UW ME Industrial Advisory Board
- 14 years in SNL Wind Energy Technology, 2 years in SNL Water Power
- Chair of ASME Wind Energy TC, 2008-2010
- Led wind energy projections in structural analysis and design tools, composite materials research and testing, manufacturing, and blade reliability.
- Current Sandia Water Power Projects

MHK Reference Models
MHK Industry FOA Support
MHK Tech and Environmental Tools
CH Seasonal Optimization
Very Large Rotor Study
Offshore VAWTs

Recall: What is a Complex System?

- A **complex system** is a system composed of interacting elements that as a whole exhibit one or more properties (behavior among the possible properties) not obvious from the properties of the individual parts
- Common Attributes
  - Multiple interacting phenomena
  - Heterogeneous element
  - Non-linear dynamics and effects
  - Adaptive behavior
  - Elements with memory
  - Large network of elements or nested complexity

Recall: Approaches* to Complex Systems

- Mathematics
- Physical-Cyber-Behavior
- Threat and Risk
- Systems Engineering
- Sandia Software Tools
- Sandia Disciplines

These represent approaches or resources that an analyst or engineer may apply to a systems engineering challenge. They are not intended to be a complete set, just one chosen to add structure to this course.

*Note: These approaches represent a simplified set of complex systems concepts chosen for the ENG505 systems lectures. Please see the initial two systems lectures for additional detail and expanded references.

Exceptional service in the national interest

Sandia National Laboratories

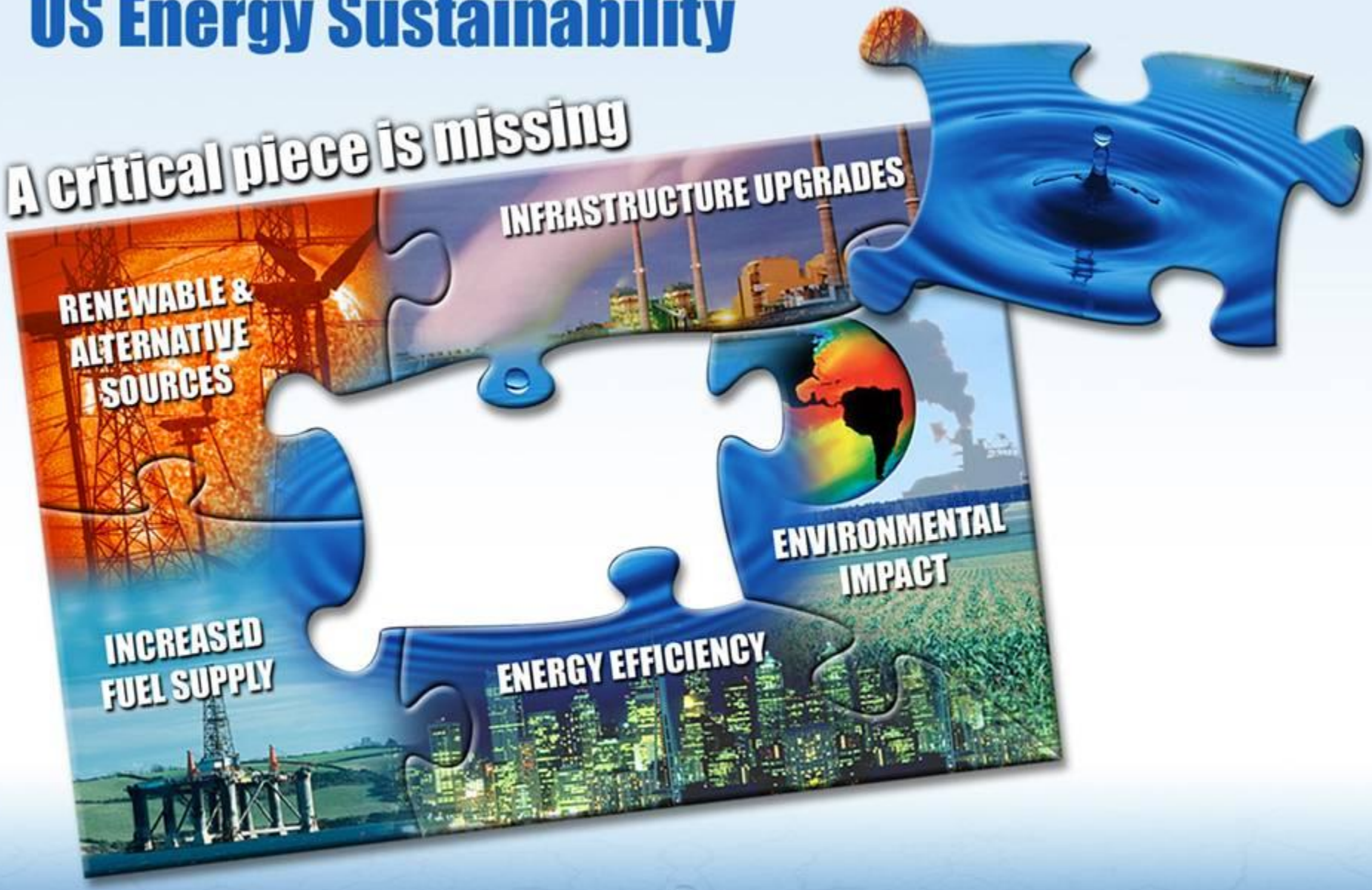
Energy-Water Nexus

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

US Energy Sustainability



ENERGY and WATER

Energy and Water are Inextricably Linked

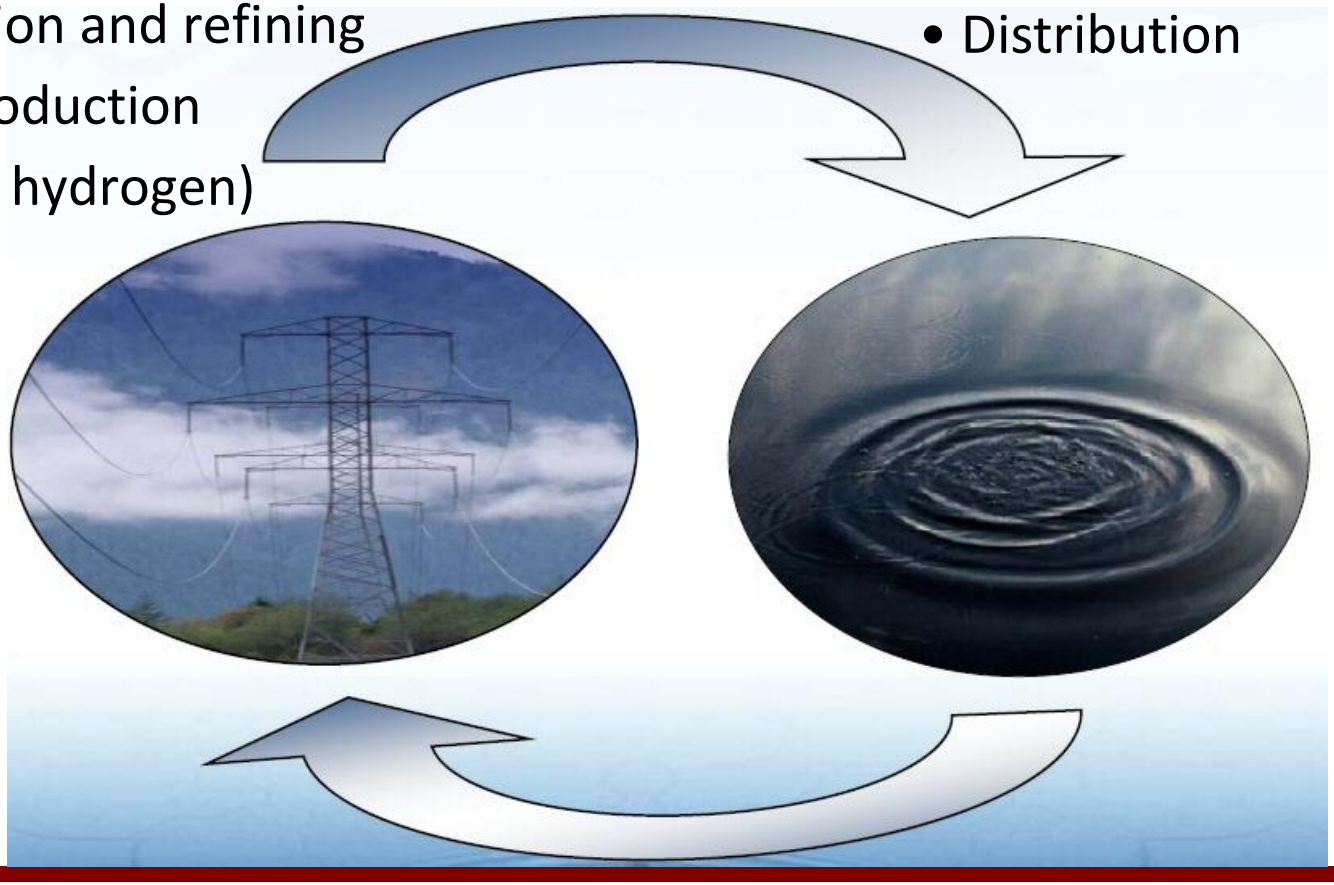
Water for Energy

- Thermoelectric cooling
- Hydropower
- Extraction and refining
- Fuel production

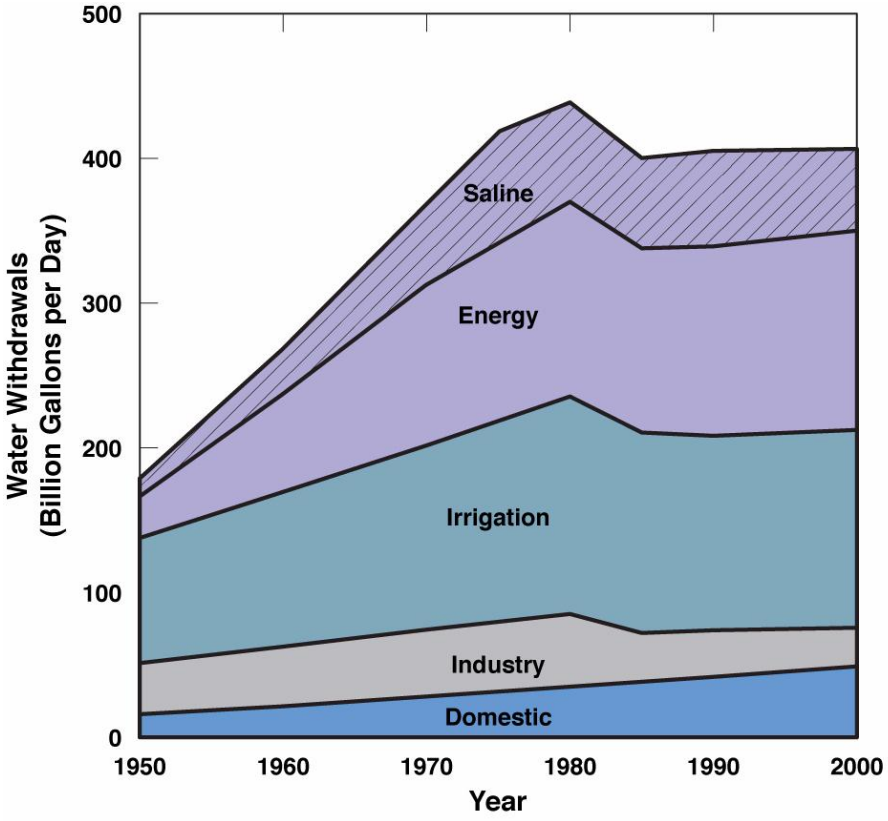
(ethanol, hydrogen)

Energy for Water

- Pumping
- Treatment
- Distribution



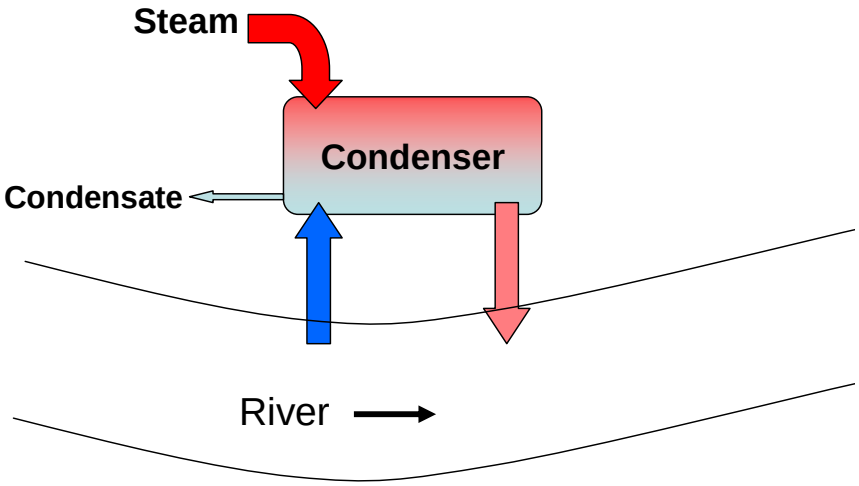
Water Withdrawal Trends by Sector



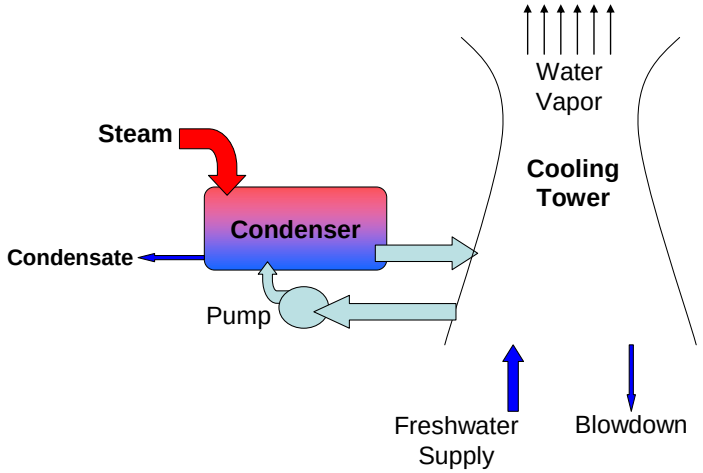
[USGS, 2004]

Tremendous amount of water needed for energy

Withdrawal versus Consumption



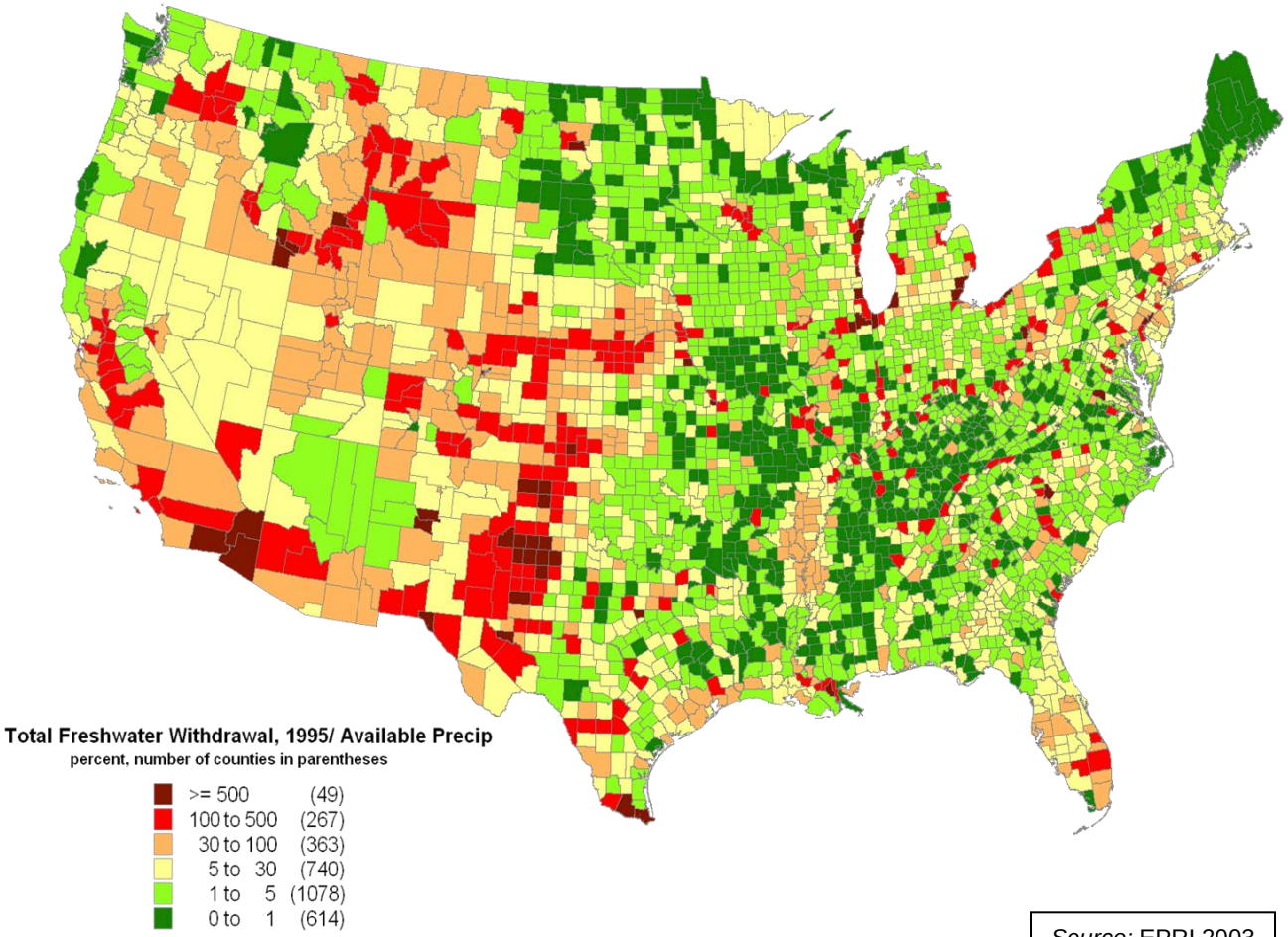
Constraint: Thermal Discharge Limits, Water flows



Constraint: Absolute Water Consumption

Sustainable Withdrawal Of Freshwater Is National Issue

Sandia National Laboratories



Source: EPRI 2003

Electric Power Generation Water Use for Various Cooling Options

Sandia National Laboratories

Plant-type	Cooling Process	Water Use Intensity (gal/MWh$_e$)		
		Steam Condensing[a]		Other Uses[b]
		Withdrawal	Consumption	Consumption
Fossil/ biomass steam turbine[c]	Open-loop	20,000–50,000	~200-300	~30-90[d,i]
	Closed-loop	300–600	300–480	
	Dry	0	0	
Nuclear steam turbine[c]	Open-loop	25,000–60,000	~400	~30[d]
	Closed-loop	500–1,100	400–720	
	Dry	0	0	
Natural Gas Combined-Cycle[c]	Open-loop	7,500–20,000	100	10[e]
	Closed-loop	~230	~180	
	Dry	0	0	
Coal Integrated Gasification Combined-Cycle[c]	Closed-loop	200	170	150[c,e]
	Dry cooling	0	0	150[c,e]
Geothermal Steam[f]	Closed-loop	2000	1350	NA
Concentrating Solar[g,h]	Closed-loop	750	740	10
	Dry cooling	10	0	10
Wind and Solar Photovoltaics[j]	N/A	0	0	1-2
Carbon sequestration for fossil energy generation				
Fossil or biomass[k]	All	~30% increase in water withdrawal and consumption		

Energy-Water Nexus Complexity

Sandia National Laboratories

- ✓ Multiple interacting phenomena
  - evaporation, heating of rivers, hydrology of ground water, drought, etc.
- ✓ Non-linear dynamics and effects
  - hydrological cycle, climate effects
- ✓ Adaptive behavior
  - withdrawal to consumptive, river species
- ✓ **Large network of elements or nested complexity**
  - multiple watersheds, population changes, changing environmental regulations, changing power regulations, technology changes, carbon issues, competition from agriculture, …
    - ✓ Mathematics
    - ✓ Physical-Cyber-Behavior
    - ✓ Systems Engineering
    - ✓ Sandia Software Tools
    - ✓ Sandia Disciplines

Exceptional service in the national interest

Sandia National Laboratories

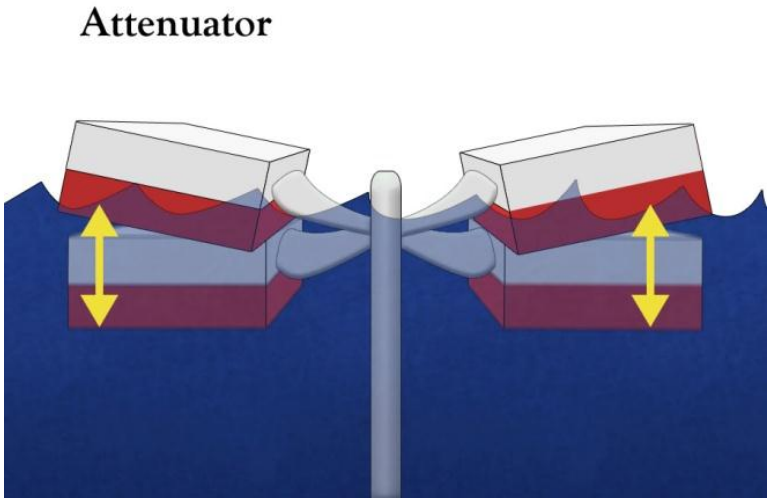
Marine Hydrokinetic Power

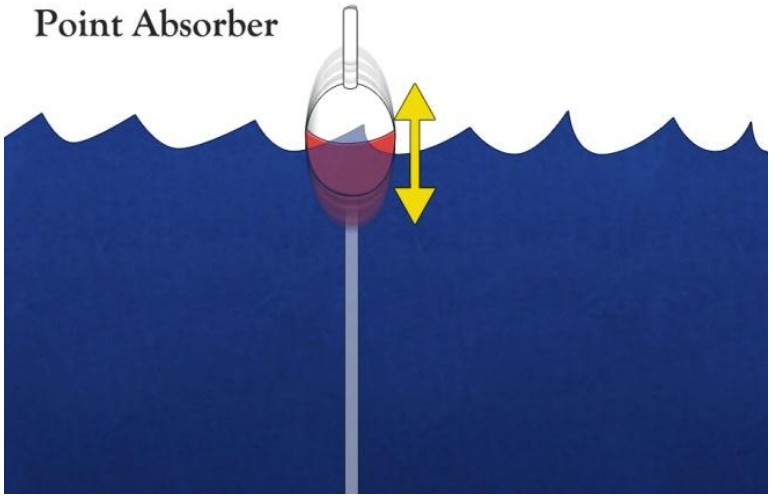
U.S. DEPARTMENT OF ENERGY

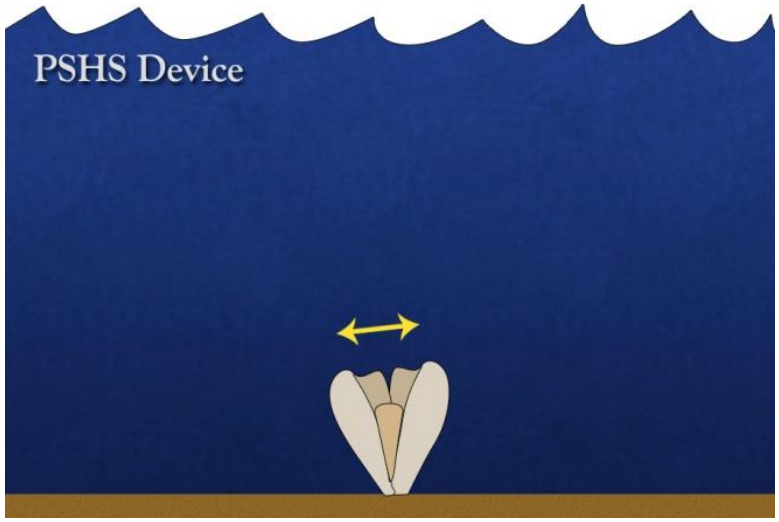
NNSA National Nuclear Security Administration

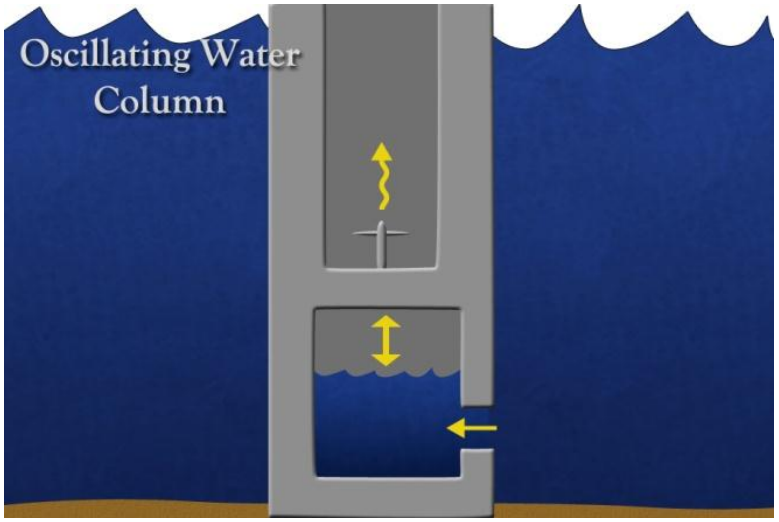
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Major Wave Technologies

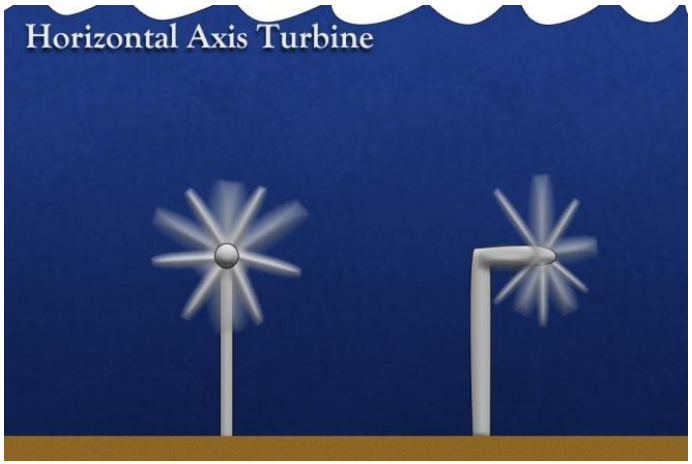


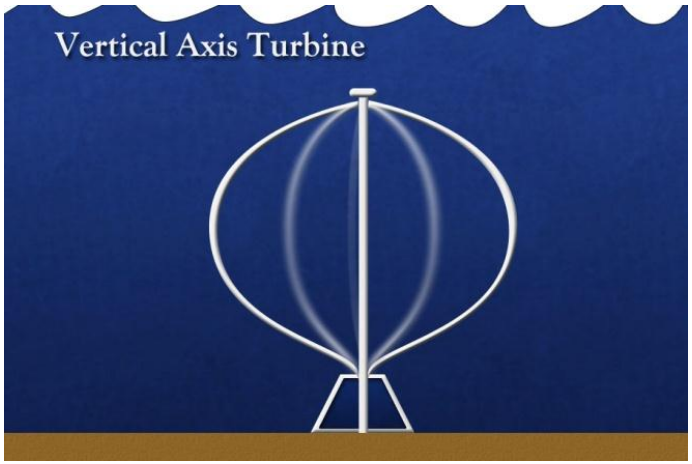


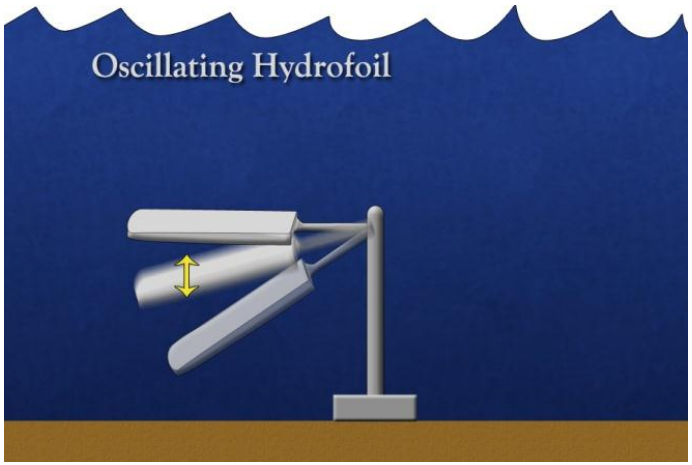


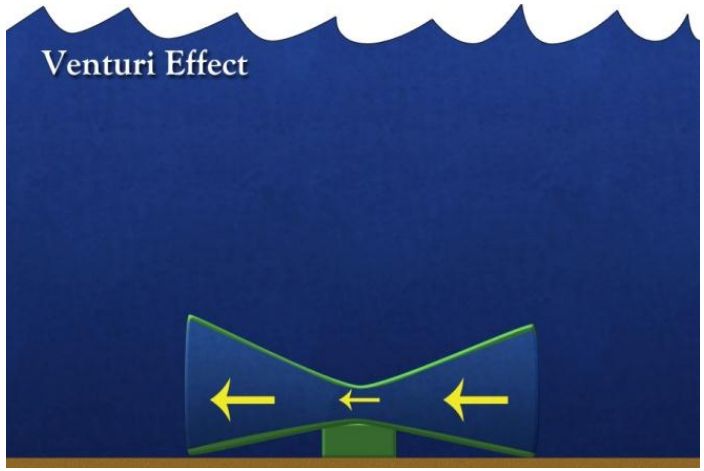


Current/Tidal Technologies





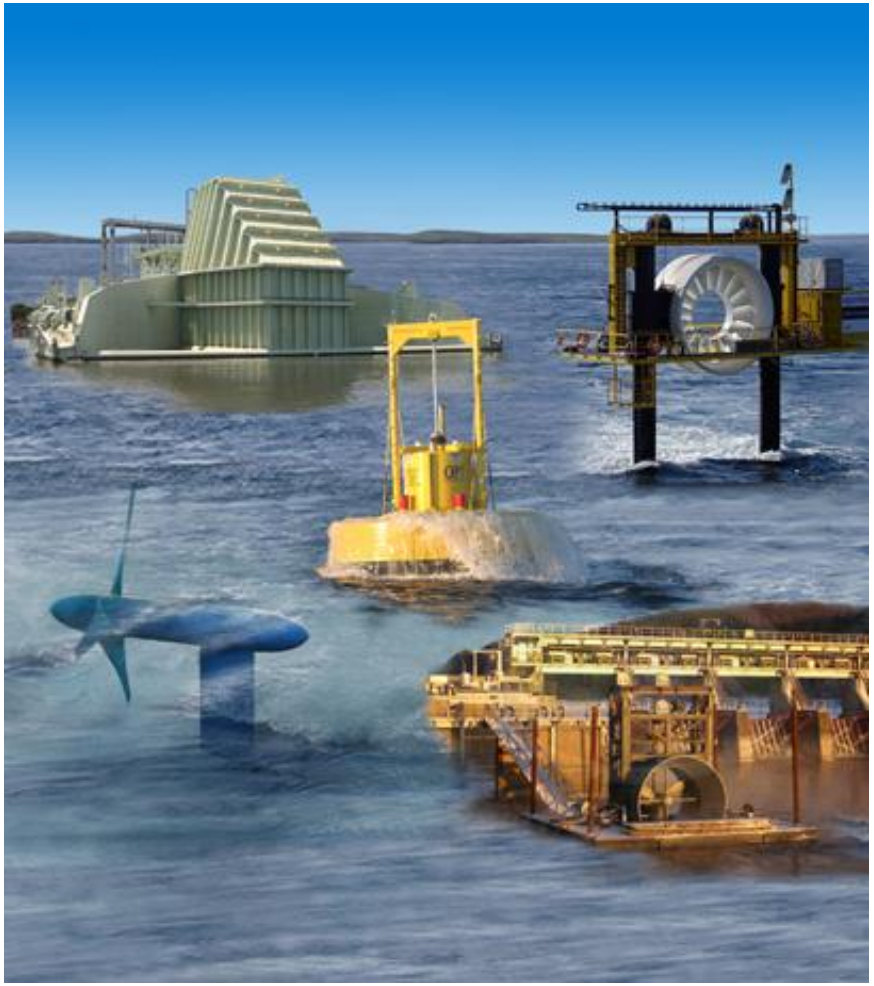




State of the Marine Hydrokinetic (MHK) "Industry"

Sandia National Laboratories

- **Wave: >100 Devices***
  - Attenuator
  - Pitching/Surging/Heaving/Sway (PSHS)
  - Oscillation Water Column
  - Overtopping Device
  - Submerged Pressure Differential
- **Current/Tidal: >60 Devices***
  - Horizontal Axis Turbine
  - Vertical Axis Turbine
  - Oscillating Hydrofoil
  - Venturi

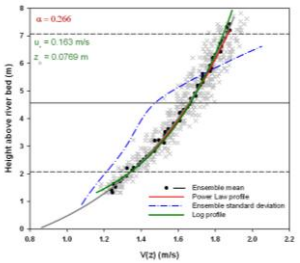


***Includes conceptual ideas, prototypes and demonstration projects. There are no commercial units on the grid.**

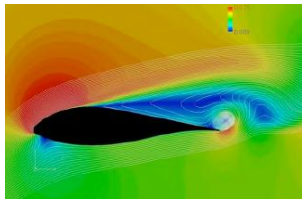
Verdant Power Composite Rotor Project

2008-present

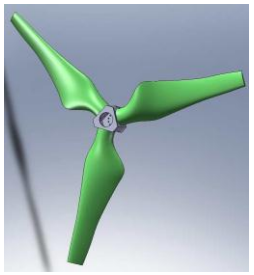
- Verdant Power requested assistance with rotor design, analysis, and testing
  - CRADA – 2008, WFO - 2009
- Leverage Sandia's extensive expertise in composite wind turbine rotors
- Team: VPI, SNL, NREL
- Program/Industry Impact
  - Development of water current inflow characterization and modeling tools
  - Leverage wind technology investment for MHK applications
  - Advancement of U.S.-based renewable energy design and manufacturing base



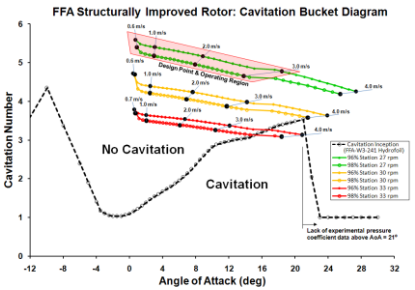
Characterize Inflow and Loads



Utilize High-Performance Computing to Simulate and Select Hydrofoils



Develop Design



Perform Full-System Simulations

Lab and Field Testing

Deployment

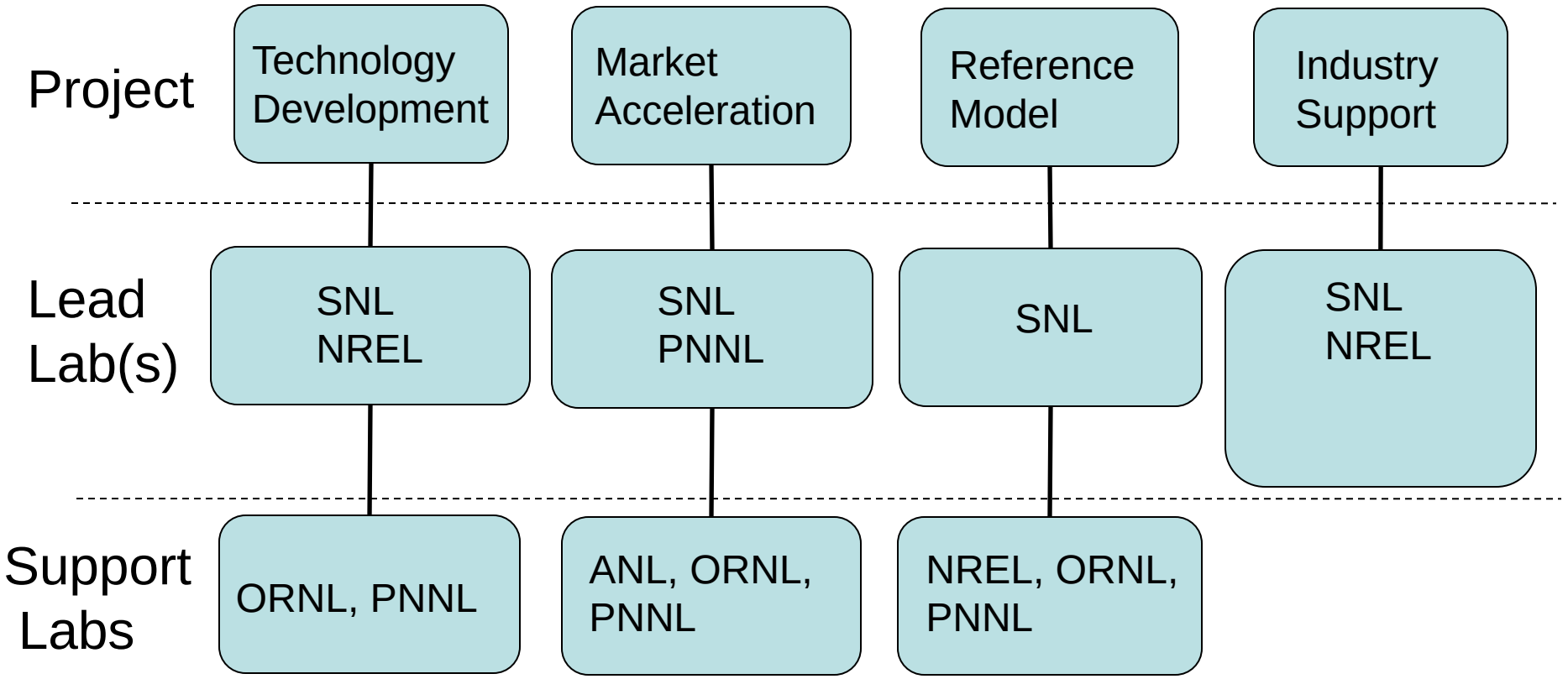
Sandia MHK Research Program

- Started in 2009
- Funded by DOE/EERE
- Heavily leveraged Sandia resources in
  - wind energy research
  - science and engineering core competencies
  - hydrodynamics
  - sediment transport

- **Current Program Elements**
  - Technology Development
  - Reference Model Development

Market Acceleration

Primary DOE/National Lab MHK Projects

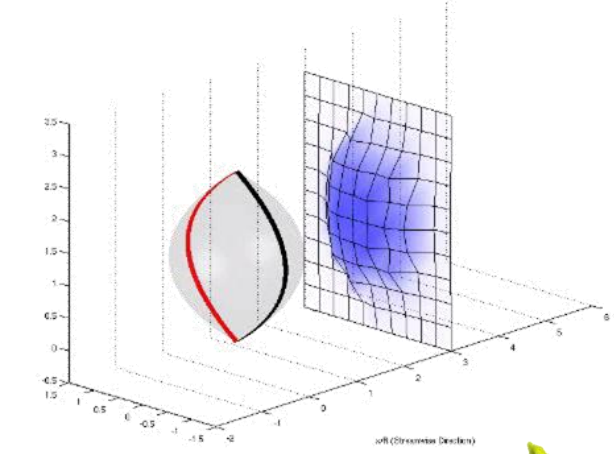


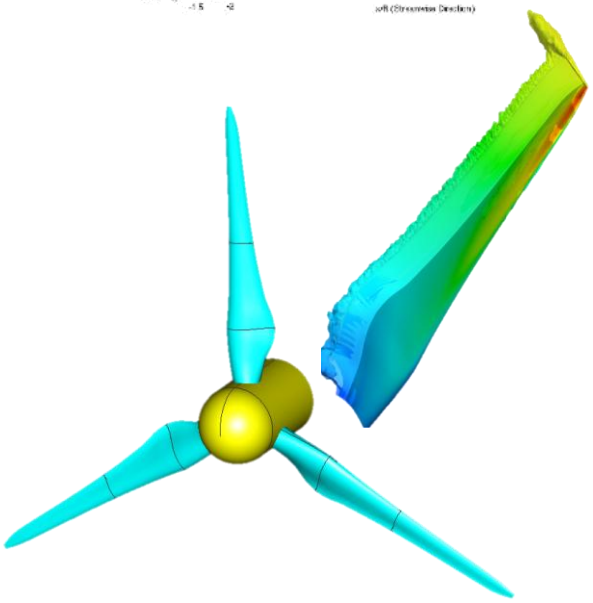
Sandia National Labs (SNL), National Renewable Energy Lab (NREL), Pacific Northwest National Lab (PNNL), Oak Ridge National Lab (ORNL), Argonne National Lab (ANL)

Technology Development

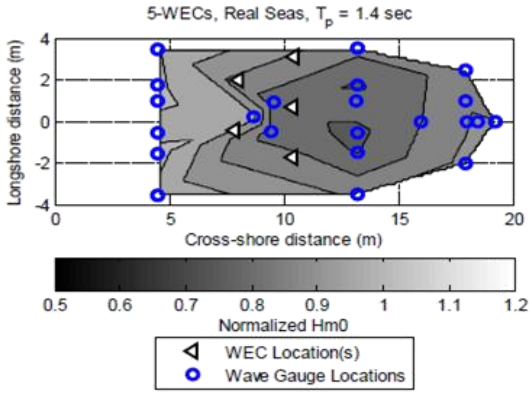
Sandia National Laboratories

Simulation Tools

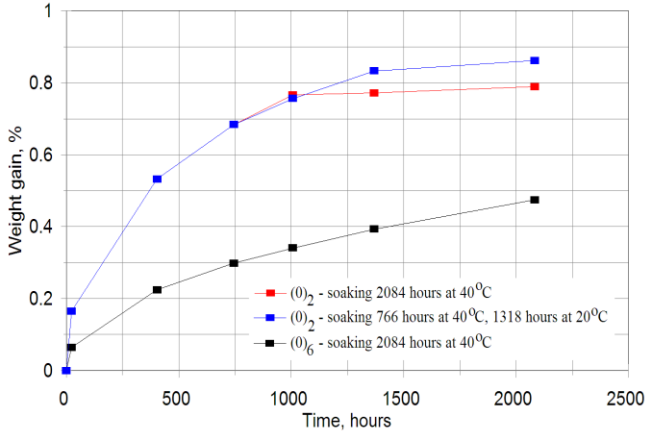


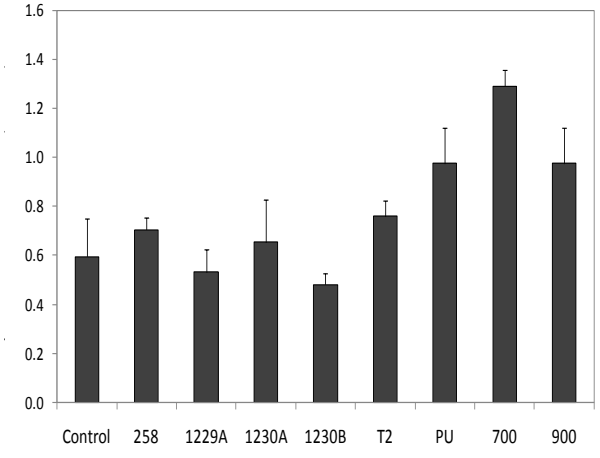


Experimental Validation



Materials





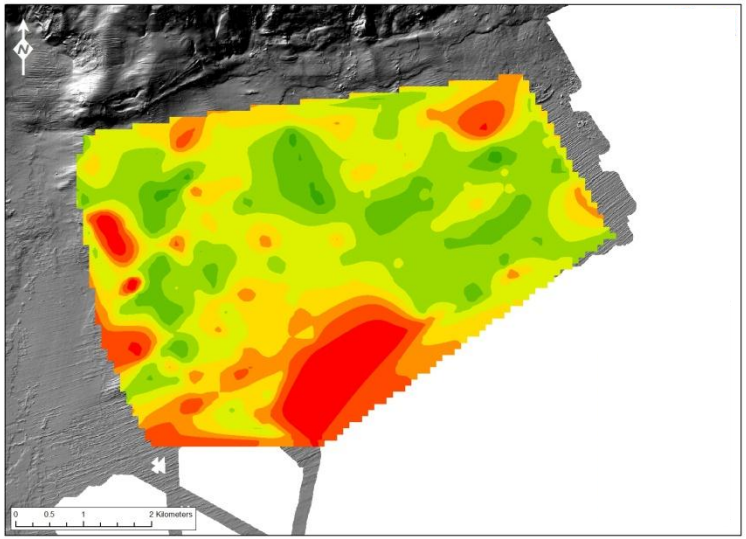
Market Acceleration

Environmental Effects

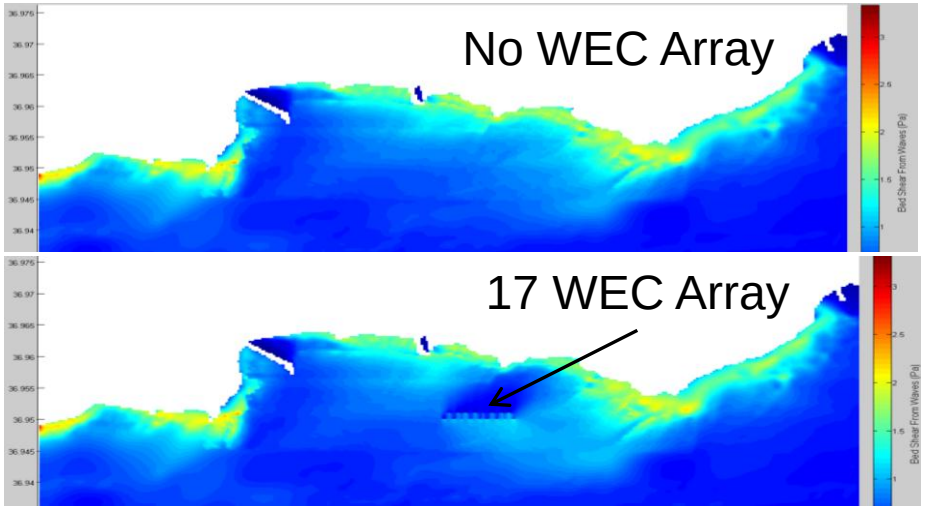
Sandia National Laboratories

Sediment Stability Maps

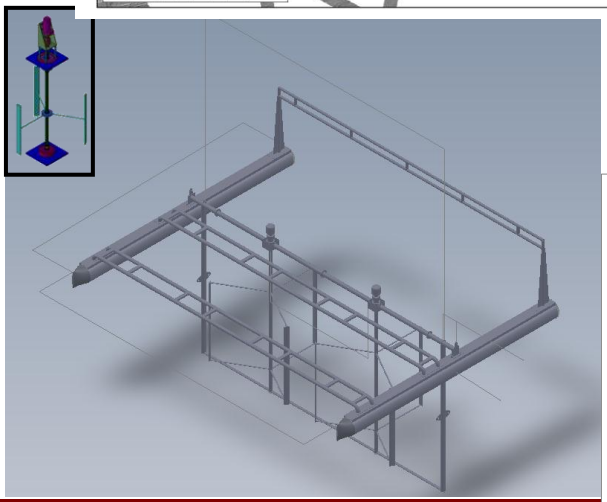
Erosion potential after 10 years

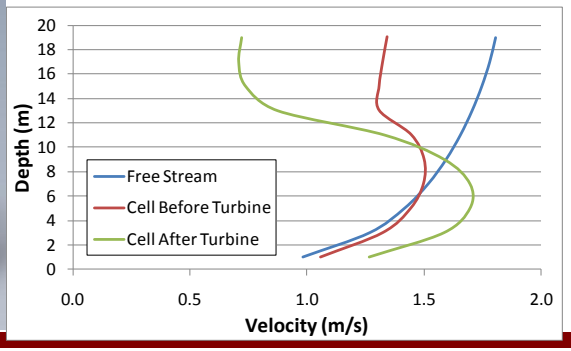


Array Modeling



Device Simulation

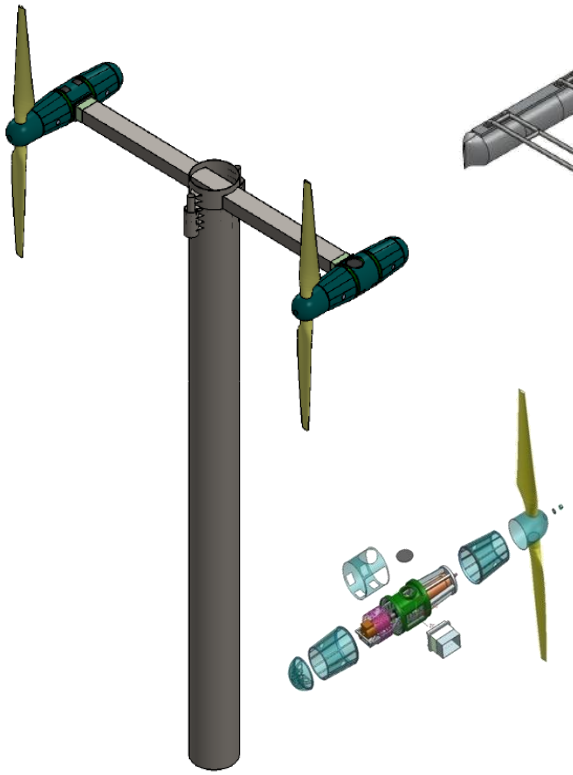




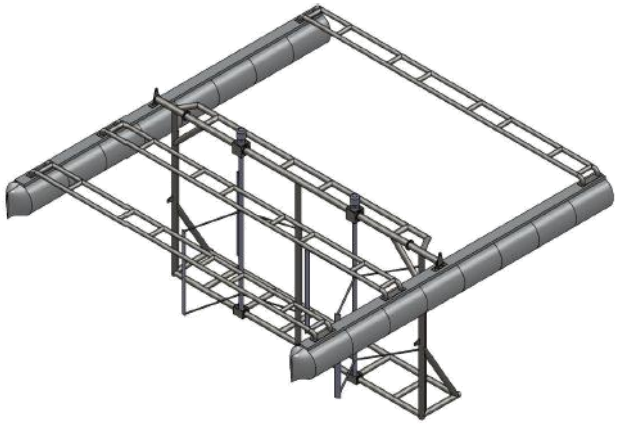
Field Testing

Reference Models

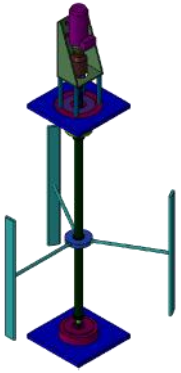
Develop Reference Models for the MHK industry to develop baseline cost of energy (COE) and evaluate key cost component/system reduction pathways.

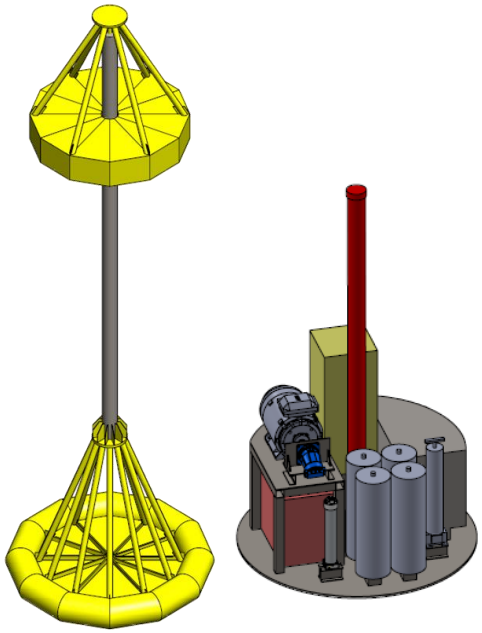


RM#1 Tidal Turbine



RM#2 River Turbine

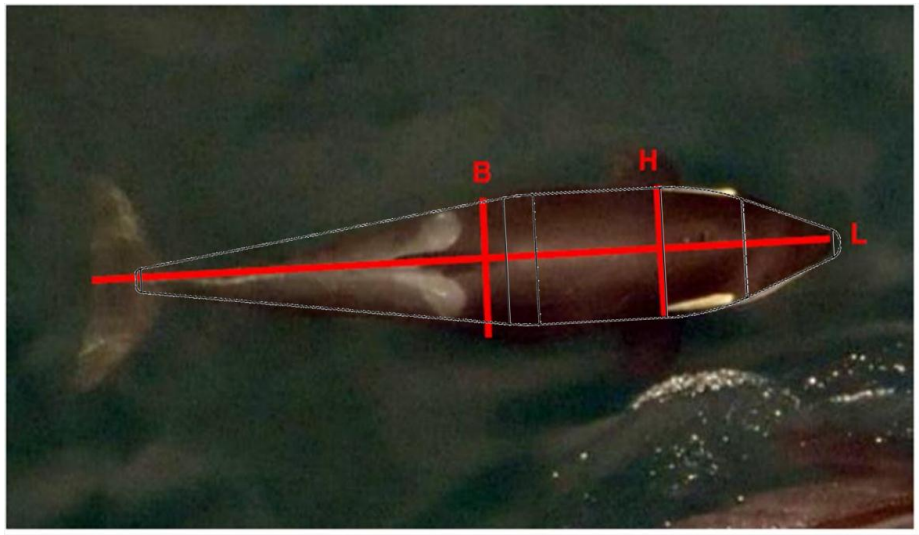


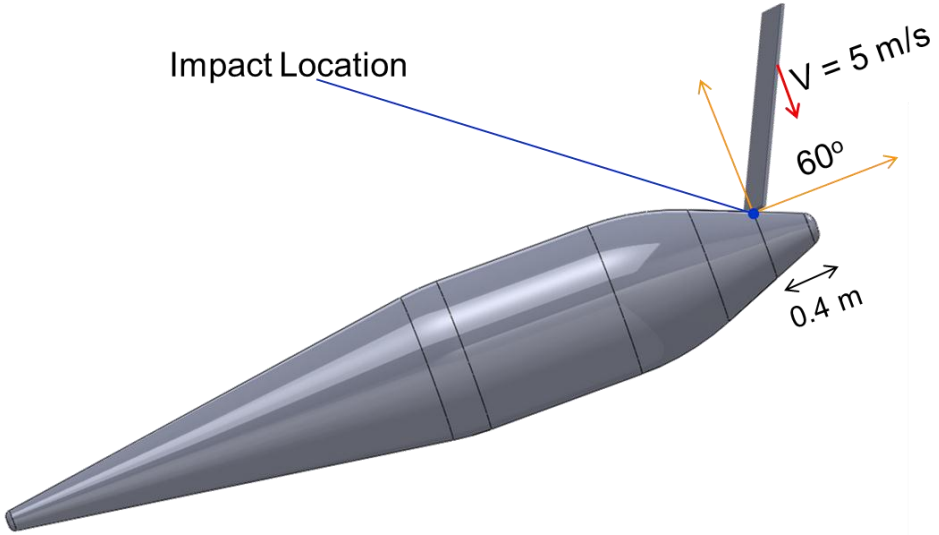


RM#3 WEC Point Absorber

Industry Support

- Public Utility District No.1 of Snohomish County
  - Tidal current device - Puget Sound
  - Concern regarding Southern Resident Killer Whales





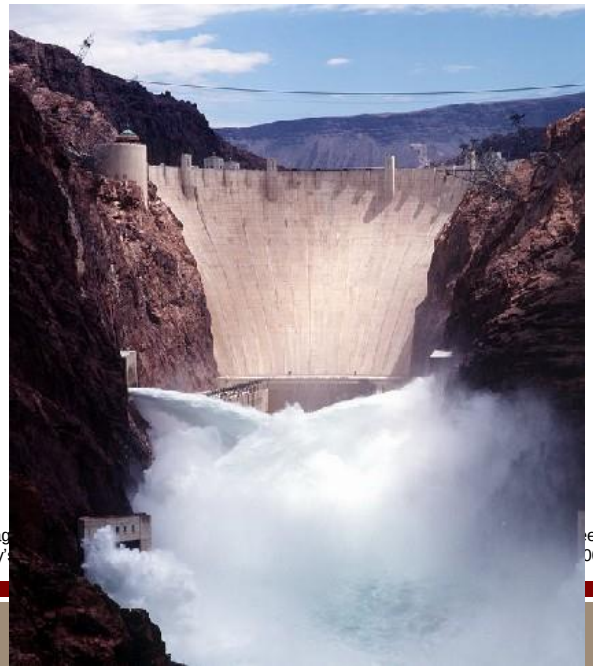
MHK Complexity

- ✓ Multiple interacting phenomena
  - wave loading, wind loading, corrosion, device operation, etc.
- ✓ **Non-linear dynamics and effects**
  - device motion due to wave and wind loading, operation, and anchoring/mooring
  - ✓ Mathematics: non-linear dynamics
  - ✓ Physical-Cyber-Behavior: interactions among all three
  - ✓ Systems Engineering: safety, reliability, scalability, maintainability, survivability, affordability
  - ✓ Sandia Disciplines: energy systems, HPC, sediment transport labs
- ✓ Adaptive behavior
  - active-tuning of device
- ✓ Large network of elements or nested complexity
  - multiple regulatory jurisdictions, multiple use demands (fishing, shipping, defense, recreation), significant environmental constraints, …

Exceptional service in the national interest

Sandia National Laboratories

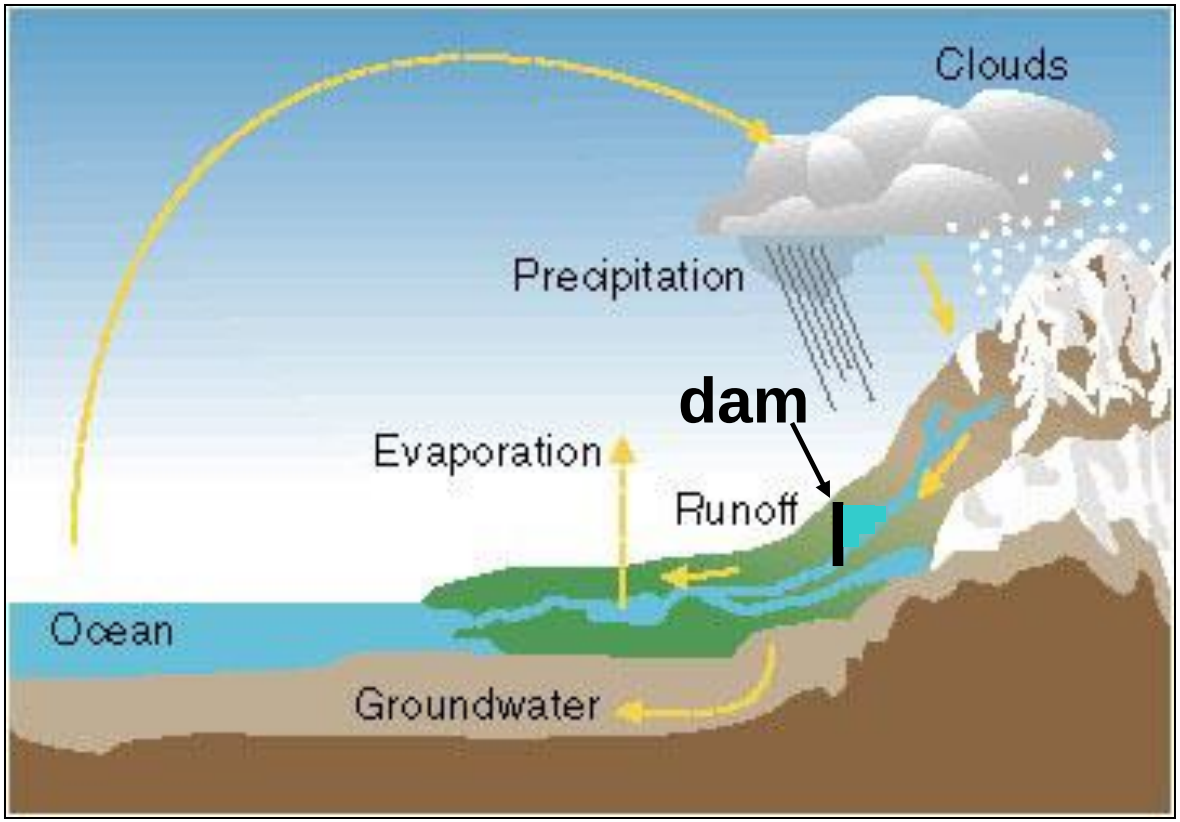
Conventional Hydropower



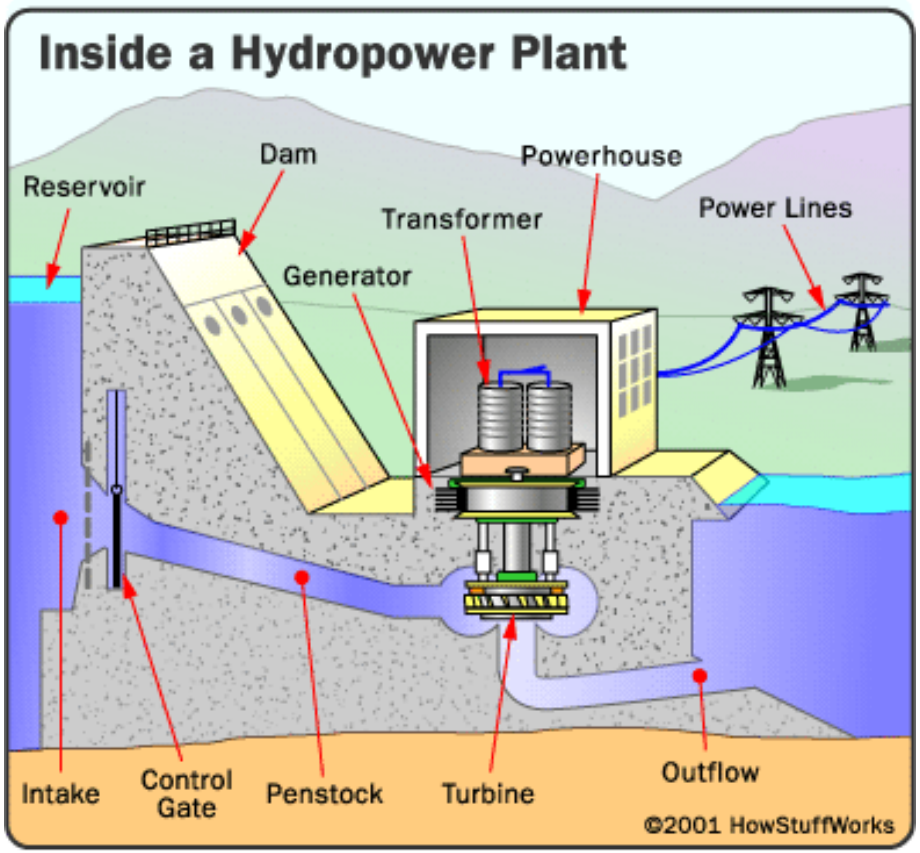
Sandia National Laboratories is a multi-program laboratory manag… eed
Martin Corporation, for the U.S. Department of Energy's … 00.

Conventional Hydro

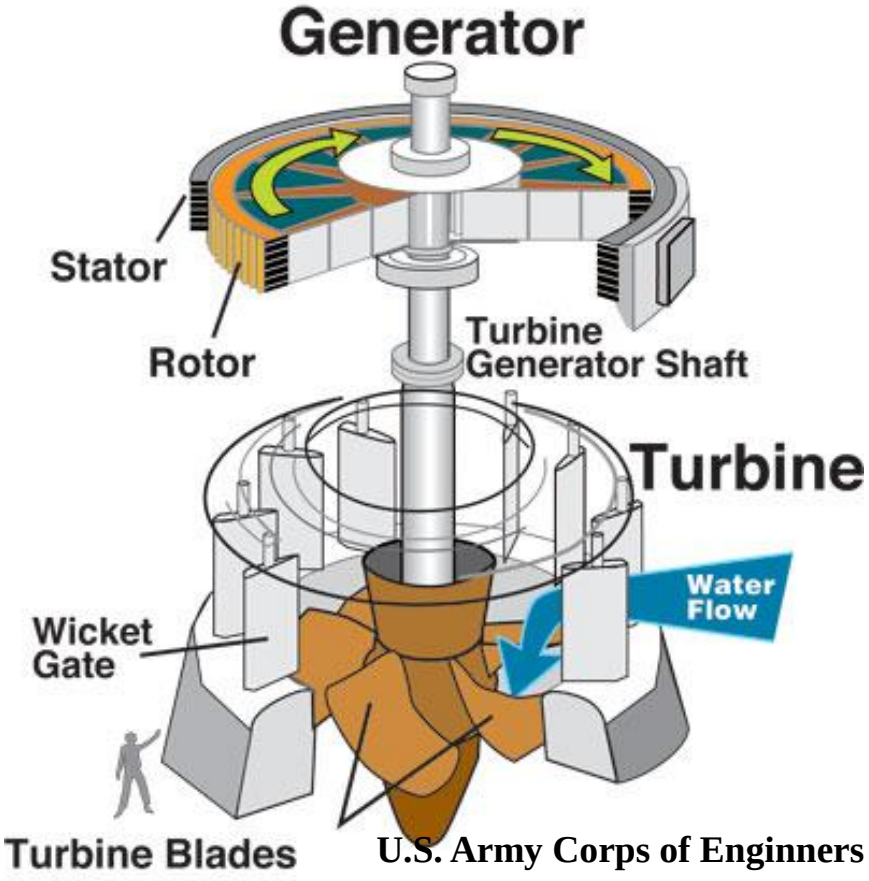
Rainwater flows into a reservoir created by a hydroelectric dam



Conventional Hydro



Power is generated by running water through turbines as it flows from the high side of the dam, reservoir, to the low side (original river)



U.S. Army Corps of Enginners

ga.water.usgs.gov

DOE's Conventional Hydropower Program and the Water Use Optimization Project

Argonne NATIONAL LABORATORY | Sandia National Laboratories | Oak Ridge National Laboratory | Pacific Northwest NATIONAL LABORATORY

DOE's resource assessment identified 5,677 sites in the United States with undeveloped capacity of about 30,000 MW. By comparison, today there is about 80,000 MW of hydroelectric generating plants in the United States.

http://www.water.ca.gov/swp/facilities/Oroville/index.cfm

The DOE's conventional hydropower activities

- **Increasing generating capacity and efficiency at existing hydroelectric facilities**
- Adding hydroelectric generating capacity to non-powered dams
- **Reducing environmental effects**

Link of the Water Use Optimization Project to DOE's Program Objectives

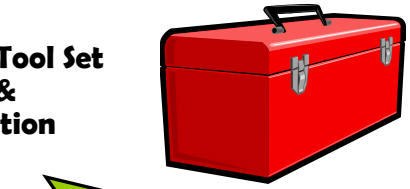
- Increase power production by optimizing operations within the myriad of constraints
- Allow for rapid evaluation of new technologies and management options
- Evaluate new development within the regulatory framework

http://www.ag.unr.edu/saito/research/Blue_Mesa.htm

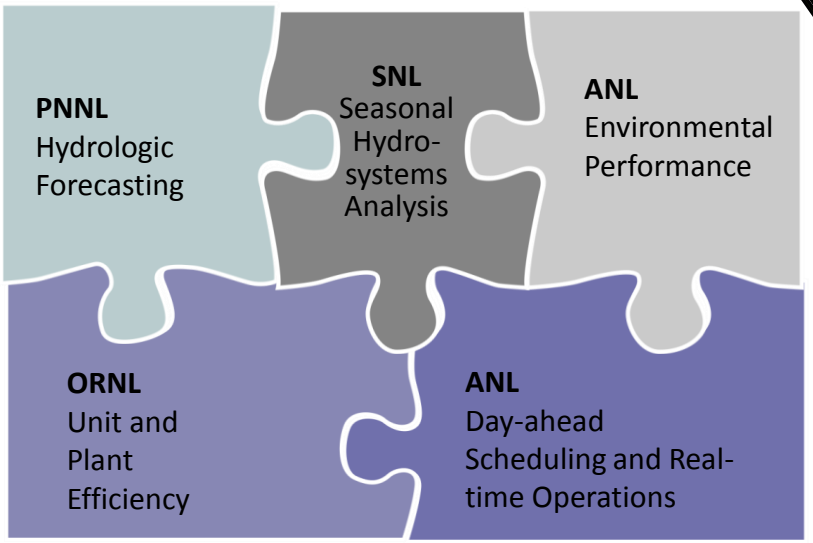
Purpose, Objectives, & Integration

- **Purpose:** Develop and demonstrate a hydropower water use optimization tool set that links water supply, power generation and ancillary services and environmental performance for planning and operations
- **Challenge:** How to operate conventional hydropower plants in an increasingly uncertain and competitive water-constrained environment

Optimization Tool Set Testing & Demonstration



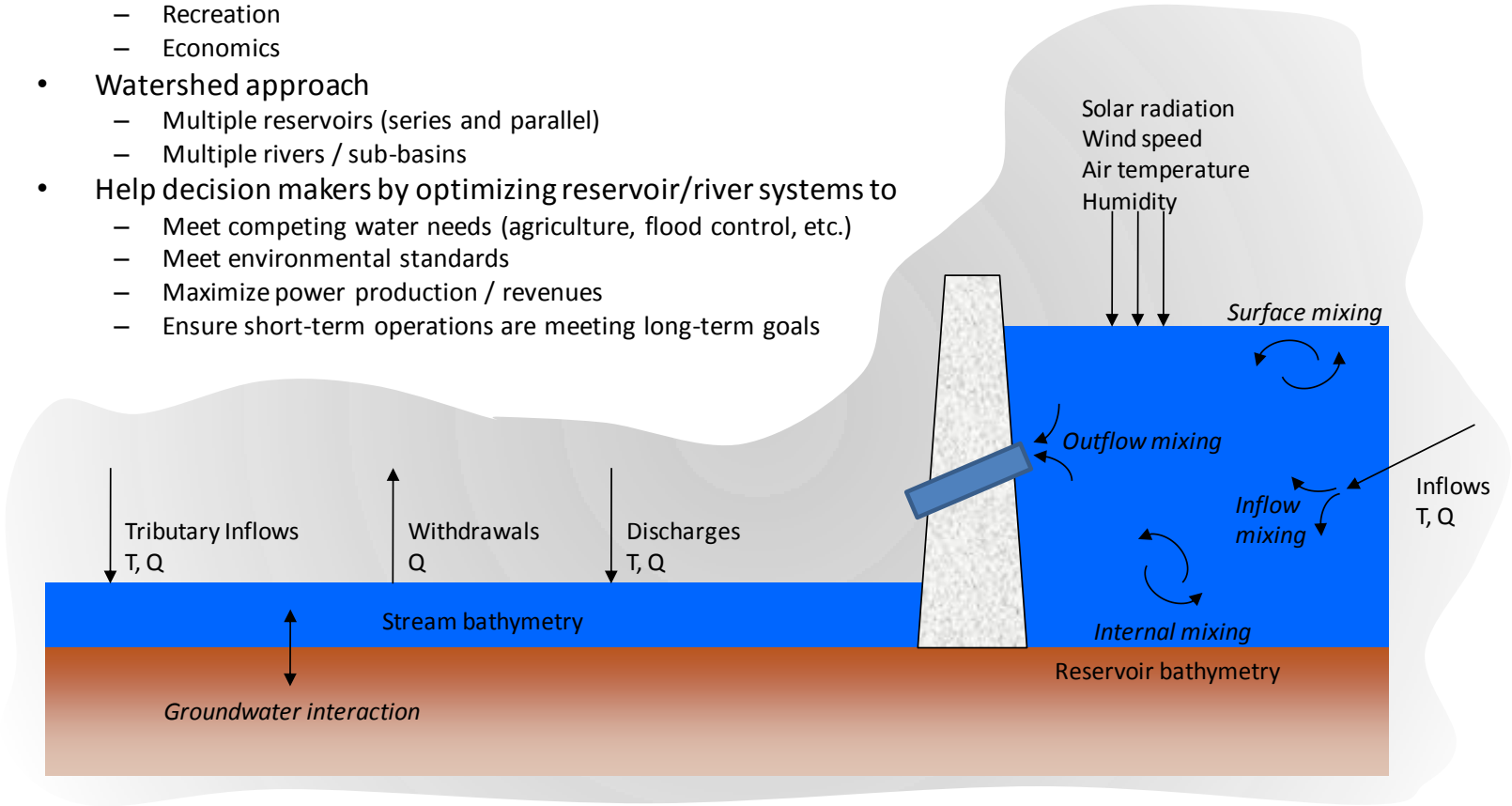
Optimization Toolbox Development



Hydropower Best Practices Identification, Assessment, Demonstration	Hydrologic Forecasting Enhancement	Asset Scheduling Enhancement	Unit and Plant Optimization
Increase Hydropower Production	✓	✓	✓
Improve Environmental Performance	✓	✓	✓
Increase Hydropower Flexibility	✓	✓	✓
Enhance Hydropower Economics	✓	✓	✓

Seasonal Hydrosystems Analysis

- Simulate in reservoirs and rivers
  - Key environmental and hydrologic metrics (temperature, flow, DO, etc.)
  - Power production
  - Recreation
  - Economics
- Watershed approach
  - Multiple reservoirs (series and parallel)
  - Multiple rivers / sub-basins
- Help decision makers by optimizing reservoir/river systems to
  - Meet competing water needs (agriculture, flood control, etc.)
  - Meet environmental standards
  - Maximize power production / revenues
  - Ensure short-term operations are meeting long-term goals



Conventional Hydro Complexity

- ✓ Multiple interacting phenomena
  - evaporation, heating of rivers, hydrology of ground water, drought, etc.
- ✓ Non-linear dynamics and effects
  - hydrological cycle, climate effects
- ✓ Adaptive behavior
  - modified operation due to regulation changes, river species
- ✓ **Large network of elements or nested complexity**
  - multiple watersheds, population changes – new power demands, changing environmental regulations, changing power regulations, technology changes, power pricing, …
    - ✓ Mathematics: non-linear dynamics
    - ✓ Physical-Cyber-Behavior: interactions among all three
    - ✓ Systems Engineering: safety, reliability, maintainability, survivability
    - ✓ Sandia Software Tools: DAKOTA
    - ✓ Sandia Disciplines: energy systems, physical security, cyber security, HPC

Exceptional service in the national interest

Sandia National Laboratories

Offshore Wind Energy

U.S. DEPARTMENT OF ENERGY

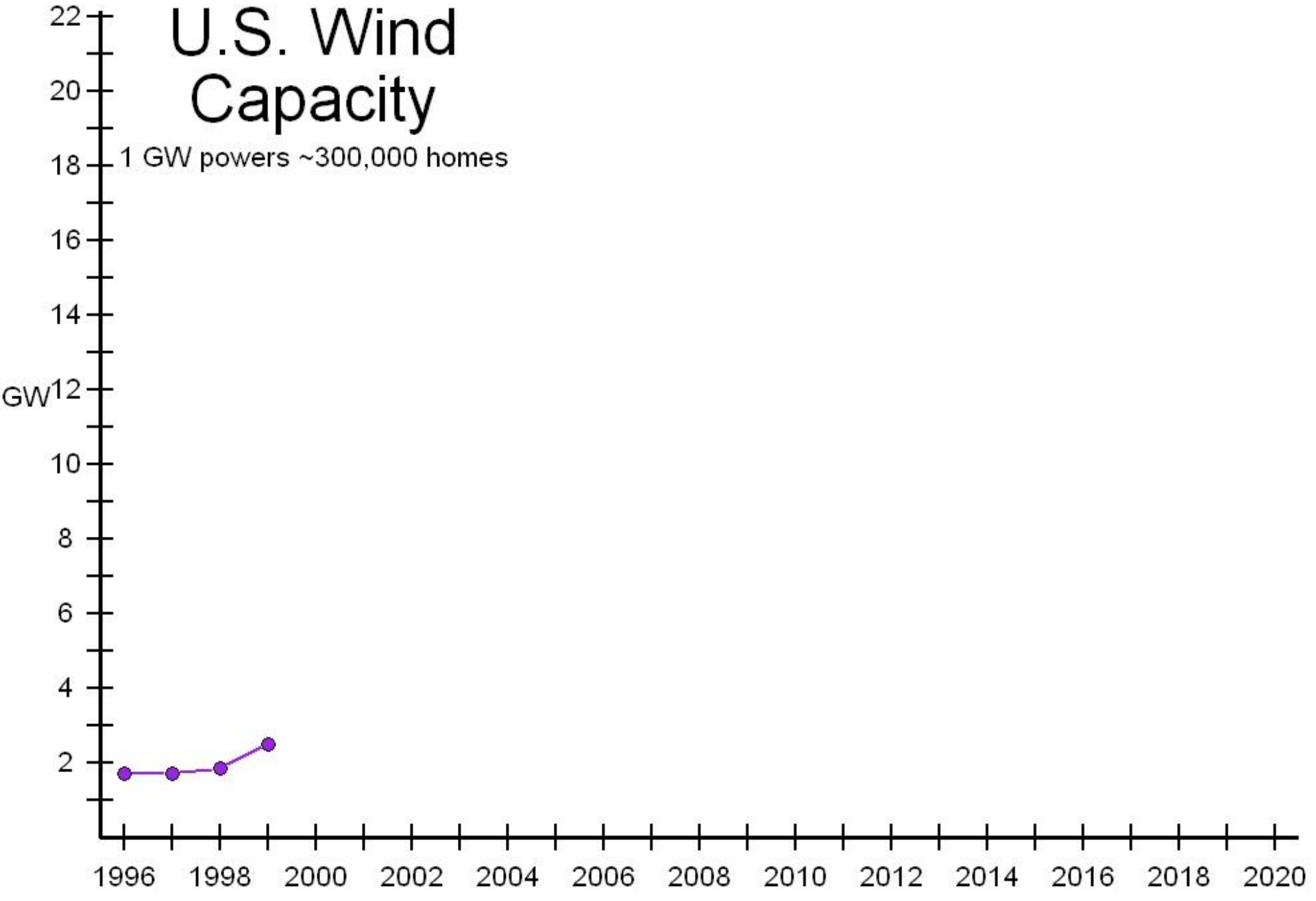
National Nuclear Security Administration

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

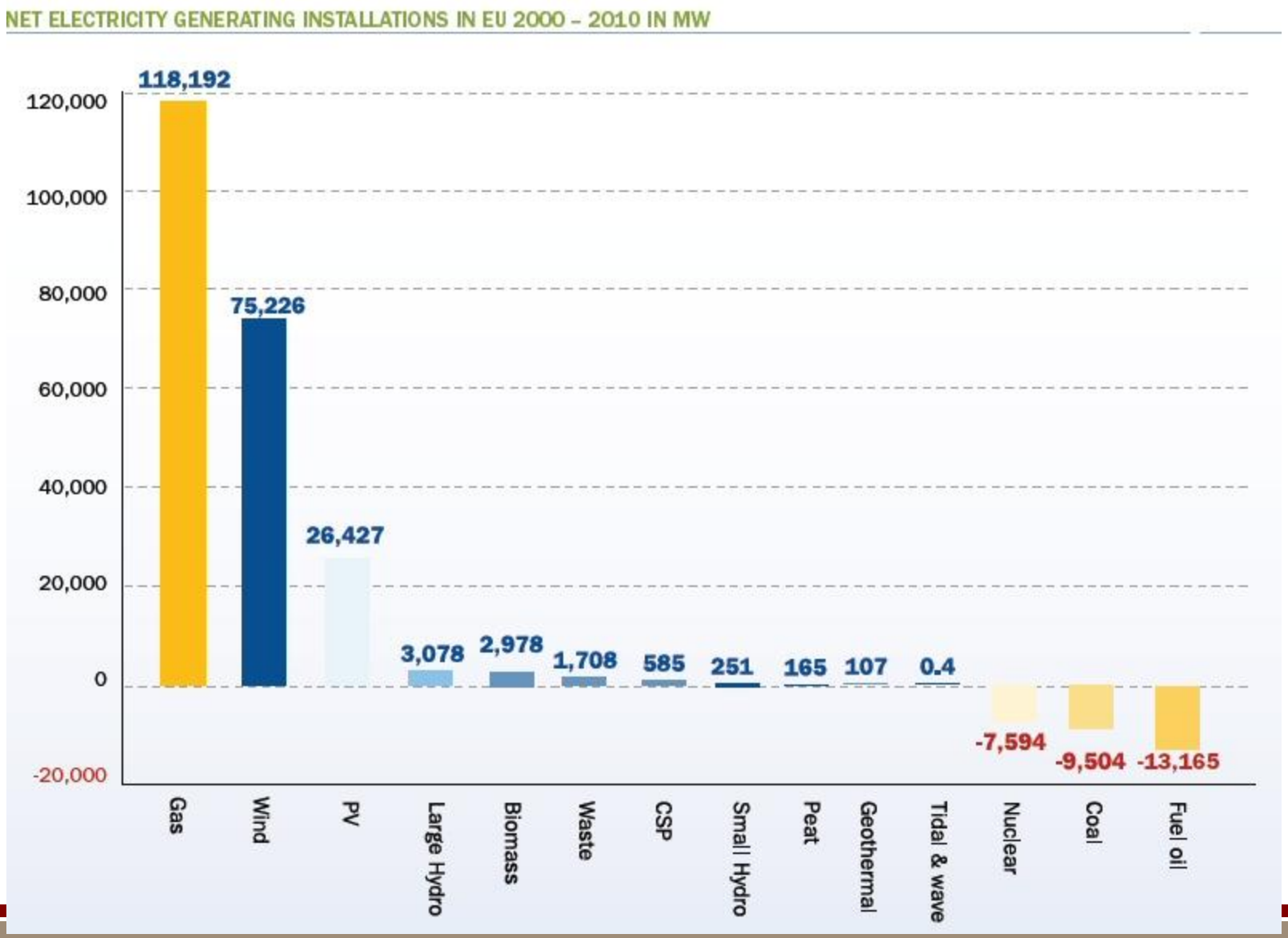
Sandia National Laboratories

Forecasts and Predictions

"There are three kinds of lies:
lies, damned lies, and statistics."


U.S. Wind Capacity
1 GW powers ~300,000 homes
GW
22
20
18
16
14
12
10
8
6
4
2
1996
1998
2000
2002
2004
2006
2008
2010
2012
2014
2016
2018
2020

Much More Mature Industry

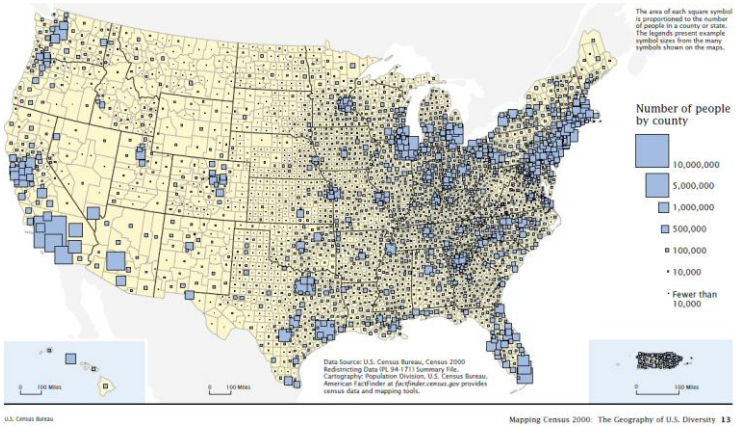


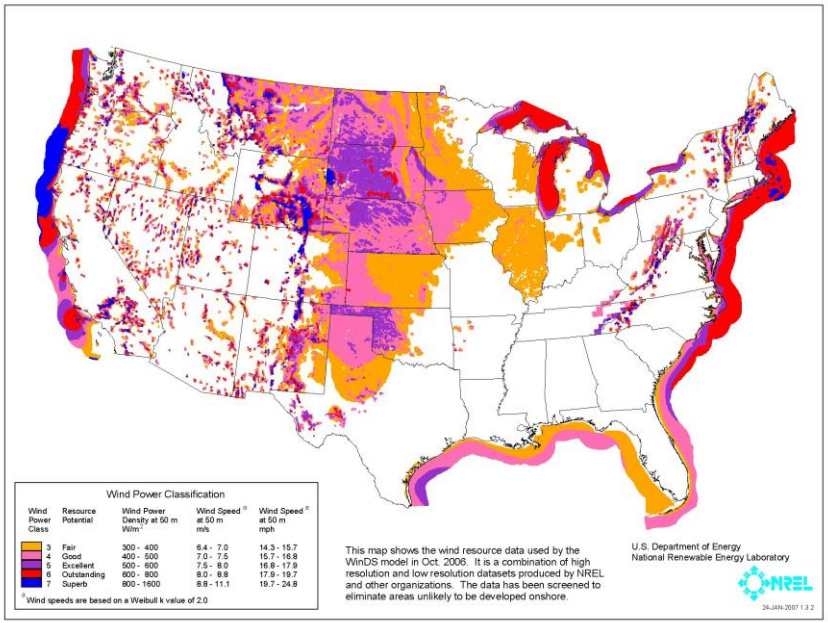
European Wind Energy Association, Feb 2011

Why Go Offshore?

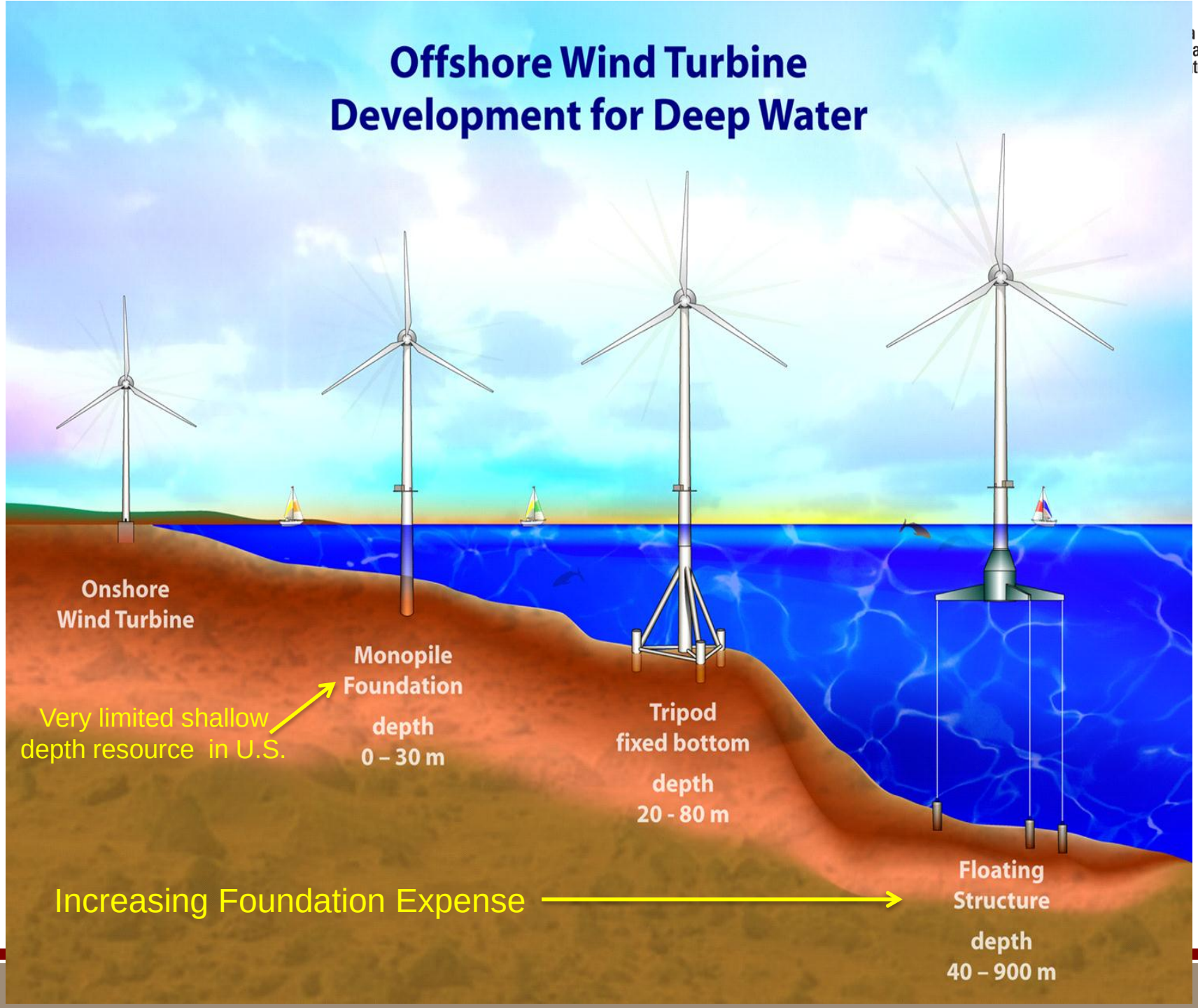
- Limited land-based opportunities
  - ✓ Europe
  - x US

- Better wind resource
- Close to load centers





$$WindPower = \frac{1}{2}\rho A C_P V_\infty^3$$

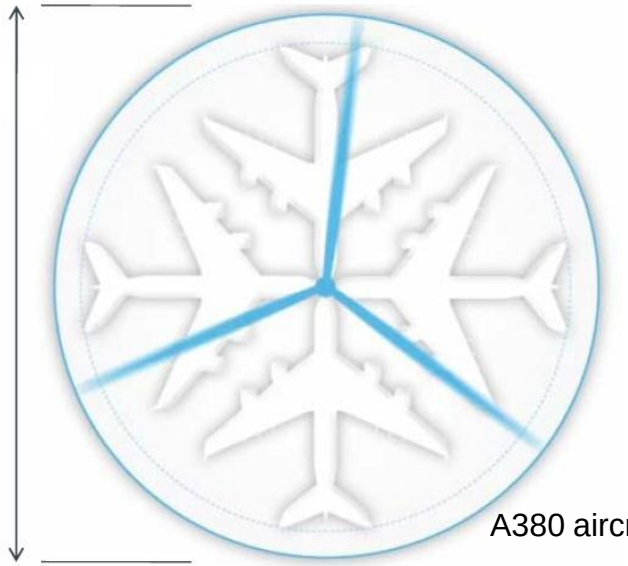

Offshore Wind Turbine
Development for Deep Water
Onshore
Wind Turbine
Monopile
Foundation
depth
0 – 30 m
Very limited shallow
depth resource in U.S.
Tripod
fixed bottom
depth
20 - 80 m
Floating
Structure
depth
40 – 900 m
Increasing Foundation Expense

Offshore Wind Turbines are Large

High foundation cost leads to larger turbine

Vestas V164 – 7.0 MW Offshore Turbine

Swept Area:	**21,124 m²**
Mega Watt:	**7.0**
Blade Length:	**80 m**
Min. Hub Height:	**105 m**
Rotor Diameter:	**164 m**
Tip Height:	**187 m**
Weight:	**~800 ton**



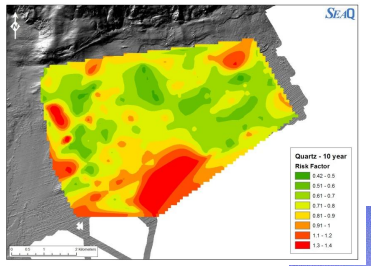
A380 aircraft

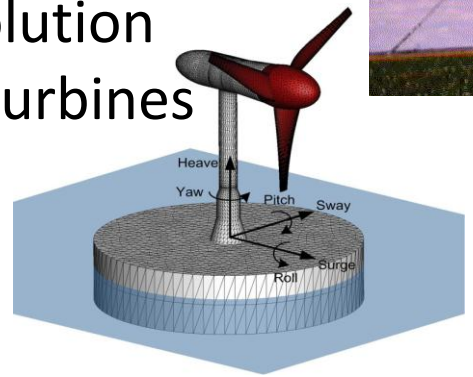
21,124 sq meters = 25,263 sq yards

Source: *Vestas: A new era for offshore wind power*

Sandia Efforts in Offshore Wind Energy

- Structural Health and Prognostics Management
- Large Offshore Rotor Development
- Sediment Transport, Scour and Foundation Impact Analysis
- Radar Mitigation
- DE-FOA-0000415, Innovative Offshore VAWT Rotors
- DE-FOA-0000415, High-resolution modeling of offshore wind turbines and farms





Offshore Wind Energy Complexity

Sandia National Laboratories

- ✓ Multiple interacting phenomena
  - wind loading, wave loading, corrosion, device operation, etc.
- ✓ **Non-linear dynamics and effects**
  - combined device motion due to wind and wave loading, wind shear, turbulence
  - ✓ Mathematics: non-linear dynamics
  - ✓ Physical-Cyber-Behavior: interactions among all three
  - ✓ Systems Engineering: safety, reliability, scalability, maintainability, survivability, affordability
  - ✓ Sandia Software Tools: DAKOTA
  - ✓ Sandia Disciplines: energy systems, cyber security, HPC
- ✓ Adaptive behavior
  - yaw systems, active ballast control, prognostics management
- ✓ Large network of elements or nested complexity
  - multiple regulatory jurisdictions, multiple use demands (fishing, shipping, defense, recreation), significant environmental constraints, …

ENG 505 - ENERGY SURETY & SYSTEMS

Water

Sandia National Laboratories

THANK YOU!

QUESTION & ANSWER