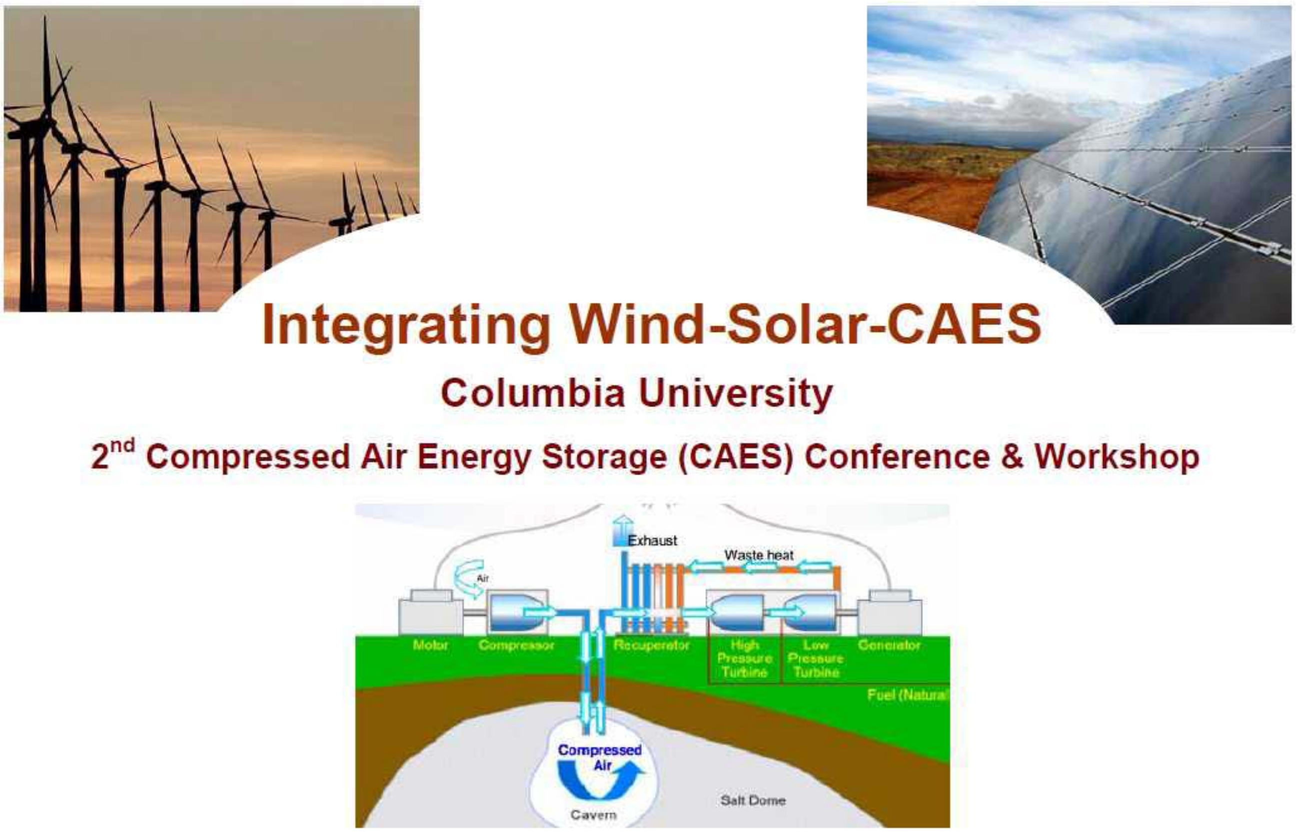
2nd Compressed Air Energy Storage (CAES) Conference & Workshop



OCTOBER 20 & 21, 2010

Organized by

Vasilis Fthenakis

Center for Life Cycle Analysis/ Earth and Environmental Engineering

Sponsored by the New York State Energy Research and Development Authority (NYSERDA)

Acknowledgment

I would like to thank all the workshop participants for their valuable input in the form of presentations and participation in discussions. Special thanks are due to the speakers and the participants of the round table discussions: Stephen Bauer, William Bailey, Alfred Cavallo, Paul Denholm, Easan Drury, Jim Harvilla, Timothy Havel, Kent Holst, George Lucas, Robert Kraft, Li Kou, John Martin, James Mason, Harry Miller, Thomas Nikolakakis, Michael Nakhamkin, Curtis Oldenburg, Georgianne Huff, Peter Roth, Nick Simos, William Steely, Samir Succar, Mark Torpey, Rob van Haaren, Daniel Wolf, and Stefan Zunft.

The workshop was organized by the Center for Energy & Life Cycle Analysis of Columbia University. It was sponsored by the New York State Energy Research and Development Authority (NYSERDA); we thank Mark Torpey, Program Director, for his foresight, support and encouragement.

Vasilis Fthenakis*, Workshop Organizer, Columbia University.*

Workshop Objective

Solar and wind have become the fastest growing segments in the energy market as the feasibility of a major transition to renewable and sustainable energy of the country's energy infrastructure is established. Although deployment of solar and wind systems in the U.S. may increase an order of magnitude from current levels without the need for adding storage, eventually, storage will be required for these intermittent technologies to become the major constituents of our energy mixture. Furthermore, incorporating storage in the system improves the flexibility of the grid in satisfying load demands. Currently, most energy storage systems are expensive; however, compressed air energy storage (CAES) is economical for large bulk storage and can provide cycling capability, regulation and quick start for both peak and base load applications. This workshop brings together nationally- and internationally-renown CAES technology experts and system analysts with the goal of collectively investigating the potential and value of CAES in supporting large penetration of wind and solar energy in the electricity grid, addressing national security and global climate change challenges.

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Session 4: Risks & Challenges in Underground Reservoirs

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Round Tables (October 21st, 2010) Summary

CAES R&D needs - Questions and Panel Recommendations

Question: Are improvements needed in CAES technology before implementation?

Recommendations:

- Demonstrations are needed for 2nd generation CAES plants. The science is well established but documentation of the physics and thermodynamics of 2nd generation technology need to be published and become widely available.
- Demonstrations are needed of the feasibility of small CAES plants (e.g., 5 MW) for distributed renewable energy grid integration.
- Cost analyses and case specific market analyses are needed for distributed and central CAES systems.

Question: Can a 1st generation small (e.g., 5MW) plant be cost effective?

Recommendations:

- It is difficult to make it economically feasible. Cost of machinery (per kW) increases with size reduction. However, cost of components can decrease in mass production.
- Inhibiting factor is the high cost of above ground air storage. Specially, the safety standards to be met for high pressure vessels is a significant cost driver.
- More documentation is needed for dissemination to the public. There is a sense of urgency. A handbook needs to be published to get everything summarized.

Question: What are the biggest challenges related to implementing very large scales of CAES in the U.S.?

- Economic – Competition with natural gas in terms of energy economics (gas peakers vs. CAES) and in terms of usage of available underground caverns; however, the need for gas storage in New York would be reduced due to the Millennium pipeline. Load for gas is becoming more leveled. A long-term view on fuel prices and necessary carbon emissions reduction is needed to overcome competition from natural gas.
- Technical – Identifying large volumes of suitable underground reservoirs.

- Finding suitable formations for air storage underground has proven to be a challenge in Iowa. However, the likehood of large suitable underground formations in New York is very good; this is documented in NYSERDA reports.
- Include CAES in long-term transmission planning for renewable penetration in the grid.
- There has to be a raise of awareness that CAES is to be treated as a transmission asset as well.
- Identify the best CAES locations for lowest cost support of renewable penetration.
- Raise utilities' interest in CAES development, demonstration and implementation.

Question: Is there a need for R&D on thermal energy storage systems?

- Thermal storage is the key for CAES cost and environmental sustainability advancement.
- The CAES community can benefit from R&D on thermal storage in other systems (e.g., Concentrated Solar Power, hybrid photovoltaics).
- The R&D roadmap of a DLR-led European adiabatic-CAES program specifically focus on thermal storage development for multi-hour storage of compression generated heat and a demonstration plant is planned for 2013. The U.S. will be benefited by developing parallel development and demonstrated plans.

Question: What are the CAES assessment needs?

- Assess future natural gas price and their effect on economic risks of conventional and adiabatic CAES systems.
- Assess the carbon reductions and other environmental benefits attributed to CAES integration in the grid.
- Economic analyses for various modes of CAES integrated in the grid.
- Economic analyses of developing underground storage including site assessments and permitting.
- Load analyses with wind, solar and CAES; CAES interface with grid management.
- Demonstrate and document CAES start-up and ramp rates for current and proposed designs.

Question: What are the model development and modeling needs?

- A modeling roadmap is needed.
- Develop models of integrating wind, solar and CAES for satisfying regional loads.
- Conduct transient modeling for different operation states (e.g., from frequency regulation to arbitrage).
- Integrate models of equipment (e.g., compressor, expander, and turbine) performance with models of electric grid dynamics.
- Conduct tests to validate equipment and integration models

Question: Is there competition for underground storage between storage of natural gas or CO_2 and CAES?

- At the moment there is no competition. However, in large scales implementation there could be competition with natural gas storage; the outcome would depend on the price of fuel and the incentives for CAES. Potash solution mining also presents a potential competition, since depleted salt mines are used for liquid waste disposal.
- Underground CO_2 storage requires greater depths than CAES and poses significant safety risks that differentiate it from air storage.

Question: What are the safety and risk analyses needs for CAES?

- The industry reports detailed safety studies of the above ground machinery used in CAES (e.g., compressors, expanders, turbines). Safety relief valves are built-in and air is a benign medium.
- Underground storage requires flammability studies and cavity integrity and vulnerability studies.

CAES Business needs - Questions and Panel Recommendations

Question: Can CAES qualify for renewable energy credits?

- It is matter of classification. Currently CAES is classified as green but not renewable technology since it requires fuel to operate. Perhaps a partial credit (e.g., 70% of capacity) reflecting the wind and solar related input into CAES could materialize.

- Storage should be a new item besides transmission and generation. The markets should allow for benefits from the plant to be reflected in revenues.
- Showing the benefits CAES brings to the whole grid is important for gaining support from the general public, regulators and legislators.

Question: Ways to fund CAES? Do people want to be taxed for a plant? How can the public be involved in CAES?

- Wind and solar generation of electricity can carry some premium. CAES enables wind and solar and thus should share some of the premium allowed for renewable energy development.
- Cost/benefit scenarios of CAES integration of wind and solar into the grid should be shown.
- Surcharge on electric bills for wind and solar electricity either directly or via CAES is a mechanism for generating funds to fund CAES R&D and deployment.
- Quantify the measure of grid stability; not only what is the cost of CAES, but also what is the cost of ‘no storage’.

Question: How urgent is storage for grid stability?

- With current rates of wind and solar deployment in Europe and the US large storage may be needed by 2015-2020 to reliably satisfy loads under transmission cost and congestion constraints.
- CAES reliability is a selling point.

Question: Do we need very fast responding storage systems (e.g., flywheels, batteries) in addition to CAES?

- Theoretically, CAES ramping rates are in the order of a few minutes which in many cases could satisfy all grid stability and load following requirements; however, field demonstrations are needed to verify this.
- Batteries and/or flywheels will be needed in leveling highly variable resources and provide power quality services. In the future renewable energy generators like wind power and PV themselves will be able to provide short term power quality services.

- In future scenarios excess capacity from car batteries (V2G) could compliment CAES services in short timescales.

Question: What is the status of CAES demonstration?

- There is a great need for the first demonstration plant linked with wind or solar generation to be deployed as the two existing CAES plants are outdated and are not connected to renewable energy sources.
- Industry members are working with developers to develop projects, and with commercial teams to supply turnkey CAES plants. There are promising opportunities.

Conclusion

The CAES 2010 Workshop at Columbia University brought together, and facilitated interaction among, experts on energy system analysis, industry partners and university and national lab researchers. The consensus was that although the need for CAES may not be eminent, in 10-20 years we would need a lot of large-scale storage in the electricity grids of the country and now is the time to plan for it. Market analysis, modeling of the integration, demonstration of the performance under variable inputs and R&D of advanced CAES designs are needed.

1. Keynote Address: New York State Energy Planning

Mark R. Torpey, *NYS Energy Research and Development Authority (NYSERDA)*

Mark currently serves as the Director of R&D at the New York State Energy Research and Development Authority (NYSERDA) where he manages the power systems, transportation, environmental and business development programs. Mark is also responsible for managing New York State's Renewable Portfolio Standard (RPS) initiative with an aggressive target to produce 30% of the State's electric energy consumption with renewable resources by 2015. Mark has been an active member of Governor Paterson's Climate Action Council which is responsible for developing a policy framework to achieve an 80% reduction in greenhouse gas emissions below 1990 levels by 2050 (a.k.a. the "80 by 50" Challenge). Mark recently helped establish the New York State Smart Grid Consortium (a not-for-profit 501 (c)6 corporation) to develop a long-term implementation strategy for deploying the "smart grid" in NYS. Mark is a Fellow of the American Society of Mechanical Engineers.

Integrating Wind-Solar-CAES
Columbia University
2nd Compressed Air Energy Storage (CAES) Conference

New York State Energy Planning

Wednesday, October 20th, 2010

Mark R. Torpey
Director R&D
NYSERDA

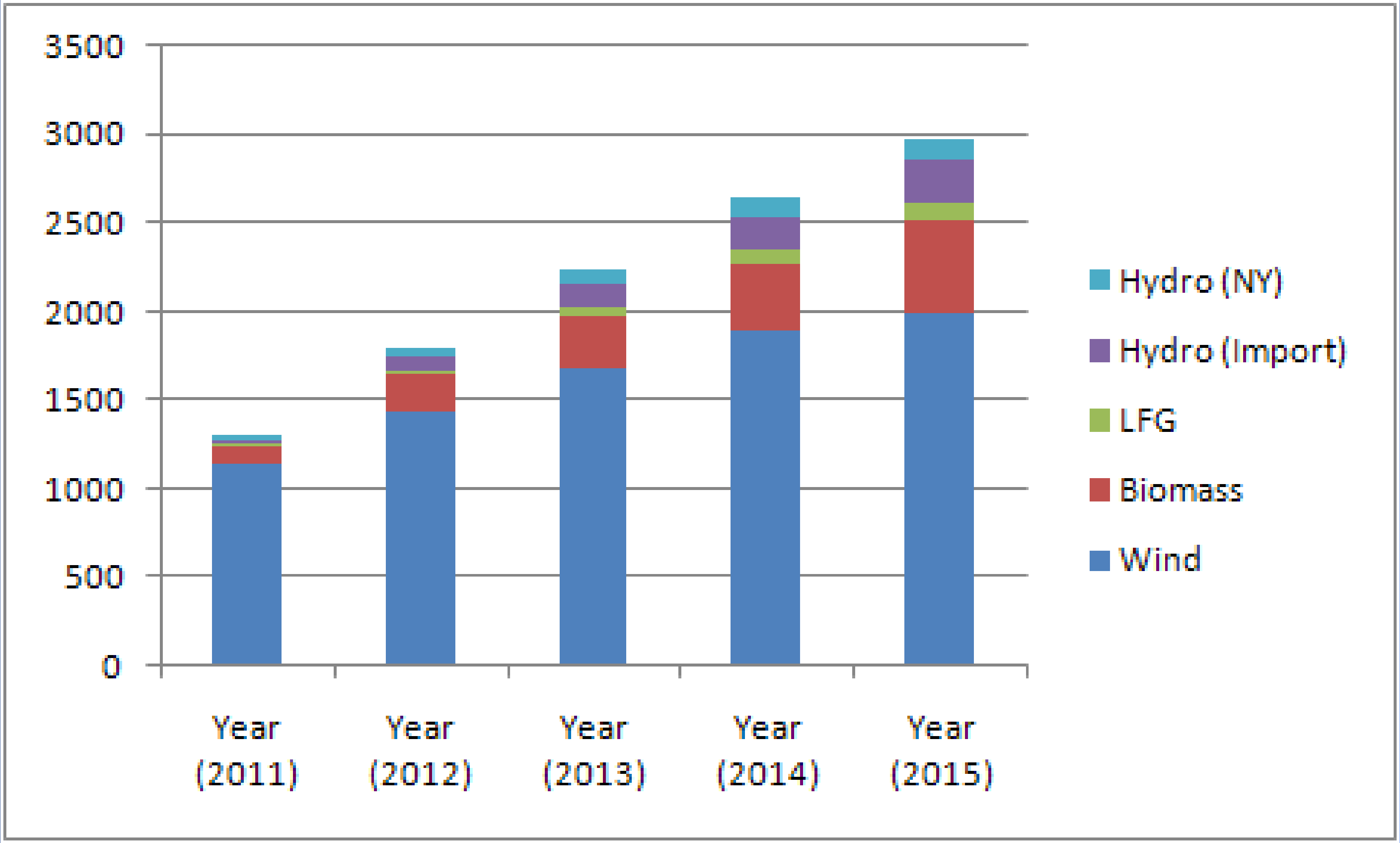
Much has happened since the last CAES meeting ….

Headline Story (10/21/2008):

Former Fed Chair Alan Greenspan told Congress the economic crisis unveiled "a flaw" in his view of world markets.

New York has increased its Renewable Portfolio Standard (RPS) goal (30% Renewable Resources by 2050)

(MW)



Installed Wind: 1,275 MW (2010) vs. 700 MW (2008)

New York received federal support for "smart grid" projects

Company	DOE Category	Project	Stimulus Funds	Total Cost
Consolidated Edison	SG Investment Grant	Distribution System Automation	$136,170,899	$272,341,798
NYISO	SG Investment Grant	PMU and Capacitors	$37,382,908	$75,710,735
LIPA	SG Regional Demonstration	Route 110 Smart Grid Pilot	$12,496,047	$25,293,735
NYPA	SG Regional Demonstration	Dynamic Thermal Rating	$720,000	$1,440,000
Consolidated Edison	SG Regional Demonstration	Secure Interoperable Smart Grid Pilot	$45,388,291	$92,388,217
Energy East	SG Energy Storage Demonstration	150 MW Compressed Air Energy Storage	$29,561,142	$125,006,103
			$261,719,287	$592,180,588

Beacon Power: $43 million loan guarantee (Stephentown, NY)
Premium Power: $8 million (Syracuse, NY)

New York established the NYS Smart Grid Consortium

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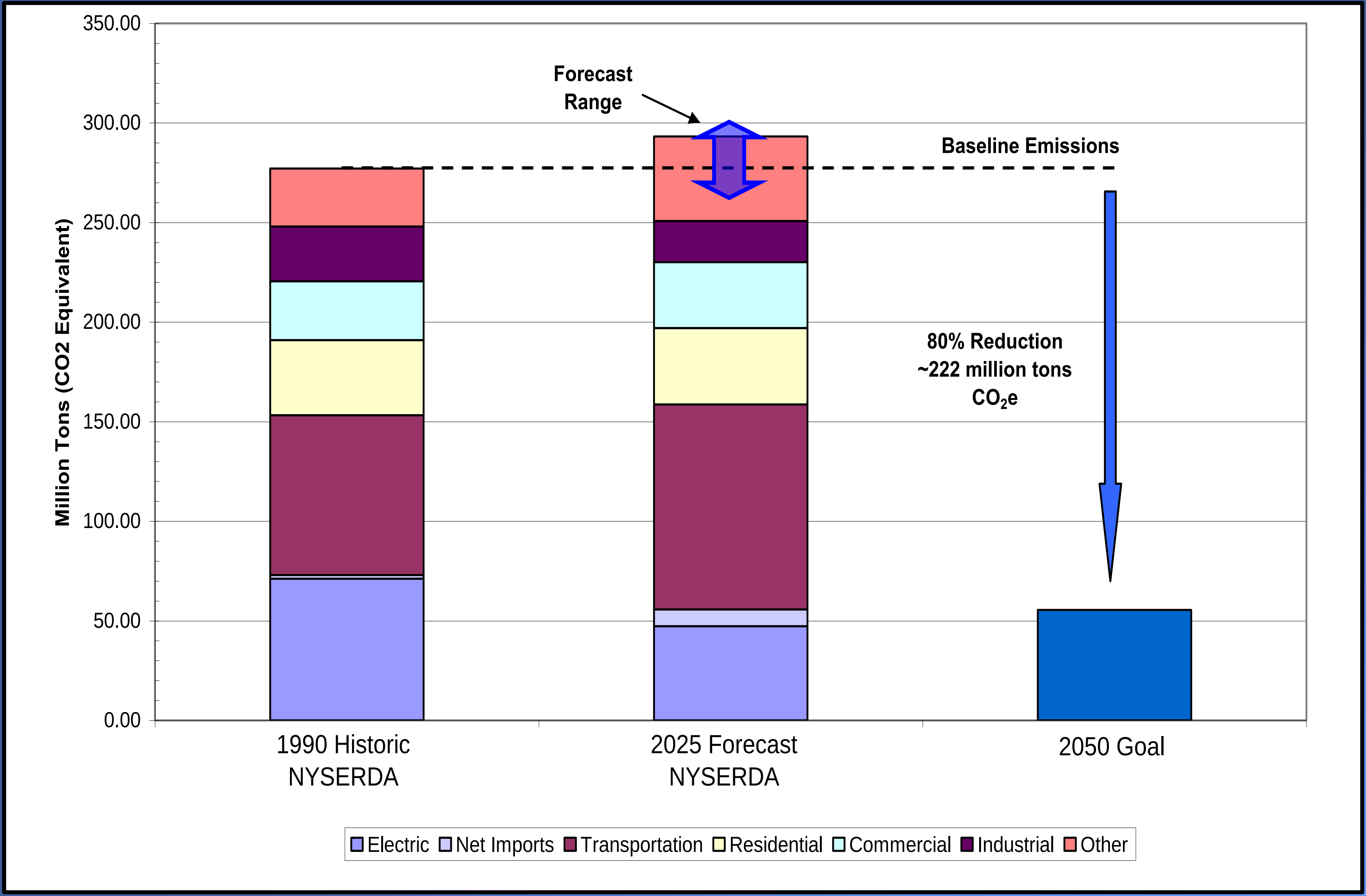
New York is completing a Climate Action Plan to reduce GHG emissions ("80 by 50")



http://www.nyclimatechange.us/ewebeditpro/items/O109F22816.pdf

New York is supporting a variety of good projects

General Electric
Variable Frequency Transformer
300 MW (December 2009)

Beacon Power
Flywheel Technology
20 MW (1st Qtr 2011)

Thank You

Please visit the website (www.nyserda.org)

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2. Solar Energy Prospects in the U.S.

Vasilis Fthenakis, Columbia University and Brookhaven National Laboratory

Prof. Vasilis Fthenakis is the founder and director of the Center for Life Cycle Analysis (CLCA) at Columbia University. He also leads the National Photovoltaics (PV) Environmental Research Center operating at Brookhaven National Lab (BNL) under the auspices of the DOE since 1982. The centers are synergistically engaging students and researchers in the two institutions and have formed close collaborations with the U.S. PV industry, the European PV Industry Association and several European Universities on the LCA area. He leads the International Energy Agency (IEA) Task on PV Environmental Health and Safety. He is the author or coauthor of 250 publications on energy and the environment and a Fellow of the American Institute of Chemical Engineers and of the International Energy Foundation.

Solar Energy Prospects

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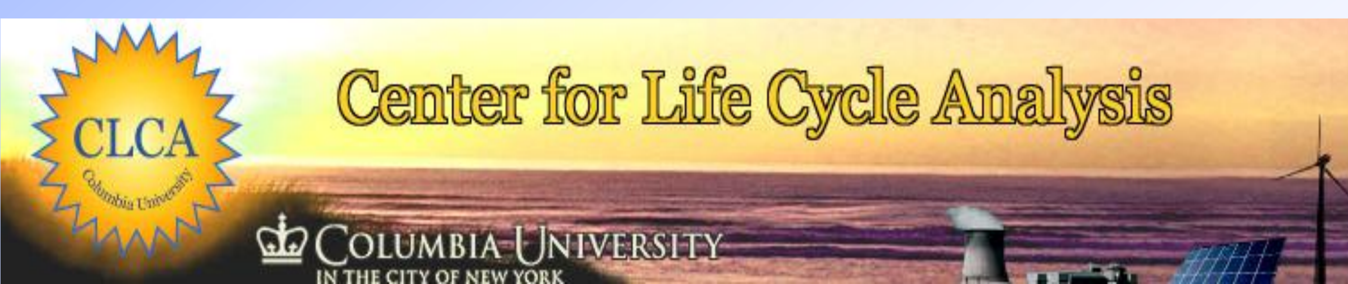
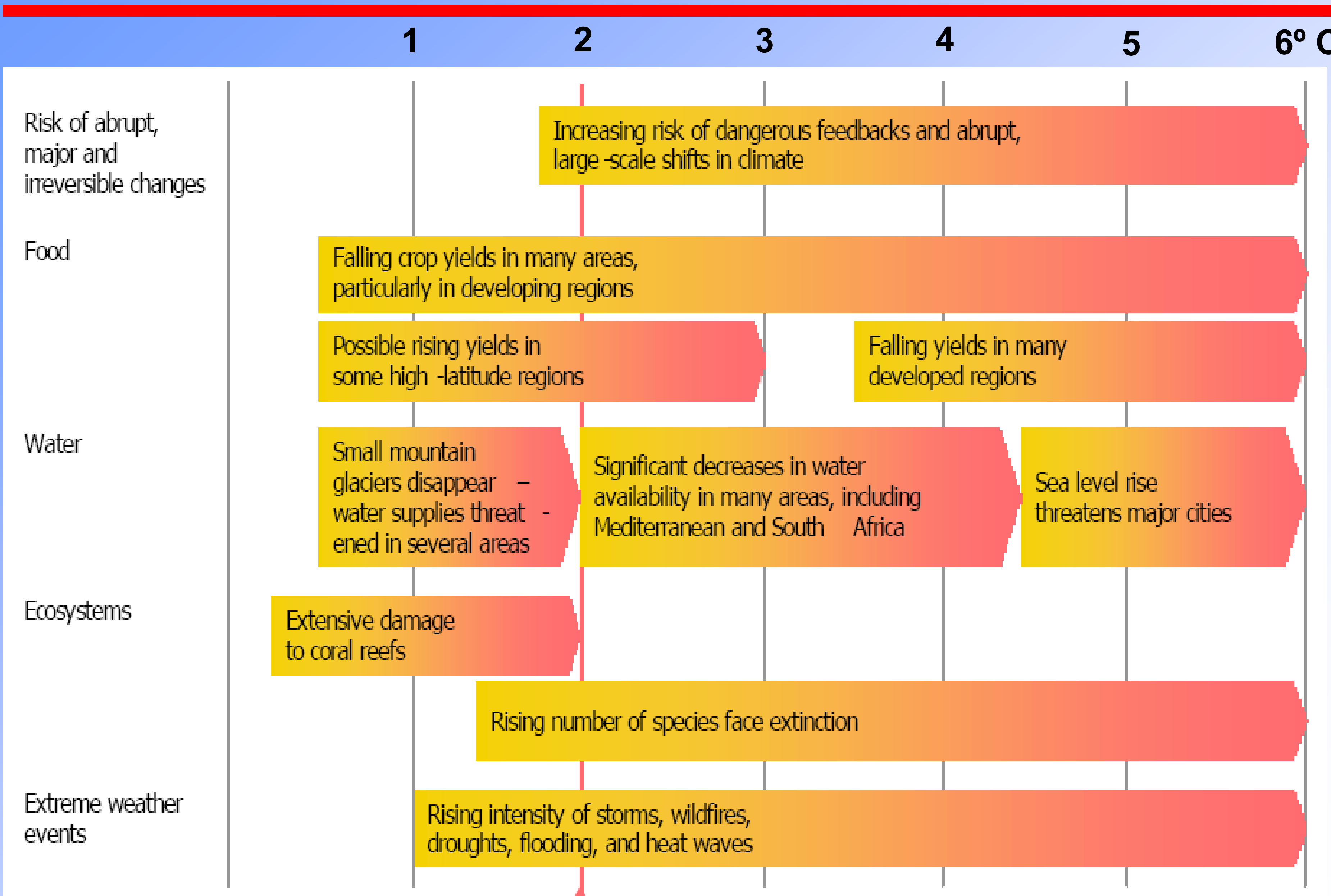
Director, Center for Life Cycle Analysis, Columbia University
and
PV Environmental Research Center, Brookhaven National Laboratory



email: vmf5@columbia.edu
web: www.clca.columbia.edu

Potential Dangers of Climate Change



Source: Adapted from Stern Review, 2006

Conventional Energy Resources:
How much is left at what cost?

- Oil: 40 – 125 years (Hubbert's Peak ~ 2015?)
- Natural Gas: 65 - 210 years
- Coal: 250 – 360 years
- Uranium: 80 – 300 years

Science **329**, 786 (2010)

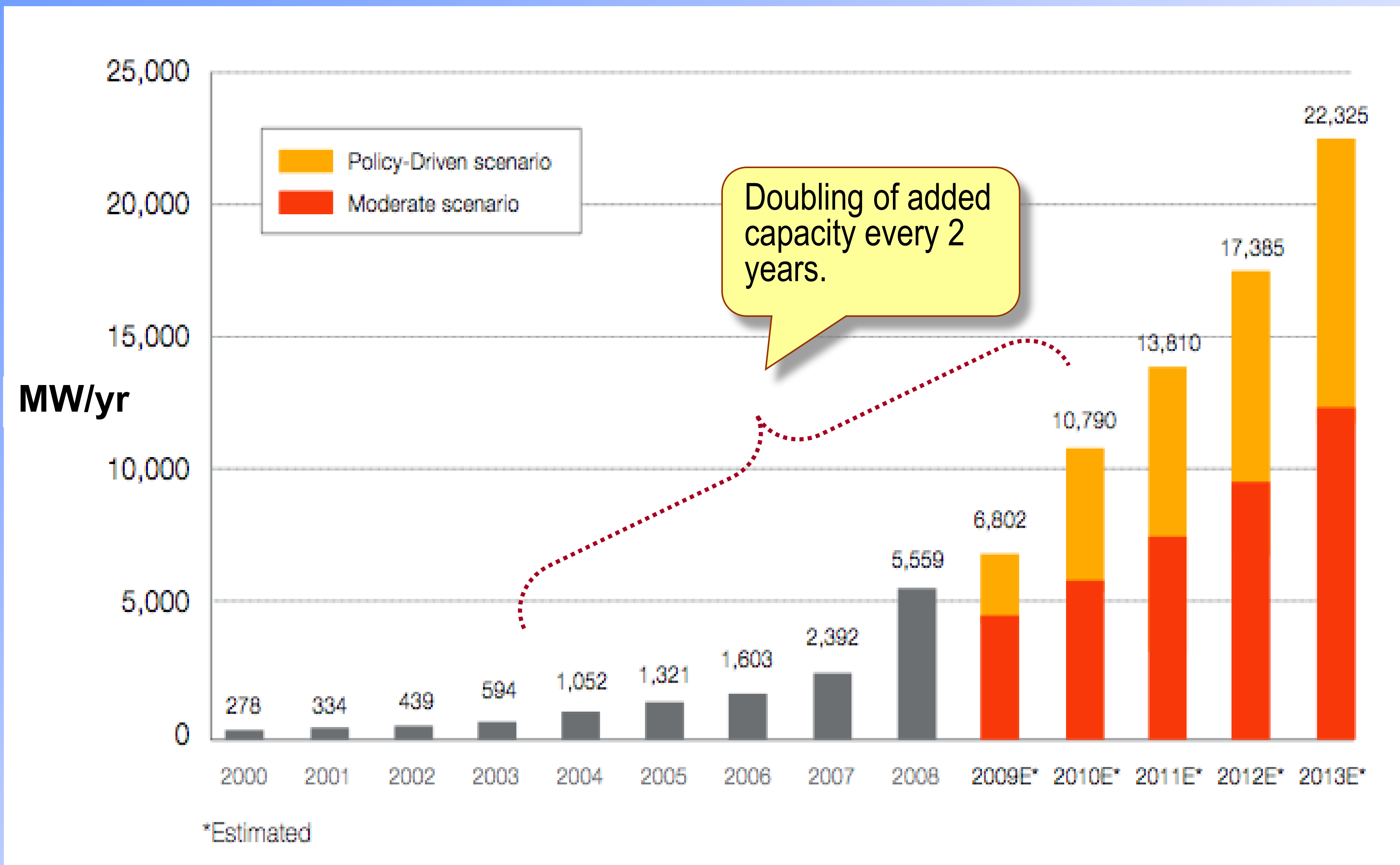
More Difficult/Costly/Risky

13

Renewable Energy Resources: How much at what cost?

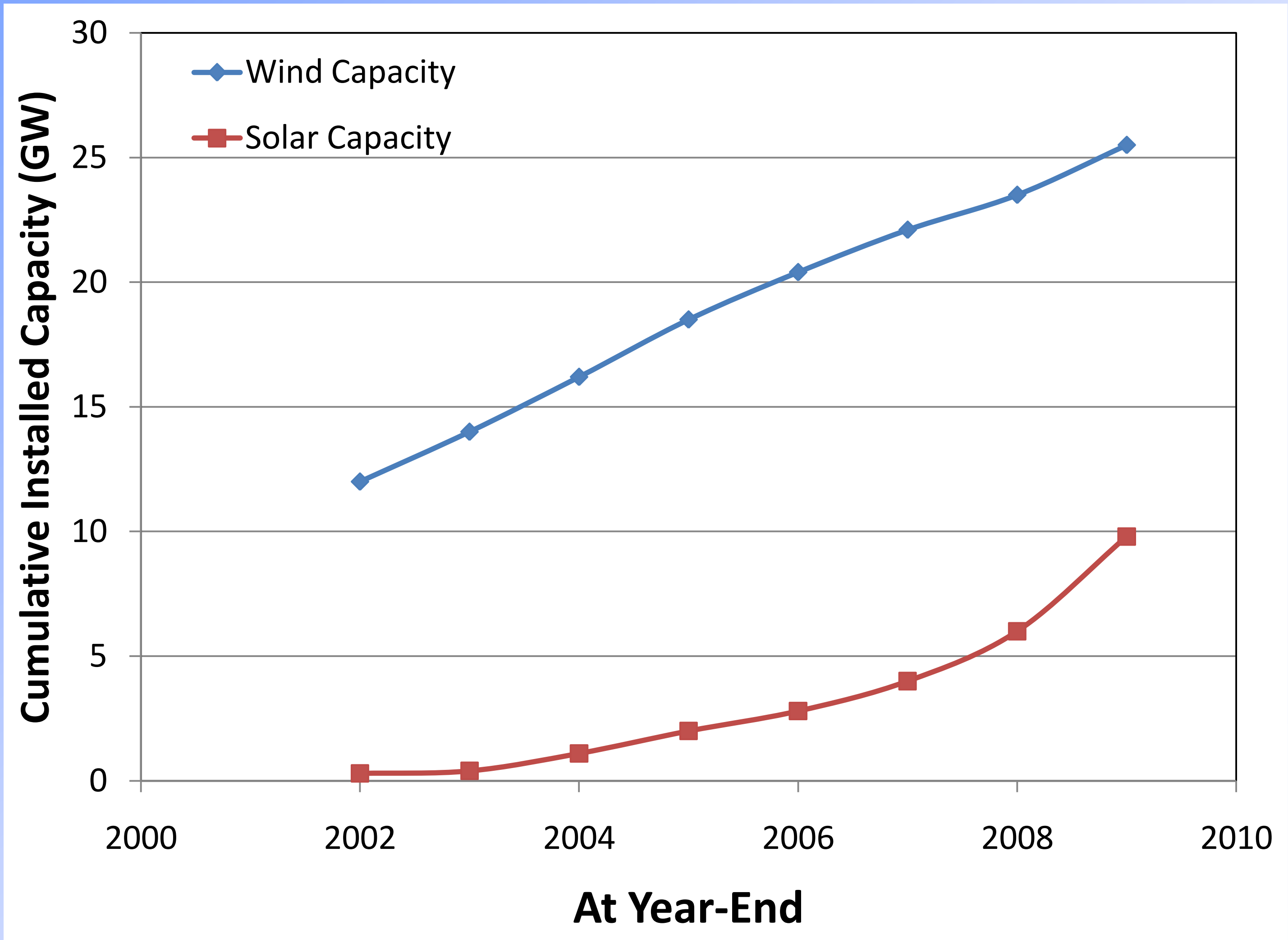
- Abundant resources
- Wind: Best sites are cost competitive already
- Solar: Best sites to be cost competitive in 3-4 years

Photovoltaic Global Sales and Projections



Source: PV Market Outlook European Photovoltaic Industry Association 2009

Renewable Energy Portfolio-driven Growth in Germany



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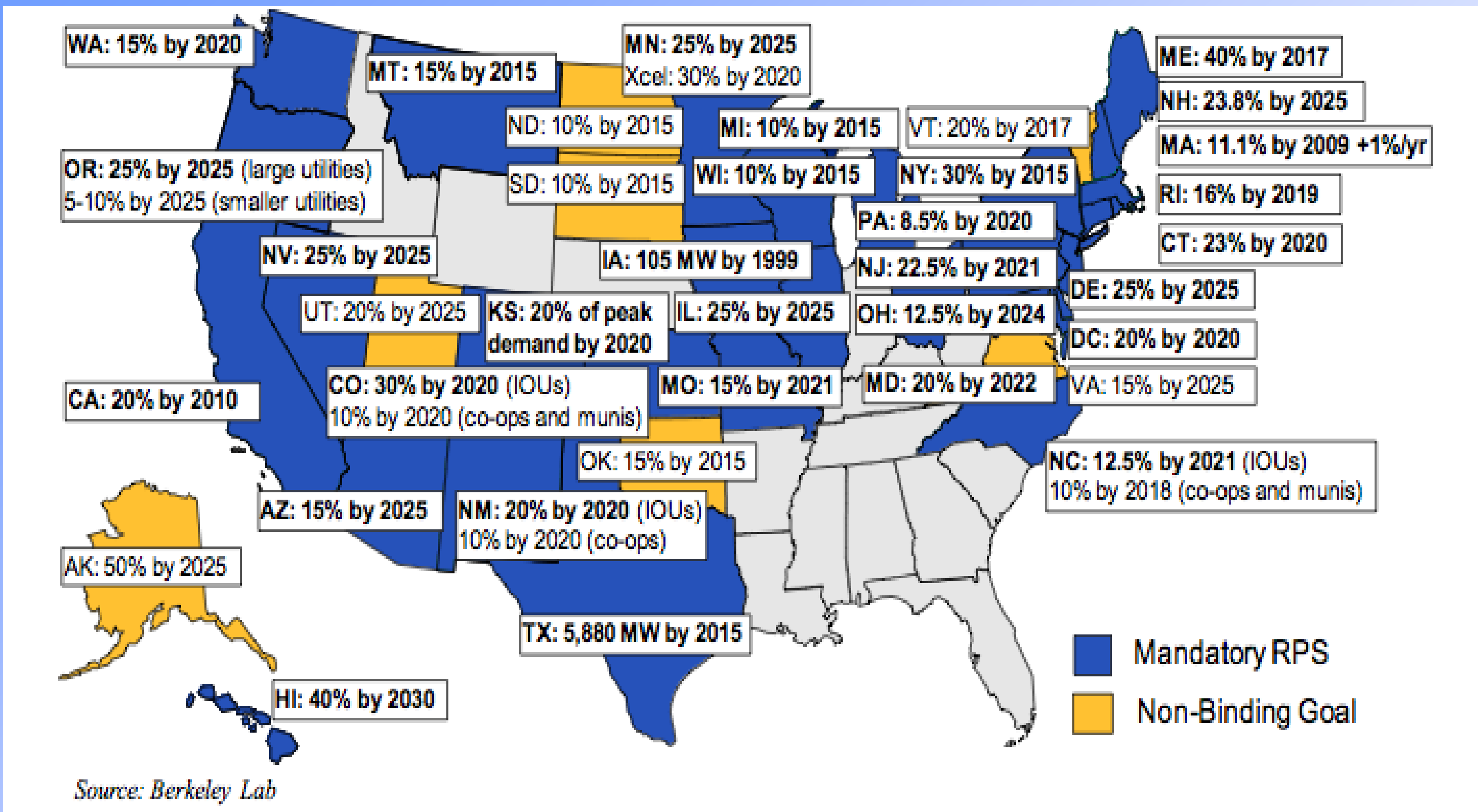
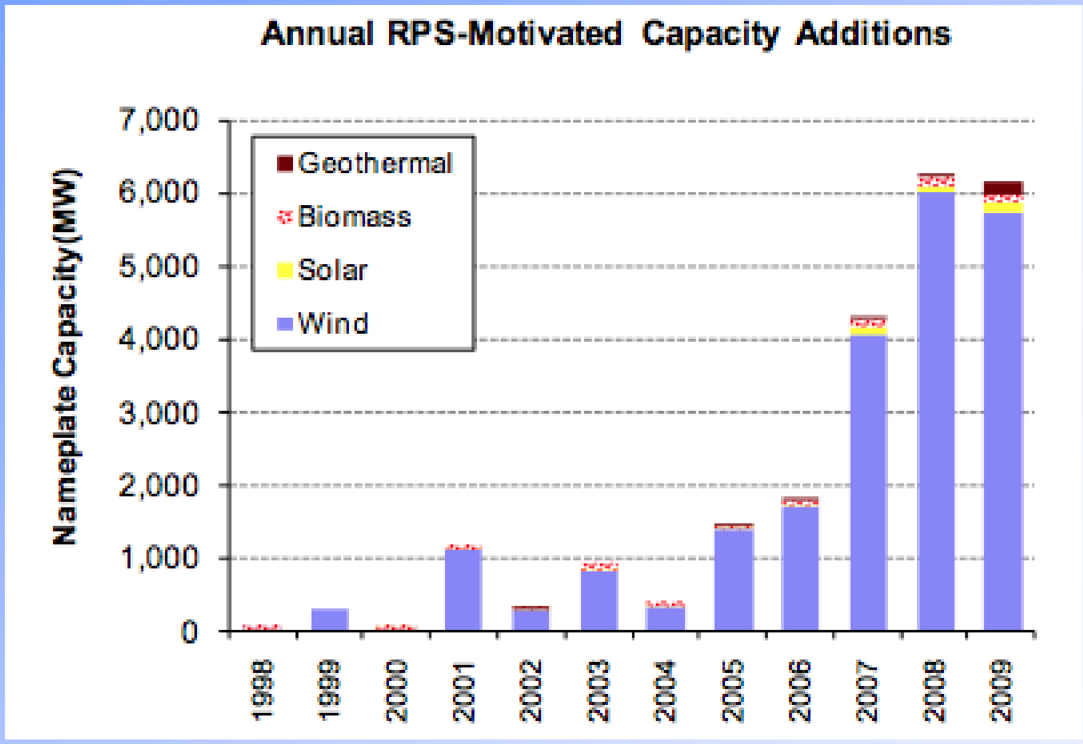
State Renewable Portfolio Standards



- Current RPS will require 73 GW of new RE capacity by 2025

Source: Wiser et al., LBNL, Oct. 2010

State RPS Largely Supported Wind so far



RPS motivated capacity additions total 23 GW in 1999-2009

93.9% wind

3.2% biomass

1.4% geothermal

1.5% solar

Source: Wiser et al., LBNL, Oct. 2010

But Solar is Coming Strong

Utility Scale Solar Projects

- in Operation: 601 MW
  - CSP 433 MW
  - PV 168 MW
- Under Construction: 192 MW
  - CSP 77 MW
  - PV 115 MW
- Under Development: 23,500 MW
  - CSP 10.3 GW
  - PV 13.2 GW

- BLM Fast-Track* Renewable Energy Projects (* for approval by Dec 2010)
  - Solar: 6,306 MW
  - Wind: 816 MW
  - Geothermal: 411 MW
  - Transmission: 1076 miles

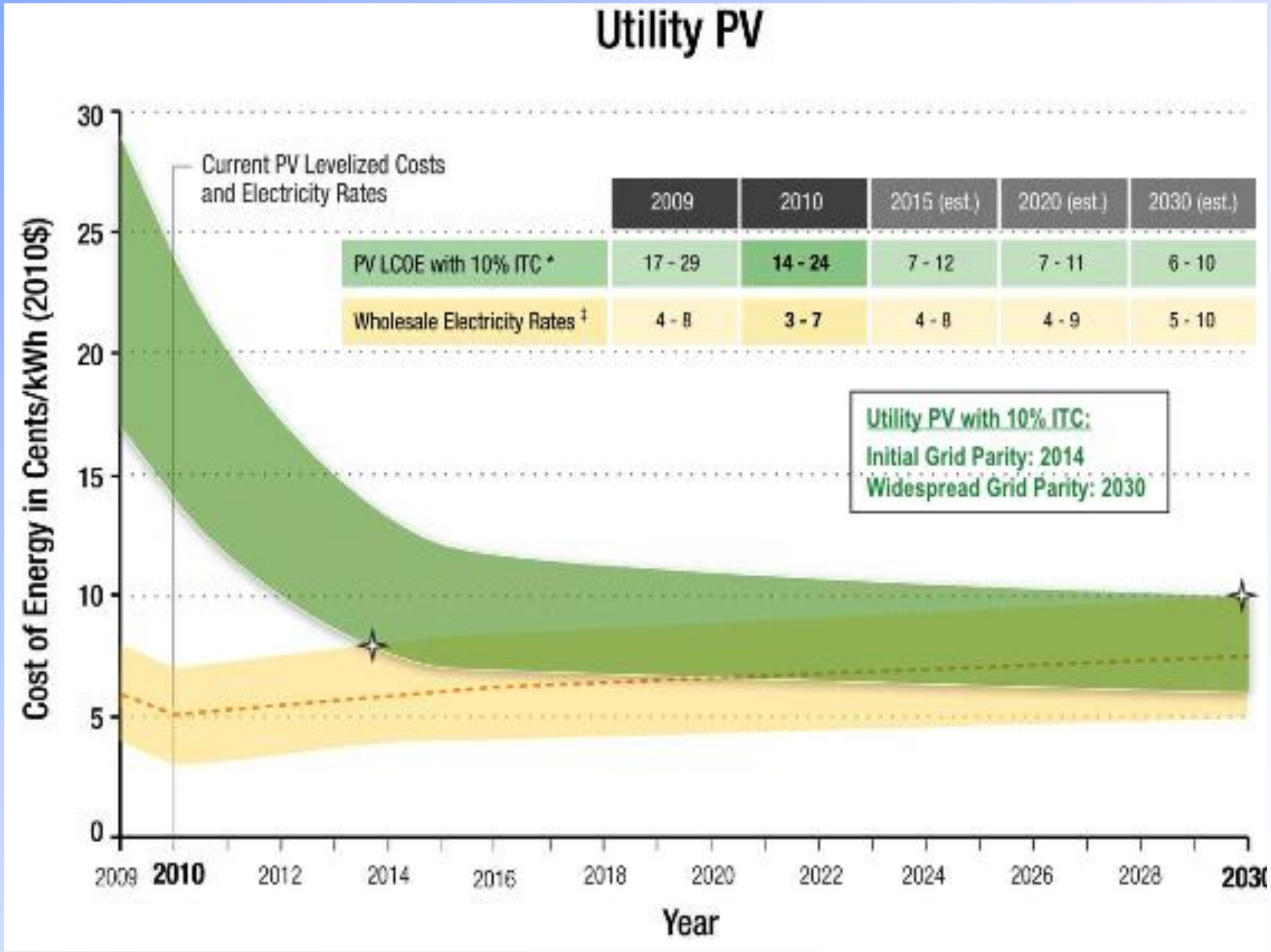
DOE Projected PV Growth and Electricity Price Targets

Geographic Locations

Phoenix, AZ
Kansas City, MO
New York, NY

Financing Conditions

Low: 8.2% after-tax WACC
High: 9.9% after-tax WACC

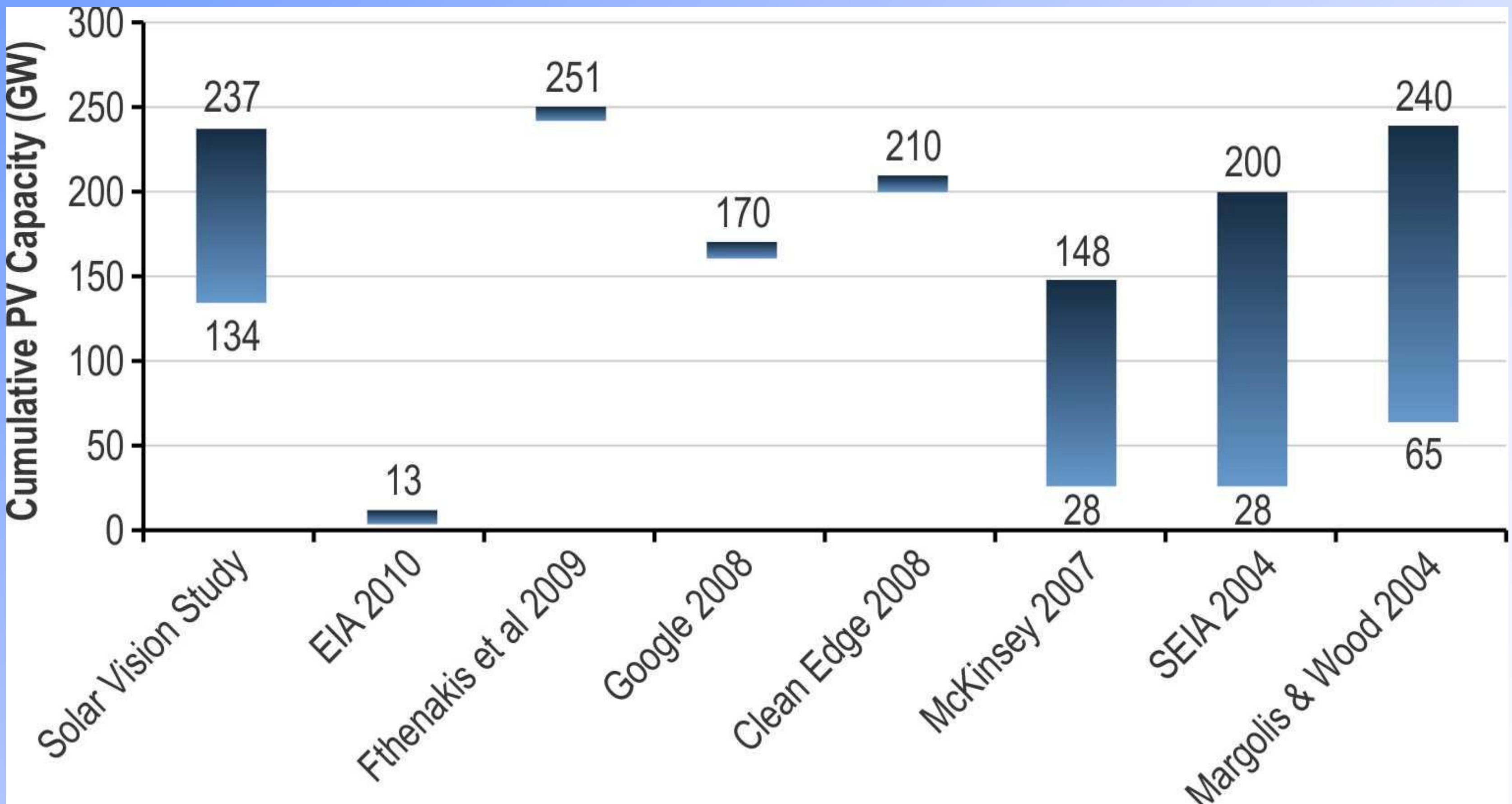


•Assumes IOU or IPP ownership of PV, and thus the LCOE includes the taxes paid on electricity generated. Includes 5-yr MACRS but not state or local incentives.

For a complete list of assumptions see DOE Solar Cost Targets (2009-2030), in process.

Source: J. Lushetsky, Solar Technologies Program, EERE, DOE, 25th EUPV, Valencia, Spain, Sept. 2010

DOE-EERE Solar Vision Feasibility Study 10-20% Penetration by 2030

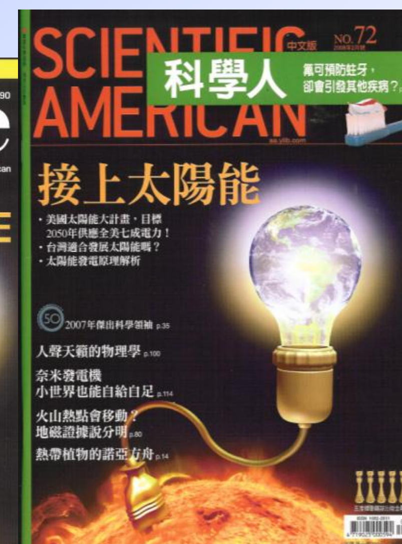


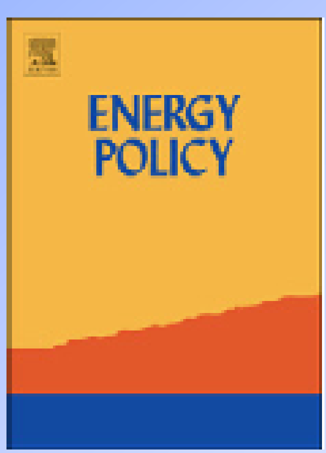
PV market projections for the United States by 2030

Draft in progress: Not to be cited

A Solar Grand Plan

By 2050 renewable energy to supply 69% of electricity, 35% of total energy needs of the U.S.
Zweibel, Mason, Fthenakis

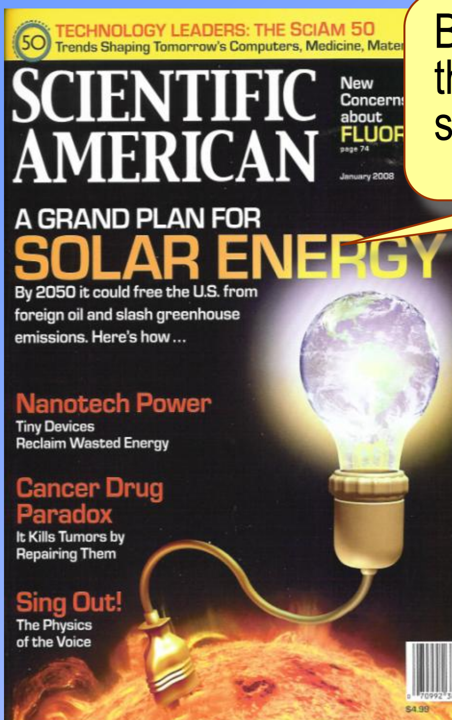




The technical, geographical, and economic feasibility for solar energy to supply the energy needs of the US

Vasilis Fthenakis James E. Mason Ken Zweibel *Energy Policy* 37 (2009)

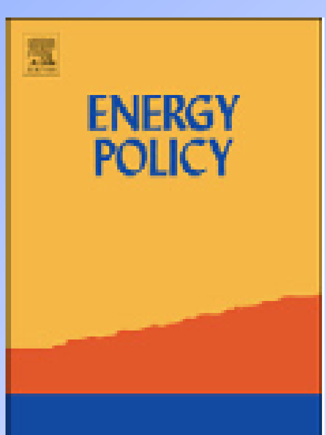
A Solar Grand Plan



By 2050 solar power could free the U.S. from foreign oil and slash greenhouse emissions

Components

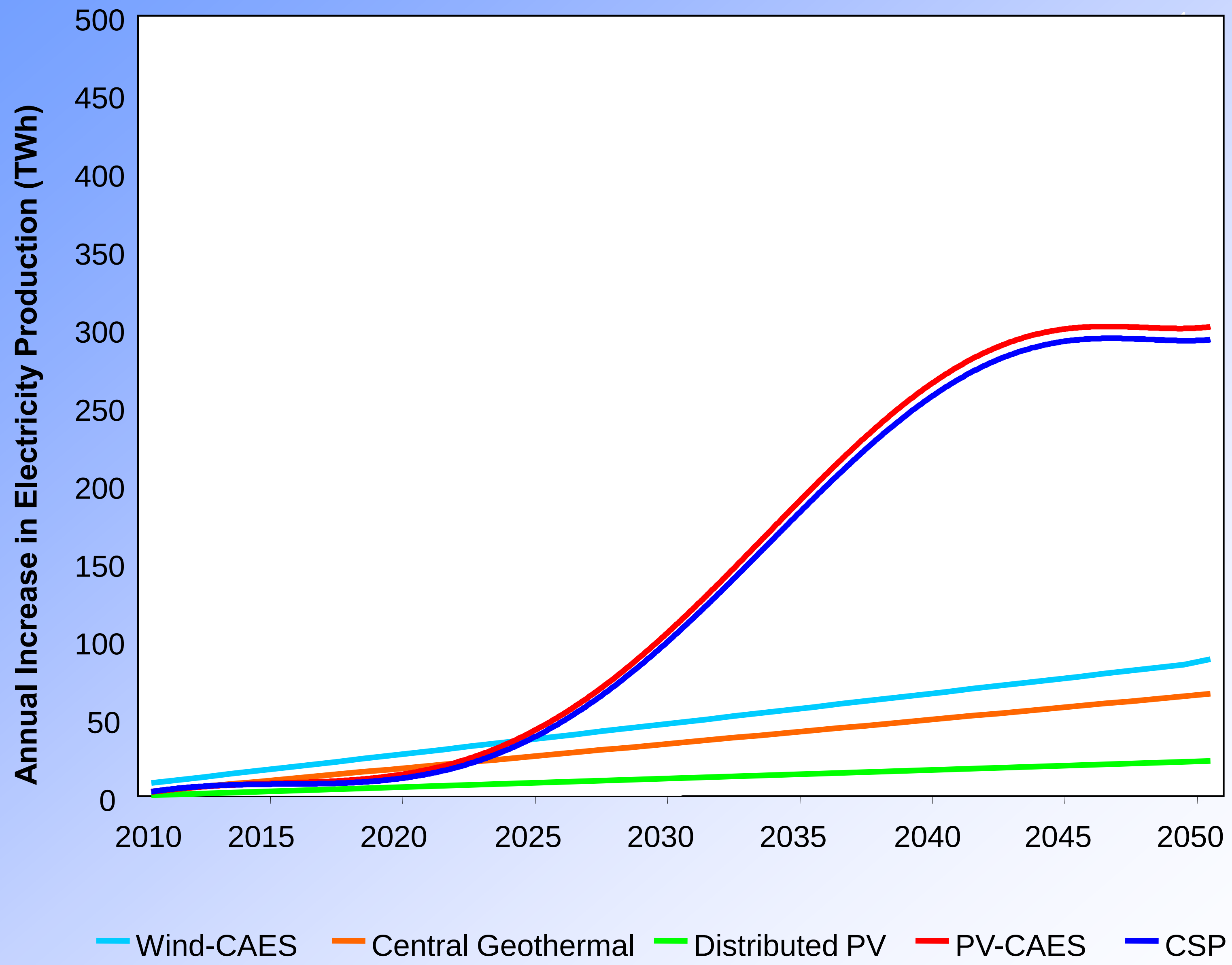
- Photovoltaics
- Wind
- Compressed Air Energy Storage
- Concentrated Solar Power
- Geothermal, Biomass
- High Voltage DC Transmission
- Hybrid plug-in electric cars
- Hydrogen infrastructure



The technical, geographical, and economic feasibility for solar energy to supply the energy needs of the US

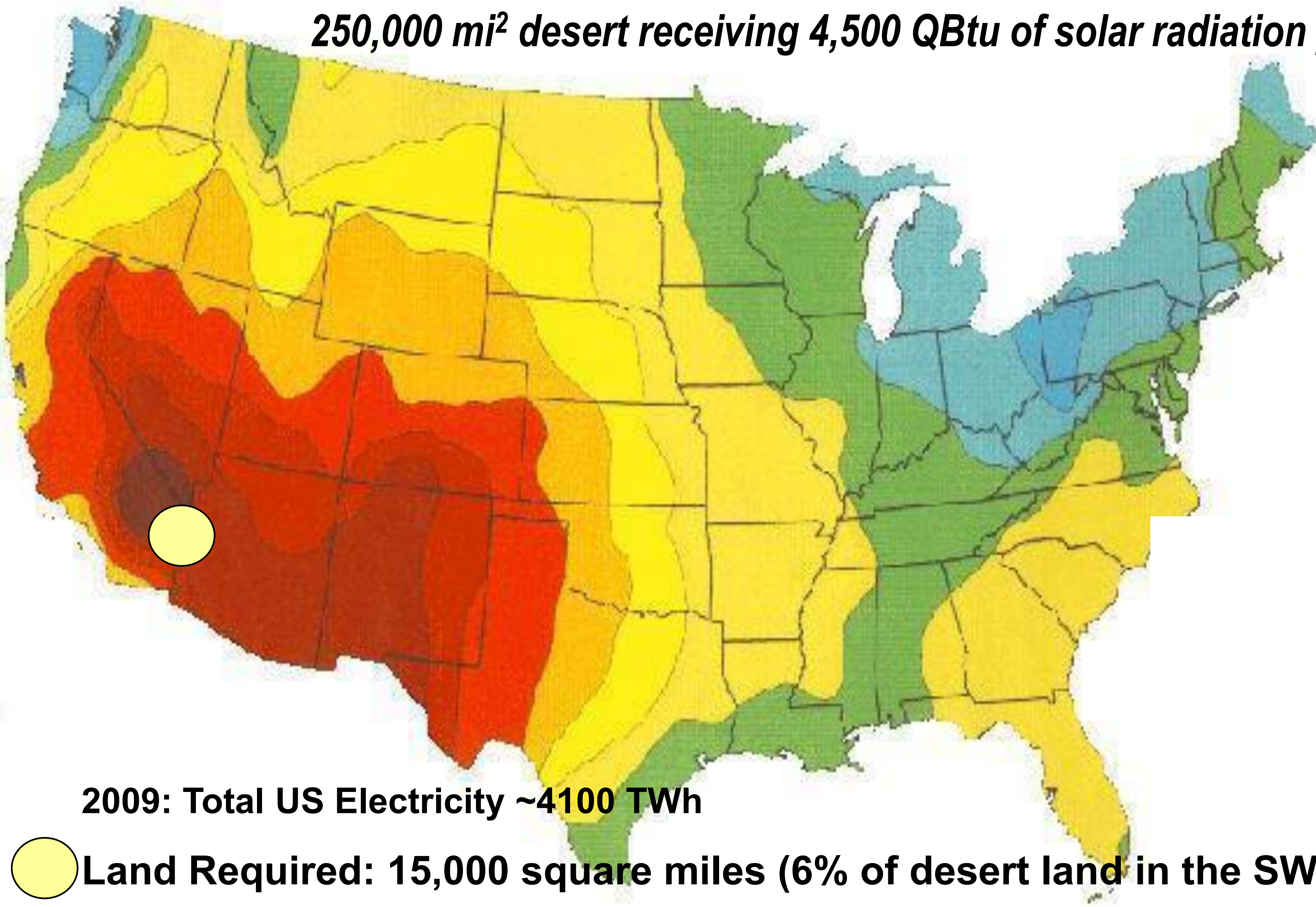
Vasilis Fthenakis James E. Mason Ken Zweibel *Energy Policy* 37 (2009)

Annual Electricity Growth from Renewables



Solar Irradiation and Desert Lands are Abundant

250,000 mi² desert receiving 4,500 QBtu of solar radiation per yr

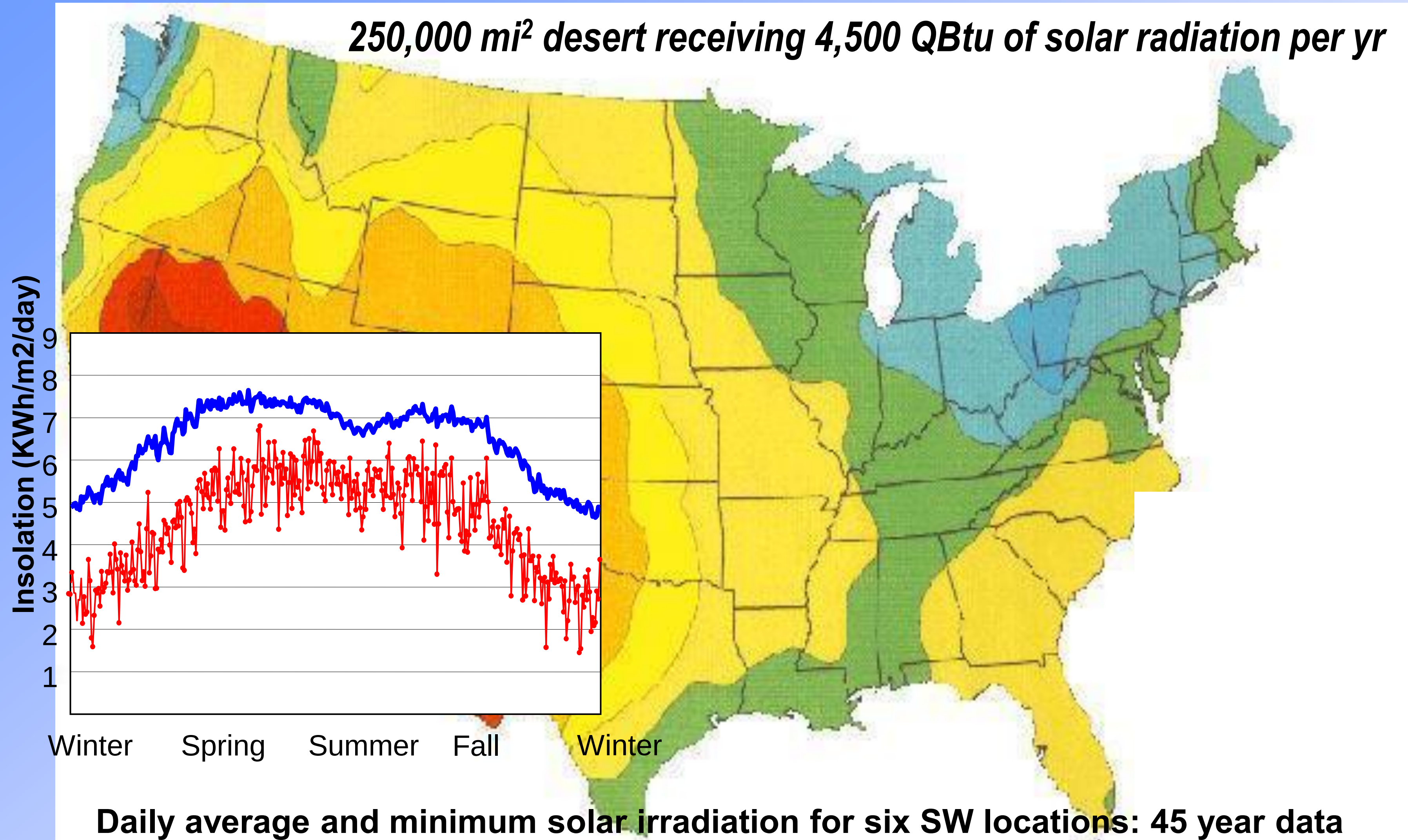


2009: Total US Electricity ~4100 TWh

Land Required: 15,000 square miles (6% of desert land in the SW)

(PV Efficiency=14%; performance ratio=0.8; packing ratio =2.6)

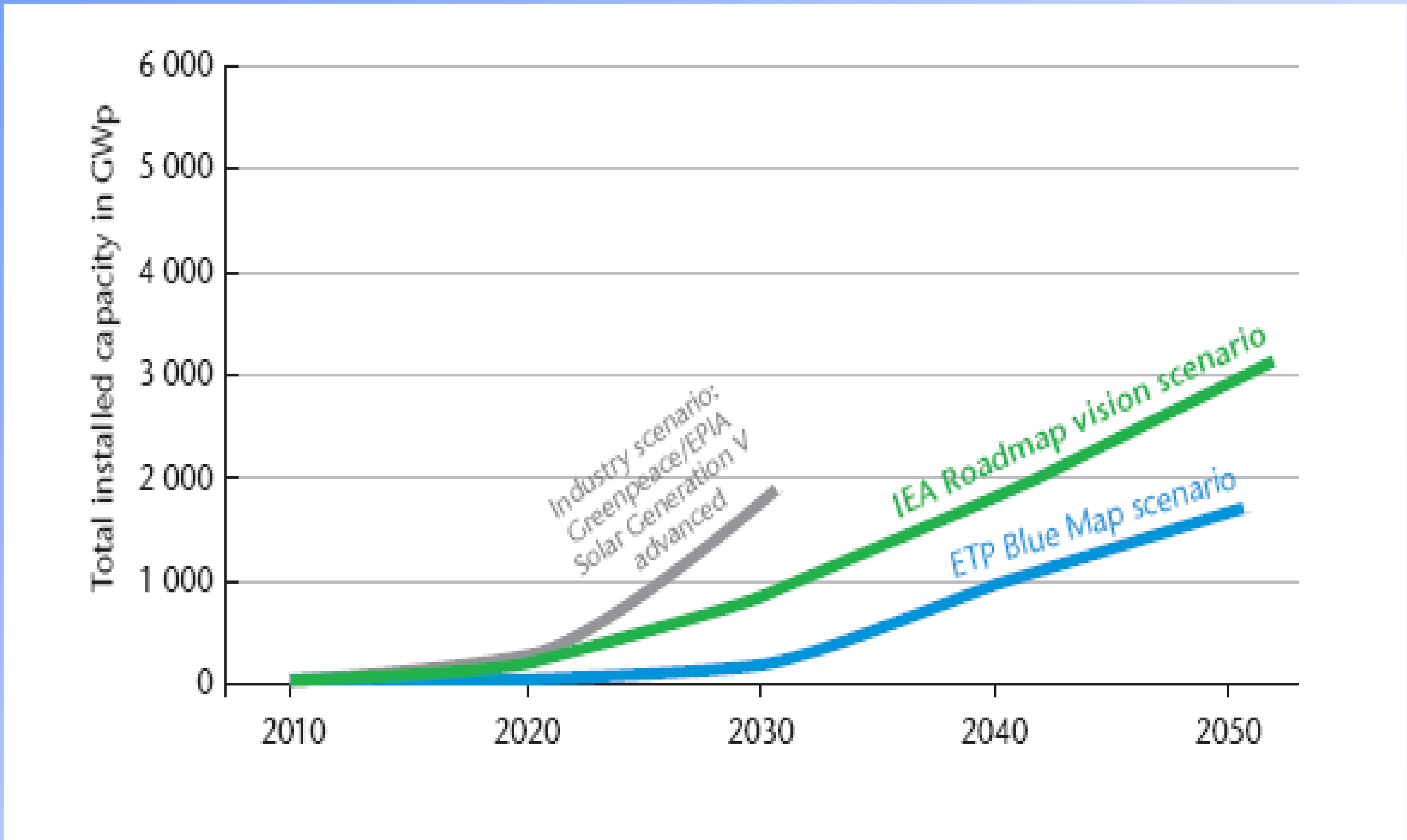
Consistent Solar Energy from SW in the Winter



Daily average and minimum solar irradiation for six SW locations: 45 year data (El Paso, Albuquerque, Tucson, Phoenix, Las Vegas, Daggett)

26

International Energy Agency PV Roadmap Vision



PV cumulative installed capacity to reach 900 GW in 2030 and 3000 GW in 2050

Source: Frankl, IEA, 2010

Concluding Remarks

- Solar (and wind) penetration occurs fast
- Large scale low cost storage will be needed eventually for RE to replace a large fraction of fossil fuels
- There is only a 10-20 yr window and the time to plan for storage is now

3. Dresser-Rand SmartCAES Technology

George Lucas, Harry Miller, *Dresser-Rand*

We will present an overview of the experience with the machinery provided for the Power South 110MW CAES Plant as well as numerous enhancements made to the original equipment configuration which comprise the Dresser-Rand current SmartCAES 135 MW solution. Characteristics such as equipment ramp rate, turndown, heat rate, operational flexibility, and reliability will be discussed.

George M. Lucas has 34 years of experience in the design, analysis, and operation and maintenance of turbines, generators, and other large rotating equipment. George received B. Sc. and M. Eng. degrees from Cornell and started his professional career as a Design Engineer with FMC's Coffin Turbo-Pump Operation. He subsequently joined Dresser-Rand's Steam Turbine Division in 1978, where he held a number of positions including Director of Engineering. He led the design team responsible for the design and manufacture of the gas turbines for Alabama Electric Cooperative's McIntosh CAES plant and continues to support the CAES products, including developments and enhancements reflected in Dresser-Rand's SMARTCAES Solutions. .

Harry Miller is the Product Manager- Marketing of Turbo Products at Dresser-Rand. His career in turbomachinery began 35 years ago with Dresser Clark, and he has held a variety of Design Engineering and Marketing positions, most recently, being Manager of Development Engineering and Leader of the DATUM Multistage Centrifugal Compressor Development Team. He received a B.S.M.E. degree from Northeastern University, and a M.B.A. degree from Lehigh University. His areas of expertise include turbo compressor and gas turbine design and application. He has authored several technical papers and has contributed to several patents, and has won the Dresser Industries Annual Technical Achievement Award.

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Dresser-Rand's ***SMART****CAES*™ Compressed Air Energy Storage Solution

2nd Compressed Air Energy Storage Conference & Workshop

Columbia University Center For Lifecycle Analysis & NYSERDA

George Lucas & Harry Miller - October 20 & 21, 2010

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Safe Harbor Disclosure

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Agenda

- Welcome to Dresser-Rand's World
- Compressed Air Energy Storage (CAES)
- Dresser-Rand's CAES McIntosh Experience
- Dresser-Rand's ***SMART***CAES Solution
- Dresser-Rand's CAES Solution Advantages
- Why Dresser-Rand?

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Welcome to Dresser-Rand's World….

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What is CAES?
How Does It Work?

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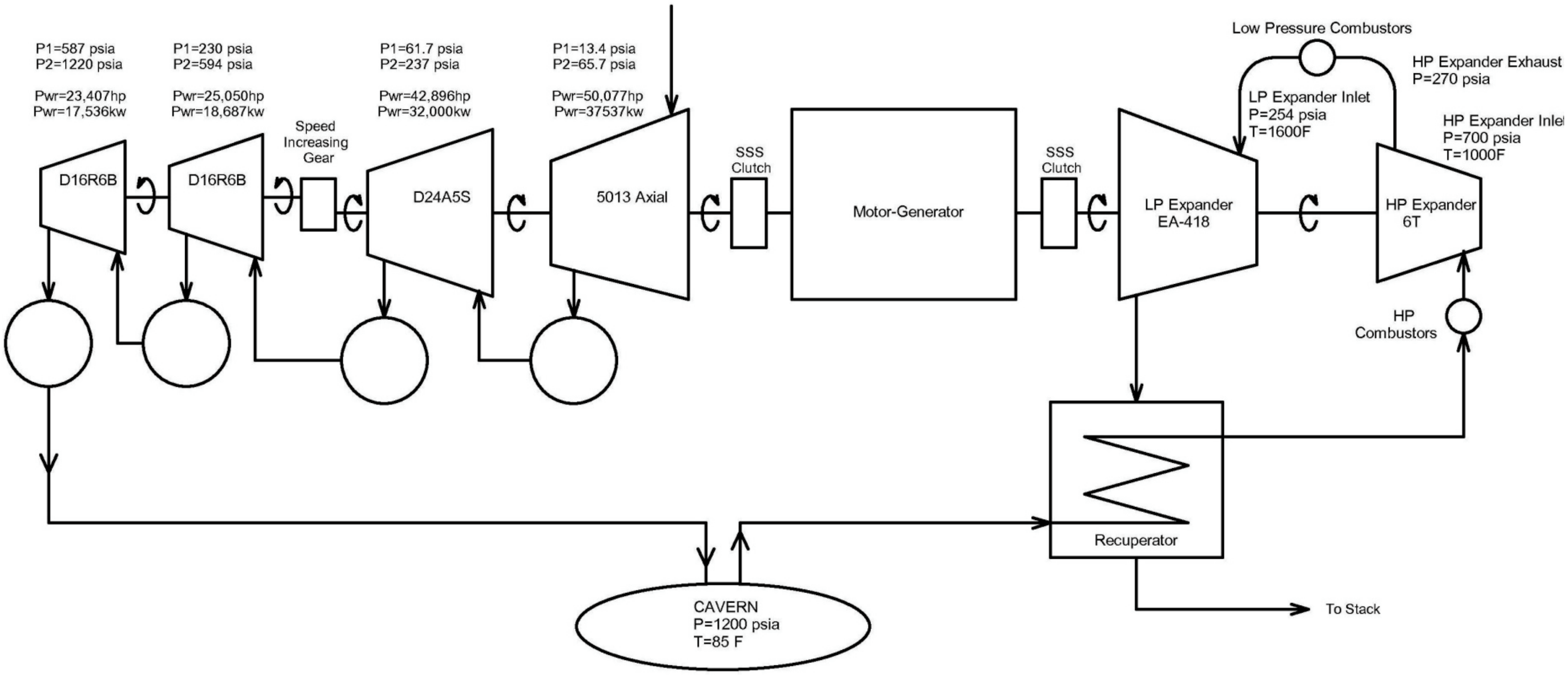
How does CAES work?



Dresser-Rand SmartCAES System Schematic

***Typical example based on 1200 psia mean storage pressure**

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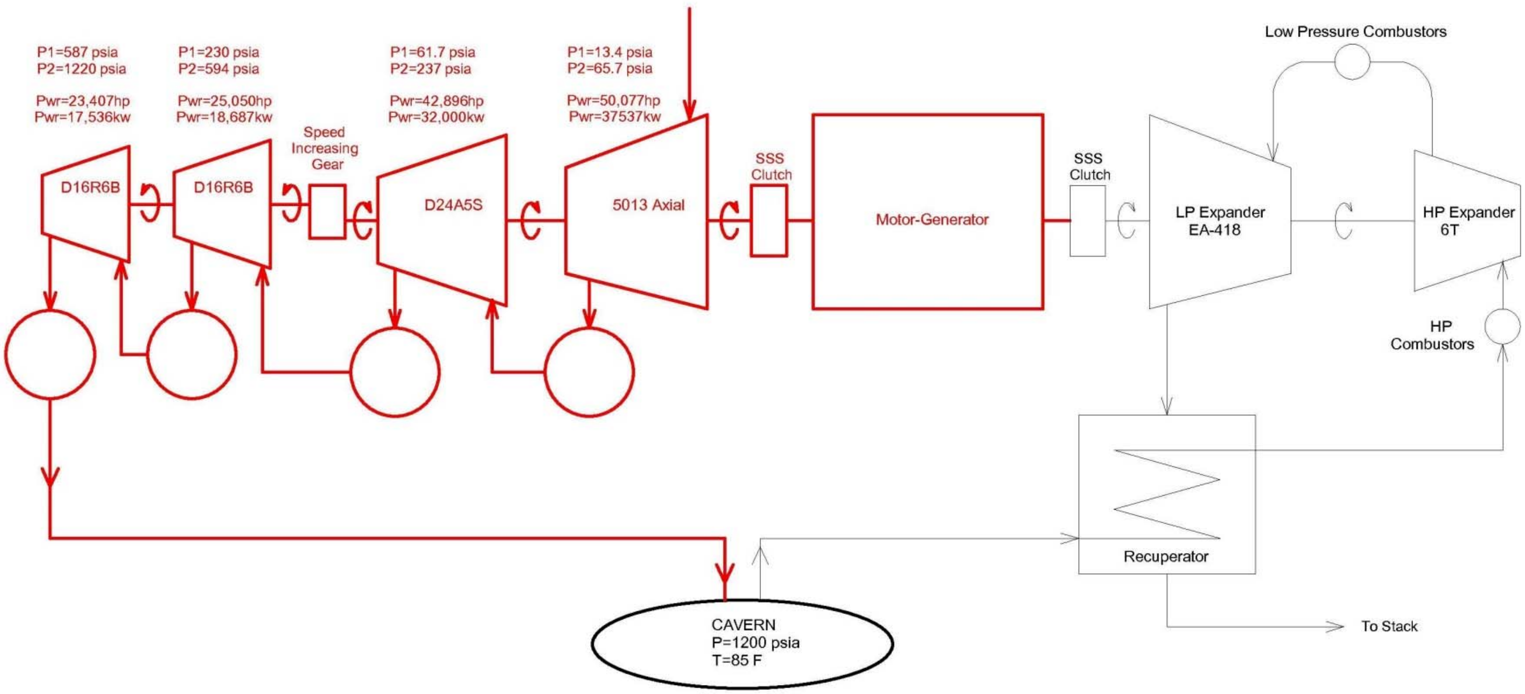
CAES Compression Mode



Dresser-Rand SmartCAES Compression Mode

***Typical example based on 1200 psia mean storage pressure**

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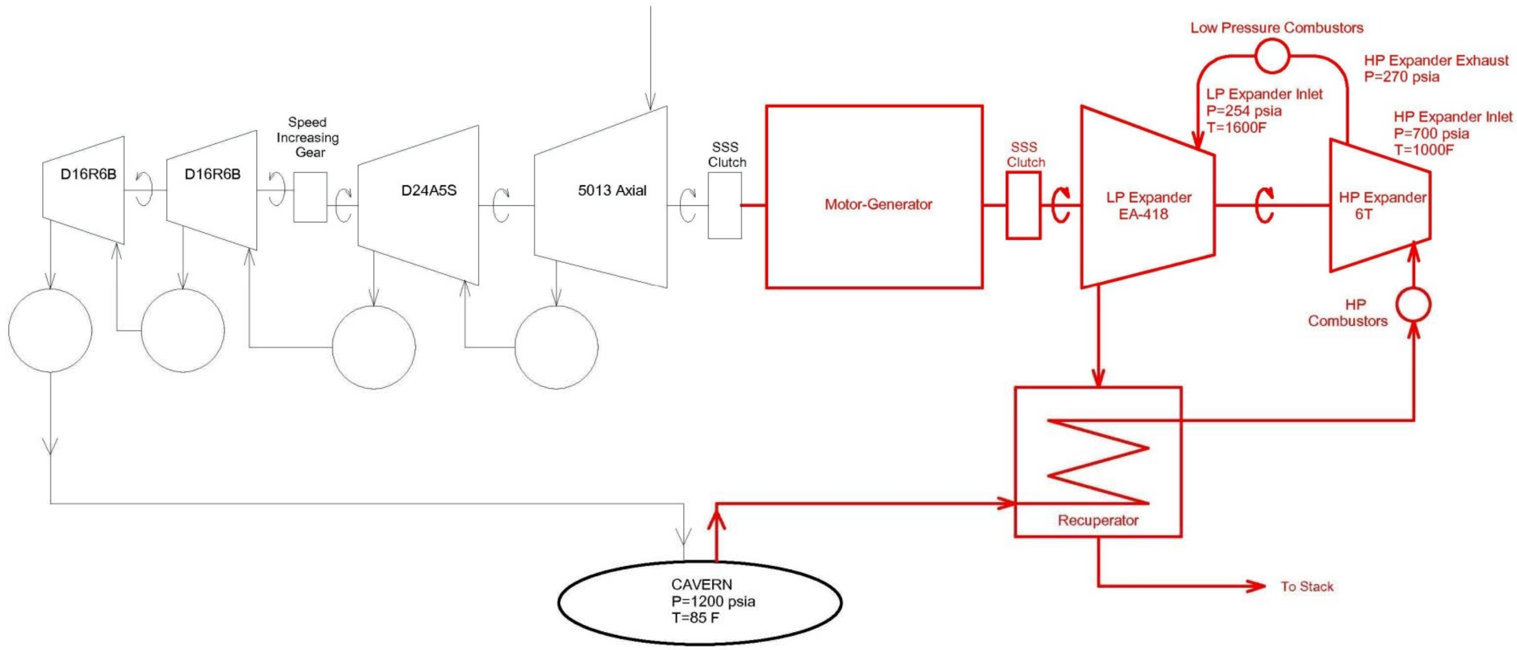
CAES Power Generation Mode



Dresser-Rand SmartCAES Power Generation Mode

***Typical example based on 1200 psia mean storage pressure**

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CAES Operating Characteristics

- Rapid start
  - Power generation - <10 minutes to rated output
  - Compression - < 5 minutes to rated flow & pressure
- High ramping rates
- High turn-down ratios
- 3 Modes of operation
  - Compression
  - Power generation
  - Synchronous condensing

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Benefits - How can CAES be used?

- Arbitrage (Compress off-peak, generate on-peak)
- Regulation & frequency support
- VAR support (synchronous condensing & compression modes)
- Spinning and/or ready reserve
- Black start capability
- Support renewable energy penetration
  - Prevent curtailment at times of peak renewable output
  - Dispatchable
- Transmission capacity management

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SMART*CAES*
Performance

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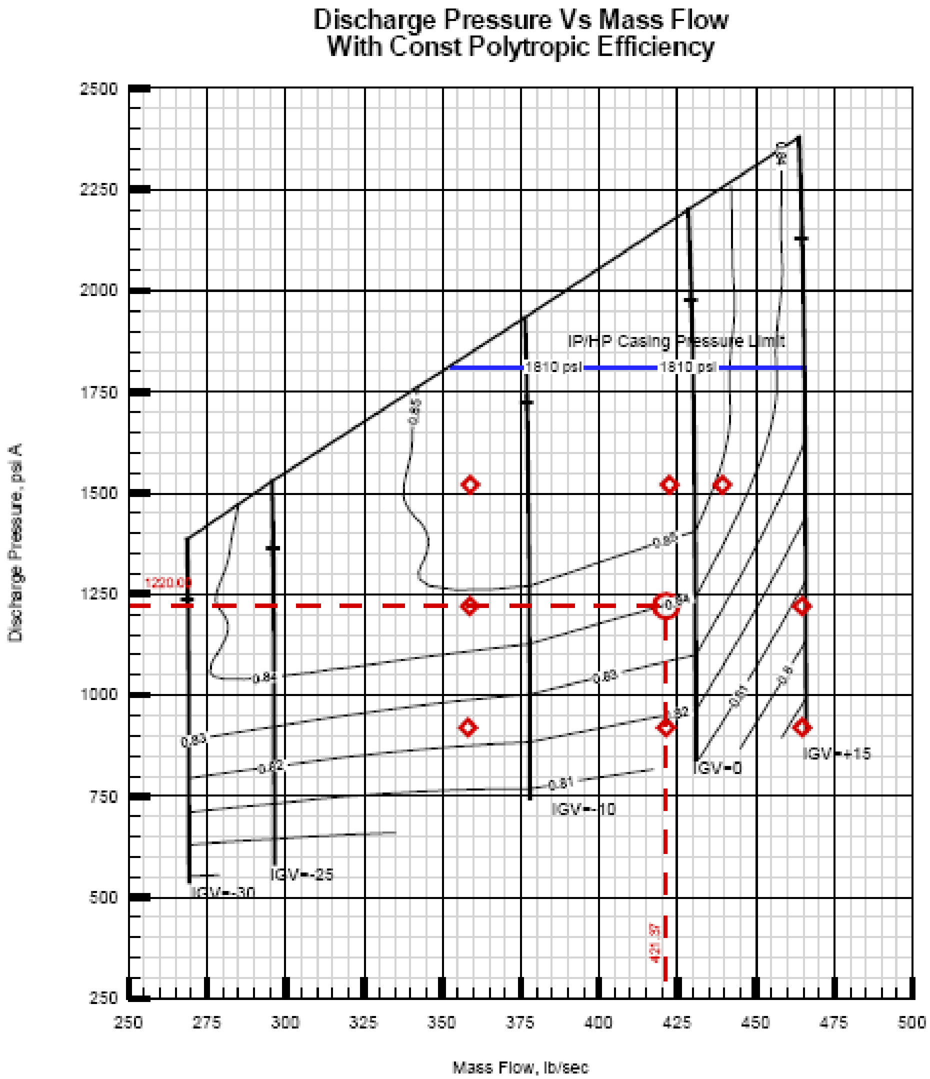
CAES Compressor Train IGV Controls



Section # 1

Ps	13.94	psi
Pd	62.60	psi
Ts	46.0	°F
Td	383.0	°F
Flow	340510	ACFM
MW	28.886	
Zs	0.9994	
Zavg	0.9994	
pKavg	1.395	
RPM	3600.0	

Section # 2

Ps	58.60	psi
Pd	211.00	psi
Ts	64.0	°F
Td	346.0	°F
Flow	82682	ACFM
MW	28.915	
Zs	0.9981	
Zavg	1.00230	
pKavg	1.397	
RPM	3600.0	

Section # 3

Ps	204.00	psi
Pd	483.00	psi
Ts	64.0	°F
Td	241.0	°F
Flow	23623	ACFM
MW	28.954	
Zs	0.9958	
Zavg	1.00260	
pKavg	1.400	
RPM	6711.1	

Section # 4

Ps	476.00	psi
Pd	1220.00	psi
Ts	64.0	°F
Td	257.0	°F
Flow	10077	ACFM
MW	28.963	
Zs	0.9922	
Zavg	1.00830	
pKavg	1.401	
RPM	6711.1	

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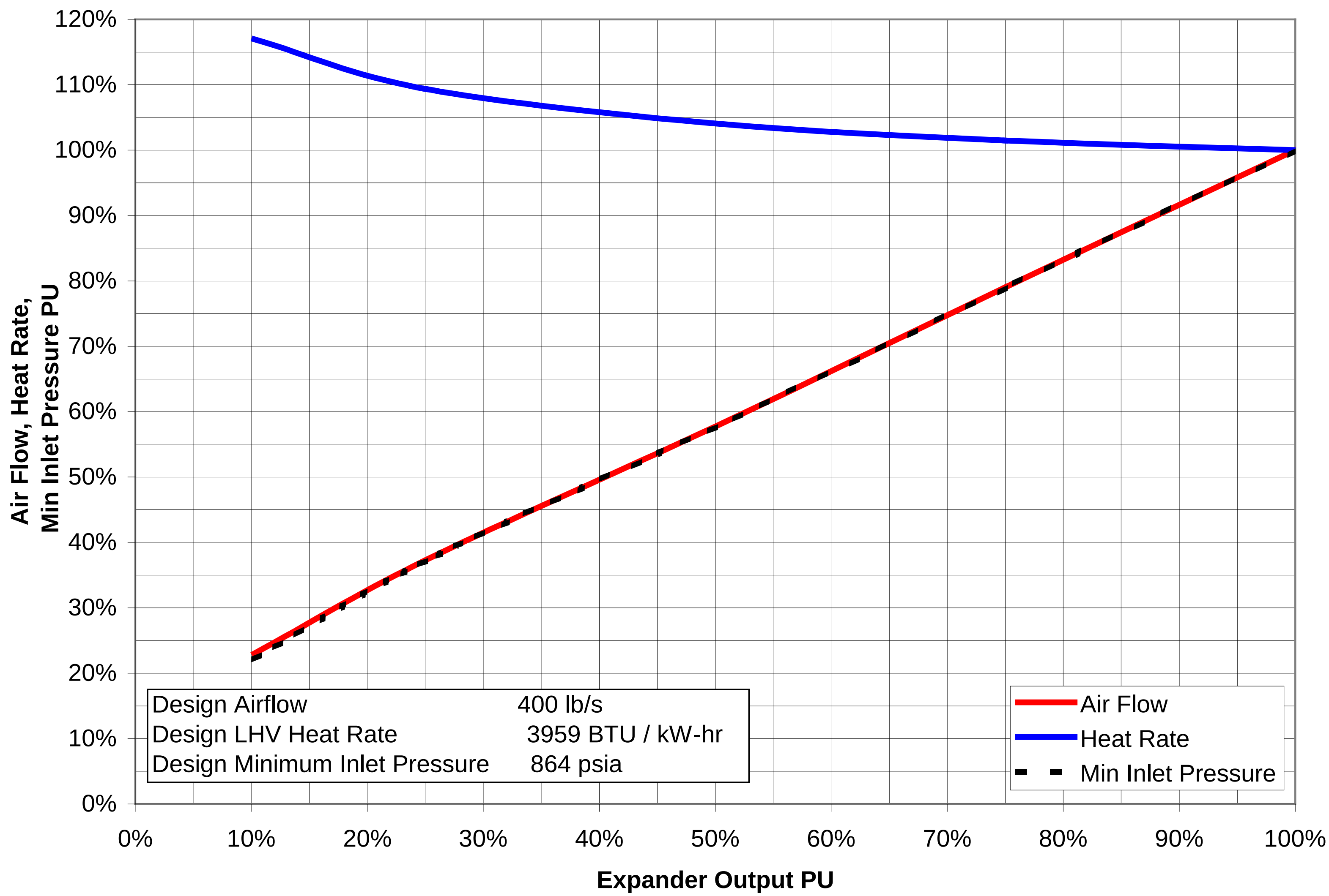
CAES Expander Train Performance



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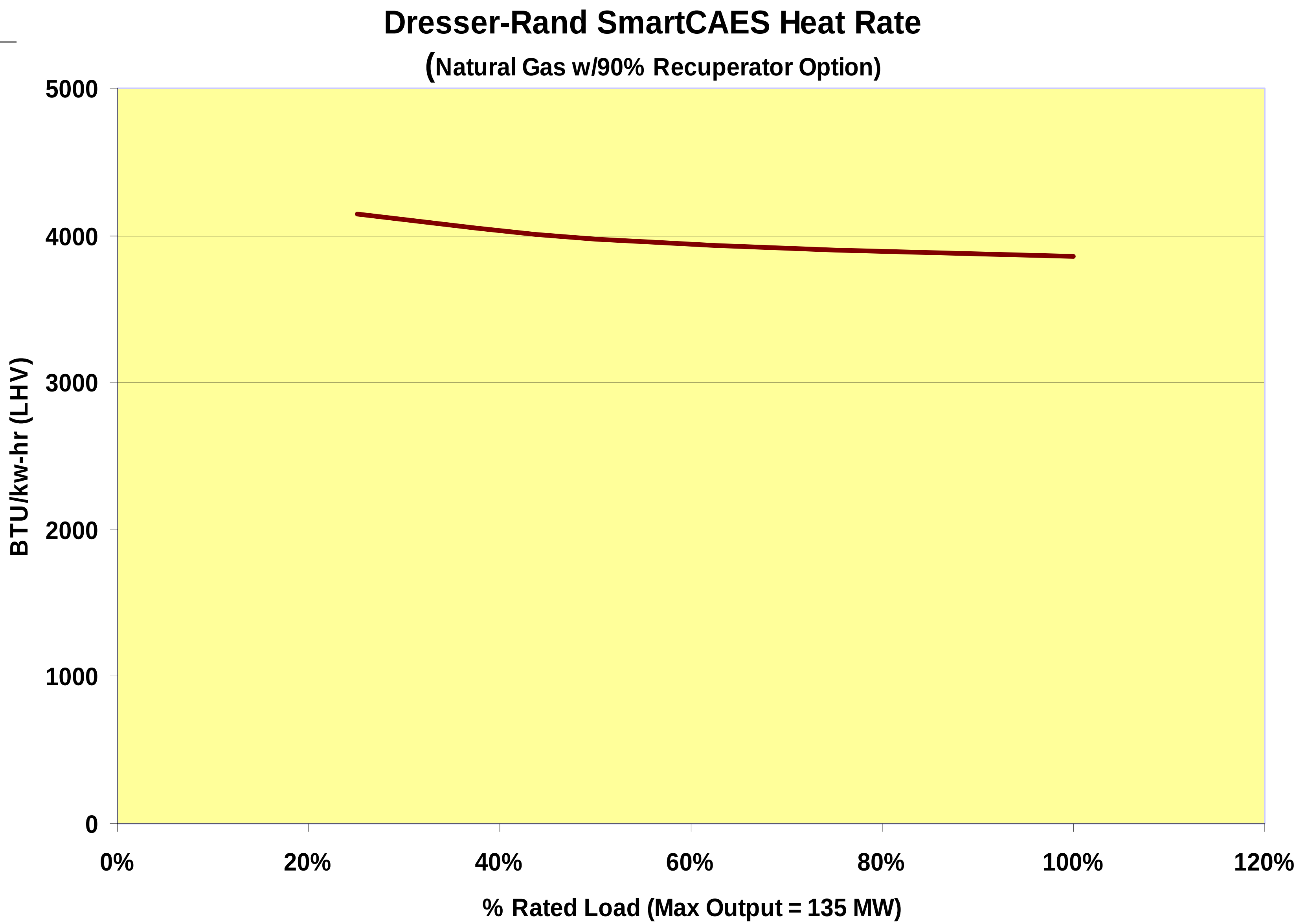

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CAES Efficiency

- **SMART**CAES system is a Brayton-cycle engine with enhancements
  - Compressor inter-cooling
  - Recuperation
  - Reheat
  - Compression energy comes from outside the cycle and displaced in time from generation
- Conventional efficiency metrics fail to characterize this cycle because the energy input comes in two forms
  - Compression power from electricity
  - Thermal input from hydrocarbon combustion

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CAES Efficiency

- A representative range for CAES Energy Ratio is **0.70 - 0.85**, depending on numerous variables:
  - Compressor inlet temperature
  - "In & out" pressure losses (depends on cavern piping / well design as well as operating philosophy)
  - Compressor operating point relative to optimum
- A representative Heat Rate is ~**3,900 BTU / kW-hr** at design condition
  - Roughly 85% of the fuel used is converted to electricity
    - Compare to roughly 30% for simple cycle GT, 55% for combined cycle GT

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Dresser-Rand's CAES McIntosh Experience

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PowerSouth McIntosh CAES Site – McIntosh, AL

* Formerly, Alabama Electric Co-Op (AEC)

Plant located near Mobile, AL

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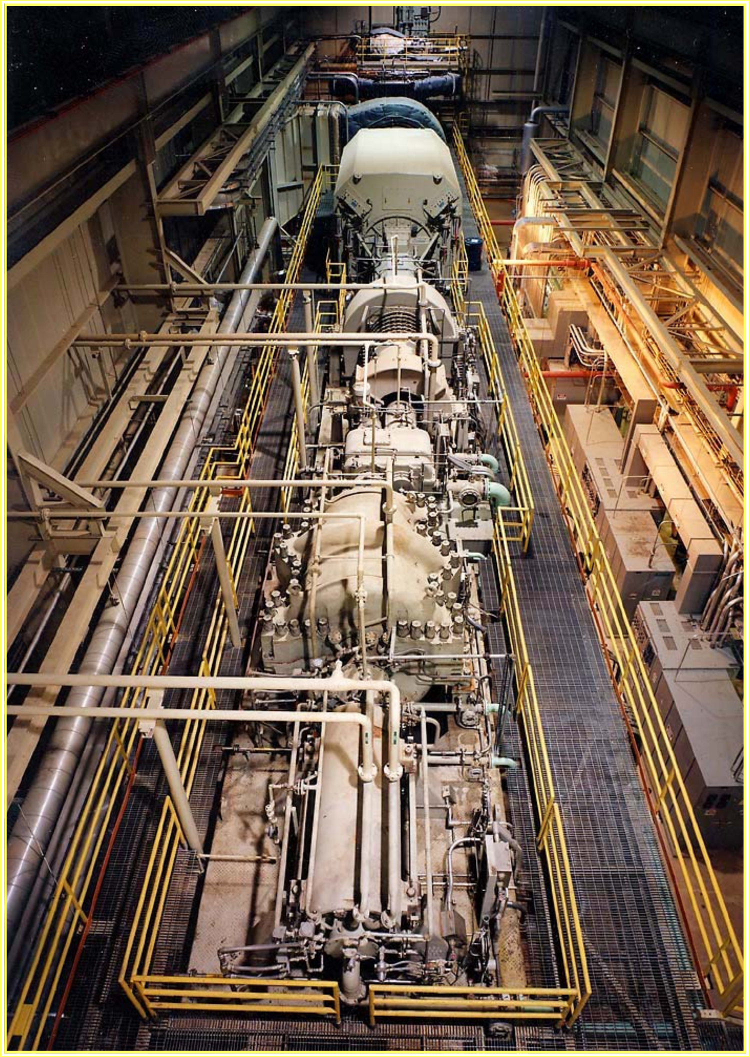
PowerSouth McIntosh CAES Installation



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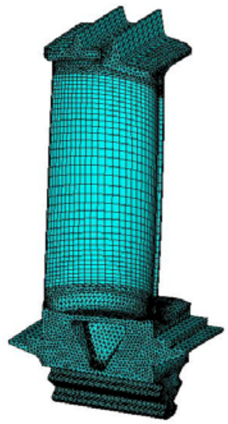
Dresser-Rand's McIntosh CAES Experience



- Dresser-Rand supplied all rotating equipment
  - Compressors, turbo-expanders, and auxiliaries
  - Engineered, designed, manufactured, tested, commissioned
- In its 20th year of successful operation
- Serviced equipment continuously since 1991
- D-R's CAES Team
  - Many of the original McIntosh Project Management, Engineering, and Support personnel are still with D-R
  - Most of the original McIntosh suppliers and/or their successor companies are still key suppliers to D-R

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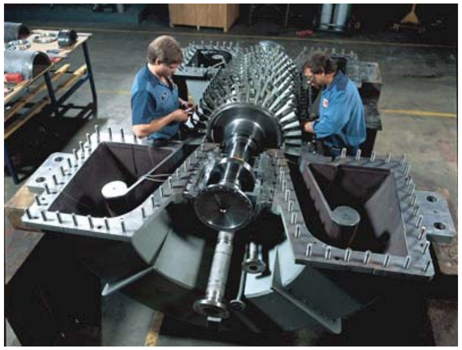
PowerSouth McIntosh CAES Plant Experience



- Commercial Operation – May, 1991
- Generation
  - 11,484 hours – 97% running reliability
  - 3,717 total starts
    - 97.6% starting reliability (2010 to date)
- Compression
  - 12,292 hours – 100% running reliability
  - 2,264 total starts
    - 100% starting reliability (2010 to date)

600 thousand MW-Hrs of generation to date

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*Dresser-Rand's **SMART**CAES Solution*

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D-R **SMART**CAES – The One Stop CAES Solution

- Dresser-Rand supplies & warrants the complete Power Island
  - All rotating equipment
    - HP & LP Turbo-Expanders with integrated combustion system
    - Motor, Generator (or combination Motor/Generator)
    - Compressors
    - SSS Clutches
  - Heat Exchangers - Recuperator, Intercoolers and Aftercooler
  - Pollution Abatement - SCR system w/CO catalyst
  - Plant controls
  - Auxiliaries
- Project Management
- Performance, Emissions, Operational Guarantees
- Services - For the long term

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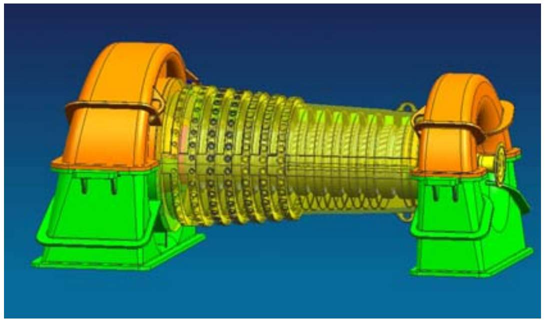
SMARTCAES System



- Power outputs up to 135 MW
- Turbo-expanders designed specifically for CAES requirements
  - High pressure ratio
  - Cyclic operation
- Patented DATUM compressor technology
  - Industry leading efficiency, noise control, reliability
- VFD for compression starts
  - Faster compression starts
  - Shorter transitions between modes (power gen/compression)
  - Eliminates emissions for compression start-up
  - Reduces turbo-expander starts thus longer life

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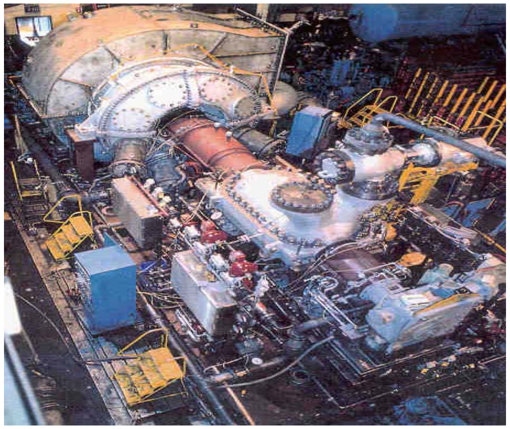
SMARTCAES System



- Emission Abatement Technology
  - Meets all current permitting requirements
    - Down to 2 ppm NOx
    - Down to 2 ppm CO
  - In many cases, can be permitted as a small source emitter
- Advanced Recuperator Design
  - Increased effectiveness
    - 85% effectiveness standard recuperator
    - 90% effectiveness options available
  - Incorporate design features to eliminate corrosion
  - Up to 7% improvement in heat rate over McIntosh

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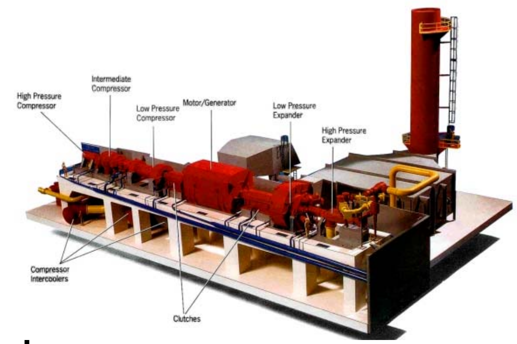
*D-R **SMART**CAES Operational Flexibility*



- High turndown capability
  - Can operate 25% to 100% in power-gen mode
  - Flat heat rate over 25% to 100% load
  - Load following
- Rapid start capability
  - Start-up to Full load <10 min in power generation
  - Start-up to Full load < 5 min in compression mode
- Transition times
  - Compression to power generation
    - <15 mins using VFD (with braking capability)
  - Power generation to compression
    - <5 mins using VFD (with braking capability)

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Dresser-Rand SMARTCAES Operational Flexibility

- 3 Modes of Operation
  - Power Generation mode
  - Compression mode
  - Synchronous Condensing mode

- High turndown capability
  - Can operate 25% to 100% in power-gen mode
  - Flat heat rate over 25% to 100% load
  - Load following

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*Why Dresser-Rand **SMART**CAES for Your CAES Solution?*

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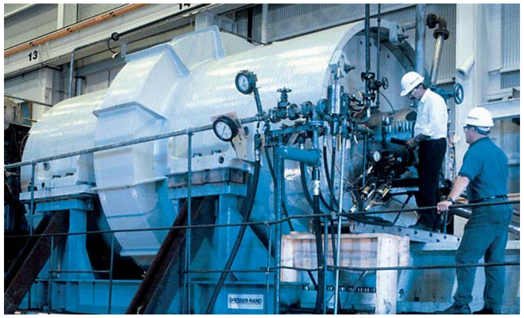
Why D-R?



- D-R provides more value, lower risk
  - Proven designs, equipment, and experience
  - Lower total energy consumption across the board
  - Solution is financeable
- D-R total capabilities and experience
  - Design, Manufacturing, Testing, Installation, Commissioning, and Service
- D-R provides total responsibility & technical prime
  - Complete Power Island Integration
  - Complete Power Island Performance Guarantee
  - Complete Power Island Warranty
  - Complete Power Island Services Support Resources

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Questions?

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4. 180 MW and 300 MW Advanced 2nd Generation CAES Plants to Support Renewable Energy and Smart Grid

M. Nakhamkin, B. Kraft, R. Daniel, P. Conroy, *Energy Storage and Power*

R. Schainker, *EPRI*

We will present performance, operational and economic characteristics of 180 MW and 300 MW projects based on the 2nd Generation of the Compressed Air Energy Storage Technology (CAES2). These projects received DOE stimulus funds and are in initial execution stage. We will also present on upcoming 15 MW and 450 MW CAES projects. Compared to the first generation CAES technology in Alabama, the CAES2 technology is estimated to be less expensive to build, has lower operating costs, and has more flexible operating characteristics. The turbomachinery in this new CAES plant design uses standard multi-size compressors, new or existing combustion turbines and separate expansion turbines. The emissions from this type of CAES plant has NOx levels in the single digits due to very low heat rate of approximately 3800 Btu/kWh and the storage efficiency is in the 80% to 90% range.

Dr. Michael Nakhamkin, PE is the Chief Technology Officer and Founder of ES&P. He has been the preeminent voice in the power industry on compressed air energy storage for over two decades. Dr. Nakhamkin holds 16 patents that form the basis of ES&P's CAES and Power Augmentation technologies. In addition, he has supervised the development, engineering and execution of numerous combustion turbine and natural gas-based power projects worldwide during the course of his career. At Gibbs & Hill Dr. Nakhamkin was the Chief Engineer where he oversaw a 5,000 plus person engineering organization.

Energy Storage and Power LLC

Advanced Second Generation of CAES Technology

180MW, 310 MW and 450 MW CAES Plants

Adiabatic Concepts

Performance, Operations, Economics, Renewable Load Management, Green Energy

Dr. M. Nakhamkin, B. Kraft, C. Moran
Energy Storage and Power, LLC (ES&P)

CAES 2010

Columbia University in the City of New York

Second Generation of CAES Technology- Performance, Operations, Economics, Renewable Load Management, Green Energy

Topics of Presentation

- 110 MW CAES project (Alabama, USA) built in 1991
- Second Generation CAES Technology (CAES2) : 180 MW ; 310 MW and 450MW Projects – General Performance and Operational Characteristics
- The CAES2 Plants Design Performance and Operational Flexibility to Meet Renewables/ Smart Grid Requirements
- Cost Estimates and Economics
- Adiabatic CAES Plant
- Conclusions

Energy Storage and Power LLC

The 110 MW CAES Project for Alabama Electric Cooperative

CAES 2010

COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

CAES Technology Background/Objectives

CAES technology was developed as a load management plant with the prime purposes:

- To store the off-peak energy that is not needed and inexpensive and to increase load factor of base-load plants (Coal, Nuclear)
- To release this energy during peak hours when energy is needed and the price is high
- Huntorf Project is exclusively for peak shaving/emergency reserve

The AEC's 110MW CAES Project had been driven by two factors:

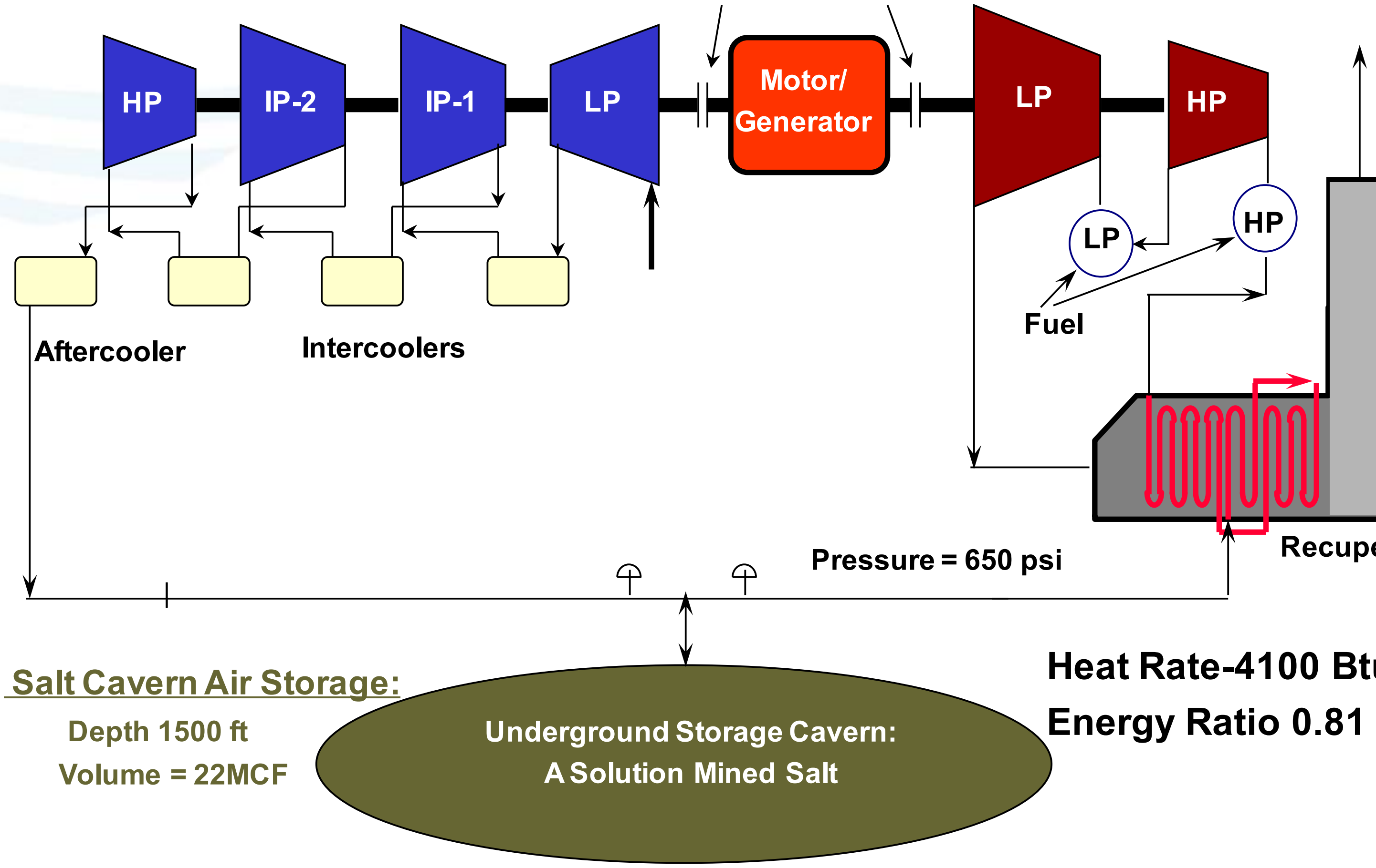
- Due to very low off peak loads, two 300 MW coal-fired plants during off-peak hours operated at very low loads with extremely high heat rates and sometimes had been shut down
- AEC had shortage of peak power

- The current development of **Renewable/Wind Power-** the primarily uncontrollable energy source- and **Smart-Grid** optimizations requires the CAES plants to store wind energy produced during off-peak hours and distribute it with additional benefits during peak hours when energy is needed and cost of energy is high.

The 110 MW CAES Plant

EPC Contractors - G&H/Herbert:
Subcontractors: DR: Turbomachinery Components; AIT: HP and LP Combustors
SW: Advanced Recuperator; PB: Underground Storage

ESPC: Developed and optimized the CAES Concept and Parameters/ Technical Supervision Project



Heat Rate-4100 Btu/kWh
Energy Ratio 0.81 kWh in/out

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Alabama Compressed Air Energy Storage Plant
Peak Power 110 MW; 26 hrs of continuous Power Generation;
Heat rate is 4100 Btu/kWh; Off-Peak Power 51MW, Capital Cost $600/kW

Ground Breaking and Successful project Delivery Ceremonies

Ground Breaking Ceremony
Dr. R. Schainker, EPRI
Ray Claussen, AEC
Dr. M. Nakhamkin, ESPC

ESPC Received EPRI's Achievement Award
Dr. R. Schainker, EPRI
Dr. M. Nakhamkin, ESPC

ESPC Developed, Optimized and Specified
The Unique and Customized 110 MW CAES Plant
Based on AEC Specific Conditions

ESPC was conducting technical supervision of the project execution including:

- Supervision of the turbomachinery performance characteristics-designed, engineered and delivered by Dresser Rand
- Supervision of the HP combustors development by AIT
- Development of the test procedures
- Supervised performance guarantee tests and issued the Test Report
- Under contract with EPRI, ESPC recorded key plant parameters during 1991-1994 - three years after the project commercialization, and issued " Value Engineering" Report

First generation CAES
Lessons Learned- Required Improvements

Summarized in the published by EPRI's "Value Engineering" report (produced by ESPC)

The 110 MW CAES project is unquestionably successful- It met all performance guarantees, schedule and budget.

The single-shaft turbomachinery train with multiple (9) components and a number of unique components provide the following challenges:

- **significant operational restrictions and maintenance complications**
- **significant restrictions as it relates to the overall CAES plant optimization and integration with a various underground compressed air storage parameters**

Conclusions: Multiple standard off-shelf components - compressors and expanders - provide operational flexibility and maintenance advantages

The unique HP/LP combustors will provide additional plant optimization and operations restrictions including very high emissions

Conclusions: Novel HP/LP combustors should be replaced by standard DLN combustors developed by OEMs

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Second Generation CAES Technology (CAES2)
180 MW, 310 MW and 460MW CAES2Projects
General Performance and Operational Characteristics

CAES 2010

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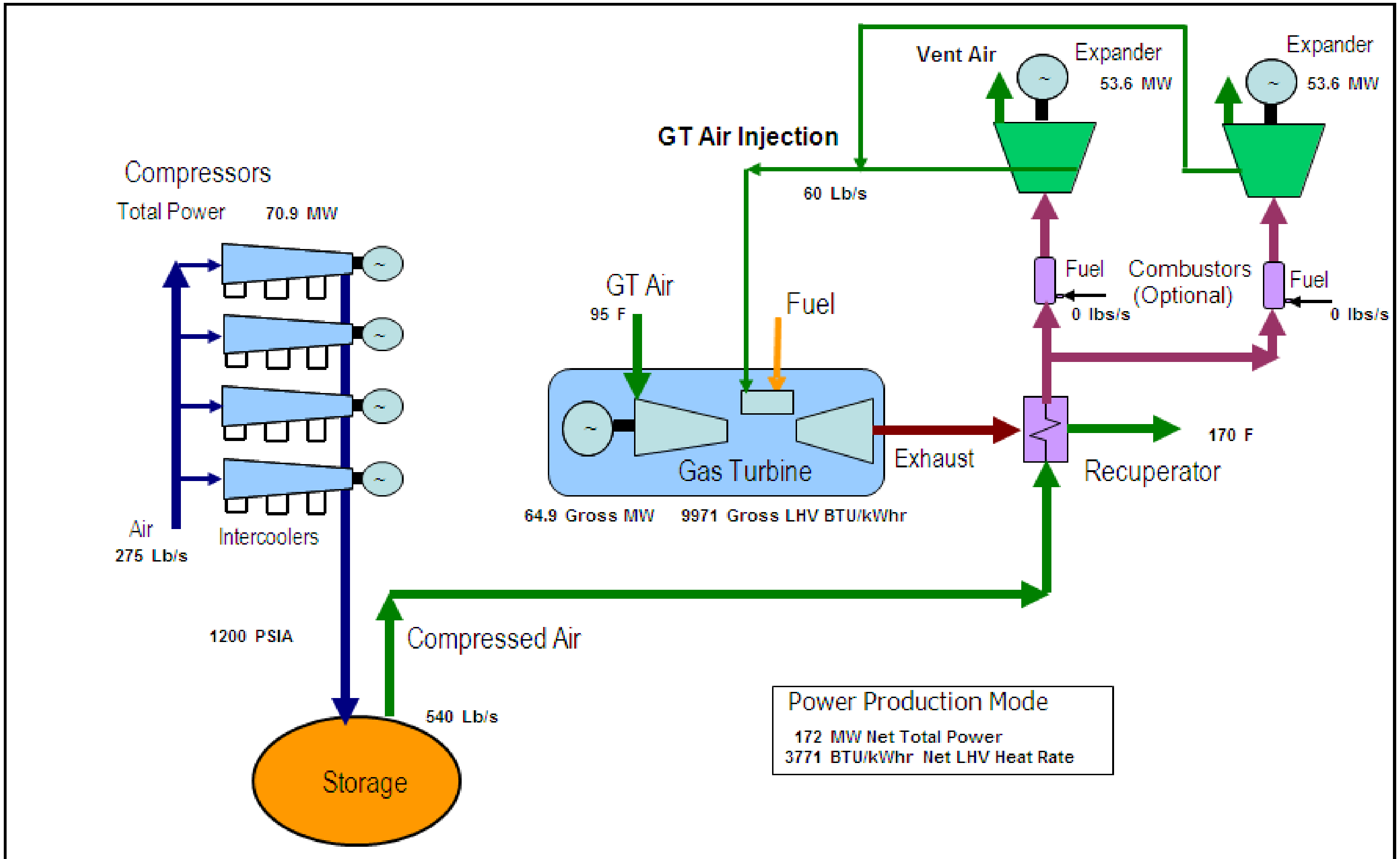
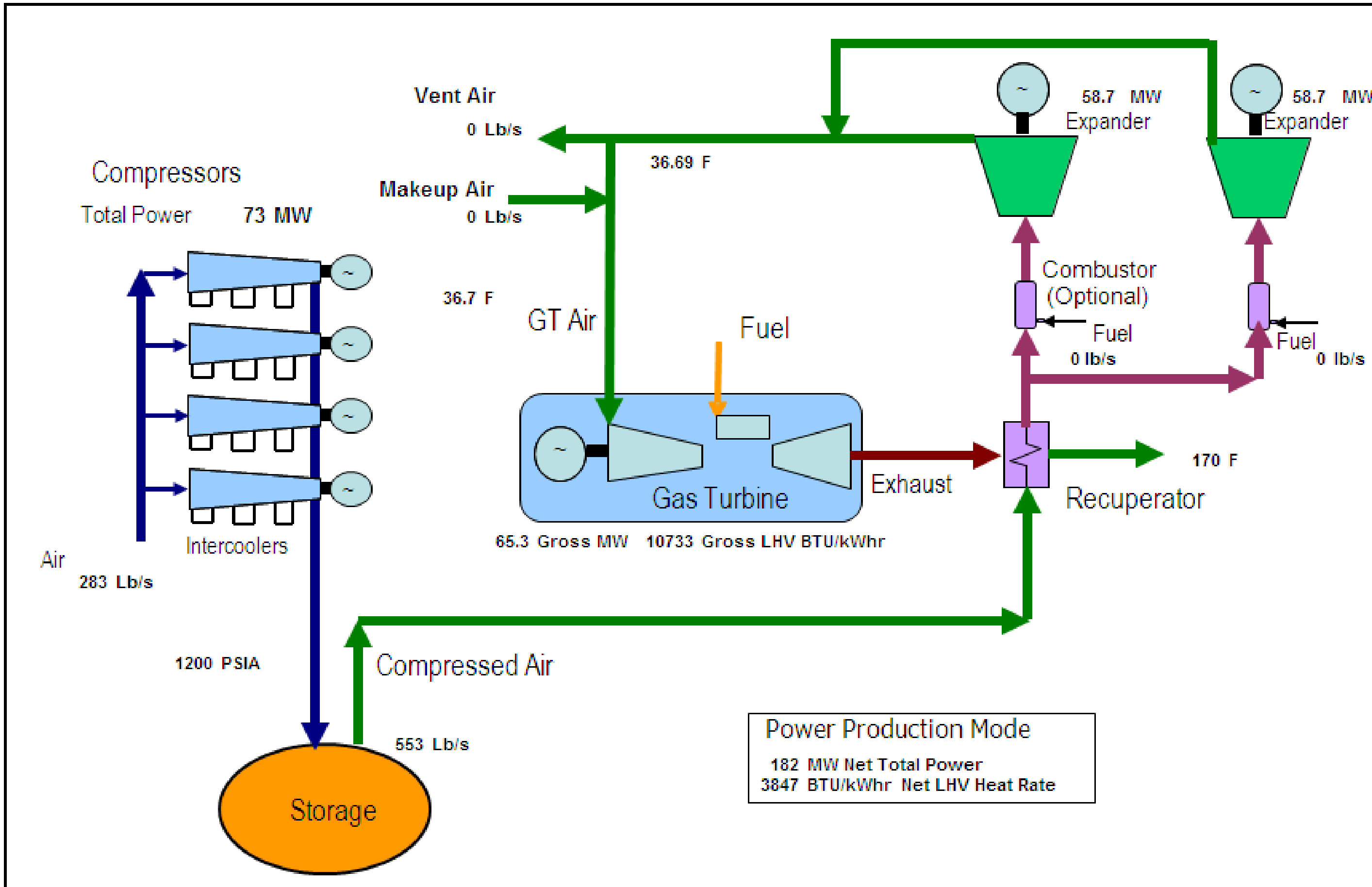
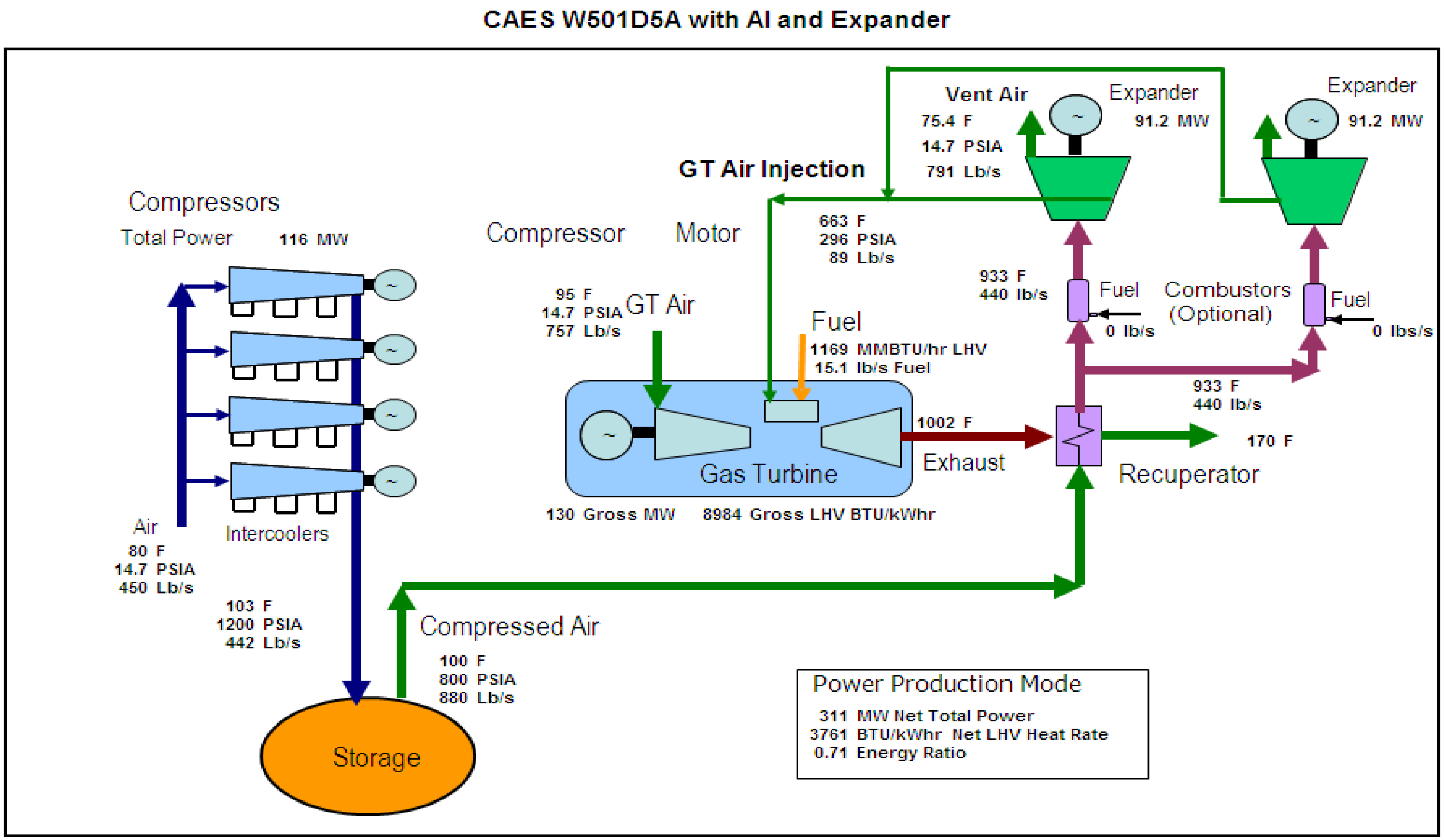
170 MW CAES plant Concepts with Air Injection Power Augmentation



180 MW CAES plant Concepts with Cold Air Supercharging Power Augmentation

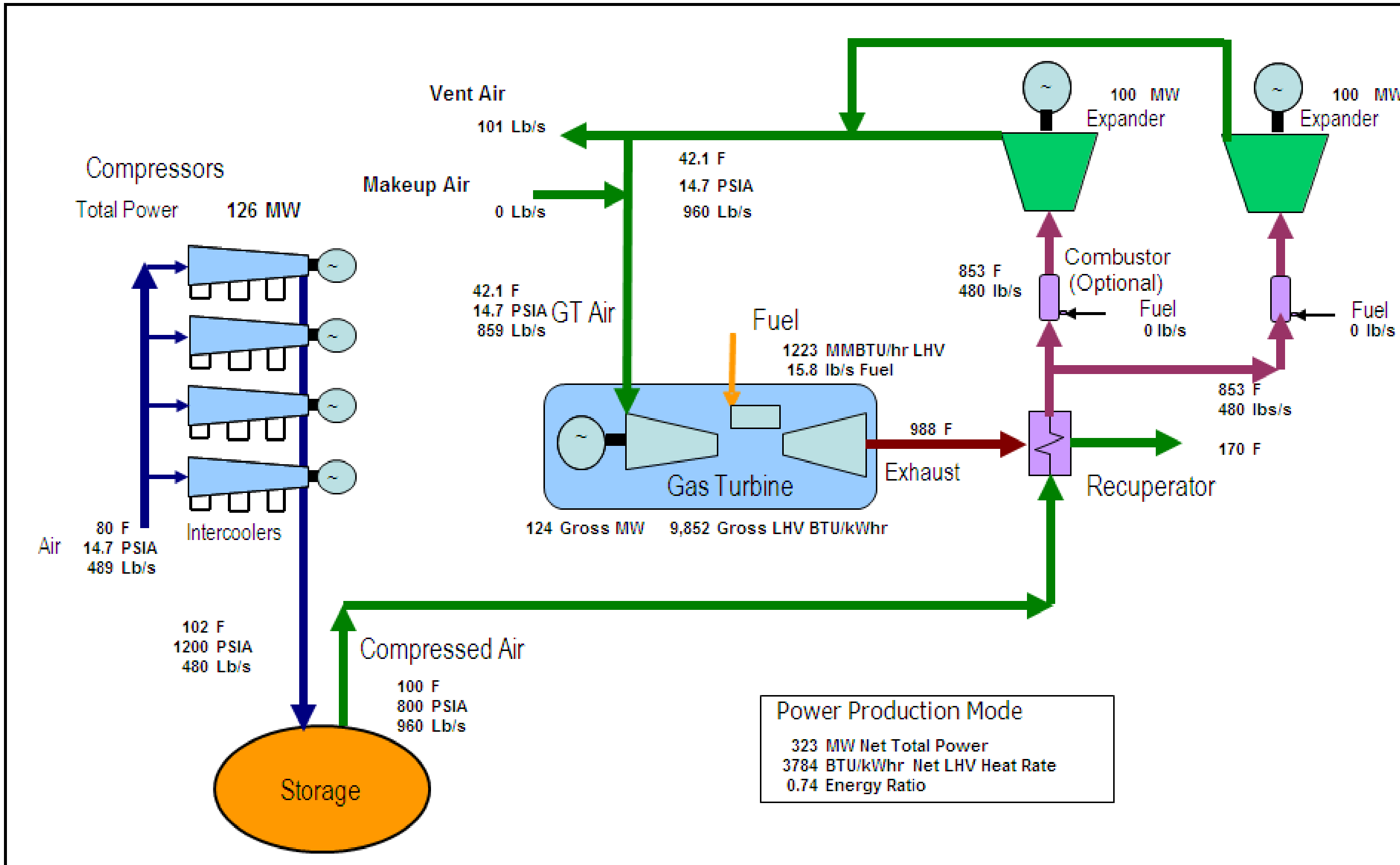


310 MW CAES plant Concepts with Air Injection Power Augmentation

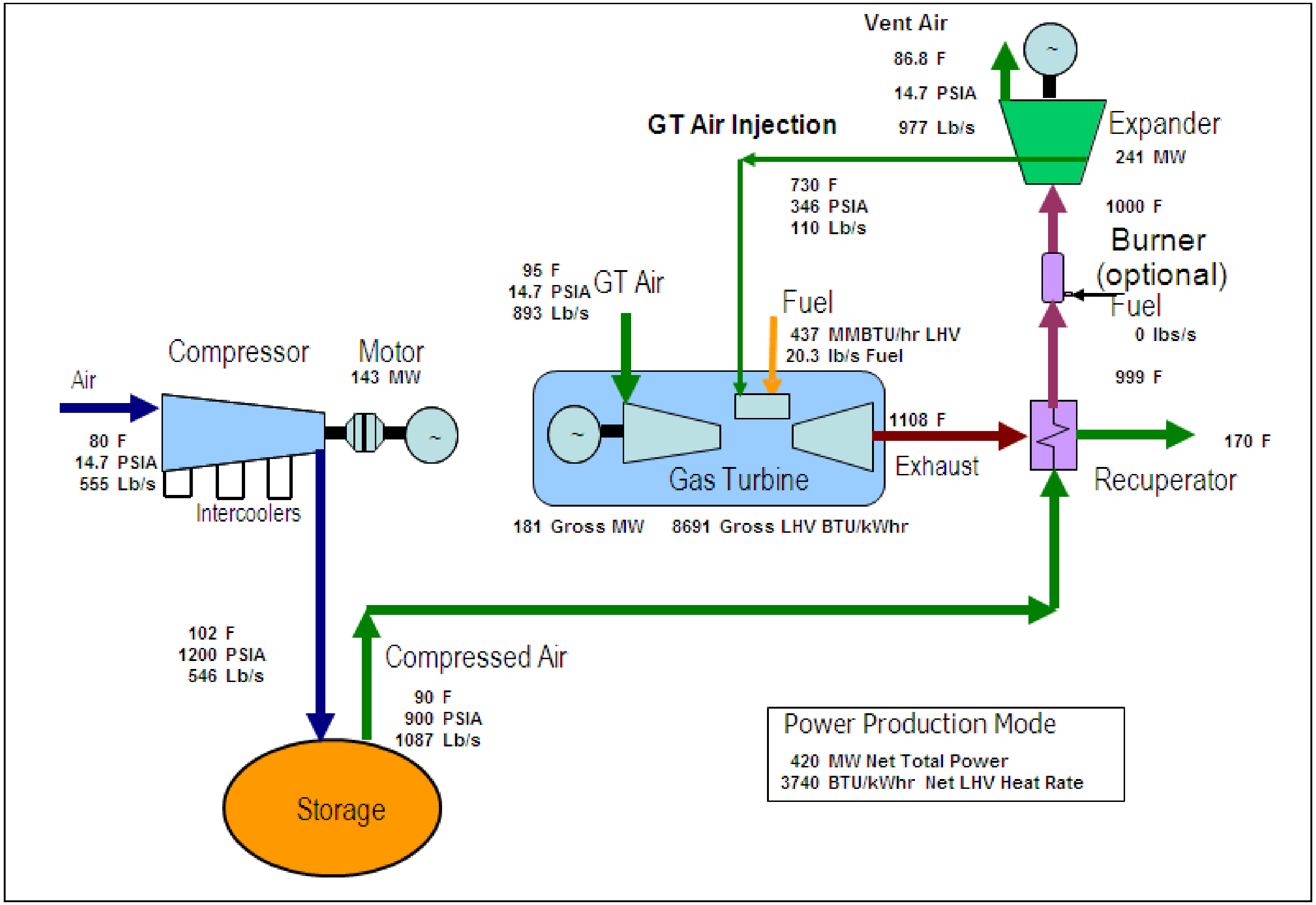


320 MW CAES plant Concepts with Cold Air Supercharging Power Augmentation

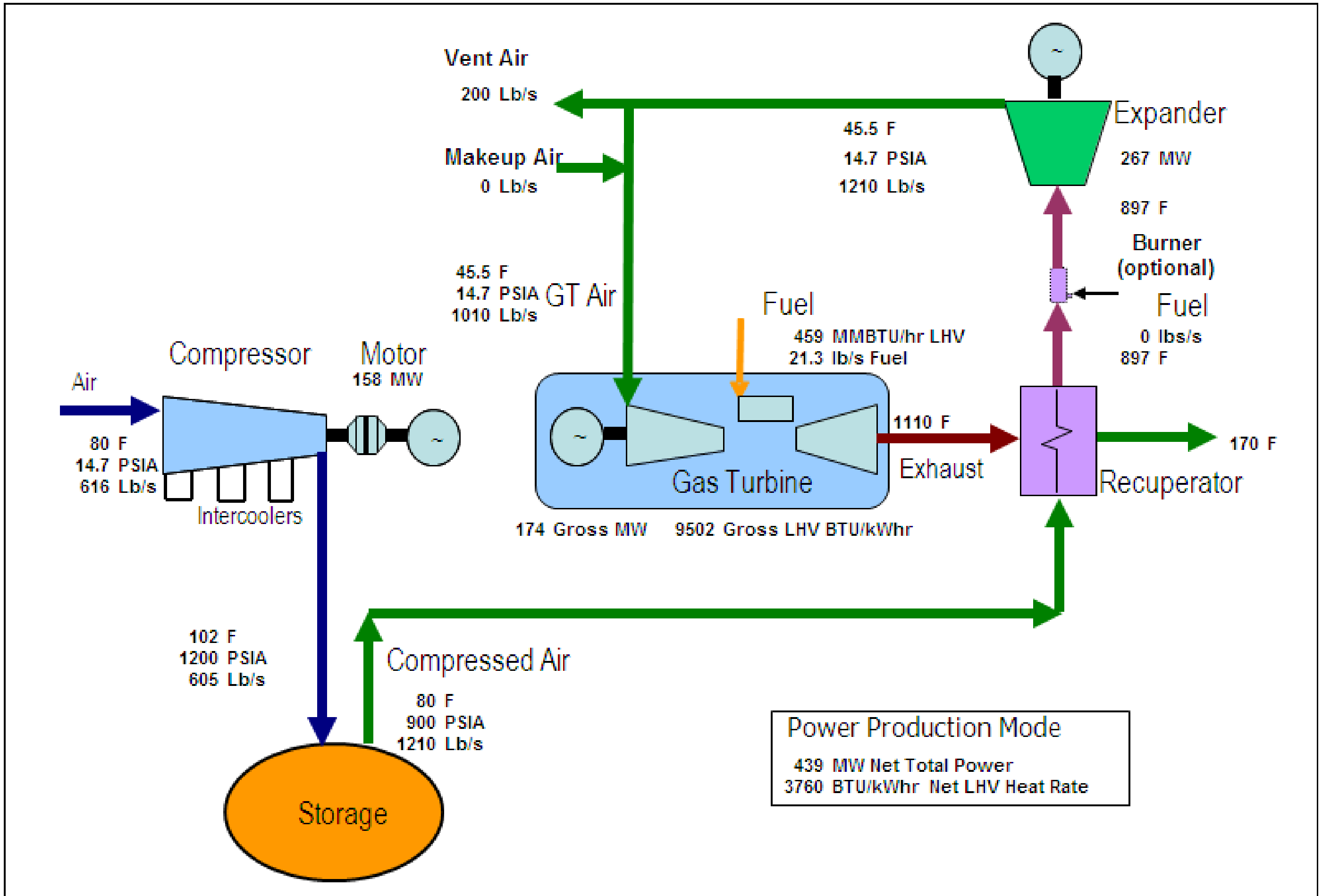
CAES W501D5A with Expander & GT Inlet Air Cooling



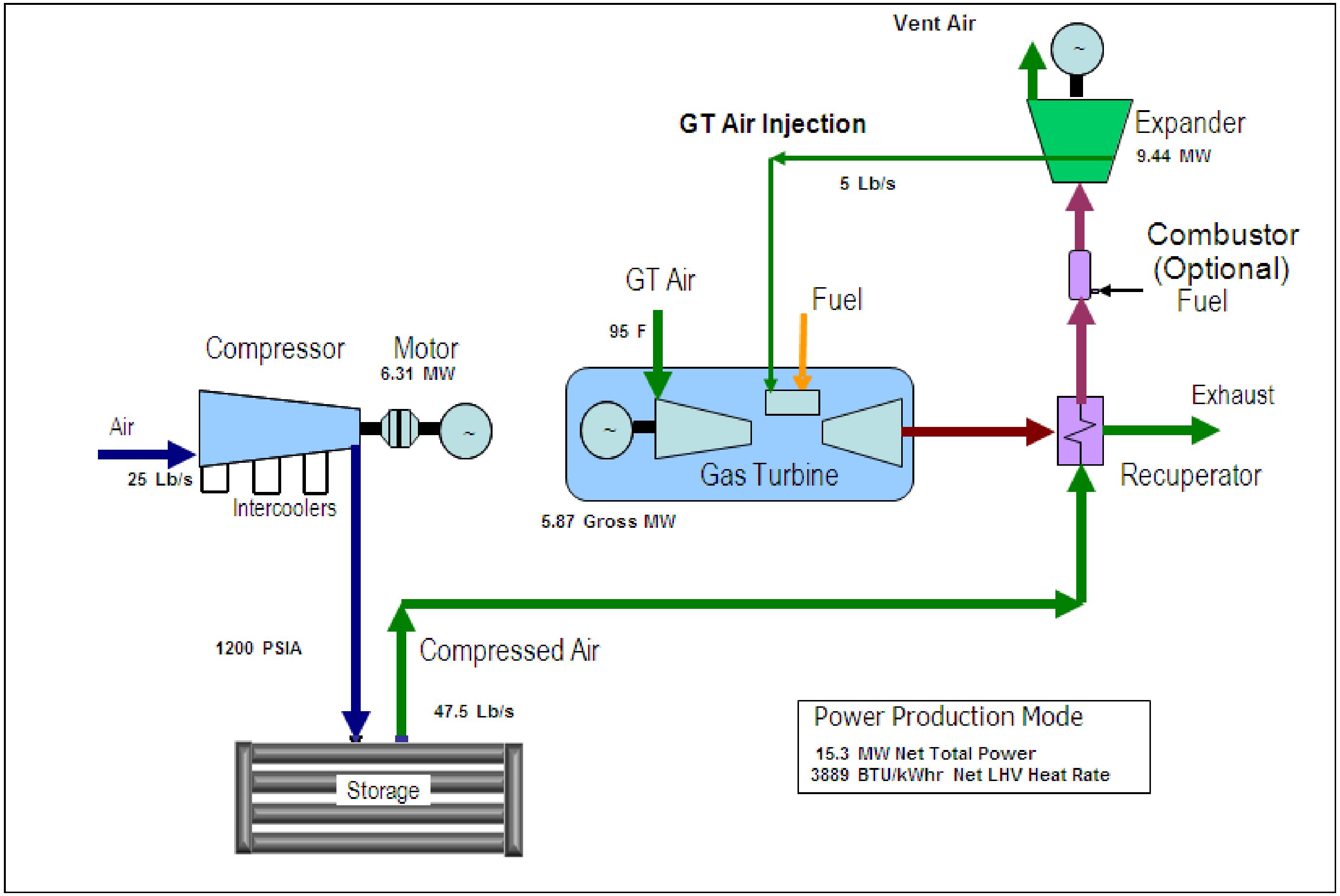
CAES Plant Concept Based on GE 7241with CT Power Augmentation w. Air injection and Bottoming Cycle Expanders (420 MW)



CAES Plant Based on GE 7241 with Bottoming Cycle Expanders and the CT Power Augmentation by Inlet Chilling (440 MW)



15MW CAES plant Concepts with Air Injection Power Augmentation



The CAES2 Plants Performance and Operational Flexibility to Meet Renewables/ Smart Grid Requirements

The CAES2 Plants Flexibility to Meet Capacities Requirements

In the CAES2 the combustion turbine capacity (new or existing) represents approximately 30% of total integrated CAES2 plant capacity with the bottoming cycle producing app. 70% of the Green Energy.

CAES2 plants of various capacities are based on various combustion turbines:

- 400 MW CAES2plant, the design can be based on app. 170-190MW-class CT such as GE's Fr 7FA model;
- 250MW CAES2 plant can be based on app. 100MW-class gas turbine like the Fr 7EA.
- 170MW CAES2 plant can be based on app. 60MW-class gas turbine like the Fr 7B (Fig. 1a and 1b)
- 15MW CAES2 plant can be based on app. 6MW-class gas turbine like the Solar Taurus 60 (Fig. 1c)

Performance Characteristics of CAES2 Technology

Power is generated:

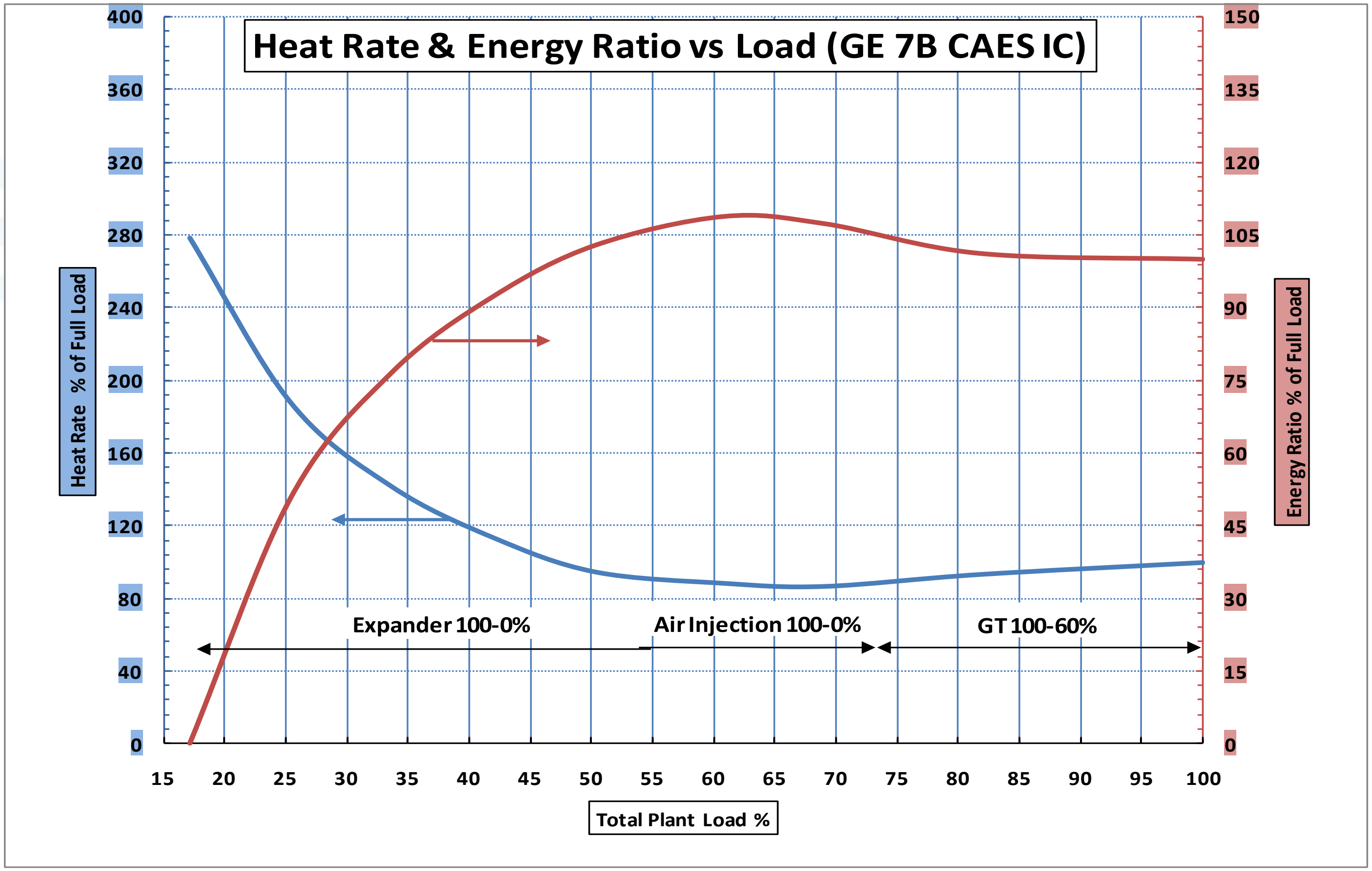
- **35% by a stand alone combustion turbine –new or existing**
- **65% by Green power generated by stand-alone multiple standard air expanders utilizing the CT exhaust gas heat to preheat the stored air**

Heat Rate: Approximately **3700-3800 Btu/kWh** plant heat rate;

Energy Ratio: Approximately 0.65 to 0.75 kWh-In (off-peak kWh energy used to charge the storage system) over kWh-Out (CAES plant energy produced during the plants generation cycle).

Capital Cost: Approximately **$800-850 /kW** for large plants using below ground air storage systems and approximately **$1200/kW - $1400/kW** for small plants using above ground air storage systems.

Heat Rate and Energy Ratio at Part Loads



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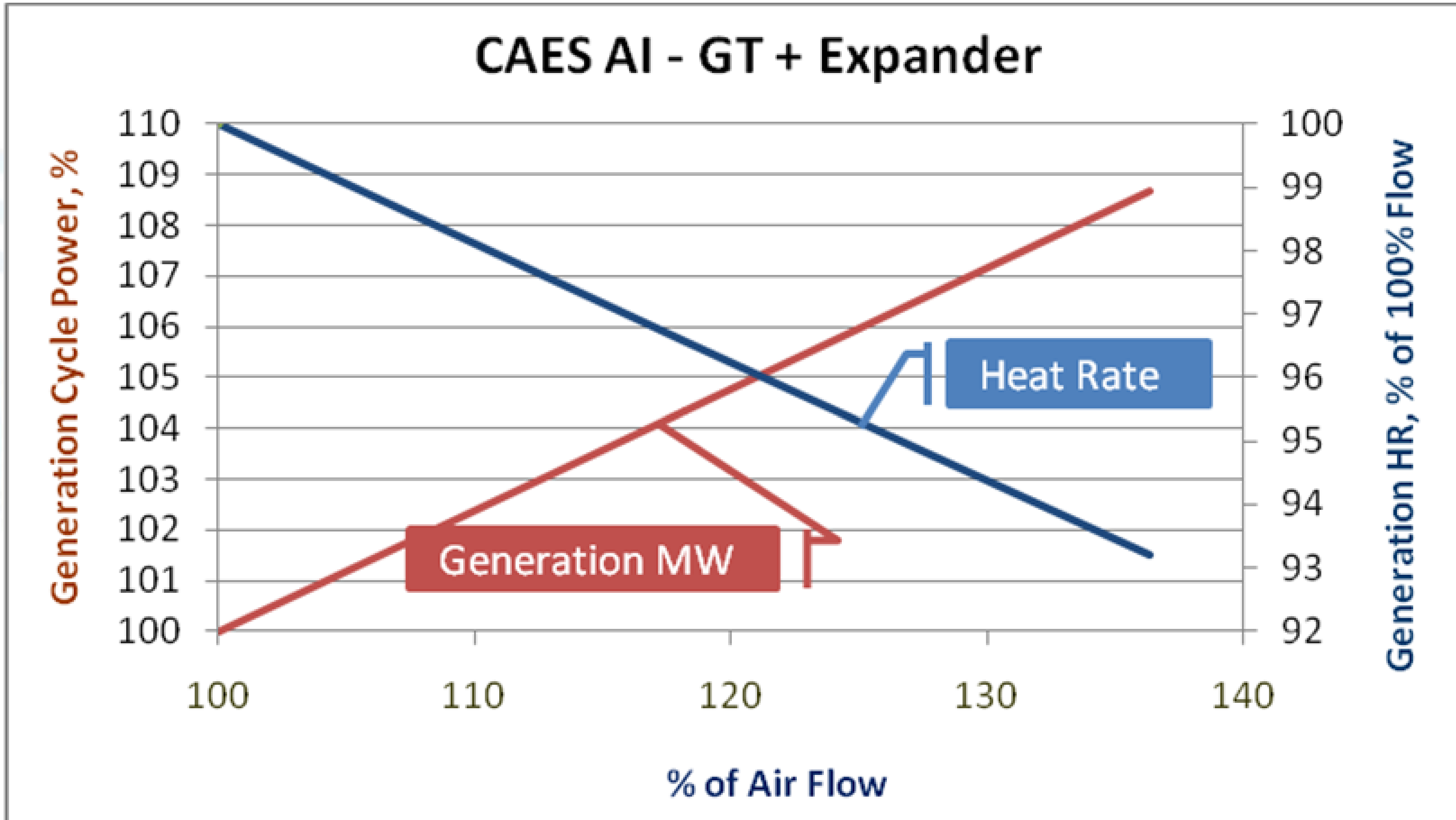
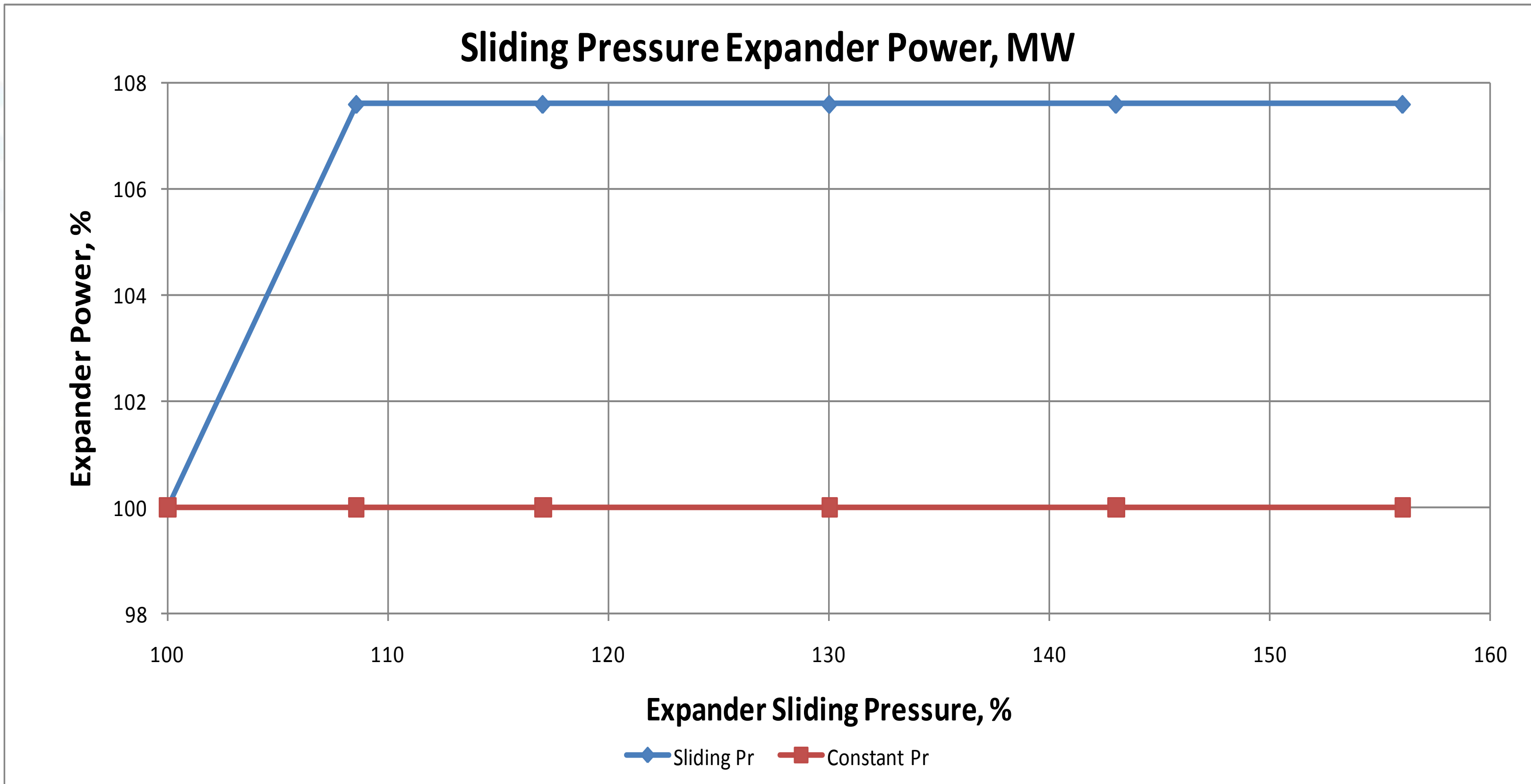
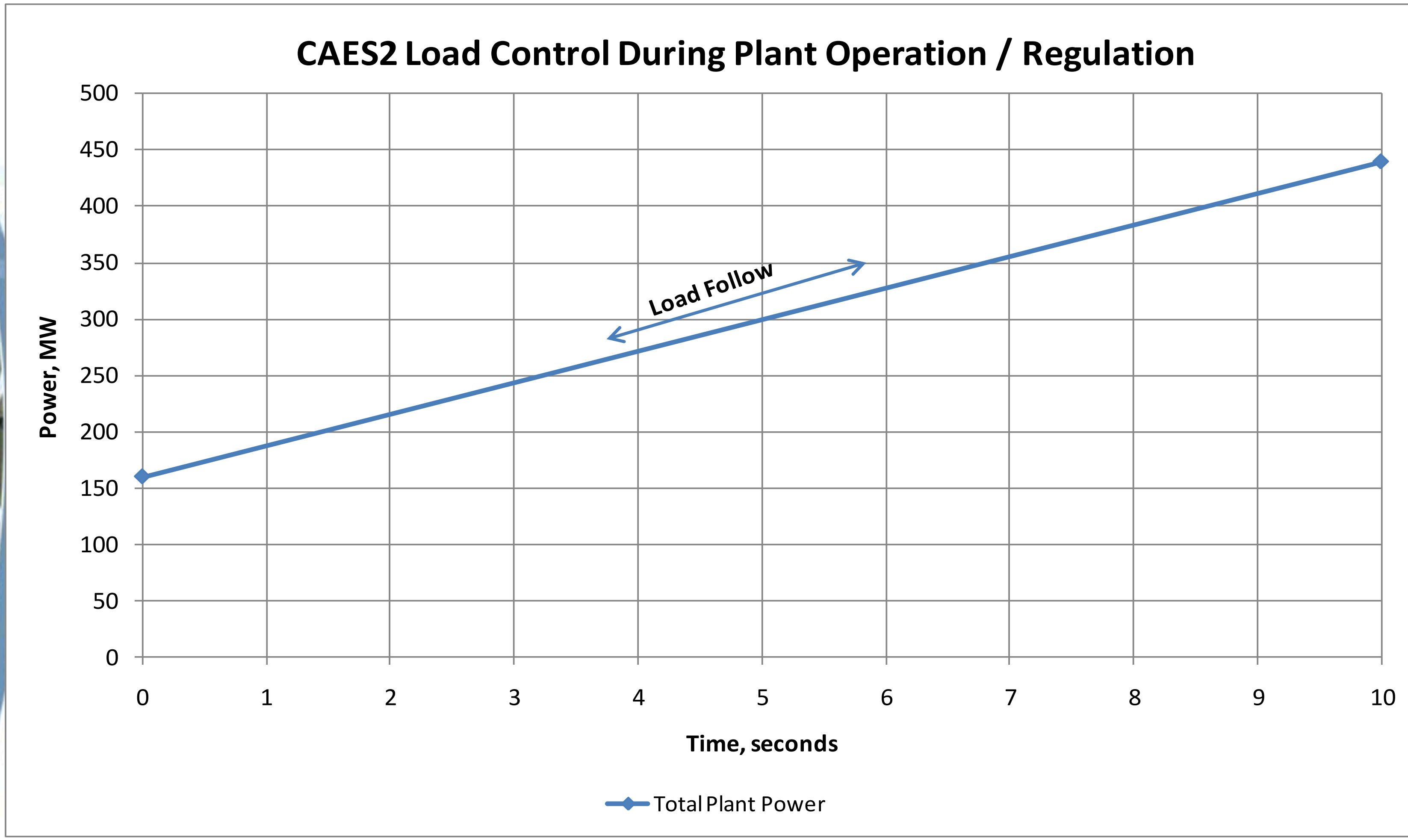
Flexibility for Peaking Power Delivery by Flow Control

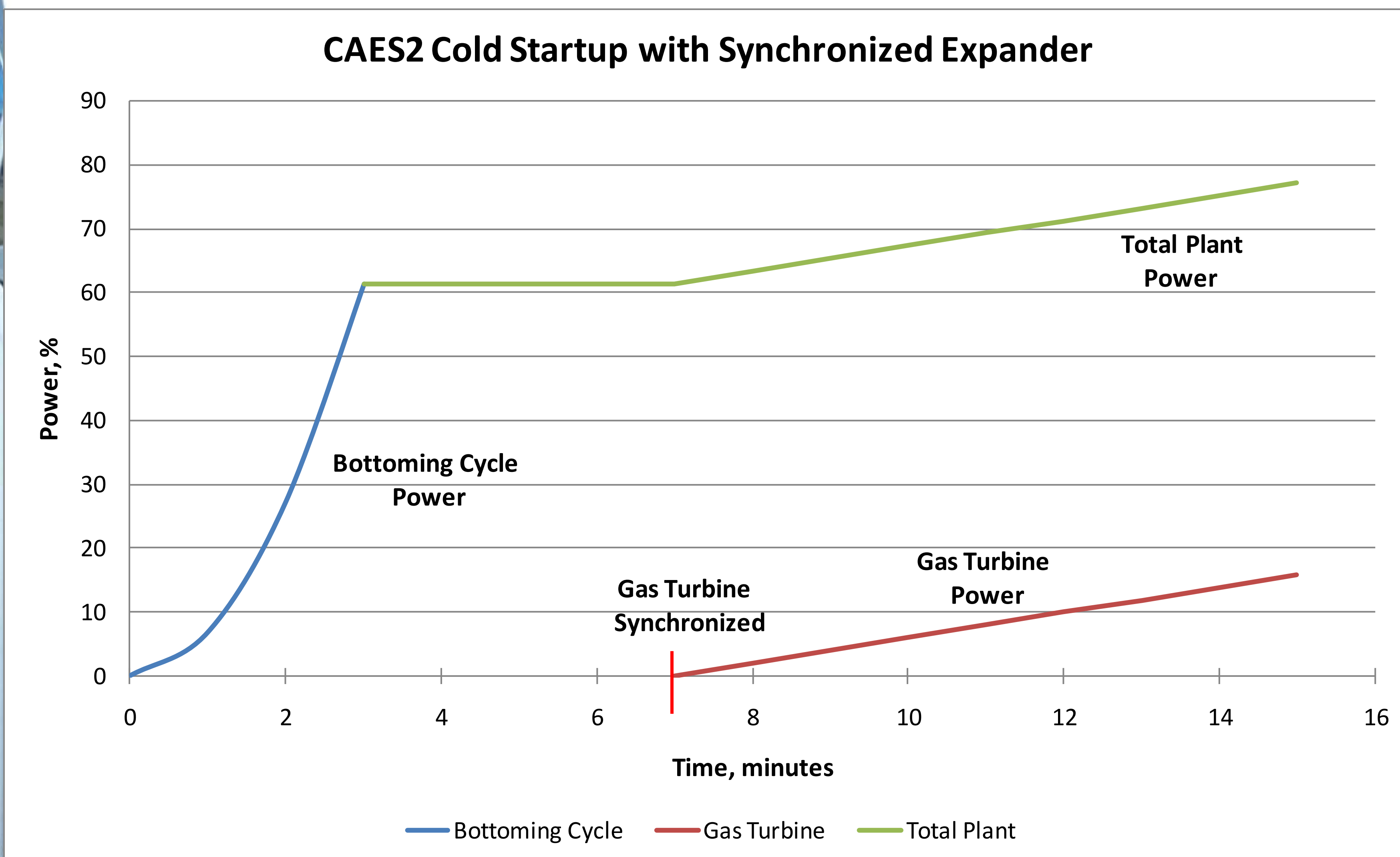


Flexibility for Peaking Power Delivery by Sliding Pressure Operation



CAES2- Load Following




CAES2 Cold Startup with Synchronized Expander
Power, %
90
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
14
16
Time, minutes
Total Plant Power
Bottoming Cycle Power
Gas Turbine Power
Gas Turbine Synchronized
Bottoming Cycle
Gas Turbine
Total Plant

Performance Characteristics of CAES2 Technology

Grid Operations:

- Regulation - flexibility to provide load following in the range from 20% to 100% of the CAES plant capacity **within 3-5 minutes**
- Synchronous Reserve- sudden load response up to 70% of the CAES plant capacity **within ~3-5 min**

Emissions; Combustion turbines with dry low emission (DLE) combustors have single digit Emissions which are further diluted (on a per kWh-Out basis) in this type of second generation CAES plant, due to the extra power generated by the zero-emission "green" power generated by the expanders

Reliability & Availability: This second generation CAES Plant is based on standard /off-the-shelf components; namely, a combustion turbine module (new or used), multiple motor-driven compressors and multiple expanders-driving electric generators.

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Cost Estimates and Economics

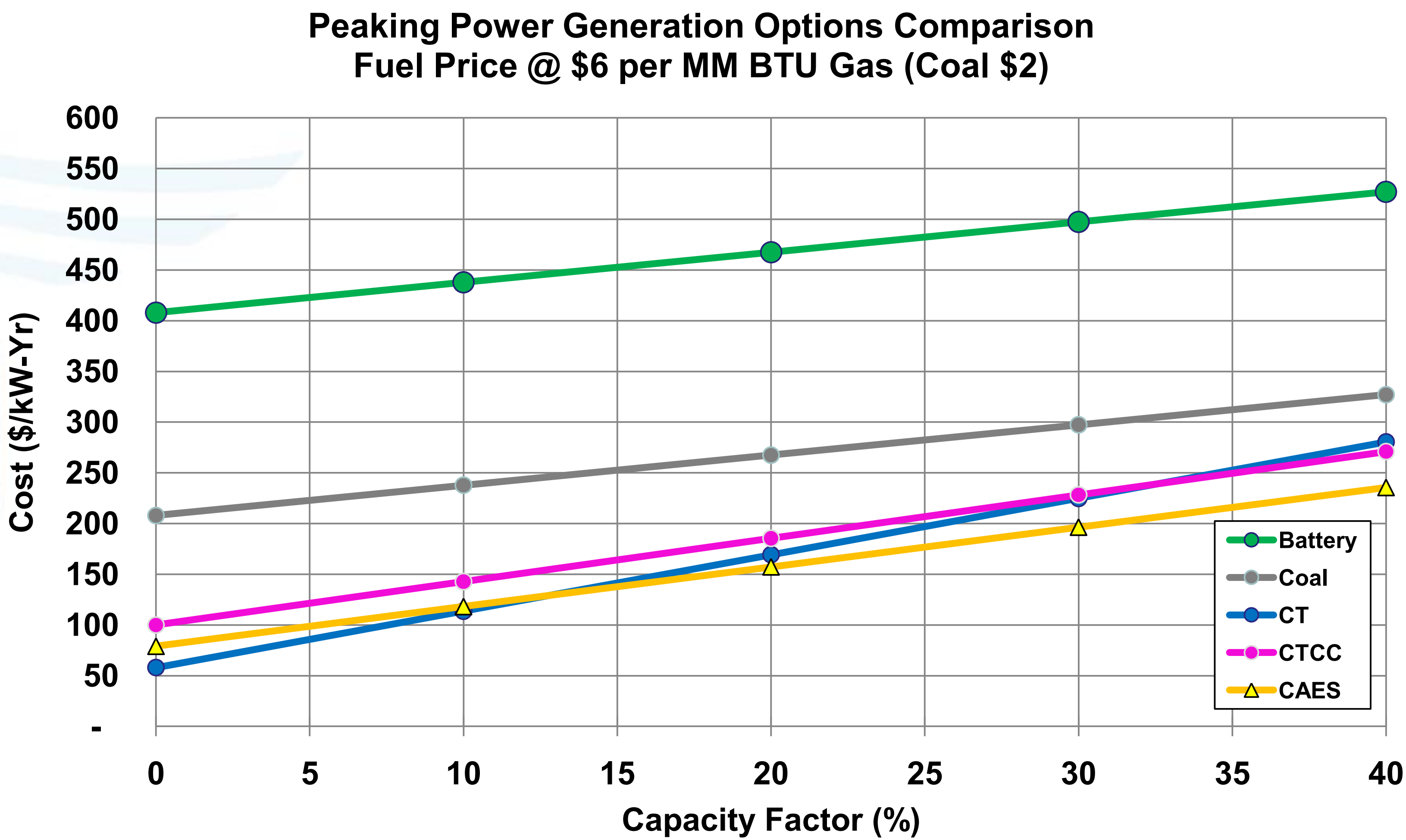
Summary of CAES vs. Conventional Power Plants Performance Metrics and Capital Cost Estimate

Parameters	160 MW Simple Cycle Comb. Turbine	500 MW 2x1 CT Comb. Cycle	400 MW CAES2 with below ground storage	180 MW CAES2 with below ground storage	15 MW CAES2 with above ground storage
Total Power, MW	160	500	420	180	15
Off-Peak Comp. Power, MW			286	146	6.9
Fuel Related HR, Btu/kWh	10,500	6,500	3,740	3,760	3,900
Estimated Specific Capital Costs, $/kW	550	1,200	850	900	1,200
Start-up Time	30 min to achieve 100 % capacity	60 min to achieve 100 % capacity	3-5 min to achieve 70% capacity 30 min to achieve remaining 30% capacity	3-5 min to achieve 70% capacity 30 min to achieve remaining 30% capacity	3-5 min to achieve 70% capacity 30 min to achieve remaining 30% capacity
Smart Grid Support:					
Arbitrage	No	No	Yes	Yes	Yes
Regulation	No	No	Yes	Yes	Yes
Synchronous Reserve	No	No	Yes	Yes	Yes
Load Management	No	No	Yes	Yes	Yes

Summary of CAES vs. Batteries, Pump- Hydro – Performance and Capital Cost Estimate

Parameters	Batteries	Pumped - Hydro	400 MW CAES2 with below ground storage	180 MW CAES2 with below ground storage	15 MW CAES2 with above ground storage
Total Power, MW	10-20	500	420	180	15
Storage Hours ours	4	10	10	10	4
Estimated Specific Capital Costs, $/kW	2800	2500-4000	850-900	850-900	1,200
Estimated Capital Costs, $/kWh	700	250-400	85-90	85-90	400-450

Comparative analysis of the generation costs of various power generation plants. CAES2 is estimated to have practically the lowest generation costs over the whole range of load factors even w/o considerations of additional external renewable energy/smart grid economical benefits



Conclusions

CAES2 provides wide range of capacities from 10MW to 500 MW with design and operational flexibility to meet renewable, based load (nuclear-coal plants) and smart grid operational and economic requirements

CAES2 is based on utilization of off-shelf standard components providing very high R&A

Extremely low heat rate - NG/Fuel oil consumption reduction by 50-70%

Specific features to support and optimized operations of " smart grids" via providing unique arbitrage, regulation and synchronous reserve

Significant reduction of emissions by adding of approximately 70% of the total capacity as Green Energy- w/o fuel consumption

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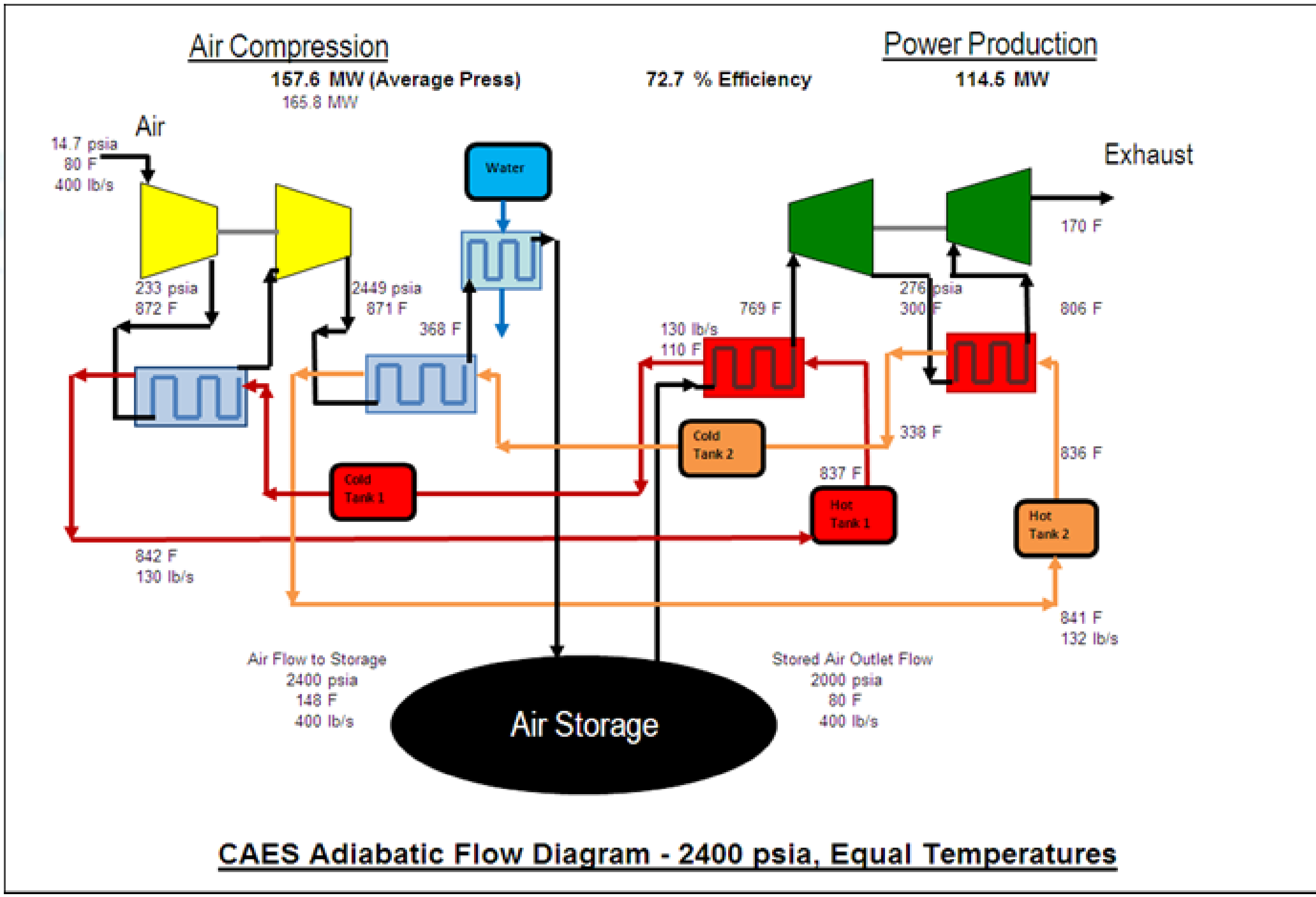
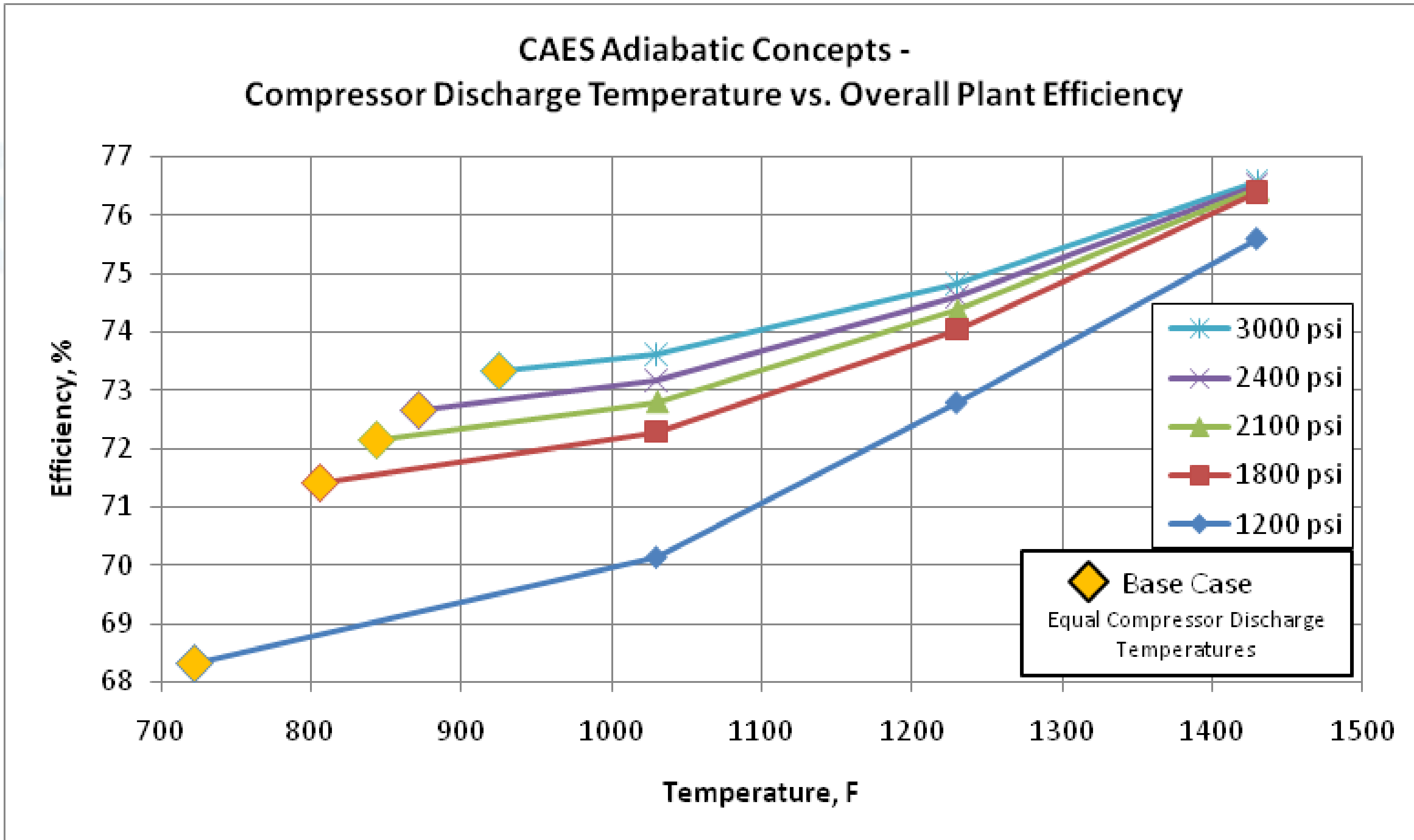
Adiabatic CAES Plant Concept

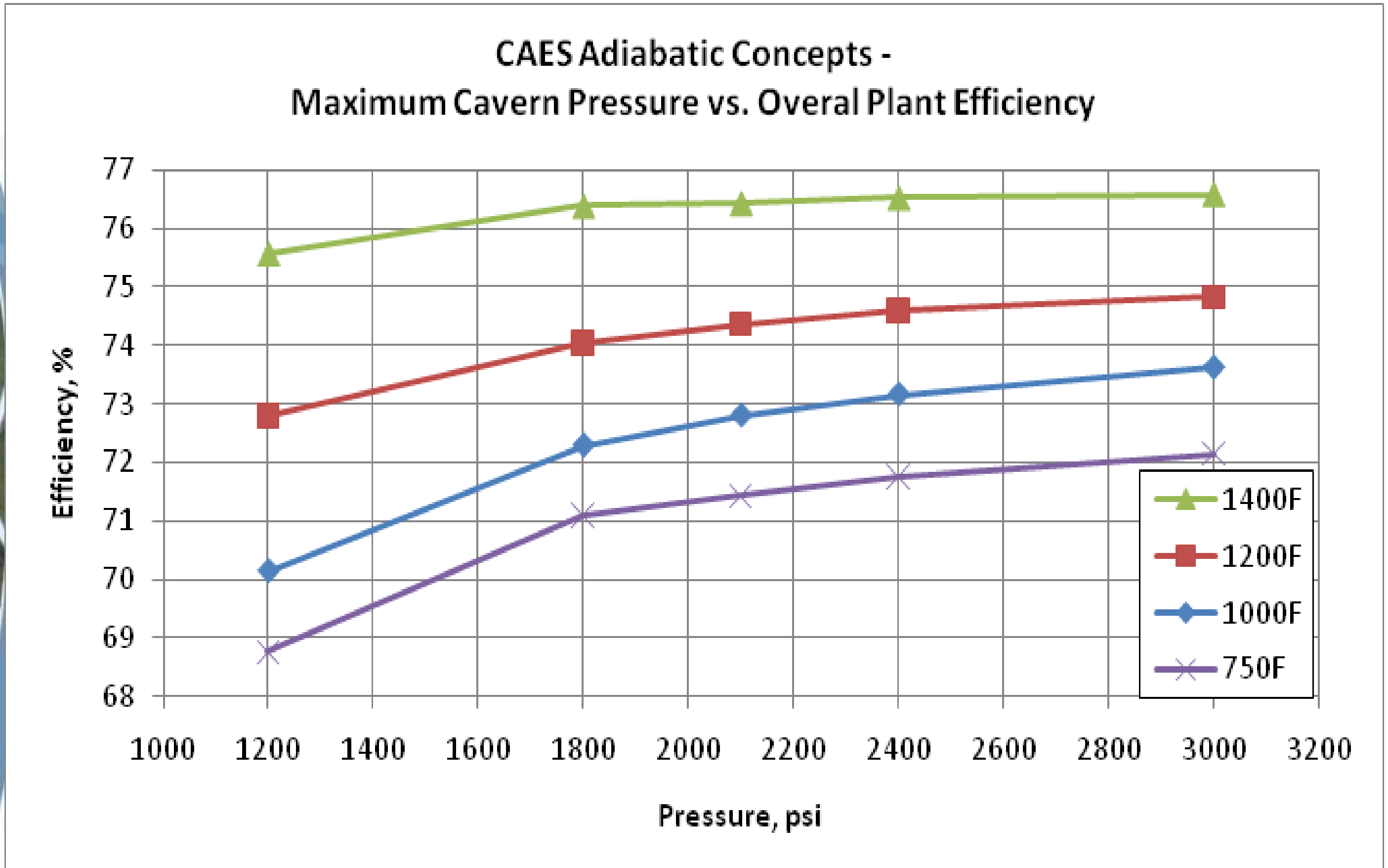
Heat and Mass Balance for the Storage Pressure of 2400 psia and Compressor Discharge Temperature of app. 870F



ACAES Plants Efficiency vs. Compressor Discharge Temperature Curves for Specific Storage Pressures



ACAES Plants Efficiency vs. Storage Pressures for Specific Compressor Discharge Temperatures



5. Adiabatic CAES: Opportunities and Challenges

Stefan Zunft, *German Aerospace Center (DLR)*

An increasing share of electricity from renewable sources is the stated aim of national and European energy policies. However, a grid-compatible integration of this fluctuating energy production to the European electricity systems is expected to be an issue in the mid-term – in particular in coast regions close to offshore wind farms. Large-scale storage technologies can substantially mitigate the expected shortages of balancing and transport capacities. The concept of Adiabatic Compressed Air Energy Storage is a promising candidate, representing a locally emission-free, pure storage technology with high storage efficiency and a high application potential in Europe. This talk will outline the technology and give an overview on past and present activities for this technology.

Dr. Stefan Zunft studied at the Universities of Hannover and Stuttgart, graduated as a mechanical engineer from the University of Stuttgart in 1991 and received his Ph.D. degree in 2002. In 1991, he joined the Institute of Technical Thermodynamics of the German Aerospace Center (DLR). His research interests and his previous work in numerous international projects have been focussed on solar thermal energy and rational energy use in industrial processes. Currently, he is a research area manager of the institute's industrial heat transfer and heat storage activities.

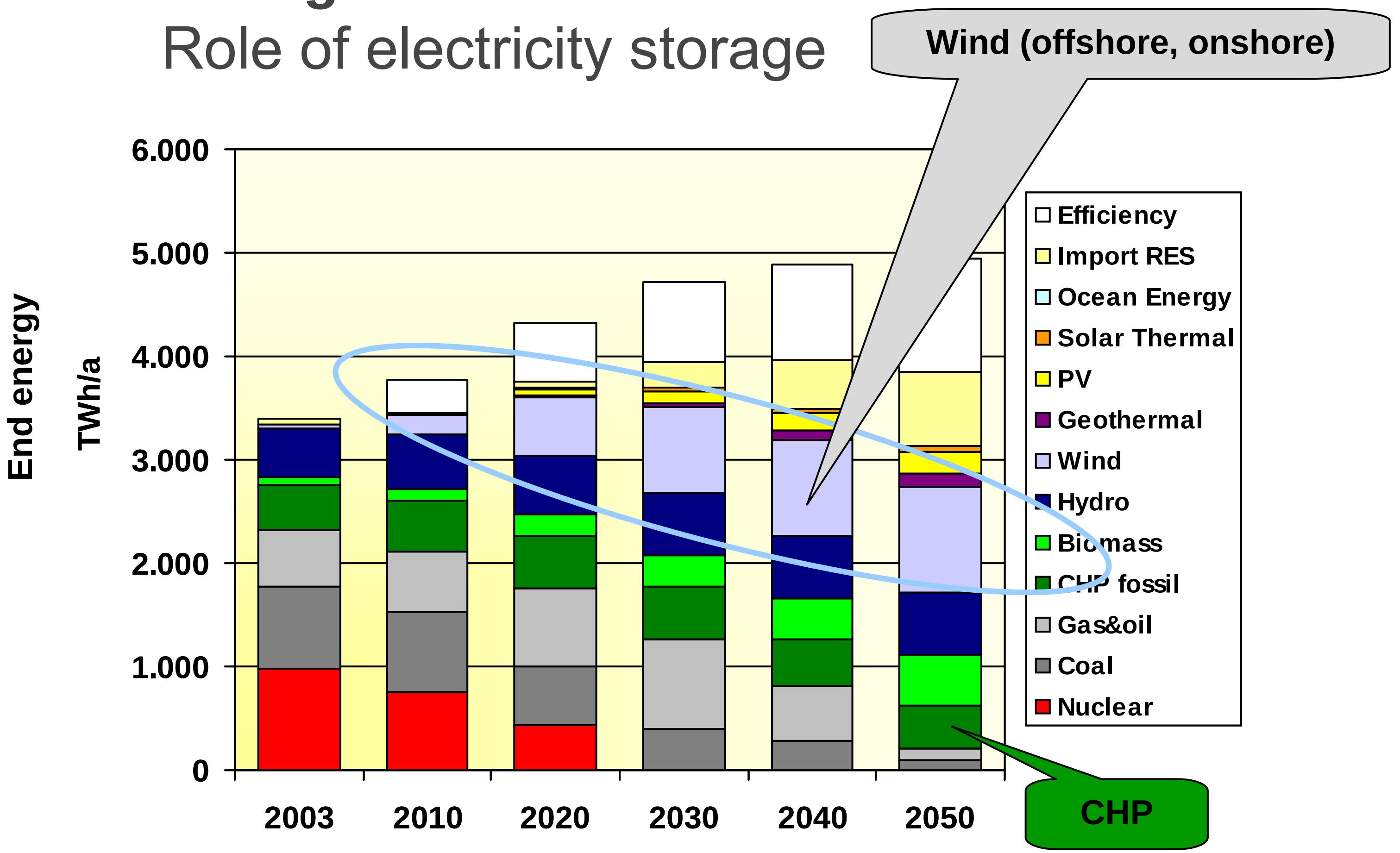
2nd CAES Conference & Workshop, Columbia University
New York, October 20, 2010

Adiabatic CAES: Opportunities and Challenges

S. Zunft, German Aerospace Center (DLR)

Deutsches Zentrum
für Luft- und Raumfahrt e.V.
in der Helmholtz-Gemeinschaft

Background
Role of electricity storage

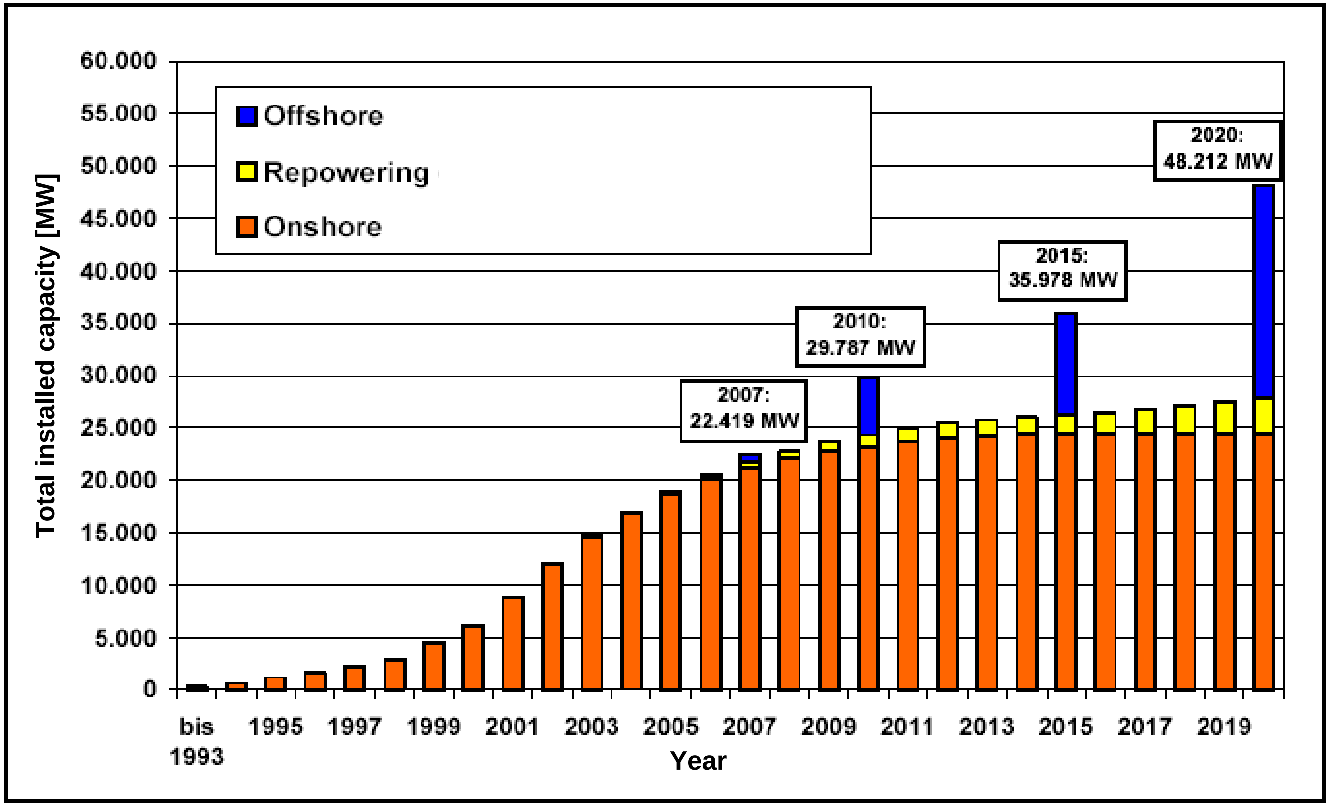


Future electricity supply OECD Europe - 2º C Scenario. DLR 2008

Dispatchability? Grid integration?

Background

Expected Deployment of Wind Power in Germany

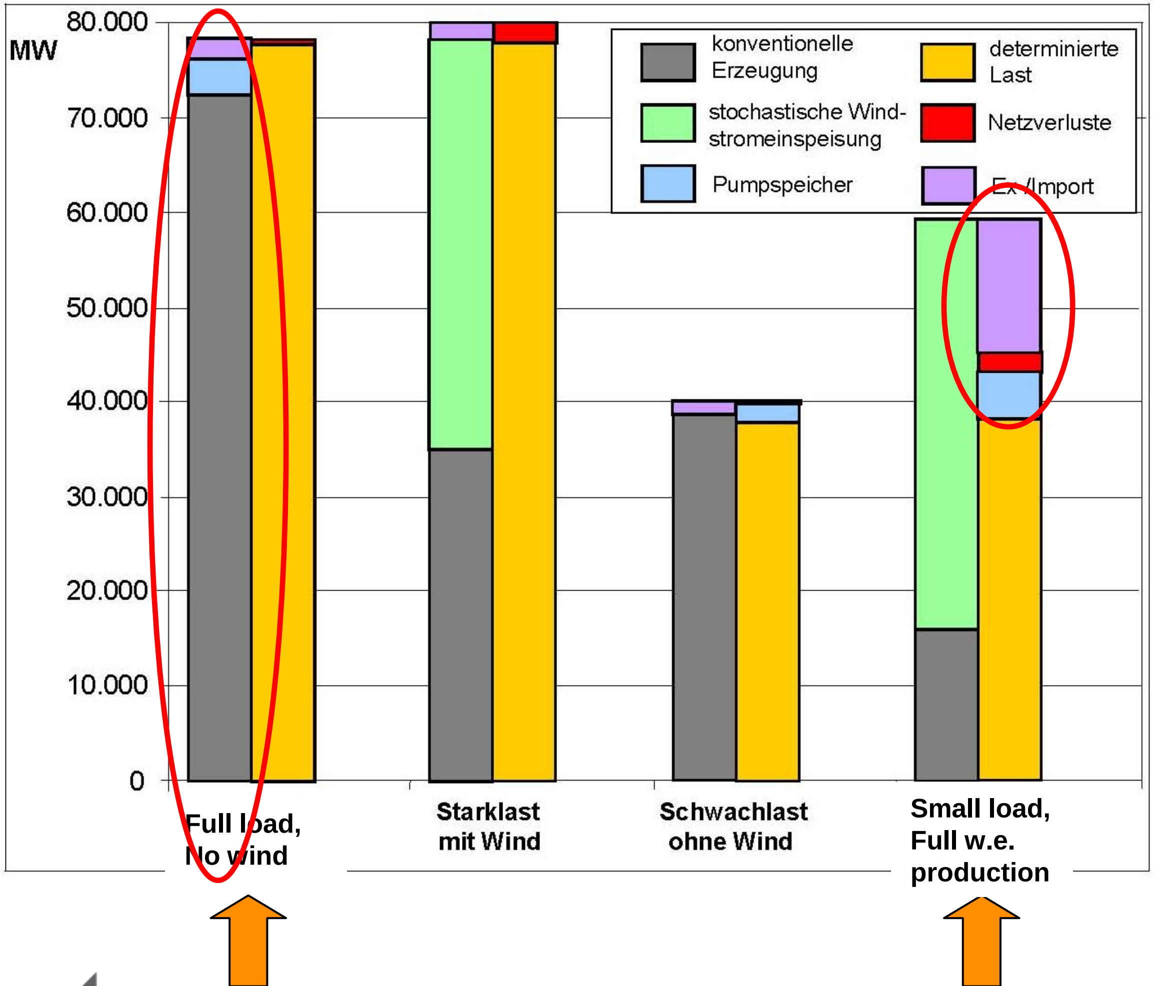


Source: dena (deutsche energie agentur)

dena grid study 1:
wind feed-in scenario 2015:
Onshore 26,2 GW
Offshore 9,8 GW

Germany: Further increased RE share mainly through offshore wind; onshore increase mainly due to repowering (substitution by bigger units)

Background
Grid Balancing with increased share of RES



"dena grid study 1" wind feed-in scenario 2015:
Expected RE electricity share: 20% by 2015

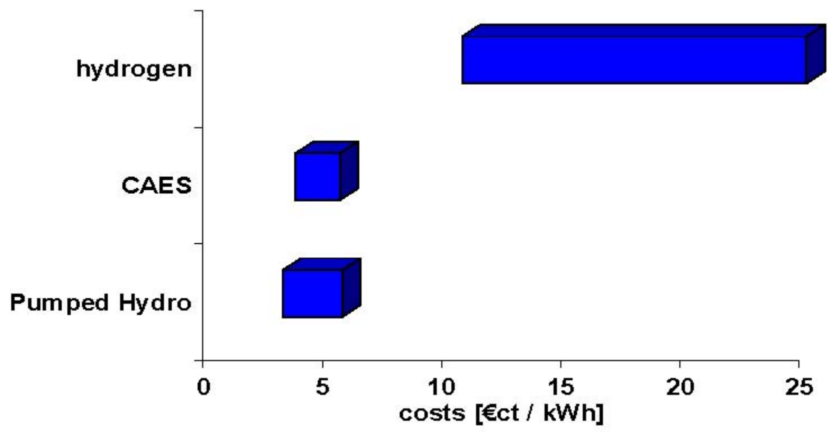
- Wind capacity credit: ~6%
- Fossil backup
- Fossil grid balancing of prediction mismatch, increasing balancing demand in spite of good prediction quality
- Excess electricity generation at certain load situations

⇨ Price volatility expected to increase

Graph: Electricity generation and electricity loads in 2020
Source: DENA-Netzstudie 2005

Storage Technology Options

	X-Large Scale	Large Scale	Medium Scale
Response time	> 15 min	< 15 min	1 s -30 s [1]/ 15 min [2]
Typical discharge times	days to weeks	hours to days	minutes to hours
Storage technologies	Hydrogen storage systems	Compressed air storage (CAES) Hydrogen storage systems Pumped hydro	Batteries (Li-Ion, lead-acid, NiCd) High-temperature batteries Zinc-bromine batteries Redox-flow batteries
Suited applications	reserve power compensating for long-lasting unavailability of wind energy	secondary reserve minute reserve load levelling	primary reserve [1] secondary & minute reserve [2] load levelling, peak shaving



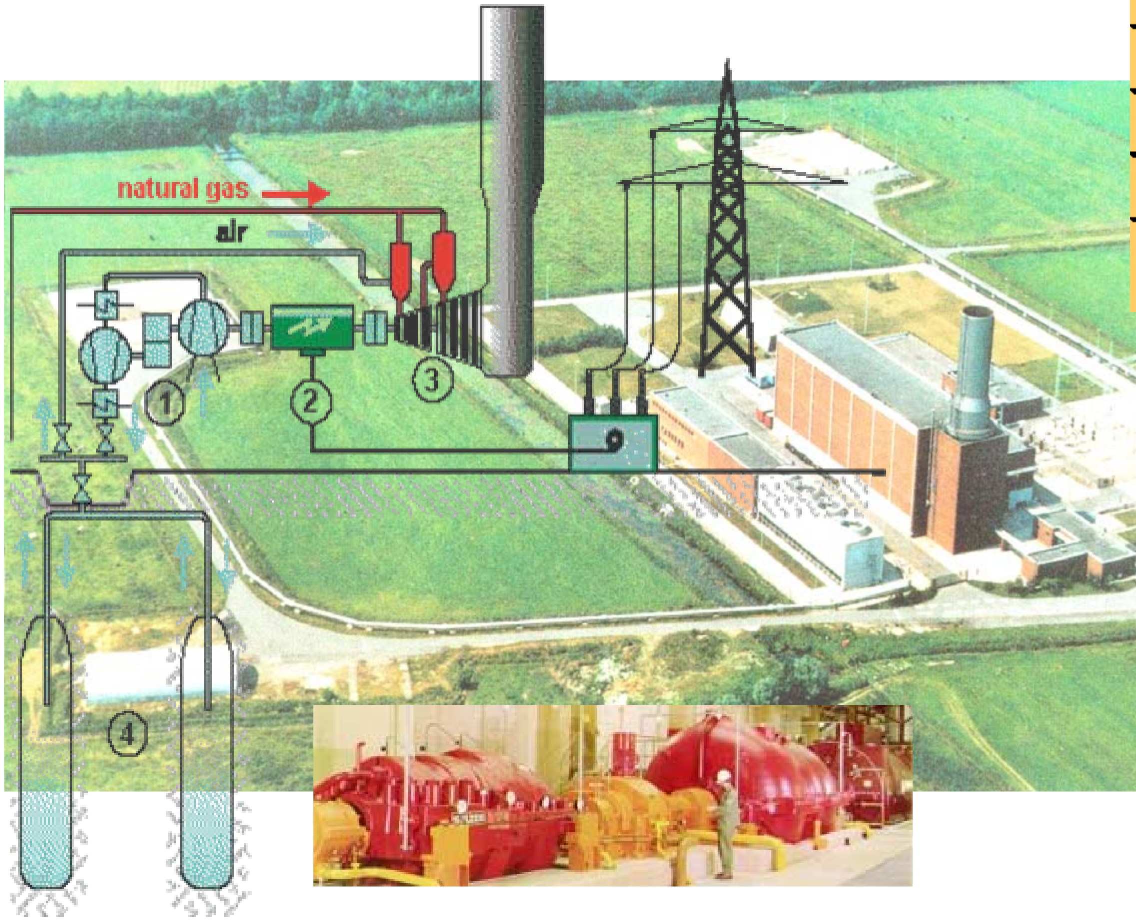
Source: Kleimaier M.; Zunft S. et al.: Energy storage for improved operation of future energy systems. In: 2008 CIGRE Session, Paris, France, 24-26 August 2008

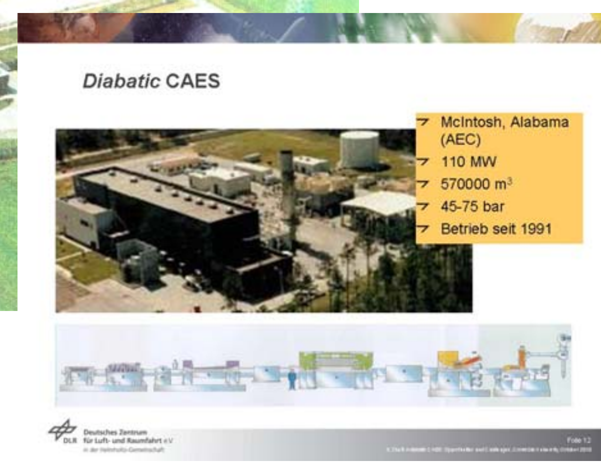
CAES Grid Applications

Modus	Target application/ Strategy of Operation	Typical Size [MW]
Central Storage Device	Revenues from spot market price spreads and system services, improved utilisation of transport capacities (peak shaver, reserve capacity, a.o.)	300
Decentral Storage Device	Large wind farms: increase of full load hours, ancillary services, peak price sales, improved utilisation of transport capacities	150
Island Solution	Combined wind/CAES system in island grid: saving of grid connection or gas turbine. Increased full load hours of wind turbines	30

Diabatic ("conventional") CAES

- Huntorf, Germany (E.ON)
- 321 MW (2h)
- 310000 m^3
- 46 – 66 bar
- Operation since 1978, turbine refurbishment in 2007

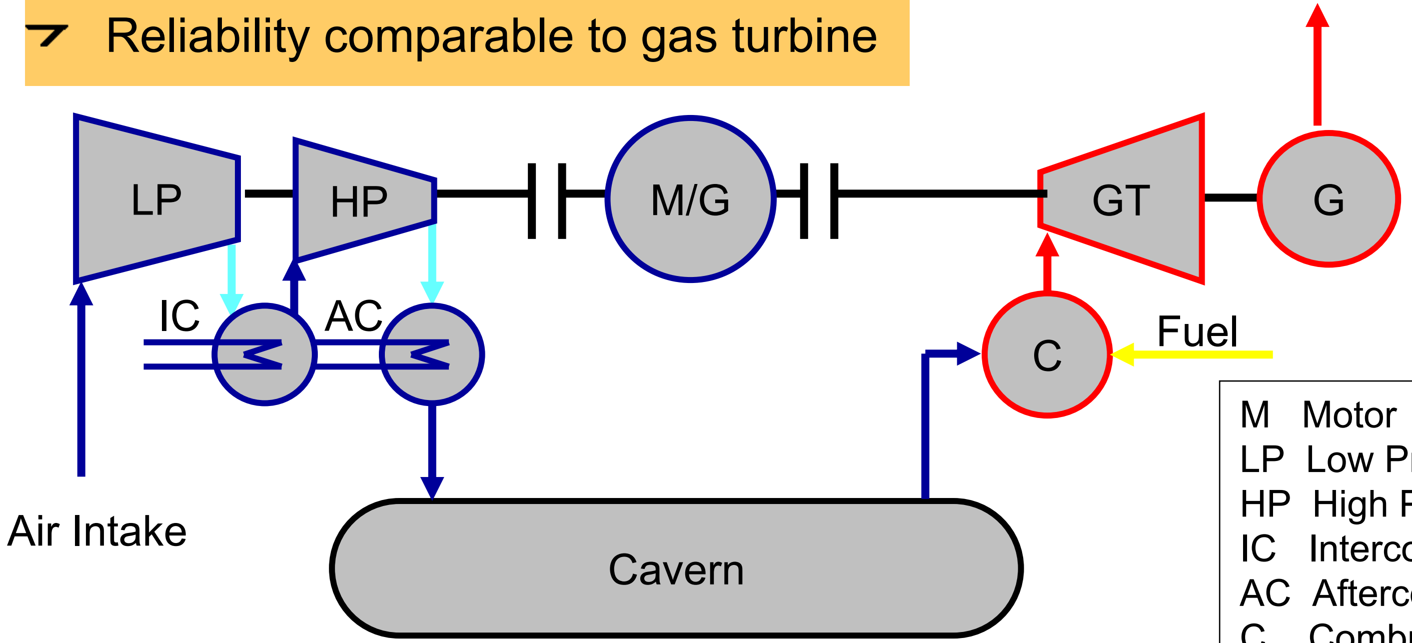




Diabatic CAES

- Simple setup, well-proven components
- Operation experience (300 MW) since 1978
- Reliability comparable to gas turbine

- Hybrid operation only
- Efficiency limitations

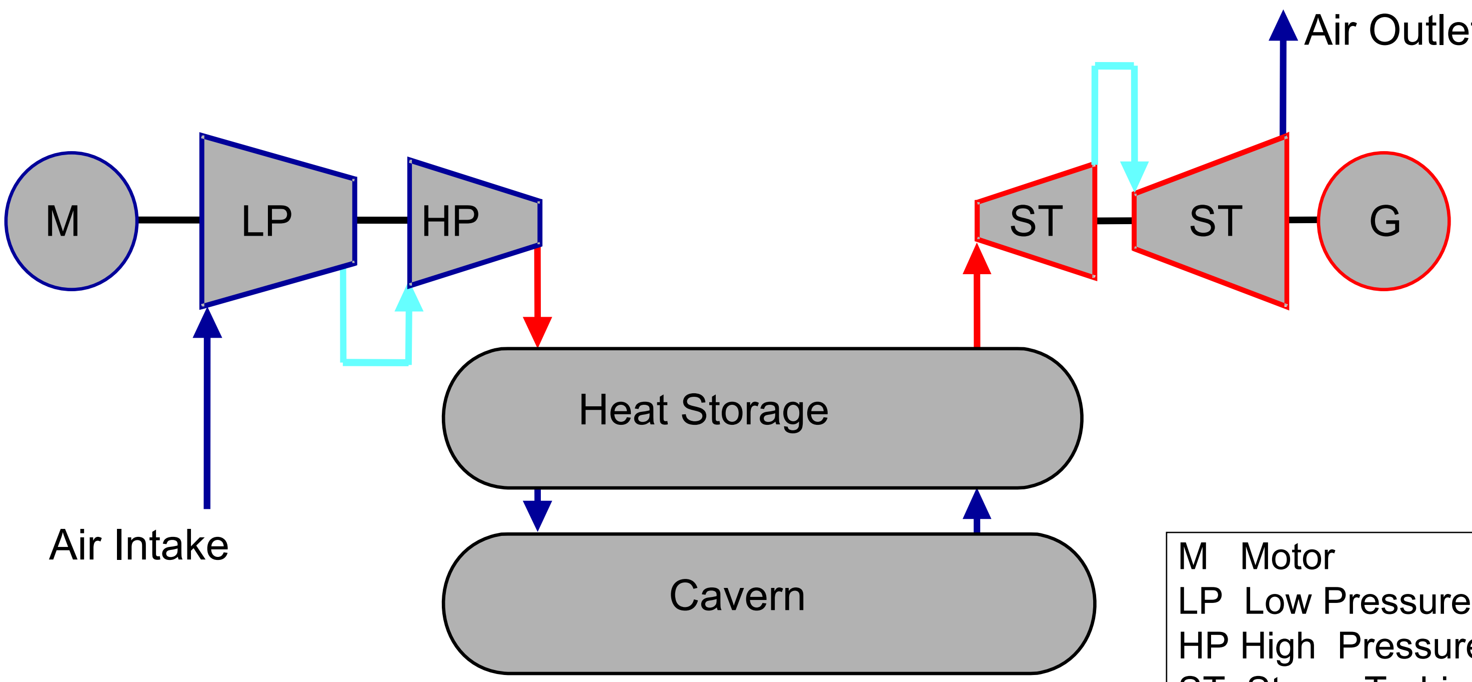


M Motor
LP Low Pressure Compressor
HP High Pressure Compressor
IC Intercooler
AC Aftercooler
C Combustor
GT Gas Turbine Derivative
G Generator

Adiabatic CAES

- Pure storage technology, locally emission-free
- High storage efficiency

- Heat storage needed
- Demanding (but feasible) compressor specifications

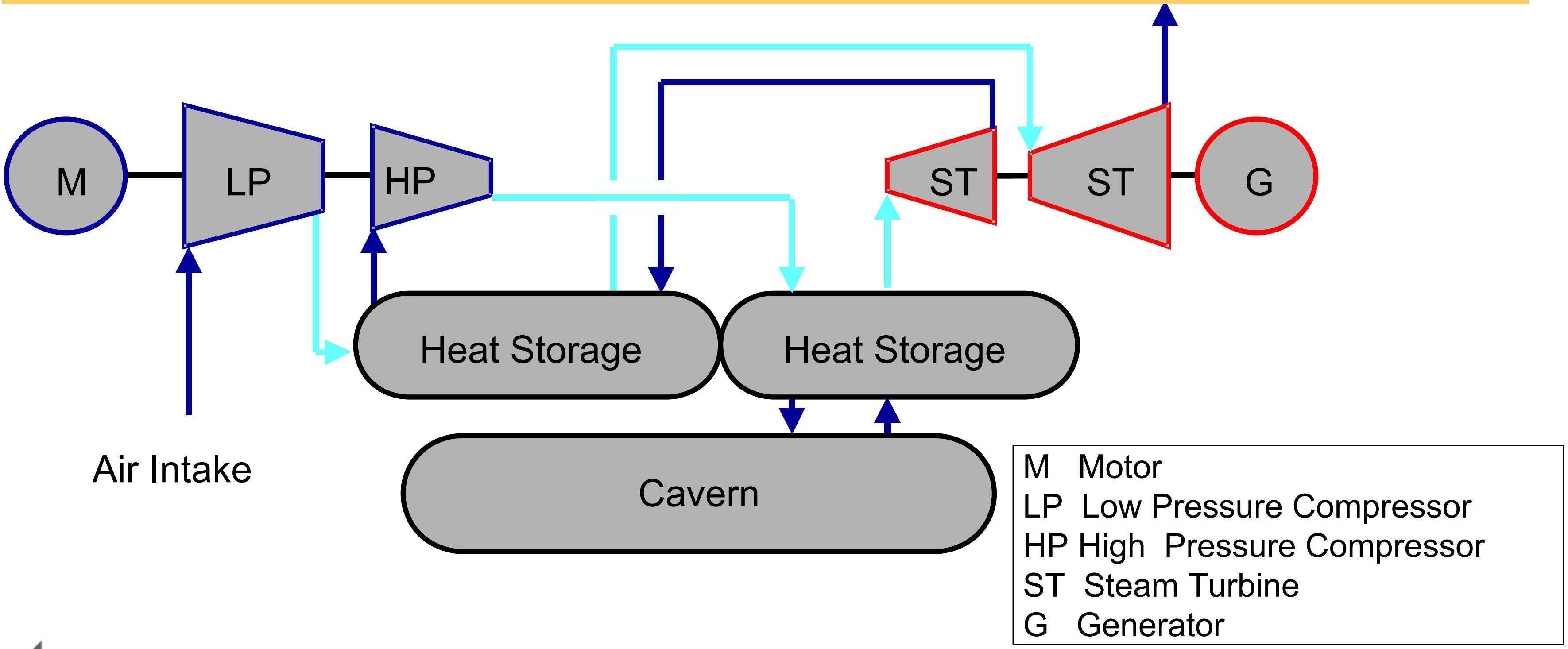


M Motor
LP Low Pressure Compressor
HP High Pressure Compressor
ST Steam Turbine
G Generator

Adiabatic CAES

Two-stage configuration:

- Higher pressure with lower temperature
- Improved storage density
- Two heat storages
- Increased complexity of plant



EU-Project “AA-CAES”

- 5. Frame Program, Contract period Jan 2003 – Dec 2006
- 19 Partners from industry and research
- Objectives:
  - Technology-Screening (feasibility, Capital costs, commercial viability) for various plant configurations and component solutions
  - Detailing of two selected configurations
  - Elaborations of a lead concept

Preparatory study RWE/GE/DLR

- Contract period 2008
- Partner:
  - RWE Power AG, Essen
  - GE Oil&Gas Florence, Italien
  - GE Global Research, München, Germany
  - Erdgasspeicher Kalle, Germany (RWE-ESK)
  - DLR, Stuttgart
- Objectives:
  - Concept study turbo machines
  - Technical and economical aspects of heat storage design and cavern
  - Overall process layout
  - Economic studies

Preparatory study
Outcome: Ambitious but feasible

Turbo machinery / Overall process (GE O&G, GRC Munich):

- Compressor for 600 - 650°C feasible, leveraging turbine features
- Air turbine on basis of gas turbine and steam turbine technology
- Development risks quantified, back-up options identified
- Target efficiency 70% is ambitious but feasible (app. 300 MW, 1GWh)

Cavern (ESK Erdgasspeicher Kalle GmbH – RWE Group)

- Cavern technology can be adapted, Construction time 3-6 yrs

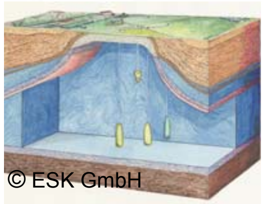
Thermal energy storage (DLR)

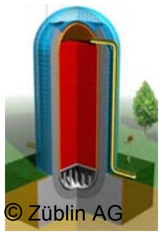
- Storage options based on regenerator technology
- High technological risk

Economics and operational requirements (RWE)

- Adiabatic CAES is not yet in the market,
  expected increase of the peak/off-peak spread boosts economic performance

→ Adiabatic CAES is feasible
Main technical risk „thermal energy storage“, highest economical risk „price spread“



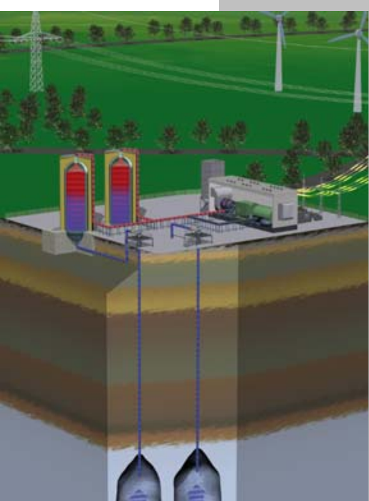


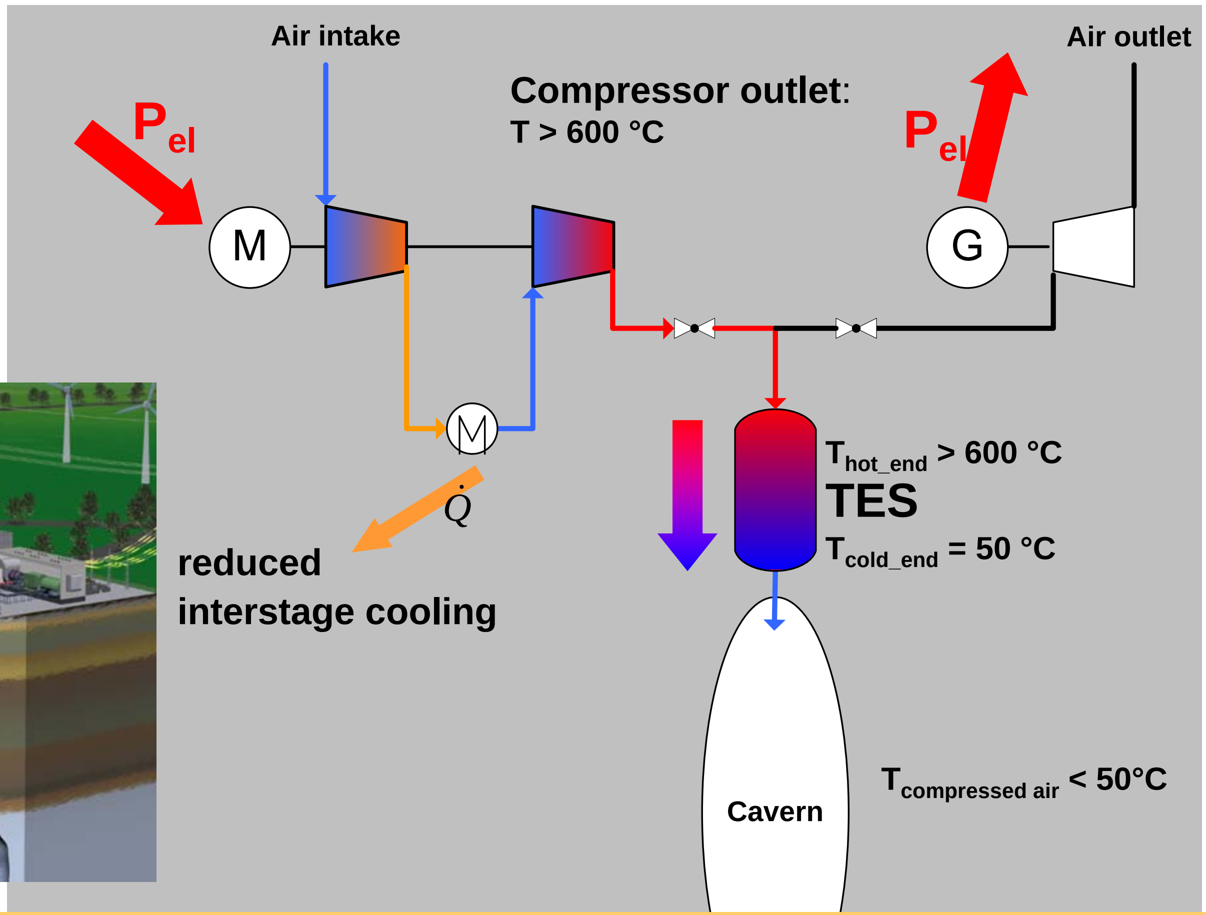
ADELE Joint Development Program

- Status: started in 12/2009
- Tasks, partners
  - Operational requirements, Economic optimisation, Coordination : RWE Power AG, (Essen, Germany):
  - Compressor, Air turbine: GE Oil&Gas (Florence, Italy)
  - Plant concept, BoP: GE Global Research (Munich, Germany)
  - Cavern, Site screening: Erdgasspeicher Kalle (RWE-ESK) (Germany)
  - Heat storage: Ed. Züblin (Stuttgart, Germany)
    OIH (Darmstadt, Germany), DLR (Stuttgart, Germany)
- Budget: ~ 10 Mill. €, partially funded by BMWi
- Objectives: Perform remaining component development, economic optimisation, design demo plant, develop technology to market readiness

2008	2009	2010	2011	2012	2013 +
feasibility study		development programme ADELE			demo phase

ADELE: Cycle operation



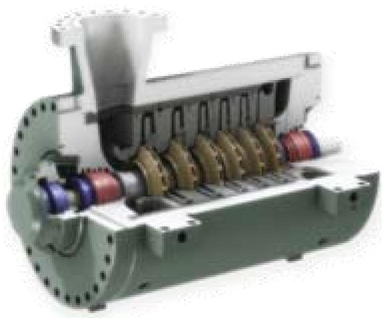


Target figures for a commercial application

- Turbine output: ~ 250 MW
- Compressor power: ~ 200 MW
- Storage capacity: ~ 1 GWh
- Round trip efficiency: ~ 70%

- Charge operation: Interstage cooling minimised, compression heat stored in TES
- Discharge: compressed air heated from TES, air expansion without gas burner

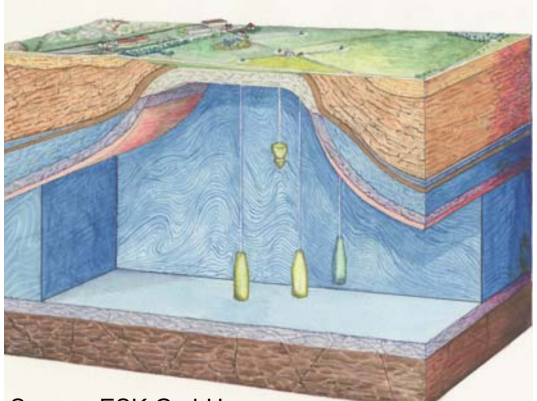
ADELE: Technical challenges



Source: GE Oil & Gas

➘ Thermal Energy Storage:

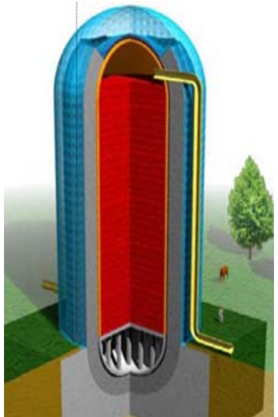
- large storage capacity , high heat rates
- effective heat transfer is essential
- pressurised containment, active cooling
- efficient insulation concept
- condensate handling
- 600 … 650 °C, 50 … 100 bar
- durability, costs



Source: ESK GmbH

➘ Adiabatic Compressor:

- Adaptation of existing components according to specific requirements
- Challenges:
  temperature and pressure level in last stages
  load change frequency



Ed. Züblin AG

➘ Salt Cavern:

- Mature technology from natural gas storage, but:
- significant higher flow rates
- larger well diameters
- large geometric volume
- increased corrosion risk

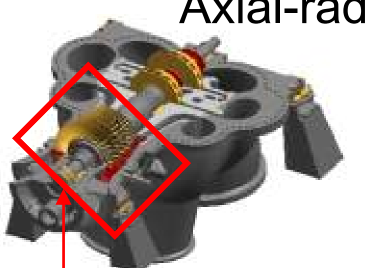
➘ Thermal energy storage and compressor: high development effort

ADELE: Compressor train

- Development based on proven solutions from GT technology and O&G compressors
- Compression requires at least two casings; train may include axial, radial, axialradial compressors
- Various configurations possible, allows adaptation to plant requirements (size, maximum temperature etc.)
- Challenges: Thermal expansion of components during transients, sealing concepts, materials

- Leverage design features from steam and GT technology

Axial-radial



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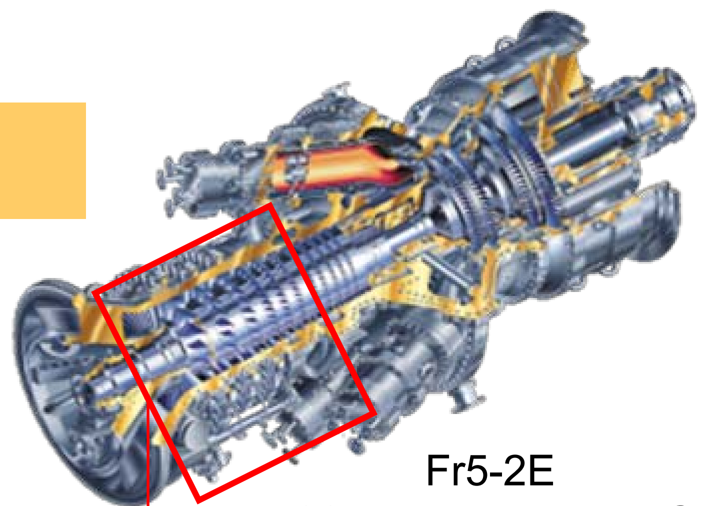
Barrel

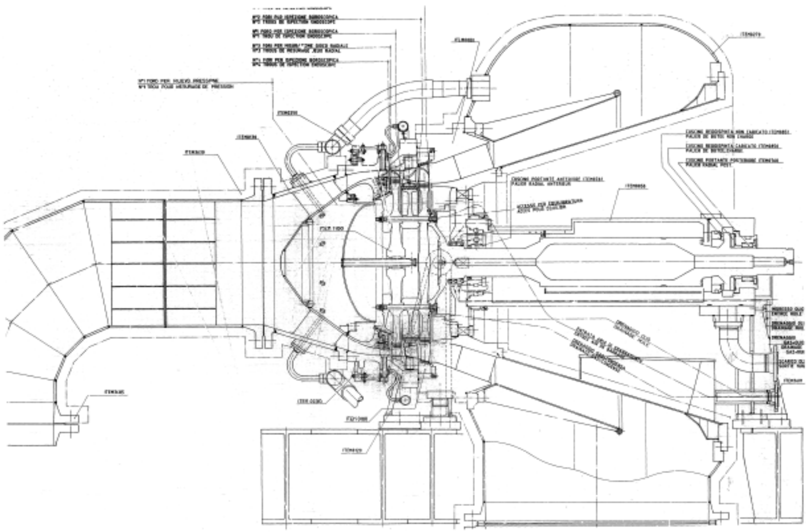


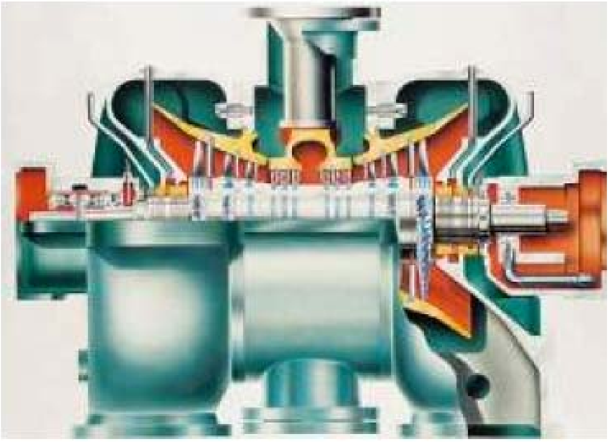
Fr5-2E
~32MW Heavy Duty GT

ADELE: Air turbine

- Adapt steam turbine and gas turbine technology to match unusual flow conditions
- Use of gas turbine features is important to allow:
  - higher efficiency
  - start-up time 5-10 min, order of magnitude faster than steam turbines
- Use of steam turbine features is important to allow:
  - Large mass flow variations typical of CAES applications
  - expander operability and control
- Both high speed (8000 rpm) and low speed (3000 rpm w/o gbx) options were analysed

imagination at work

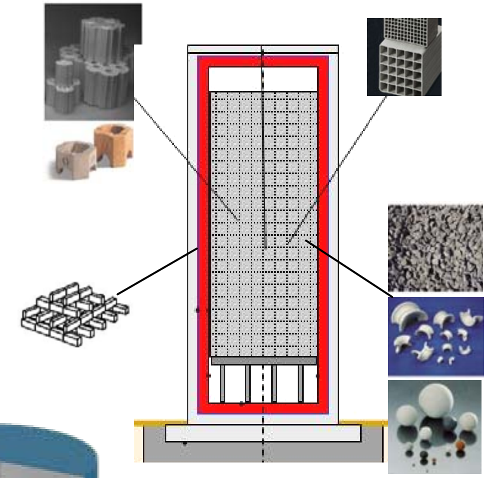


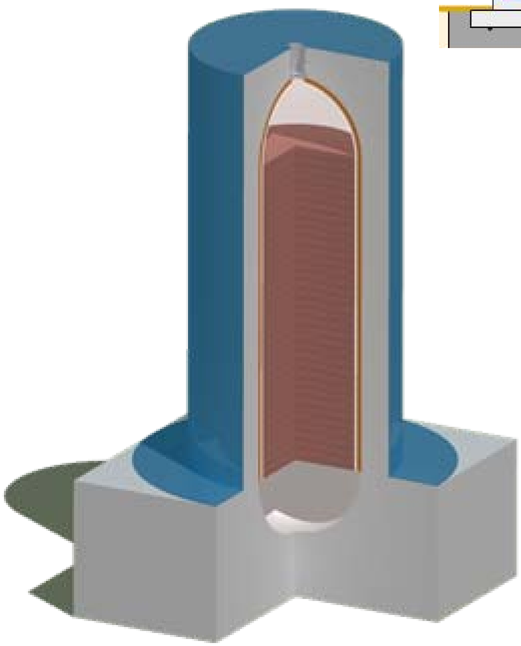


ADELE: Thermal Energy Storage

Technology based on regenerator technology

- Arrangement and type of inventory, thermal design, thermal part-load behaviour
- High-temperature insulation, Active cooling system
- Condensate handling
- Inventory materials: hot and humid atmosphere, cost-effectiveness, durability
- Material qualification: laboratory and pilot scale testing
- Pressurised concrete containment: Exceptional mechanical loads, Liner construction, Material durability, 40 yrs lifetime, Maintainability of subcomponents, Monitoring

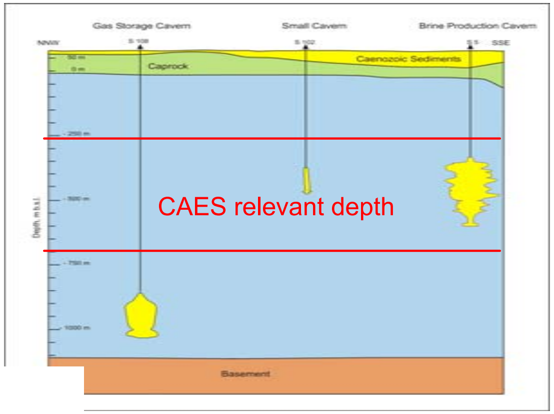


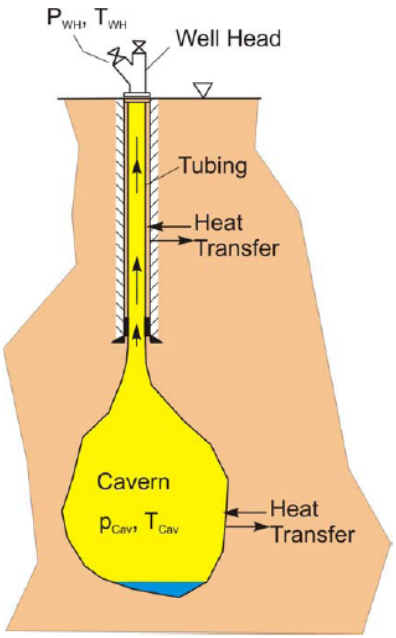


Test rig “HOTREG” for high-temperature regenerator storage at DLR

ADELE: Cavern

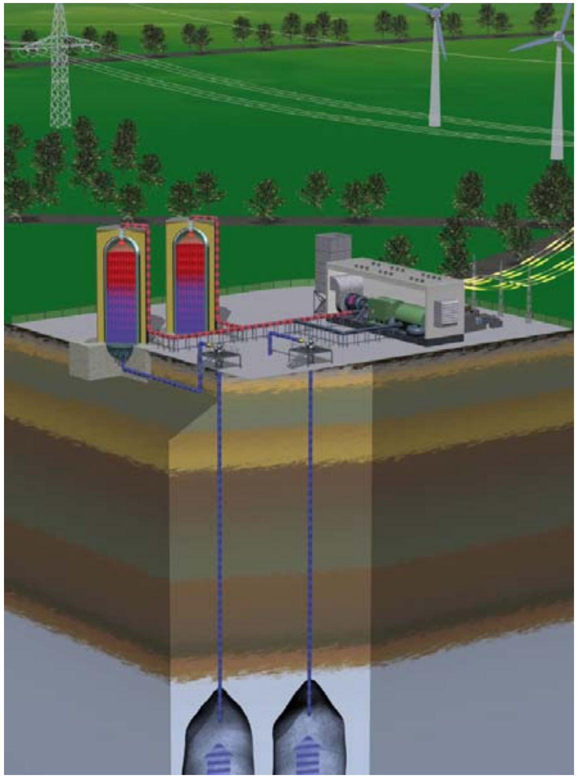
- Screening and ranking of potential salt deposits in selected countries (geology, infrastructure, legal aspects)
- Investigation of rock mechanics (cavern configuration, load scenarios, lab investigations of stress and deformation states)
- Adaptation of well completion wellhead equipment (reduction of friction losses, corrosion resistance of materials)
- Thermodynamic modelling





Summary and conclusion

- The grid integration of wind energy and other RE will raise new flexibility requirements; electricity storage is part of the solution
- Adiabatic CAES is a promising option:
  - large scale, locally emission-free, high efficiency level
  - large application potential, in particular close to offshore regions
- Component specifications demanding, but are considered feasible
- Project ADELE initiates development work, aims at preparing the demonstration of the technology



2nd CAES Conference & Workshop, Columbia University

New York, October 20, 2010

Adiabatic CAES: Opportunities and Challenges

Contact:

stefan.zunft@dlr.de

Deutsches Zentrum für Luft- und Raumfahrt e.V.
in der Helmholtz-Gemeinschaft

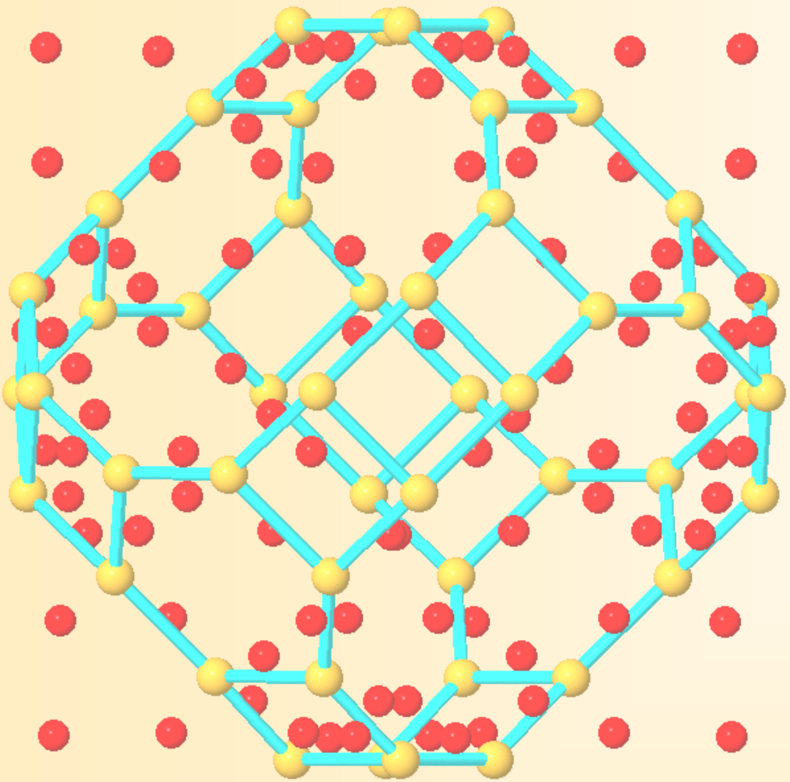
6. Adsorption-Enhanced Compressed Air Energy Storage

Timothy F. Havel, *Energy Compression Inc.*

Adsorption-Enhanced Compressed Air Energy Storage (AE-CAES) uses an adsorbent for air to reduce the volume needed to store a given quantity of compressed air at pressures well below those previously regarded as practical for CAES. This can not only free it from the geological or topographical constraints of underground or underwater air storage, but also has the potential to substantially reduce its cost compared with other forms of "surface" CAES in several ways: a) the cost of the tank needed to confine the air is reduced along with its volume; b) the cost of efficient air compressors and expanders goes down with the pressure they must handle; c) the use of an adsorbent changes the effective equation of state of the system, making it practical to operate it at essentially constant pressure by cycling the temperature instead; d) whereas existing high-pressure CAES facilities use the combustion of natural gas to reheat the expanding air, AE-CAES would need only low-temperature (ca. 100°C) heat.

Dr. Tim Havel received his PhD in Biophysics from the Univ. of California Berkeley in 1982. He did postdoctoral work at the Swiss Federal Technical Institute in Zürich and subsequently held positions at the Scripps Research Foundation in La Jolla, the University of Michigan in Ann Arbor, the Harvard Medical School in Boston and the Dept. of Nuclear Science and Engineering at MIT, where he helped to demonstrate the first prototypes of quantum computers by means of NMR. He is presently an Affiliate of the MIT Dept. of Mechanical Engineering, assisting with the development of "supersprings" based on carbon nanotubes, and the CTO and Founder of a nanotechnology-based "clean-tech" company, Energy Compression Inc.

NYSERDA CAES
Workshop (Oct. 2010)



Adsorption-Enhanced Compressed Air Energy Storage

Timothy F. Havel

Energy Compression, Inc.

tim@energycompression.com

Columbia Univ.,
New York City

What this Talk is Going to Cover

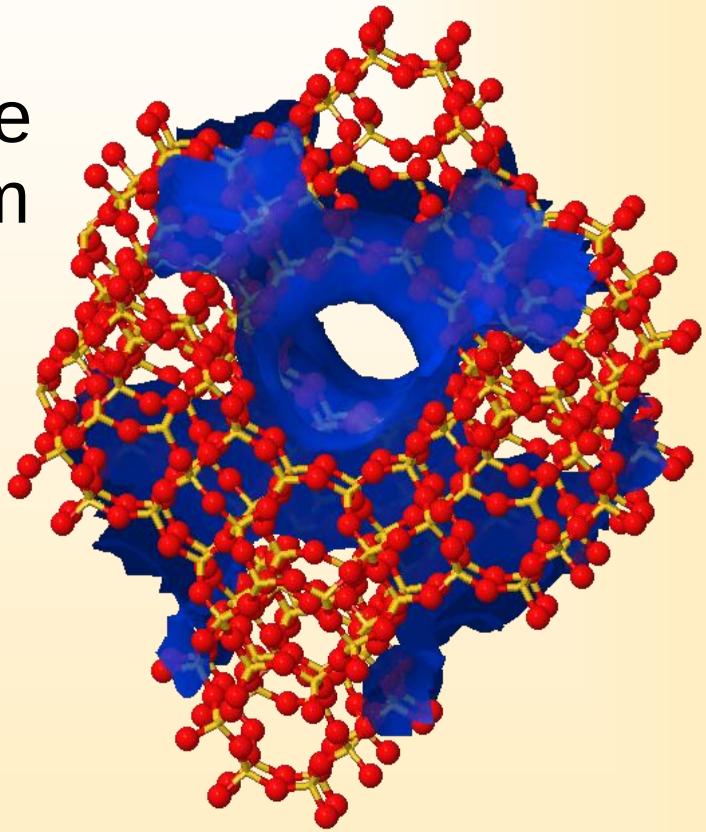
- A new kind of CAES, called *Adsorption-Enhanced CAES* (AE-CAES), which differs from conventional CAES in significant ways:
  - The “effective” equation of state is different
  - It uses a new thermodynamic cycle based on a temperature rather than pressure swing
  - It can use low-grade waste or solar heat to make up for losses (economic vs. physical efficiency)
  - It stores hot & cold as well as mechanical energy

Some Terminology I Will be Using

- Gas compression / expansion – a transduction mechanism that converts work to heat / and back
- Kinds of CAES – where does the heat of compression / expansion go to / come from?
  - Adiabatic – heat never leaves the air itself
  - Isothermal – heat goes to / comes from the ambient environment
  - Diabatic – heat goes to environment / but comes from burning a fuel (or other high-temperature source)
  - Advanced adiabatic – heat is stored and recovered

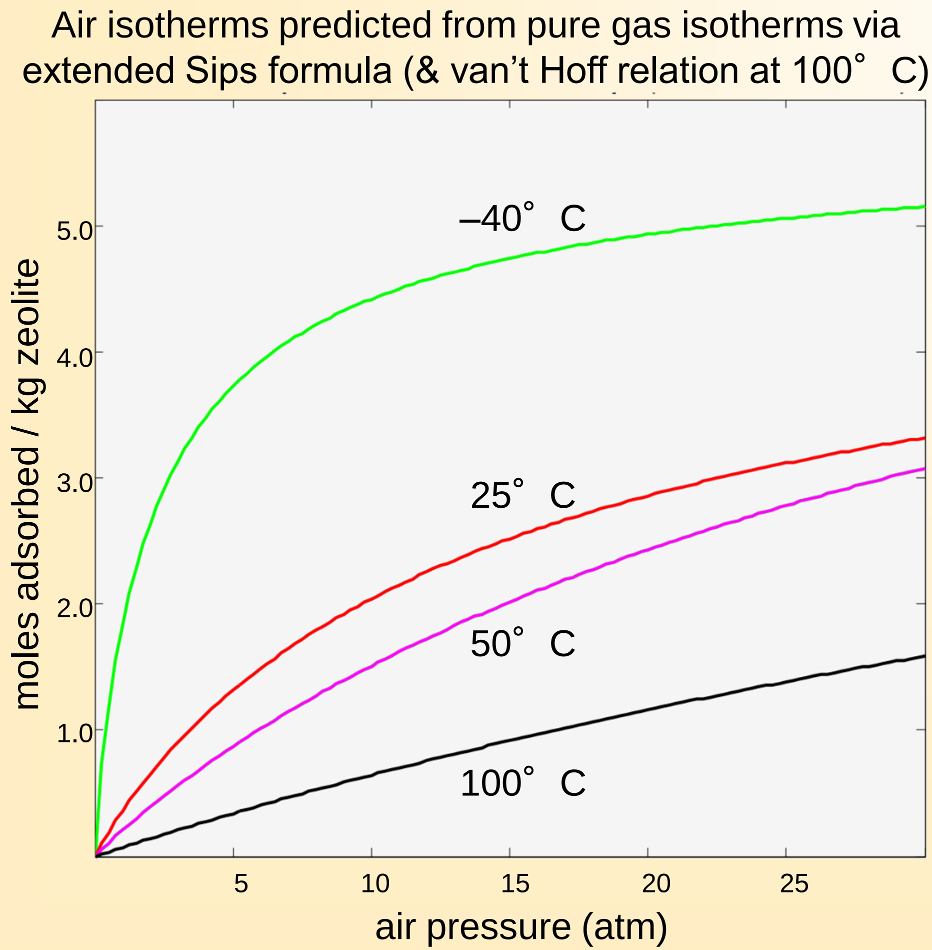
The Zeolite Minerals: *La Roca Magica!*

- Frameworks of *O*, *Si* & *Al*+*X* atoms (*X* = cation) which enclose networks of channels about 1 nm in diameter
  - Uniform channel diameter means that they serve as size-specific "molecular sieves"
- Industrially used for separation, purification & catalysis
  - And in particular, to separate nitrogen and oxygen from air



Picture produced by web apps at Intnl. Zeolite Assoc., http://www.iza-online.org

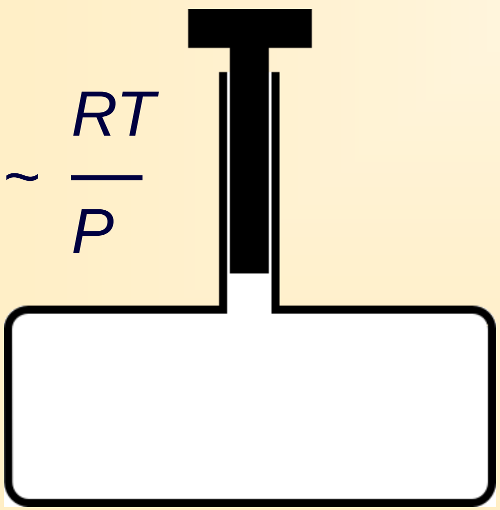
Zeolites Can Soak Up 50X their Volume in Air



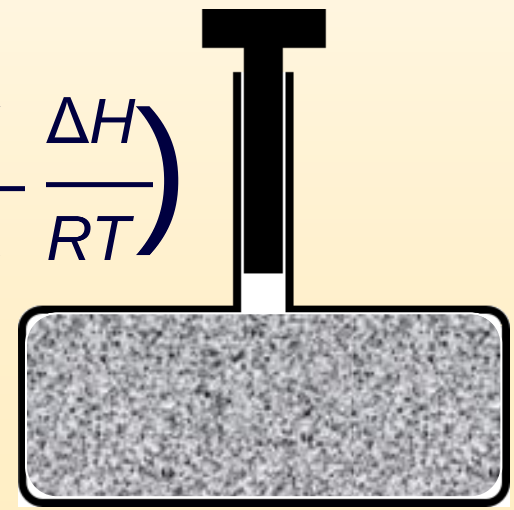
In Effect, We Get a New Equation of State for Air

- At least at low coverage and for a small change in volume, we can say the that dependence on temperature goes from linear to exponential (van't Hoff relation)

$$V \sim \frac{RT}{P}$$



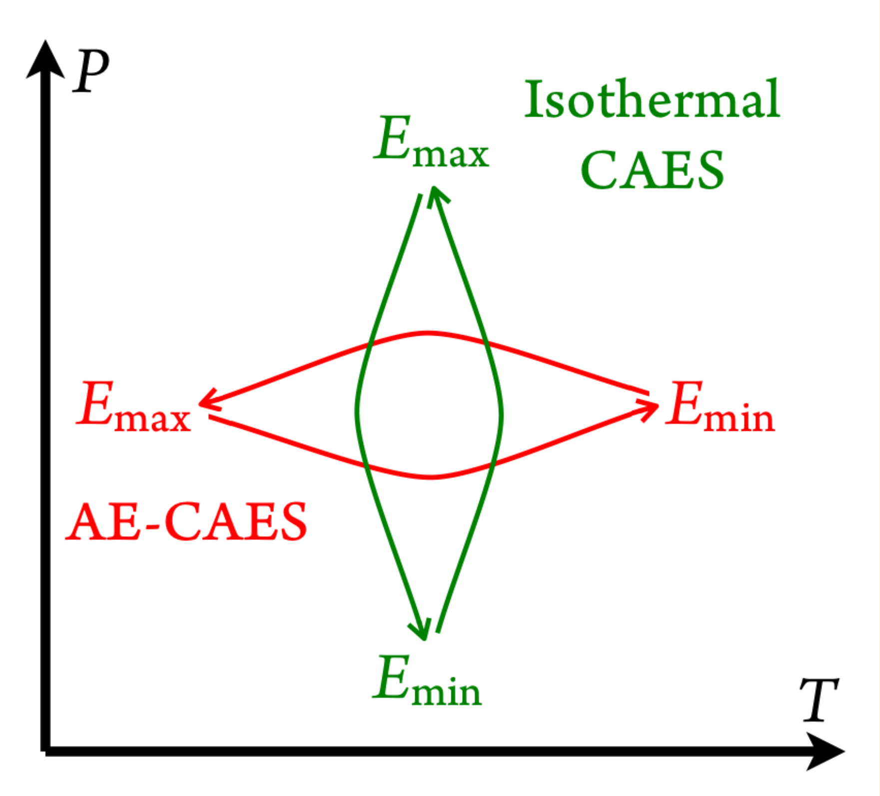
$$V \sim \frac{RT}{P} \exp\left(-\frac{\Delta H}{RT}\right)$$



Temperature Swing vs. Pressure Swing

- This strong dependence on temperature allows the pressure to be kept largely constant by varying the temperature instead:
  - we call the resulting thermodynamic cycle a ***temperature swing***
- Advantages of zeolites fall off as pressure increases due to saturation effects
  - so we use a low (10-30 bar) and constant pressure

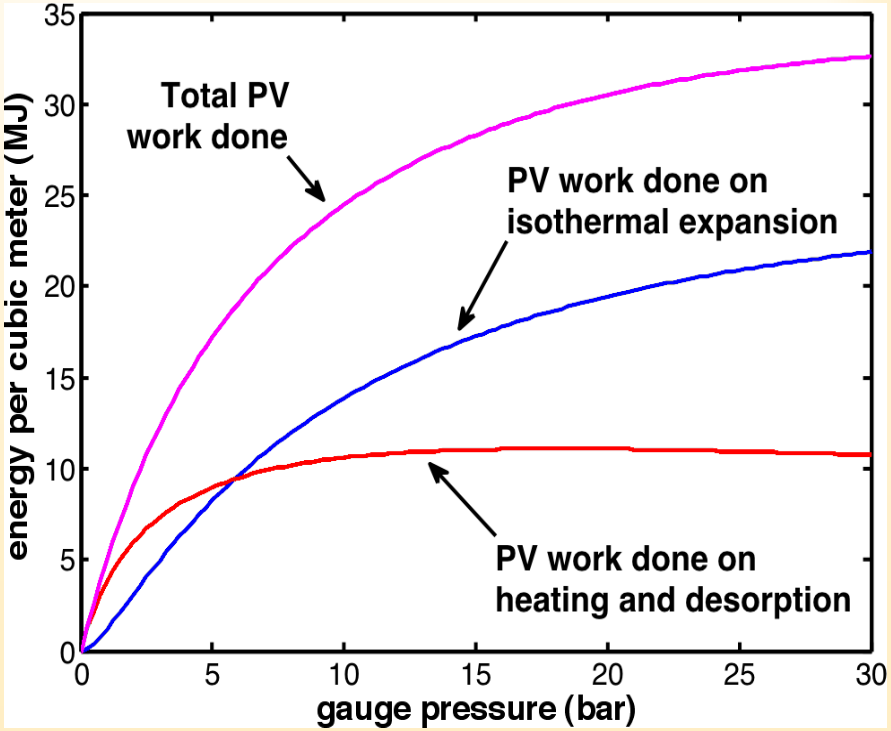
How a temperature swing differs from the usual ("isothermal") pressure swing



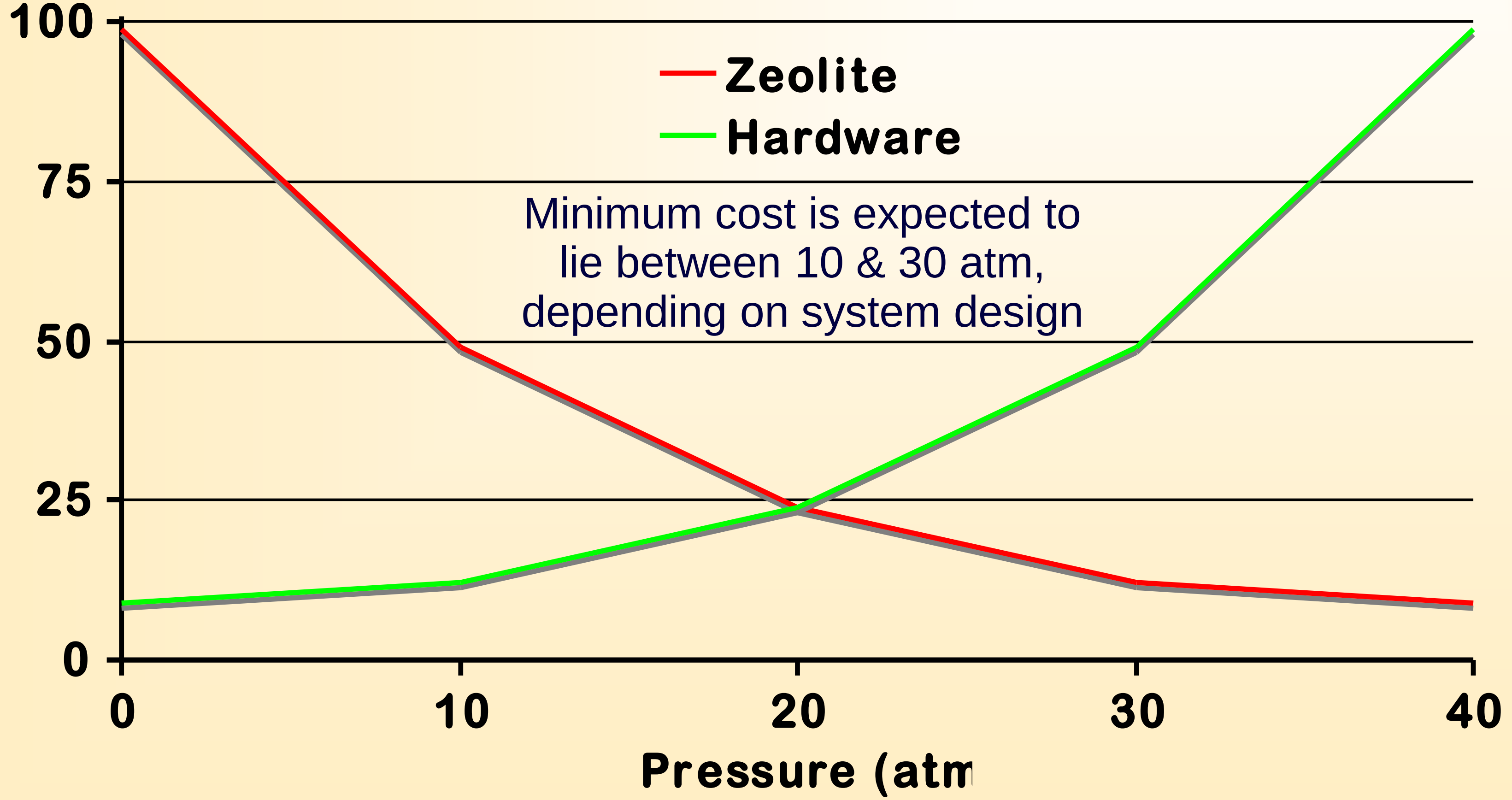
Low Energy Density, but Safe & Green as Can Be

- Weakness:
  - ~ 1/10th the energy density of a lead acid battery
- Strength:
  - very safe: a tank filled with air + zeolite at our low pressures won't explode even if machine gunned full of holes
  - very green: nothing in it but rock, air, water and other natural refrigerants

Energy Density vs. Pressure with a [−40° C, +100° C] Temperature Swing:



The Great Operating Pressure Tradeoff



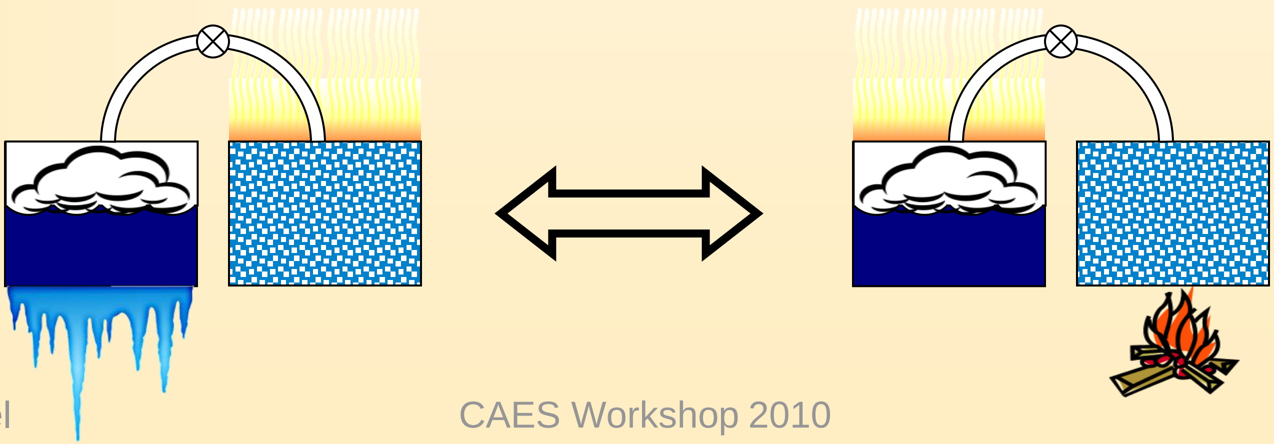
Heat: Store It, Harvest It, or – Make Use of It?

- Depending on the operating pressure,
  - the heat generated by the exothermic process of adsorption may exceed the heat of compression
- Given a temperature swing > 30° C or so,
  - the sensible heat taken from the zeolite bed will be even larger yet (assumes heat capacity ~1 kJ / kg-K)
- Pure energy storage would require all this heat to be stored and recovered ($$$) but
  - low-grade heat is not hard to come by, and many of the heat transfers needed will even be spontaneous at STP

Harvesting Heat to Cool Zeolite when Charging

ENERGY COMPRESSION

- ✯ Adsorption of a refrigerant can drive evaporative cooling, transferring the heat to the adsorbent
- ✯ Adsorbent can later be regenerated by heating it to drive refrigerant off – no mechanical energy needed
- ✯ Common adsorbate + adsorbent examples include
  - ➢ water + silica gel or zeolite, methanol or ammonia + activated carbon or activated carbon fiber



Synergy with Diurnal Wind Power Levelizing

- Wind blows more at night when the power is not needed
  - while during the day we can get the heat we need from (noncon-centrated) solar most of the time (even in cold climates), so …

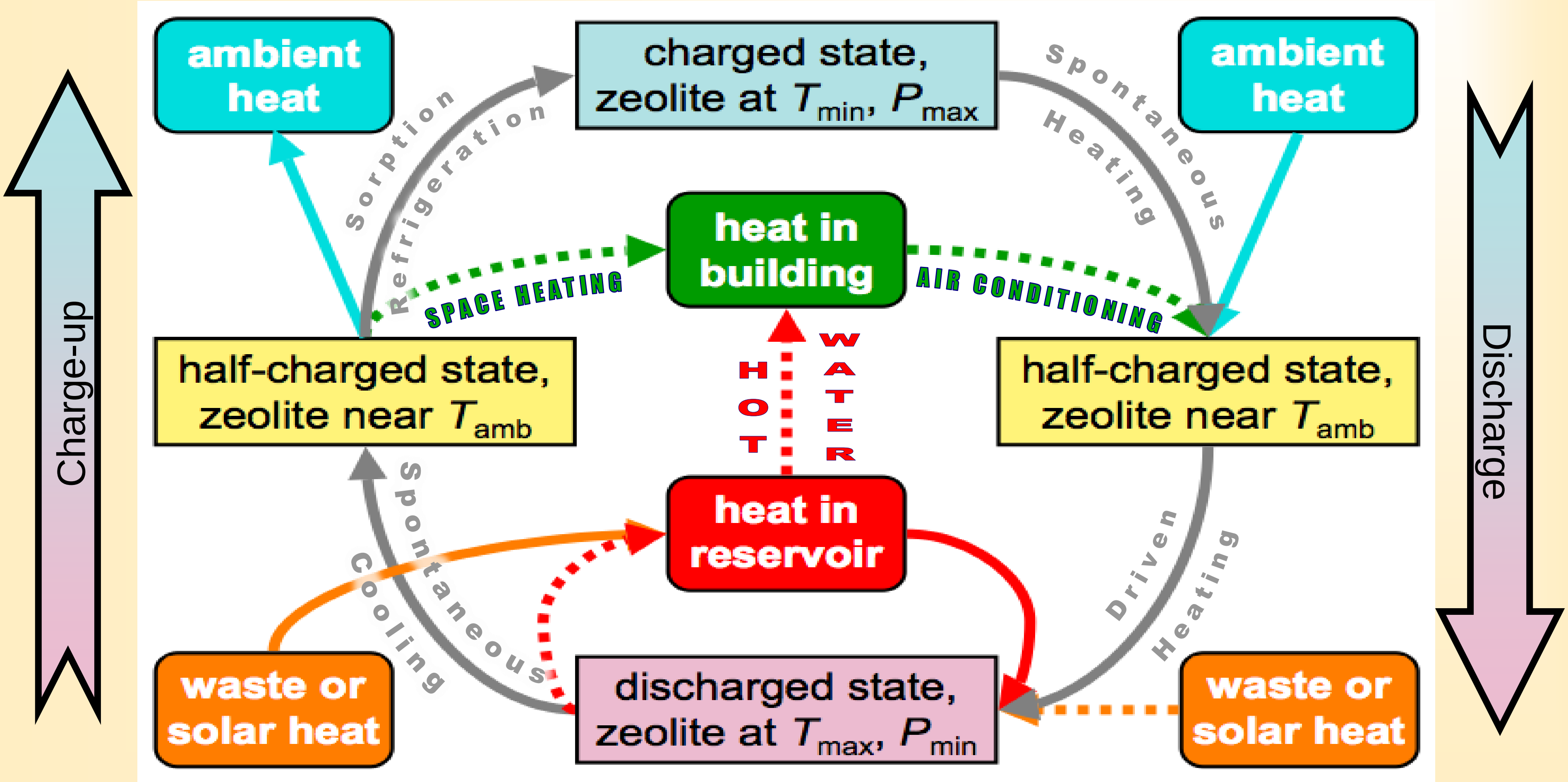
During the night, use wind power to compress air and an adsorption refrigerator to cool the zeolite

During the day, use solar heat to promote discharge of the air and to regenerate the refrigerator's adsorbent

Don't Like Solar Thermal? We Could also Burn Gas

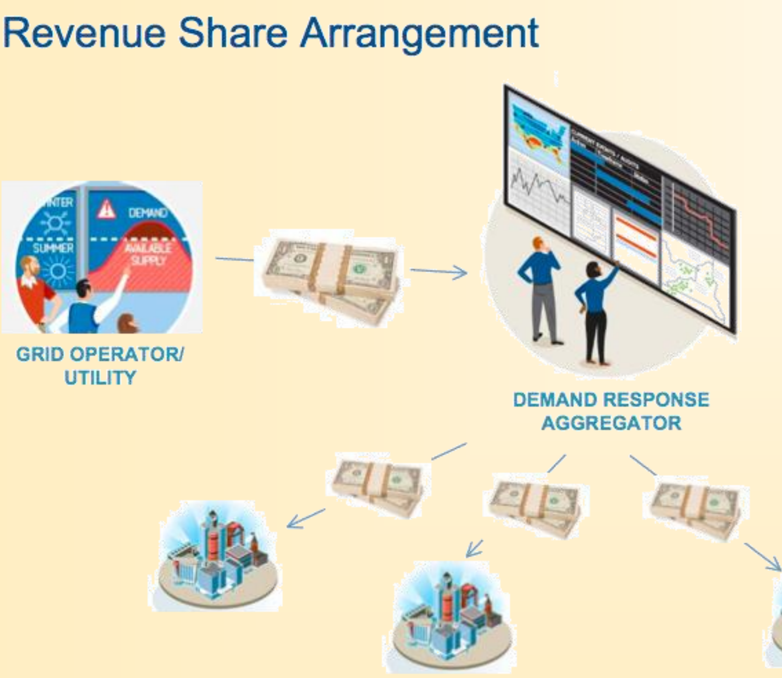
- The air could be used (perhaps with a bit of additional compression) to turbo-charge a combustion turbine as in diabatic CAES
- While the exhaust heat from the turbine is used to fully desorb the air (and regenerate the adsorbent of an adsorption refrigerator)
  - the economics of this combination need further study (collaboration, anyone?)

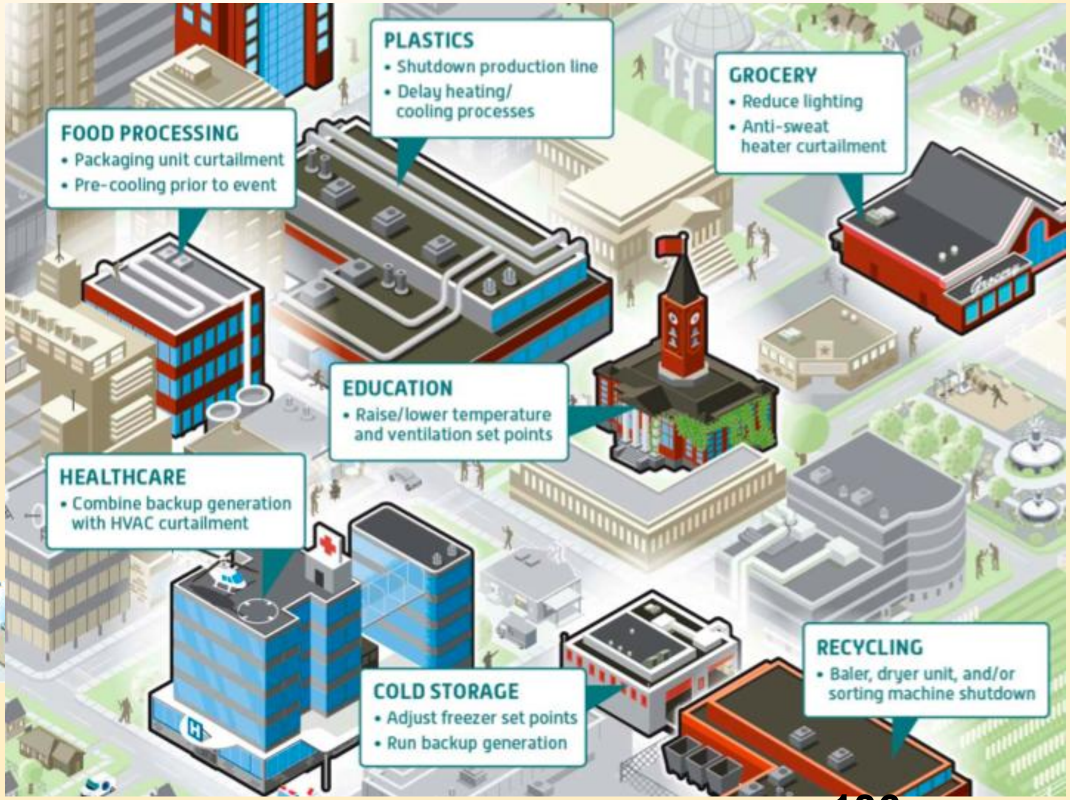
Using the Heat & Cold for HVAC in Buildings



Synergies with Demand Management Programs

- ✯ Pays participants to cut power consumption upon request
  - ➢ and they usually coast thru the reduction period on thermal inertia





Figs. Courtesy of EnerNOC

Summary and Prospects

✯ Adsorption-Enhanced CAES:

- renders CAES freely locatable (not tied to the site of an underground cavern or aquifer)
- lowers the cost by lowering the pressure needed to attain a reasonable energy density
- can use low-grade heat instead of a gas-fired turbine for reheat (as well as recool), and so can be carbon neutral
- timing of diurnal storage cycle’s heat transfers offers good synergies with wind power, demand management, and potentially even net zero energy building operation

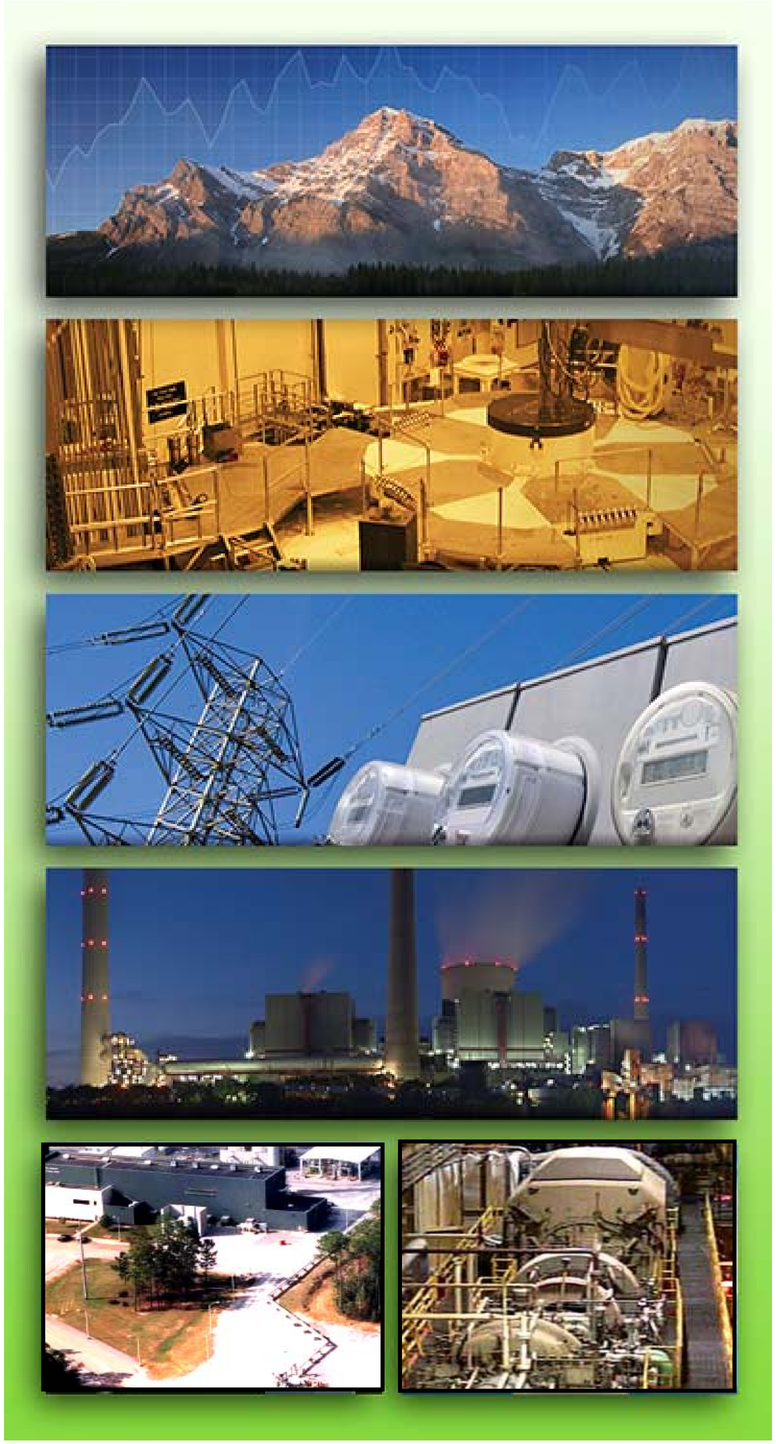
7. Insights from EPRI's CAES Economic Benefit-Cost Analyses

Robert B. Schainker, William Steeley, *EPRI*

Economic value justification to build energy storage plants are often focused on arbitrage benefits: buying low and selling high. However, the energy arbitrage benefit stream is only one of a number of potential benefit streams provided by a CAES plant—perhaps not even the most significant benefit stream. This paper summarizes a number of EPRI benefit-to-cost analyses on CAES plants, with a special focus on identifying a full set of benefit types CAES plant offer and how that these benefit types are quantified and then compared to a CAES plants capital costs. As such, this type of analysis is useful to utility decision makers when making CAES plant "build" decisions. The types of benefit types investigated, beyond arbitrage benefits, include capacity credit, ancillary services (including frequency regulation, spinning reserve, ramping, VAR support, and black-start capability), renewable support, and CO_2 reduction benefits. The paper will conclude with estimates (high and low) for each benefit type based on a wide set of EPRI utility analyses.

Dr. Robert Schainker is Senior Technical Executive in the EPRI Power Delivery and Utilization Sector. His research activities cover energy storage, generation and transmission technologies with special focus on compressed air energy storage, battery energy storage, strategic planning, electric grid dynamic stability, transmission substations, high voltage power flow controllers, transformers, and power quality.

William (Bill) Steeley is Senior Project Manager in the Energy Storage and Distributed Energy Resources Program at the Electric Power Research Institute. His responsibilities include development of several high profile projects in the Energy Storage and Distributed Generation Program as well as in the CAES Demo area. His research areas include: energy storage technology assessments & evaluations, economic analyses, field demonstration projects, utility case studies and integration of energy storage in the emerging smart-grid. A major thrust of his work has centered on the proper electrical interconnection and integration of distributed generation and energy storage systems into the electric utility T&D system.



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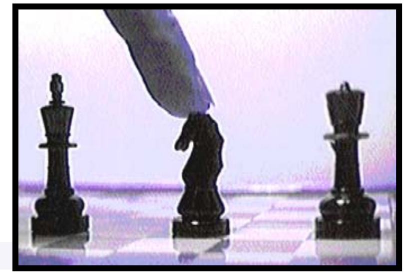
Insights from EPRI's CAES Economic Benefit-Cost Analyses for 2nd CAES Conference & Workshop

Prepared by:
Dr. Robert B. Schainker
EPRI Senior Technical Executive, and
William J. Steeley
EPRI Senior Project Manager
Vanessa MacLaren-Wray
The Resource Planning Group

October 20, 2010

CAES Plant: Economic Benefit Types
(Part 1 of 2)



- **Arbitrage Benefit***
  - **Large to Small: Depends On Assumptions for Future Prices of Off-Peak Energy (which mostly depends on wind resource forecasts) and On-Peak Energy (which mostly depends on gas fuel price forecasts)**
- **Capacity Credit Benefit***
  - **Large: Credits given every hour (24 x 7)**
  - **CAES plants in most utility-EPRI studies run many more than four hours/day**
- **"Ancillary Services" Benefits***
  - **Large: Each Independent/Regional Grid Operator has their own specific definitions, prices, and developing market**
  - **Types of Benefits**
    - **Regulation (for Frequency and/or Area Control Error): Large Benefit**
    - **Spinning Reserve (Synchronous/Non-Synchronous): Medium Benefit**
    - **Ramping (Up and/or Down): Large Benefit - Particularly in the Future**
    - **VAR Support: Small to Medium Benefit**
    - **Black Start Capability: Small Benefit**

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* Definition of Benefits given in Appendix

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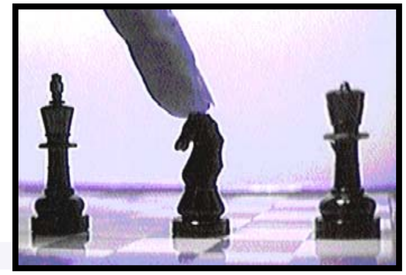
CAES Plant: Economic Benefits Types
(Part 2 of 2)



- **Renewable Benefits: Large, but challenging to quantify**
  – **Smoothes/dampens power fluctuations**
  – **Reduces up/down ramping problems**
  – **Enhances penetration of wind / solar generation resources**
- **Reduced CO_2 Emissions**
  – **Low to medium, depends on source of charging power**
  – **Dollar benefit depends on CO_2 forecasted prices (USA Climate Bill not finalized yet, but European CO_2 price/ market is already in place)**

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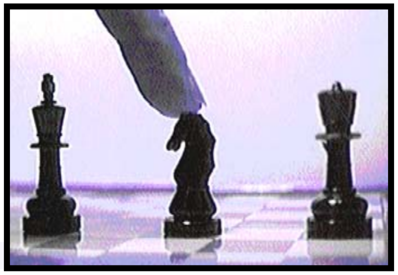
Benefits: Not All Benefit Types Are Additive, At Same Time



Benefits Are Additive For Only That Portion of Plant MW Capacity Not Being Used To Obtain Other Types of Benefits

- Arbitrage
- Capacity Credit
- Regulation
- Spinning Reserve
- Ramping
- VAR Support *
- Black Start
- Renewables
- CO_2 Credits

---

*VAR support occurs when compressor motor is used as synchronous condensor and when expander/CT generators are used as synchronous condensors when plant is in generation mode.

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Benefits Depend On Several Factors (Part 1 of 2)

Note: Benefit Priority Order Depends On Utility Specific Data

- **Fuel Price Projections**
  - Impacts peak electricity prices and resulting plant revenue from different effects on-peak vs. off-peak prices
  - In general, as fuel price increases the overall plant benefits increase since the arbitrage benefits are larger than the CAES plant operational cost increase
- **Electricity Price Projections**
  - Impacts price "spread" between on-peak and off-peak prices
- **Generation Mix (In particular, wind generation MW projections)**
  - As more wind comes on-line, off-peak prices get lower and CAES plant arbitrage benefits increase.
  - In some cases, wind off-peak energy cost is negative; thus, assumed wind MW projections greatly impact CAES plant benefit projections
- **Load Shape, Weekly/Seasonal/Yearly Changes**
  - Impacts extent and timing of off-peak charge vs. on-peak discharge
  - New generation assumptions (nuclear, coal, combined cycle, simple cycle) greatly impact CAES plant projected benefits

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Benefits Depend On Several Factors (Part 2 of 2)

Note: Priority Order of Benefits Depend On Utility Specific Data

- **Transmission Constraints**
  - Used to select "best" location for plant
- **Transmission / Substation Upgrade Deferral Opportunity**
  - Good plant locations, if possible, are current transmission bottlenecks
- **Price Signals from ISO/RTO Grid Operator**
  - Dramatically impact primary benefits & ancillary service benefits
- **Cost of Capital (Utility Capital "Fixed Charge Rate")**
  - Needs to reflect the true cost of capital.
  - Upon multiplying by plant capital cost, sets the minimum value of benefits needed to justify plant construction
- **Capital Cost of CAES Plant**
  - Upon multiplying capital cost by Fixed Charge Rate, sets the minimum value of benefits needed to justify plant construction

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Advanced CAES Plant Has Attractive Operational Performance Characteristics

- Operates in both the charge and discharge modes simultaneously with a “flat” heat rate curve (see Appendix slide for details).
  - This enables the plant to obtain spinning reserve and ramp up/down benefits while at part load.
- Plant is a flexible resource during the charge and discharge mode
  - In particular, at part load operation the plant provides a combination of arbitrage, frequency regulation and ramping benefits
- Ramp rate is about +/- 40% minute
  - For example, a 300 MW Advanced CAES Plant that is synchronized to the grid, can change output power at +/- 120 MW’s per minute. This makes the plant effective at performing up-ramps and down-ramps as wind power fluctuates, and/or, as market price signals change.

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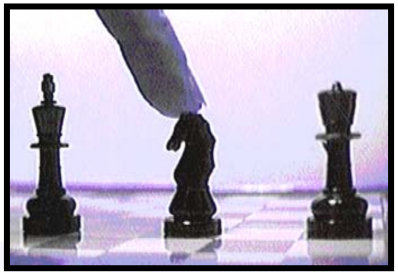
Benefits Discussion



- **Value Proposition for CAES**
  - Requires properly adding benefits from several different types of applications and/or duty cycles

- **Insight:**
  - As more wind gets installed, the off-peak price (i.e., the Locational Marginal Price) for charging energy gets lower, which increases the arbitrage benefits by widening the spread between on-peak and off-peak prices.

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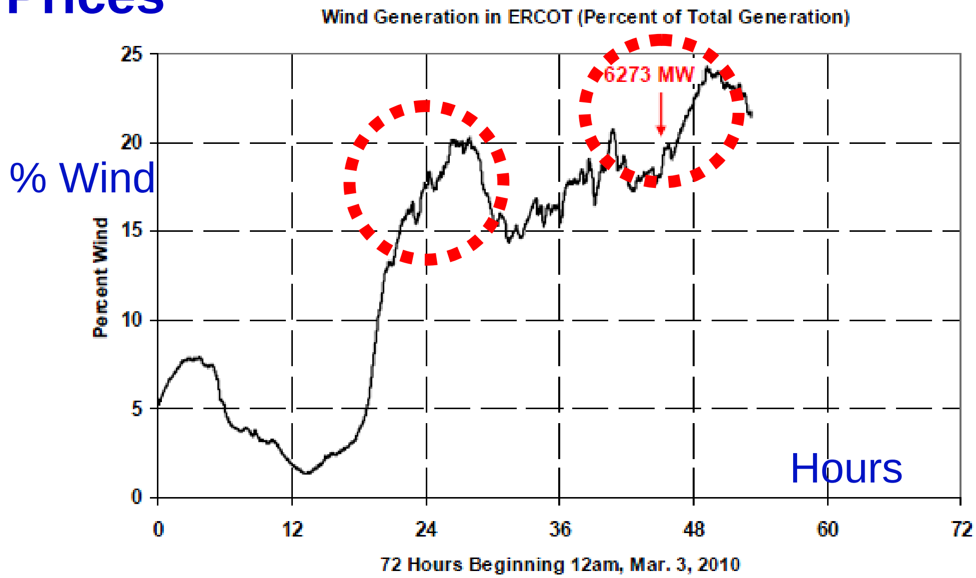
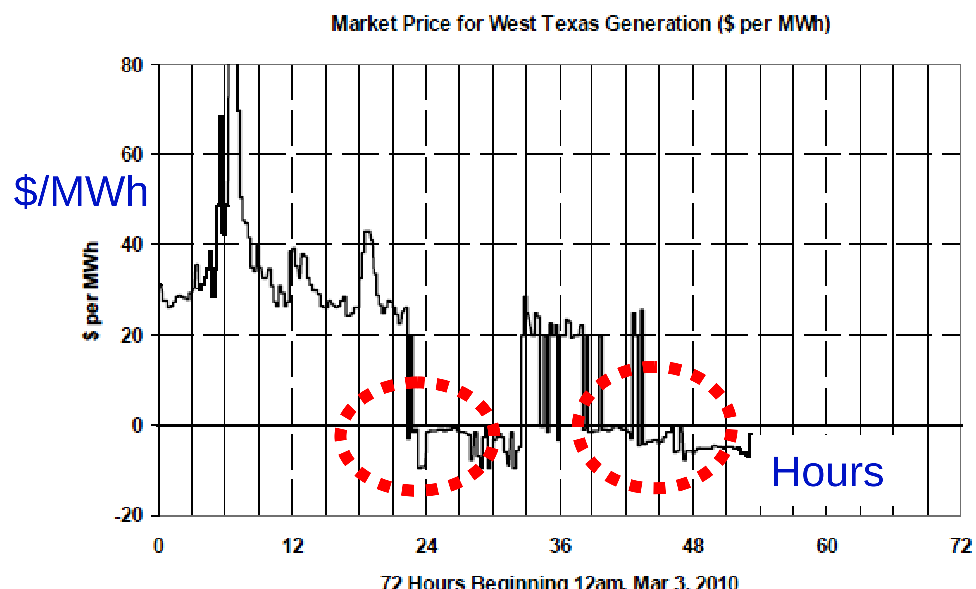
Impact of Wind Penetration: Lower Off Peak Hourly Marginal Electricity Prices

- As wind power output increased on March 3, 2010, ERCOT's electricity market prices went negative. This situation will occur more frequently as wind generation grows in Texas
- This negative price situation is also occurring in other US regions
- Recommendation: Give special attention to forecasting off-peak marginal electricity prices





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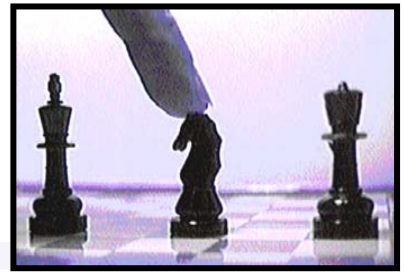
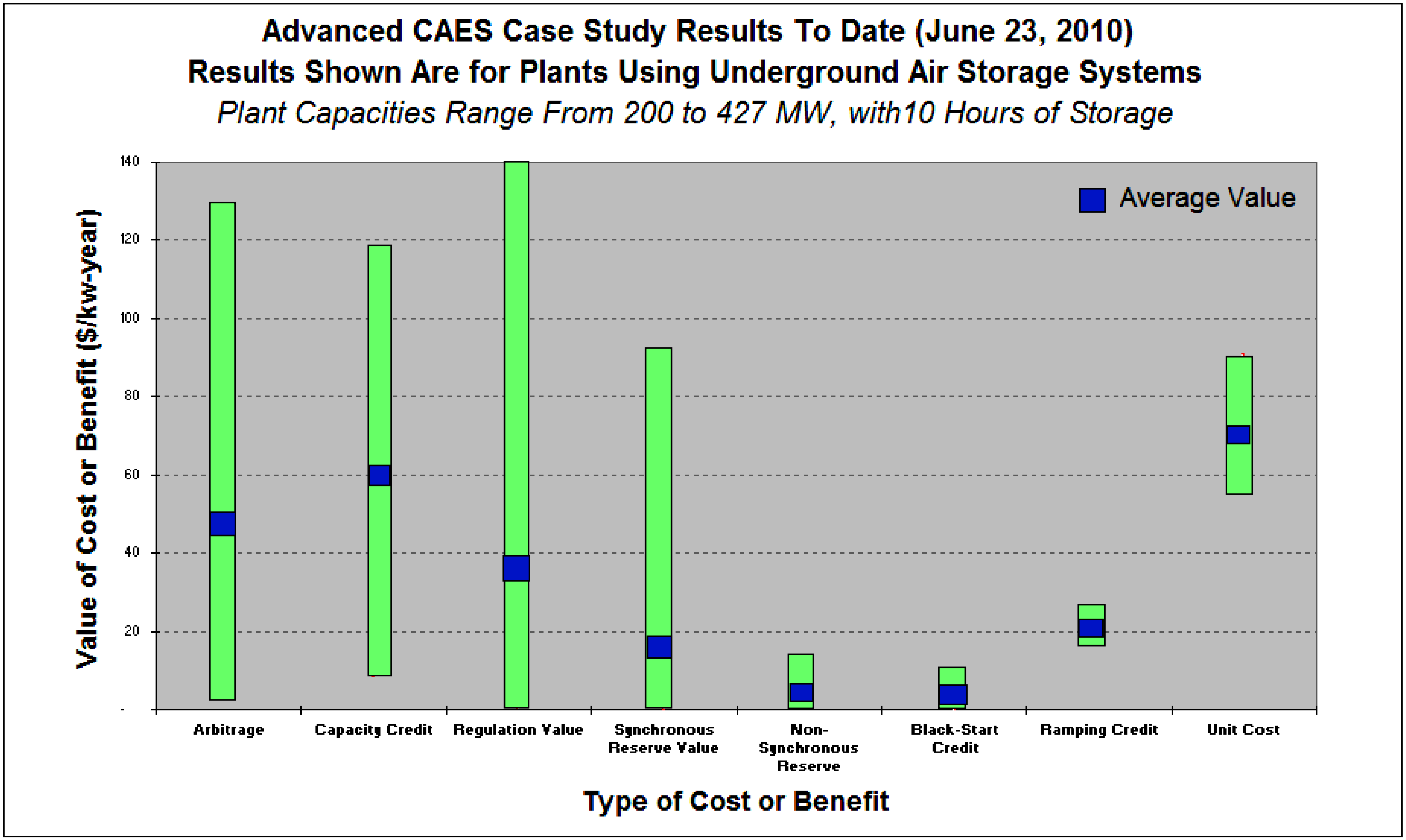
Summary of Benefit Value Ranges and Plant Cost Ranges





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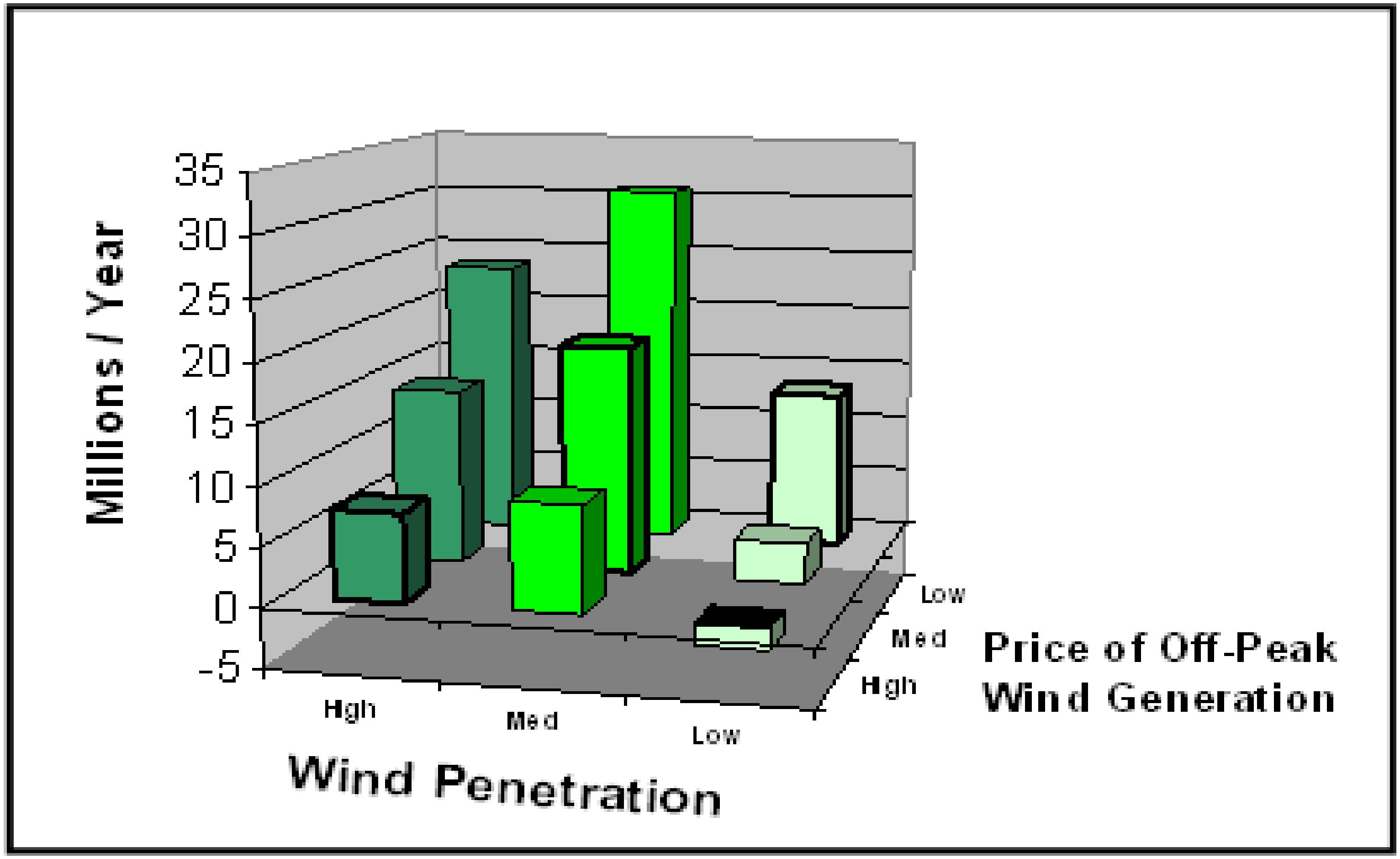
Anticipated Savings From CAES Plant Integrated with Wind Generation Resources



Key Assumptions: NE Utility Generation Mix; Cost of Capital : 10%, Study Period: 20 Yrs

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CAES Economic Benefit Types: Definitions

Arbitrage: CAES plant cost savings from using/purchasing low-cost electric energy (e.g., during off-peak night-time periods from wind generators), storing this energy and selling it back to the grid at relatively higher-price time periods (e.g., during on-peak time periods in the afternoon).

Capacity Credit: If online for a minimum, specified number of hours per day, CAES plants can provide MW capacity benefits, which can be valued at either the market price for firm capacity, in an ISO environment, or the cost of an alternative generation resource capacity, in a unit commitment-unit dispatch real time grid operation environment.

Ramping (Up-Ramp / Down-Ramp): CAES plants can obtain ramping credits if their unused capacity is available in load shape shoulder hours (e.g., during the diurnal ramp-up or ramp-down time periods), and/or can replace or reduce the ramping of other generation plants.

Reserve Capacity (Spinning/Synchronous and/or Non Synchronous): CAES provides MW spinning reserve capacity credits whenever the plant can be put in charging or discharging in less than a specified time period (e.g., 10 minutes). In the charging mode, spinning reserve MW credits are available from the MW charge level to the zero MW idle level. In the discharging mode, spinning reserve MW credits are available from the zero MW idle mode to the maximum MW discharge MW level. Also, In the discharging mode, spinning reserve credits are available when the plant is at part load; namely, the MW difference between full discharge capability and the actual MW part load discharging level in that hour.

Black Start: CAES can reach full output from an off-line state in about seven minutes, qualifying for black-start credits, where applicable.

Frequency Regulation / Regulation: When on-line, CAES unit operation is flexible enough to assist with maintaining frequency on the system and/or reducing Area Control Error (ACE).

VAR / Voltage Support: CAES plant reactive power credits can be obtained by operating the compressor motors and/or the expander generators as synchronous condensors, providing + / - VAR's to the grid.

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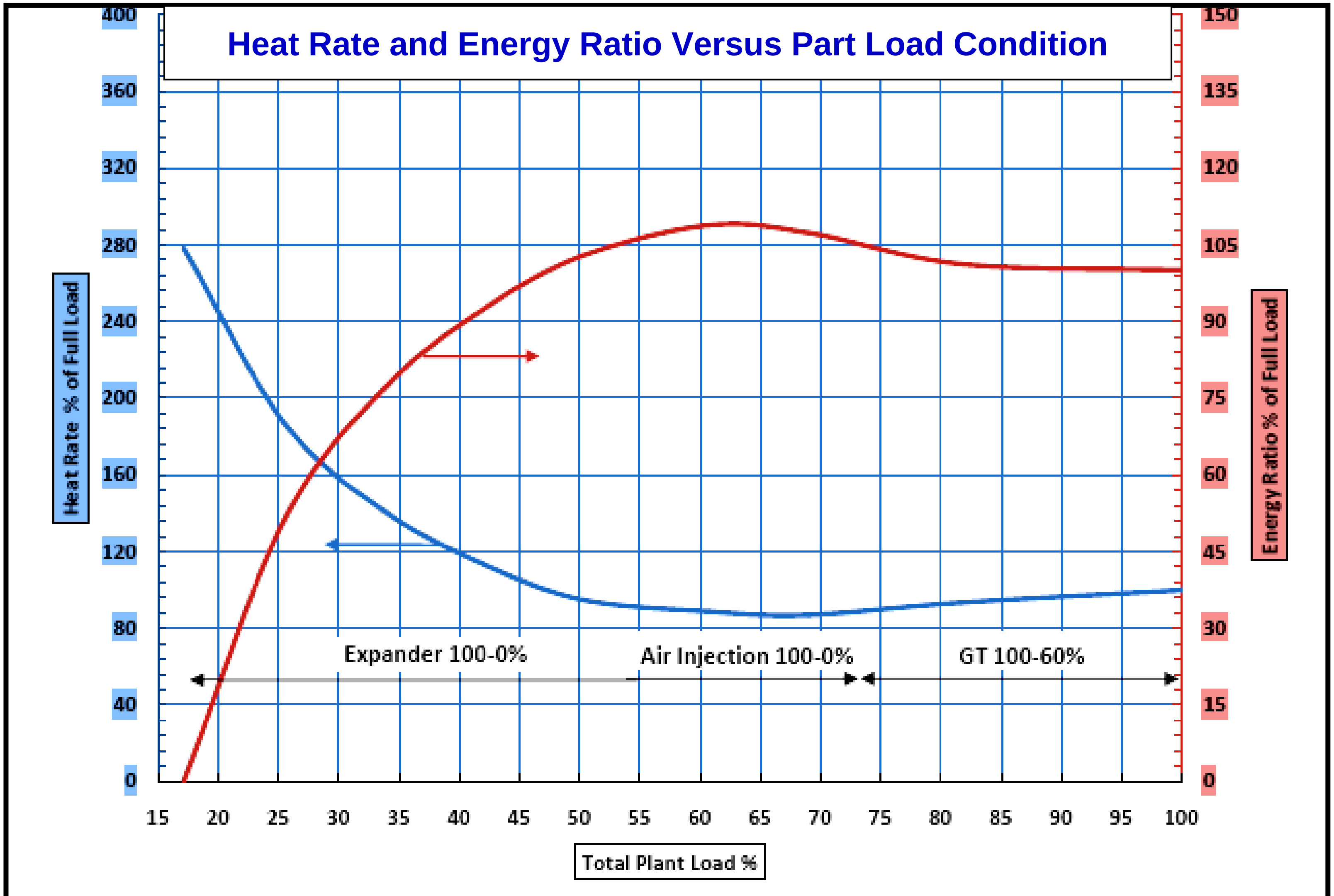
CAES Plant: Part Load Heat Rate and Energy Ratio As Plant MW Power Output Changes (Estimates)



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8. New York Power Authority's Investigation of Compressed Air Energy Storage in New York State

Li Kou, Guy Sliker, *New York Power Authority*

Robert Schainker, *EPRI*

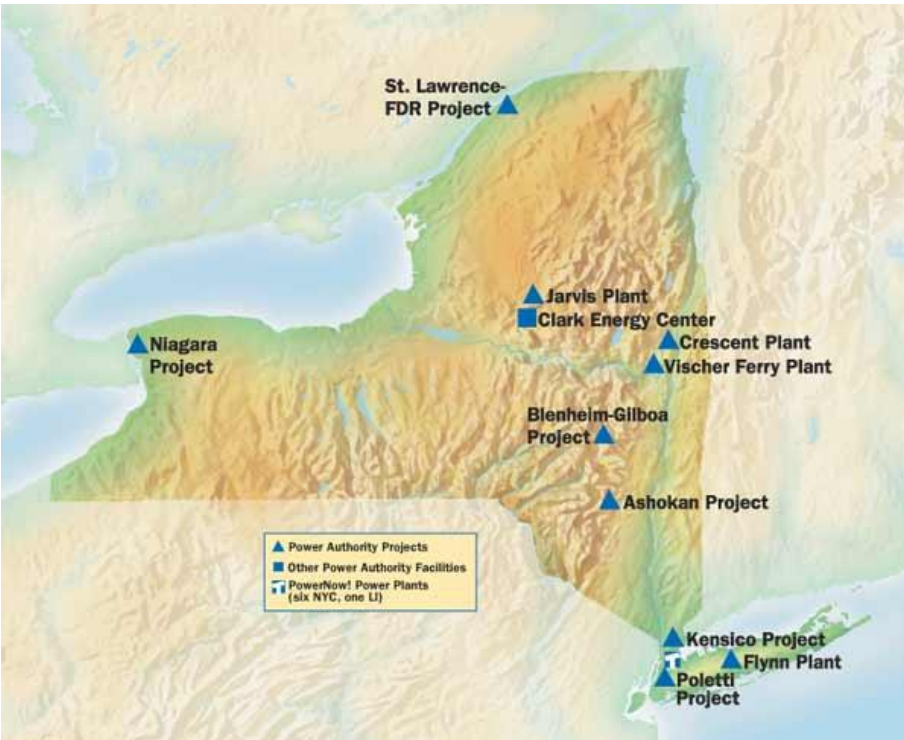
New York Power Authority (NYPA) in collaboration with Electric Power Research Institute (EPRI) performed a feasibility study of a utility-scale underground compressed air energy storage (CAES) facility in New York State. The proposed plant has 300MW generation capacity with 10 hours storage capacity. The feasibility study evaluated the engineering, economics and geologic siting of such a plant. A second generation CAES plant design was chosen which avoids the need for an expensive, high-pressure combustor, that in turn helps reduce CO_2 emissions per kWh. It is estimated that the second generation CAES design will be about 25 – 30% less expensive in capital and 10% less in operational costs than a first generation design. Based on NYPA's forecast on fuel costs, load profiles, and hourly electricity prices, it is shown that arbitrage benefits alone serve to offset capital costs for a 300MW CAES plant in NYC region. However, for the Central region, ancillary and capacity benefits will be critical components of the benefit mix. The focus of the present study is on salt mine opportunities in NYS.

Dr. Li Kou is the Senior Research and Technology Development Engineer for New York Power Authority. Dr. Kou joined NYPA in August 2007 and has been working on evaluation and implementation of various technologies, including solar, distributed wind, energy storage, biomass and waste-to-energy. Prior to joining NYPA, Dr. Kou worked for Siemens Power Generation on research and development of Solid Oxide Fuel Cells for 6 years. She holds a Ph.D. and M.S. degree in Chemical Engineering from Illinois Institute of Technology and holds a B.S. in Chemical Engineering from Zhejiang University, China.

New York Power Authority's Investigation of Compressed Air Energy Storage in New York State

Li Kou, Guy Sliker, New York Power Authority
Robert Schainker, Electric Power Research Institute
2nd CAES Workshop, Columbia University
October 20, 2010

New York Power Authority



- NYPA owns and operates **17 power plants** and **1,400 circuit-miles of transmission** lines, supplying one-fifth of New York State's electricity.
- NYPA **energy efficiency services** help schools and other public facilities **conserve power** and **cut energy costs.**
- NYPA is New York State's **leading supplier of renewable power**, investing in life extension and modernization of its hydropower resources as well as wind power, solar energy, fuel cells and other advanced energy technologies.

NYPA-EPRI Study on Advanced CAES Project – Objective

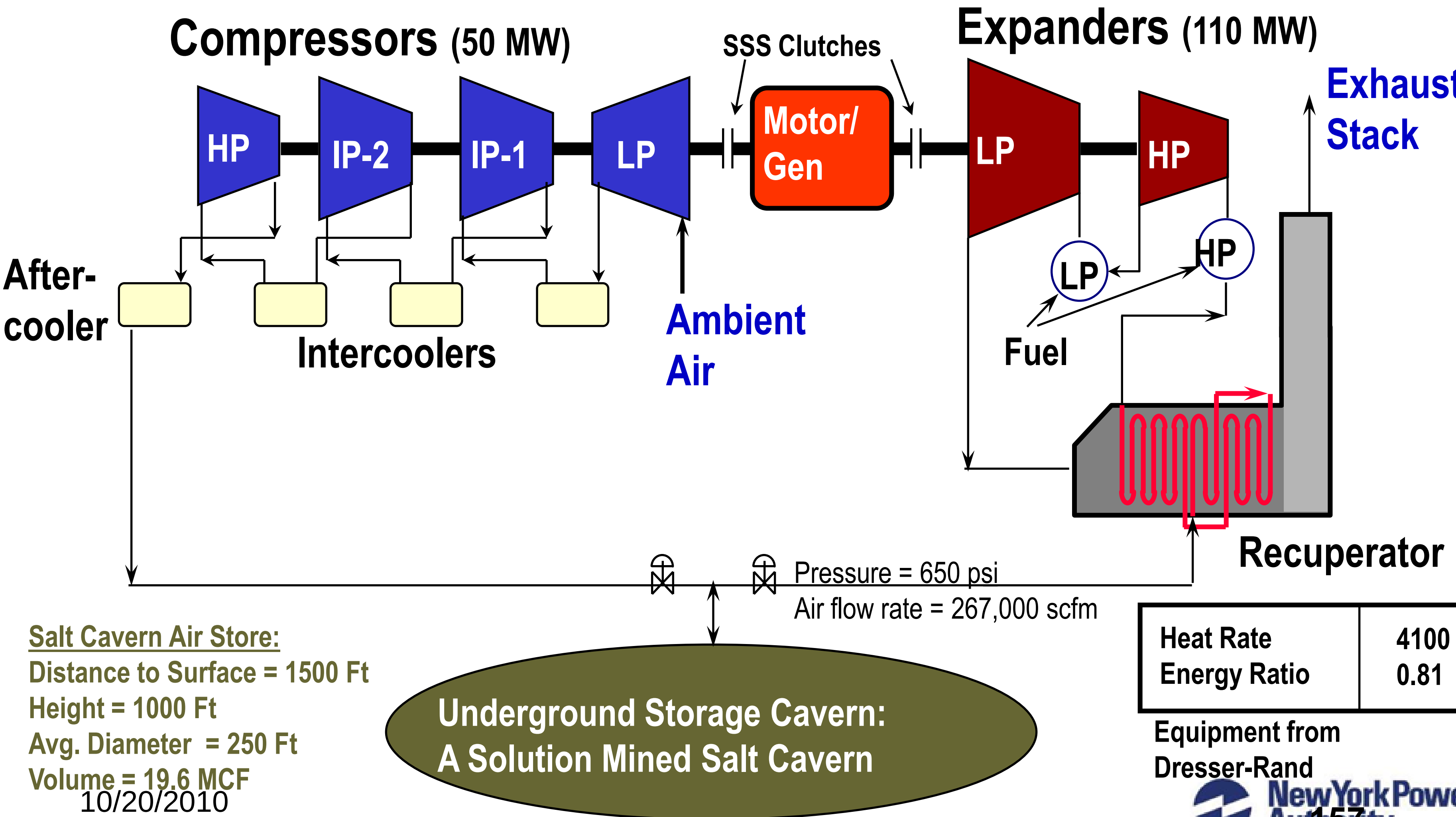
- To evaluate the feasibility of a utility-scale underground compressed air energy storage facility in NYS
  - Generation Capacity: 300MW
  - Compression Capacity: 215MW
  - Storage Capacity: 10 hours

NYPA-EPRI Advanced CAES Project – Scope of Work

- Engineering Evaluation
- Economic Benefit / Cost Analysis
- Geologic Siting Opportunities

CAES Plant Engineering Evaluation

Cap. Cost (2009 Dollars) ~ $730/kW to $830/kW + Substation, Permits & Contingencies

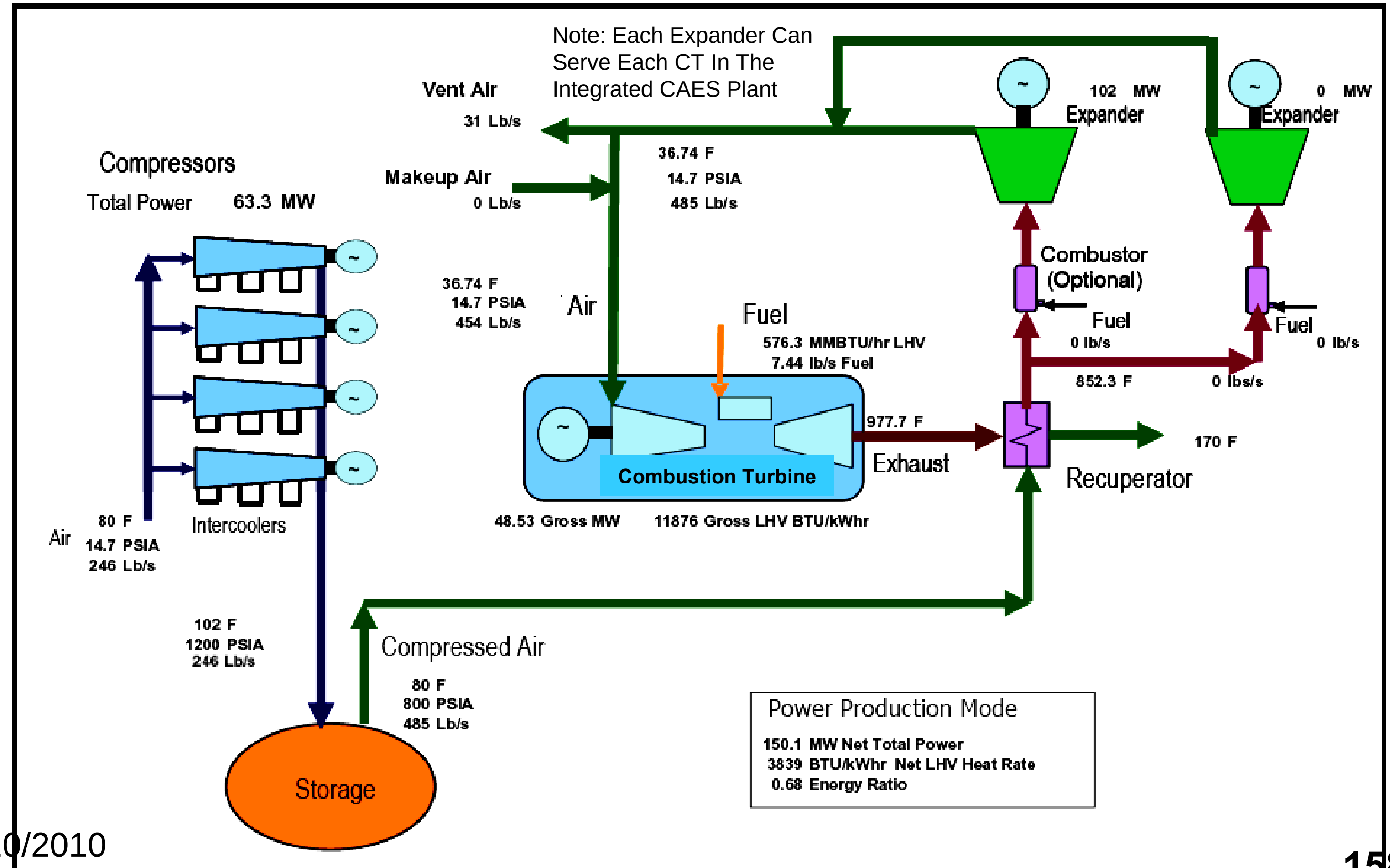


Salt Cavern Air Store:
Distance to Surface = 1500 Ft
Height = 1000 Ft
Avg. Diameter = 250 Ft
Volume = 19.6 MCF

Heat Rate	4100
Energy Ratio	0.81

Equipment from Dresser-Rand

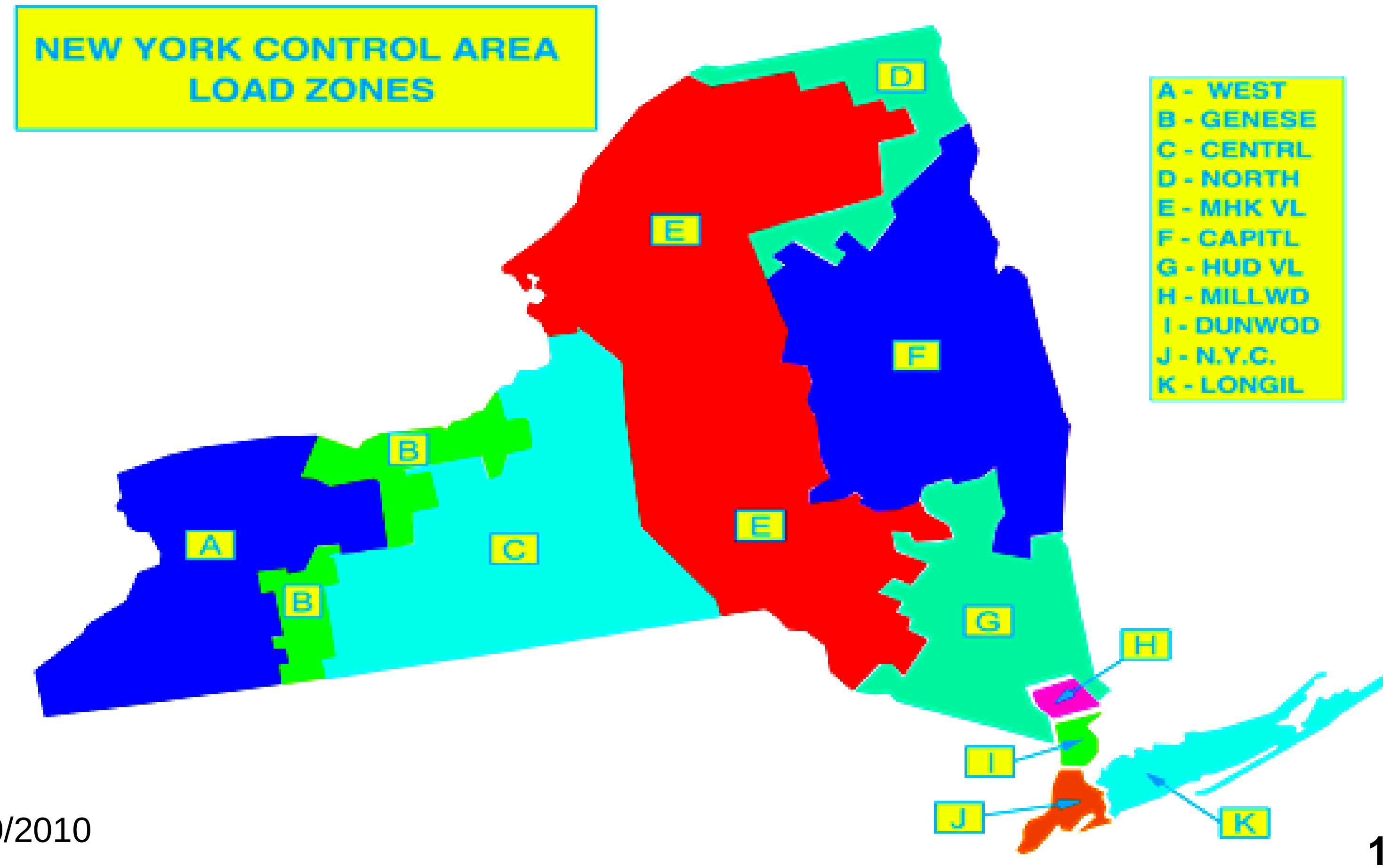
Advanced CAES Plant – Chiller Option



Advantages of Chiller-option CAES Plant

- Compression process is disengaged from power delivery process
- Constant GT inlet air condition
- Improved reliability and availability
- Better flexibility
- Lower CO_2 emissions/kWh
- 25 – 30% less expensive in capital and 10% less in operational cost than first generation CAES design.

NYS Regions Chosen for Study: NYC (Zone J), Central (zone C) & Dunwoodie (zone I)

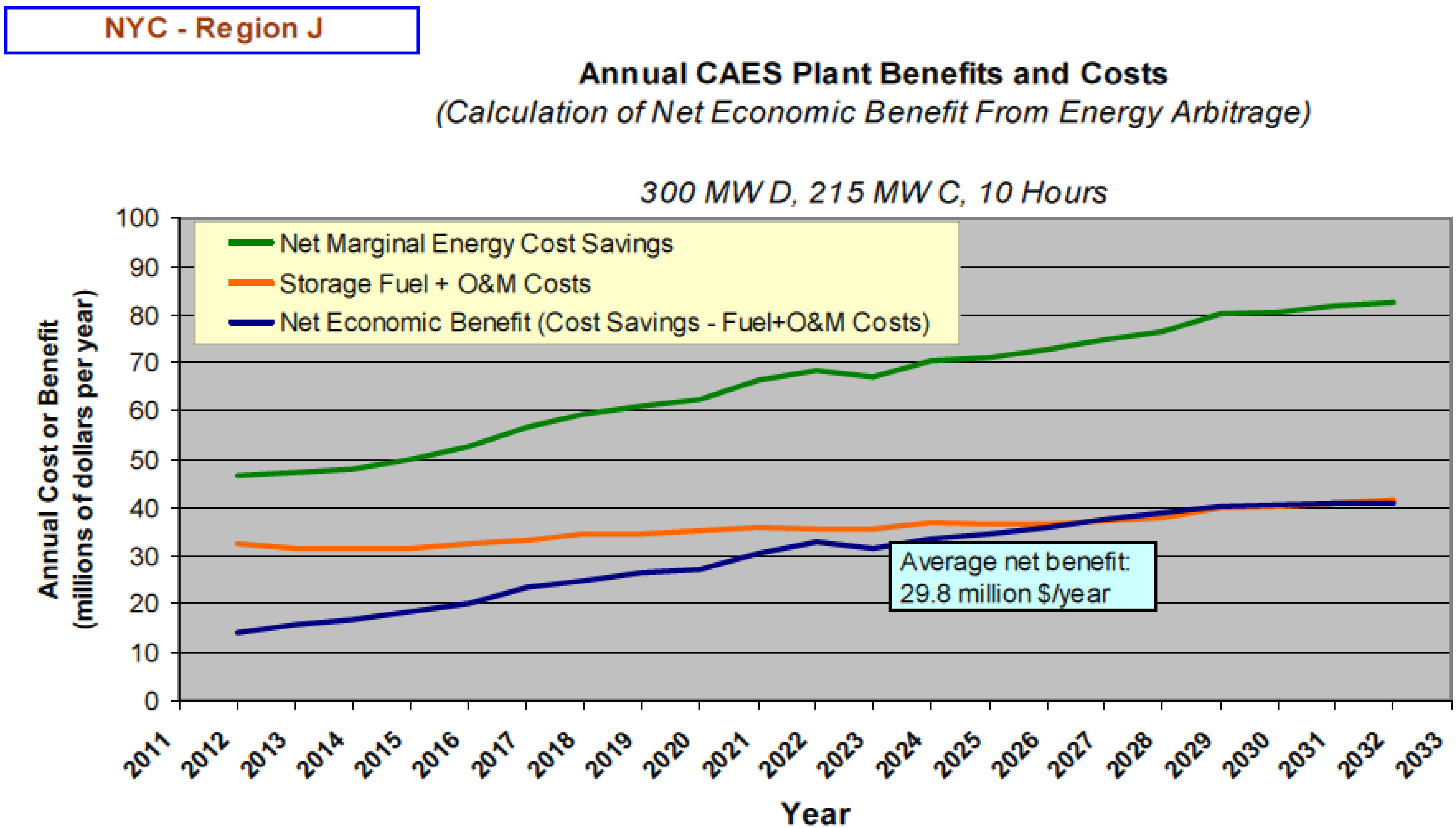


Economic Analysis Assumptions

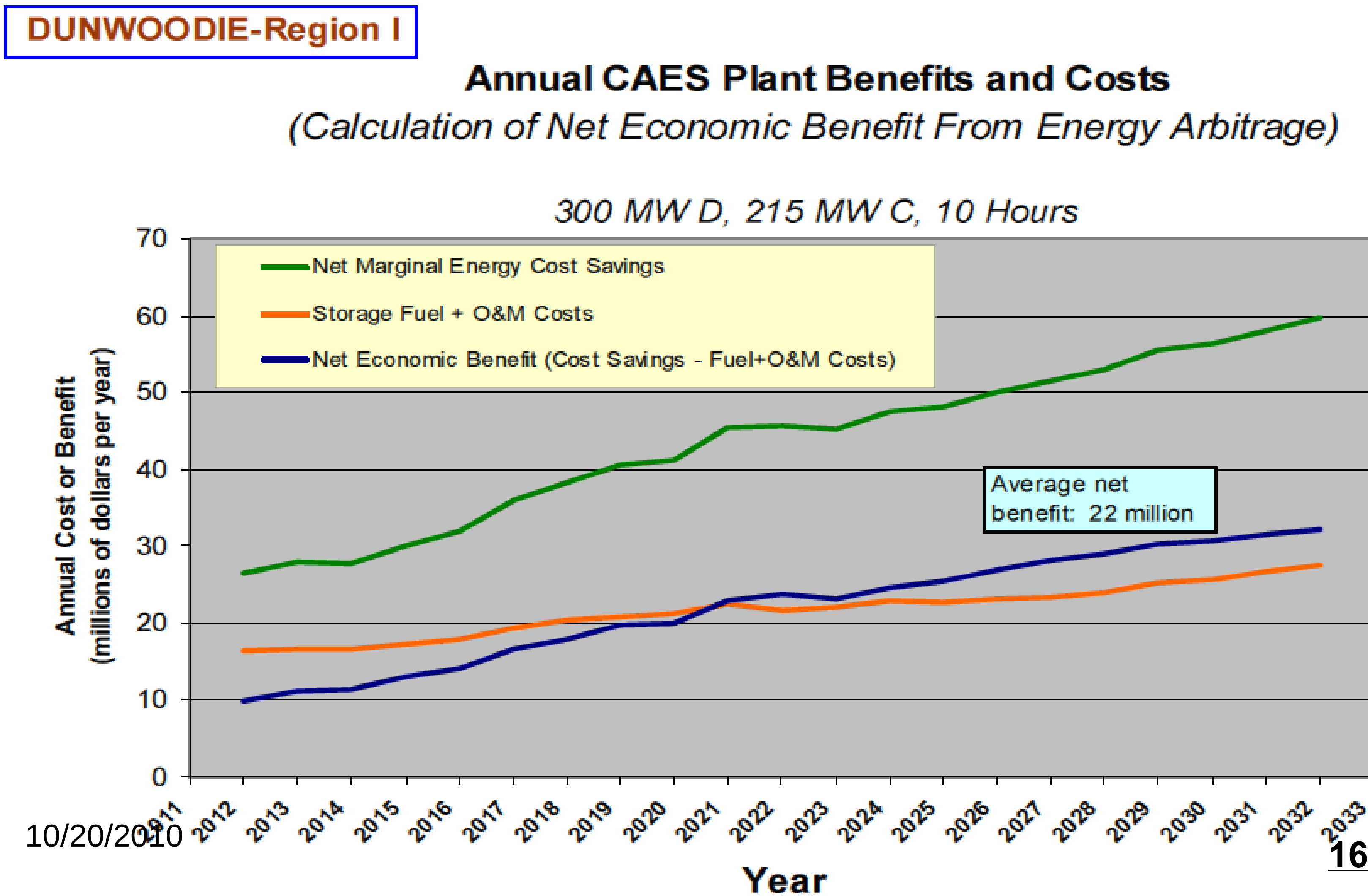
Parameter	Nominal Case
Generation Capacity (MW)	300
Compression Capacity (MW)	215
Generation Period, Max (Hours)	10
Compression Period, Max (Hours)	10
Generation Heat Rate (Btu-In/kWh)	4229
Energy Ratio (kWh–In / kWh-out)	0.70
Variable O&M ($/MWh)	3.5
Fixed O&M ($/MW-Yr)	5
Planning Horizon	2012 - 2032
Capital Cost of the plant ($/kwh)	700
NYPA Fixed Charge Rate (FCR)	13%

With forecasted electric prices, natural gas prices and load profiles

Annual CAES Plant Benefits and Costs

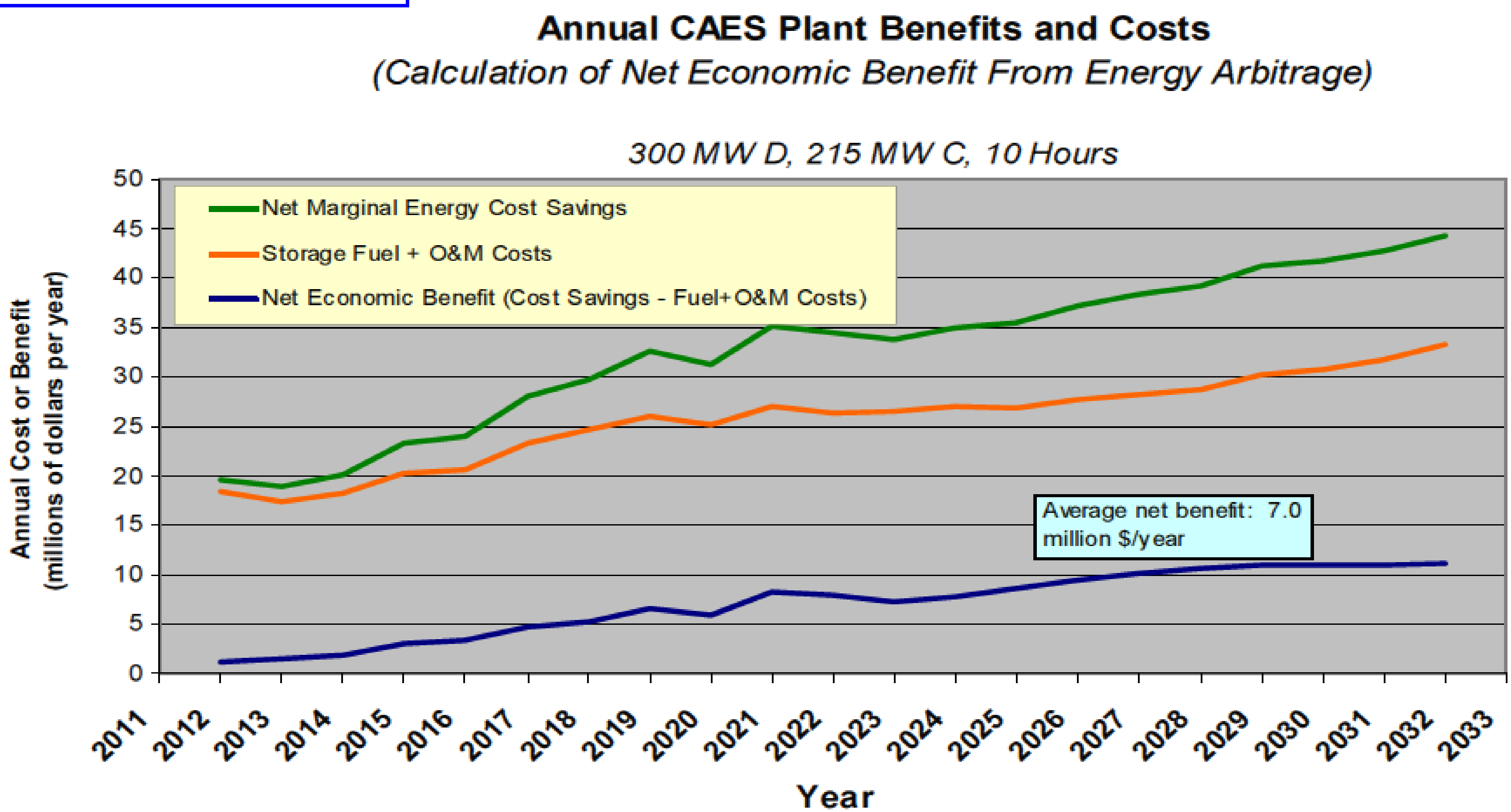


Annual CAES Plant Benefits and Costs



Annual CAES Plant Benefits and Costs

CENTRAL - Region C



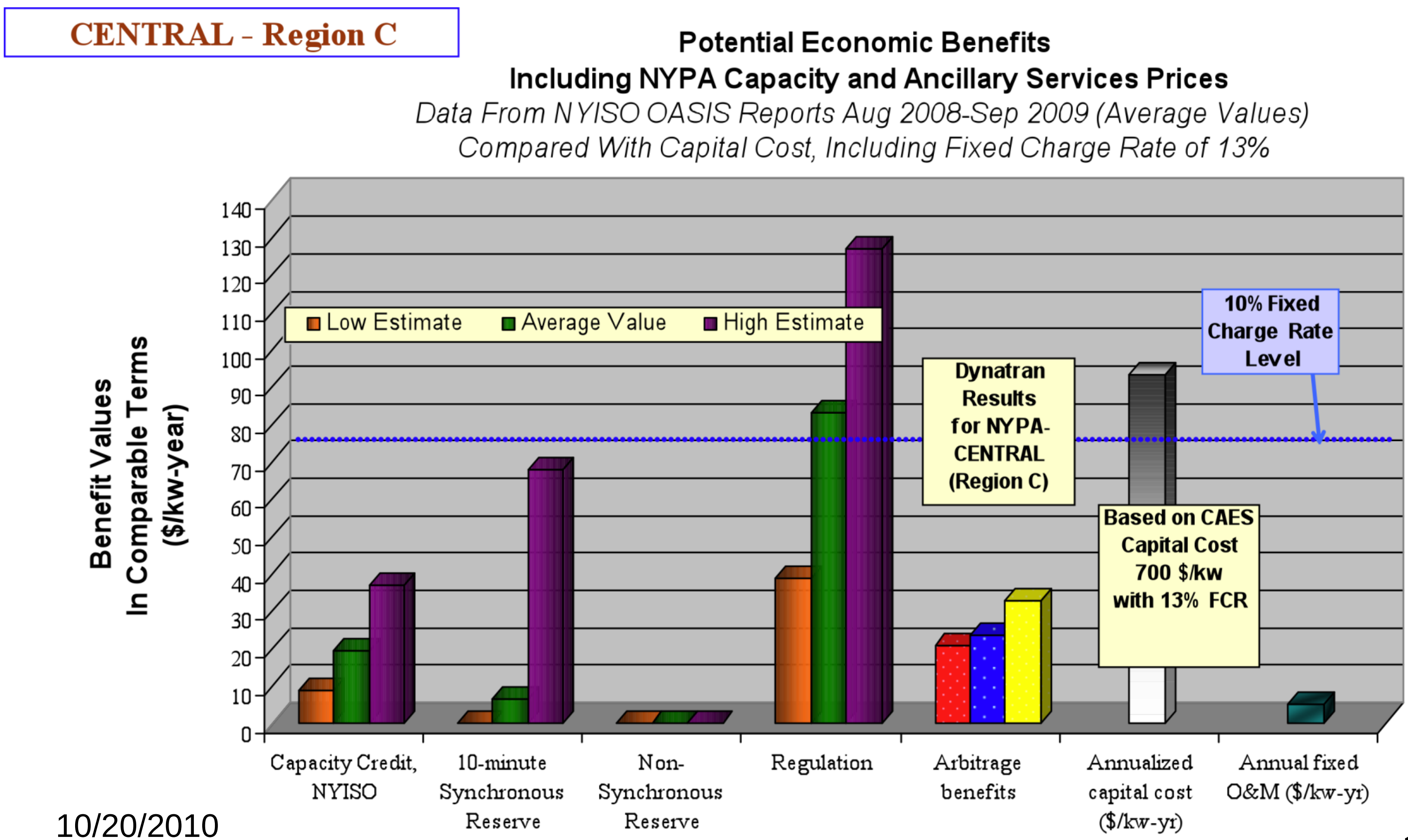
Beyond Arbitrage – Capacity and Ancillary Services

- √ Capacity Credits
- √ Spinning Reserve
- √ Regulation Service
- Ramping
- VAR
- Renewable Credits
- CO_2 Credits

Potential Economic Benefits ($/kW-Yr) for Three New York State Regions

	New York	Dunwoodie	Central
Capacity Credit High Estimate	84	84	37
Capacity Credit Average	68	68	20
Capacity Credit Low Estimate	23	23	9
10 Minute Sync Reserve High Estimate	82	92	68
10 Minute Sync Reserve Average	8	9	7
10 Minute Sync Reserve Low Estimate	0	0	0
Regulation High Estimate	123	138	127
Regulation Average	80	90	83
Regulation Low Estimate	38	42	39
Arbitrage Benefits High Estimate	123	90	28
Arbitrage Benefits Average	94	68	18
Arbitrage Benefits Low Estimate	85	62	16
Total Benefits High Estimate	412	404	260
Total Benefits Average	250	235	128
Total Benefits Low Estimate	146	127	64
Annualized Capital Cost FCR = 13	93	93	93
Net Plant Benefits High Estimate	319	311	167
Net Plant Benefits Average	157	142	35
Net Plant Benefits Low Estimate	53	34	**-29**

Potential Economic Benefits: Example Shown for Central NY State Region



Power

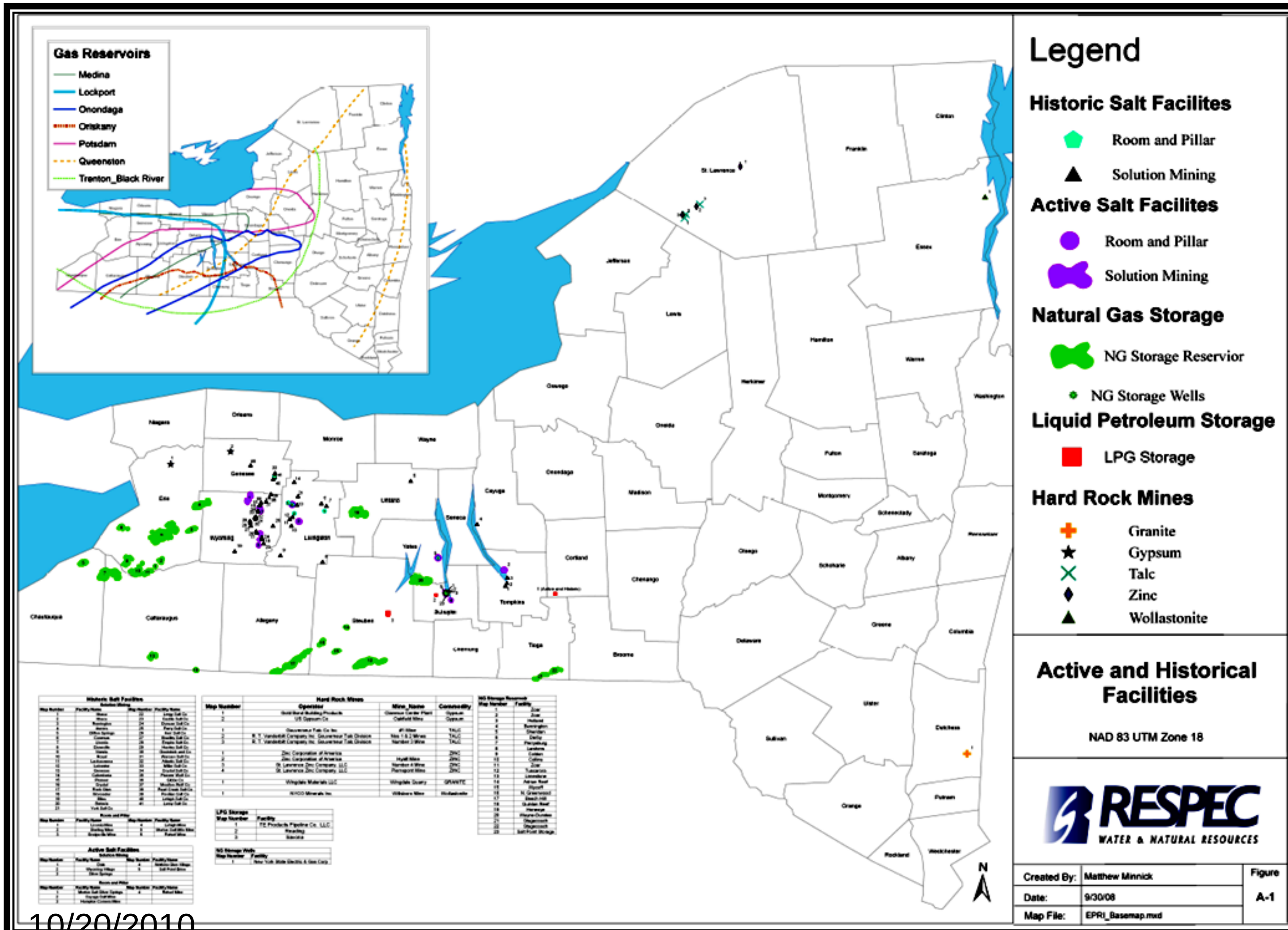
Major Conclusions of Economic Analysis

- Under current NYPA projections for fuel costs, loads, and hourly prices, arbitrage benefits alone serve to offset capital costs for a 300-MW CAES unit in the New York City region, and even a low estimate of capacity credits allows a similar unit to offset capital costs in Dunwoodie.
- In the Central region (again, under current projections), CAES benefits are likely to be sufficient, but ancillary and capacity benefits will be critical components of the benefit mix.
- With wind energy input, the benefits will be greater due to expected larger spread between off-peak and on-peak prices.

Suitable Geologic Formations

- **Salt reservoirs –** used to store oil, natural gas, and many other hydrocarbons for >30years
  - Salt cavern is a constant volume and variable pressure reservoir
- **Porous Media –** used to store natural gas for > 50years. A porous media applicable is a porous rock (sandstone or a fractured rock) with high porosity and permeability for air.
  - Use water drive system to withdraw the air, yet requiring a sizable air cushion
- **Mined Rock –** used to store pressurized hydrocarbons in hard rock caverns for >30years. Two modes of operation:
  - Uncompensated (varying pressure), similar mechanism as salt reservoir
  - Compensated (constant pressure, variable volume). Compensation is achieved by water head which is provided by surface reservoir.

CAES Siting Potential in New York State



NYS Sites:
- Solution Mined Salt Caverns
- Depleted Gas Reservoirs
- Abandoned Mines

Preliminary Geologic Sites Identified

- Western NY – salt solution mining facility at Silver Springs
- South-central NY – Cargill deicing technology Cayuga Mine and the Morton Salt mine; Cargill Watkins Glen or U.S. Salt Watkins Glen could be investigated.
- Central NY – Queenston sandstone reservoir formation and the Trenton-Black River graben reservoir (both identified as the good regions)
- Northern NY – Gouveneur Talc mine, St. Lawrence Zinc number 2-4 mine and Edwards Zinc mine.

Summary

- Selected the chiller CAES Cycle option due to its expected lower capital cost, lower operational cost, and fewer CO2 emissions per kWh.
- Arbitrage benefits alone serve to offset capital costs for a 300-MW CAES unit in the New York City region. Adding a low estimate of capacity credits allows a similar unit to offset capital costs in Dunwoodie. In the Central region (under current projections), ancillary and capacity benefits are critical components to justify the project economics.
- Preliminary geologic survey has identified some potential sites in Central and Western Region of the State.

Next Steps

- Perform more detailed geologic studies at sites in pre-determined regions
- Select a site based on these subsequent geologic analyses
- Update the economic benefits/cost and business case analyses for selected site
- Update/optimize the plant specifications to match the geological conditions of the selected storage sites

9. Energy Storage and Geographic Aggregation: Mutually Reinforcing Strategies for Integrating Wind Power

Samir Succar, *NRDC*

Robert H. Williams, *Princeton University*

The incorporation of wind resource aggregation into the optimization framework for a hybrid wind/CAES baseload power facility demonstrates that strategies for variable energy resource integration can be mutually reinforcing. By leveraging the geographic diversity of wind energy resources, the cost and emissions of baseload wind systems can be significantly reduced as a result of reduced capital cost requirements for balancing aggregated wind resources. Specifically, re-optimizing the CAES configuration, including the relative capacity of the compression and turboexpander trains as well as the storage capacity of the geologic reservoir, in response to changes in wind resource characteristics, yields significant capital cost reductions for the CAES system which translates into lower levelized cost for baseload power from wind/CAES and lower GHG emissions. This approach results in significantly reduced carbon entry prices for wind/CAES relative to alternative low carbon baseload systems.

Samir Succar is an Energy Analyst working in NRDCs New York office as part of the Center for Market Innovation. Samir's work focuses on the integration of renewable energy and the role of T&D infrastructure upgrades, demand resources, energy storage and other enabling technologies. He received a BA from Oberlin College and earned a Ph.D. in Electrical Engineering at Princeton University researching the technical and economic feasibility of utility scale wind coupled to bulk energy storage systems.

Energy Storage and Geographic Aggregation

Mutually Reinforcing Strategies for Integrating Wind Power

Integrating Wind-Solar-CAES

2nd Compressed Air Energy Storage (CAES) Conference & Workshop

Columbia University, New York, NY - 20 October, 2010

Samir Succar, Ph.D.

Energy Analyst

Natural Resources Defense Council

ssuccar@nrdc.org

Motivations and Overview

Baseload power from wind

- Low carbon energy sources are needed for climate change mitigation
- 40% of global fossil CO_2 from electricity
- Majority from coal (80% in the U.S.)
- Displacing coal means baseload (80-90% CF)

Mitigating Impacts of Wind Variability & Remoteness

a) Resource Aggregation

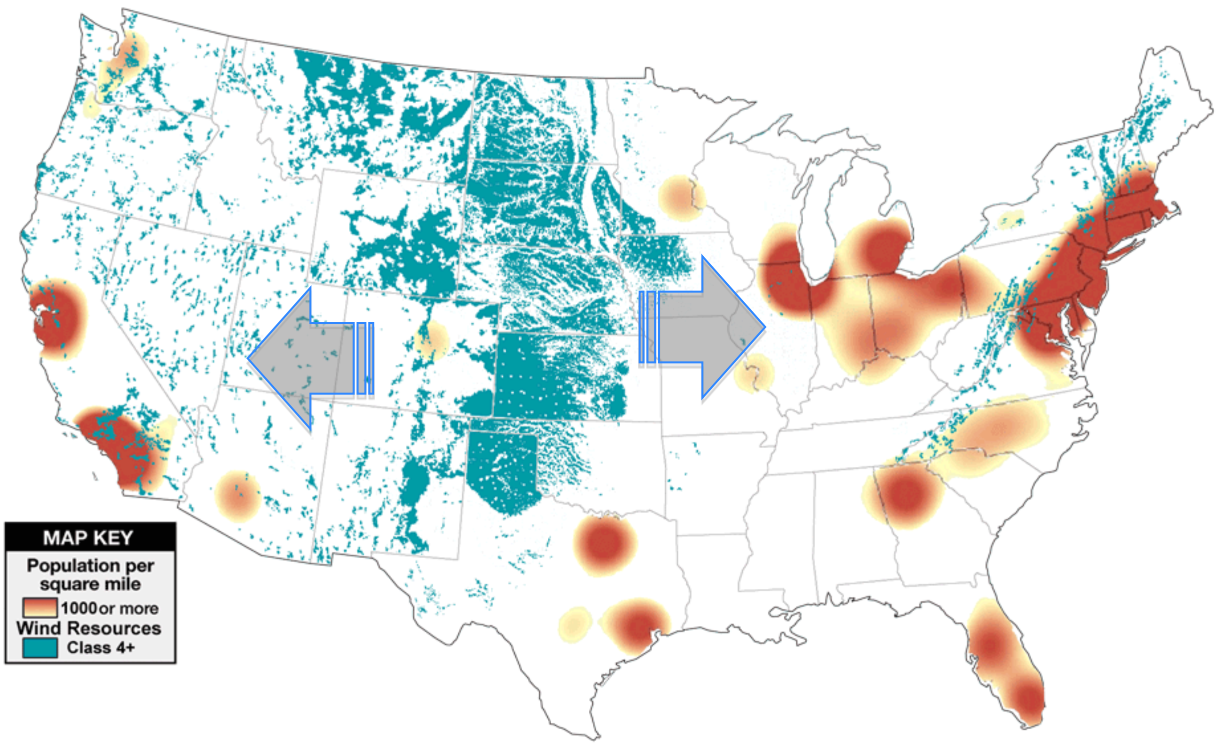
b) Backup (conventional generation, storage)

Complimentary or Mutually Exclusive?

NRDC
THE EARTH'S BEST DEFENSE

Wind Energy Resources vs Population

- Location of best resources may not be proximal to demand centers
- Additional transmission infrastructure may be required to bring remote wind energy to market
- This represents a major shift in the way transmission is planned, sited and built
- Other resources (distributed generation, offshore wind) don't obviate the need for new lines
- Transmission constraints is a major limitation for wind **today**



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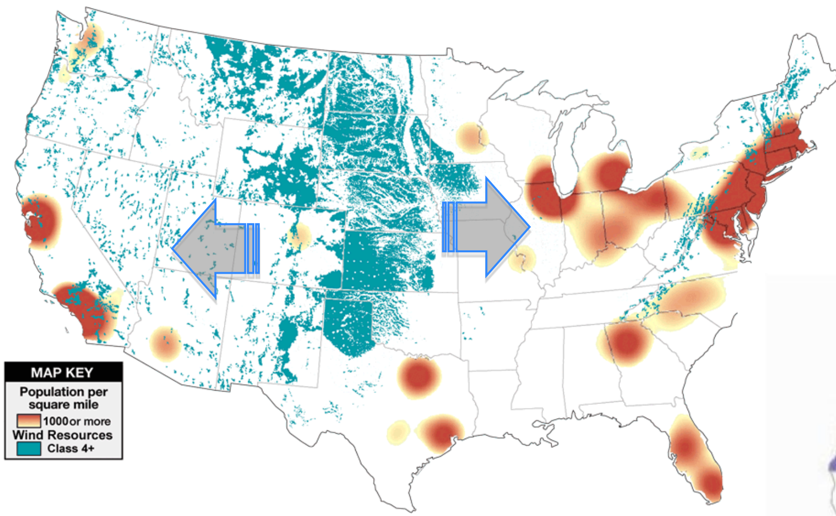

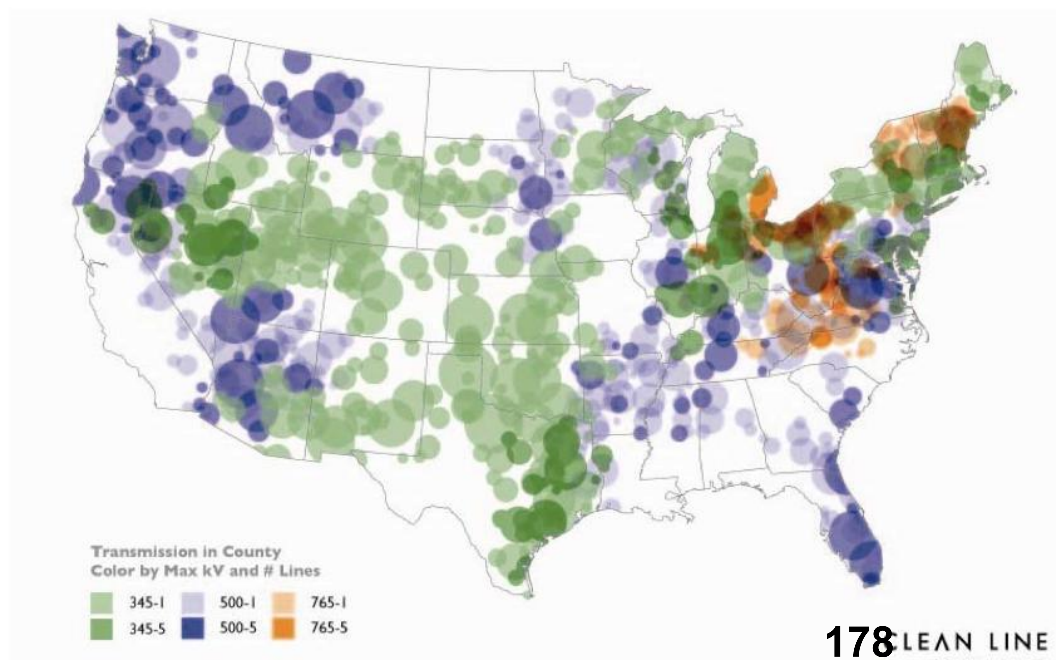

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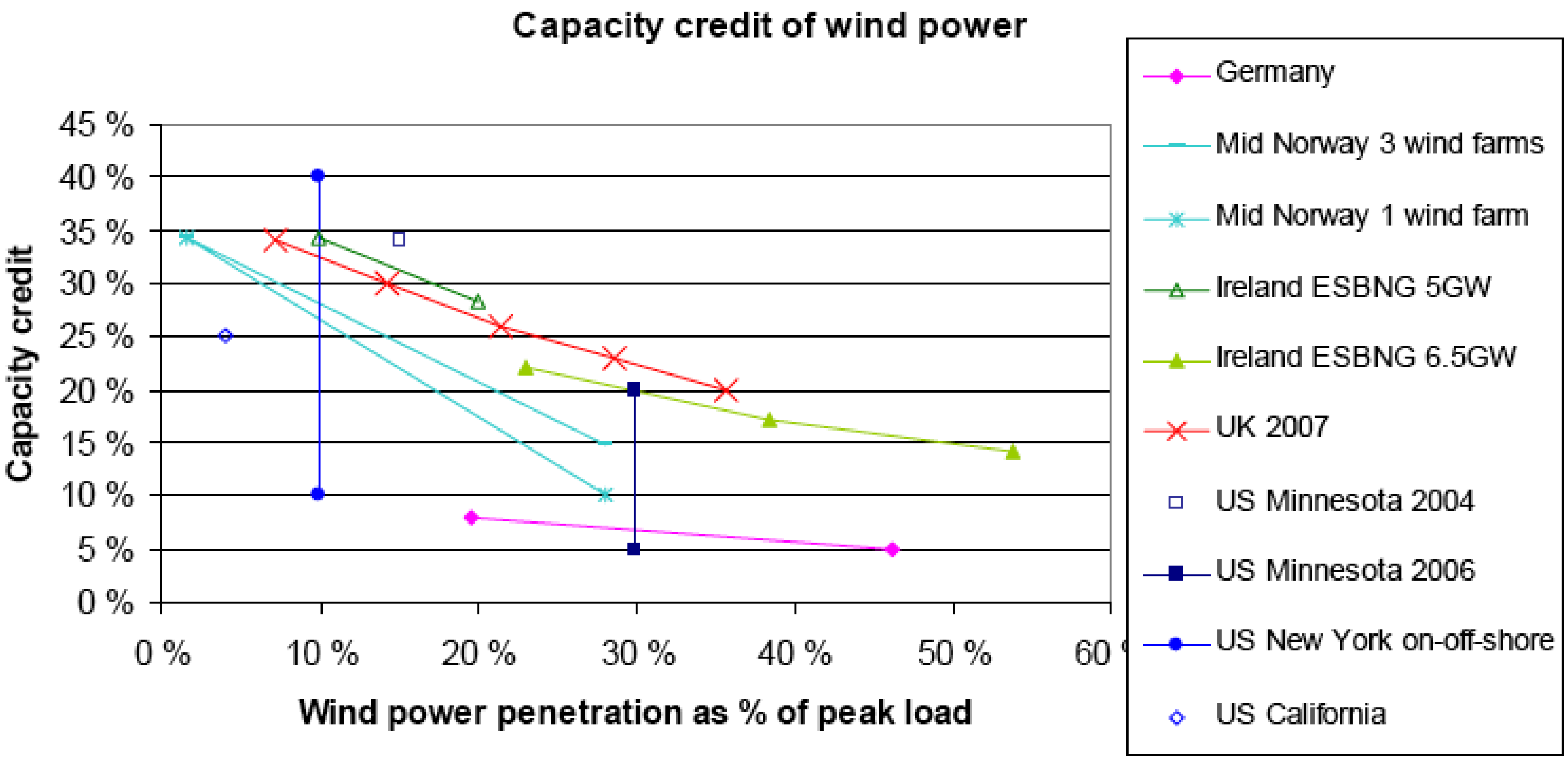
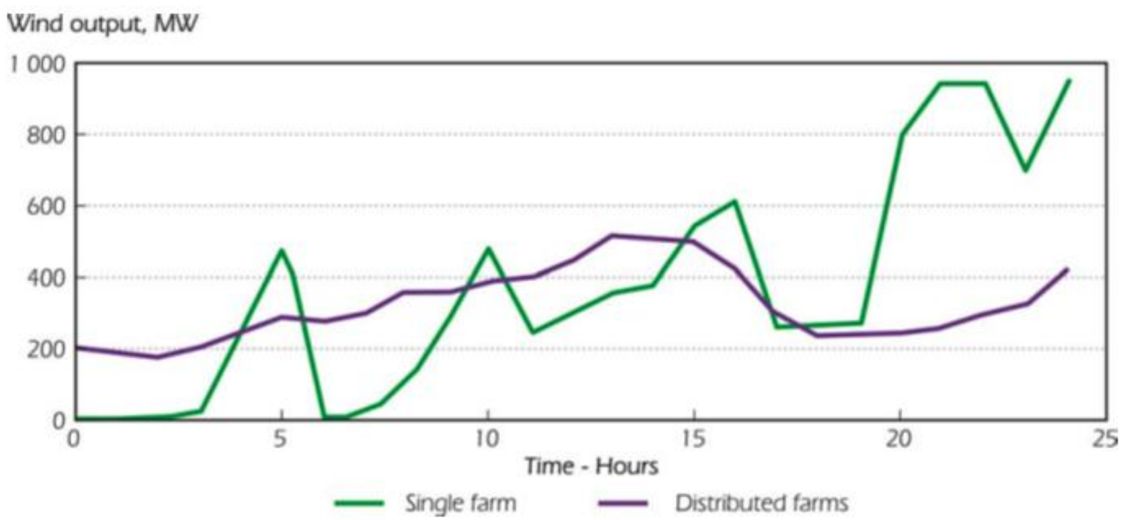
CLEAN LINE
ENERGY PARTNERS

Declining Capacity Credit



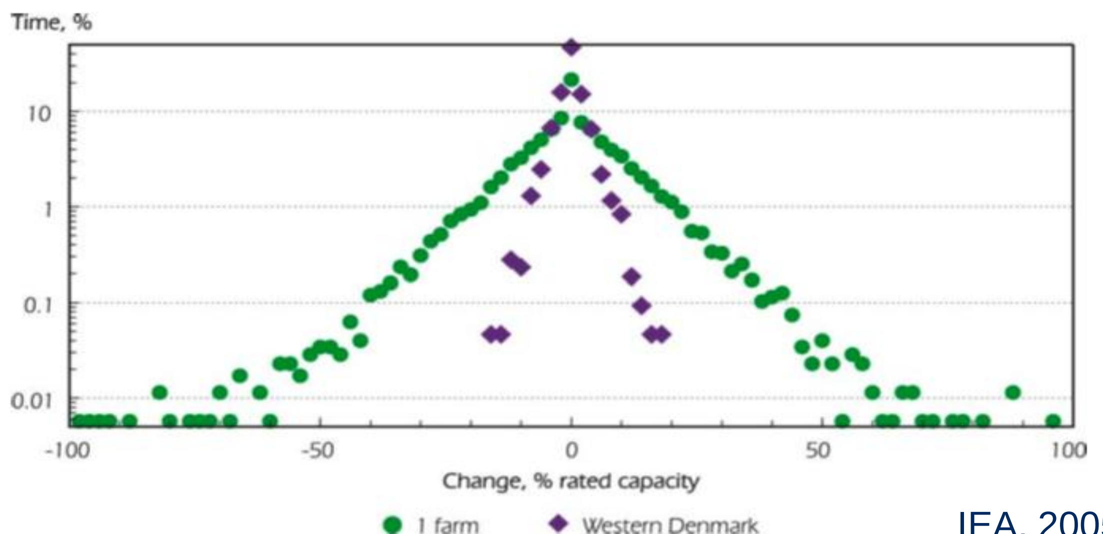
H. Holttinen, B. Lemström, P. Meibom, H. Bindner, A. Orths, F. v. Hulle, C. Ensslin, L. Hofmann, W. Winter, A. Tuohy, M. OMalley, P. Smith, J. Pierik, J. O. Tande, A. Estanqueiro, J. Ricardo, E. Gomez, L. Söder, G. Strbac, A. Shakoor, J. C. Smith, B. Parsons, M. Milligan, and Y.-h. Wan, "Design and operation of power systems with large amounts of wind power: State-of-the-art report " VTT Technical Research Centre of Finland, Vuorimiehentie, Finland VTT-WORK-82, October 2007.

Reducing Variability Through Resource Aggregation



Smoothing through

resource interconnection

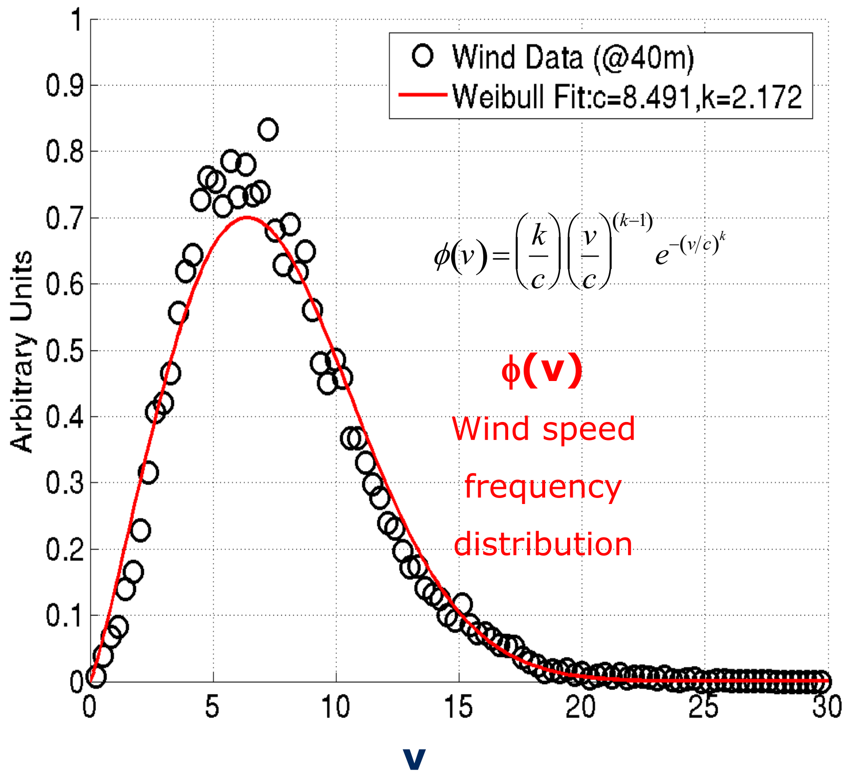


More consistent

power output

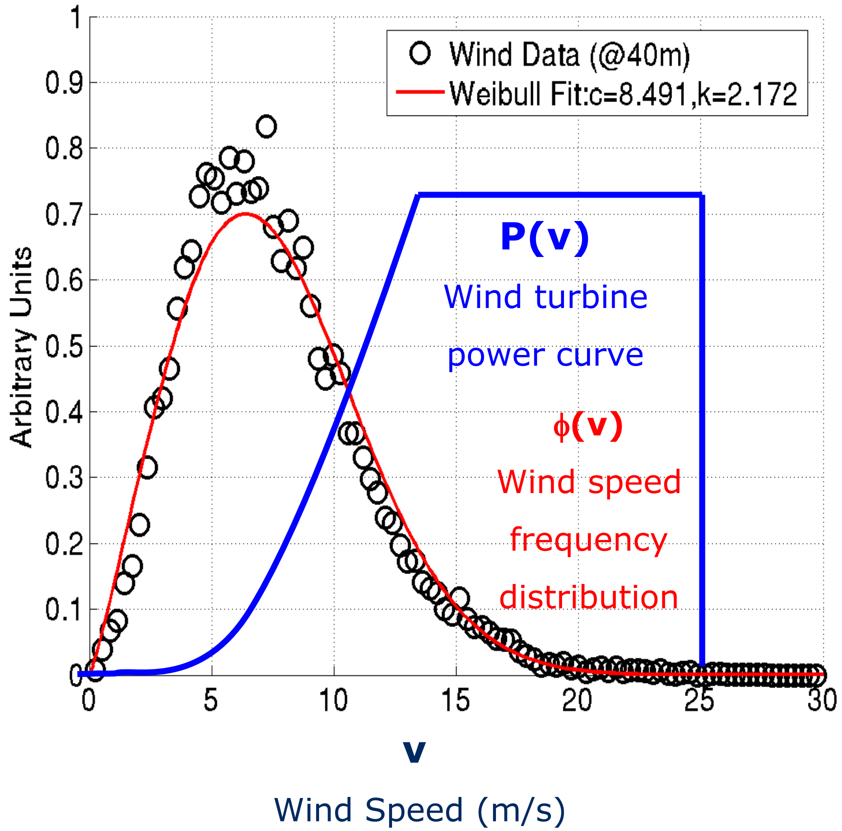
IEA, 2005

Resource Variability

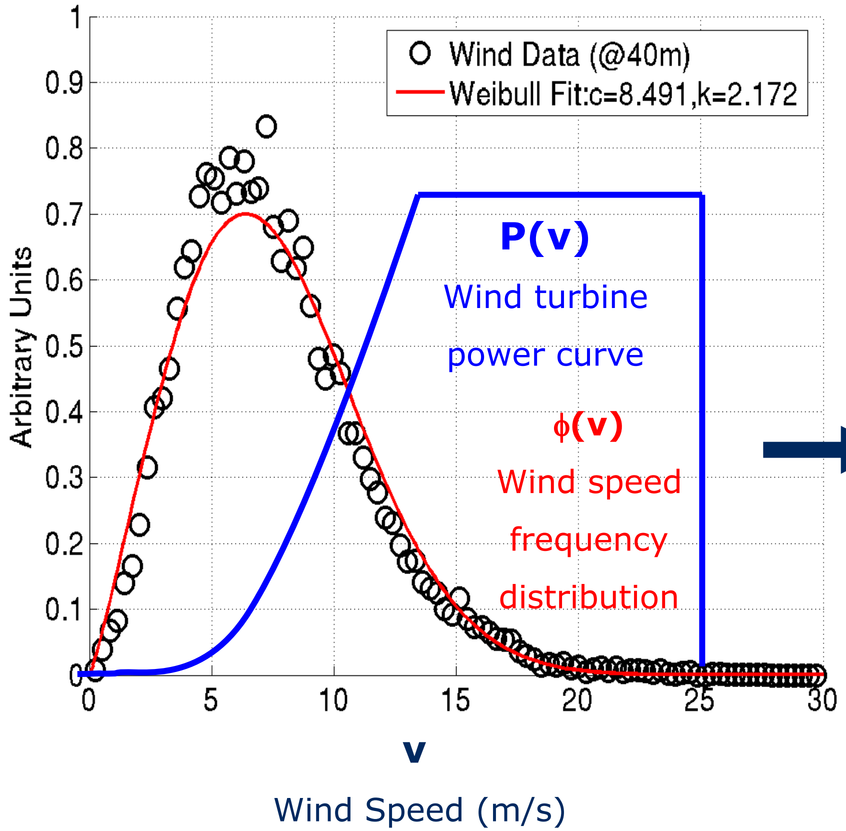


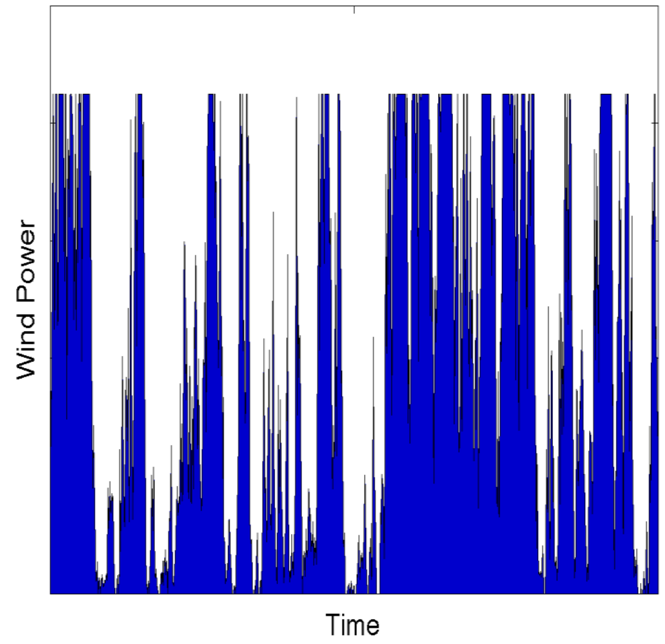
Wind speed (m/s)

Resource Variability



Resource Variability





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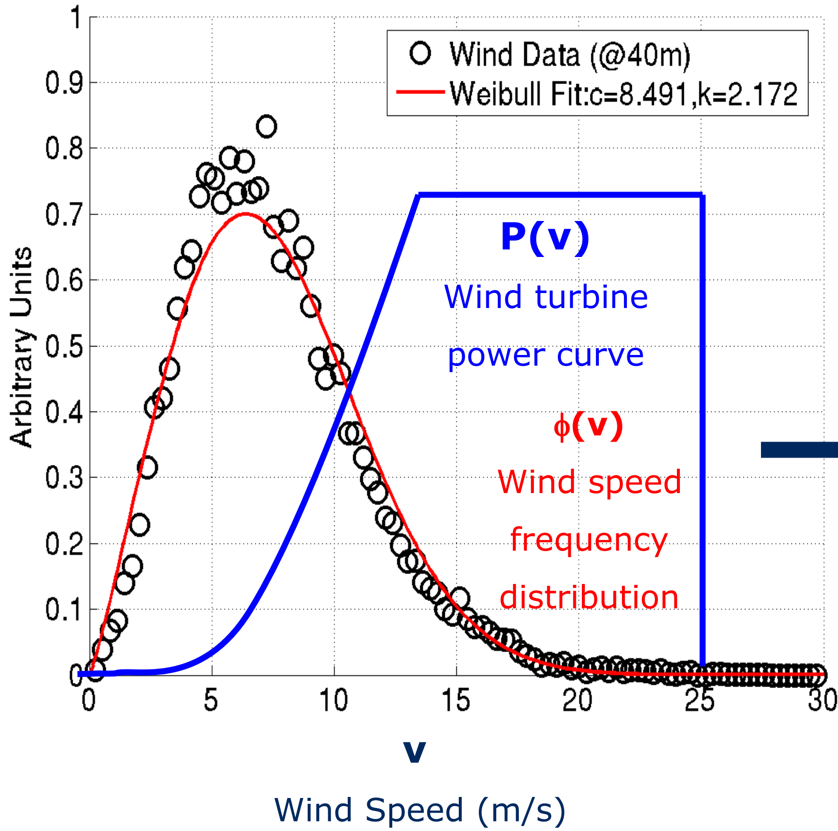
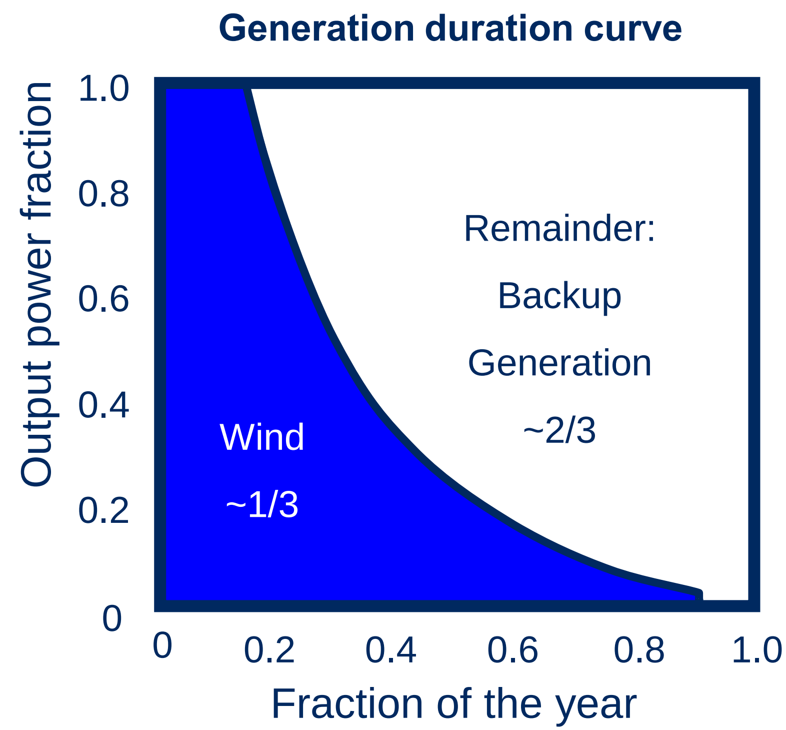
Resource Variability





- Rated Power Delivered 20% of the Year
- Typical Capacity Factor ~ 30%
- Minimum Power Output: 0 Watts (5-10%)

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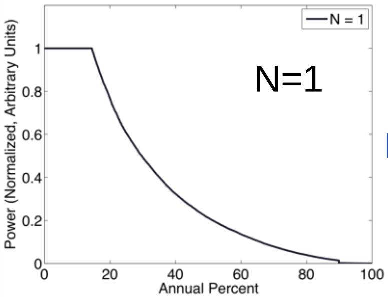
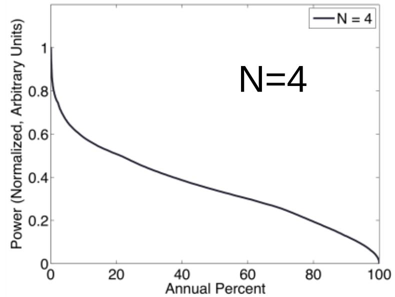
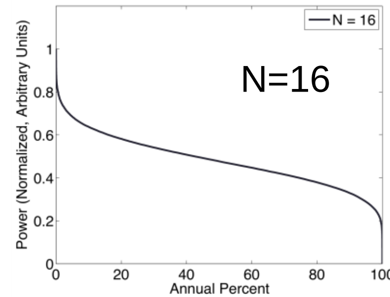
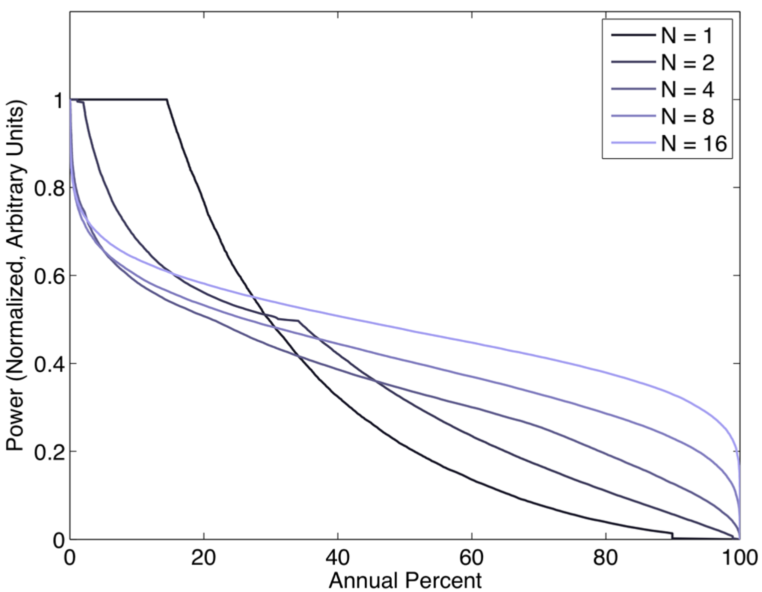
Wind Aggregation

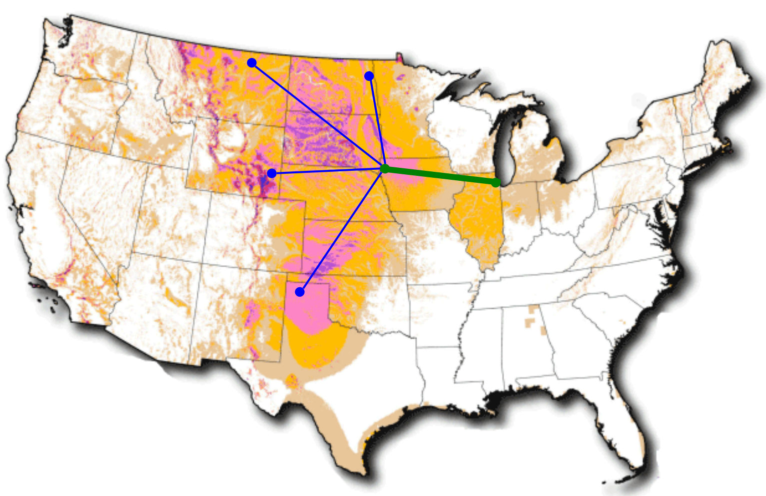
Combining weakly correlated wind resources over a broad geographic area











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Motivations and Overview

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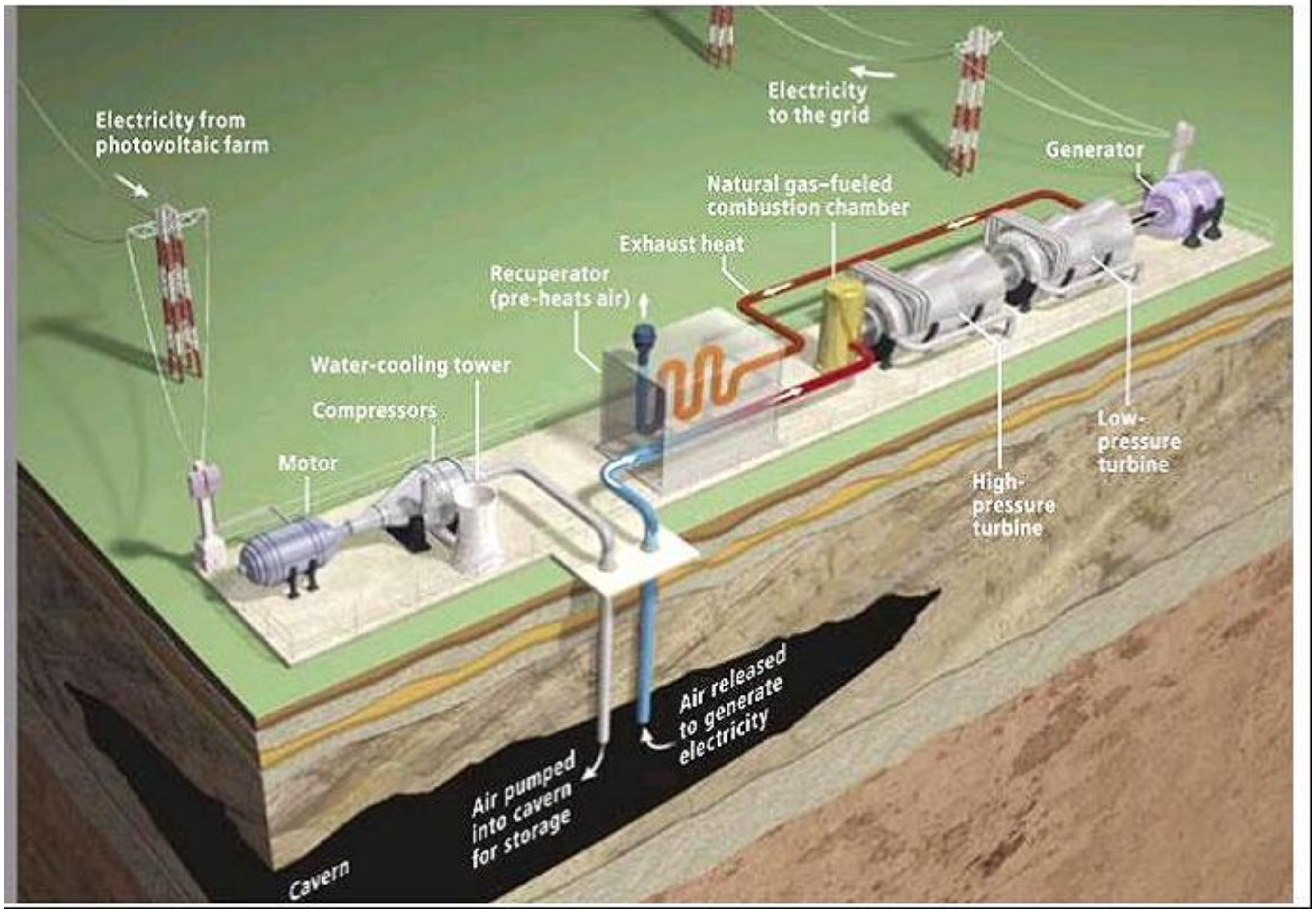
Compressed Air Energy Storage (CAES)



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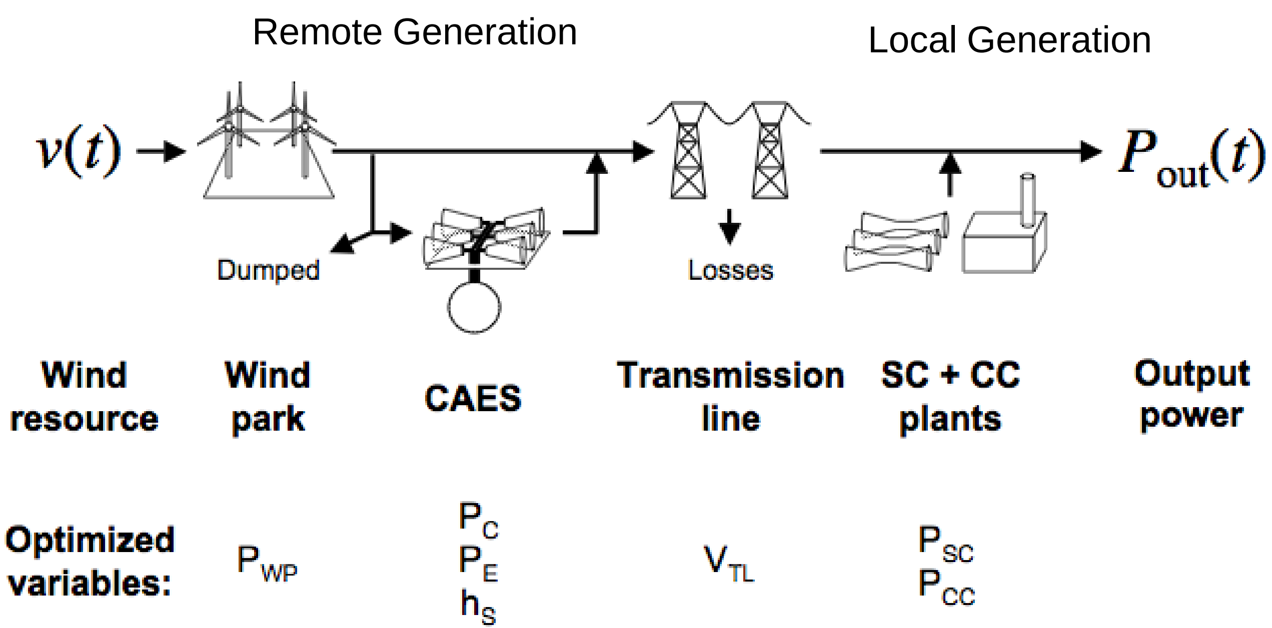
Wind/CAES Cost Model Methodology



Objective Function: Levelized Cost of Energy ($/MWh)

- CF = System capacity factor
- h_y = 8766 hours per year
- P_L = Load level (2000MW)
- A_n = Plant Annual Costs

$$COE = \frac{1}{CF * P_L * h_y} \sum_n A_n$$

$A_n = C_n * L + M_n + F_n$

- C_n = Capital Costs
- L = Levelized Capital Charge Rate
- M_n = Operations and Maintenance (O&M)
- F_n = Fuel

Constraints

- Capacity Factor ($P_{out,avg}/P_{out,max}$) = 0.85
- Gas Capacity ($P_{SC}+P_{CC}$) = P_{TL} - Wind/CAES 85% Firm Capacity

Independent Quantity: Greenhouse Gas Emissions Price ($ per tonne CO_2 equivalent)

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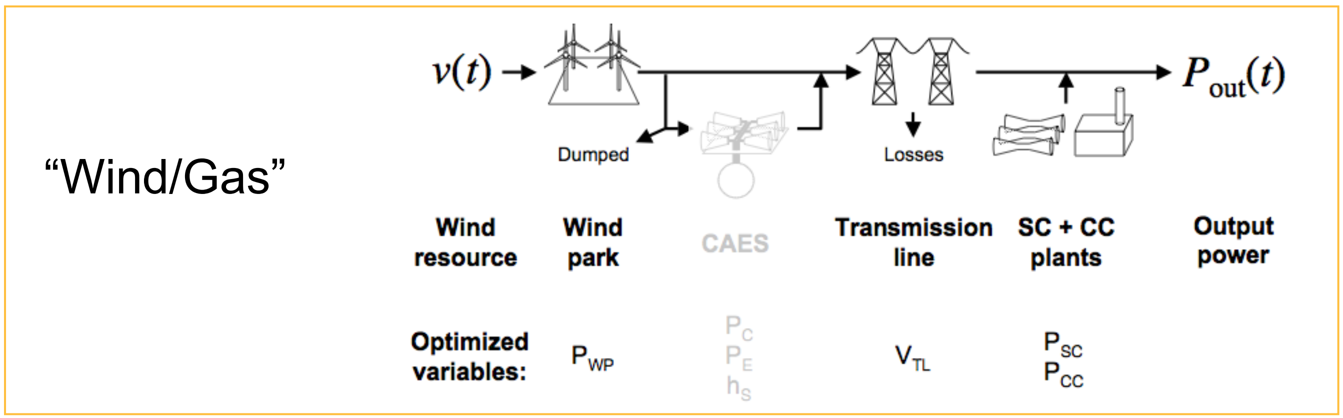
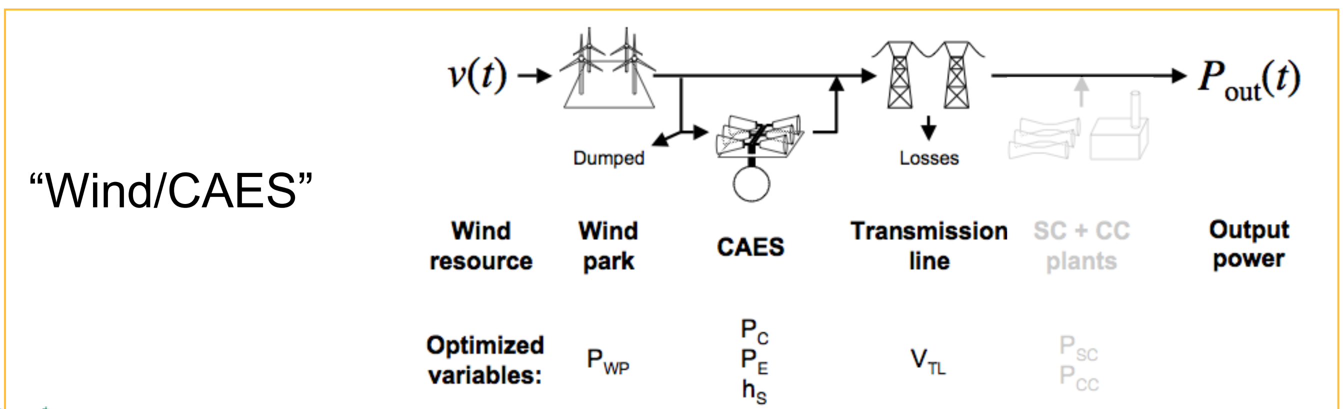
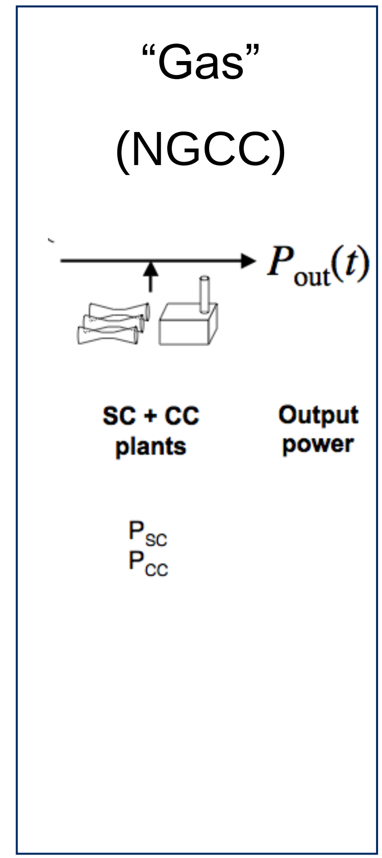
- Optimal system configuration derived through levelized cost of energy (COE) minimization
- Cost optimization based on flexible Wind/Gas/CAES framework
- Impact of alternate assumptions analyzed on the basis of optimized system configuration

Wind/CAES Cost Model

Remote Generation   Local Generation







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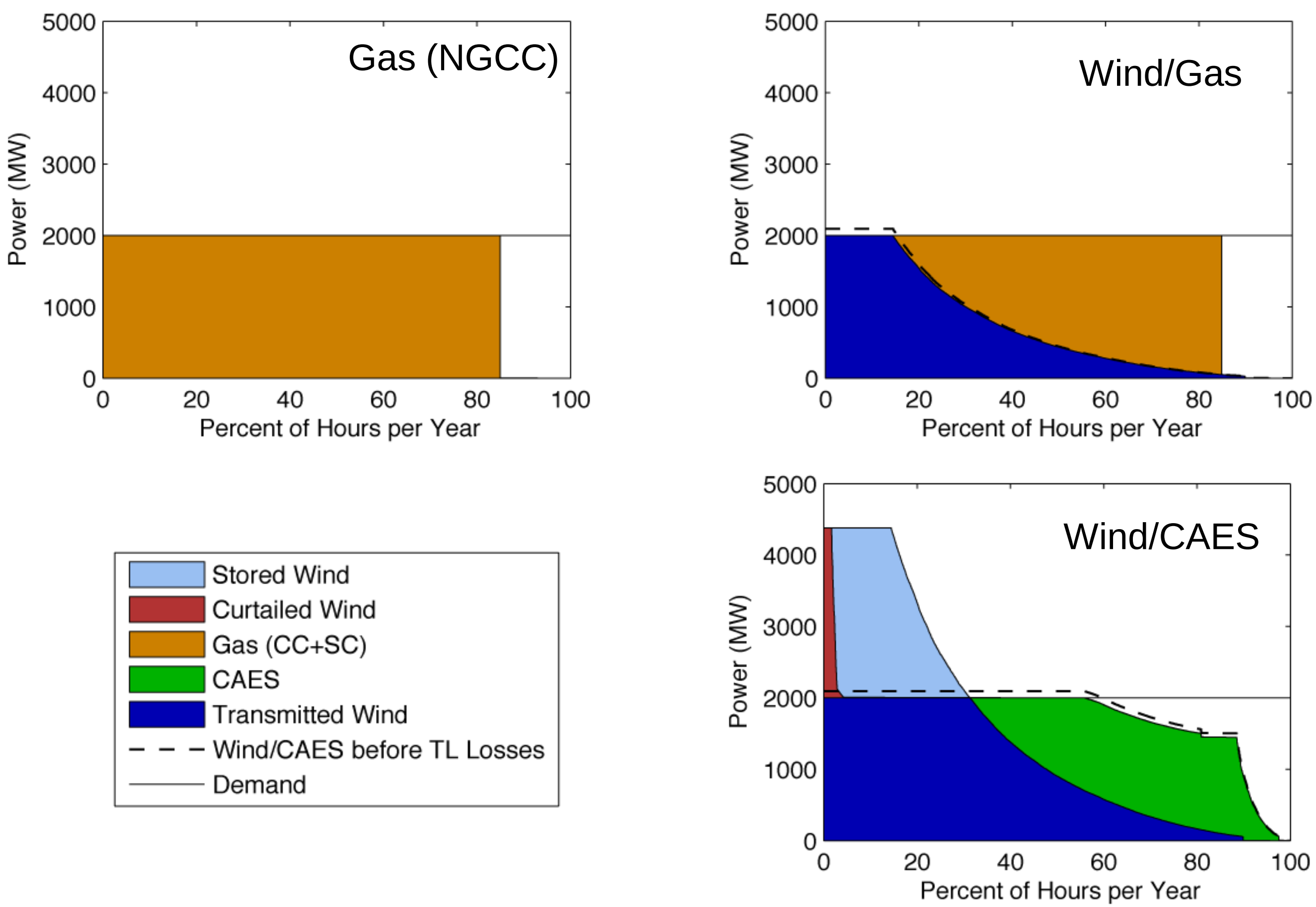
Power Duration Curves

Optimization collapses to three "static" solutions



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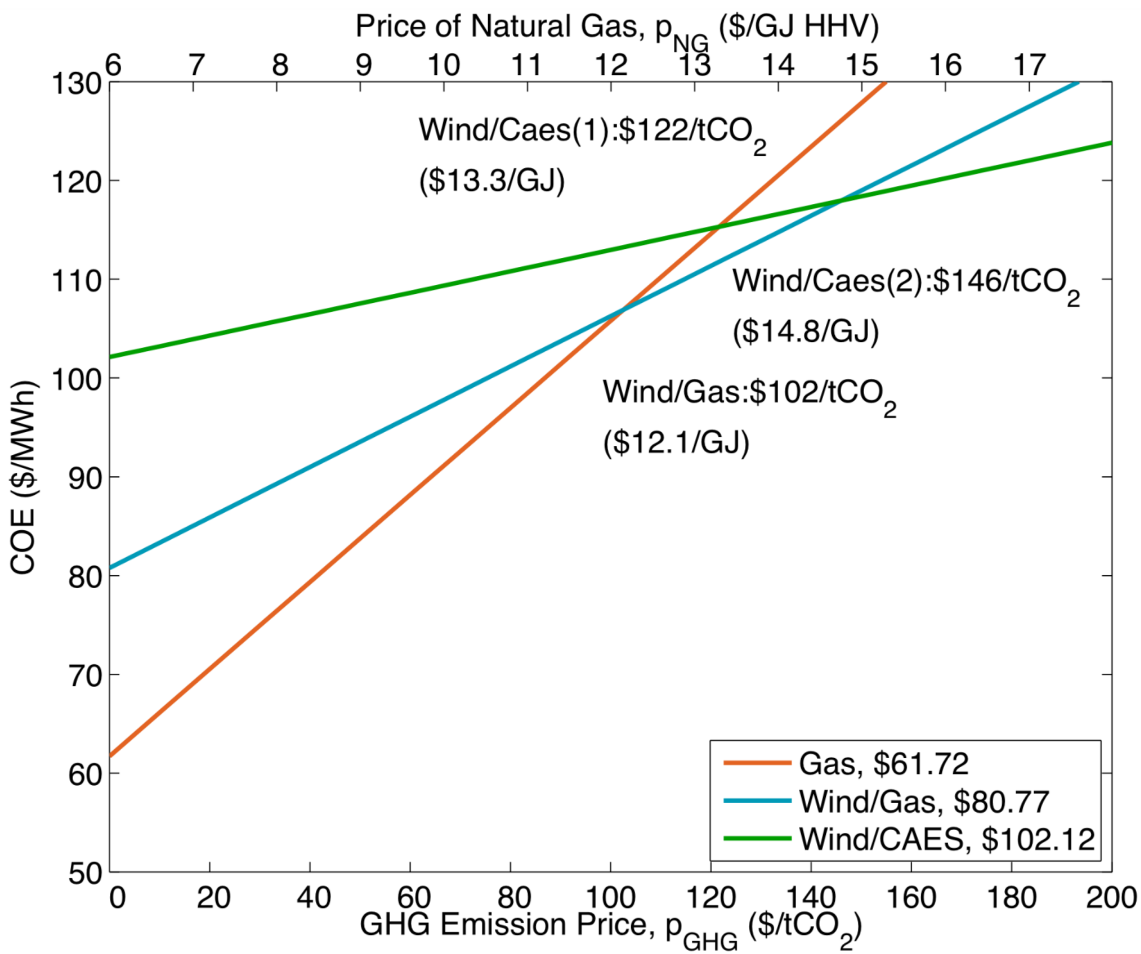
COE vs Carbon/Gas Price

Levelized cost of energy for three systems plotted against GHG emission / fuel price



Base Fuel Cost (NG):

$6/GJ HHV

GHG Emission Intensity NG (Upstream + Downstream):

66.0 kg CO_2/ GJ LHV

GHG Emission Rates

NGCC:

441 kgCO_2/MWh,

Wind/Gas:

256 kgCO_2/MWh

Wind/CAES:

108 kgCO_2/MWh

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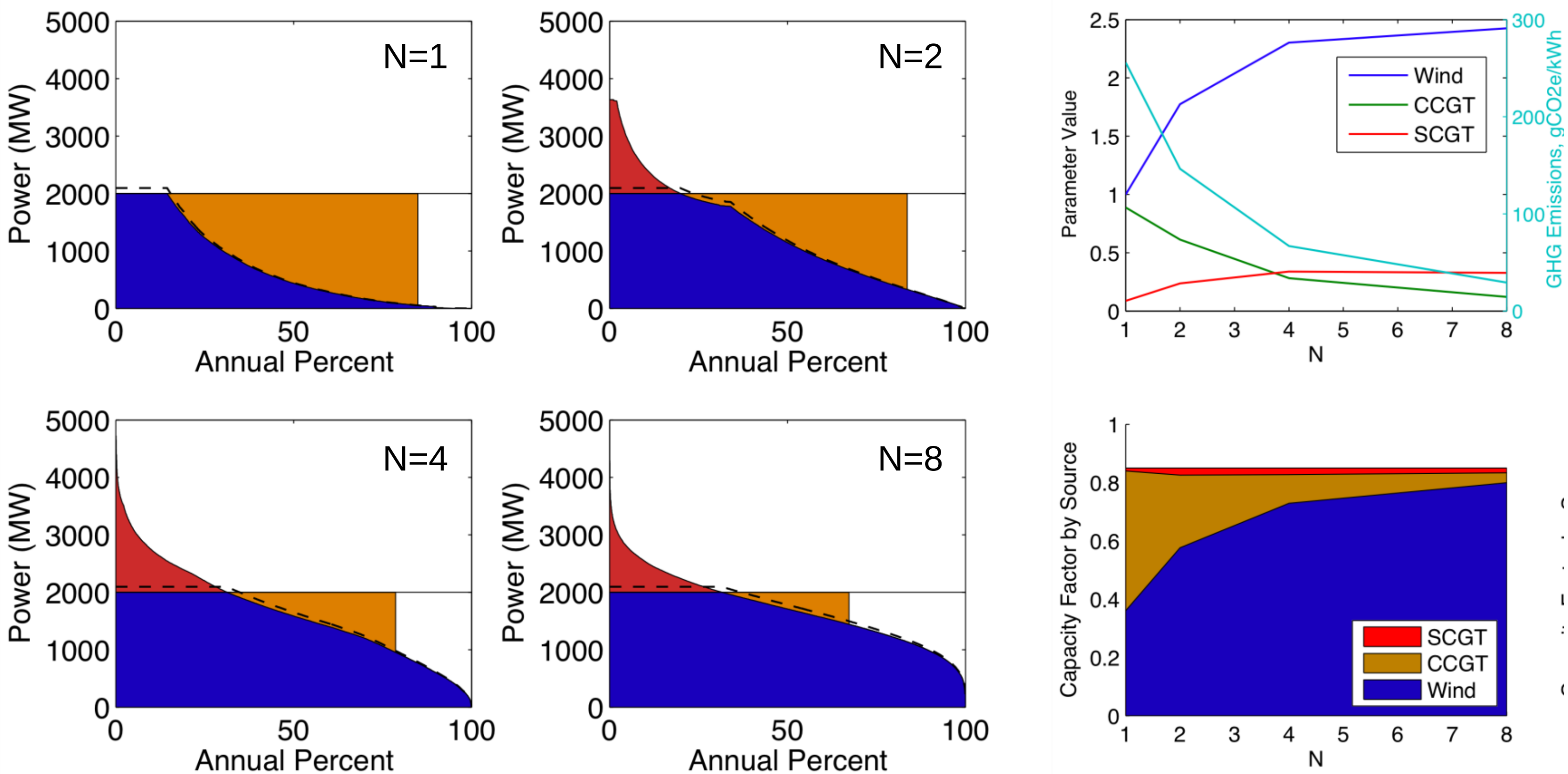
Resource Aggregation + Wind/Storage

Over-sizing the wind with respect to transmission becomes optimal at high N



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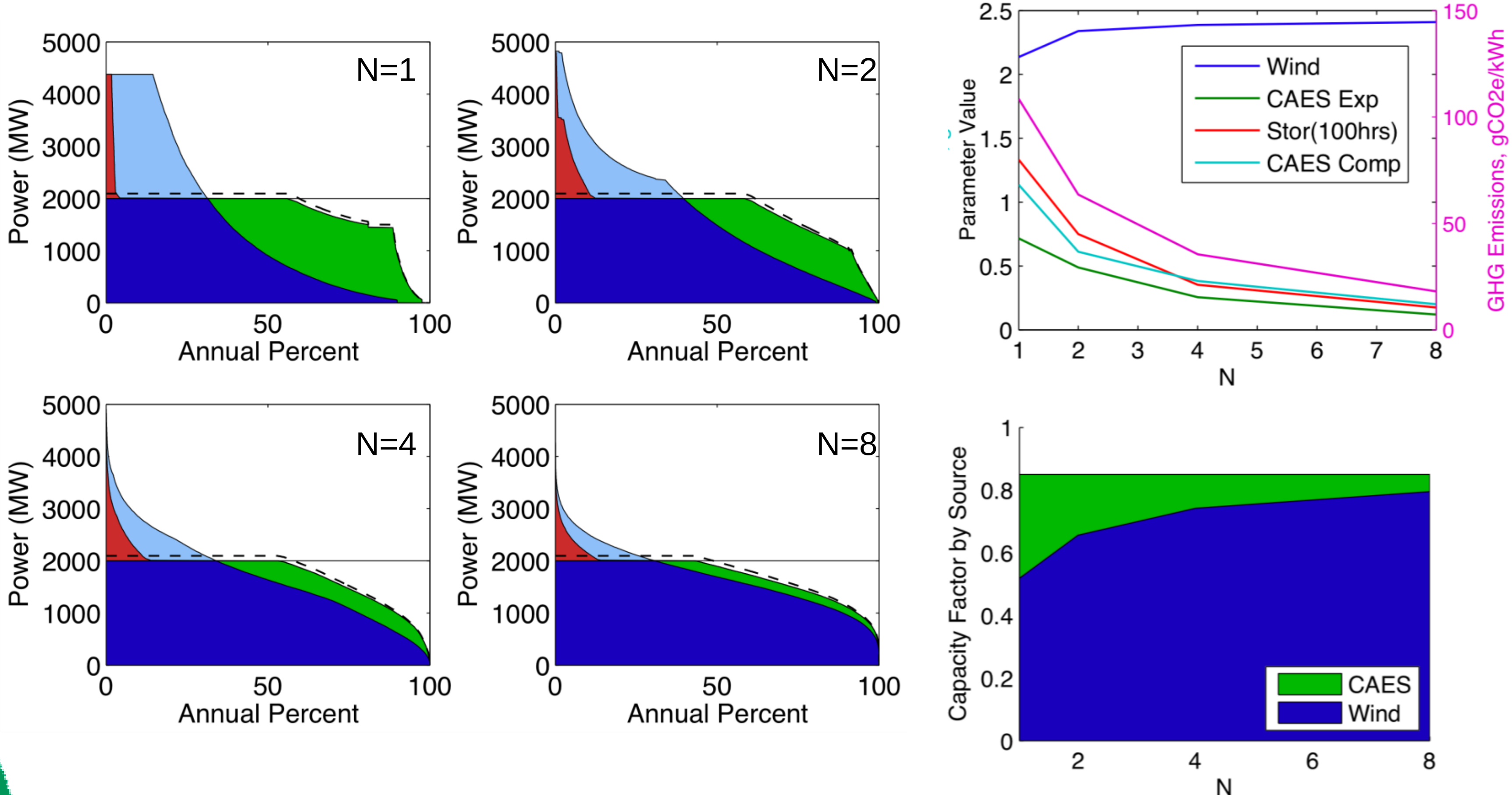
Resource Aggregation + Wind/Storage

Storage system size decreases for increasing number of wind resources



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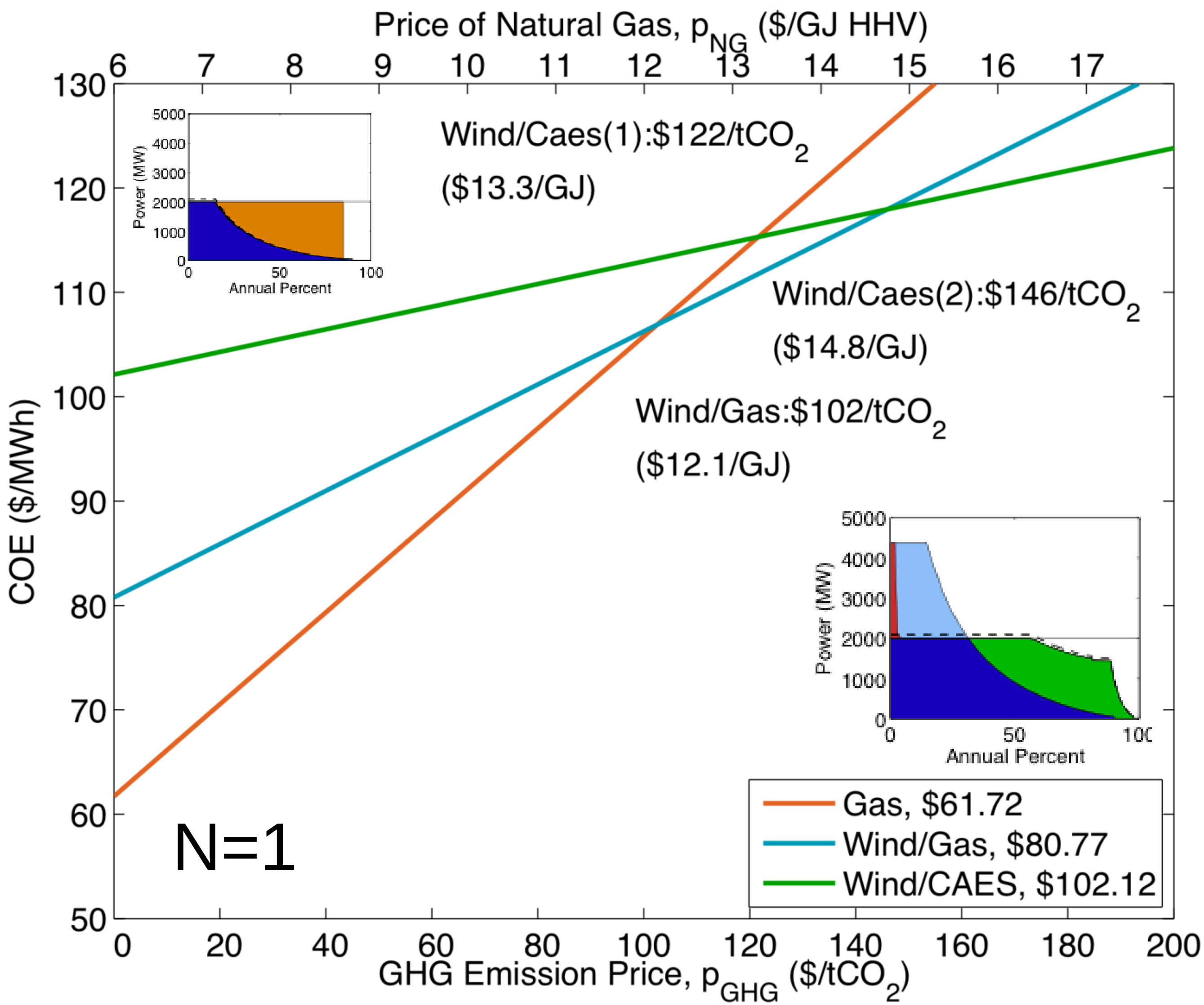
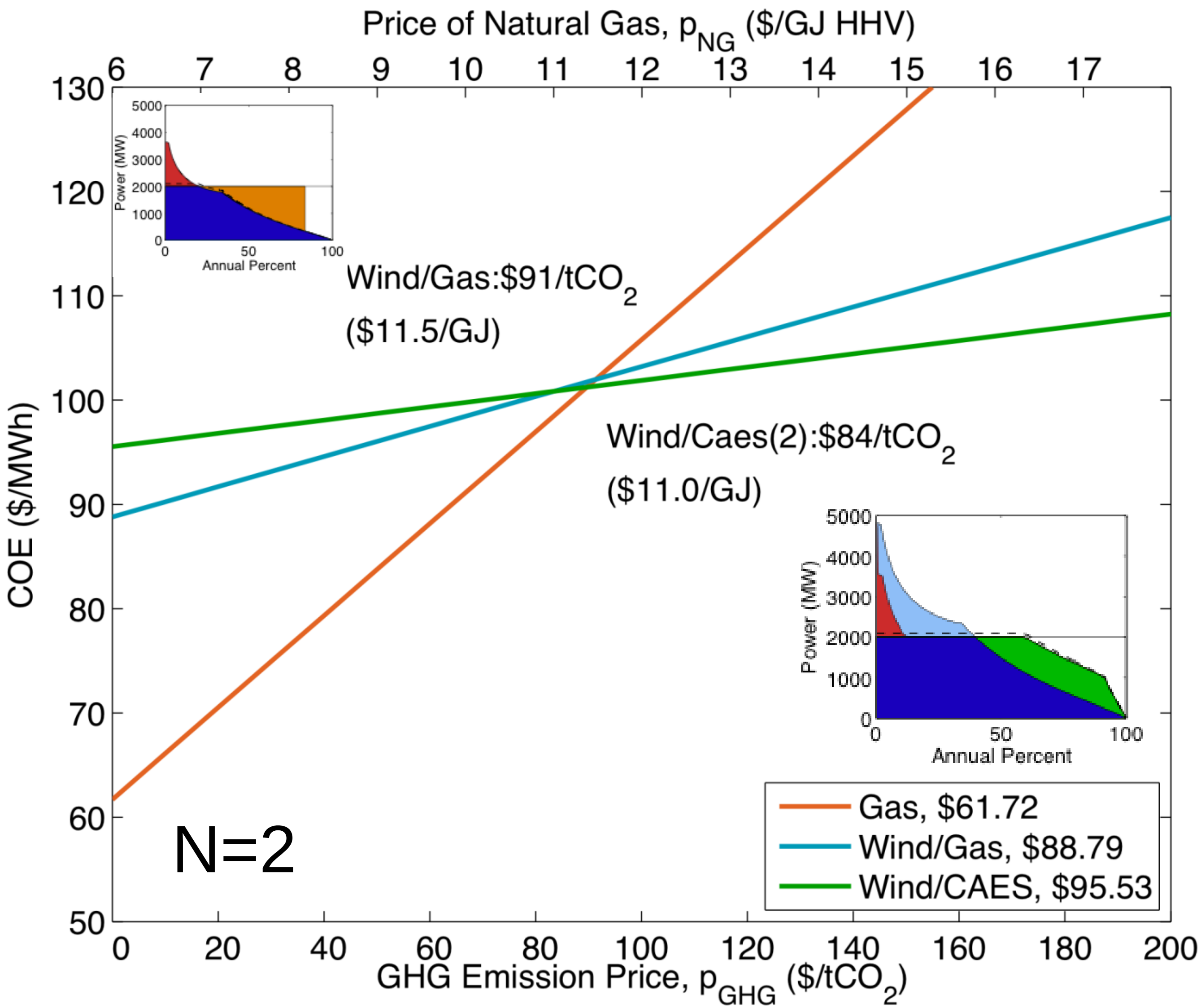
Impact on Cost of Energy



194

Impact on Cost of Energy



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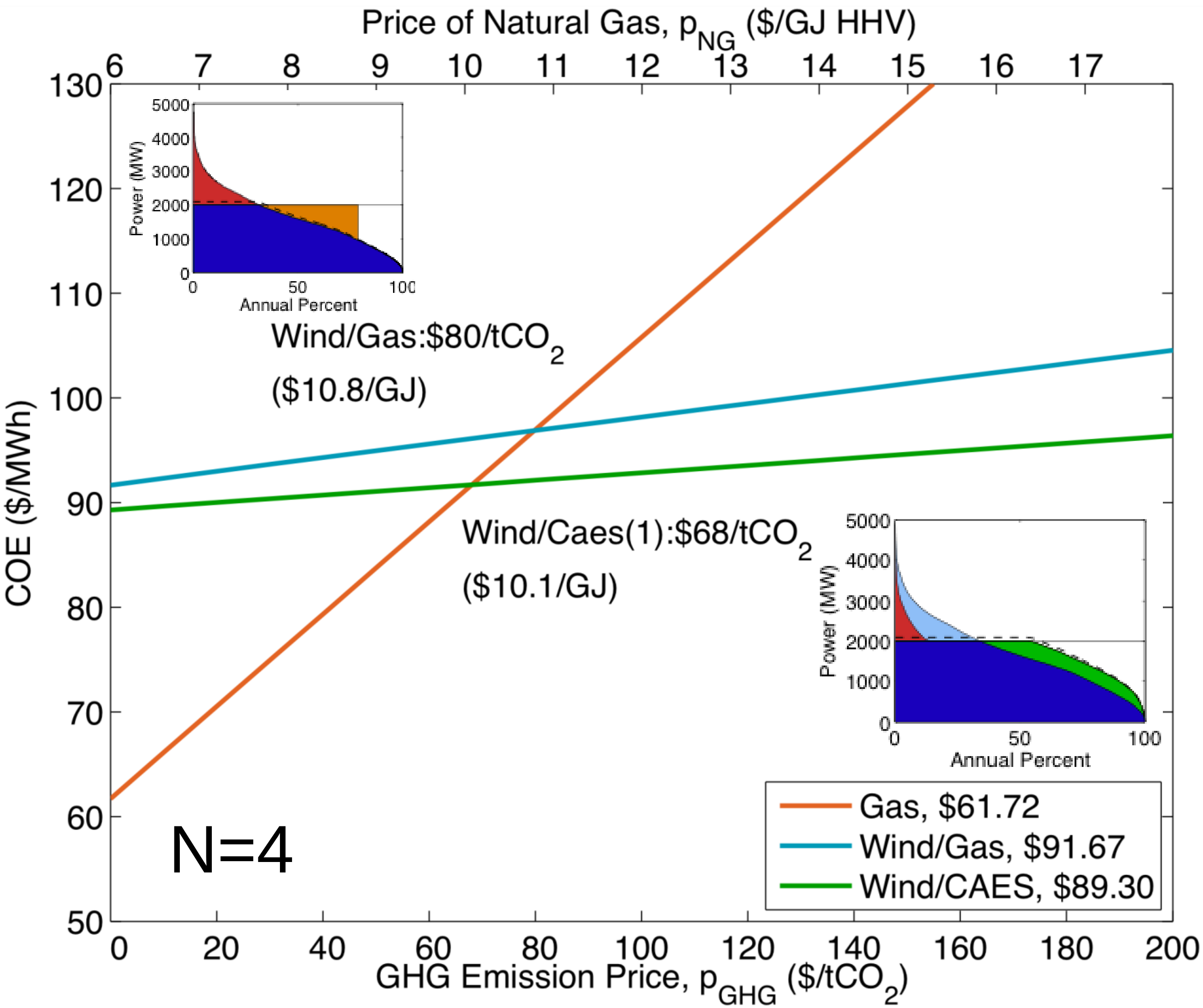
Impact on Cost of Energy



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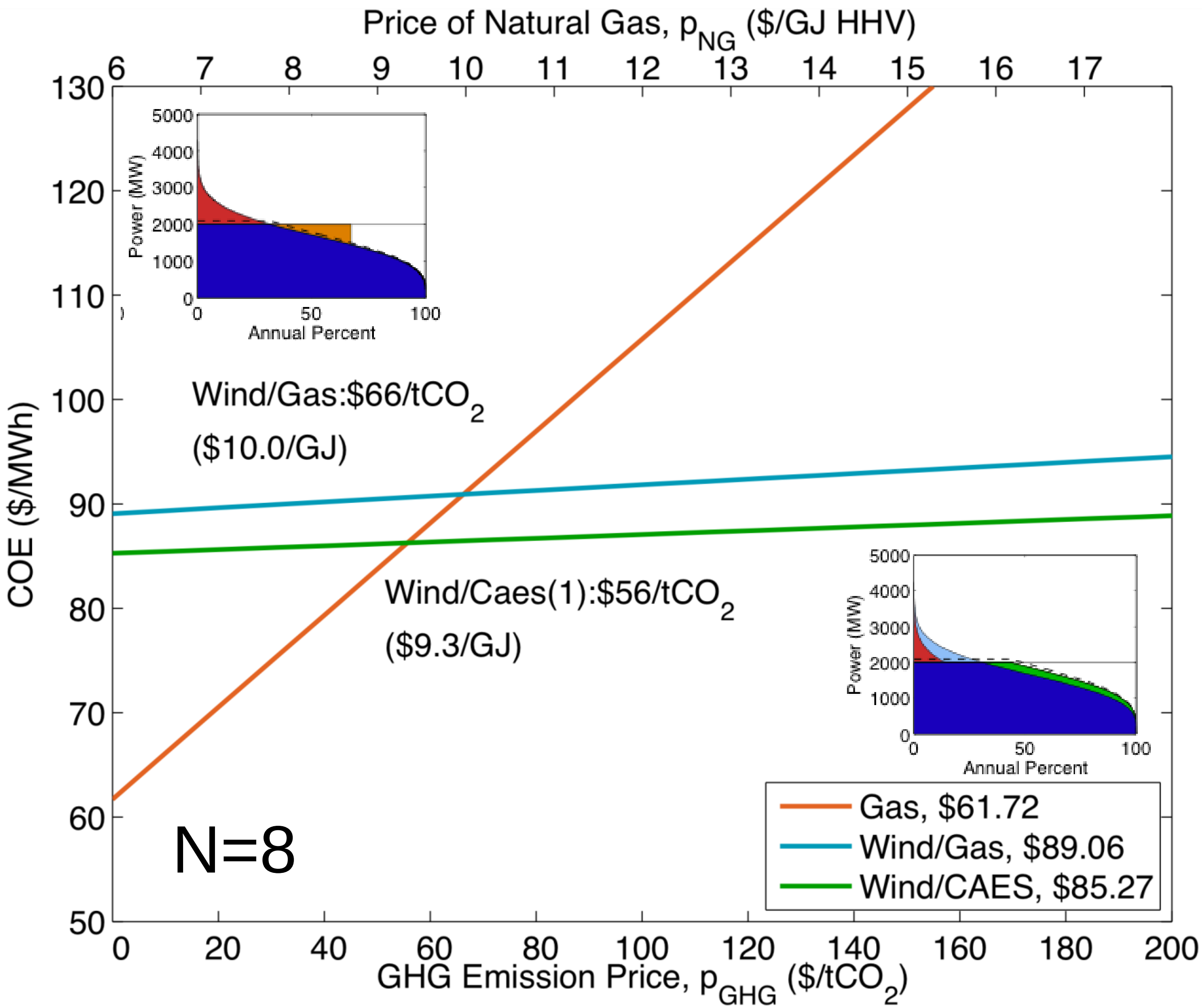
Impact on Cost of Energy



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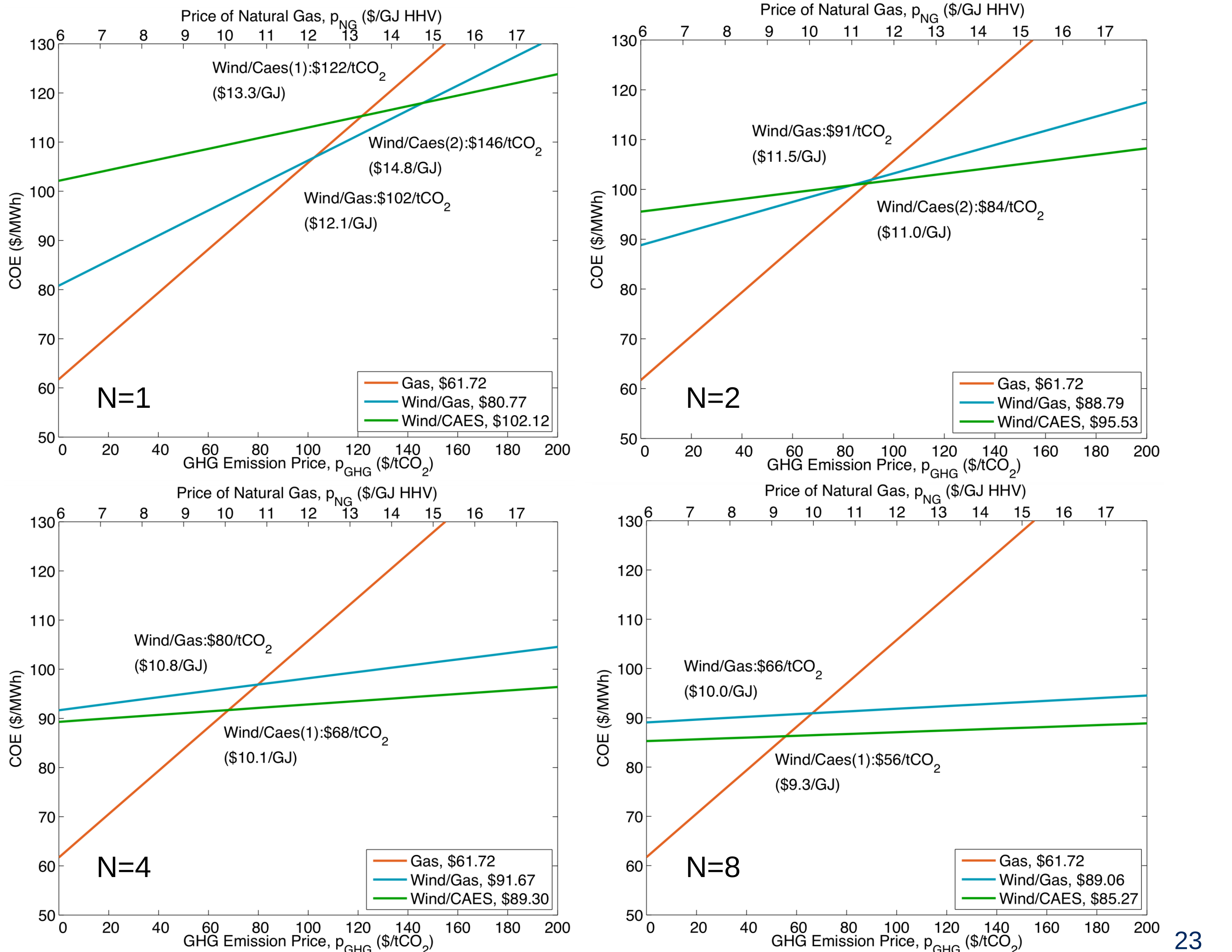
Impact on Cost of Energy



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Conclusions

- Aggregation of wind resources reduces balancing requirements for wind
- CAES surface turbomachinery and storage reservoir size can be reduced substantially
- Benefit of reduced backup for Wind/Gas offset by large increase in wind capacity requirement
- The relative cost and entry price of Wind/Gas and especially Wind/CAES decline substantially
- Resource aggregation and energy storage can be complimentary means of balancing wind

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Acknowledgements

This research was developed in collaboration with several mentors colleagues and contributors past and present:

Robert Williams
Jeffery Greenblatt
David Denkenberger
Robert Socolow
Al Cavallo

10. CAES Studies at the National Renewable Energy Laboratory

Paul Denholm, Easan Drury, *NREL*

NREL is involved in several projects to analyze the role of CAES in high-renewable futures. This paper will review these activities which include:

a) Analysis of the value of CAES in wholesale energy markets considering co-optimization with ancillary services. These studies include the part-load performance of CAES plants, as well as the constraints on operating the expansion turbine while offering spinning reserves. Several advanced cycles which improve performance or lower capital cost are also considered.

b) The value of CAES in reducing transmission constraints for remote wind and solar projects. Given the difficulty of transmission siting, a number of analyses have proposed combining wind energy and storage to increase transmission line loading and reduce transmission costs. This study quantifies the benefit of co-location considering the tradeoffs between reduced transmission costs and increased transmission constraints on CAES operation

c) The role of CAES in reducing wind and solar curtailment at high penetration. At extremely high penetration of variable sources, wind and solar generation may become unusable due to limited coincidence between energy supply and demand. Several studies have examined the value of CAES in reducing curtailment and increasing the penetration of variable generation into the U.S. power grid.

Dr. Paul Denholm is a Senior Energy Analyst in the Strategic Energy Analysis Center at the National Renewable Energy Laboratory. His research interests include examining the technical, economic, and environmental benefits and impacts of large-scale deployment of renewable electricity generation, including the role of enabling technologies such as energy storage, plug-in hybrid electric vehicles and long distance transmission. He holds a B.S. in physics from James Madison University, an M.S. in instrumentation physics from the University of Utah, and Ph.D. in Environmental Studies and Energy Analysis from the University of Wisconsin-Madison.

Dr. Easan Drury is an Energy Analyst in the Strategic Energy Analysis Center at the National Renewable Energy Laboratory. His research interests include developing market penetration models for renewable technologies, and examining the technical and economic impacts of large-scale renewable energy deployment. He holds a B.A. in physics from the University of California, Berkeley, and a M.S. and Ph.D. in Engineering Sciences from Harvard University.

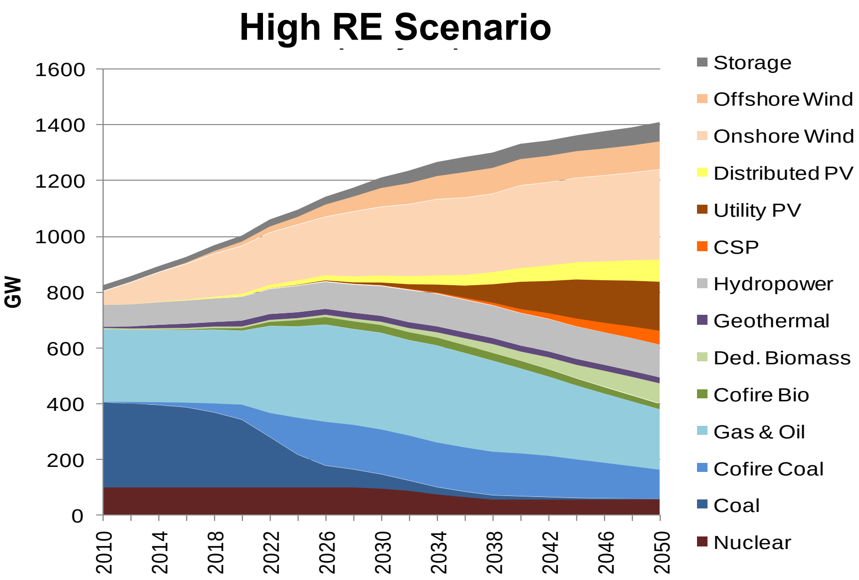
NREL National Renewable Energy Laboratory
Innovation for Our Energy Future

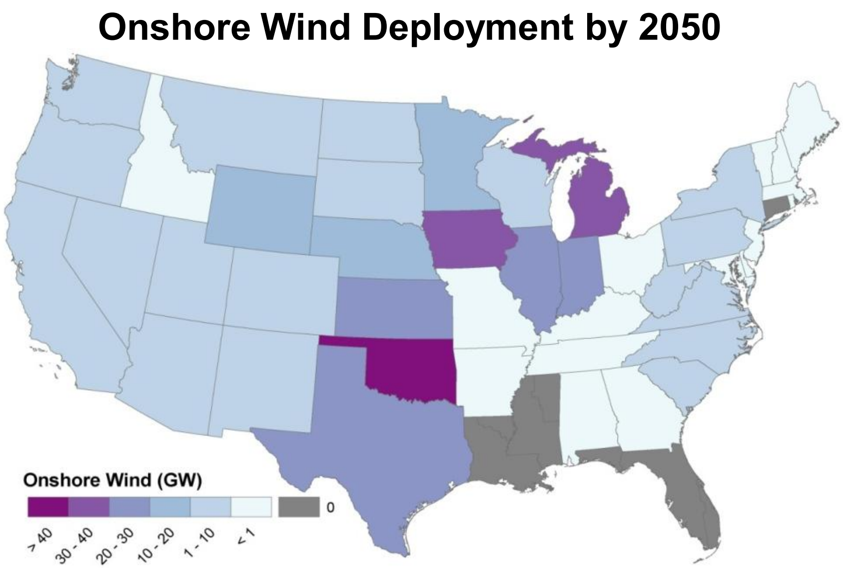
CAES Studies at the National Renewable Energy Laboratory

Easan Drury (easan.drury@nrel.gov)
Paul Denholm

2nd CAES Conference
Columbia University
10 / 20 / 2010

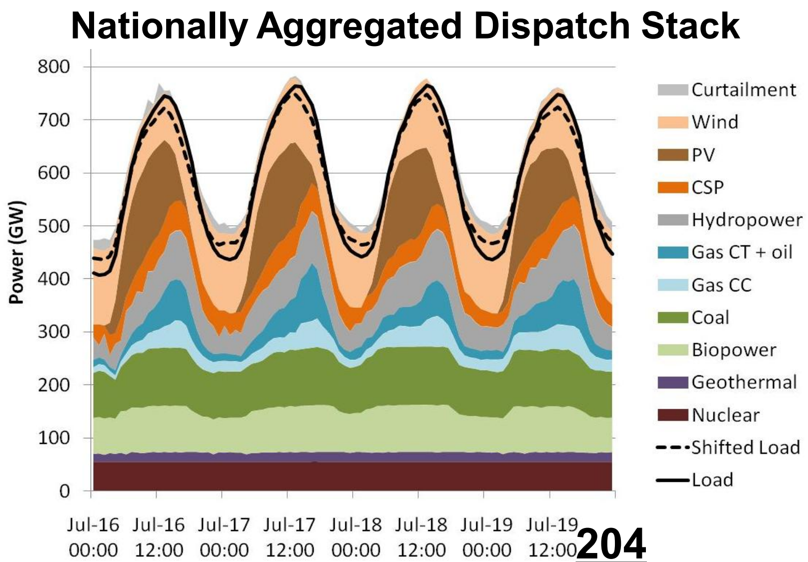
Energy Forecasting and Modeling Group at NREL





We model storage in several ways:

- **Capacity expansion**
- **Operational modeling**
- **Technical and economic analysis**



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Talk Outline

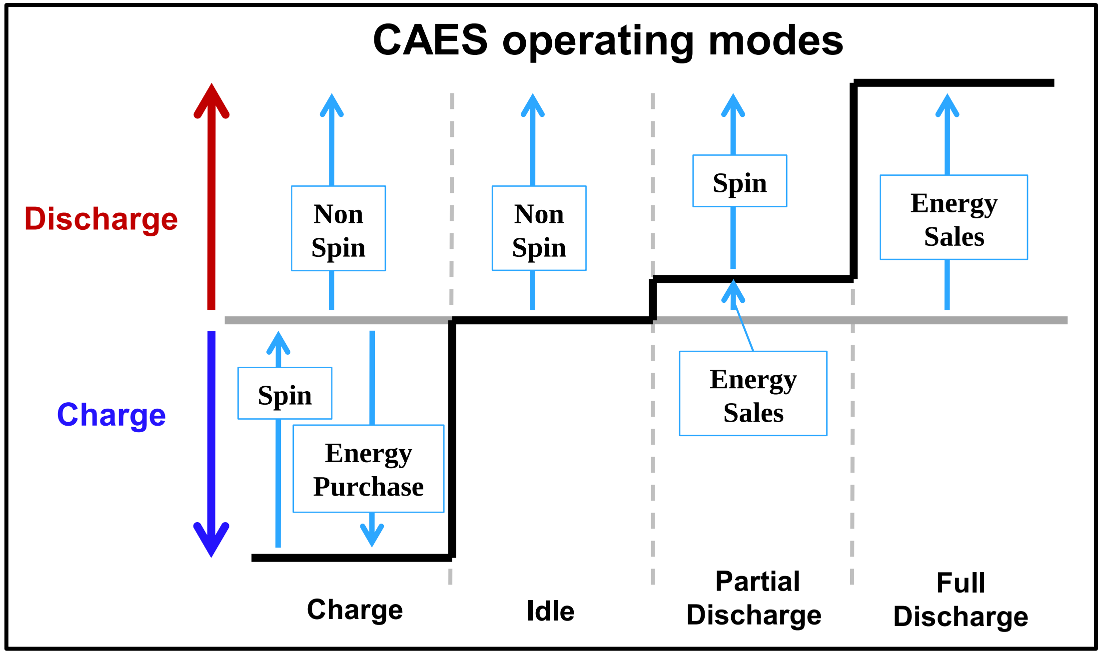
With higher RE penetration, CAES will be an important resource for:

- time shifting generation
- providing ancillary services
- increasing transmission line loading

- **Co-optimizing CAES dispatch for energy and reserves markets**
- **Co-locating CAES with wind to increase transmission line loading**
- **CAES deployment in a high RE scenario, and how CAES helps enable RE integration**

CAES optimal dispatch model

- Mixed integer linear program model
- Optimally dispatches a CAES device into historical energy and reserves markets
- True optimization model that lets you consider part load operation and the variation in heat rate



Dispatch model can be used to evaluate the economics of a CAES devices for:

- Several locations
- Years
- Device design and operational parameters
- Participating in several markets (Energy, Reserves, Regulation, Capacity)

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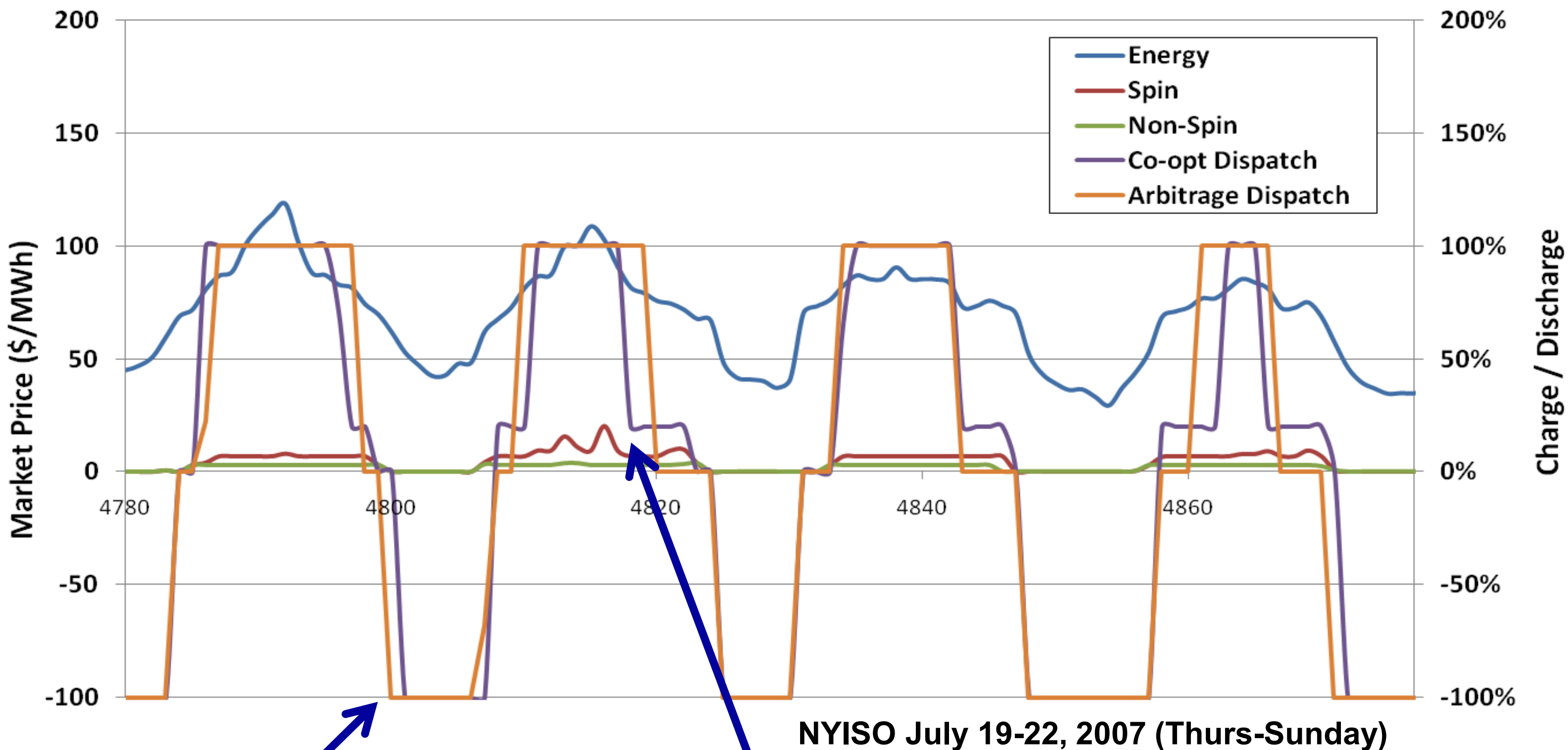
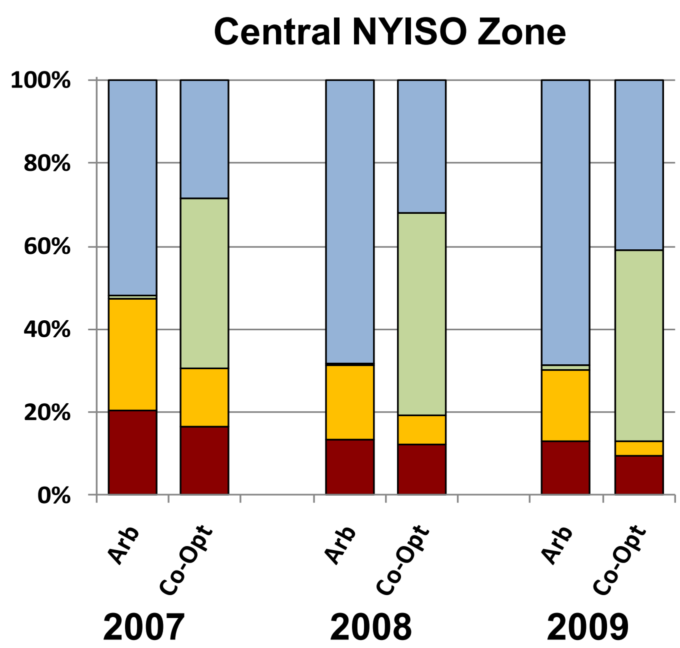
Characteristic summer CAES Dispatch

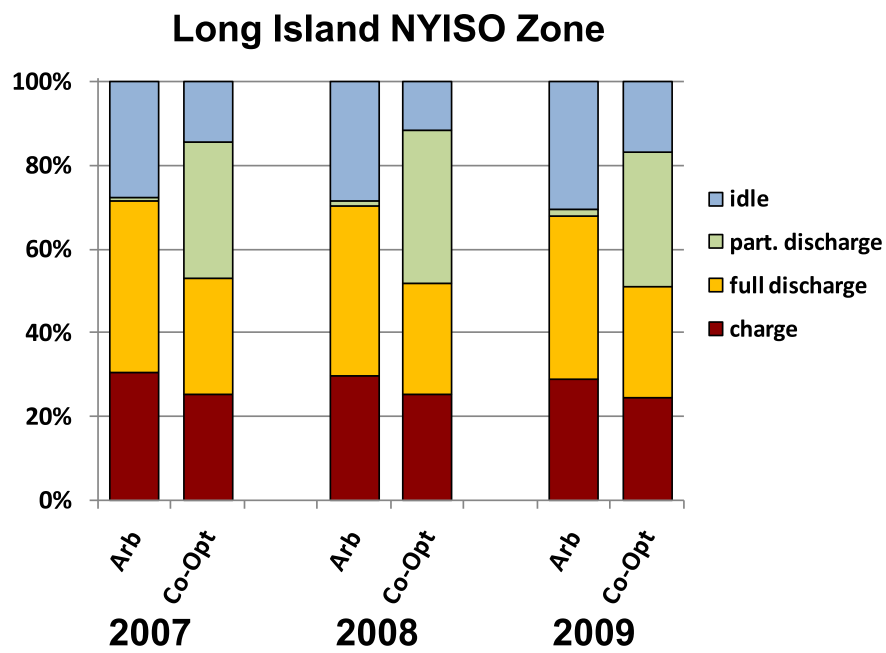


Both systems show similar charging characteristics

Co-optimized systems spend a large fraction of time partially discharging (providing spinning reserves), less time fully discharging (at higher mean prices), and less time idle

CAES operating characteristics



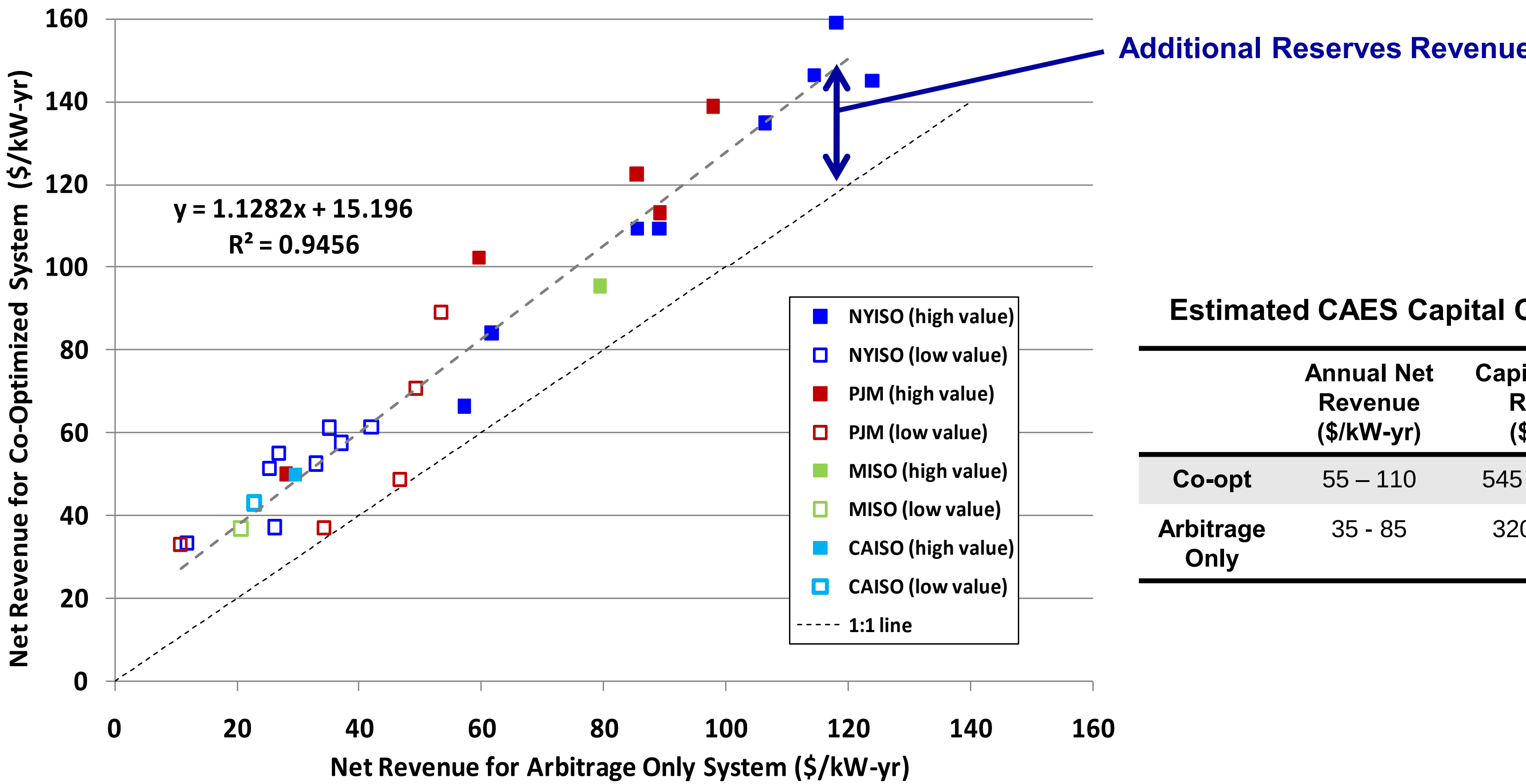


	2007	2008	2009
Mean Electricity Price ($/MWh)	61	68	36
Natural Gas Price ($/mmBTU)	8.2	10.6	5.4
Co-Optimized Net Revenue ($/kW-yr)	58	51	33
Arbitrage Only Net Revenue ($/kW-yr)	37	25	12

	2007	2008	2009
Mean Electricity Price ($/MWh)	158	178	83
Natural Gas Price ($/mmBTU)	8.2	10.6	5.4
Co-Optimized Net Revenue ($/kW-yr)	145	159	84
Arbitrage Only Net Revenue ($/kW-yr)	124	118	62

- **CAES dispatch characteristics are strongly driven by device location and market participation**
- **CAES arbitrage revenues are strongly driven by device location and interannual price variability**

Co-optimized and Arbitrage Only Net Revenues



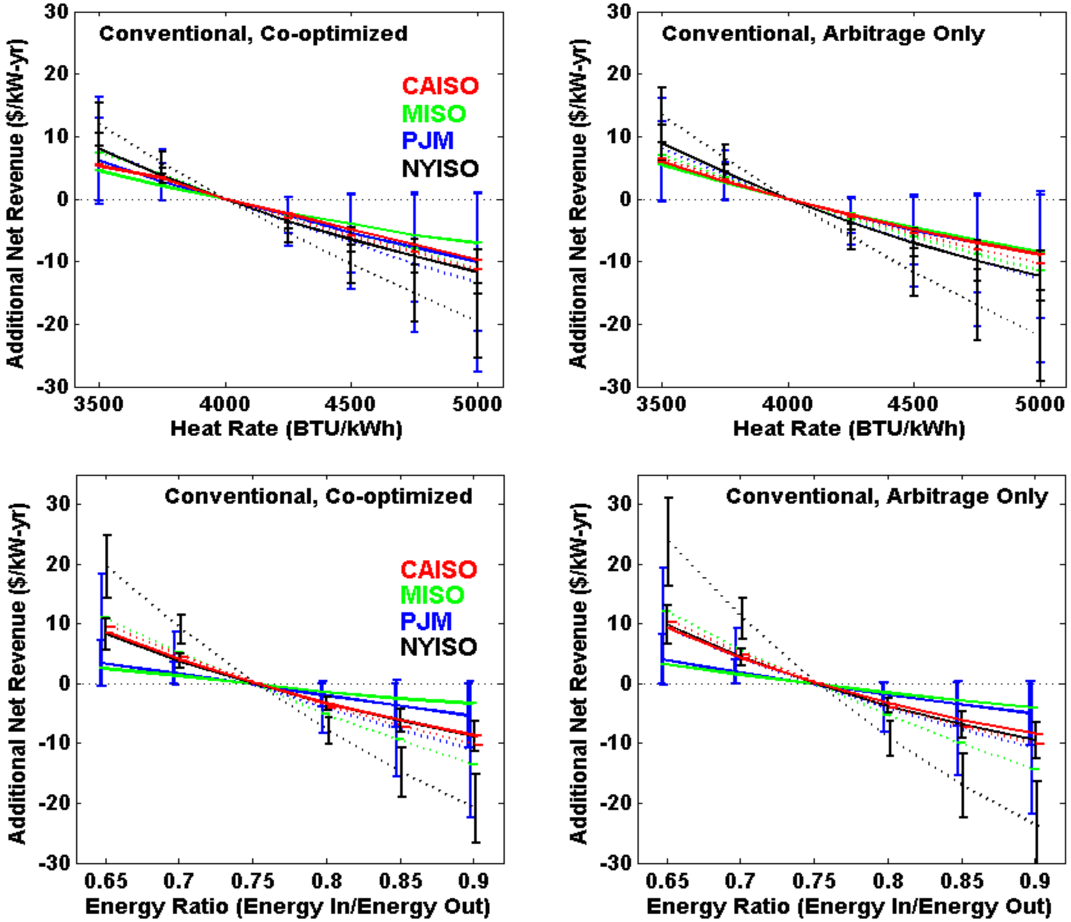
Estimated CAES Capital Costs

	Annual Net Revenue ($/kW-yr)	Capital Cost Range ($/kW)
Co-opt	55 – 110	545 – 1,000
Arbitrage Only	35 - 85	320 – 770

NYISO	**2002 - 2009**
PJM	**2005 - 2009**
MISO	**2009**
CAISO	**2009 - 2010**

- **Providing reserves increases net revenue on the order of $25/kW-yr (could support an additional $225/kW of capital cost)**
- **Arbitrage revenues have more interannual variability than reserve revenues**

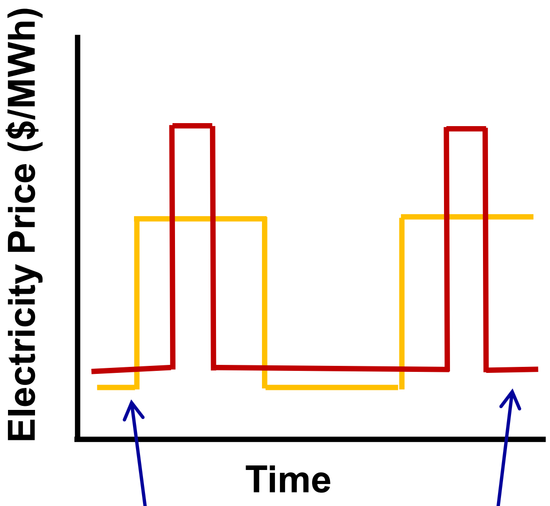
Sensitivity to Heat Rates and Energy Ratios



Reference Parameters:
Heat Rate = 4,000 BTU/kWh
Energy Ratio = 0.75
[Shainker 2007]

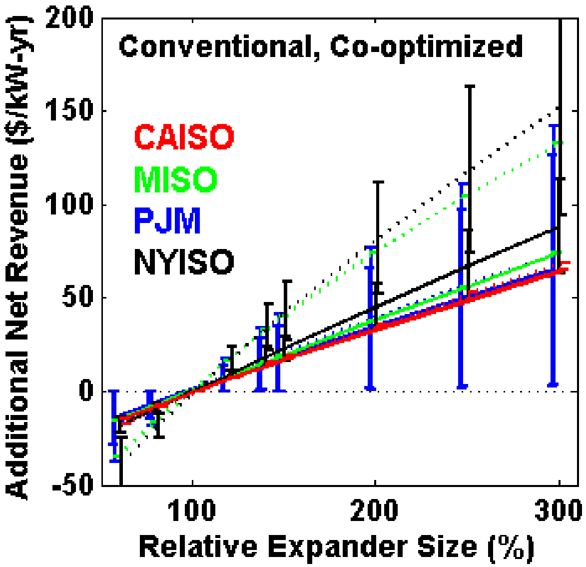
- **Arbitrage revenues are sensitive to efficiency, but reserve revenues are not (capacity resource)**
- **10% heat rate improvement increases net revenues by $5/kW-yr (~$45/kW cap. cost)**
- **10% energy ratio improvement increases net revenues by $3-8/kW-yr (~$25-75/kW cap. cost)**

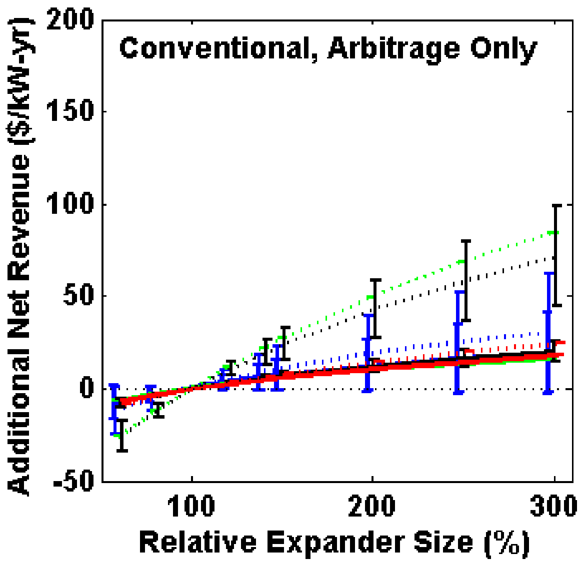
Optimally sizing the Compressor and Expander



Same compressor / expander size optimal

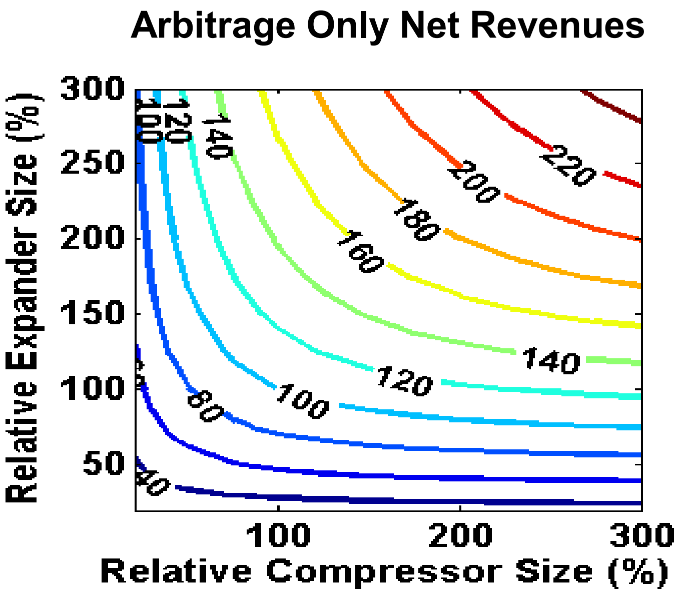
Oversized expander optimal





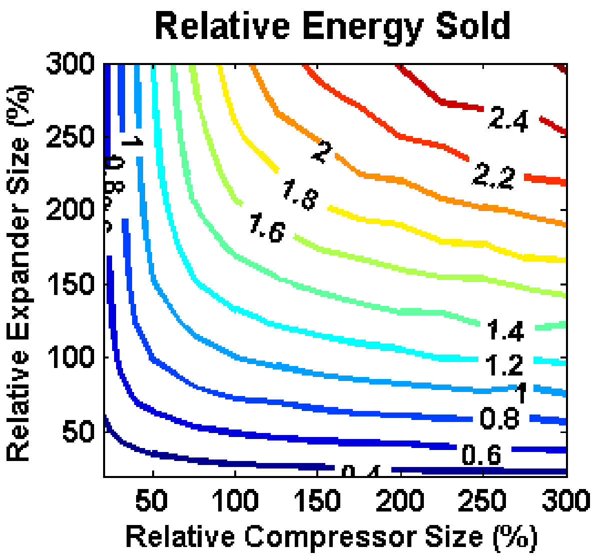
- Doubling expander size increases co-optimized net revenues by $35-70/kW-yr ($320 – 640/kW), and arbitrage only net revenues by $15-40/kW-yr ($135-365/kW)
- Doubling compressor sizes has less impact, on the order of $10/kW-yr ($90/kW)

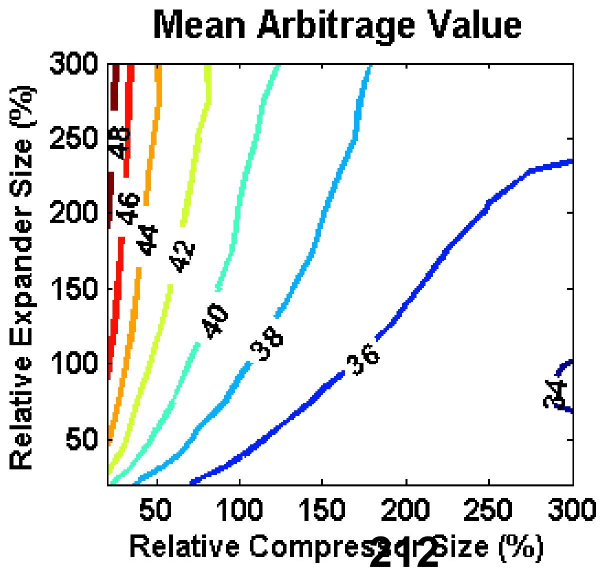
Arbitrage only net revenues (Central NYISO 2007)



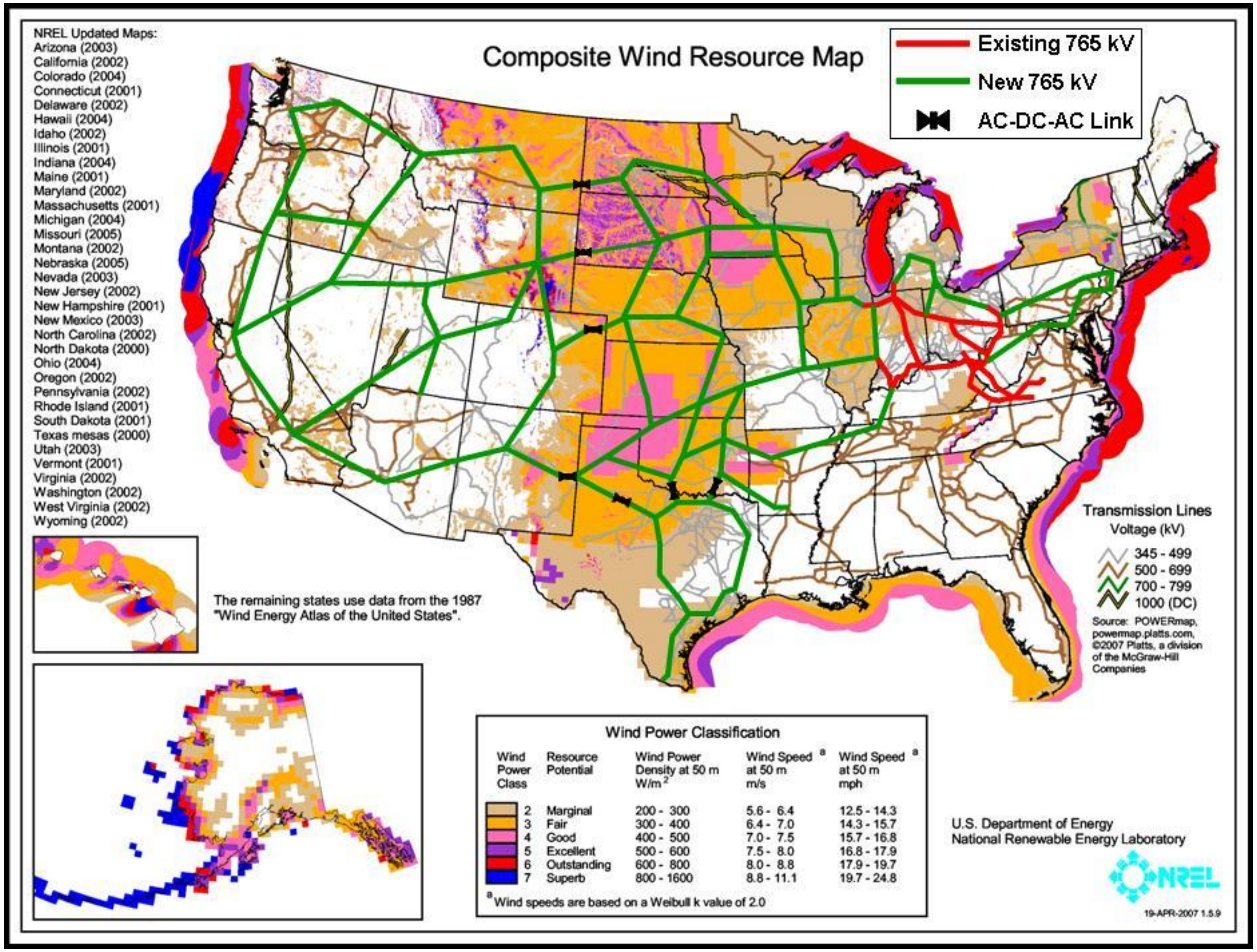
- Arbitrage only systems do not show a clear benefit from adjusting the expander to compressor ratio

- Increasing the expander and compressor sizes in tandem increases the amount of energy sold
- Adjusting relative sizes do not significantly impact mean arbitrage revenues





Economics of transmission constrained wind + CAES



Can we build this? If not, what are the alternatives?

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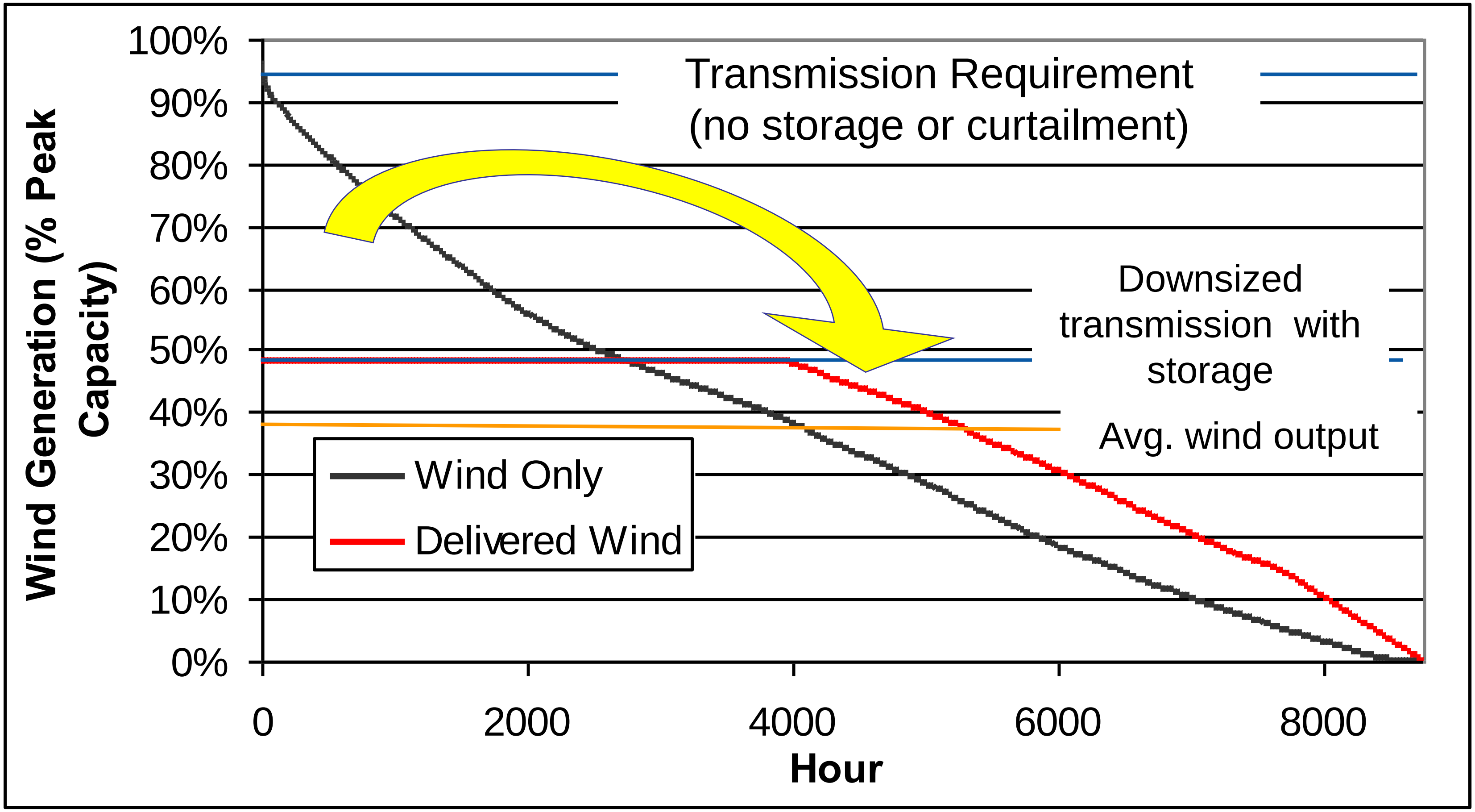
CAES as an Alternative to Transmission



- **Co-locating CAES with wind enables downsizing transmission**
- **But - Co-located CAES has lower arbitrage revenue than CAES sited at load**

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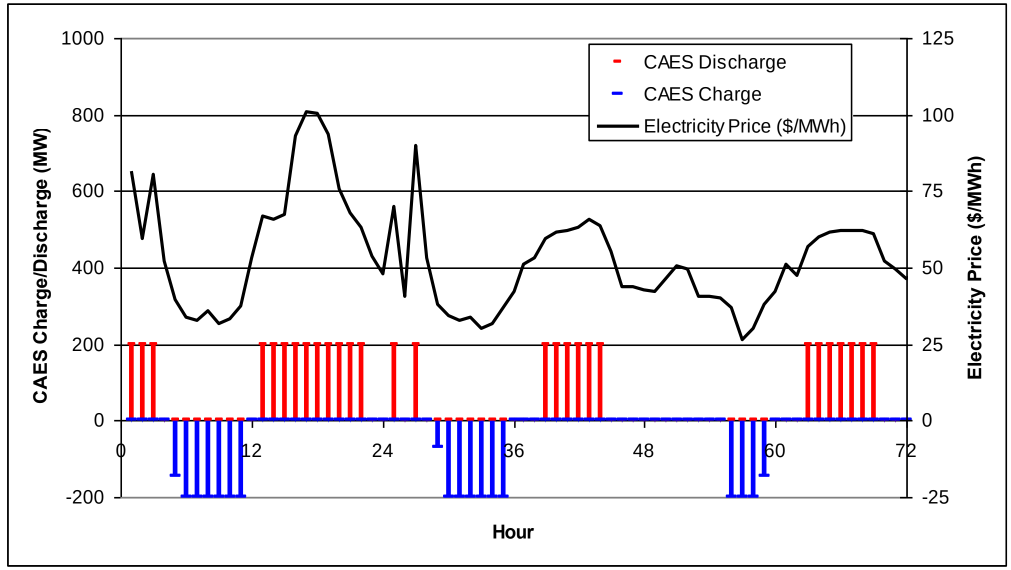
Trade-offs in collocating CAES with wind

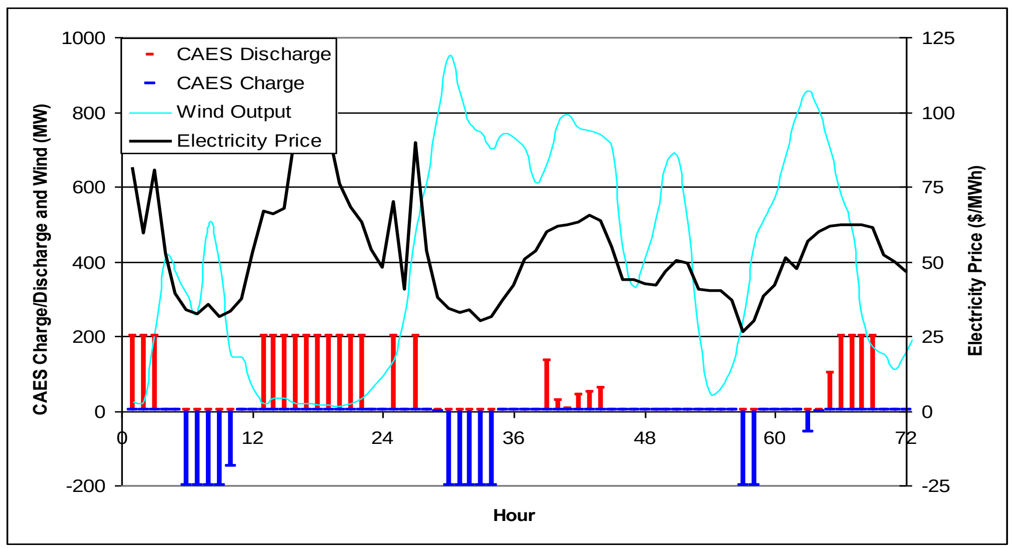
Load-sited CAES Dispatch

- no transmission constraints
- dispatch determined by hourly electricity prices



Wind-sited CAES Dispatch

- transmission constraints for CAES and wind
- dispatch is determined by hourly electricity prices and transmission capacity



ERCOT 2006

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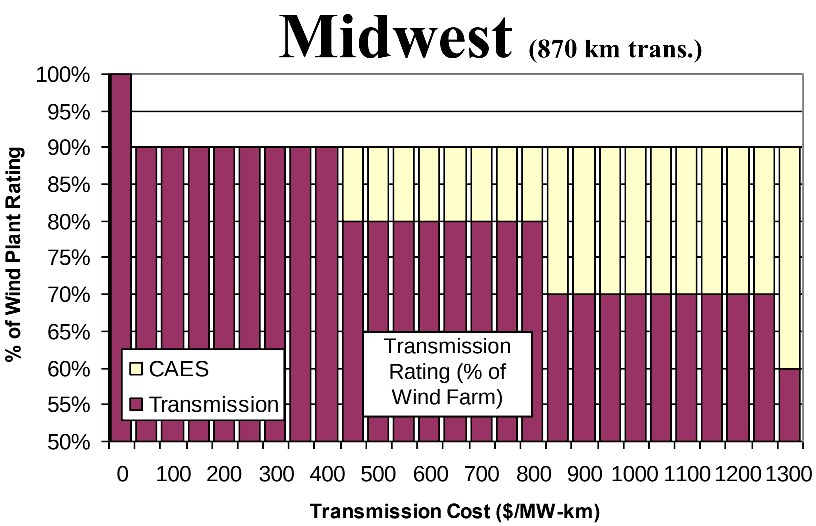
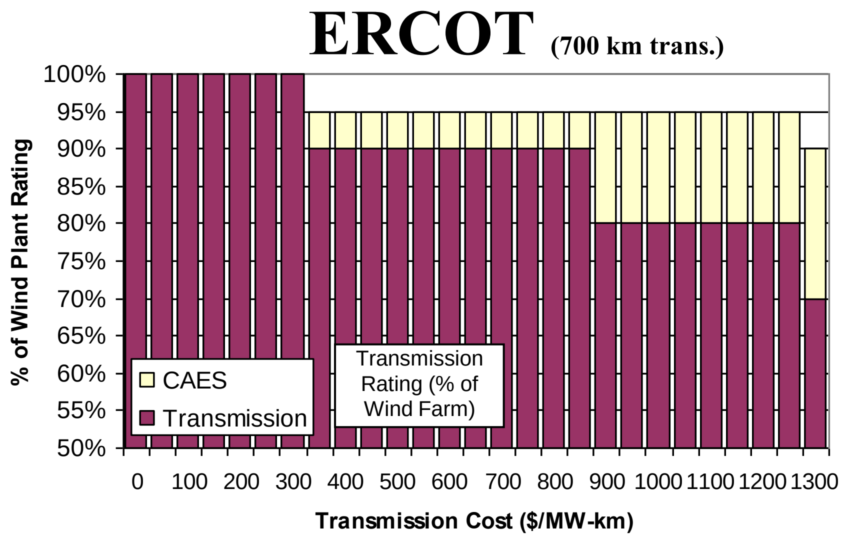
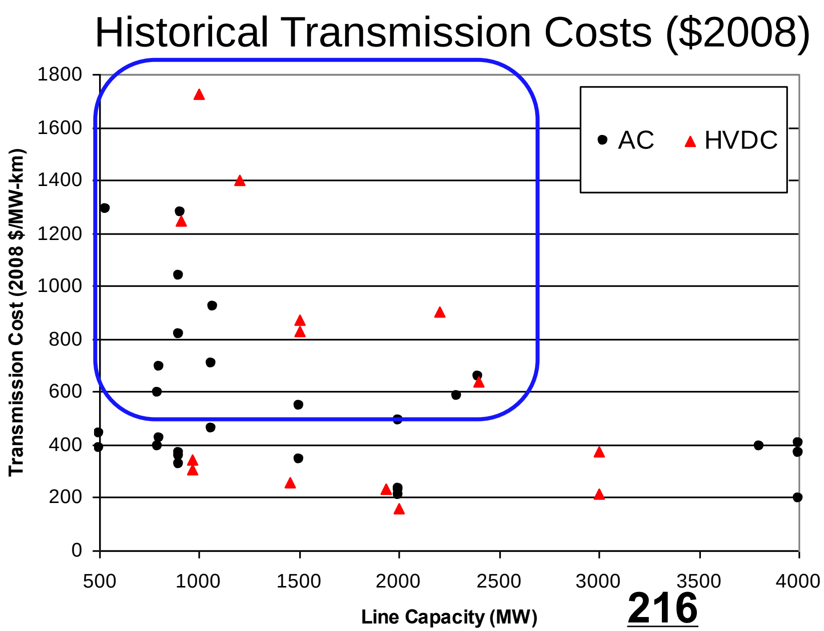
Optimum Mix of CAES* and Transmission





- **Co-locating CAES with wind resources becomes economic if:**
  - **Transmission costs > $400/MW-km**
  - **New transmission is unavailable**
- **Historical transmission costs suggest that several projects could be economic today**



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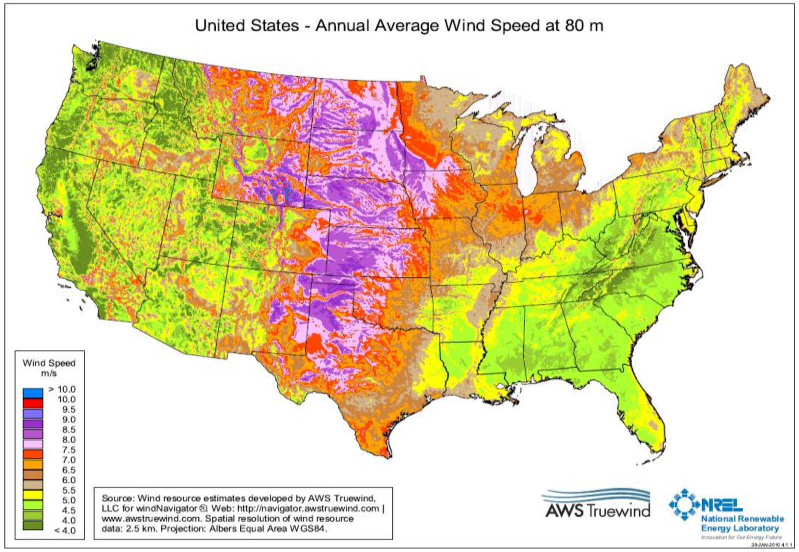
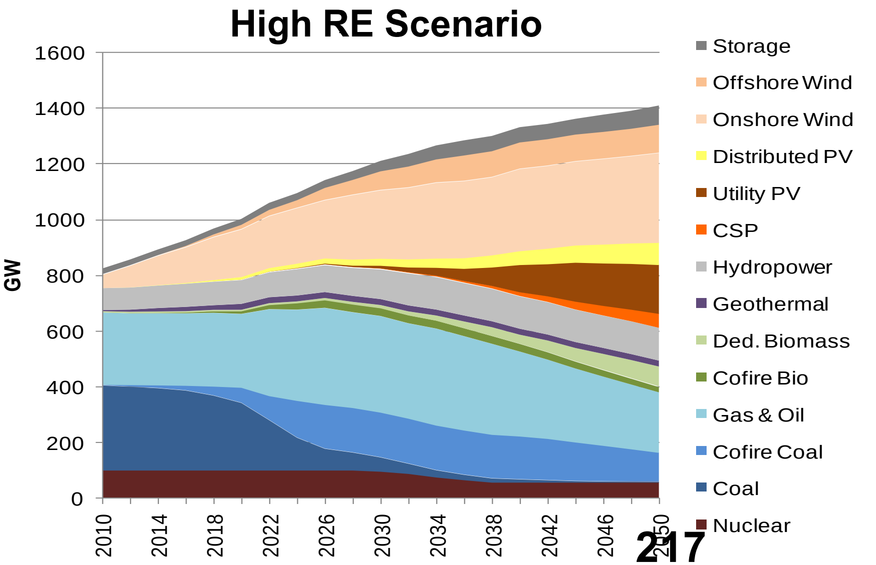
***Assuming $750/kW CAES w/ 20hrs storage, 0.72 energy ratio, 4,200 BTU/kWh**
Denholm and Sioshansi, *Energy Policy*, 37, 3149-3158, 2009

Regional Energy Deployment System (ReEDS)

- Multi-regional, multi-time period model of generation, capacity, and transmission infrastructure expansion in the U.S. electric sector through 2050
- Linear program optimizes capacity expansion and dispatch every 2 years for 20 year investment period
- Extensive GIS databases used to account for geographic diversity of renewable energy technologies
- Statistical treatment of resource variability (including correlations) – planning reserves, forecasting error reserves, surplus
- Used in the 20% Wind Study





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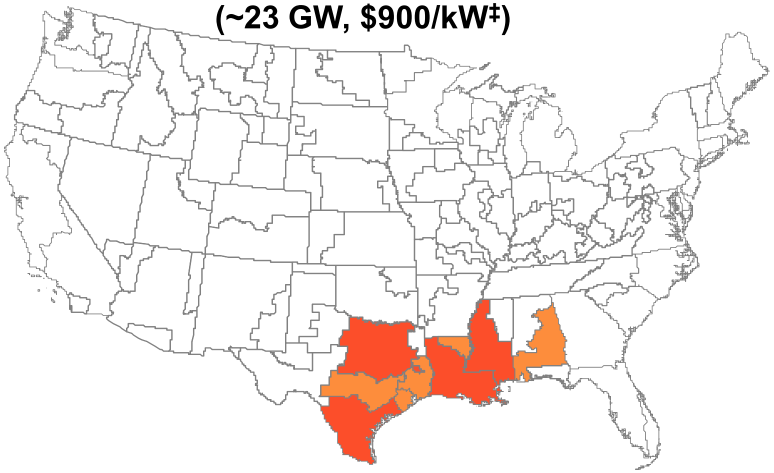
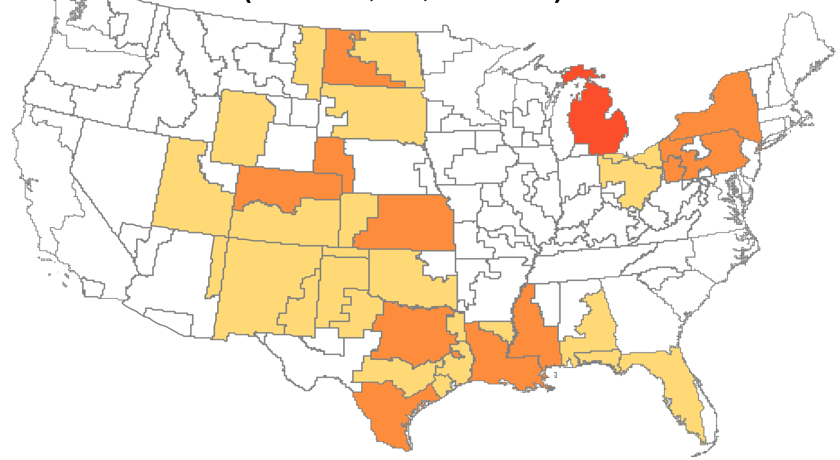
CAES deployment in a high renewable energy scenario

CAES technical potential in ReEDS†

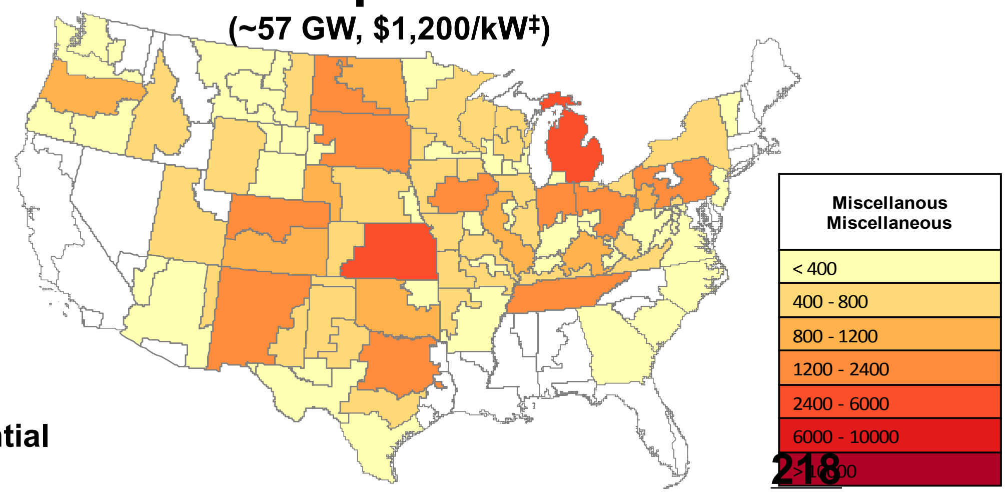
Domal Salt
(~23 GW, $900/kW‡)



Bedded Salt
(~37 GW, $1,050/kW‡)



Aquifer
(~57 GW, $1,200/kW‡)

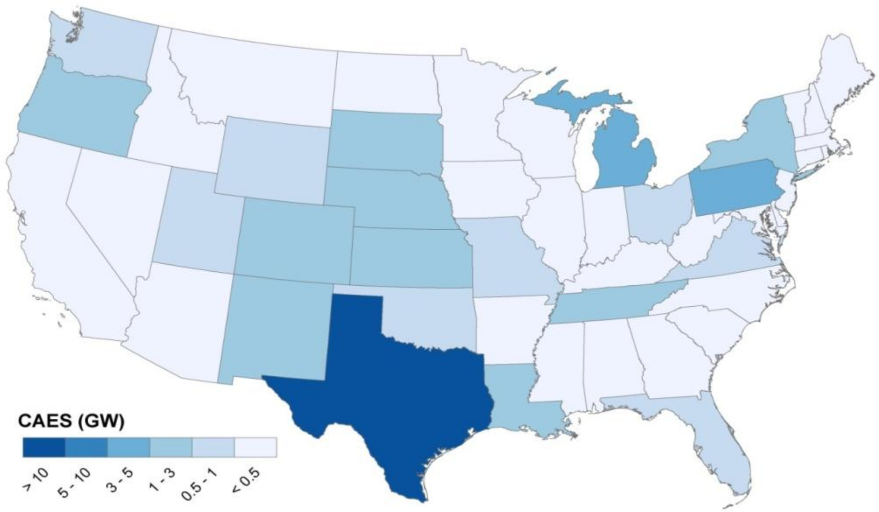


- **Does not include hard rock or abandoned mines**
- **Work in progress – we need to incorporate the latest estimates of technical potential and CAES costs**

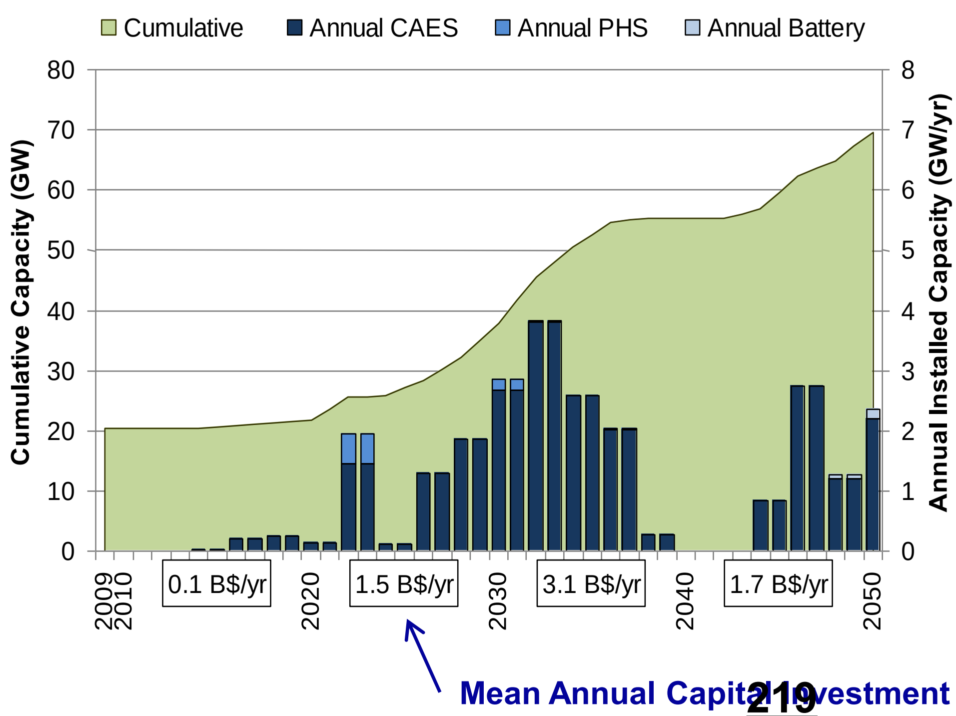
†Oak Ridge regional assessment of CAES technical potential
‡Black and Veatch, 2010

CAES deployment in a high RE scenario

2050 CAES deployment



- **47 GW CAES deployed by 2050**
- **Largely deployed in Texas (lower cost)**



- **CAES deployment peaks twice**
  - **2025-2040: corresponds to increasing wind penetration**
  - **2044-2050: corresponds to increasing PV penetration**
- **1 - 4 GW/year installation rate during peak periods**

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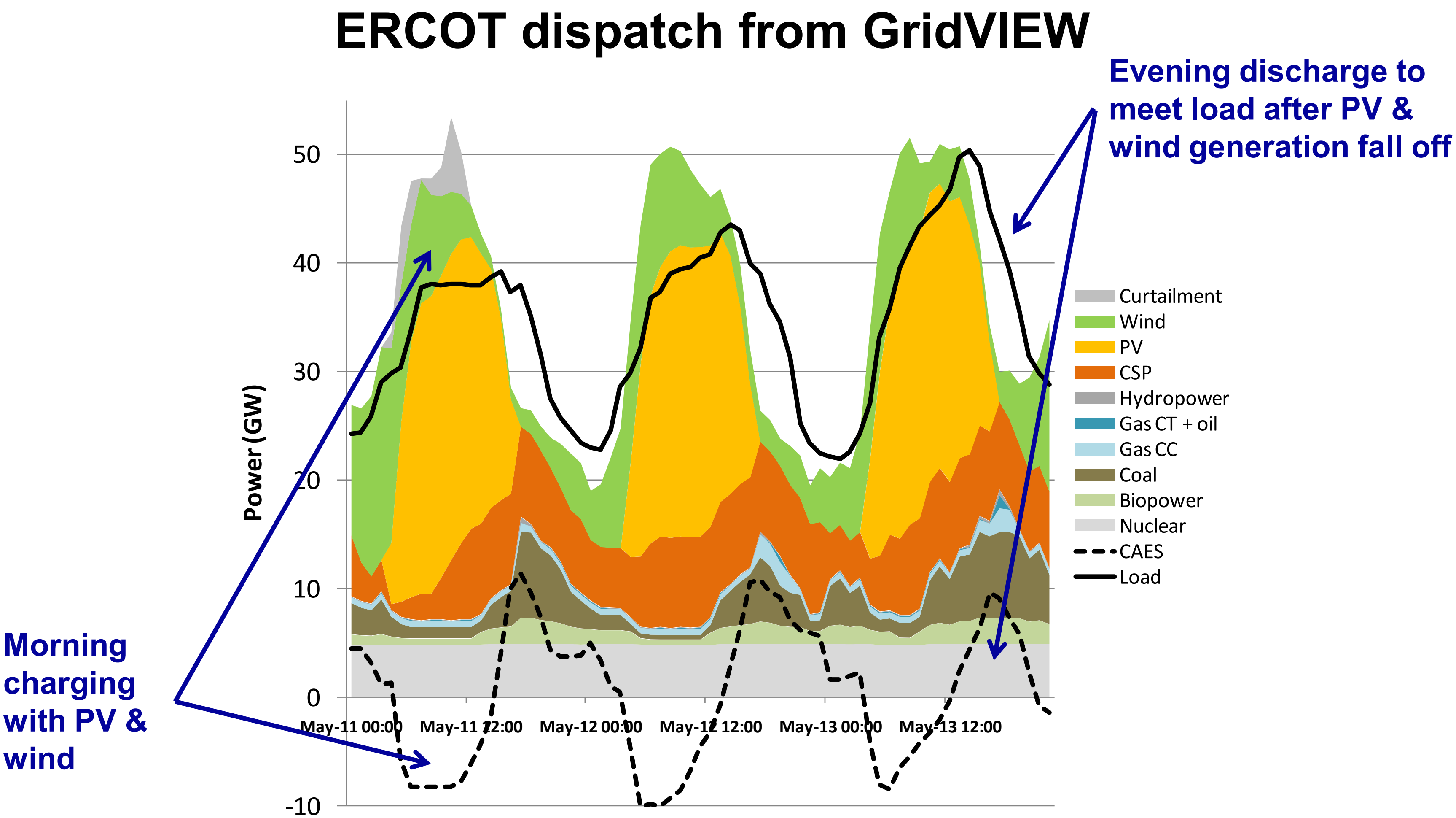
CAES in a high penetration RE scenario



- 70 GW peak load in ERCOT
- 60 GW variable renewables (25 GW wind, 28 GW PV, 8 GW CSP)
- 14 GW Bulk storage (all CAES)
- 35 GW conventional capacity (12 GW CCs, 8 GW CTs, 5 GW Nuclear, 9 GW Coal)

Conclusions

- Historical CAES arbitrage revenues about $35-85/kW-yr

- Dispatching for reserves increases revenue by about $25/kW-yr

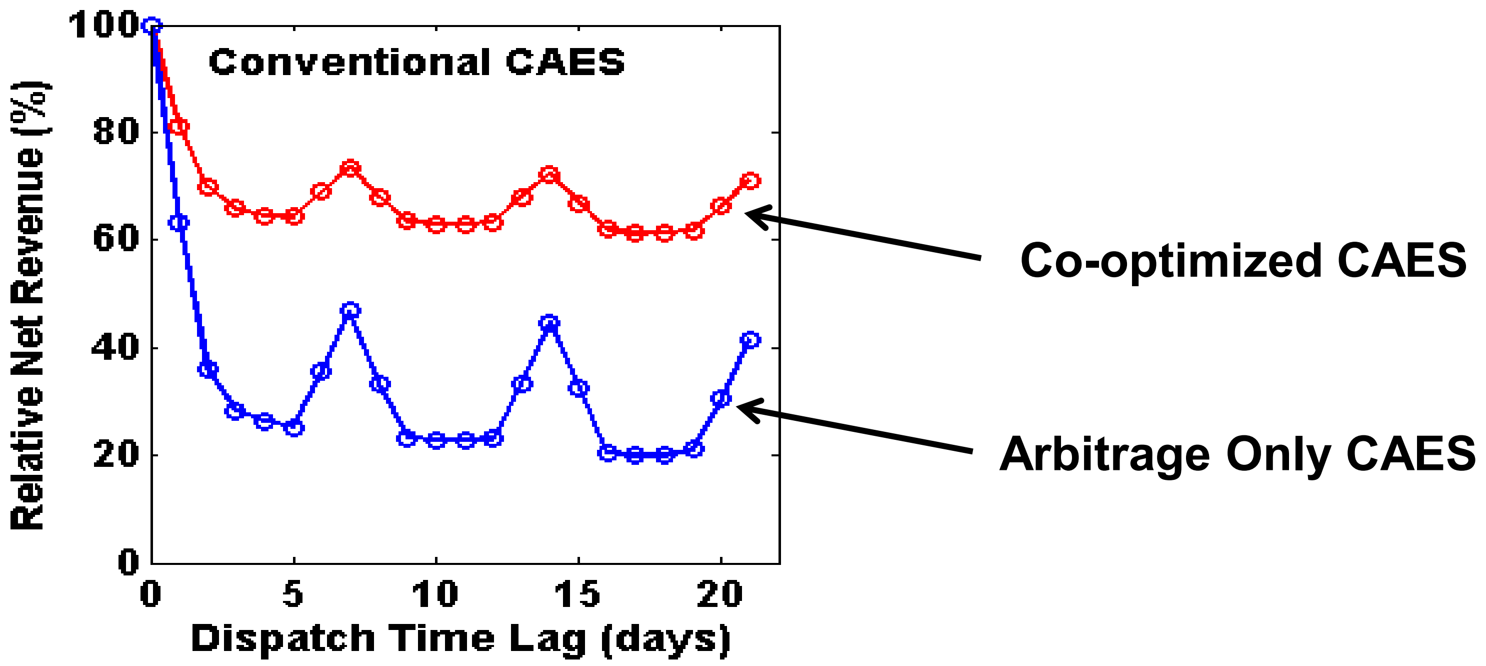
- CAES net revenues are driven by location, interannual variability, dispatch method, expander size; less strongly driven by compressor size, moderate improvements in device efficiency

- Co-locating CAES with wind becomes economic for transmission costs above $400-500/MW-km

- CAES economically deployed in high RE scenarios at a few GW/yr to enable wind and PV integration

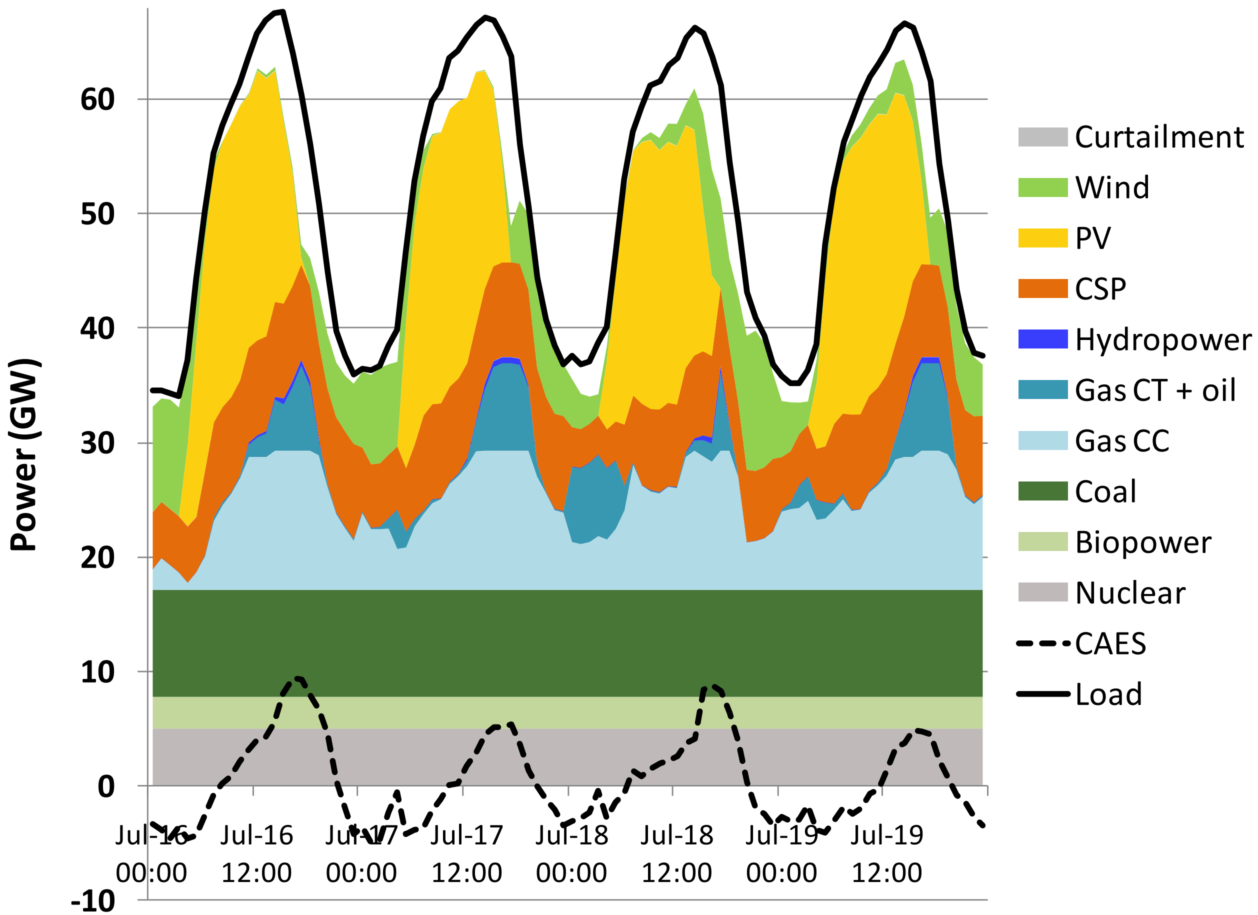
Questions?

Sensitivity of CAES net revenues to the perfect foresight assumption



Central Region NYISO, mean from 2002-2009

CAES in a high penetration RE scenario (ERCOT)



- **70 GW peak load in ERCOT**
- **35 GW conventional capacity (12 GW CCs, 8 GW CTs, 5 GW Nuclear, 9 GW Coal)**
- **60 GW variable renewables (25 GW wind, 28 GW PV, 8 GW CSP)**
- **14 GW Bulk storage (all CAES)**

11. Renewable and Sustainable Energy Research at the Center for Life Cycle Analysis

Vasilis Fthenakis, *Columbia University*

The Center for Life Cycle Analysis (CLCA) was formed in May 2006 with the mission of guiding technology and energy policy decisions with data-based, well balanced and transparent descriptions of the environmental profiles of energy systems.

The CLCA research on renewable and sustainable energy systems includes the following topics: 1) Thin-Film PV Life Cycle Analysis; 2) High-Concentration PV LCA; 3) Nano-material PV LCA; 4) Building Integrated PV LCA; 5) PV and CSP LCA Harmonization; 6) Solar, Nuclear and Fossil-fuel Cycles Comparative LCA; 7) Power Industry Supply Chain Hybrid LCA; 8) Minimizing Large PV Plant Conflicts with Wild-Life; 9) PV Recycling Technologies; 10) PV Recycling Cost Optimization; 11) Modeling the Synergy of PV and Wind; 12) Modeling PV-CAES Plants; 13) GIS-based Models of Wind and Solar Plant Sites; 14) Effects of Clouds in Large Scale PV Production; 15) Modeling Large Scale Storage for Solar and Wind Power.

Renewable and Sustainable Energy Research at CLCA

Vasilis Fthenakis

Director, Center for Life Cycle Analysis (CLCA), Columbia University
and
PV Environmental Research Center, Brookhaven National Laboratory

email: vmf5@columbia.edu
web: www.clca.columbia.edu

The Mission

- The mission of the Center for Life Cycle Analysis (LCA) is to guide technology and energy policy decisions with data-based, well balanced and transparent descriptions of the environmental profiles of energy systems.

CLCA Current Research Topics

- Resource Sustainability
  - Materials, Water, Land
- Life Cycle Analysis (LCA)
  - Thin film PV
  - High concentration PV
  - Nano-material PV
  - Building integrated PV
  - PV and CSP harmonization
- PV Recycling
  - Develop separation technologies
  - Infrastructure cost optimization modeling

Publications & Presentations 2006-2010

22 Peer-Review Journal Articles

20 Conference Proceedings Articles

8 Invited Keynote Presentations

25 Other Conference, Workshop, Symposia Presentations

Recognition by the Scientific Community

SCIENCE NEWS
THE WEEKLY NEWSMAGAZINE OF SCIENCE

Greener Green Energy: Today's solar cells give more

ieee spectrum online
For Tech Insiders

How free is Solar Energy?

Environmental Science & Technology

Science News
February 6, 2008

New photovoltaics change costs

The New York Times

Photovoltaic Cells Are Still Very Green, Comparative Test Shows *February 26, 2008*

SCIENTIFIC AMERICAN

Dark Side of Solar Cells Brightens
A life cycle analysis proves that solar cells are cleaner

Newsday, June 2010

Barons, Sept. 2010

Impacts on Policy Making

- Expert Workshops
  - German Ministry Environment (BMU)
  - French Ministry of Energy, Ecology, Land Management
- WEEE and RoHS Directives
- Bureau Land Management-DOE Environmental Impact Statements

CLCA Proposed Research Topics

- **Power Industry Supply-Chain LCA**
- **Utility RE Power Plant Assessments**
  - **Environmental /Wild Life /Land Use**
  - **Effects of clouds on PV**
  - **Modeling PV-Wind integration**
  - **Modeling of CAES**
  - **GIS-based optimization of wind and solar site selection**

12. GIS-based tools for optimizing site selection for wind and solar power plants

Rob van Haaren, Vasilis Fthenakis, *Columbia University*

Site selection is enabled via GIS-based tools and detailed simulations are based on hourly performance and load data for specific regions. The architecture of these models and some preliminary results of applying those in NYS will be presented.

Rob van Haaren finished his BS at the University of Technology in Eindhoven, the Netherlands. After this, he came to Columbia University to pursue his MS in Earth Resources Engineering and wrote his thesis on Life-Cycle Analysis of different composting methods. Van Haaren is now a PhD student at the same department, working under the supervision of Professor Fthenakis at the Center for Life-Cycle Analysis on Energy Storage in the electricity grid. In this research, his aim is to quantify the costs and environmental impact benefits from energy storage methods under high penetration of renewable electricity generation on the grid.

GIS-enabled Site selection and Grid modeling of Renewables

Rob van Haaren
PhD Student, Earth & Environmental Engineering, Columbia University

Advisor: Prof. V. Fthenakis

CAES 2010 Conference and Workshop, Columbia University, NYC, October 20, 2010

email: rv2216@columbia.edu
web: www.clca.columbia.edu

Outline

- GIS & Sustainable Energy Research
- Modeling spatial Rate of Return (ROR)
- Architecture of Model
- Results for NYS
- Further Research

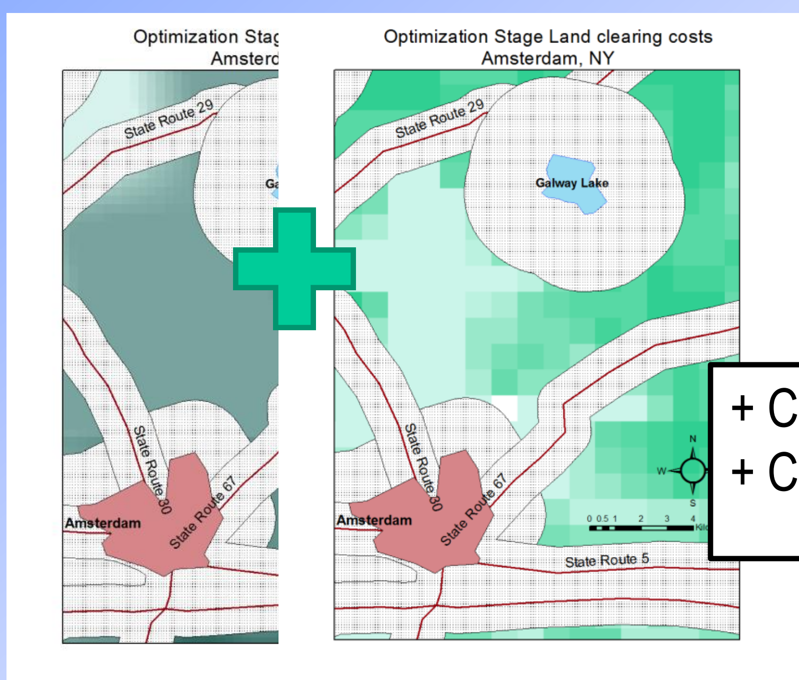
GIS-enabled Site Selection for Wind Turbine Farms

- Geographic Information Systems (GIS) provide:
  - Flexibility in user input
  - Fast processing of spatial data
  - Visual, self-explanatory output (map)

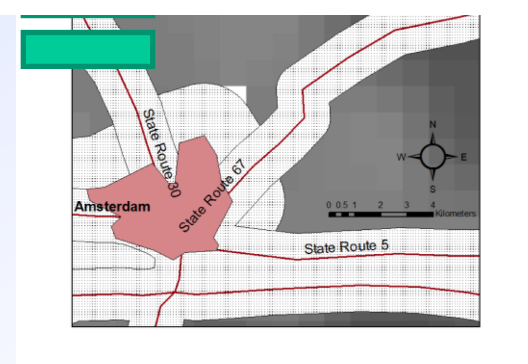
- Useful during general site selection, as well as detailed wind farm planning
  - Optimization of local expected profit
  - Insight in environmental impacts (migratory birds, bats, other species)

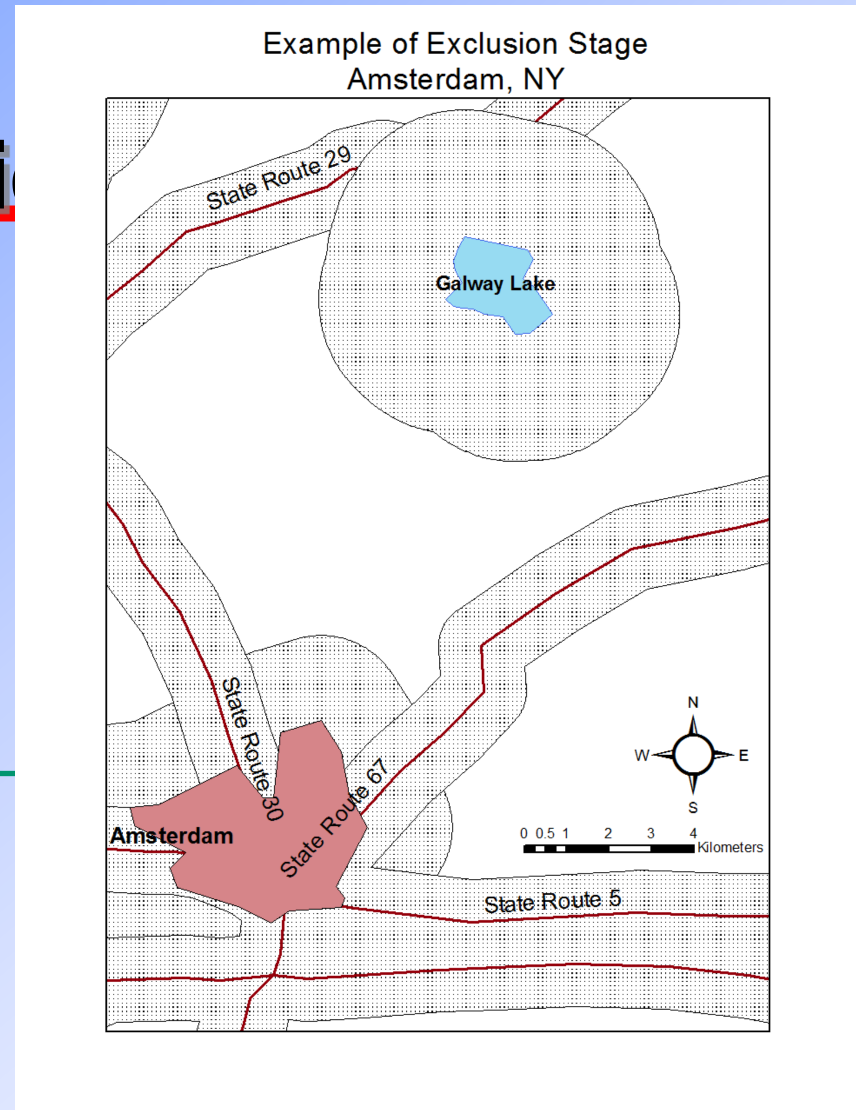
Exclusion and Optimizati

1. Exclusion of sites using buffer areas
2. Ranking of feasible sites using optimization technique:

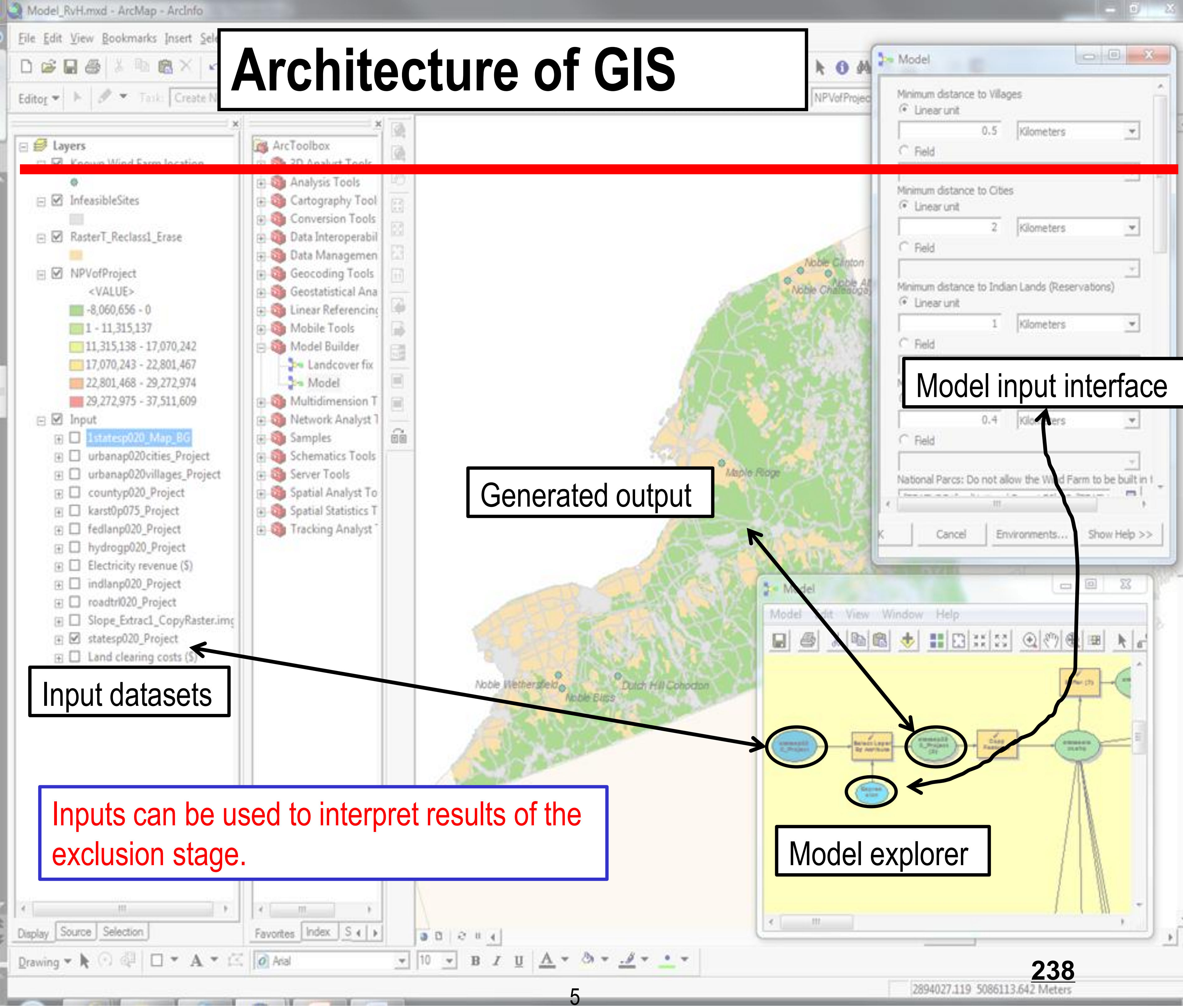


+ Cost of feeder line
+ Cost of roads





Architecture of GIS

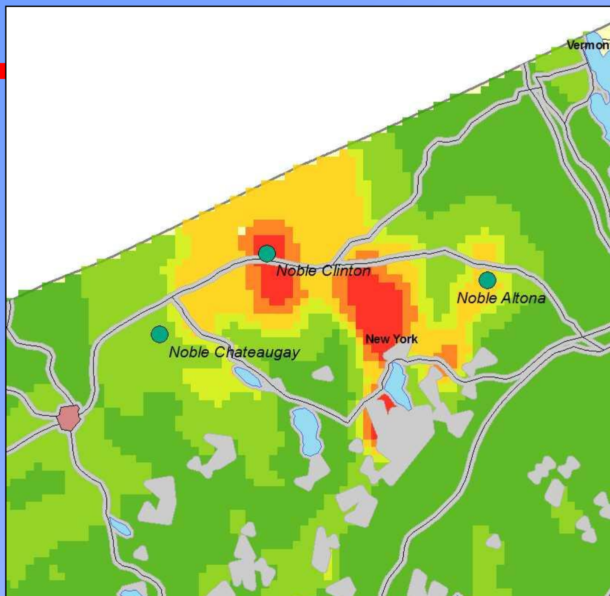


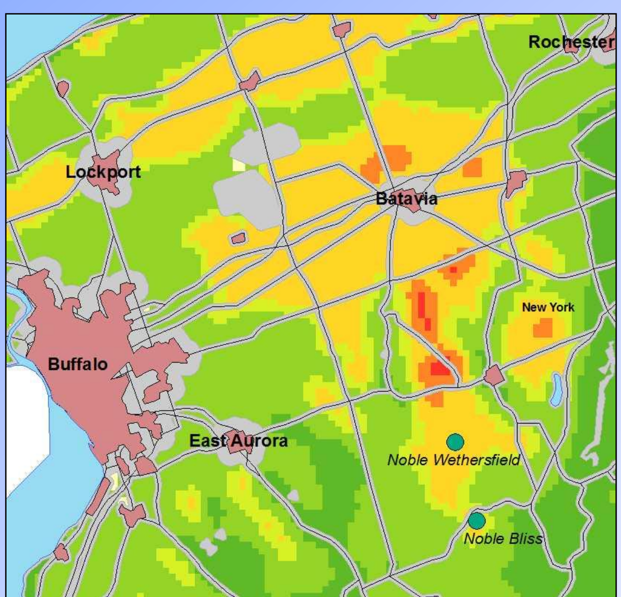
Inputs can be used to interpret results of the exclusion stage.

Example: New York State

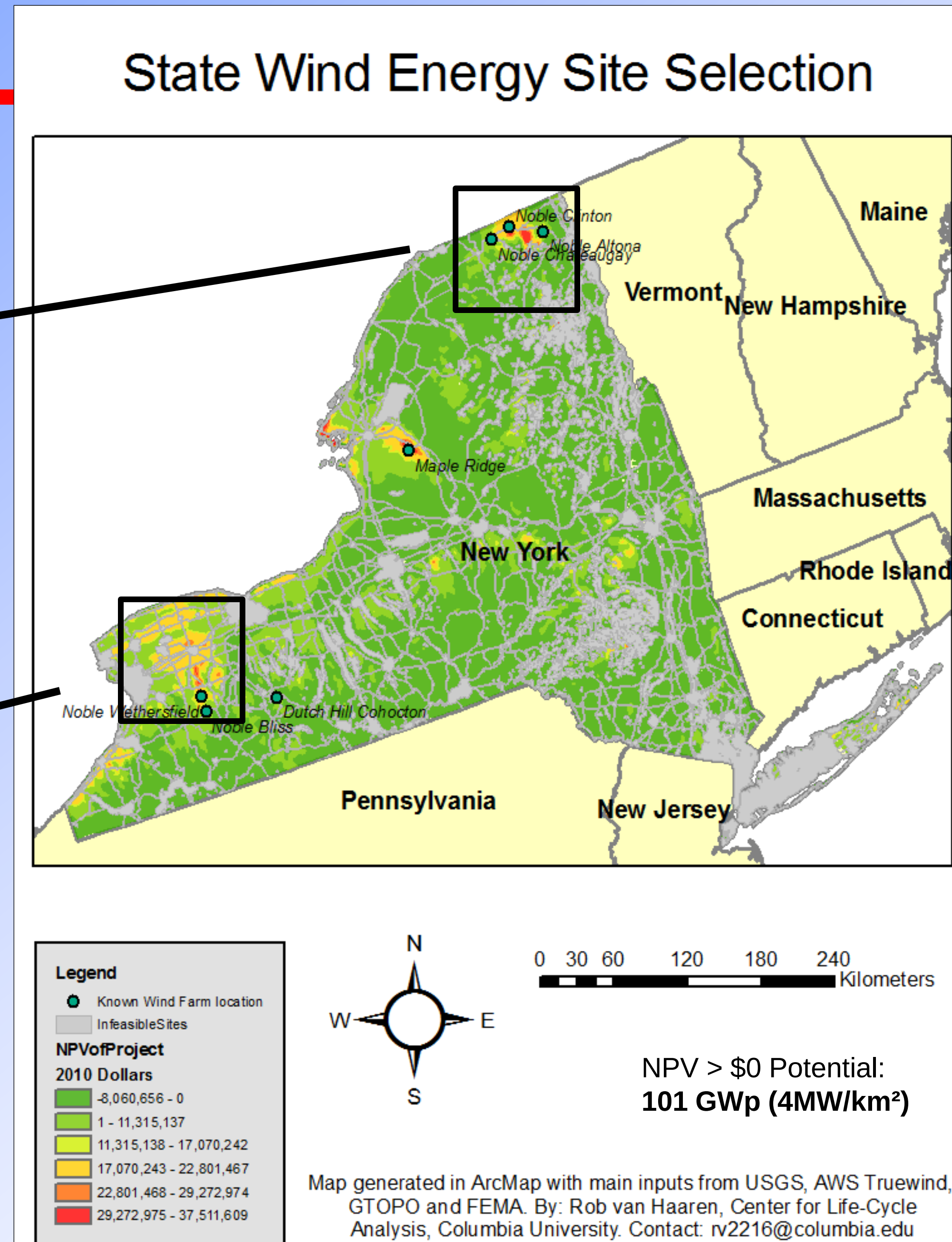
State	New York	
Slope	<10%	Baban, S. et al., 2001
Distance to towns	>0.5km	Baban, S. et al., 2001
Distance to cities	>2km	Baban, S. et al., 2001
Distance to Indian reservations	>1km	Own evaluation
Distance to water bodies	>0.4km	Baban, S. et al., 2001
Distance to roads	>0.5km	Department of Environmental Management, Rhode Island, 2009
Do not allow wind farm in the following federal lands:	For example: 'National Park, 'Air Force Base', etc.	Own evaluation
Forecasted revenue per MWh:	$40/MWh	Wiser et al., 2009
Capital cost/kW	$1,580/kW	Wiser et al., 2009

North NYS





Buffalo area



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Model Verification

- Verify model using:
- Existing wind farms in NYS
  - Maple Ridge
  - Noble Bliss
  - Noble Clinton
  - Noble Altona
  - Dutch Hill Cohocton
  - Noble Chateaugay
  - Noble Wethersfield

NPV class	# wind farms
1 (worst)	0
2	0
3	0
4	1
5	0
6	2
7	3
8	1
9 (best)	0 (tiny area)

Conclusions

- General site selection possible based on multiple GIS data sources
- Optimization with economic analysis allows accumulation of multiple criteria
- Model results were verified with existing wind farms in NYS

Further Research

- Grid congestion modeling
- Include pricing as data layer
- Environmental Impact Assessment (bats, birds)

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Earth & Environmental Engineering Department

13. Modeling co-optimization of wind and solar penetration and integration with CAES systems

Thomas Nikolakakis, Vasilis Fthenakis, *Columbia University*

Studies at the Center for Life Cycle Analysis focus on assessing the environmental impacts of solar systems and compare those with the life-cycle impacts of conventional fuel cycles in various renewable energy penetration scenarios. In conjunction, we develop models that enable accurate determinations of the technically and economically feasible degrees of penetration of solar and wind power generation for satisfying initially peak and subsequently base load demands.

Thomas Nikolakakis is currently a PhD student in the department of Earth and Environmental Engineering and a Junior researcher in the Center of Life Cycle Analysis at Columbia University. He obtained his M.S degree at Columbia University and his BS in Environmental Engineering from the Technical University of Crete, Chania, Greece, where he graduated first in the Class of 2007. In his undergraduate thesis he studied the fate and transport of copper compounds in the ground. His current research interests include: Modeling of performance of Solar and Wind energy systems; Large scale energy storage in the form of CAES; Life Cycle Analysis.

Modeling co-optimization of wind and solar and integration with CAES systems

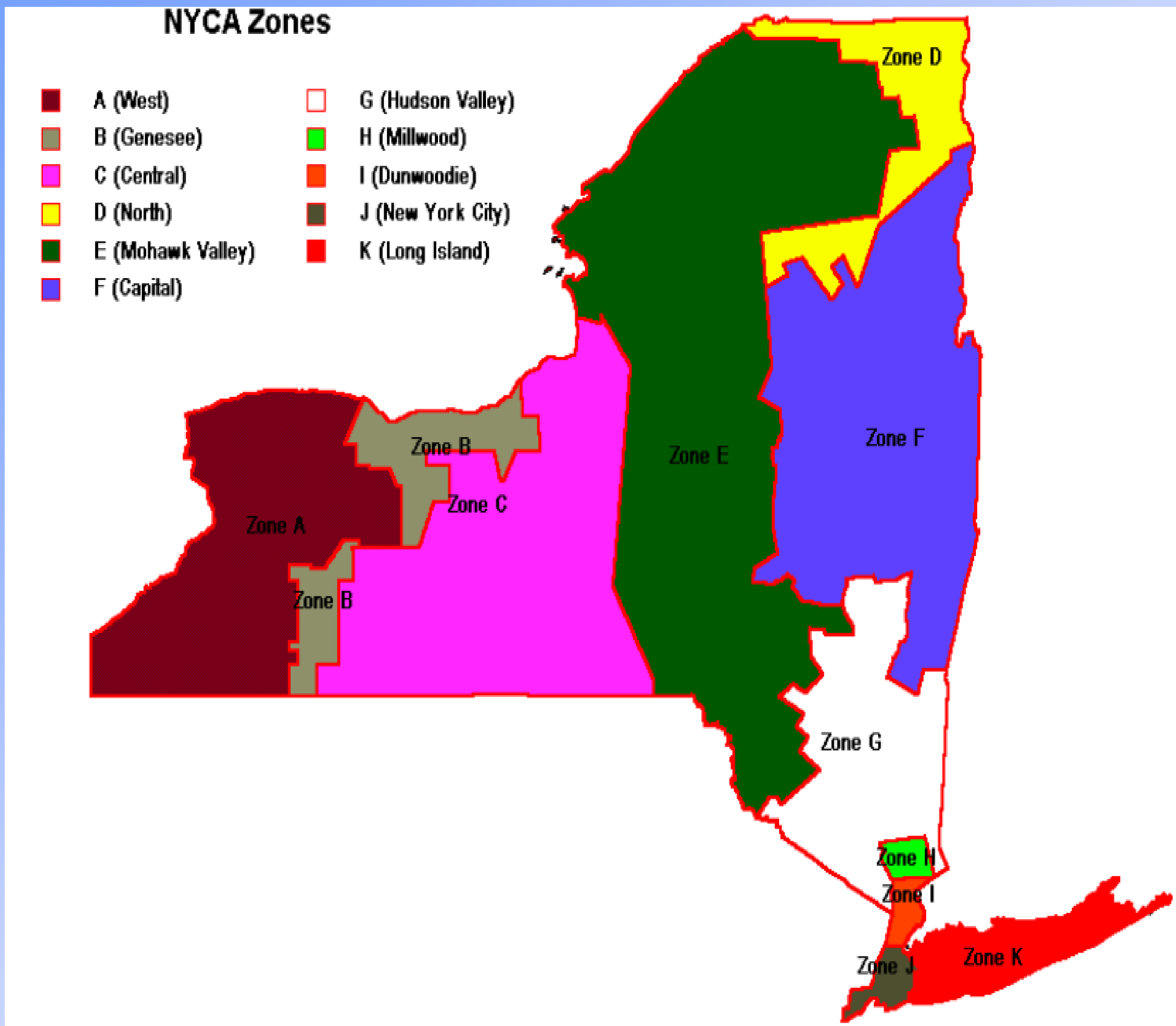
Thomas Nikolakakis
Doctorate Student, Earth & Environmental Engineering,
Columbia University

Advisor: Prof. V. Fthenakis

CAES 2010 Conference and Workshop, Columbia University, NYC, October 20, 2010

email: tn2204 @columbia.edu
web: www.clca.columbia.edu

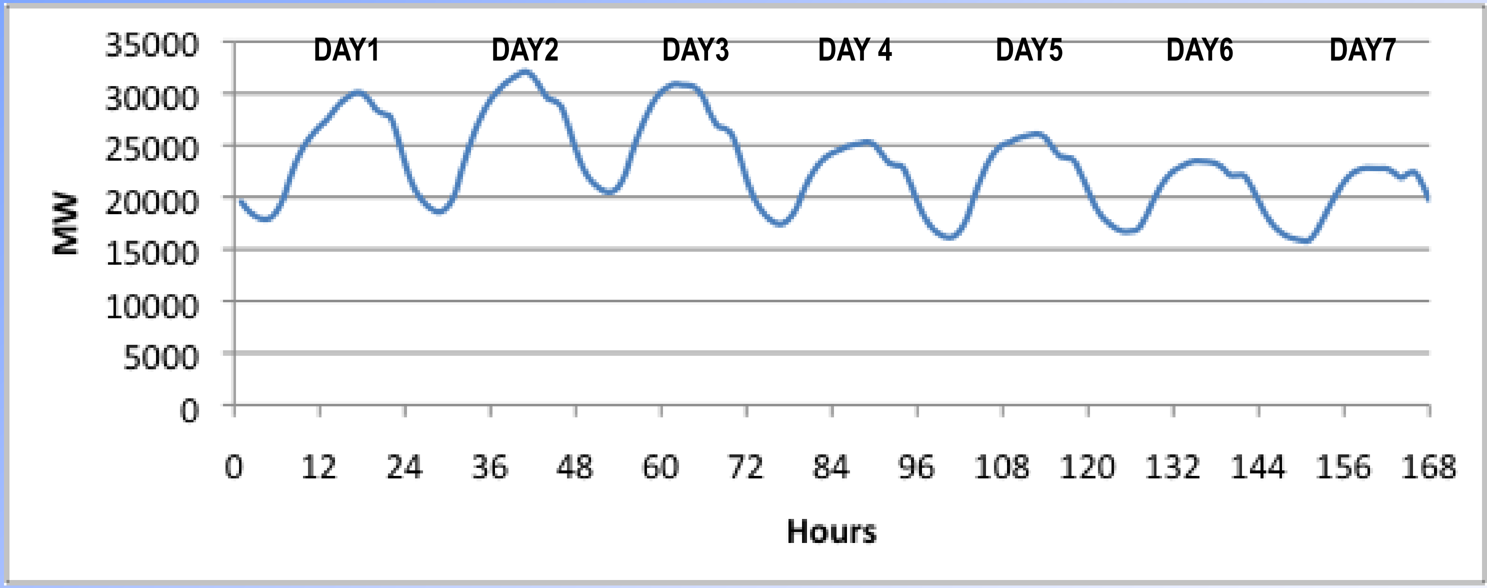
NY State Loading Zones



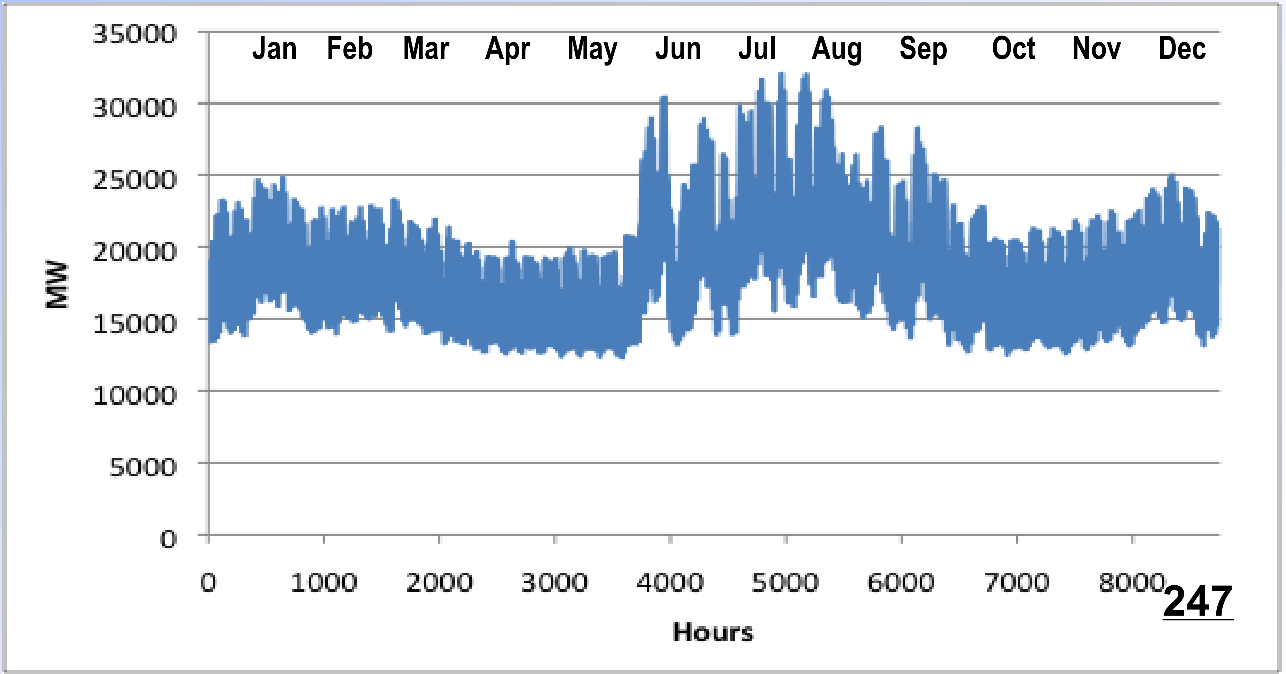
Source: NYISO

Load Profile in the NY Control Area

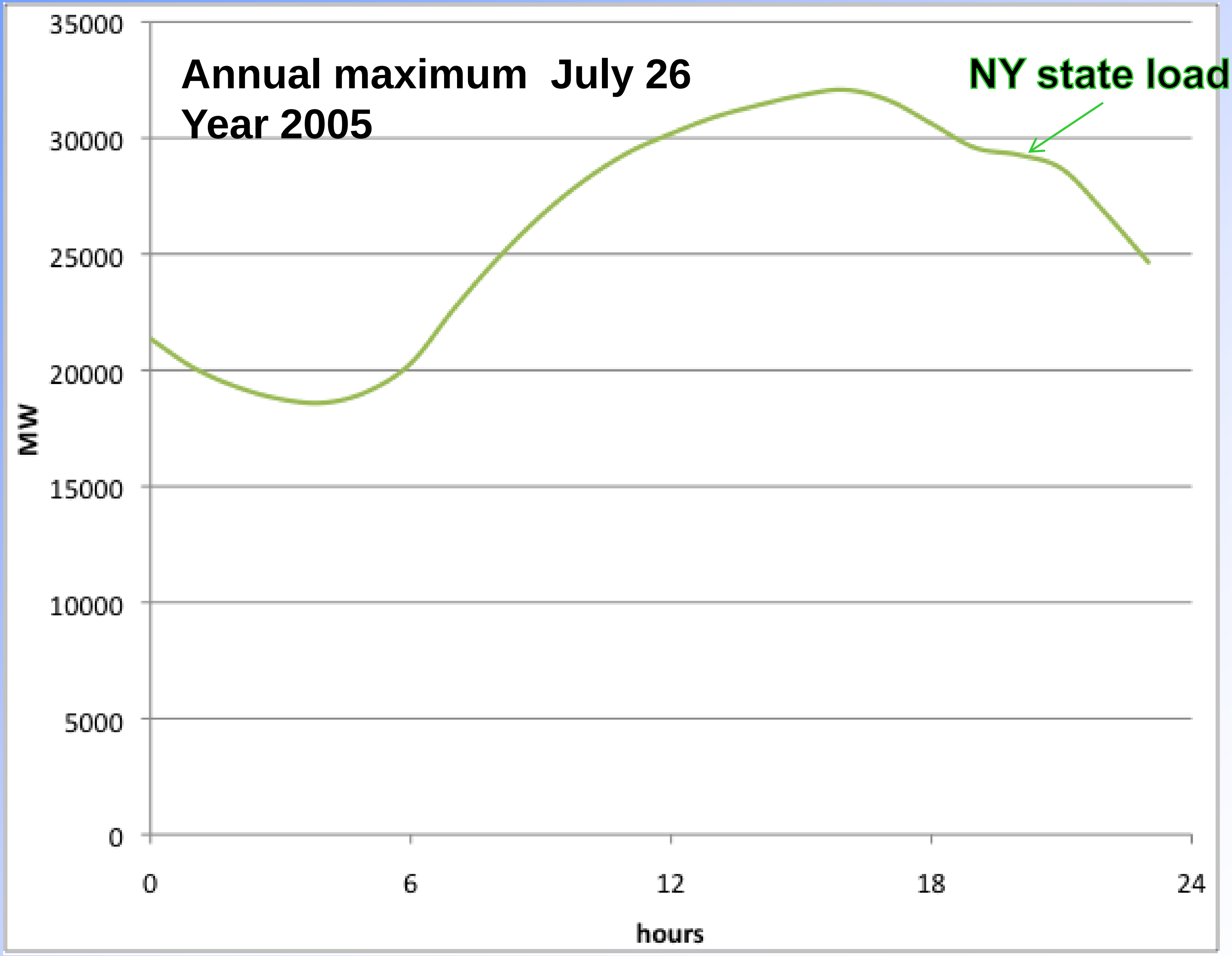
Weekly load profile



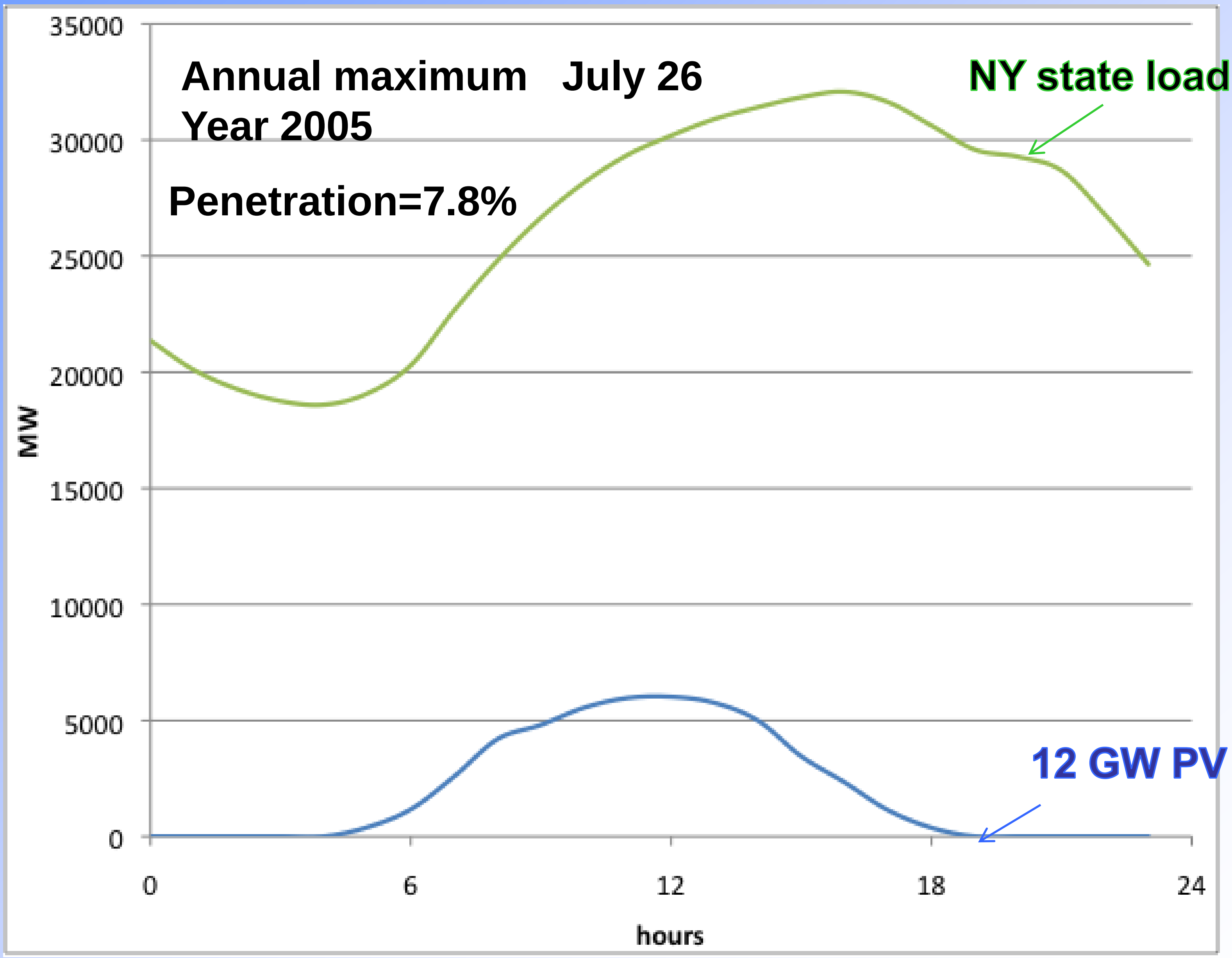
Annual load profile



NY State Load



NY State Load / 12 GW PV



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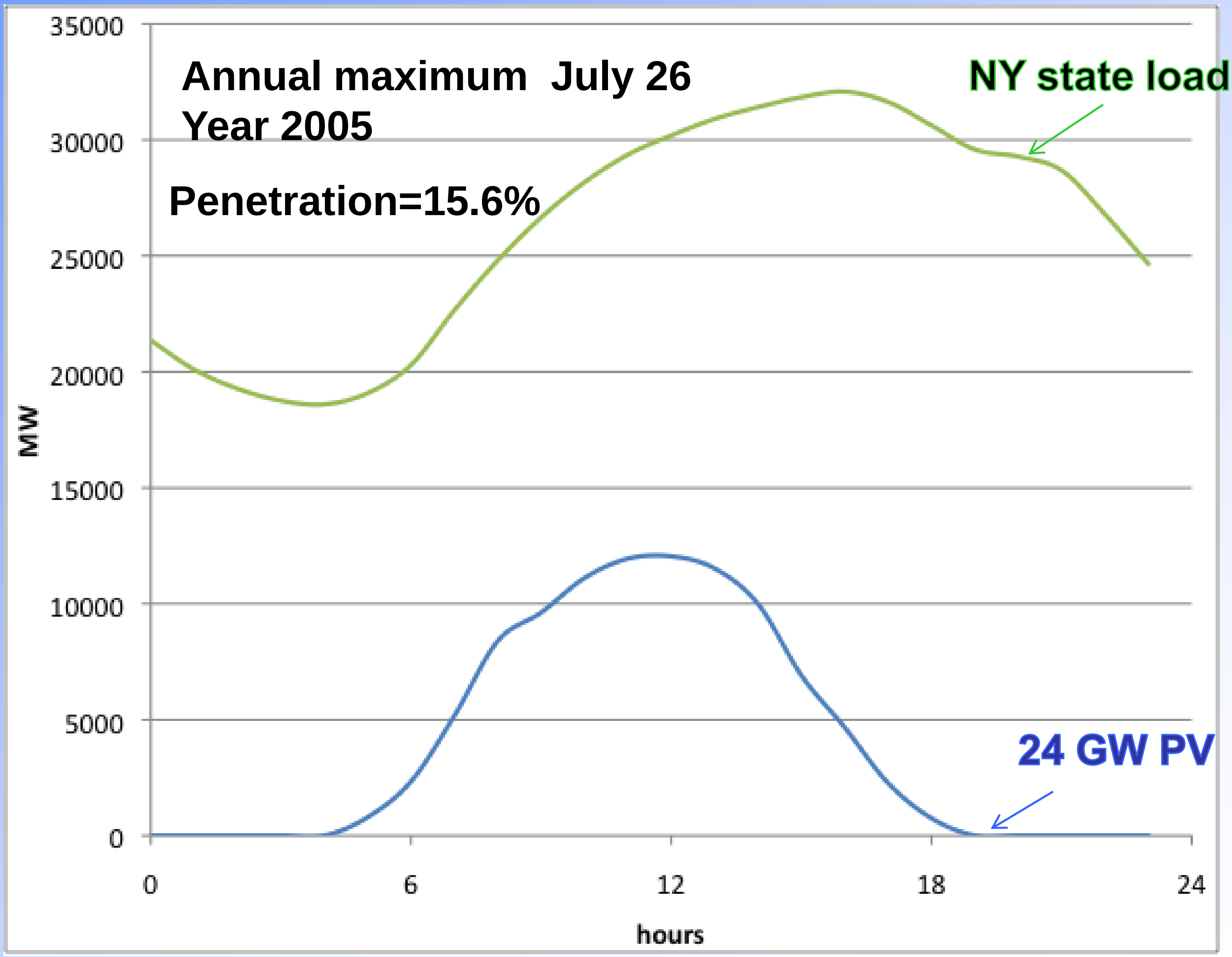
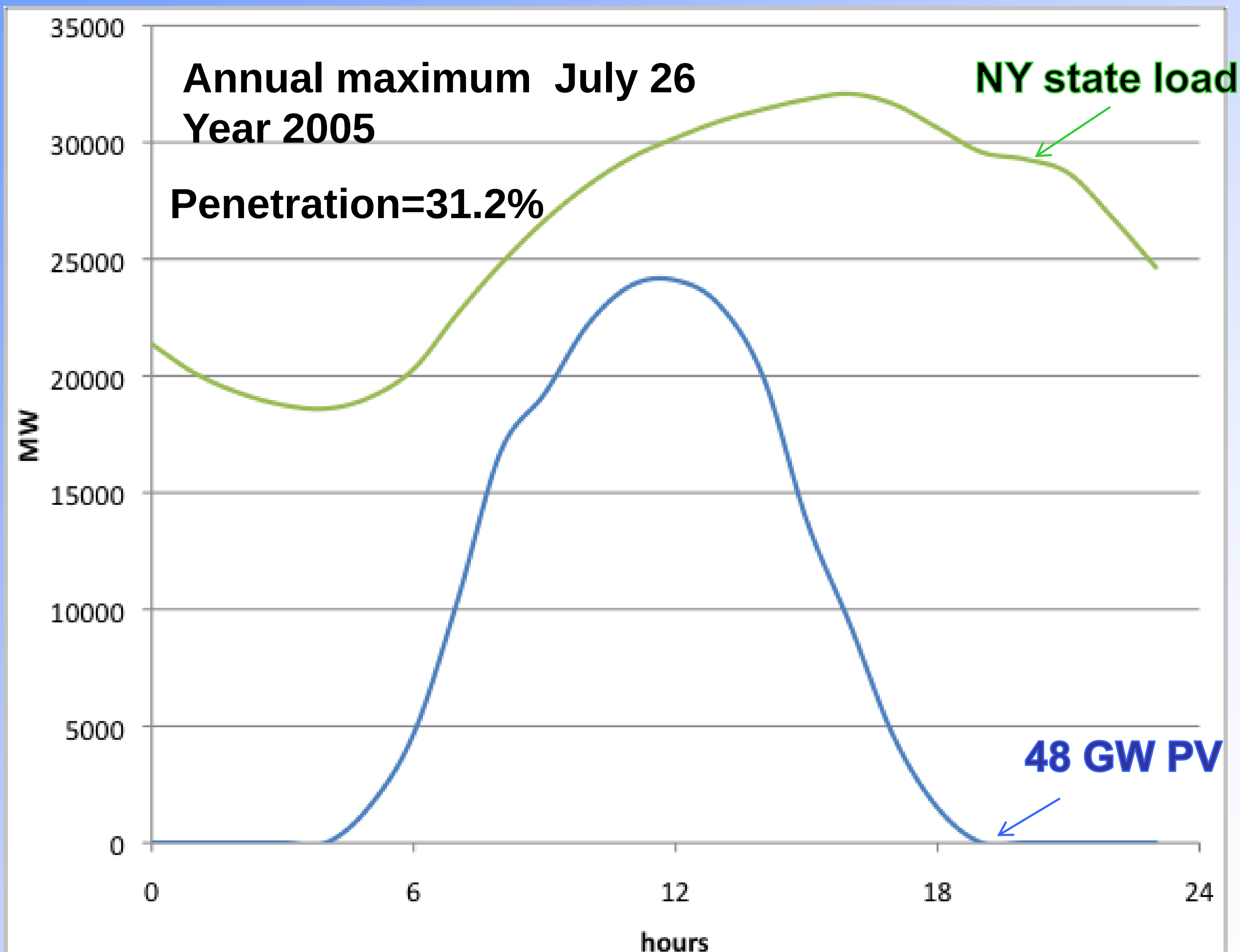
NY State Load / 24 GW PV



250

NY State Load/ 48 GW PV



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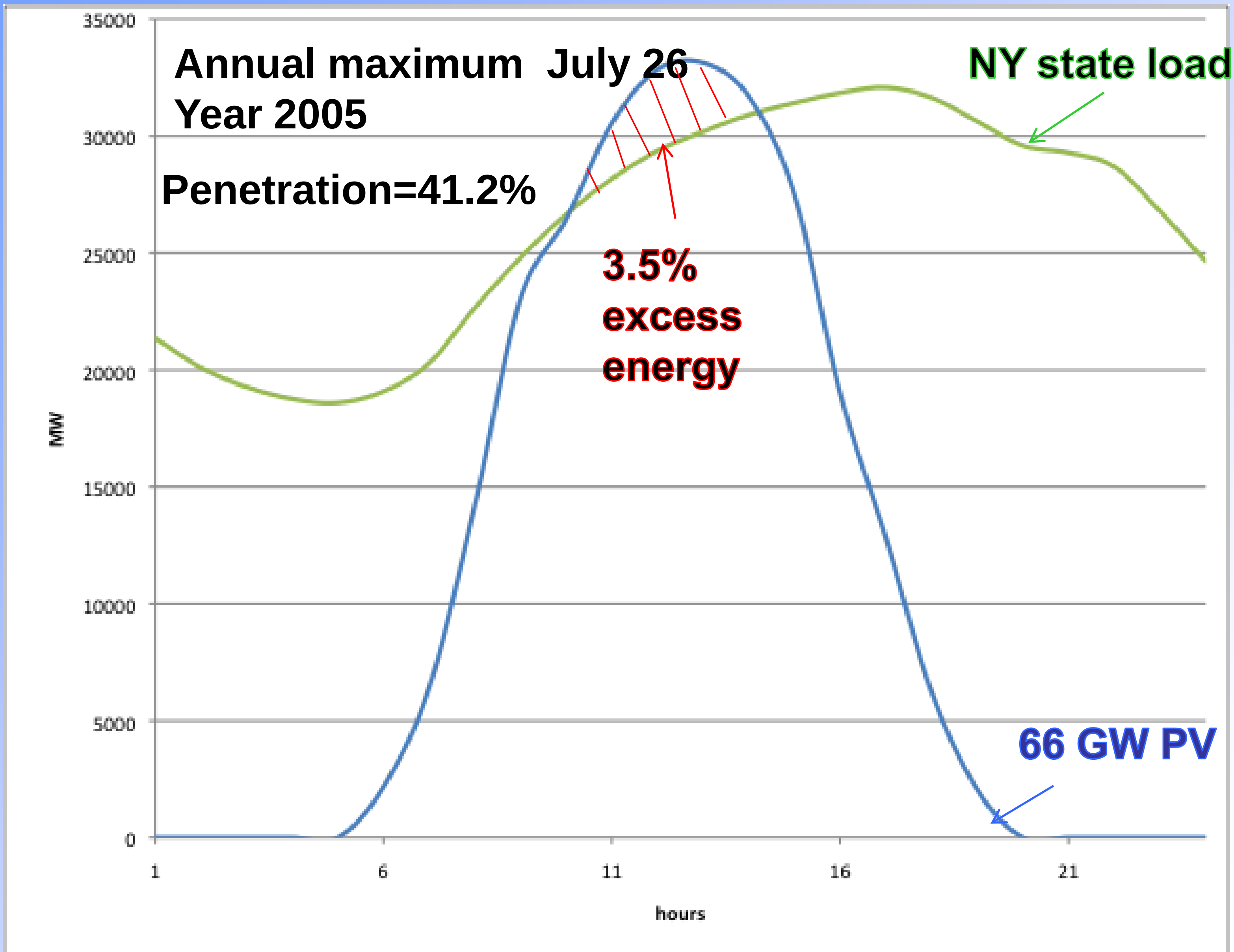
NY State Load / 66 GW PV



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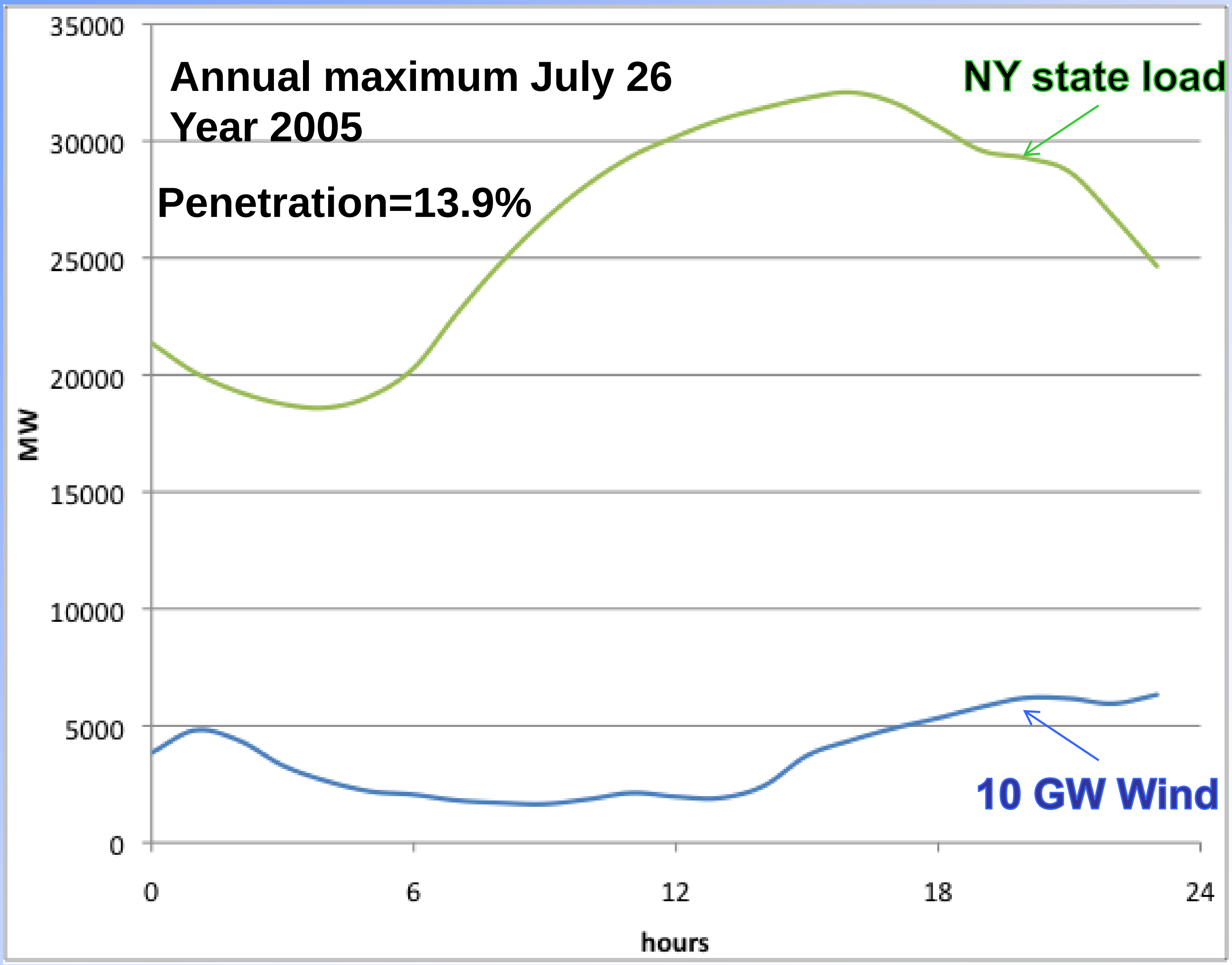
- **WHAT IF WE INSTALL WIND TURBINES INSTEAD OF PV?**

NY State Load / 3 GW Wind



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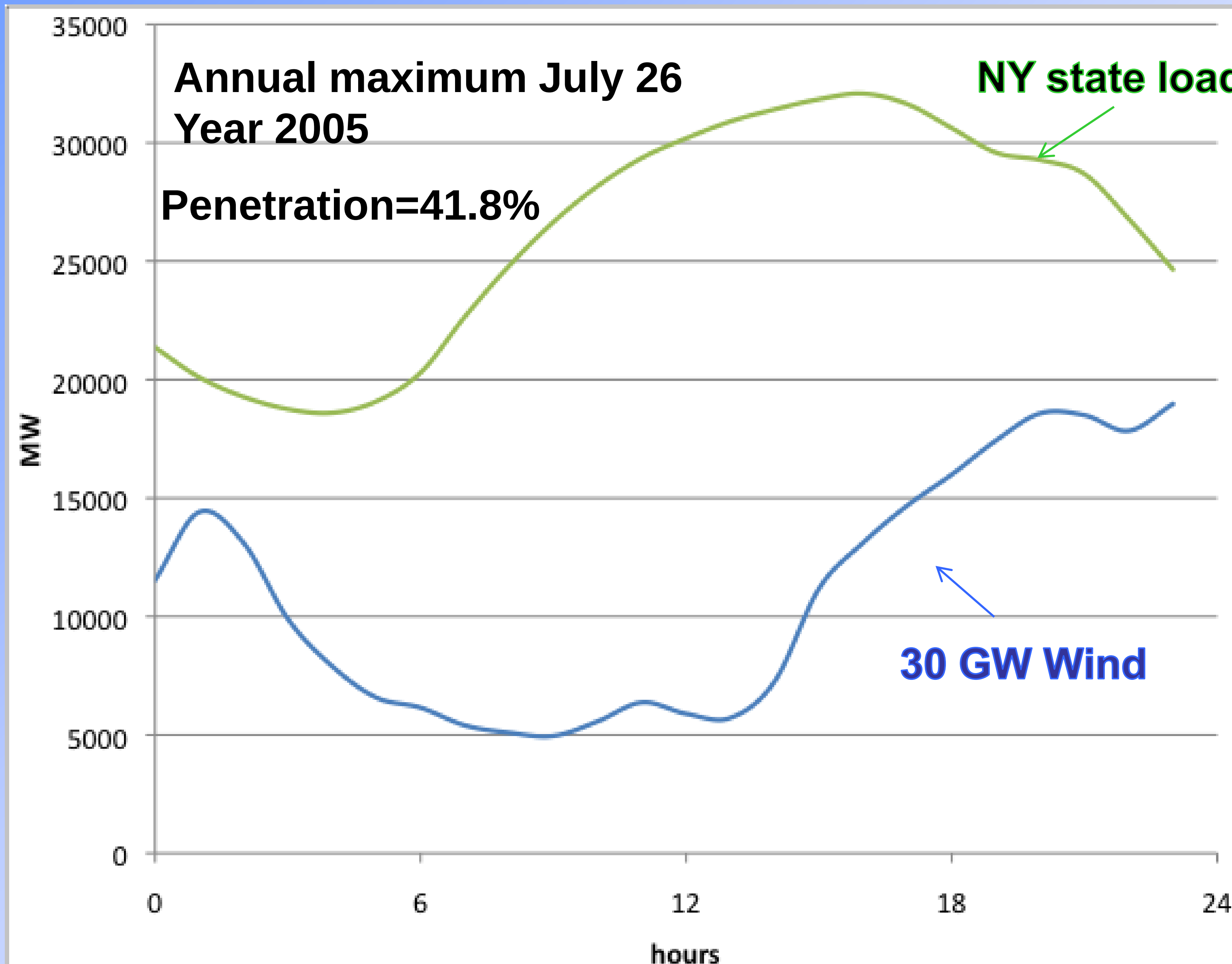
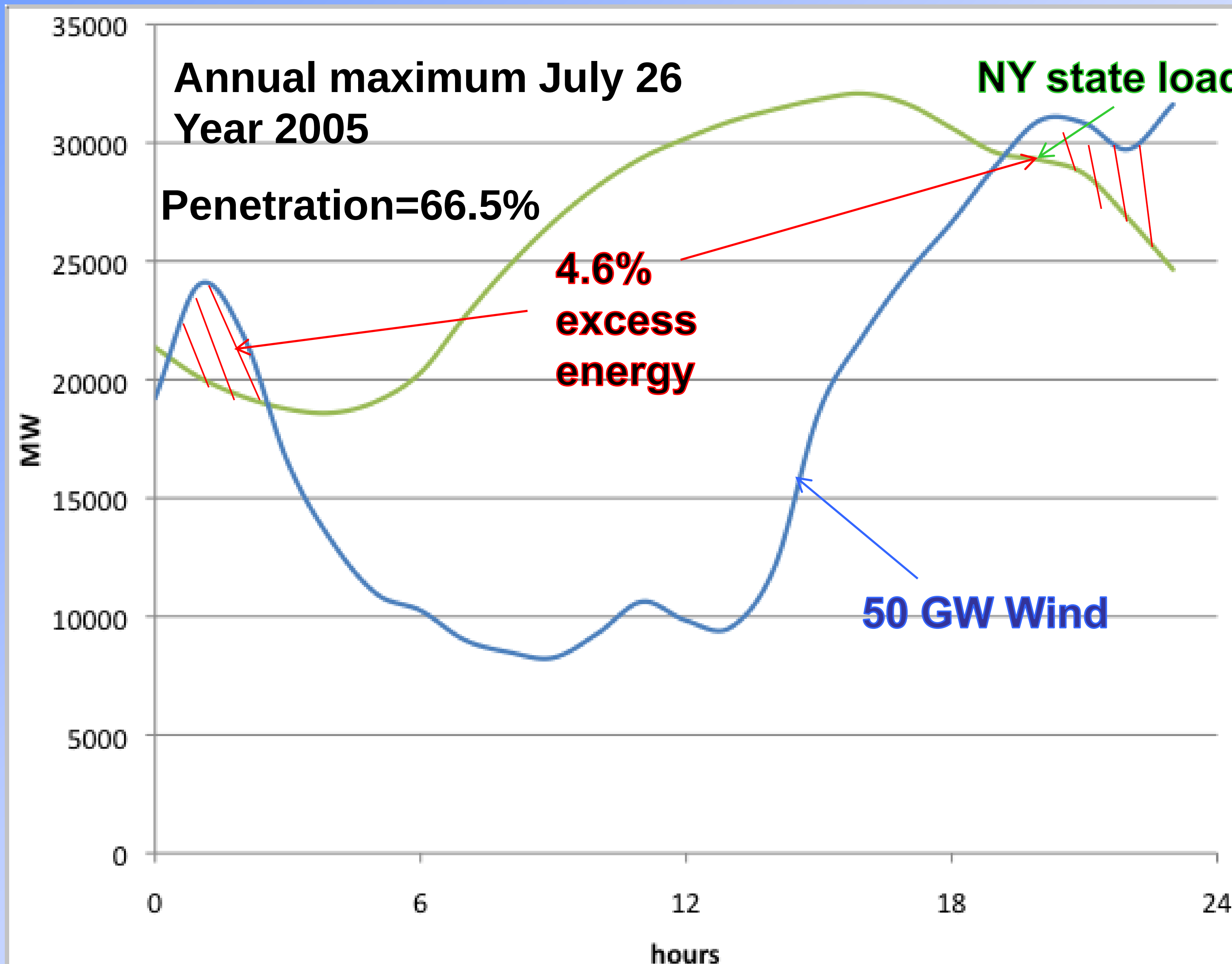
NY State Load / 30 GW Wind



255

NY State Load / 50 GW Wind



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- **WHAT IF WE INSTALL BOTH WIND TURBINES AND PV?**

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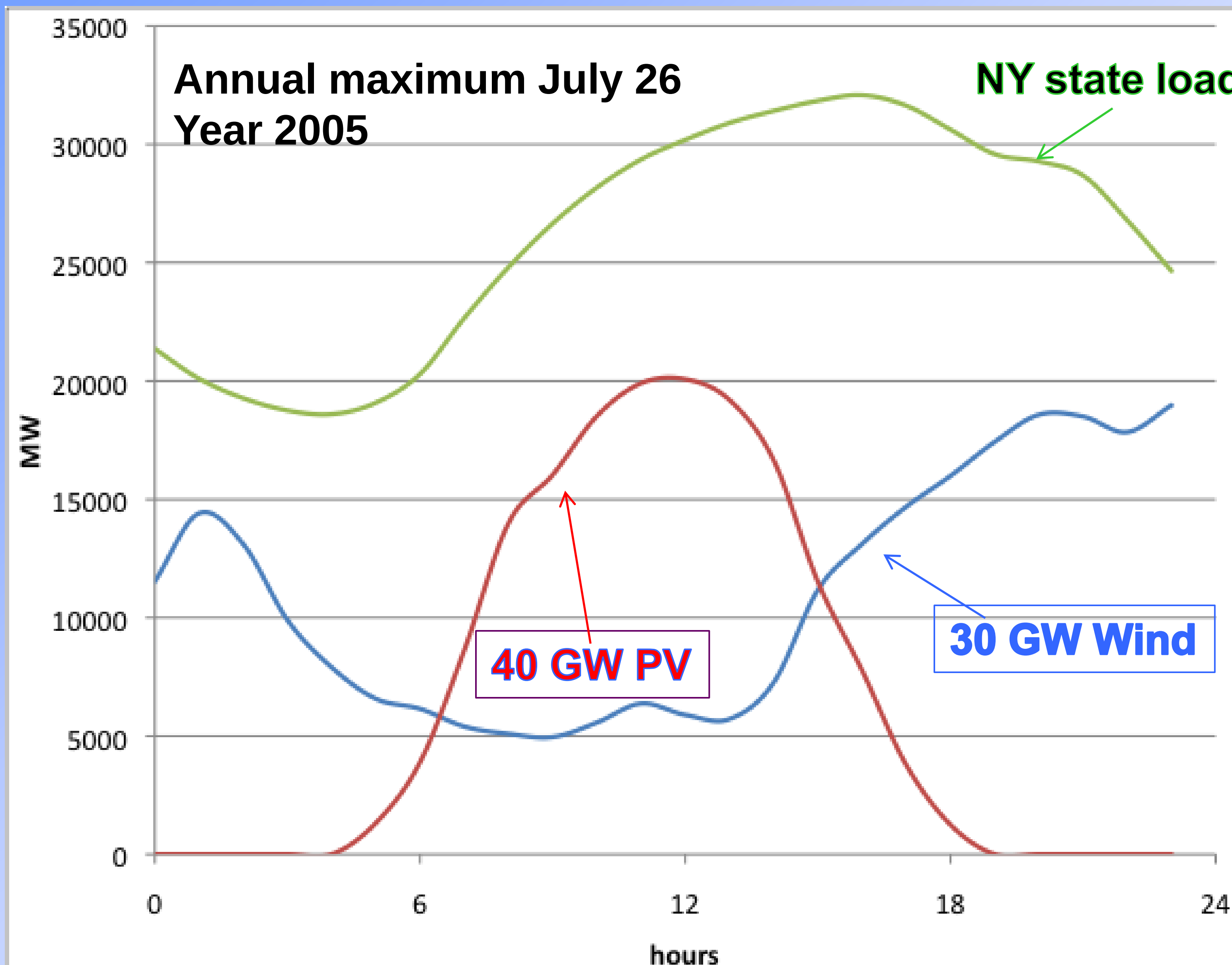
AN OBSERVATION



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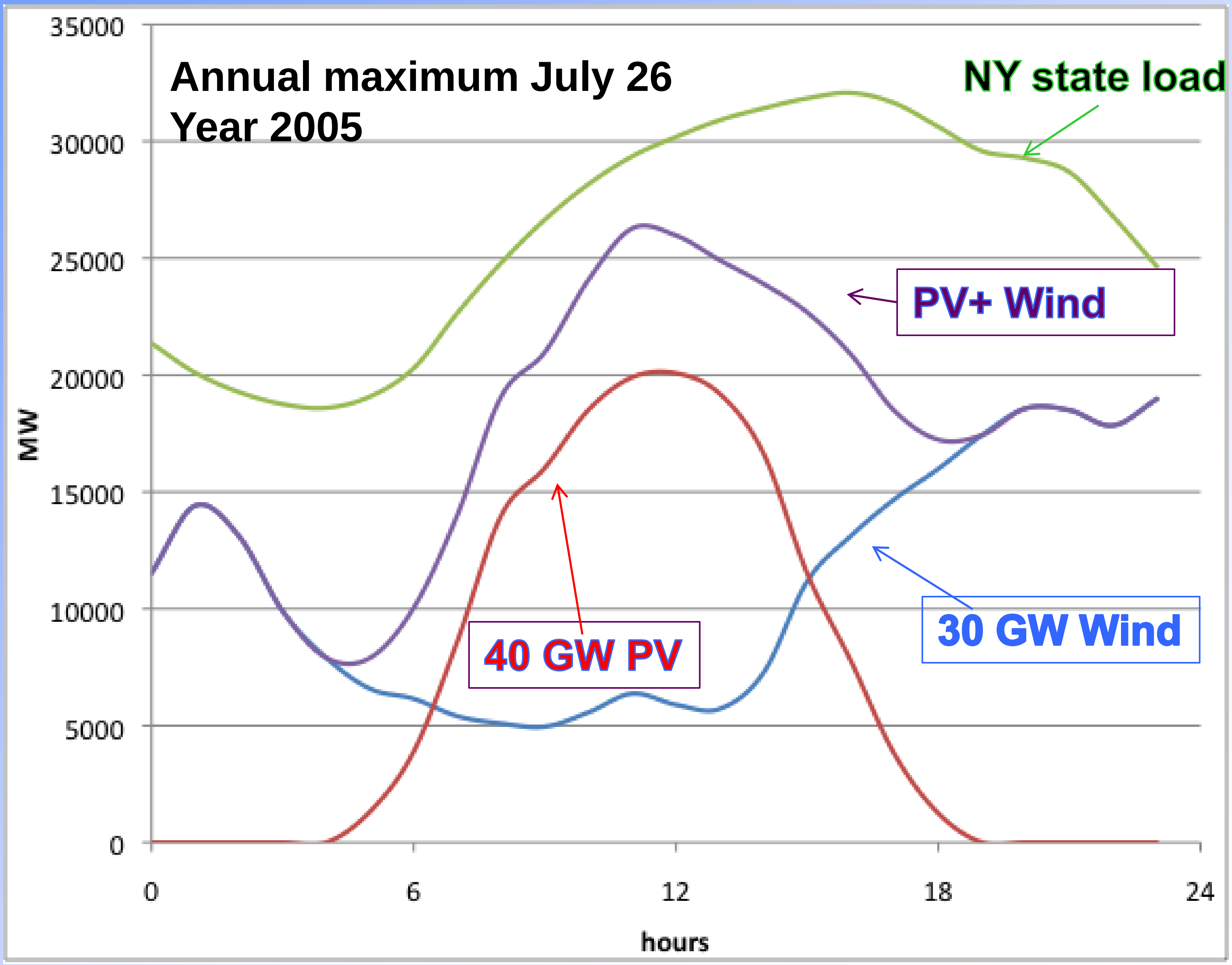
AN OBSERVATION



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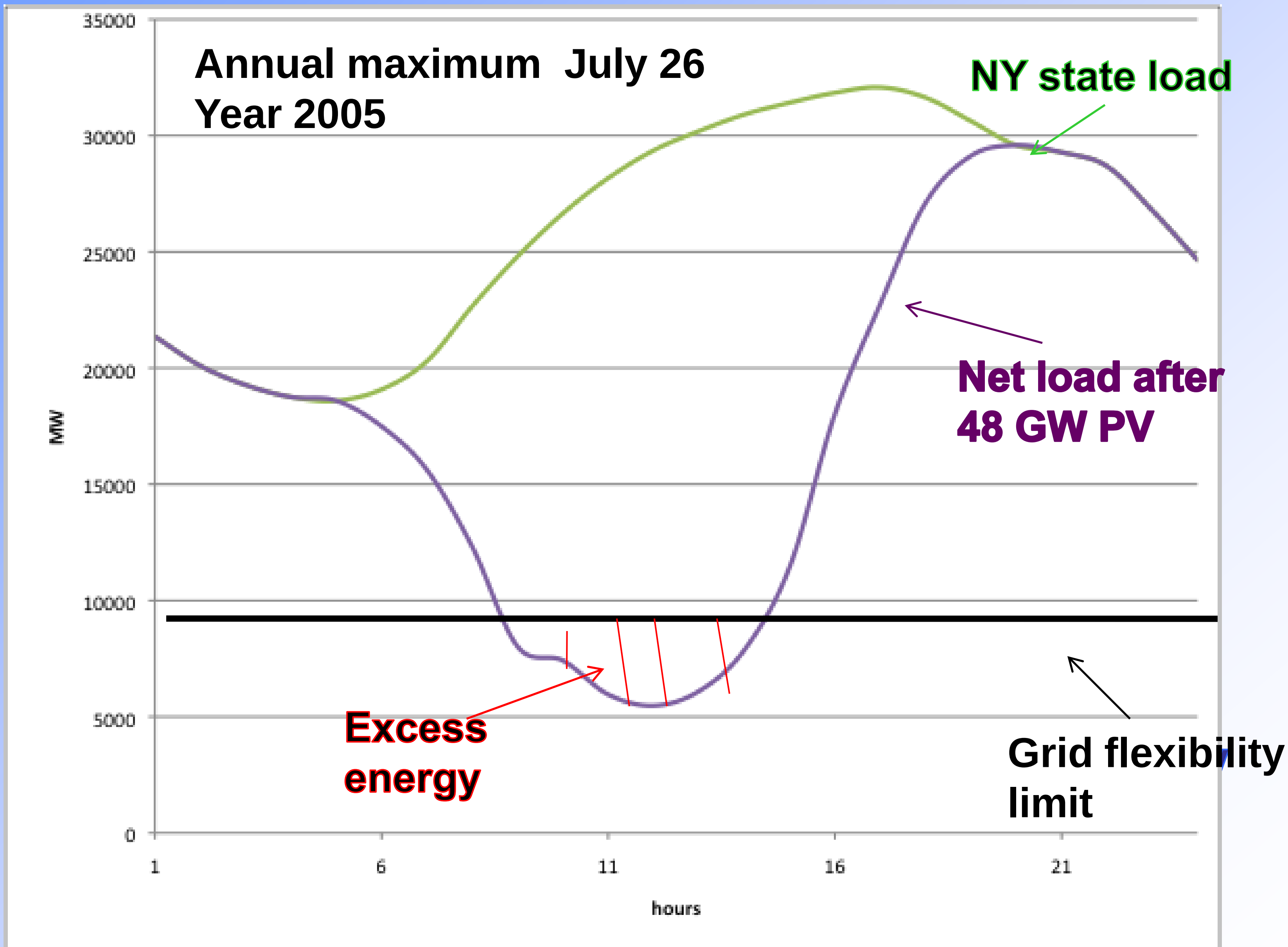
QUESTIONS TO BE ANSWERED

- Is it PV, wind or their integration that reduces the daily and annual peaks the most?

- Is it PV, wind or their integration that achieves the highest **annual** energy penetration in the NY grid?

- Among all different PV-Wind combinations which one gives the best **annual** penetration with the least excess energy?

NYS Grid Flexibility



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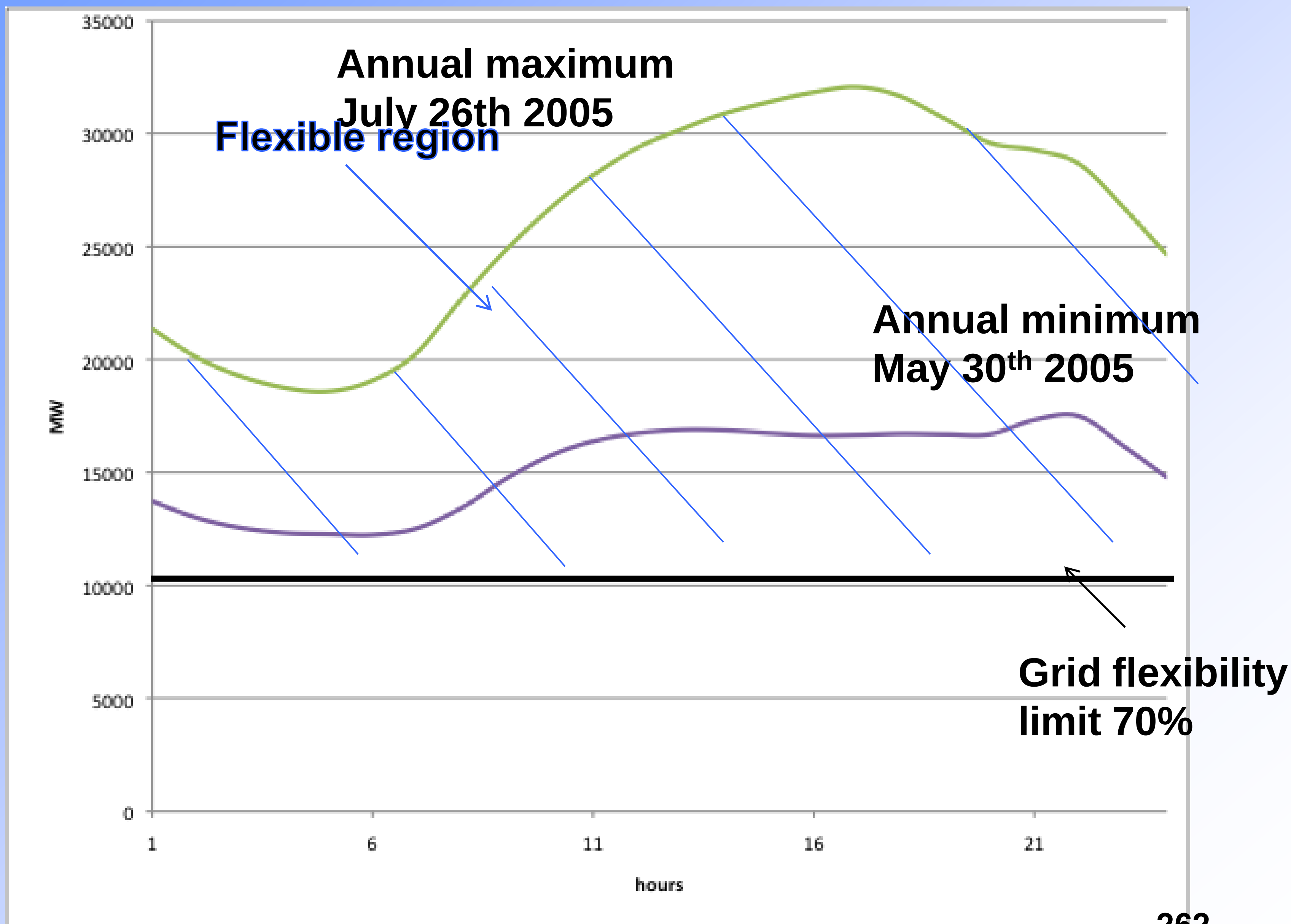
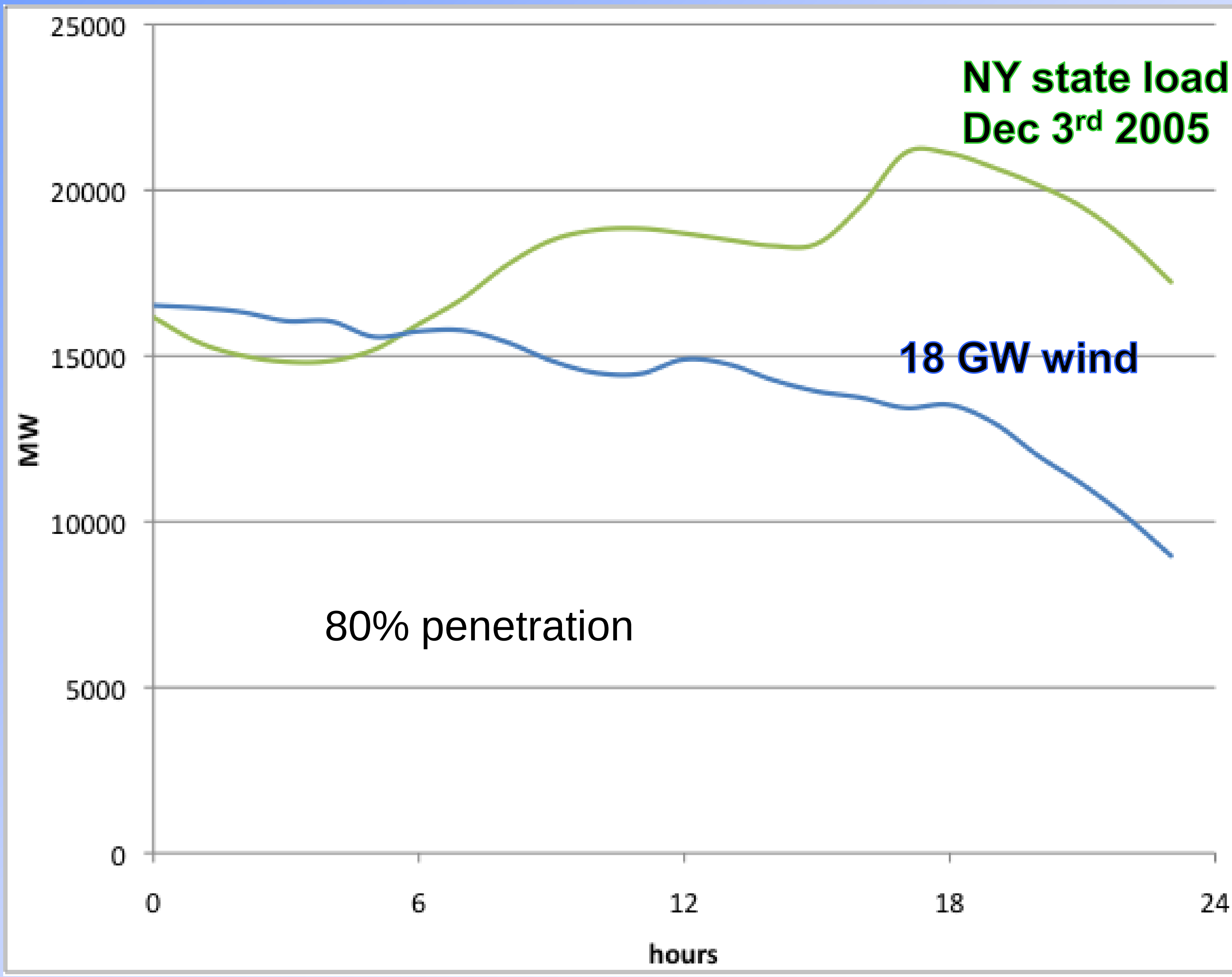
NYS Grid Flexibility



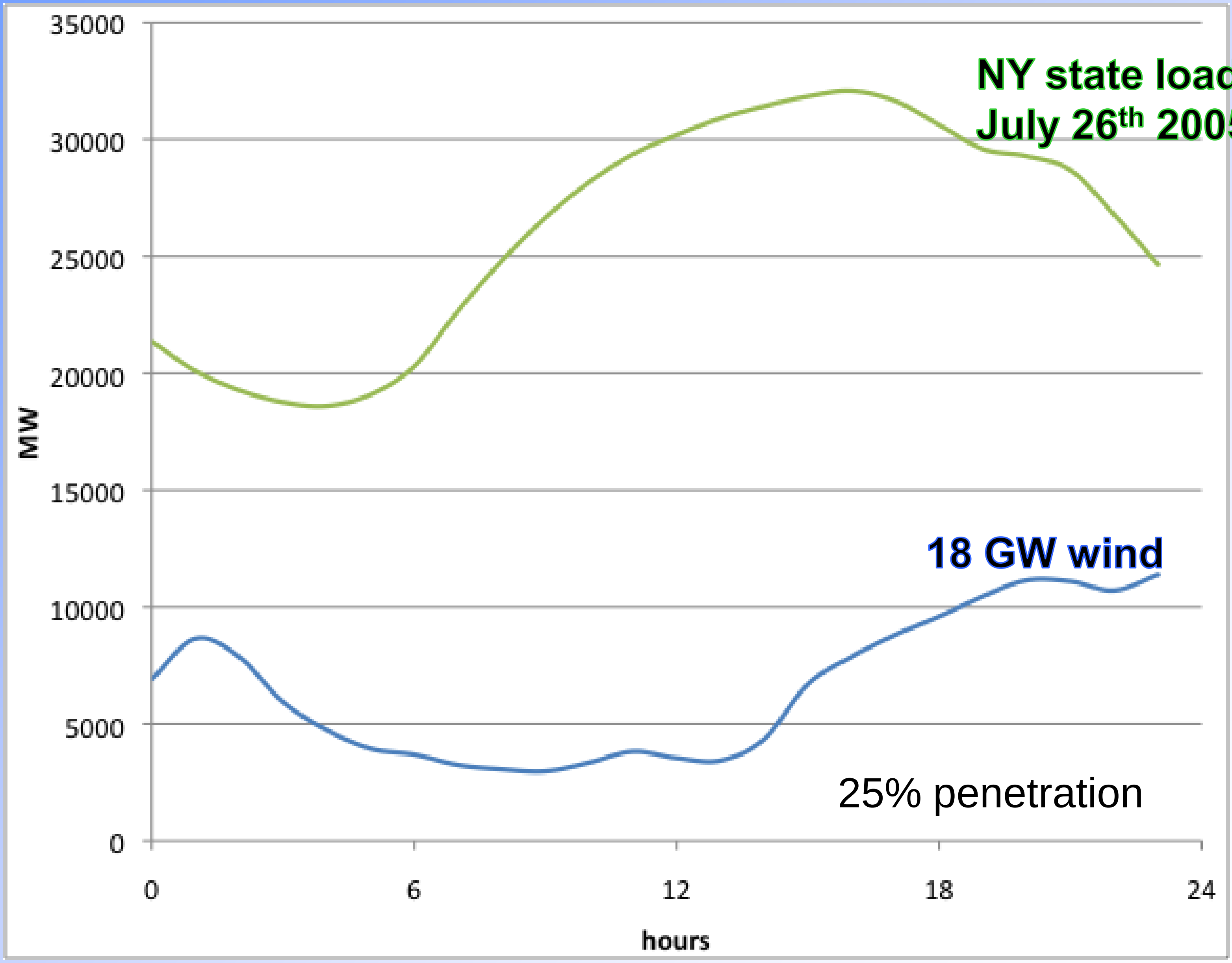
262

REJECTED ENERGY



263

REJECTED ENERGY



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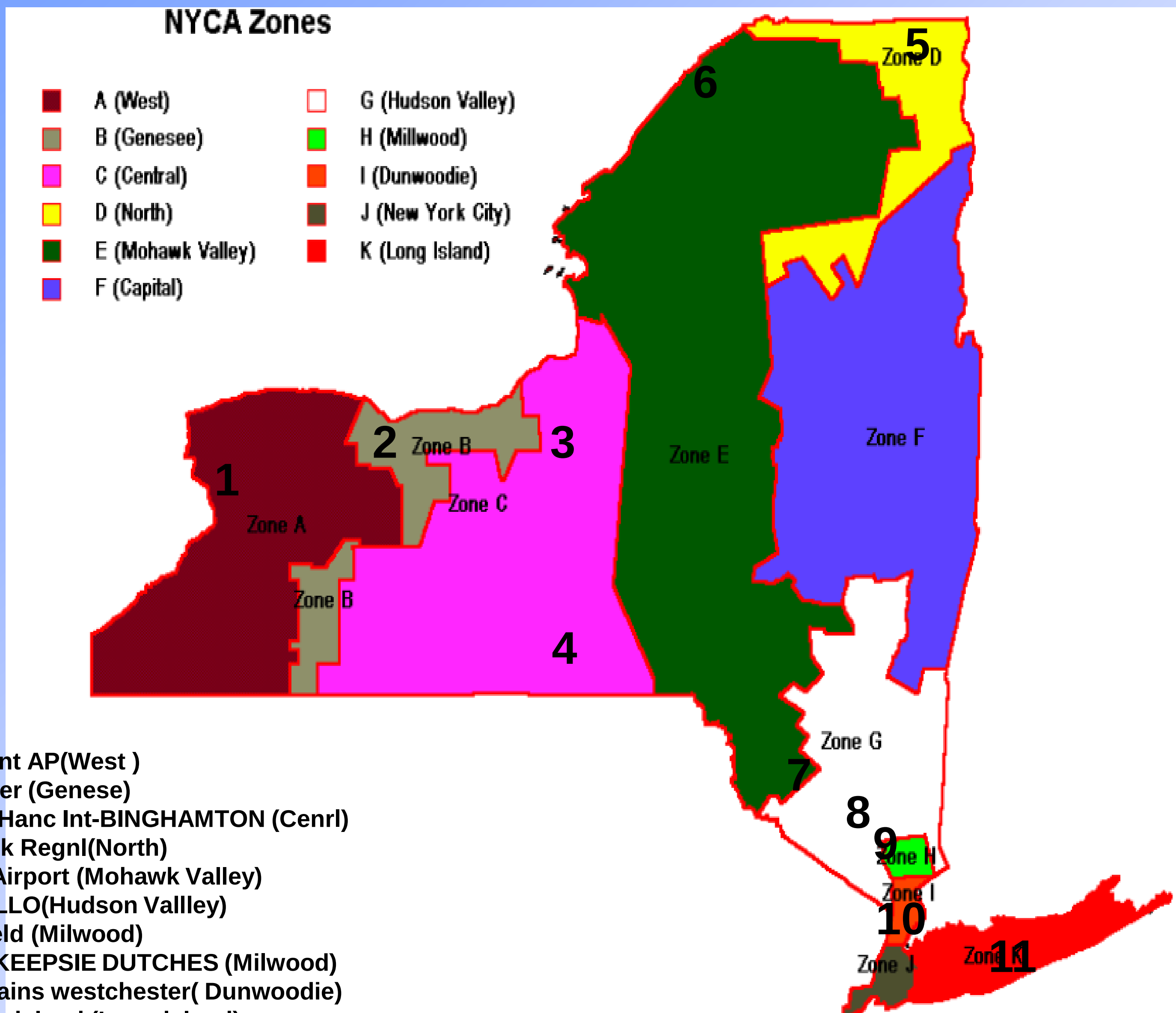
Data collection
Solar Data→ National Solar Radiation Database
Load Data →NYISO



1. Bufallo Int AP(West)
2. Rochester (Genese)

3-4 Syracuse Hanc Int-BINGHAMTON (Cenrl)

5. Adirondack Regnl(North)

6 Massena Airport (Mohawk Valley)

7 . MONTICELLO(Hudson Vallley)

8. Stewart field (Milwood)

9 POUGHKEEPSIE DUTCHES (Milwood)

10 White plains westchester(Dunwoodie)

11 Islip long island (Long island)

Source: NYISO

PV Modeling

MATLAB

Inputs
(Historical horizontal solar data)
(Albedo)
(Latitude)
(Tilt)

Output
Hourly PV performance (MWh/MW)

Modeling/conversion to tilted → **Energy received by a tilted surface** → **Modeling/PV output**

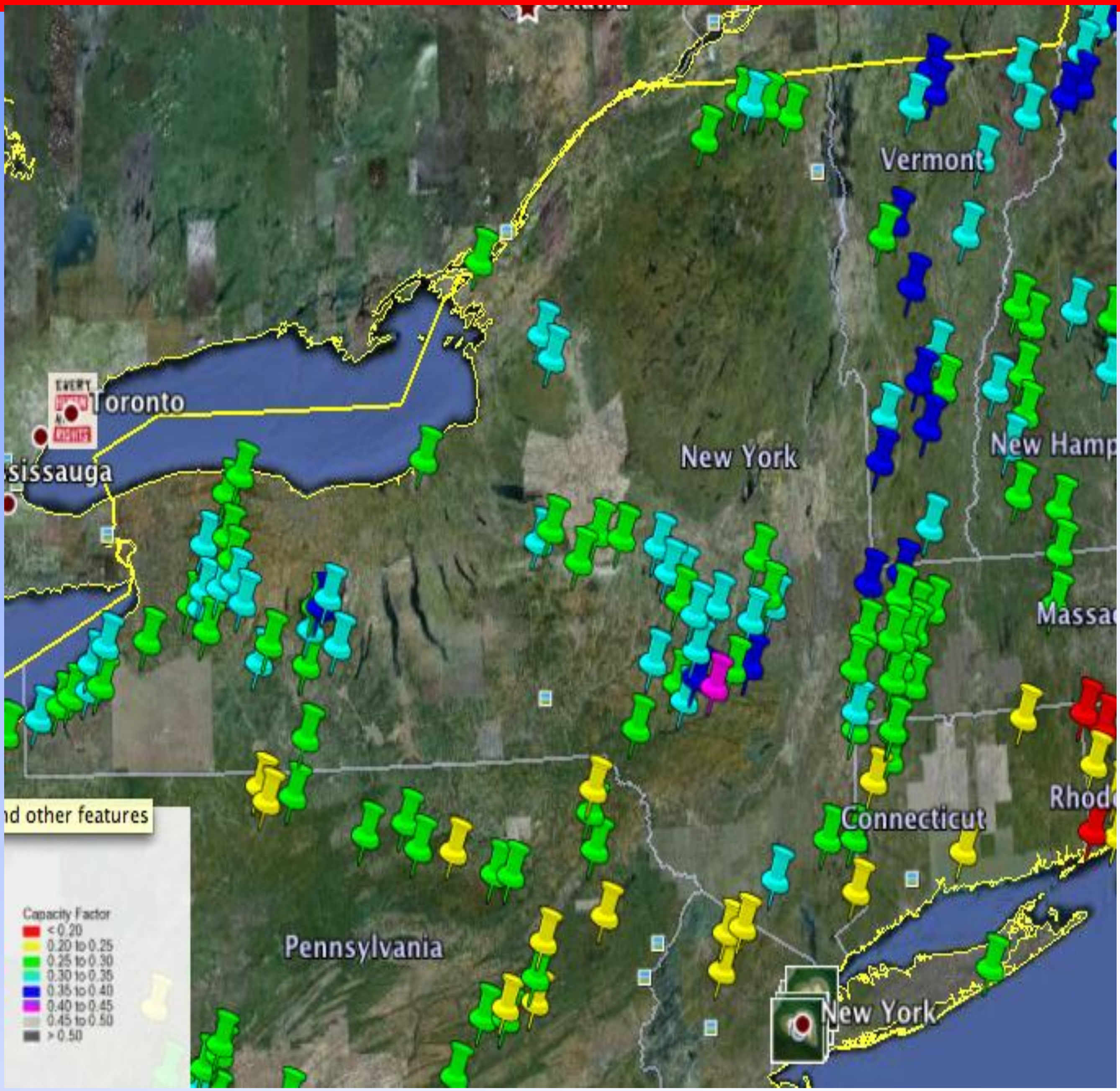
Step 1

Step 2

Wind Data Collection

- By Associated Weather Services (AWS Truewind)
- 67 sites of 10min modeled wind data converted to hourly data to match my Matlab code
- Wind output was converted to MWh/MW assuming homogenous distribution of wind farms at the locations that the wind resource is large enough

Wind sites shown on the map



Optimization Model Structure / MATLAB

Step 1: Define your flexibility level and the maximum amount of energy that you are allowed to reject over the year

Let's assume that we have a scenario of a 70% flexible system and we are allowed to reject 5% of energy over the year

Optimization Model Structure / MATLAB

Step 2: Start looping two variables, PV capacity and wind capacity; calculate the hourly output of each possible combination and keep those combinations that reject annually 5% of total energy

Optimization Model Structure / MATLAB

LAST STEP:

(combination1,penetration1)
(combination2, penetration2)

.

.

.

(combination$_{max}$,penetration$_{max}$)

.

.

(combination$_{n}$,penetration$_{n}$)

Locate the synergy of PV and wind that gives the maximum penetration in the NY grid

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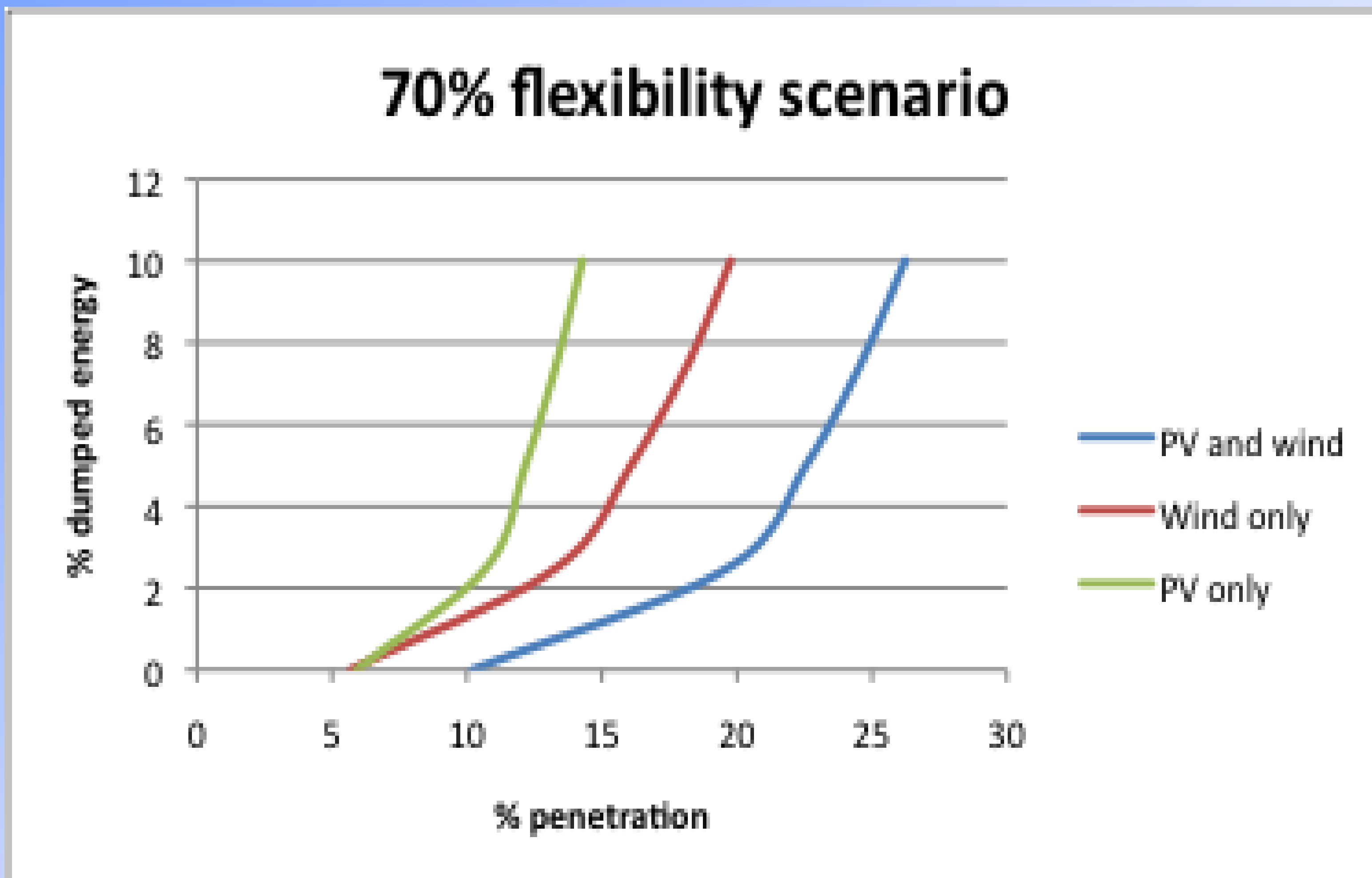
Results-Comparison of 3 cases



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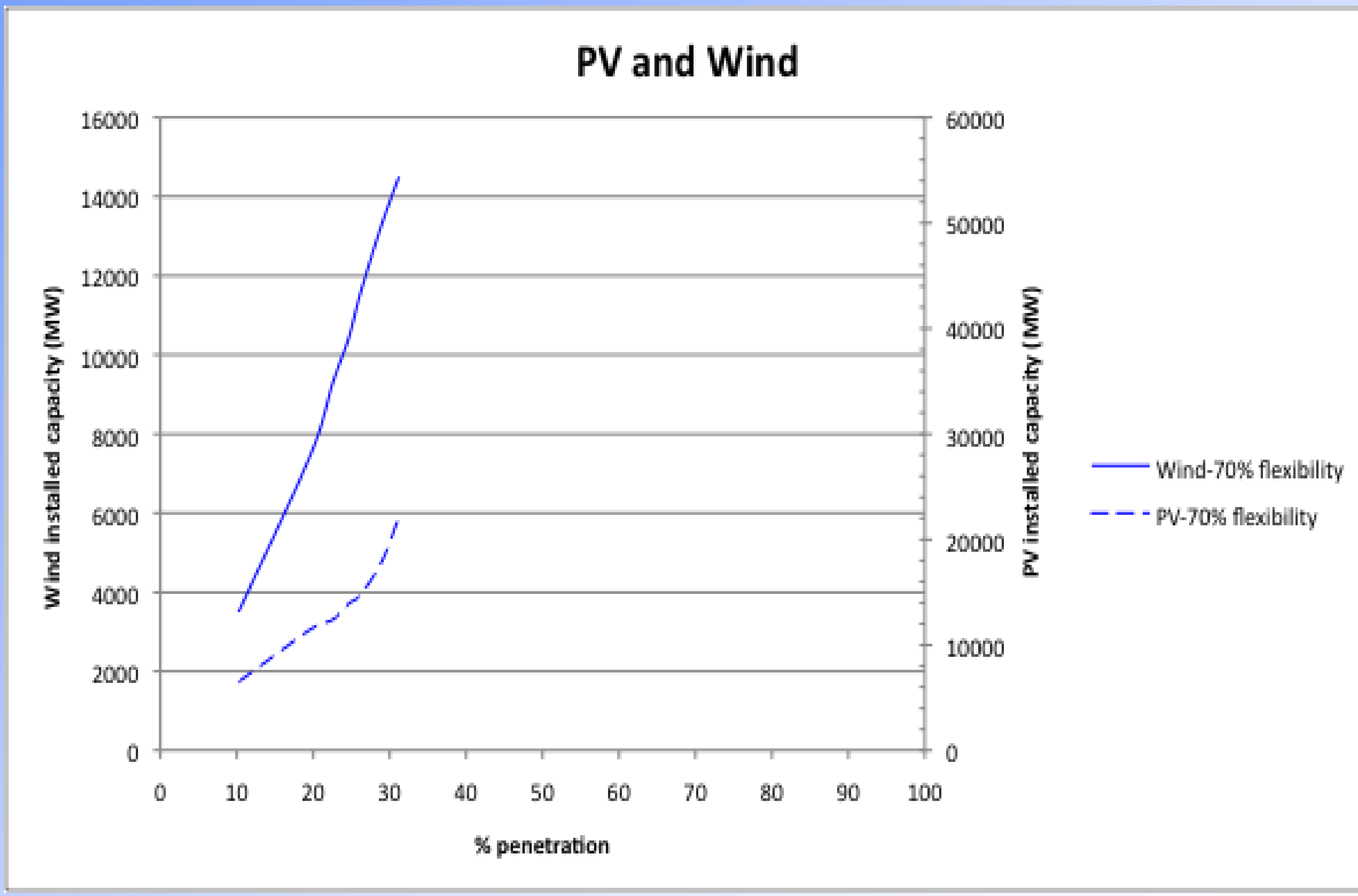
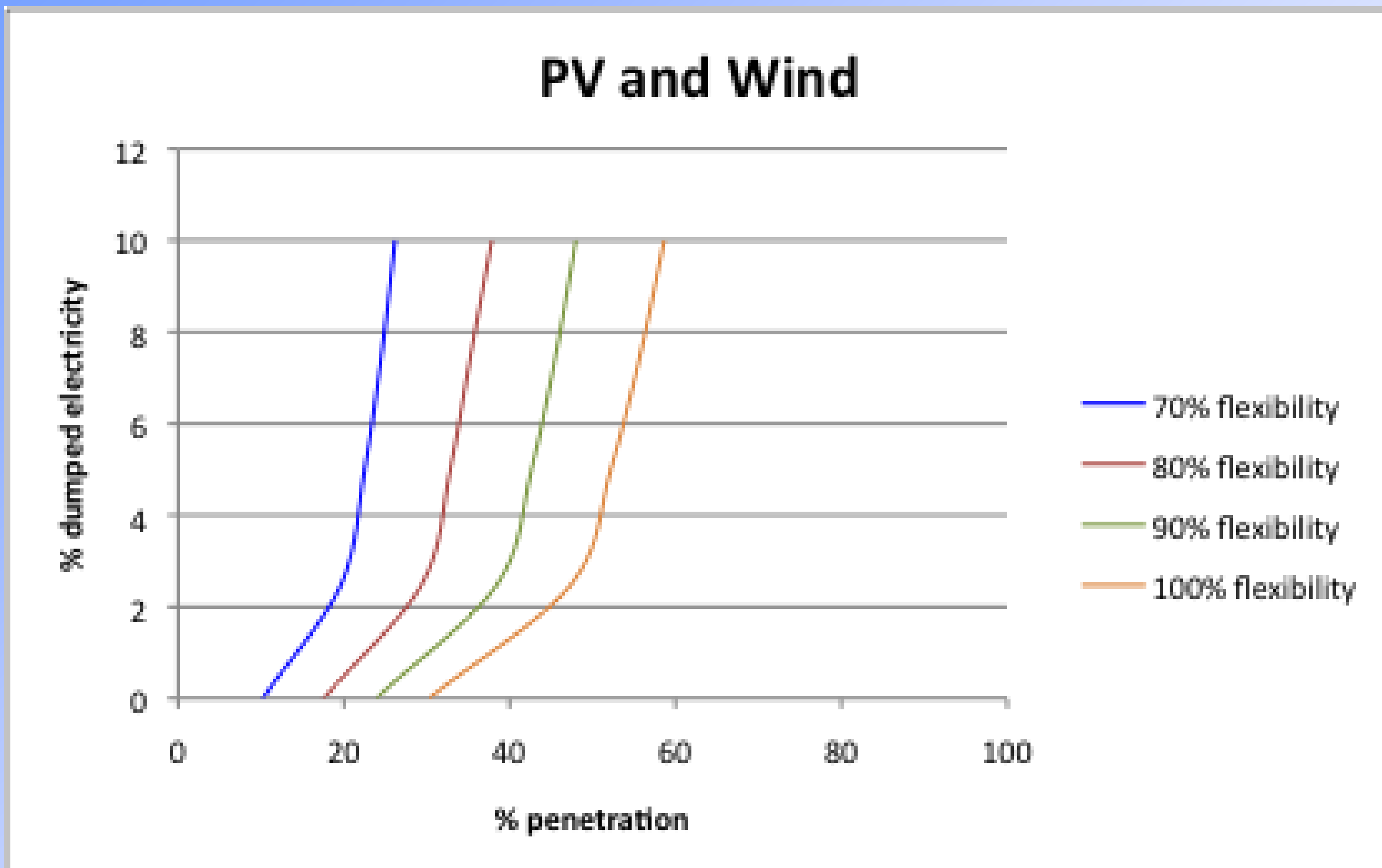
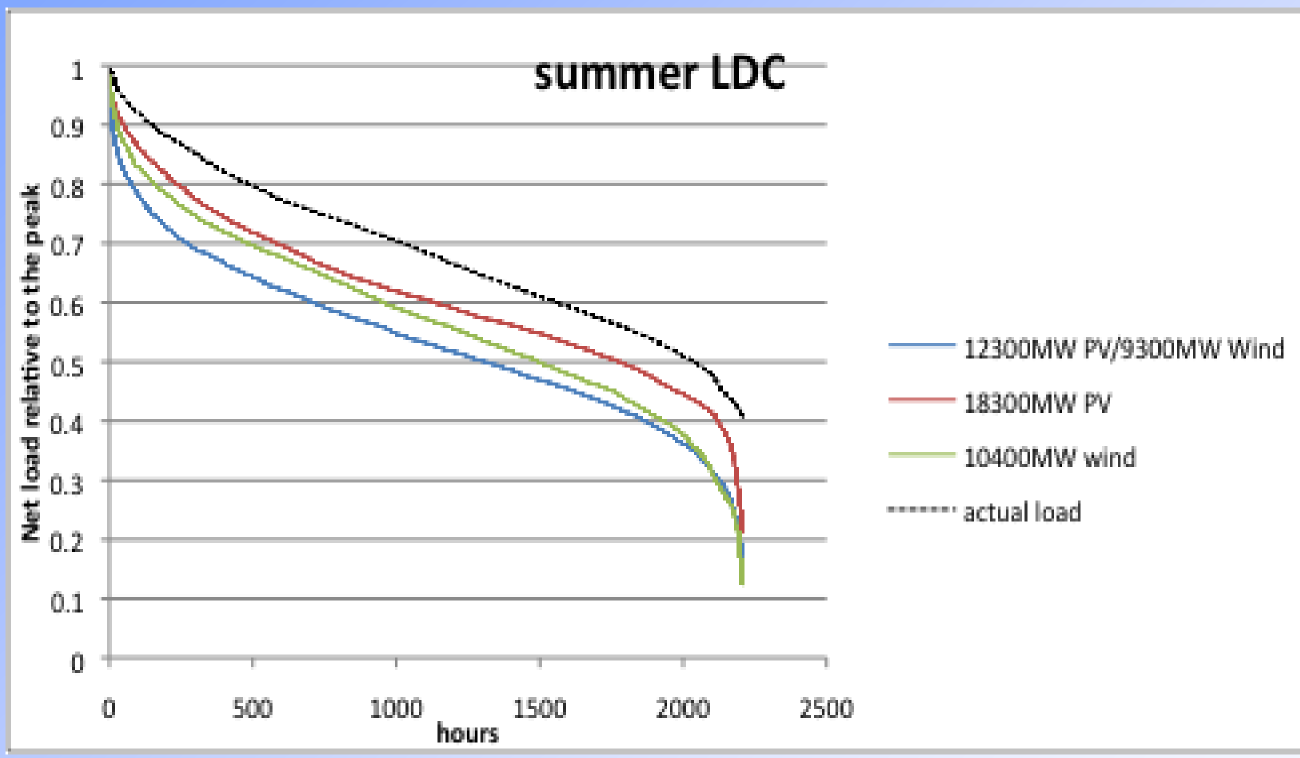
Results-PV and Wind



Results-PV and Wind

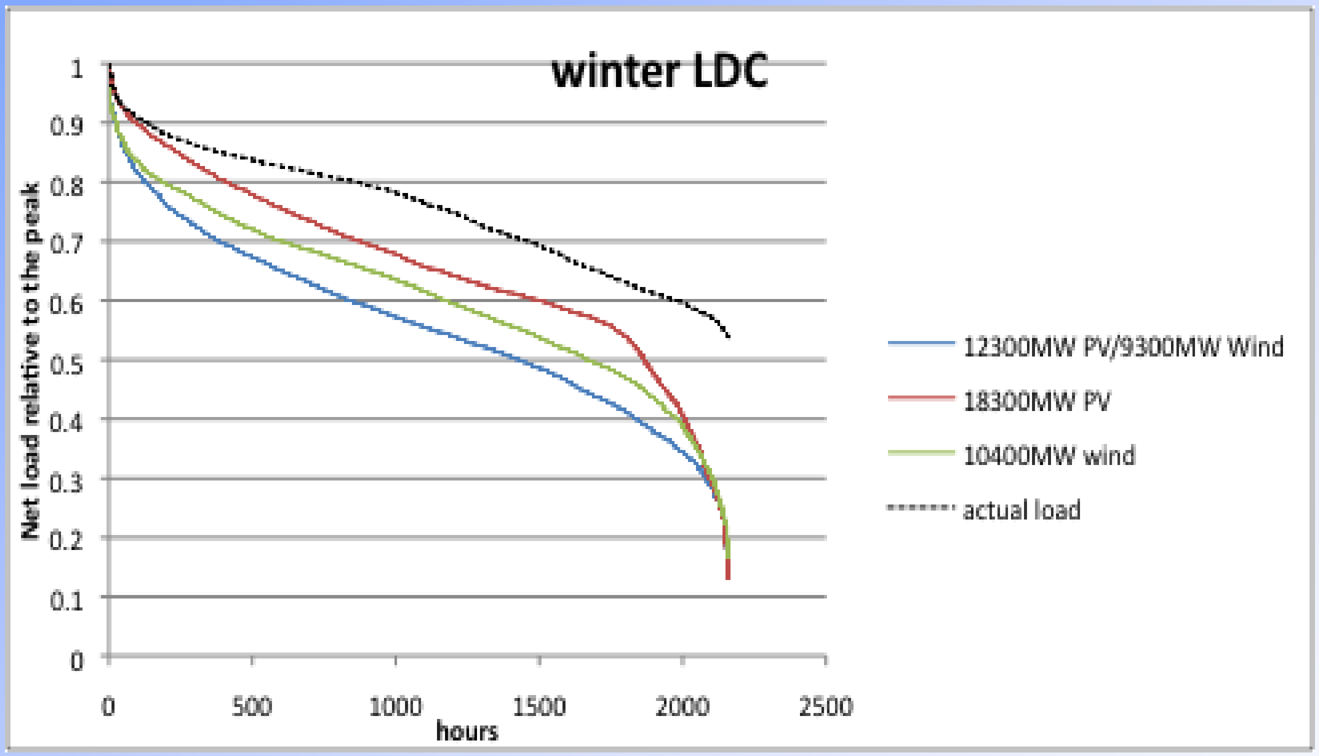


Summer Load Duration Curve



Net load duration curve for the summer months only when we are allowed to dump only 5% of annual energy.

Winter Load Duration Curve



Net load duration curve for the winter months only when we are allowed to dump only 5% of annual energy.

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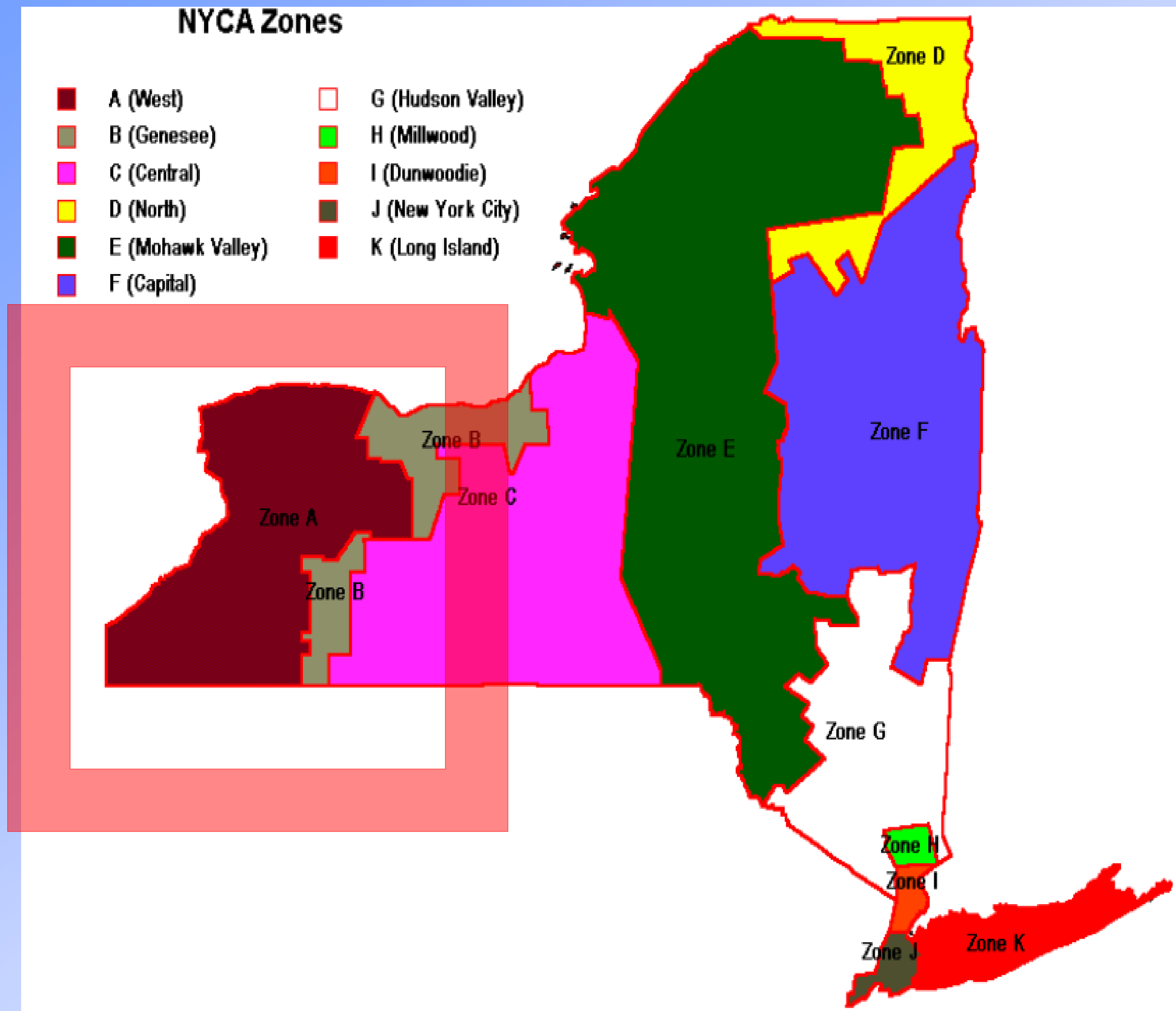
CAES Modeling

NY State Loading Zones



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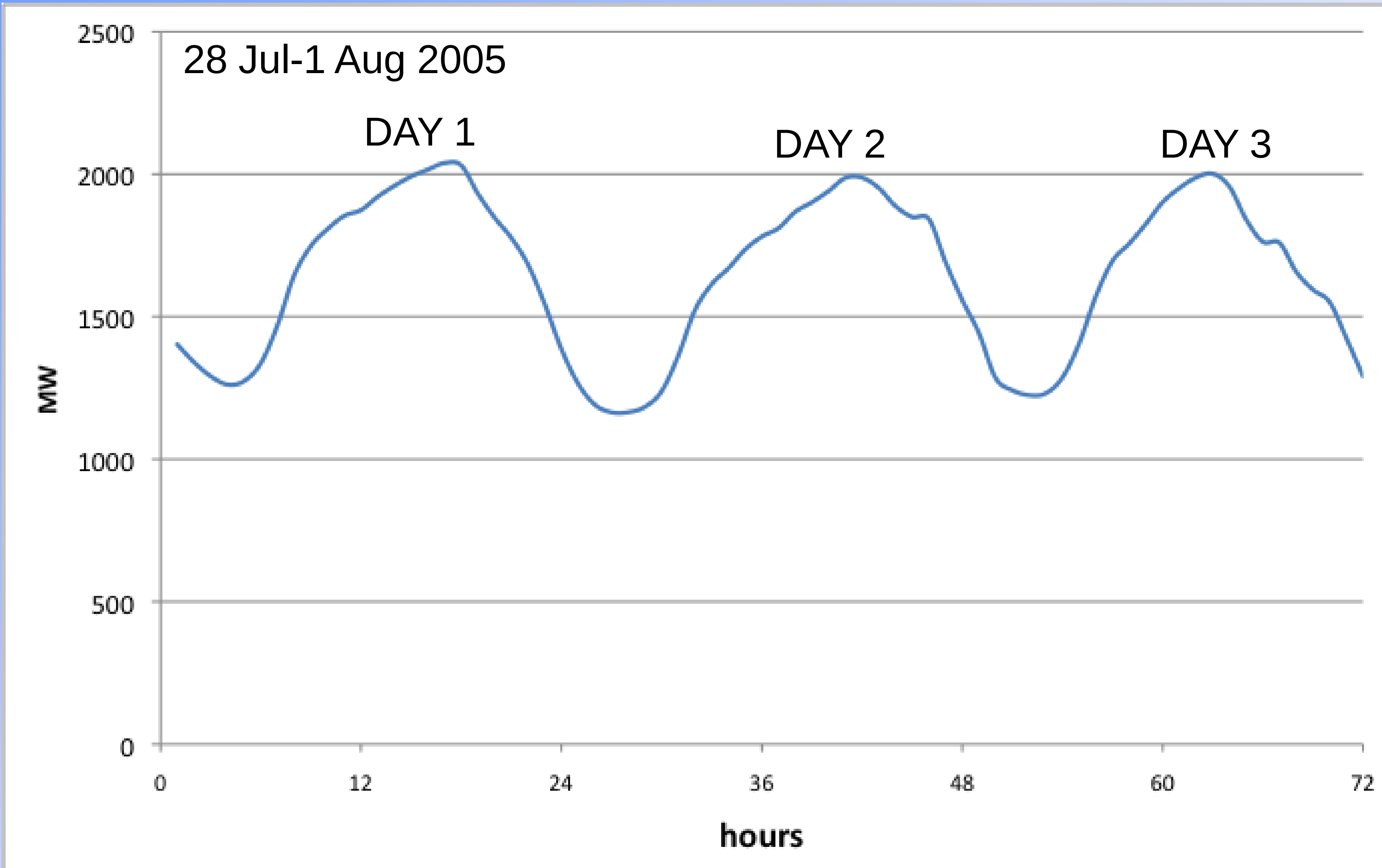
Load Profile of Zone West



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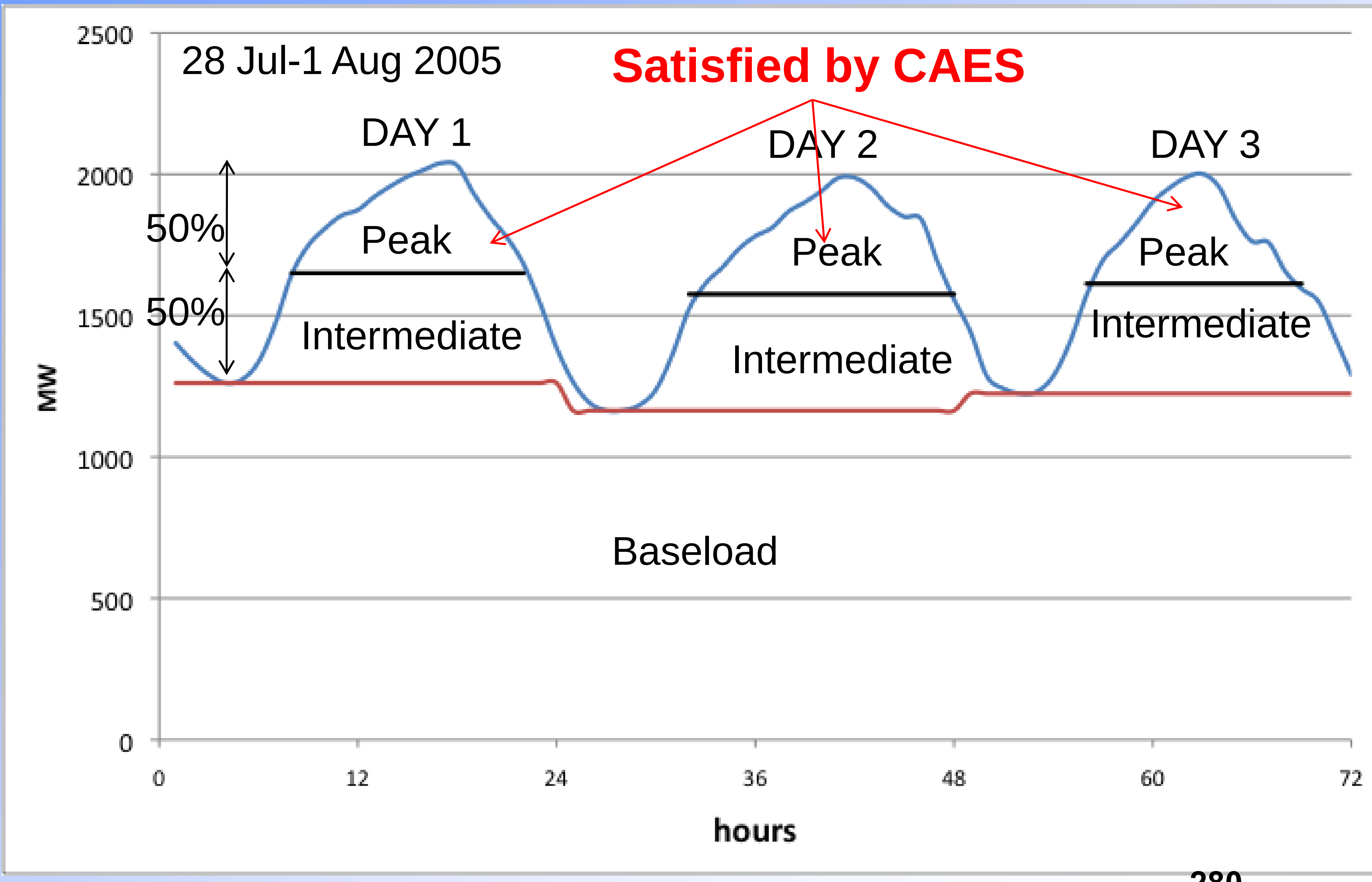
Load Profile of Zone West



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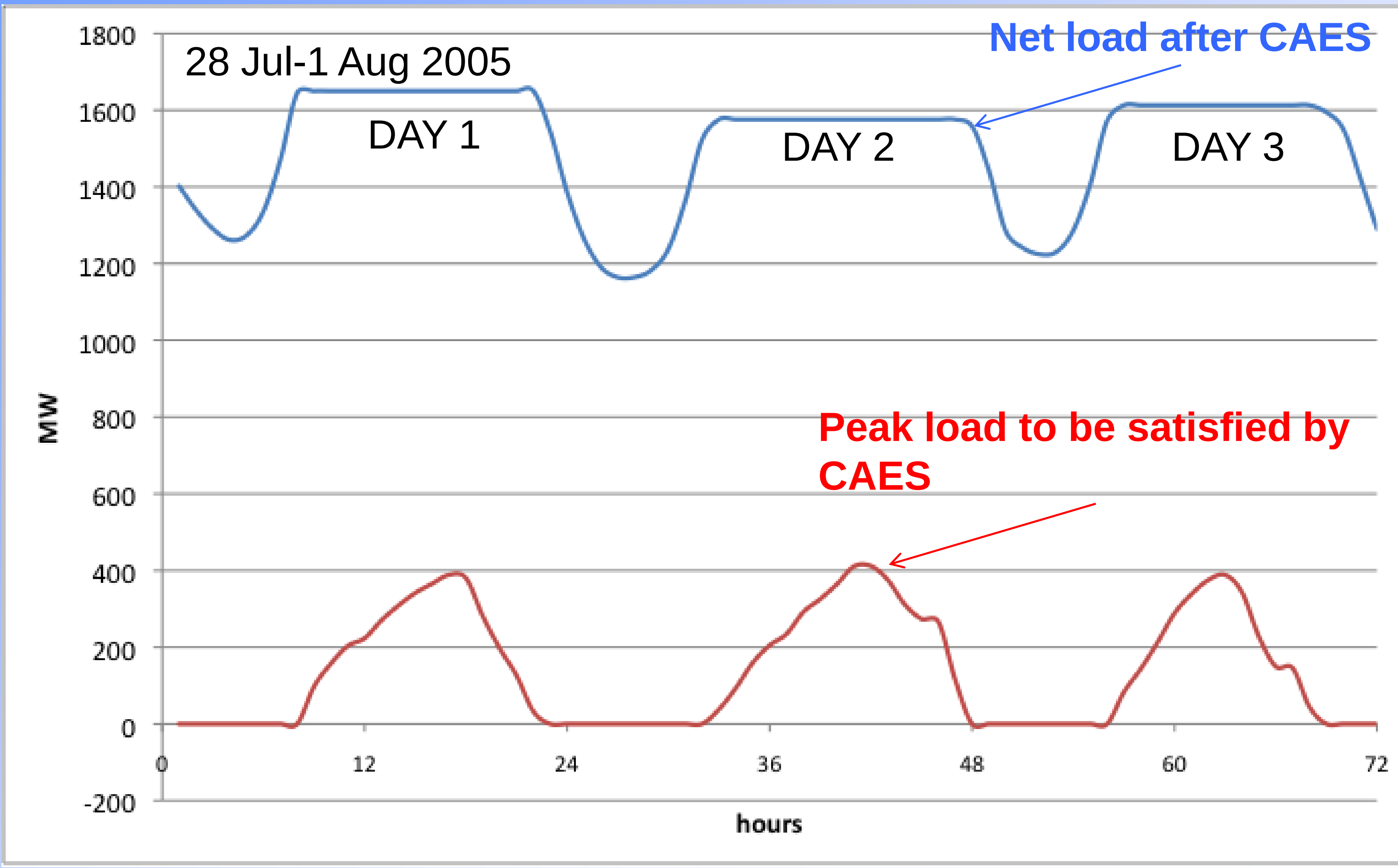
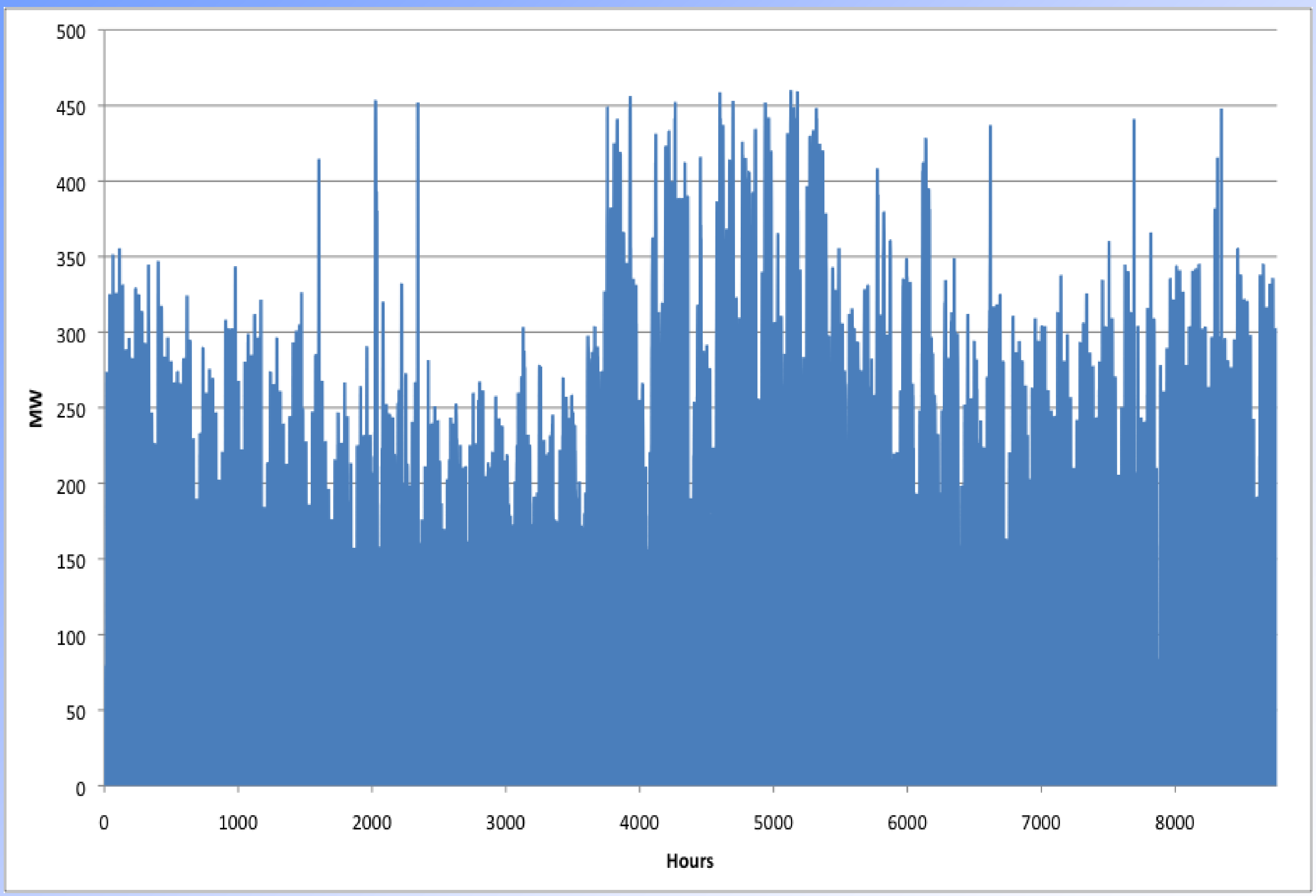
CAES Peak Shaving

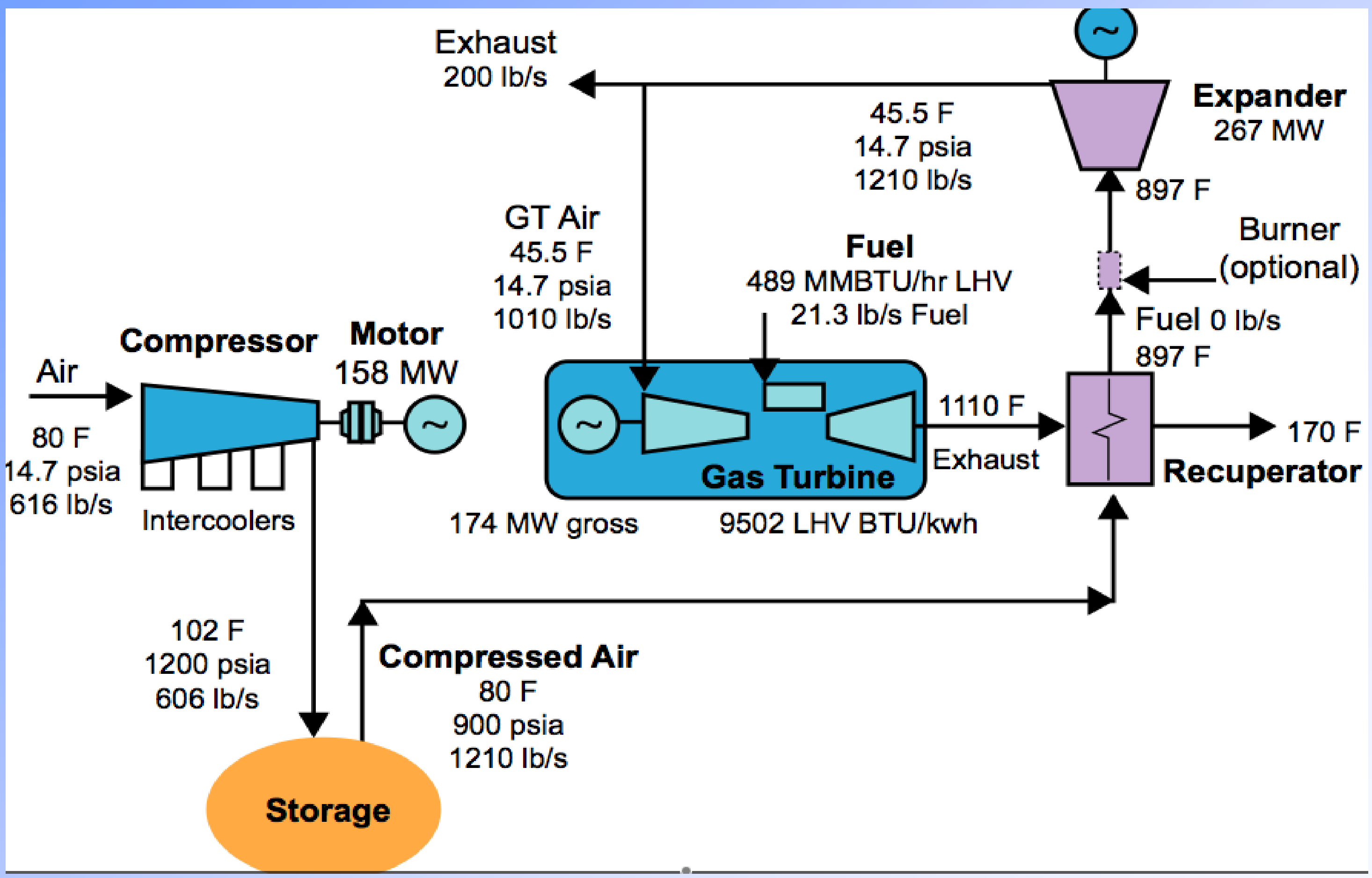


Annual Peak Load Profile- West Zone



We need a 450 MW CAES to satisfy the peak load

CAES Modeling



Source: 'Gas turbine world', vol 30, No. 2
Patented by Dr. Nakhamkin

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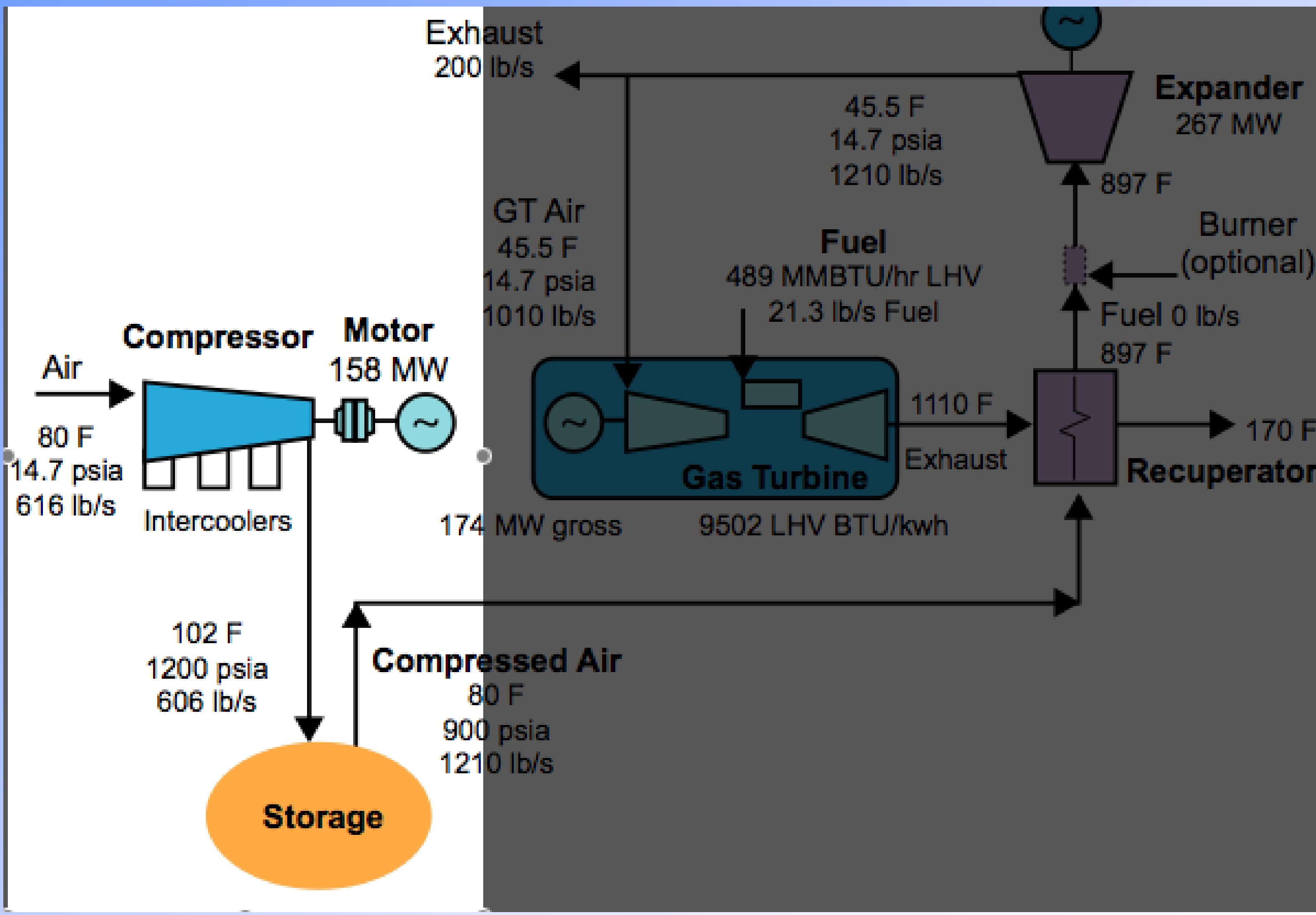
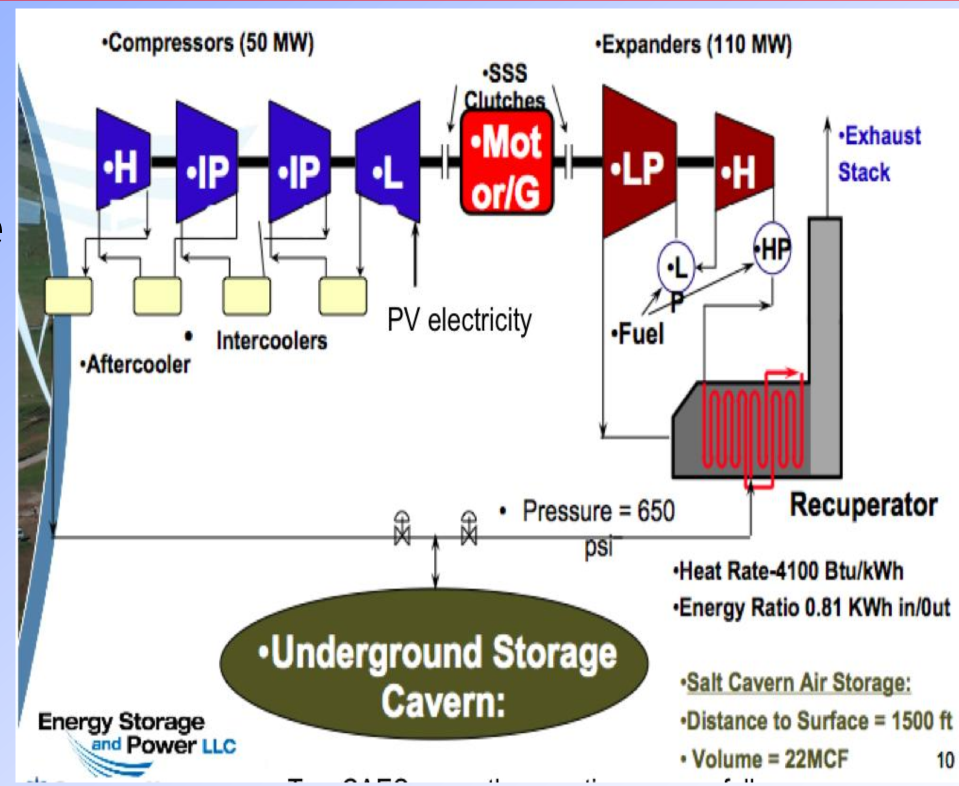
Modeling the Compression Part



Compressor type and assumptions

(Source: Energy storage and power LLC)



Assumptions

1) The compressors are of similar type as in the McIntosh plant (4 compression stages with intercooling)

2) The working capacity of the cavern is within the 900-1500psi (1200psi average pressure)

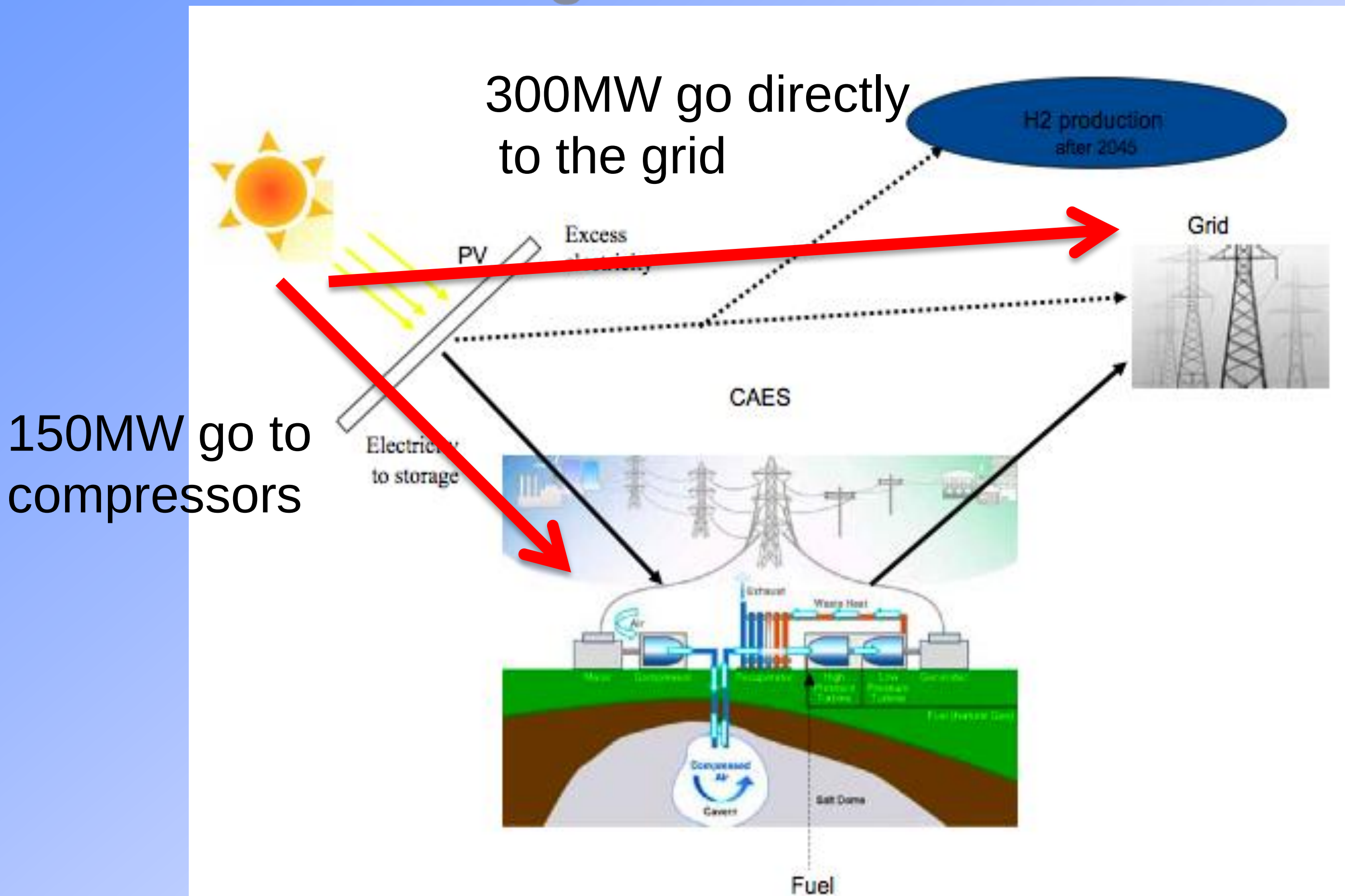
	Stages	Initial Pressure (psi)	Final Pressure (psi)	T1(K)	T2(K)	Z1	Z2	u1(m3/kg)	Total Work (kJoule/kg)
Compression LP	***Stage 1***	14.7	41	295	453	1	1.001	0.830	126.061
Intercooling	***Stage 1***	41	41	453	305				
Compression IP	***Stage 2.1***	41	131	305	421	0.999	1.001	0.310	150.573.
Intercooling	***Stage 2.1***	131	131	421	305				
Compression IP	***Stage 2.2***	131	332	305	413.15	0.997	1.004	0.096	116.486
Intercooling	***Stage 2.2***	332	332	413.15	405			0	
Compression HP	***Stage3***	332	1500	305	470	0.992	1.026	0.038	207.892
Aftercooling	***Stage3***	1500	1500	470	312				

Total work
(kJ/kg)=601.011
(kWh/kg)=0.167

$$W_{J \cdot kg^{-1}} = (y/y-1)P_1V_1\left[(P_2/P_1)^{(y-1)/y}-1\right] \times [(Z_1+Z_2)/(2Z_1)]/\text{Efficiency}$$

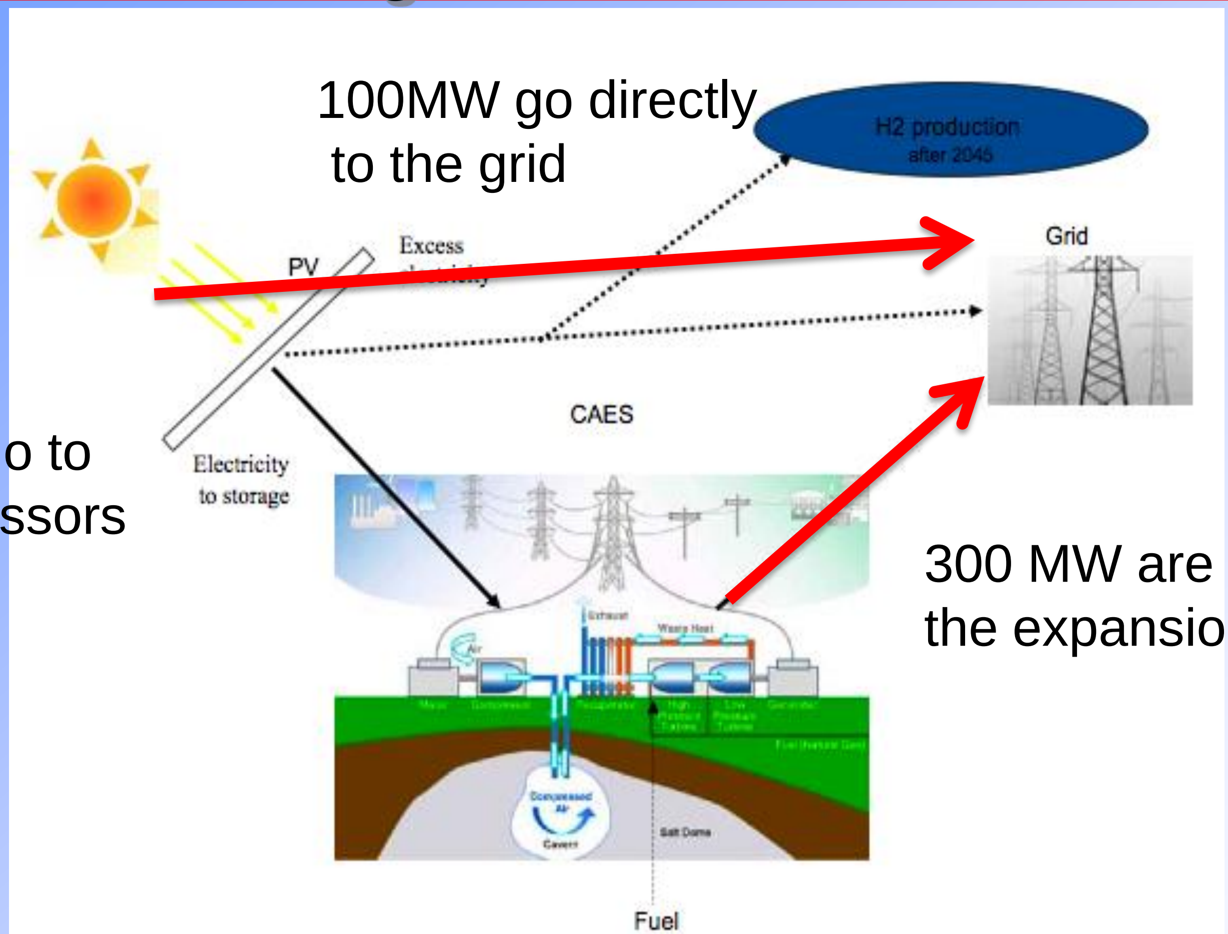
Based on calculations
Maximum power of one compressor: 73MW (at 118 kg/sec and 1500psi)
Average power of one compressor: 52.5 MW (at 93 kg/sec and 1200psi)
Minimum power of one compressor: 35.5MW (at 68 kg/sec and 900psi)

Example:
-The instant load is 300 MW
-450 MW are coming from our PV and Wind system



- We are always trying to satisfy the load first
- The compressors operate only when there is excess electricity

Example:
-The instant load is 300 MW
-100 MW are coming from our PV and Wind system



0 MW go to compressors

300 MW are produced at the expansion stage

- We are always trying to satisfy the load first
- The compressors operate only when there is excess electricity

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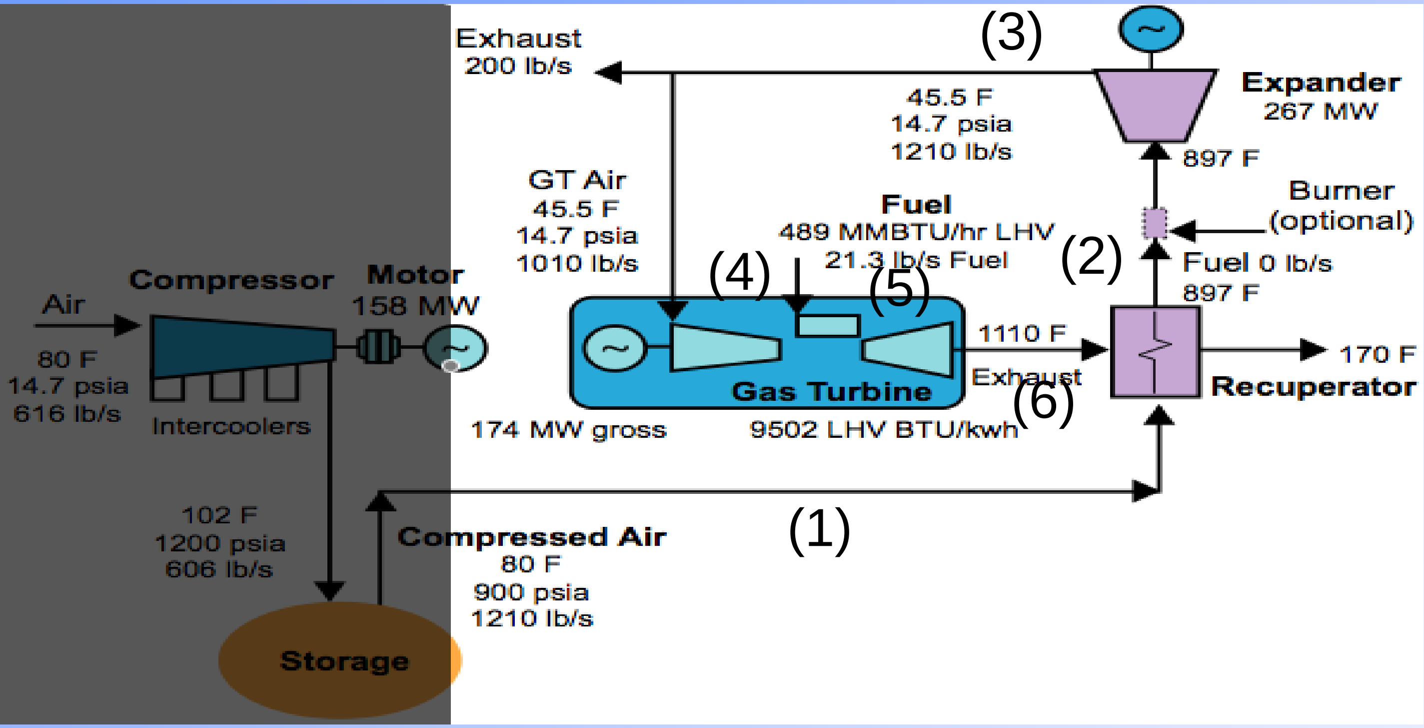
Modeling the Expansion Part



Assumptions

1. Every moment, 40% of the total output is produced at the gas turbine and 60% at the expanders
2. The temperature remains constant at both ends of each mechanical part (expander, recuperator, gas turbine); we regulate the output by throttling the air coming out of the cavern

Optimization / MATLAB

- Optimize a system that does not deplete the cavern throughout the year

- Parameters to be optimized:

1. PV capacity
2. Wind capacity
3. Cavern volume
4. Number of compressors

CAES components

- Optimization based on a 1,000,000 m^3 cavern

- Other components are:

650 MW PV

220 MW Wind

3 compressors

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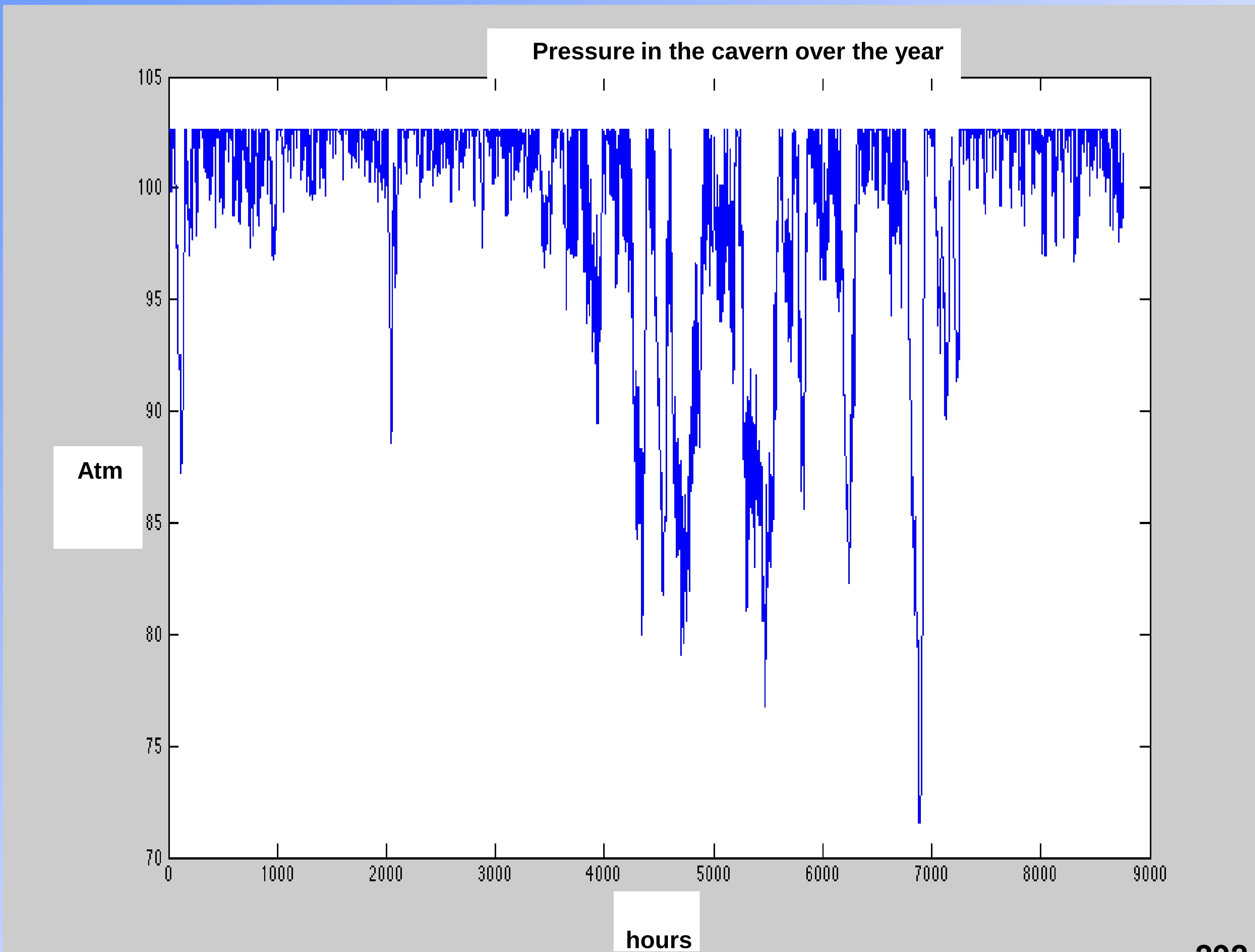
System performance over the year- Cavern pressure



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Conclusions

•Solar and wind together can achieve much higher penetration than solar alone or wind alone in NYS

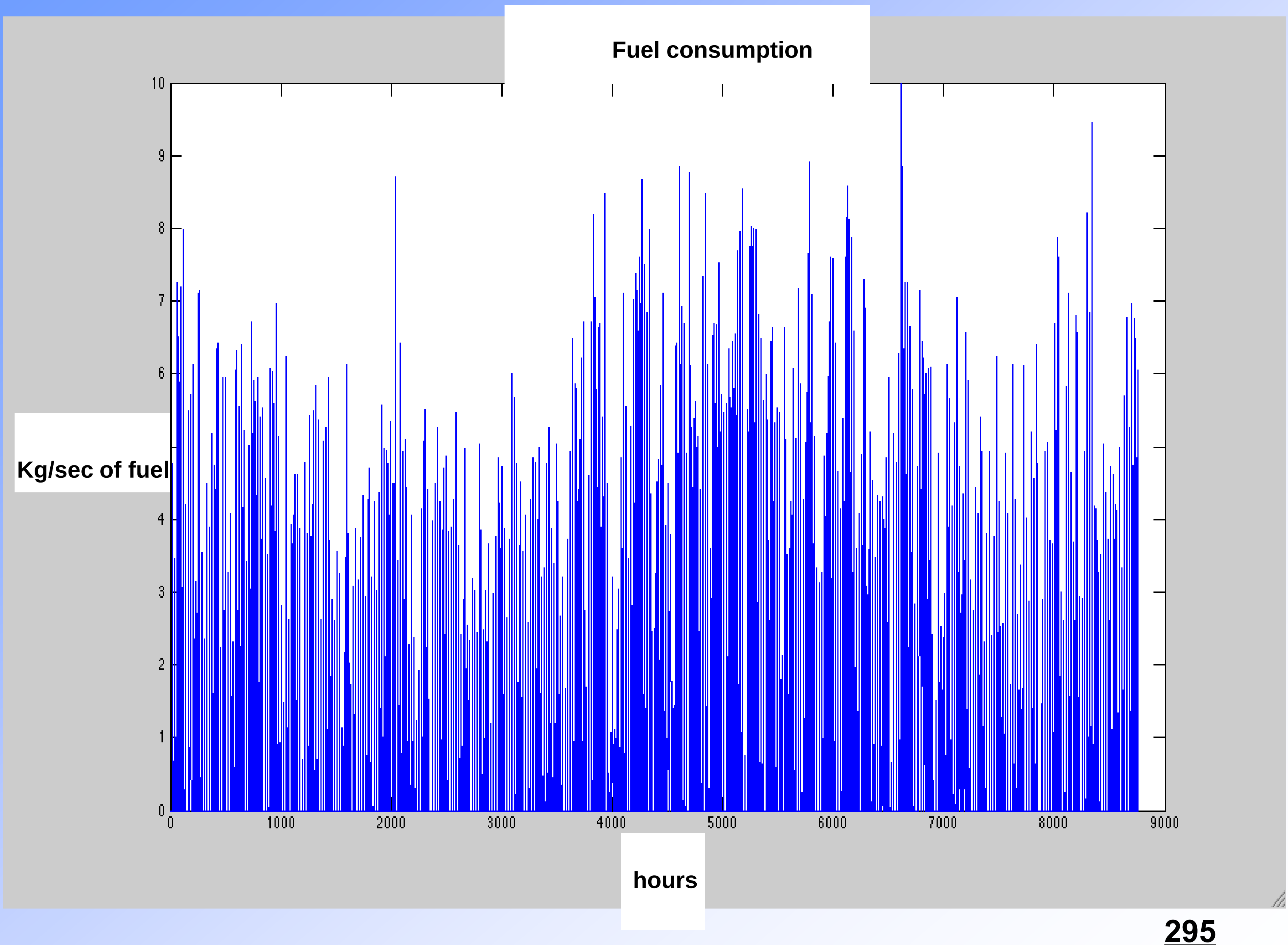
•More detailed load flow analysis with GIS is needed to include congestion issues

•CAES modeling in progress. Modeling small time scales is needed to capture CAES ramping potential

email: tn2204@columbia.edu
web: www.clca.columbia.edu

Earth & Environmental Engineering Department

System performance over the year- Cavern pressure



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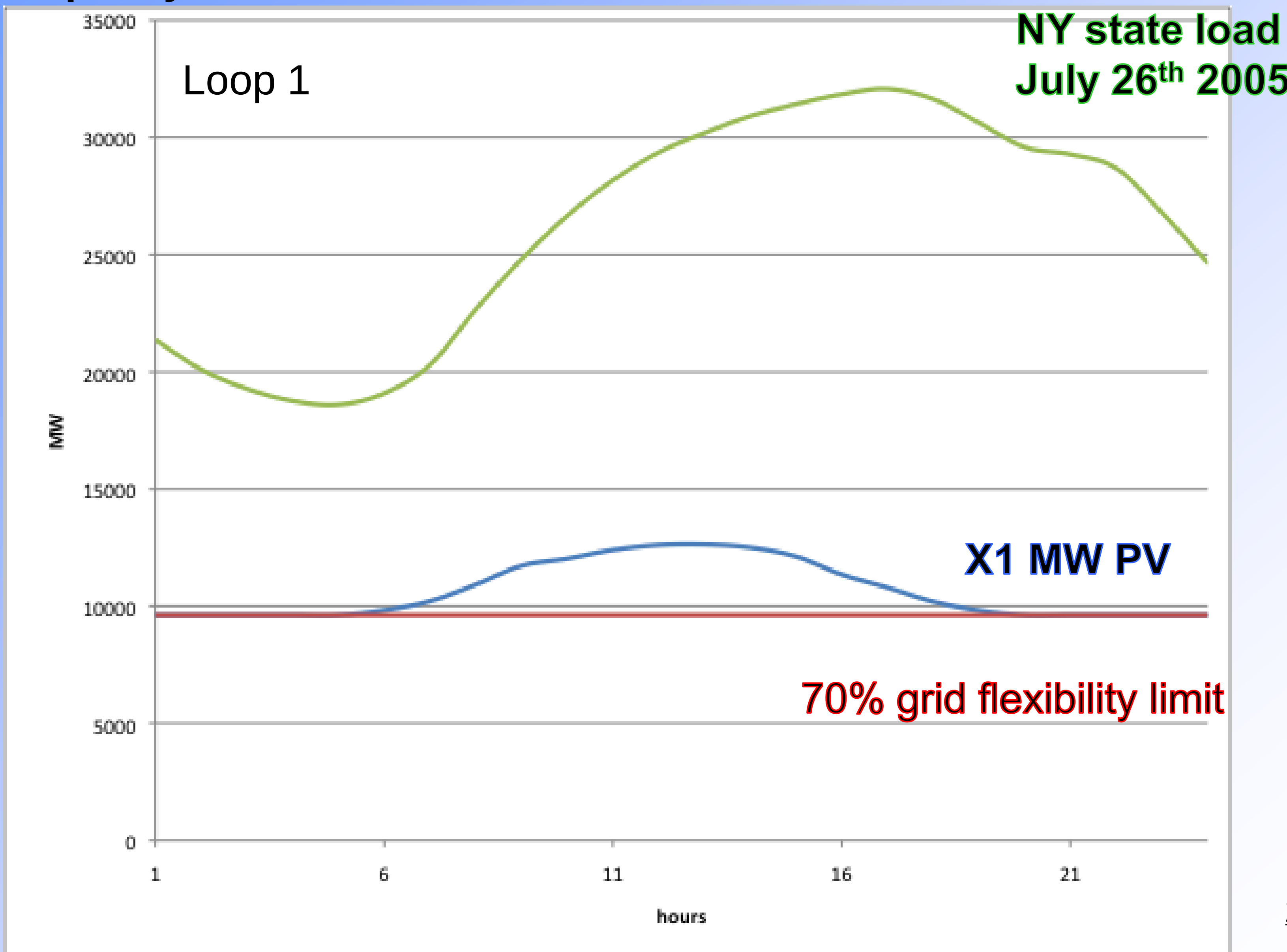
System Performance

- kWin/kWout=0.69 (0.7-0.75)
- 38% of total energy excess

- THANK YOU!!

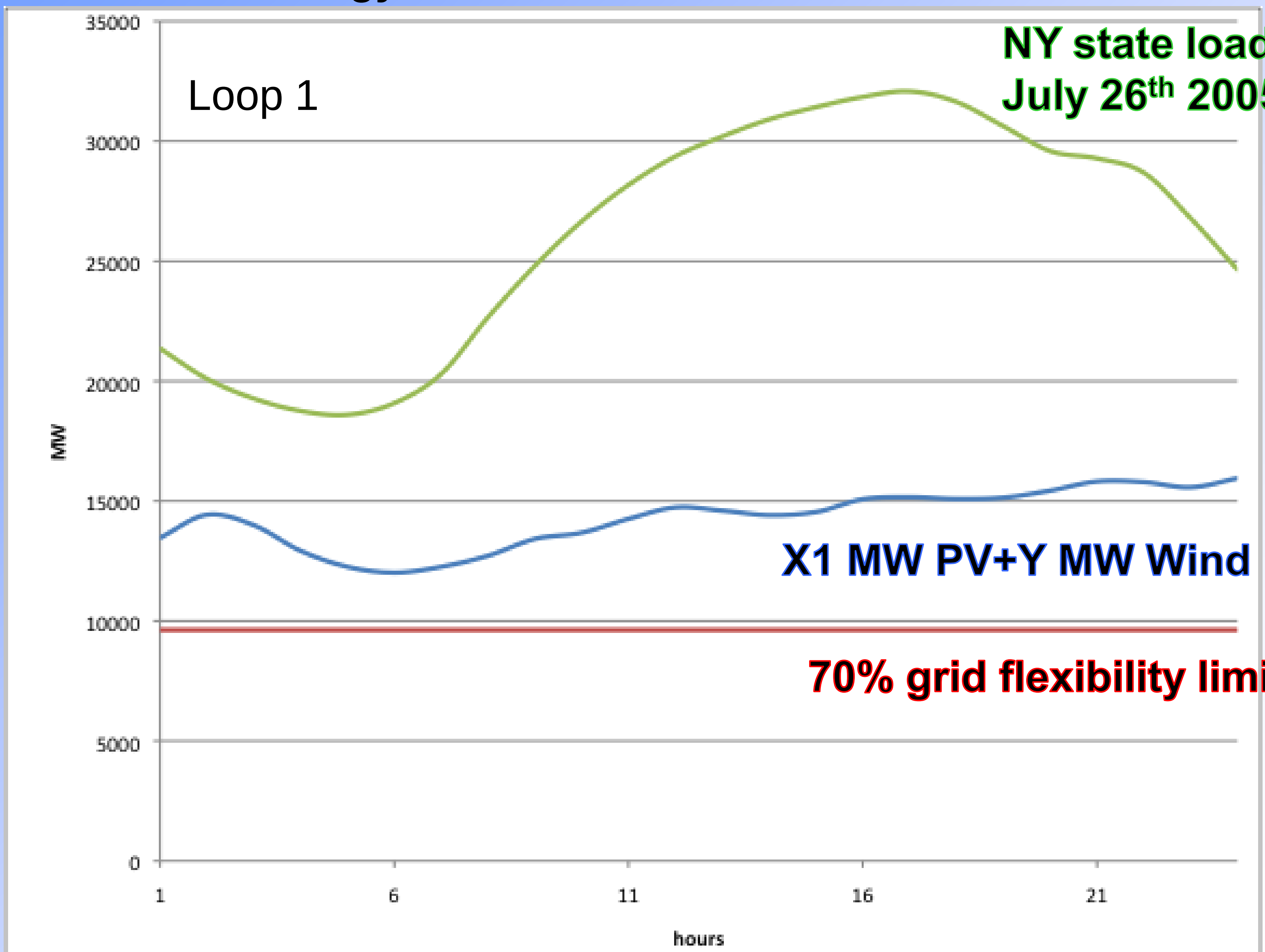
Optimization Model Structure / MATLAB

Step 2: Model the hourly output of a small PV system with capacity X1



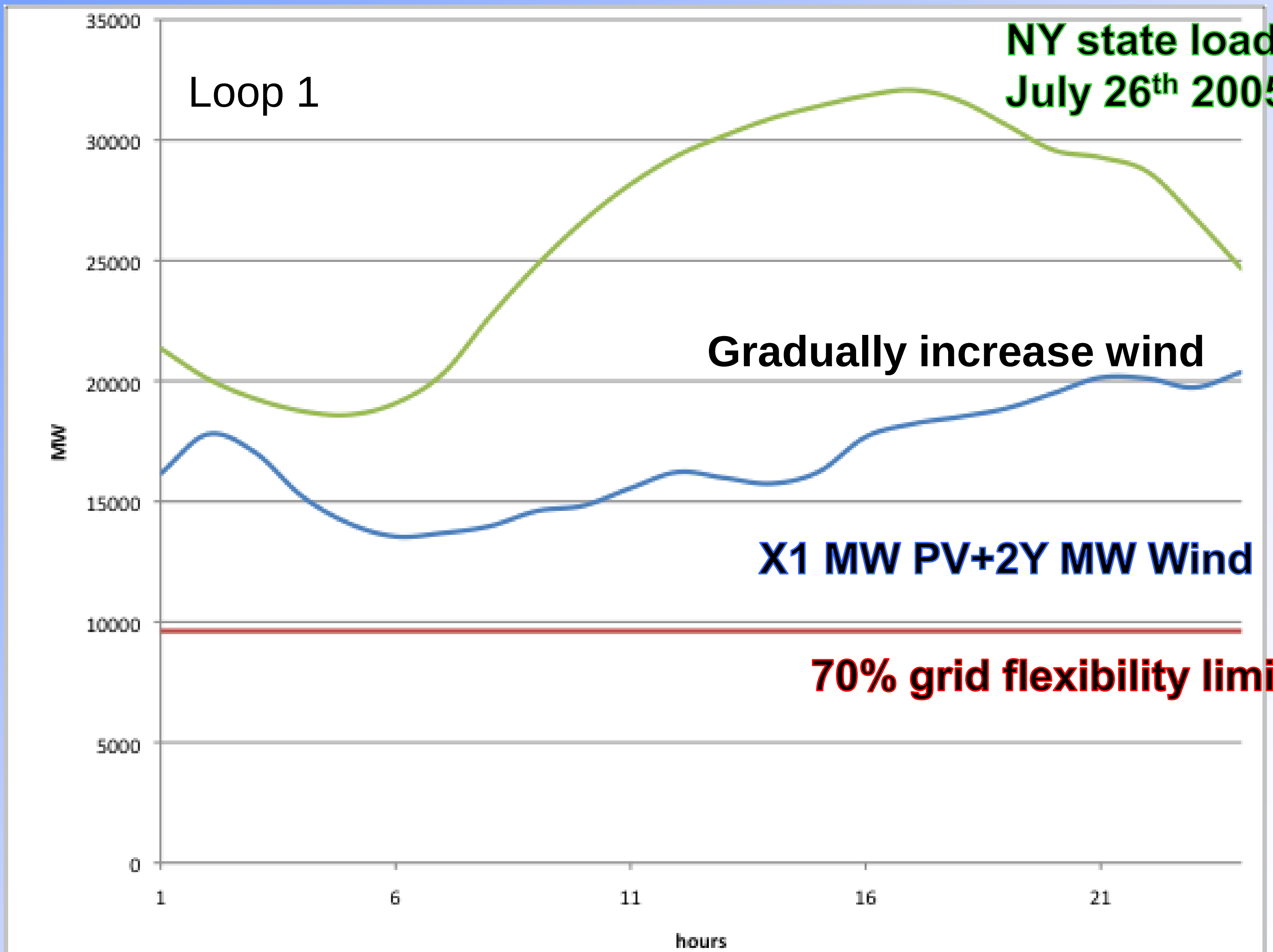
Optimization Model Structure / MATLAB

Step 3: Keep the PV output constant but gradually increase the output of wind generation and find the wind capacity Y1 that together with PV rejects 5% of annual energy



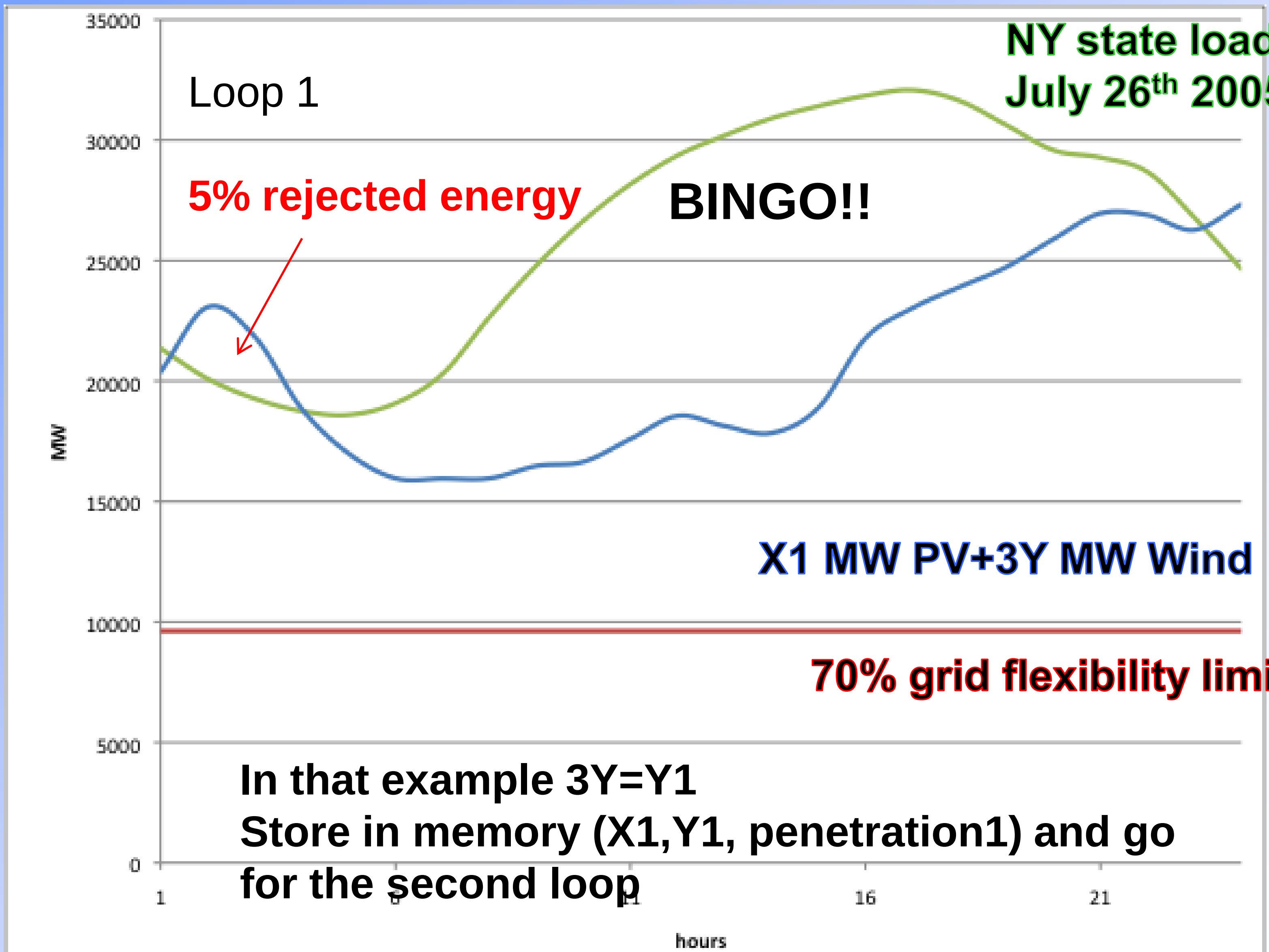
Optimization Model Structure / MATLAB

Step 3: Keep the PV output constant but gradually increase the output of wind generation and find the wind capacity Y1 that together with PV rejects 5% of annual energy



Optimization Model Structure / MATLAB

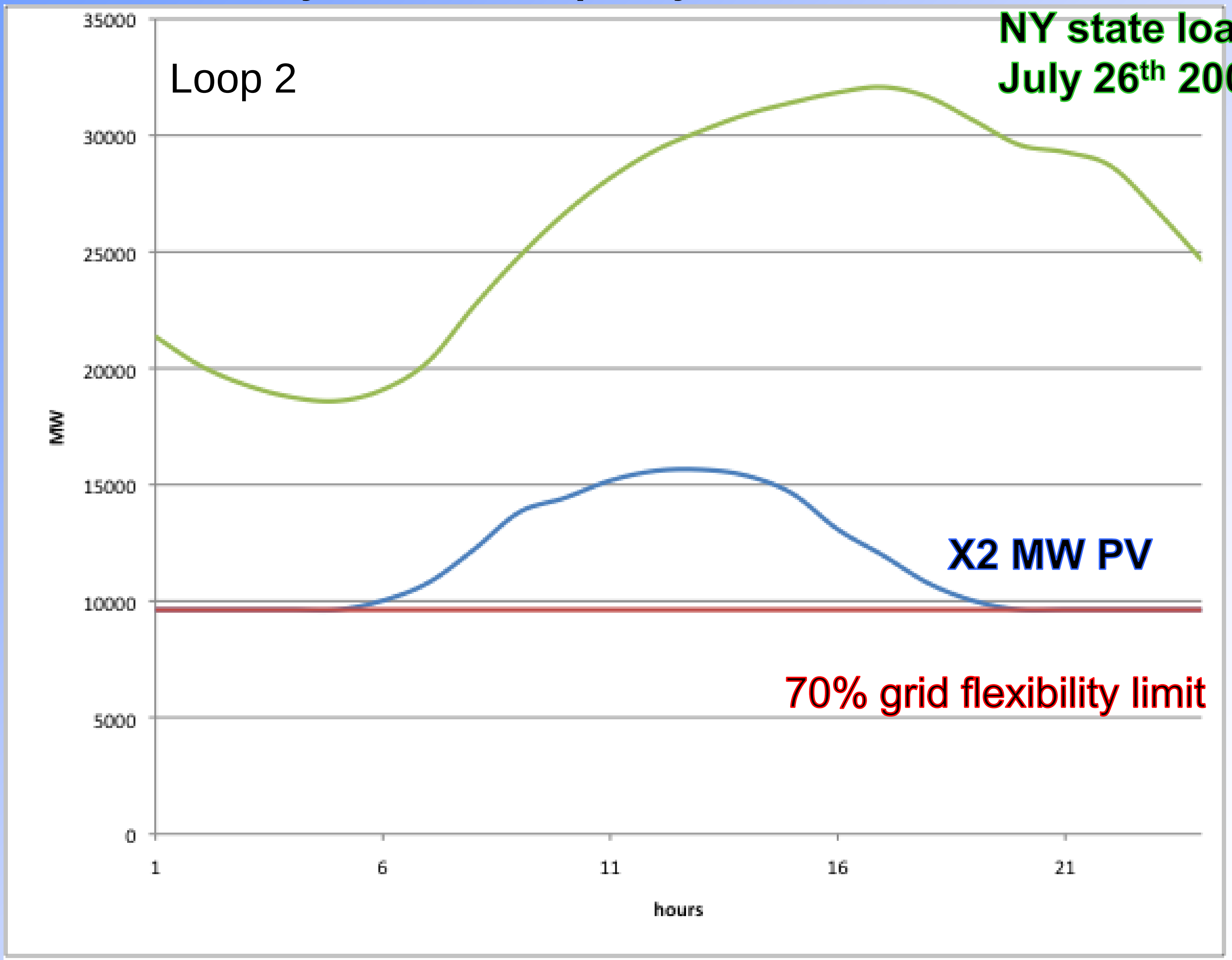
Step 3: Keep the PV output constant but gradually increase the output of wind generation and find the wind capacity Y1 that together with PV rejects 5% of annual energy



In that example 3Y=Y1
Store in memory (X1,Y1, penetration1) and go for the second loop

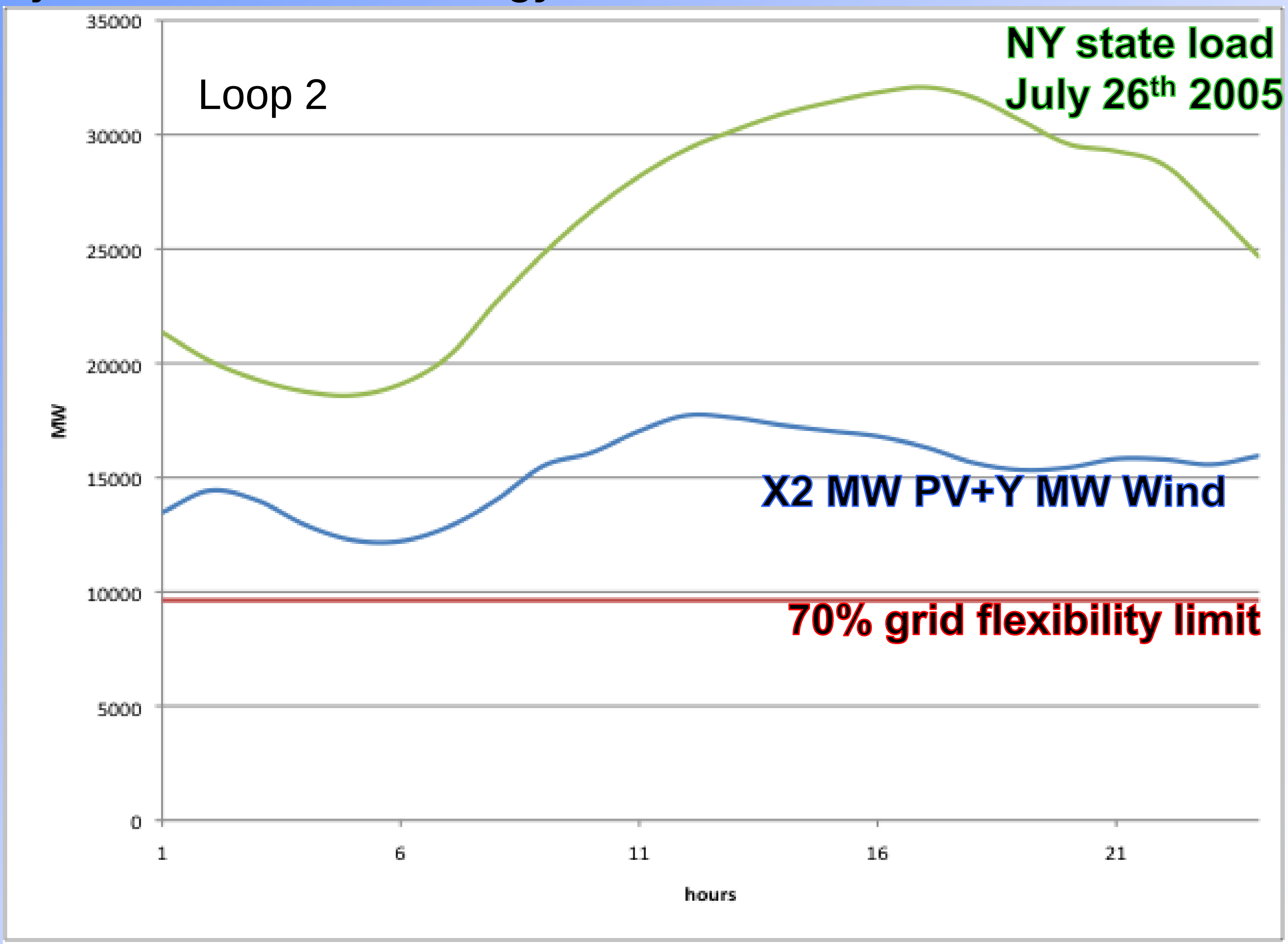
Optimization Model Structure / MATLAB

Step 1: Increase your solar output a bit. Model the hourly output of a small PV system with capacity X2>X1



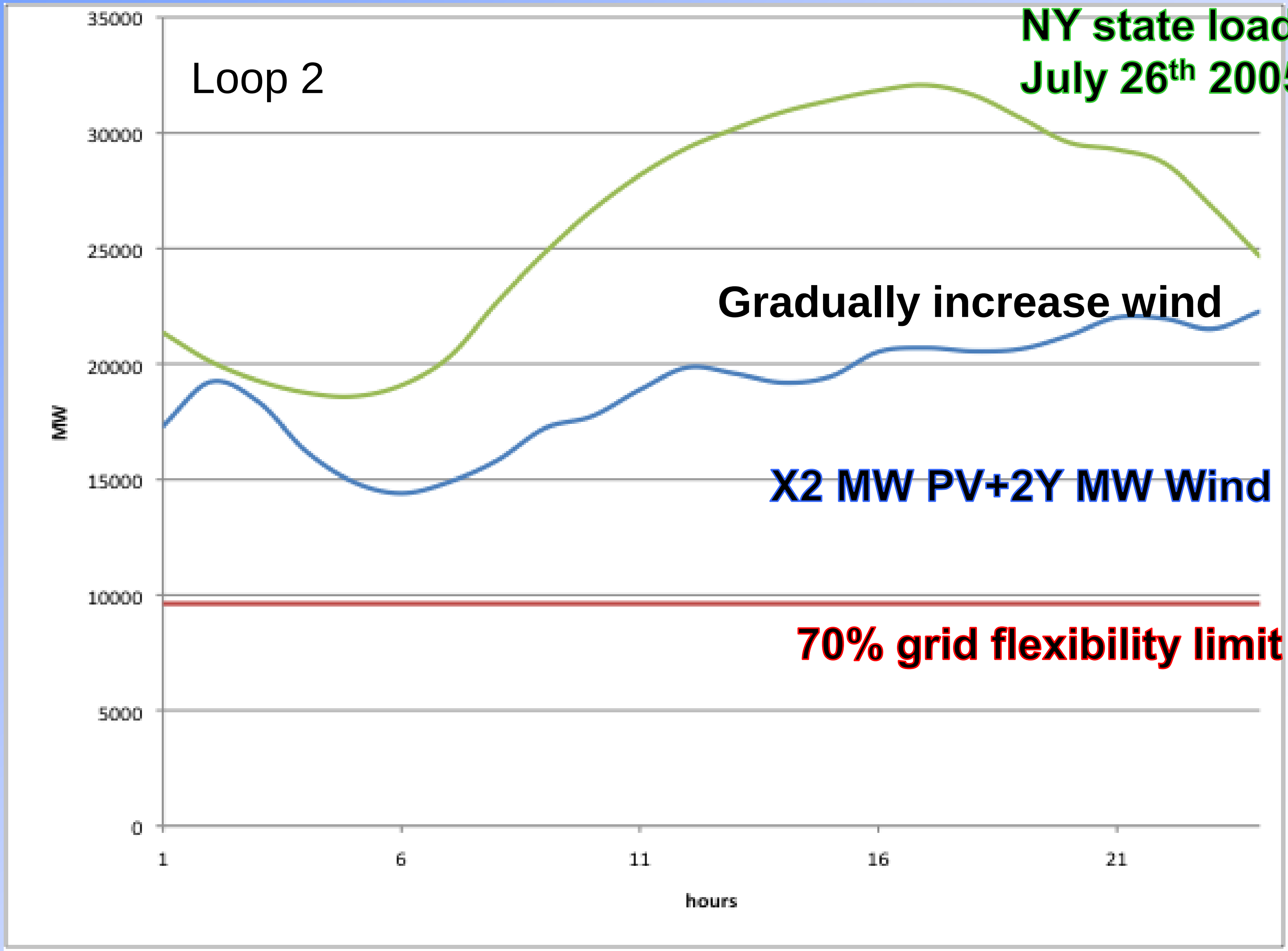
Optimization Model Structure / MATLAB

Step 2: Keep the PV output constant but gradually increase the output of wind generation and find the wind capacity Y2 that together with X2PV rejects 5% of annual energy



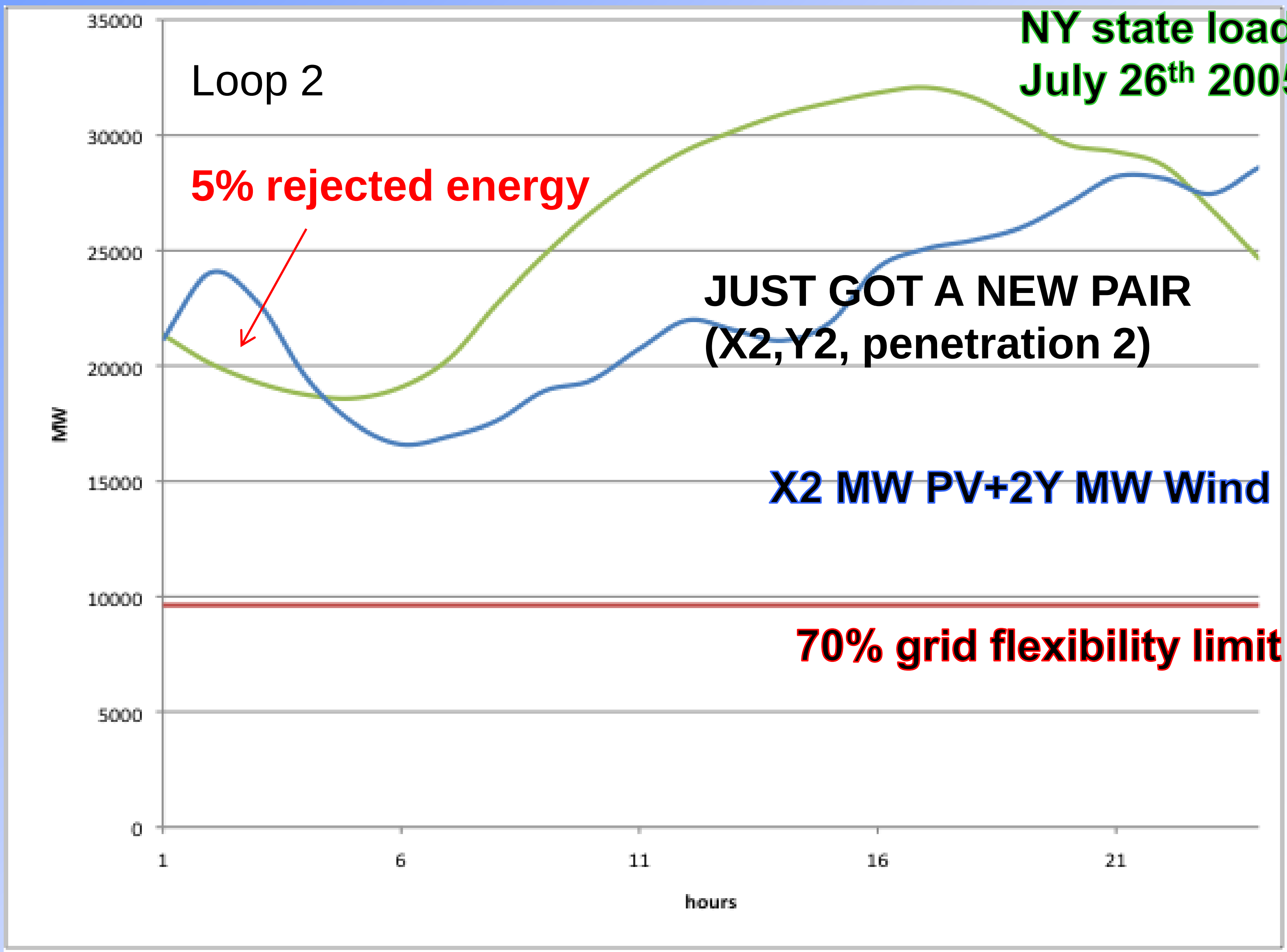
Optimization Model Structure / MATLAB

Step 2: Keep the PV output constant but gradually increase the output of wind generation and find the wind capacity Y2 that together with X2PV rejects 5% of annual energy

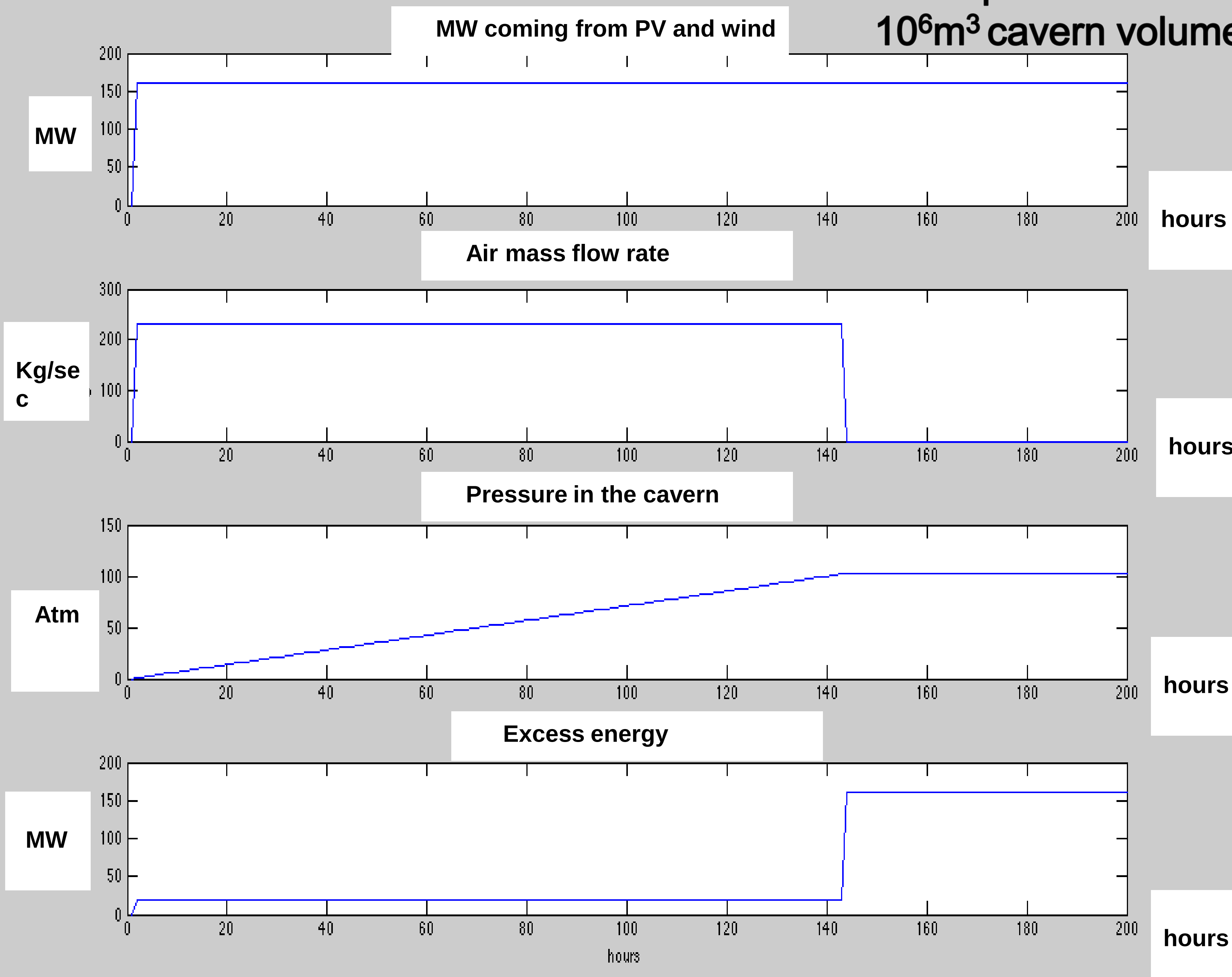


Optimization Model Structure / MATLAB

Step 2: Keep the PV output constant but gradually increase the output of wind generation and find the wind capacity Y2 that together with X2PV rejects 5% of annual energy



3 compressors
$10^6 m^3$ cavern volume



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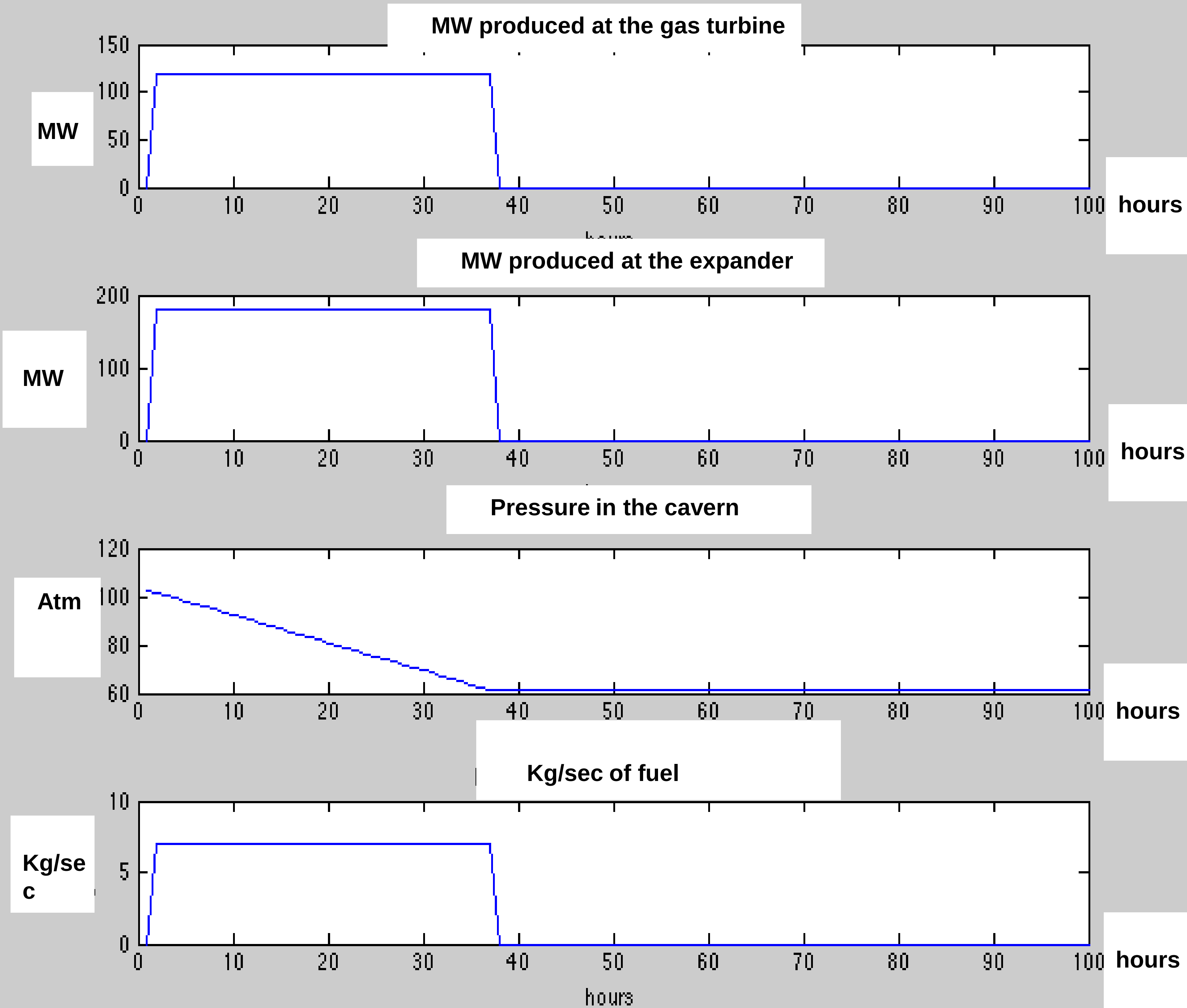
MW produced at the gas turbine
MW
150
100
50
0
0 10 20 30 40 50 60 70 80 90 100
hours
MW produced at the expander
MW
200
100
0
0 10 20 30 40 50 60 70 80 90 100
hours
Pressure in the cavern
Atm
120
100
80
60
0 10 20 30 40 50 60 70 80 90 100
hours
Kg/sec of fuel
Kg/se
c
10
5
0
0 10 20 30 40 50 60 70 80 90 100
hours
hours

14. Multi-functional Application of Co-located Wind Power and Adiabatic CAES

Daniel Wolf, Annedore Kanngießer, Christian Dötsch, *Fraunhofer Institut für Umwelt-, Sicherheits- und Energietechnik UMSICHT*

Roland Span, *Ruhr-Universität Bochum, Lehrstuhl für Thermodynamik*

CAES plants are custom made installations that can be adapted to a certain degree to their intended application. For adiabatic CAES plants these degrees of freedom are represented by the heat storage concept and dimensioning as well as by the turbo machinery's general arrangement and part load performance. The presentation gives a detailed analysis of an application of A-CAES plant co-located with a wind farm on a 110 kV grid. It entails determination of the optimal size of a wind farm and A-CAES plant for given project boundary conditions, and the operational regime of an optimized system. A Generic Optimization Model for Energy Storage (GOMES®), a high resolution optimization model has been developed and applied. It was also examined how a multifunctional storage operation can be realized comprising direct wind energy storage as well as spot market and tertiary reserve market participation simultaneously. It is shown that such a multifunctional operation improves the profitability of CAES plants compared to singular operation at only one market.

Daniel Wolf is a research associate at the Fraunhofer Institute UMSICHT in the department Energy-Efficiency-Technologies. He studied mechanical and process engineering at the Technische Universität Darmstadt, Politécnica de Madrid and Technische Universität Berlin. in 2005 he worked as a junior researcher with Prof. Tsatsaronis at the Institute for Energy Engineering at the Technische Universität Berlin on energy systems modeling and optimization. In 2007 he joined the Fraunhofer Institute UMSICHT where his work focuses on thermal design and optimization of CAES.

MULTIFUNCTIONAL APPLICATION OF ADIABATIC COMPRESSED AIR ENERGY STORAGE CO-LOCATED WITH WIND POWER

"Integrating Wind-Solar-CAES"
2nd Compressed Air Energy Storage (CAES) Conference & Workshop
CLCA, Columbia University
Oktober 20, 2010

Daniel Wolf

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D-CAES vs. A-CAES

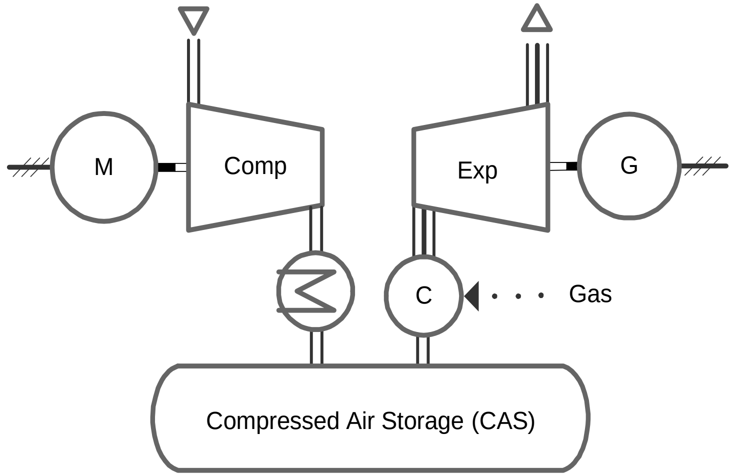


Fig.: Fraunhofer UMSICHT

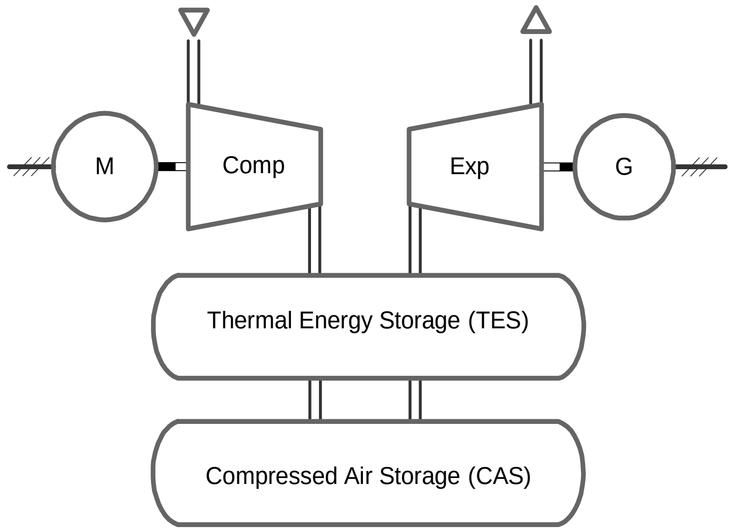
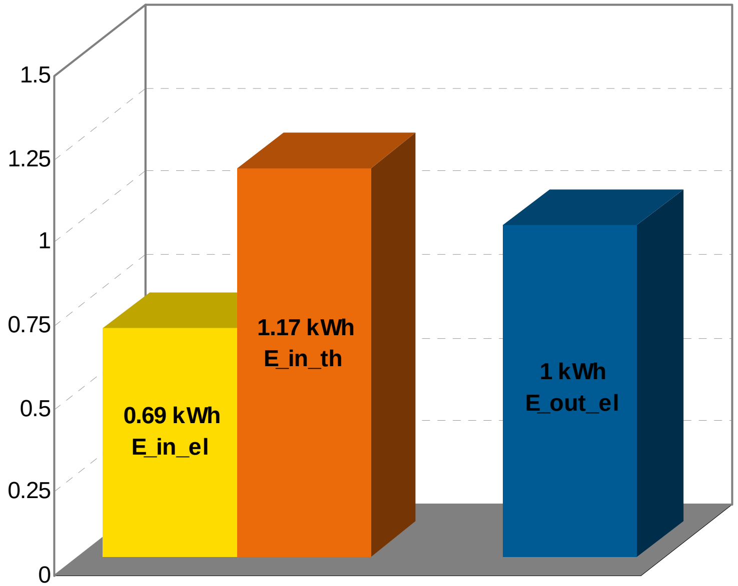
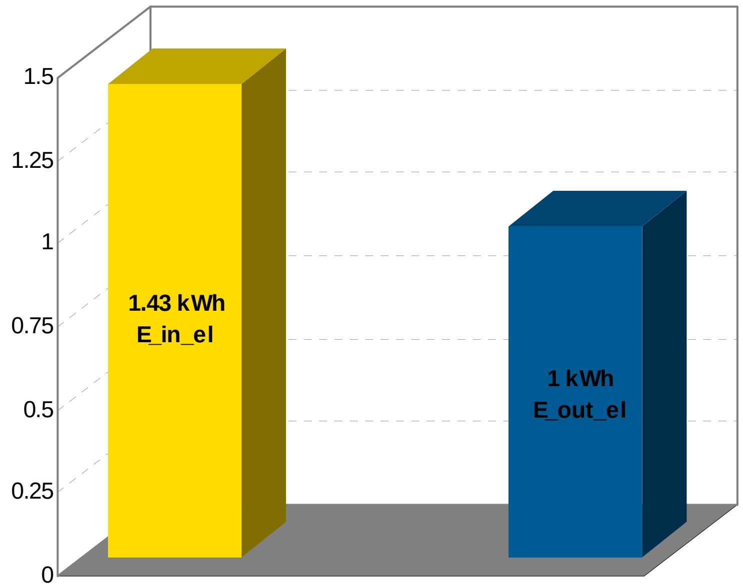


Fig: Fraunhofer UMSICHT





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D-CAES plant configuration

Fig.: E.ON Energie

Huntorf, Germany (1978)

- 60 MW_{comp} / 320 MW_{exp}
  → power ratio: 0.2
- 8h_{comp} / 2h_{exp}
  → charging period ratio: 4


Fig.: Energy Storage & Power LLC

McIntosh, USA (1991)

- 50 MW_{comp} / 110 MW_{exp}
  → power ratio: 0.45
- 38h_{comp} / 24h_{exp}
  → charging period ratio: 1.5

→ **Questions:**

- Optimal A-CAES plant configuration in view of intermittent RES integration?
- Expected A-CAES operational regime?

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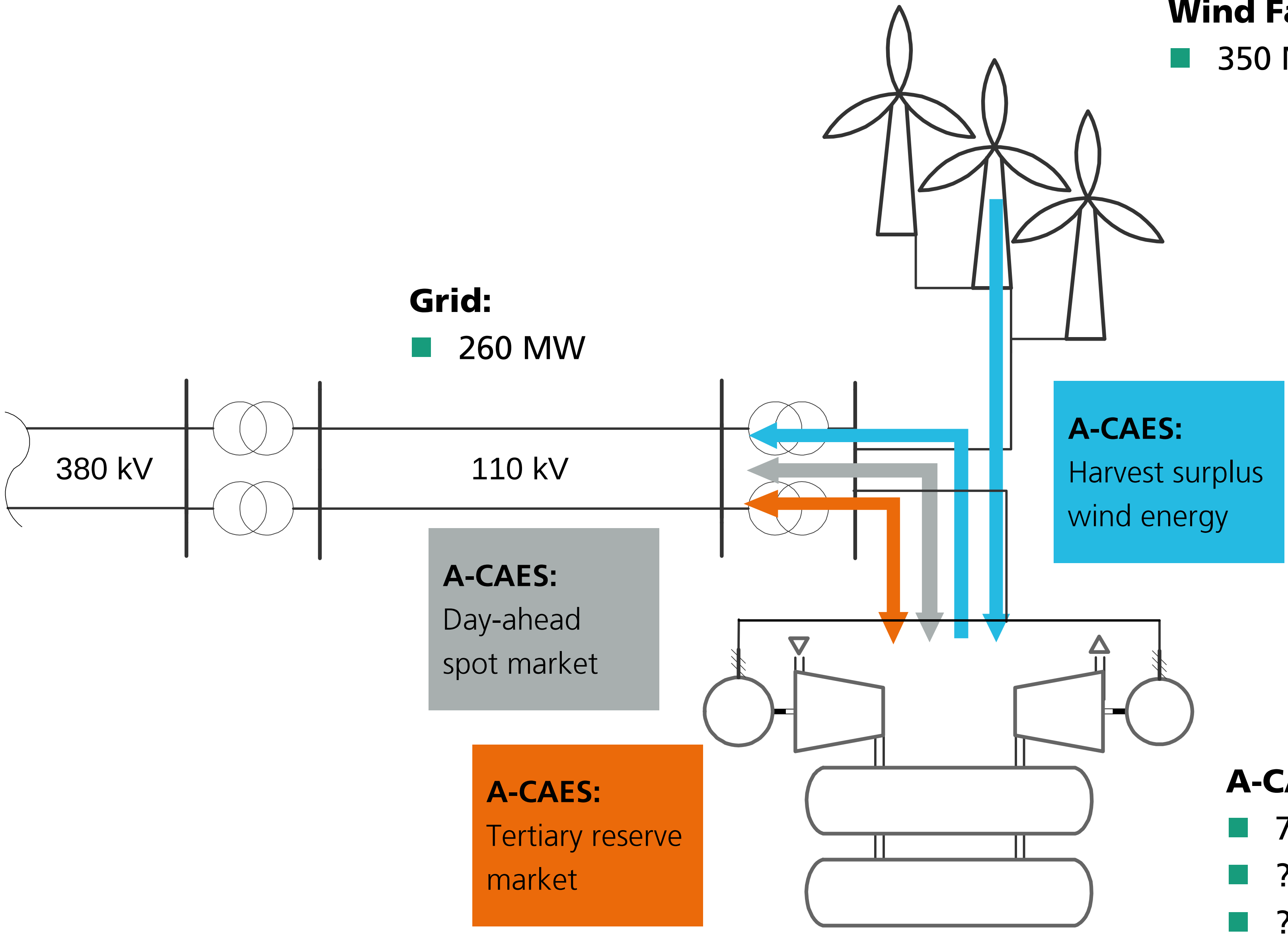
Optimal A-CAES plant configuration

Reference energy system

Wind Farm:
- 350 MW



A-CAES:
- 70 MW_{comp}
- ?? MW_{exp}
- ?? h discharge

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GOMES® - objective function and boundary conditions

A-CAES parameters	
Constant cycle efficiency	0.68
Stand-by storage losses	0.5%/day
Ramp-rate	300 MW/h
Start-up time (cold start)	15 min
Part load ability	> 50%P_{max}
Start-up cost	15 €/MW
Variable operation cost	2 €/MWh

revenue:

- Revenue from the A-CAES operator point of view

income:

- Income of the A-CAES operation

cost:

- Short term marginal cost of A-CAES operation

$$revenue = \sum_{T=1}^{365} \sum_{t=1}^{96} \left[income_{T,t} - cost_{T,t} \right] \rightarrow max!$$

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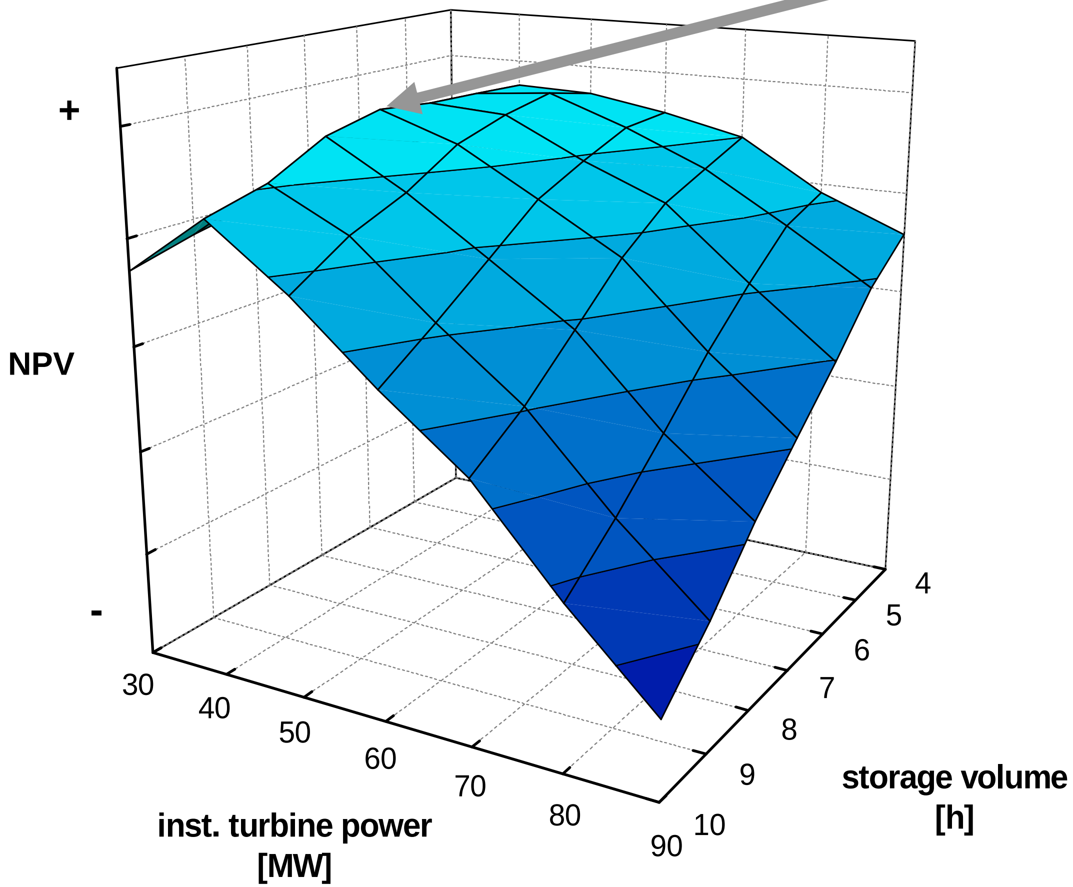
Optimal A-CAES plant configuration



Optimal A-CAES plant configuration

given an installed compressor power of 70 MW

- Turbine: 40 MW
- Storage volume: 7h

→ Power ratio: 1.75

→ Charging period ratio: 0.84

70/40/7-A-CAES configuration taken as reference to further analyze operational regime

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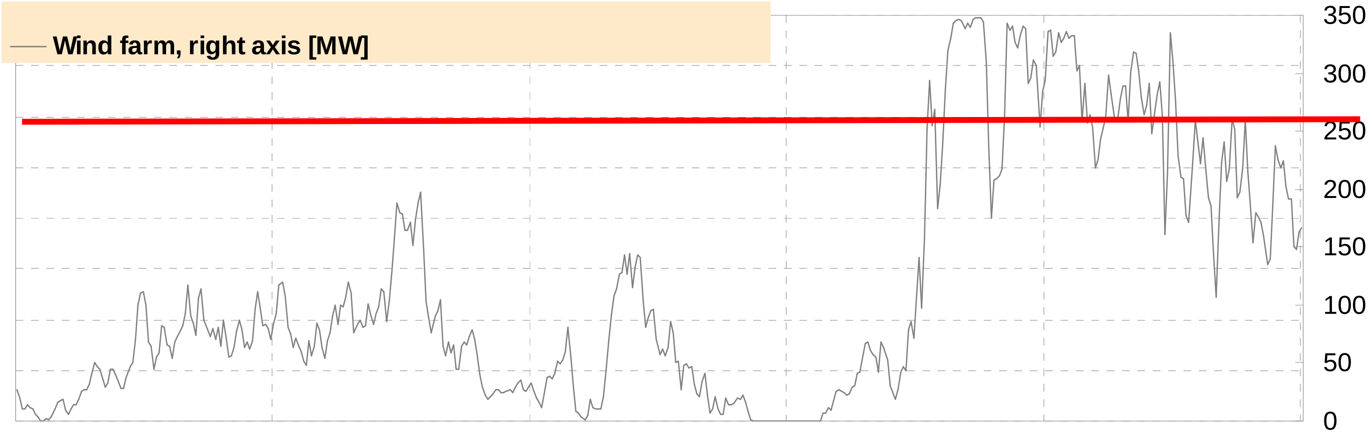
A-CAES operational regime

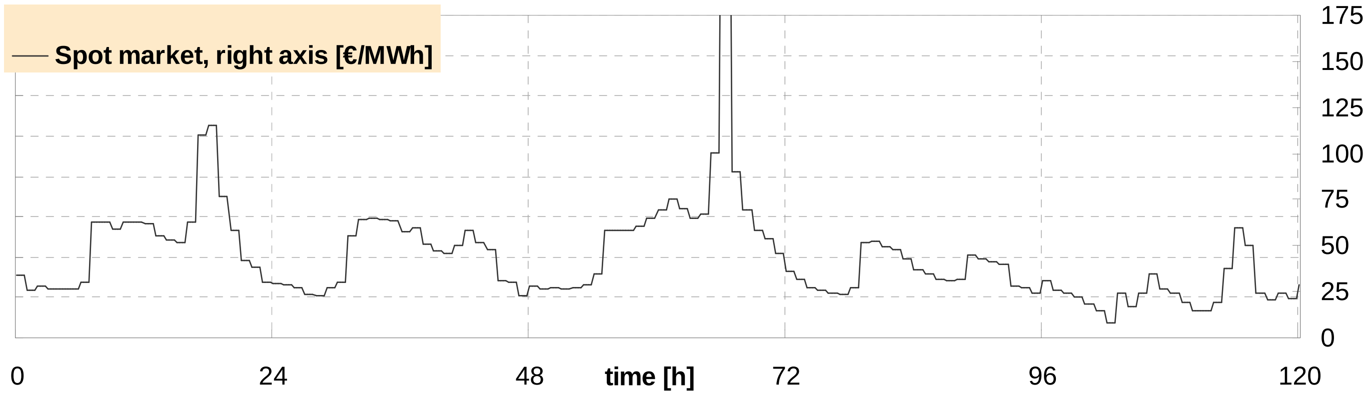
Wind farm output and spot market prices



← 110 kV transmission restriction: 260 MW

Wind farm output

Five-day period within the year 2007



Spot market price

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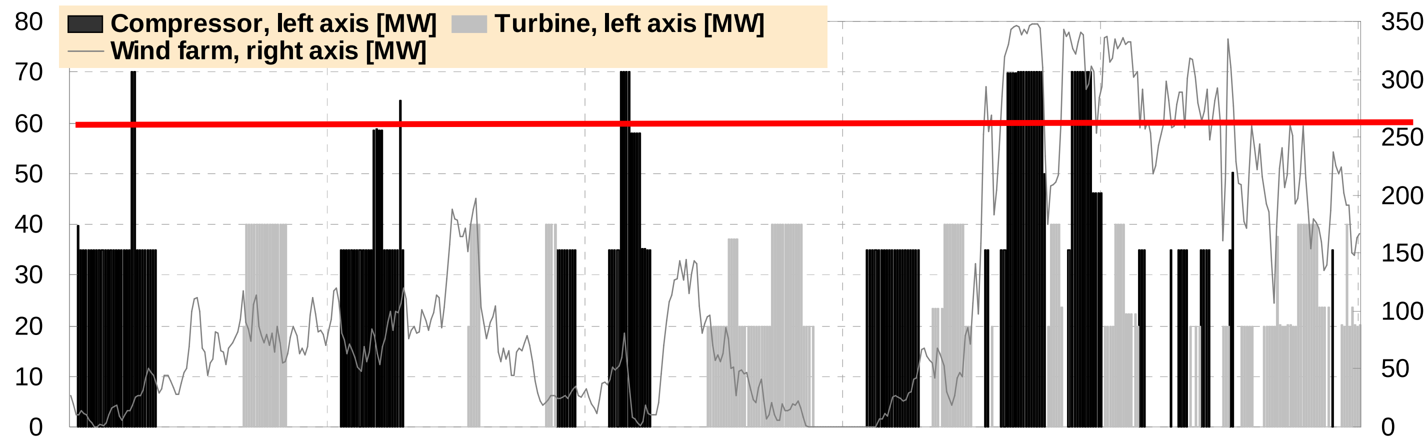
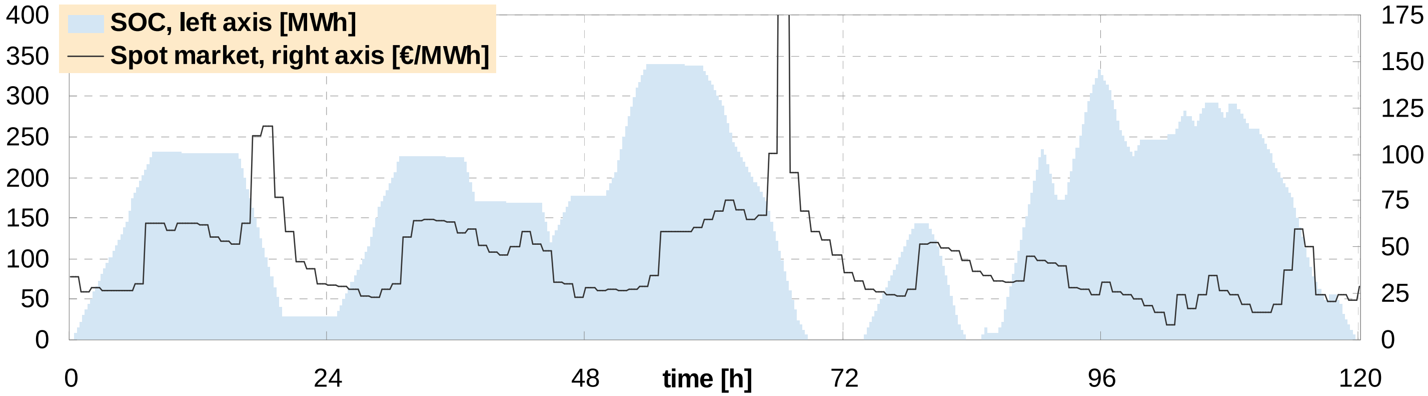
A-CAES operation





Optimal A-CAES operation based on multifunctional application comprising:

- Storage of surplus wind power
- Spot market trading
- Provision of tertiary reserve power

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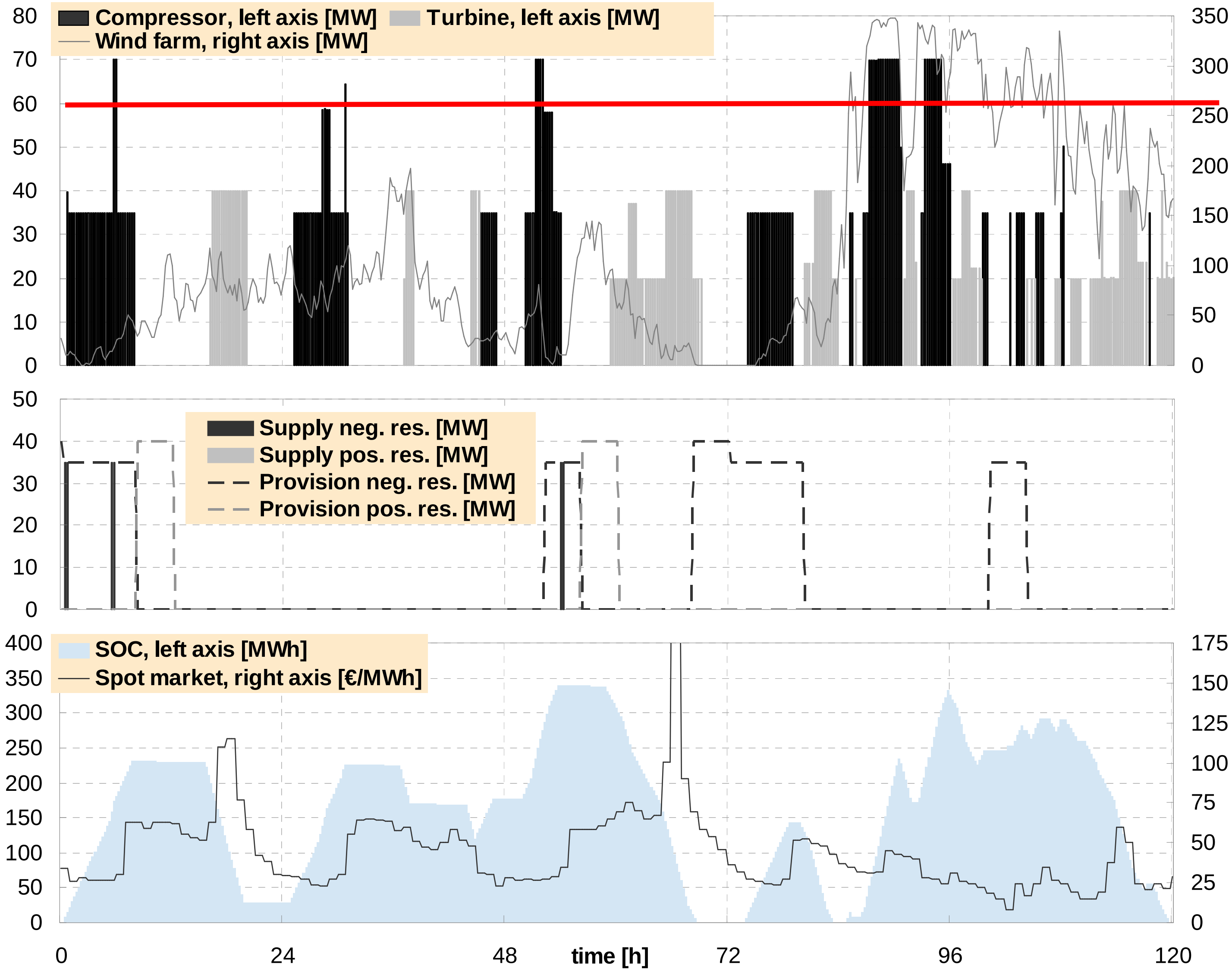
A-CAES operation



Optimal A-CAES operation based on multifunctional application comprising:

- Storage of surplus wind power
- Spot market trading
- Provision of tertiary reserve power

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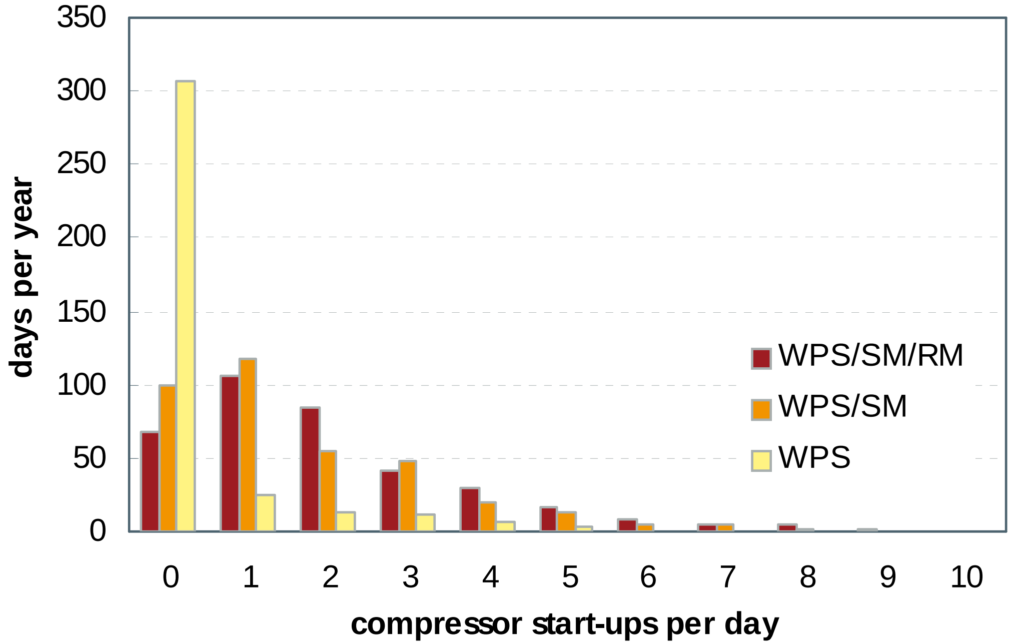
Overview on characteristic operational values

	Multifunction application (WPS/SM/RM)	Dual application (WPS/SM)	Singular application (WPS)
Full load hours total	3402 h	3421 h	286 h
Avg. stand-by period between compression	8.9 h	11.1 h	23.0 h
Number of compressor start-ups per year	732	597	123



WPS: Wind Power Storage
SM: Spot Market
RM: Reserve Market

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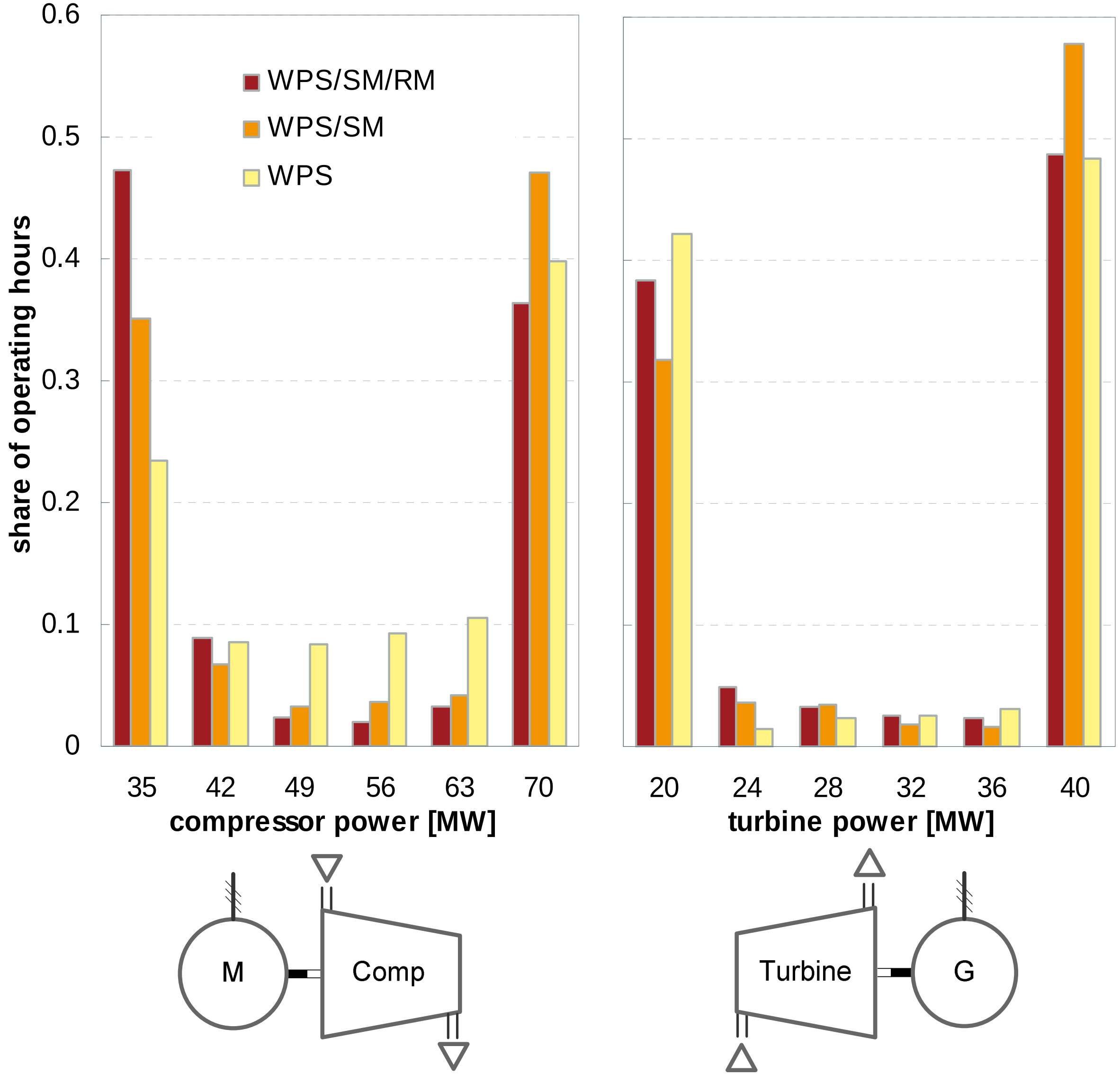
Distribution of load points



→ **Minimal and full load are dominating operational regime**

WPS: Wind Power Storage

SM: Spot Market

RM: Reserve Market

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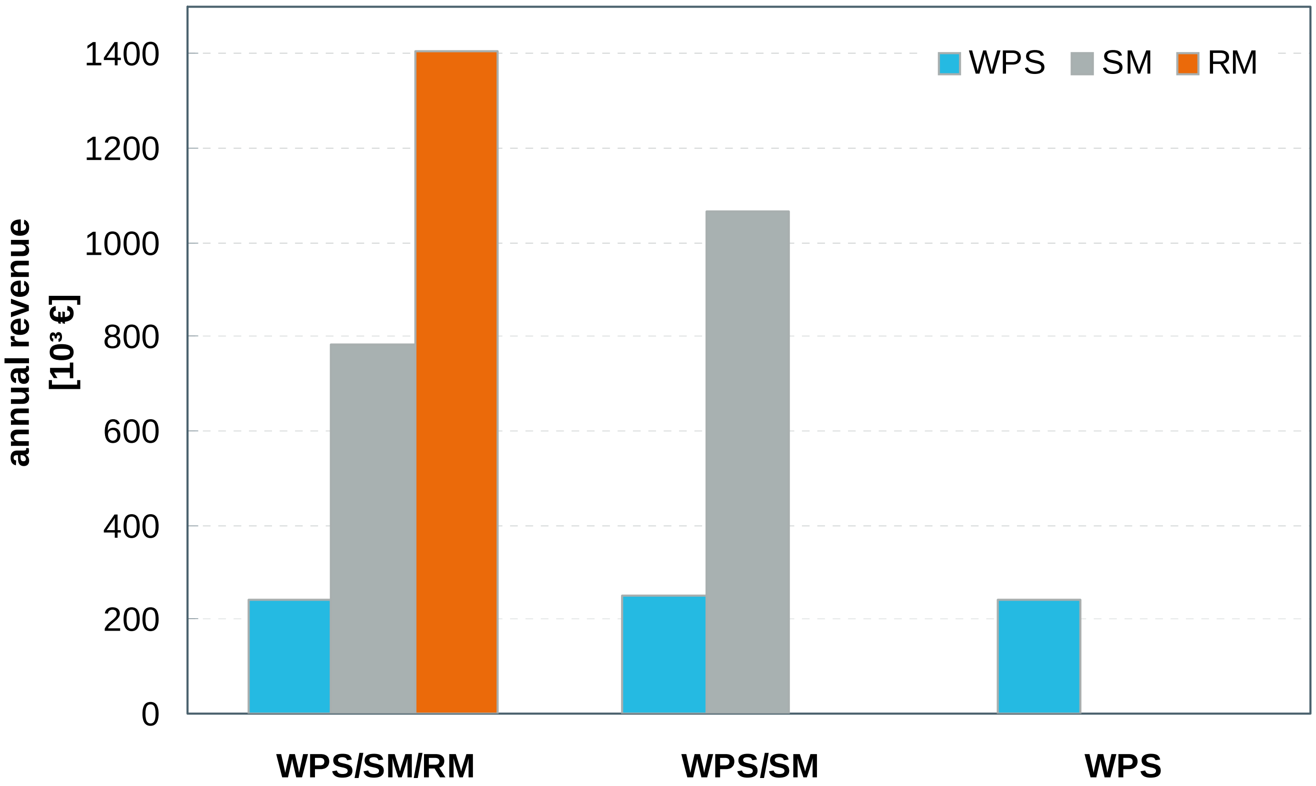
Income streams for different application modes



Rel. annual revenue: **100%** **54%** **10%**

General observations:

- RM participation decreases SM income
- Neither RM nor SM participation diminish WPS income

WPS: Wind Power Storage

SM: Spot Market

RM: Reserve Market

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Conclusion

Conclusion

- A-CAES differs significantly from D-CAES in terms of energy economics
- Rules of thumb for optimal A-CAES plant configuration co-located with a wind farm:
  - Power ratios greater than 1
    this study: 1.75 → Huntorf: 0.2; McIntosh: 0.45
  - Charging period ratios smaller than 1
    this study: 0.84 → Huntorf: 4; McIntosh: 1.5
- Multifunctional application most profitable
- Multifunctional application leads to
  - high part load shares and
  - more frequent plant starts

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questions ?

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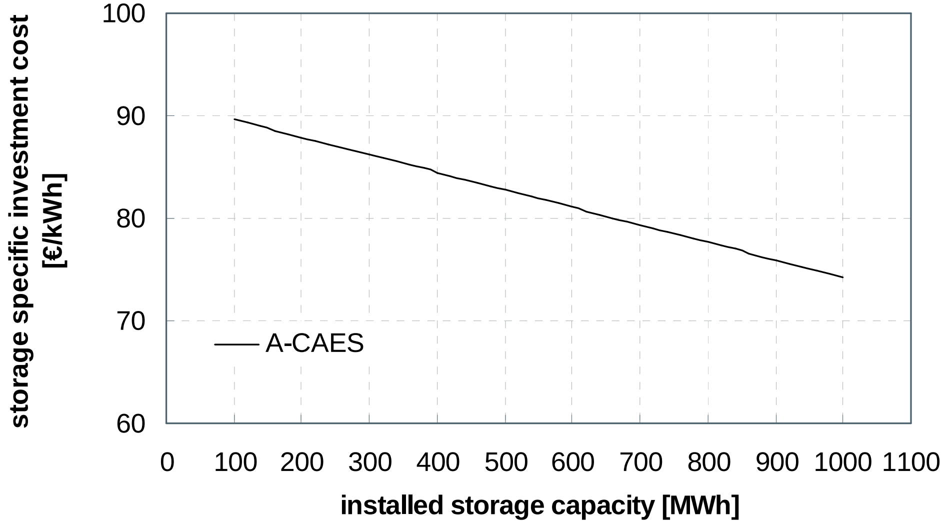
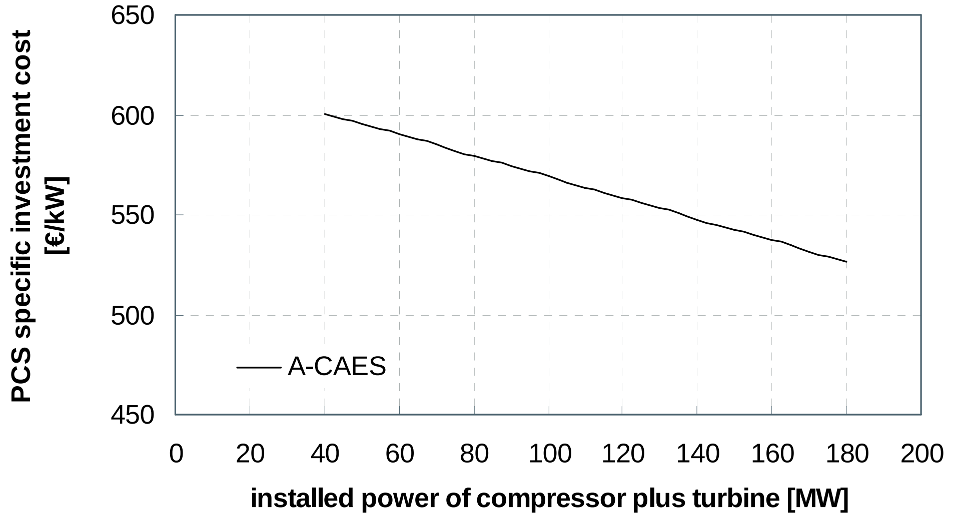
Additional slides

Assumed A-CAES investment cost



Storage specific costs

- Decrease linearly with increasing storage size
- Comprise solution mined salt cavern (CAS) and packed bed thermal storage (TES)
- 1/3 → CAS; 2/3 → TES



PCS specific costs

- Compressor and turbine accounted separately
- Decrease linearly with increasing installed power

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15. Firming and Shaping Wind Power: Comparison of CAES and Conventional Natural Gas Power Plants within the National Energy Independence Plan

James Mason, Cristina Archer, Bill Bailey, *NEIP*

The National Energy Independence Plan, NEIP, recognizes that America has about a decade before fossil fuels, starting with oil, become serially unaffordable. Working within this ten-year constraint, the NEIP's interactive models illustrate conversion of U.S. energy sources to lowest cost renewable electricity using wind in the Midwest and PV in the Southwest. Wind and solar intermittency is resolved by coupling wind and PV plants to compressed air energy storage *(CAES) power plants. Electricity is distributed to local markets nationwide via a national HVDC grid, flat-priced at about current levels. A recent DOE study of wind power supplying 20 % of the nation's electricity states that energy storage power plants are not needed. Instead, the DOE study uses conventional natural gas power plants to address wind's intermittency. This approach will increase U.S. natural gas consumption by 17% at a 20% wind penetration level and will likely create natural gas supply/demand problems in the long-term. In contrast, coupled wind-CAES plants consume 75% less natural gas. Moreover, less than 300 GW of wind capacity coupled to CAES plants can provide DOE's projected need for 100 GW of new base load power plants by 2030.

James Mason is Director of the American Solar Action Plan in Farmingdale, New York. He received a Ph.D. in economic sociology from Cornell University in 1996 and a Master's in environmental sociology from the University of New Orleans in 1991. Mason has published numerous peer-reviewed energy and environmental studies.

Cristina L. Archer is an assistant professor of energy, meteorology, and environmental science in the Department of Geological and Environmental Science of California State University Chico, as well as a consulting assistant professor in the Department of Civil and Environmental Engineering at Stanford University. Her research interests include wind power, meteorology, air quality, climate change, and numerical modeling. She received her Ph.D. in Civil and Environmental Engineering from Stanford University in 2004.

Bill Bailey is a graduate of West Point with 22 years' service as an Army Officer. His active military experience included traditional Infantry assignments, two tours in Viet Nam, national level intelligence, and academe. Since 1980 he has held positions in academe, business, and in historic structures' real estate development. He currently heads Fiscal Associates, a quantitative market analytic firm. Since early 2008, concerned about the national security implications of fossil fuel use, he has been involved with a group of scientists, engineers, and businessmen in the development of the NEIP, the National Energy Independence Plan.

Firming and Shaping Wind Power: Comparison of CAES and Conventional Natural Gas Power Plants within the National Energy Independence Plan

Presented By

James Mason, American Solar Action Plan and Hydrogen Research Institute
Cristina Archer, California State University Chico
Bill Bailey, Co-Author of National Energy Independence Plan (NEIP)

2nd CAES Conference and Workshop
Sponsored by New York State Energy Research and Development Agency (NYSERDA)
Hosted by the Center for Life Cycle Analysis, Columbia University
Columbia University, New York, New York, 20-21 October 2010

National Energy Independence Plan (NEIP)

Two Threats:

–Serial Unaffordability of Fossil Fuels within a Decade (Path A—Eliminate 28 Q-Btu of oil imports in 10 years);

–Climate Change before mid-century (Path B—Eliminate 86% of fossil fuel use before 2050).

NEIP Design around CAES/HVDC

- Synergy
- Models reflect price to energy user
- Self-funding: Electricity sales payoff debt
- Infrastructure-centric: CAES/HVDC essential
- Savings are enormous: ~$1 Trillion per year (most of savings from energy domestication)

Sample Choices

Included:

- –Existing technology
- –Light vehicle conversion, 13.4 Q-Btu of 28 Q-Btu
- –80% to 100% renewable energy penetration
- –Wind and solar with lowest retail electricity price

Not included:

- –"30% Wind by 2030" NREL Studies
- –Wind classes below 4.5
- –Distributed energy
- –Offshore wind
- –PHEV Storage

Macro View: CAES/HVDC

CAES/HVDC infrastructure permits:

- **Eliminate need to import oil within ten years;**
- **True energy independence;**
- **Savings of about $1 trillion per year.**

Not possible without CAES.

Can CAES be "*too expensive*"?

www.NEIPlan.org

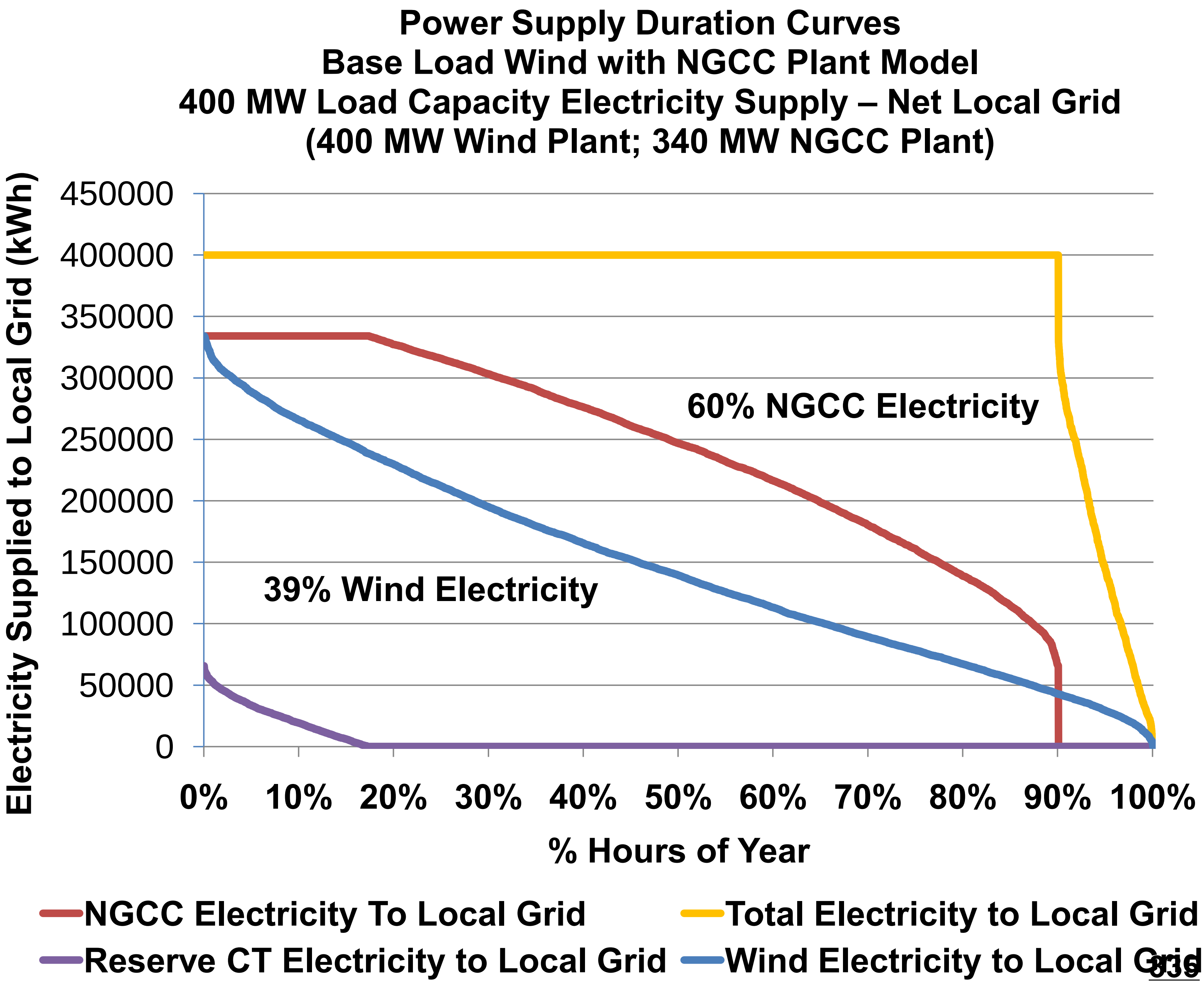
Research Question

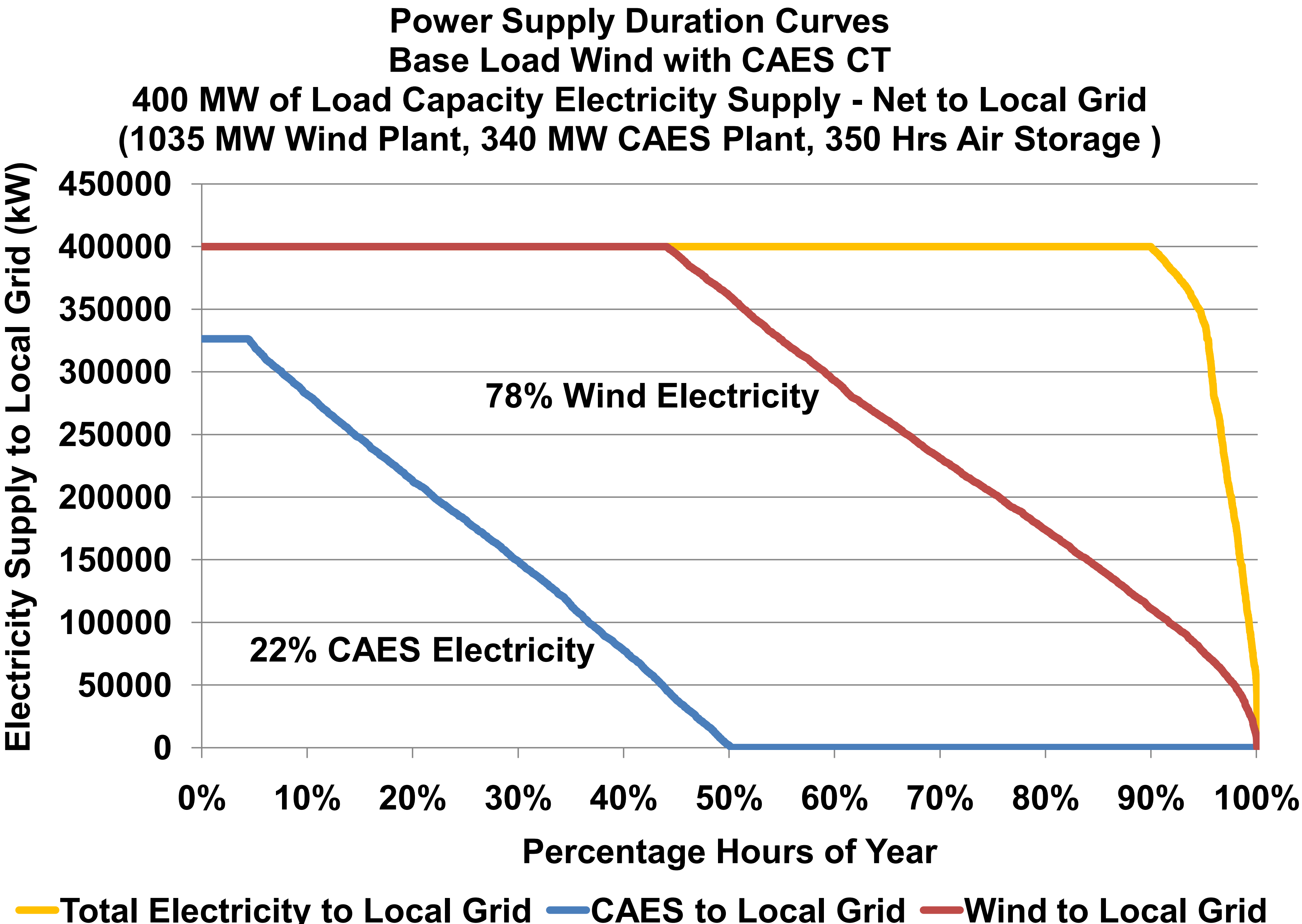
Can the added capital costs of CAES be justified for firming variable wind electricity?

Conclusion

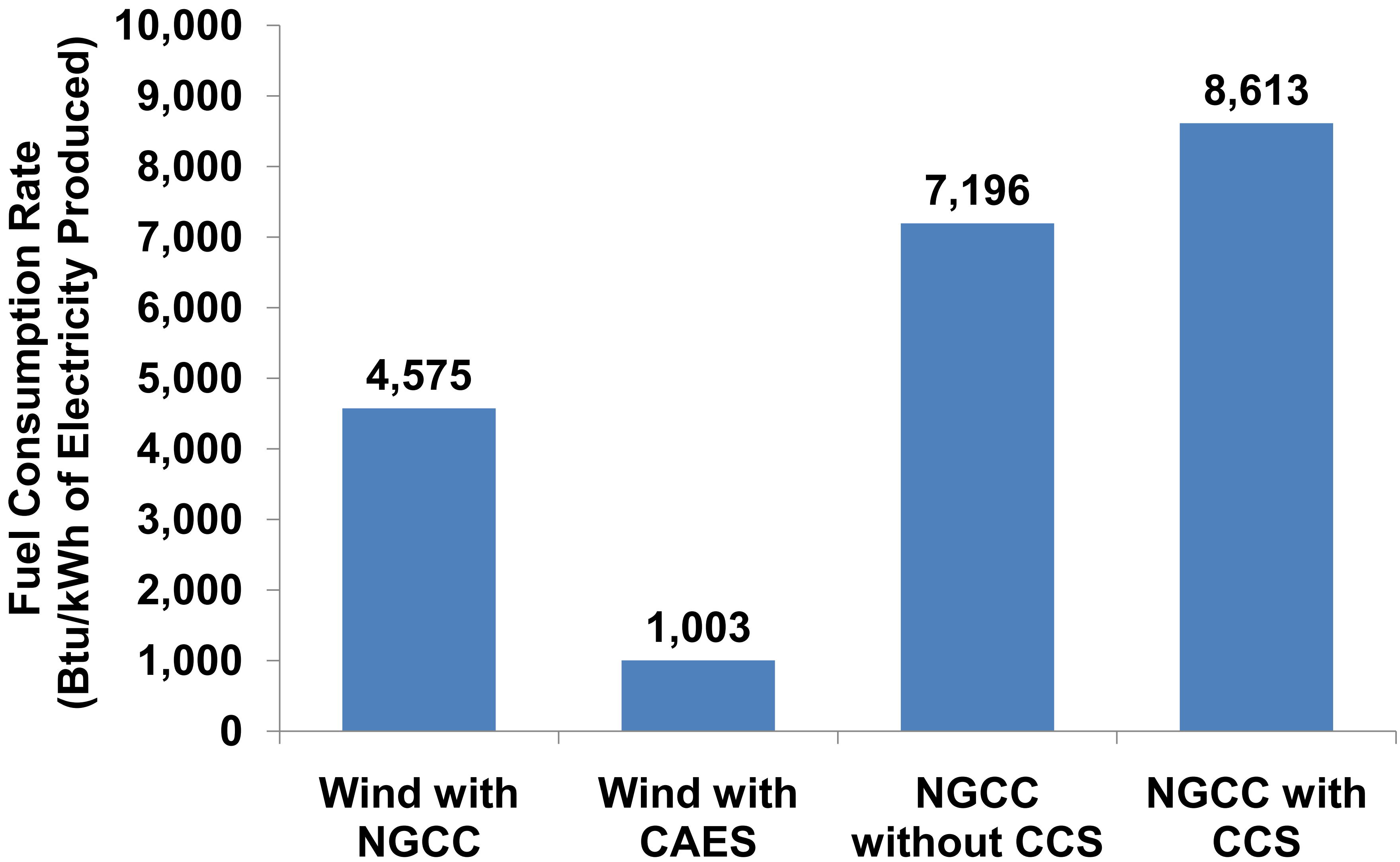
The added capital costs of CAES can be justified due to lower operating costs (fuel) when the price of natural gas is >$14/MMBtu.

Source: Mason and Archer, Wind CAES Study
www.solarplan.org


Power Supply Duration Curves
Base Load Wind with NGCC Plant Model
400 MW Load Capacity Electricity Supply – Net Local Grid
(400 MW Wind Plant; 340 MW NGCC Plant)
Electricity Supplied to Local Grid (kWh)
450000
400000
350000
300000
250000
200000
150000
100000
50000
0
60% NGCC Electricity
39% Wind Electricity
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
% Hours of Year
NGCC Electricity To Local Grid
Total Electricity to Local Grid
Reserve CT Electricity to Local Grid
Wind Electricity to Local Grid

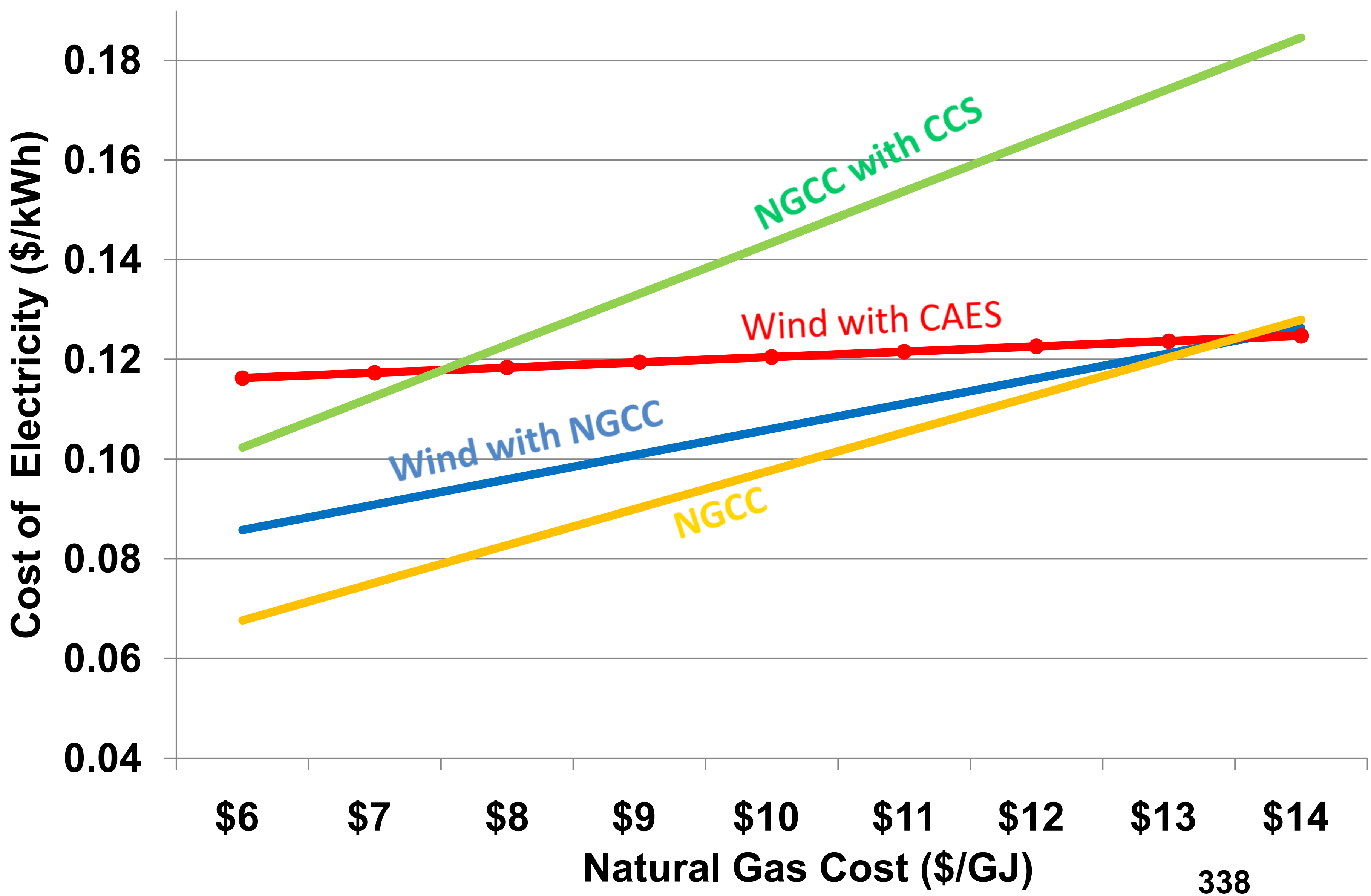

Power Supply Duration Curves
Base Load Wind with CAES CT
400 MW of Load Capacity Electricity Supply - Net to Local Grid
(1035 MW Wind Plant, 340 MW CAES Plant, 350 Hrs Air Storage)
Electricity Supply to Local Grid (kW)
450000
400000
350000
300000
250000
200000
150000
100000
50000
0
78% Wind Electricity
22% CAES Electricity
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Percentage Hours of Year
Total Electricity to Local Grid
CAES to Local Grid
Wind to Local Grid

Wind-CAES - low fuel consumption rate



Source: Mason and Archer, Wind CAES Study, Work in Progress

Electricity price is sensitive to fuel cost



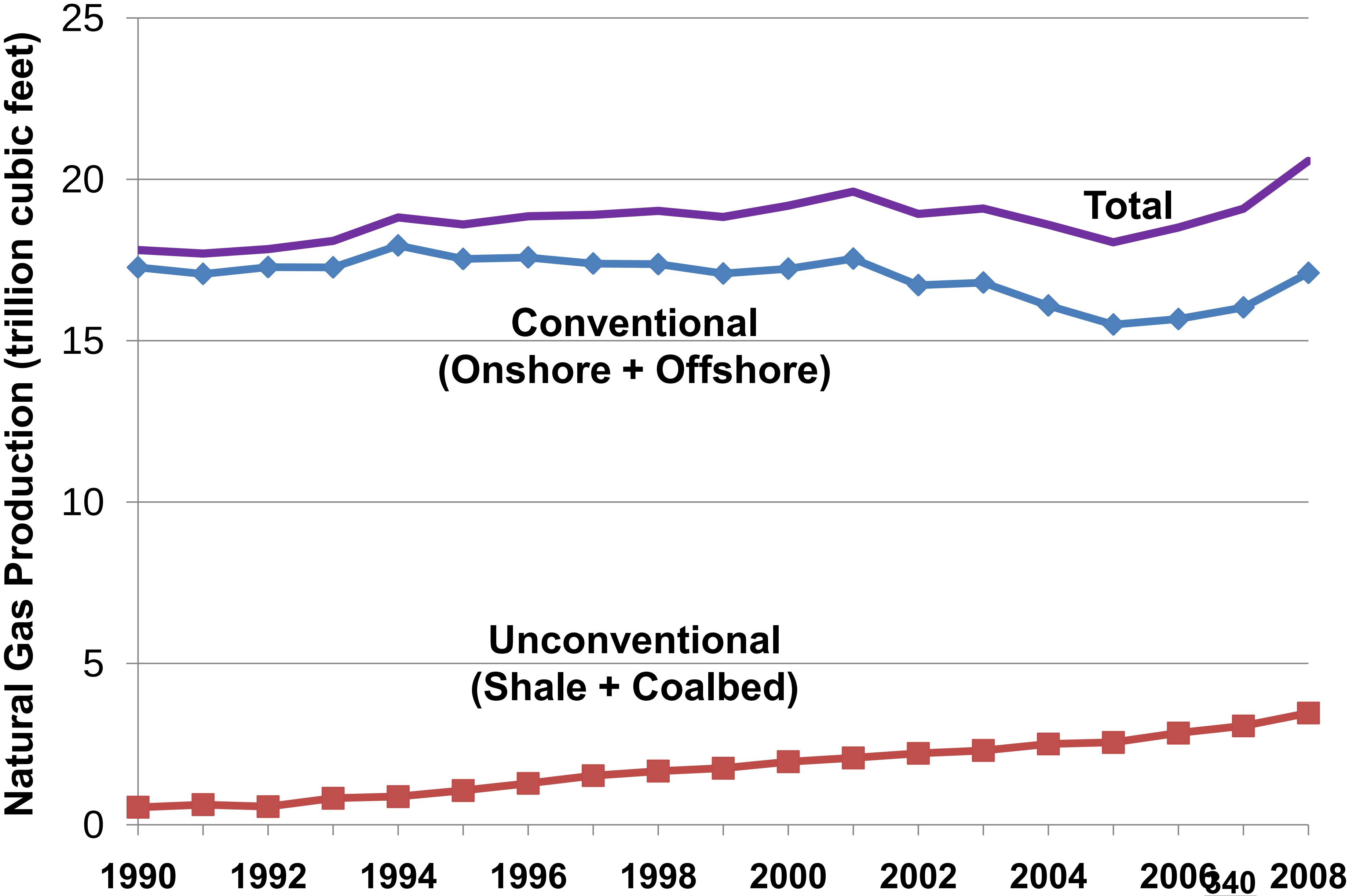
More wind = more natural gas

NREL Western and Eastern Wind Integration and Transmission Studies Project for 2030:

- **30% wind penetration (300 GW of capacity);**
- **Fewer new coal power plants (baseload);**
- **More new natural gas power plants (30 GW).**

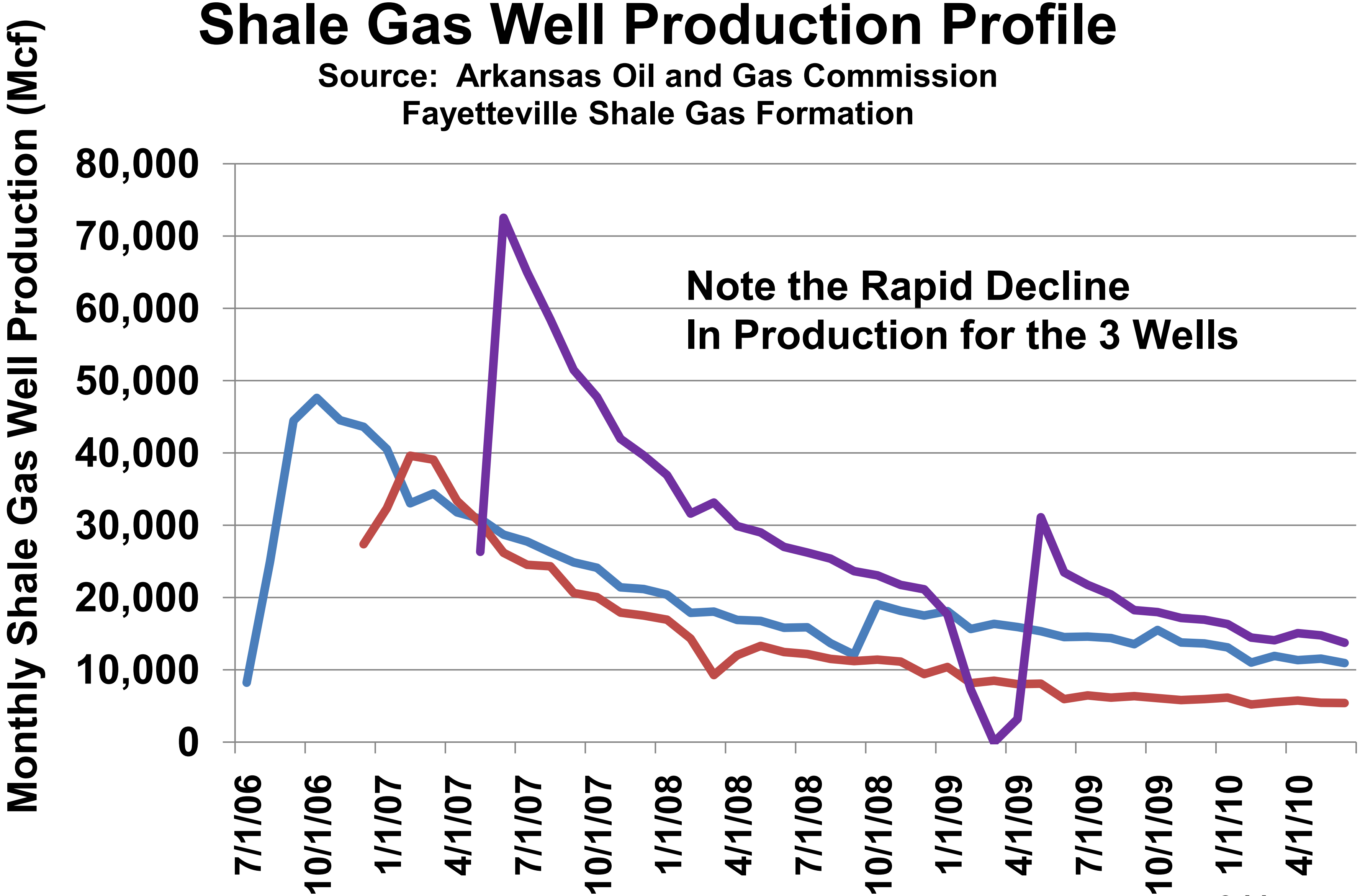
Is a 25% increase in US natural gas production in 20 years possible?

Growth of U.S. natural gas production is slow

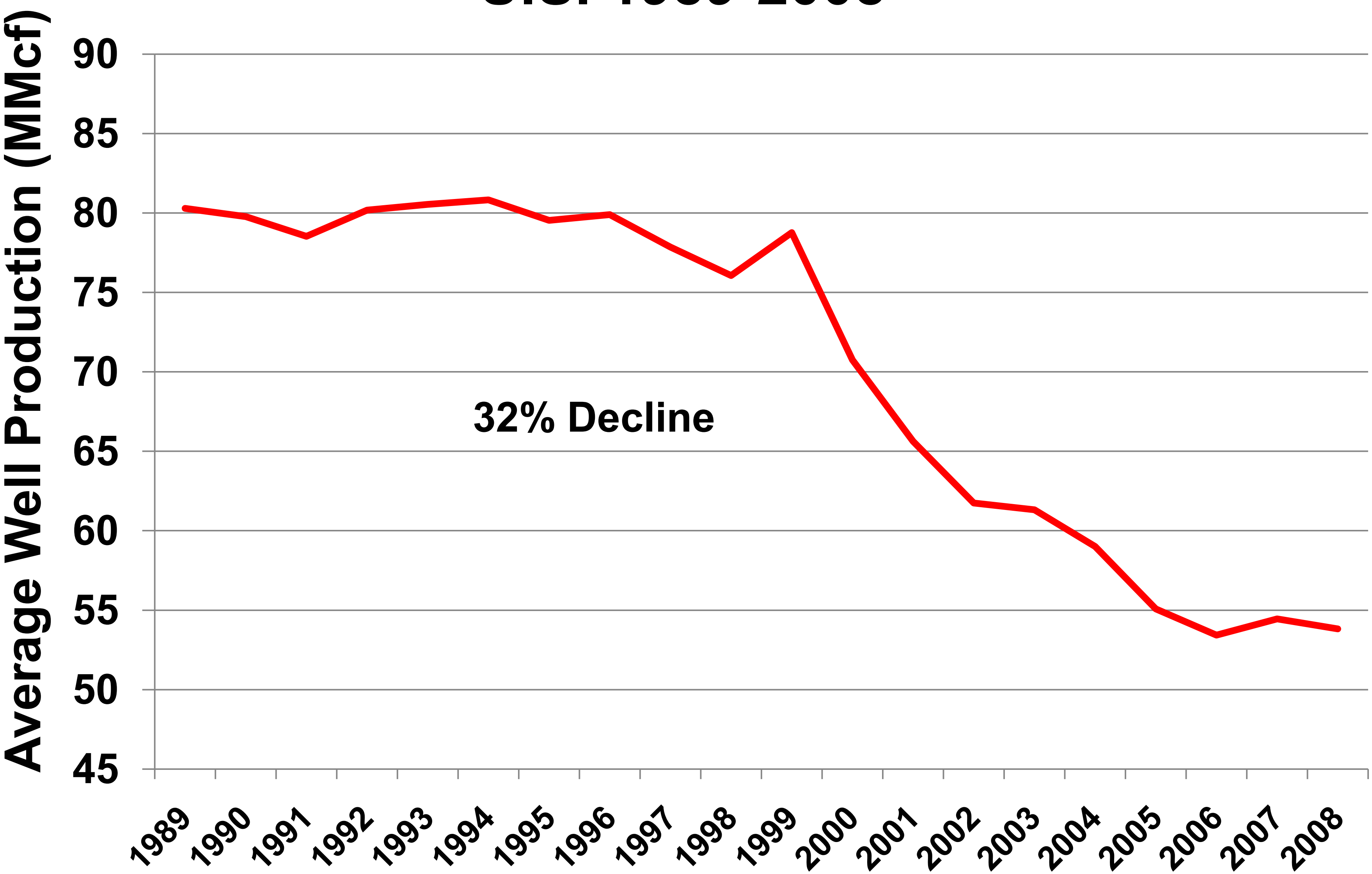


Is Shale Gas the Solution?
Shale Gas Well Production Profile

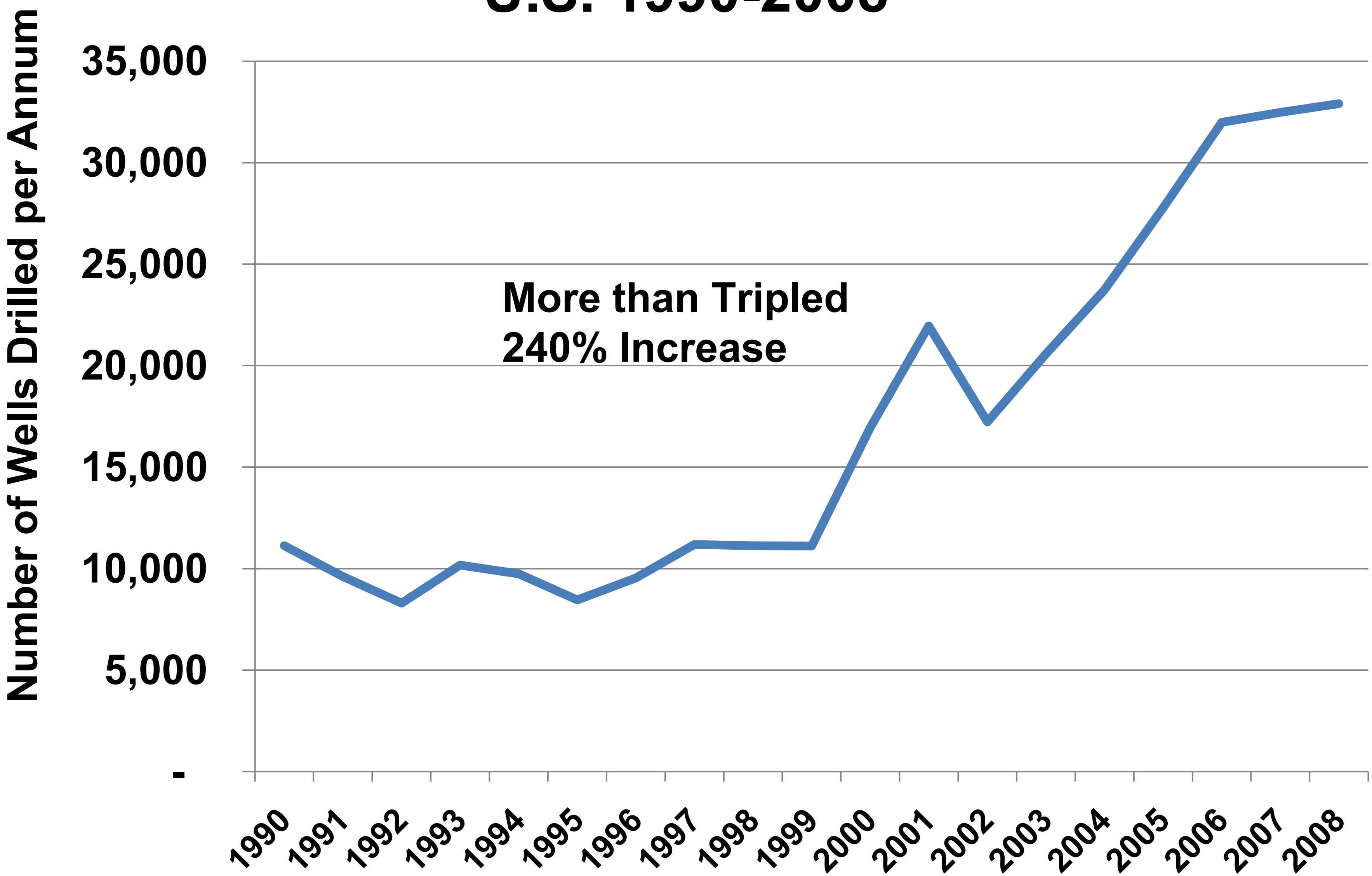
Source: Arkansas Oil and Gas Commission
Fayetteville Shale Gas Formation



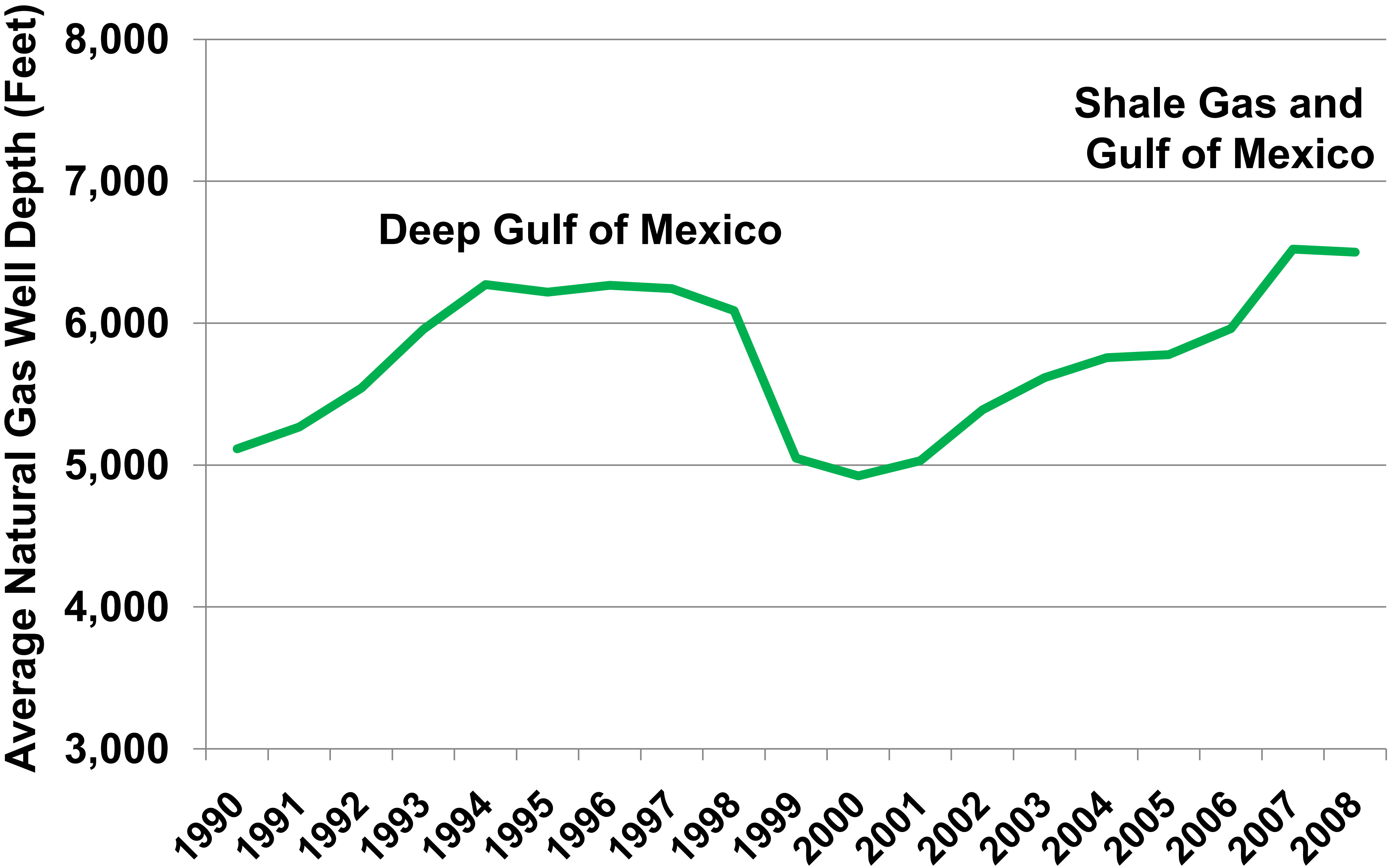
Declining natural gas well production U.S. 1989-2008



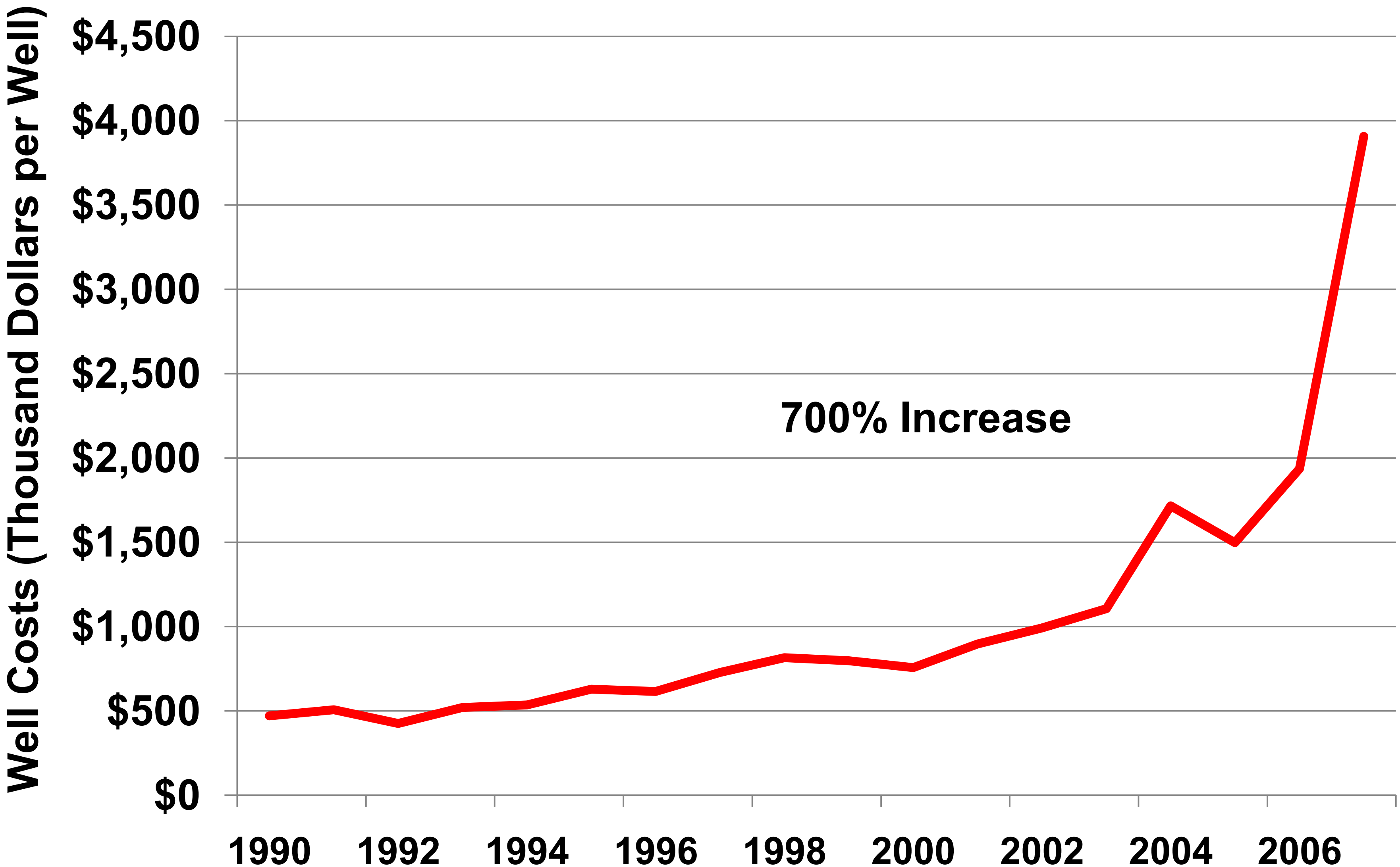
Increasing number of NG wells drilled U.S. 1990-2008



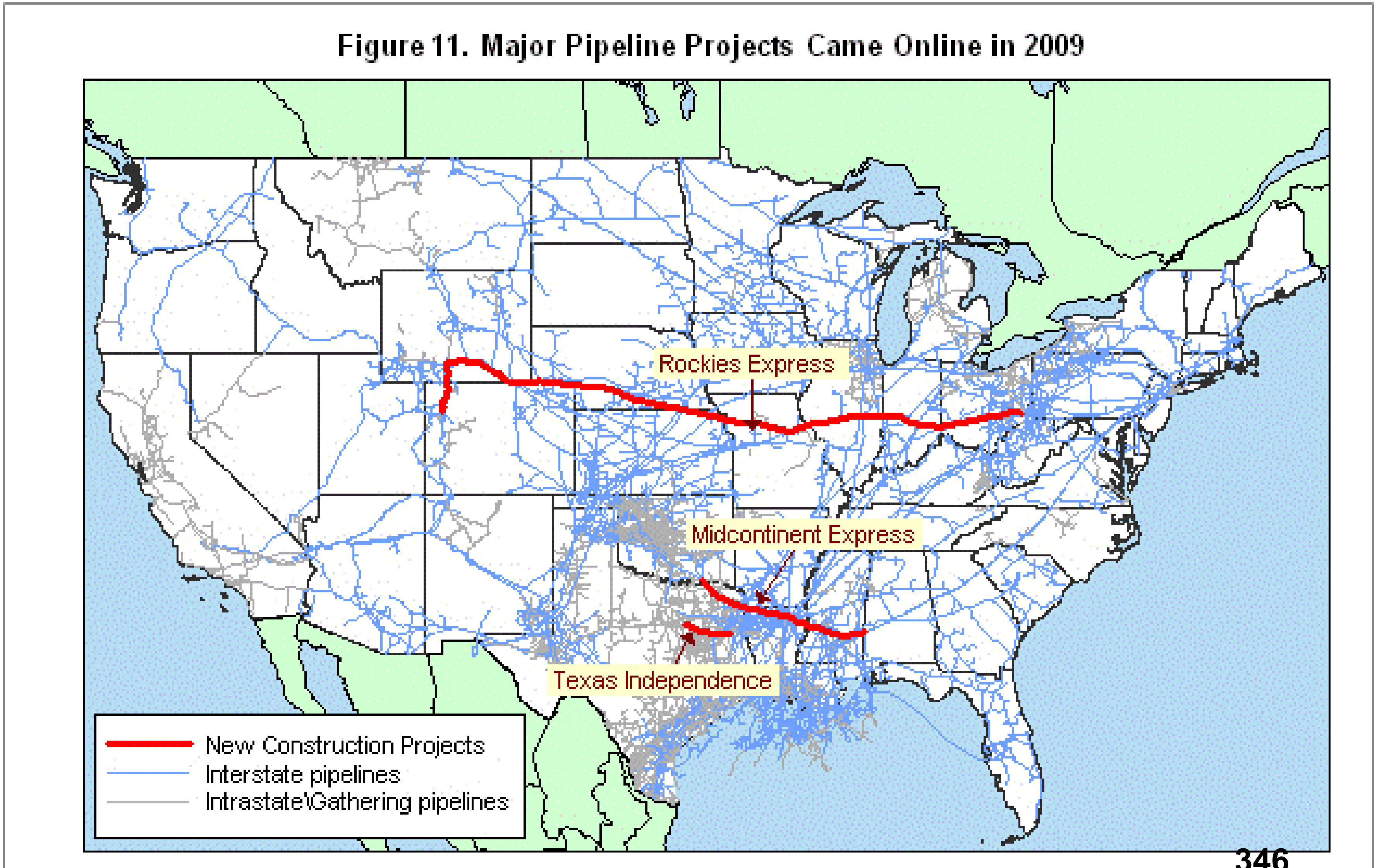
Drilling deeper natural gas wells U.S. 1990-2008



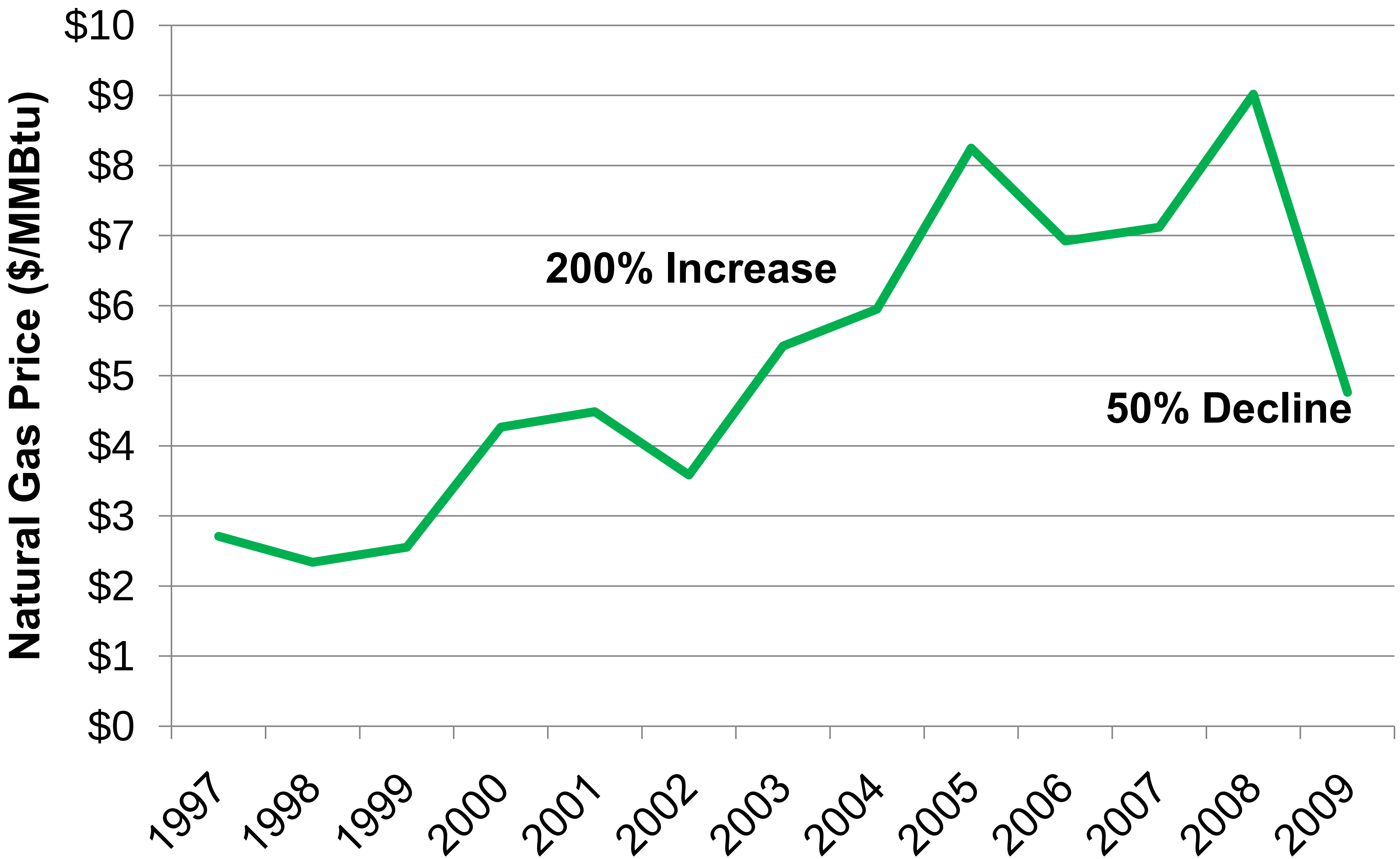
Increasing cost of drilling NG wells U.S. 1990-2008



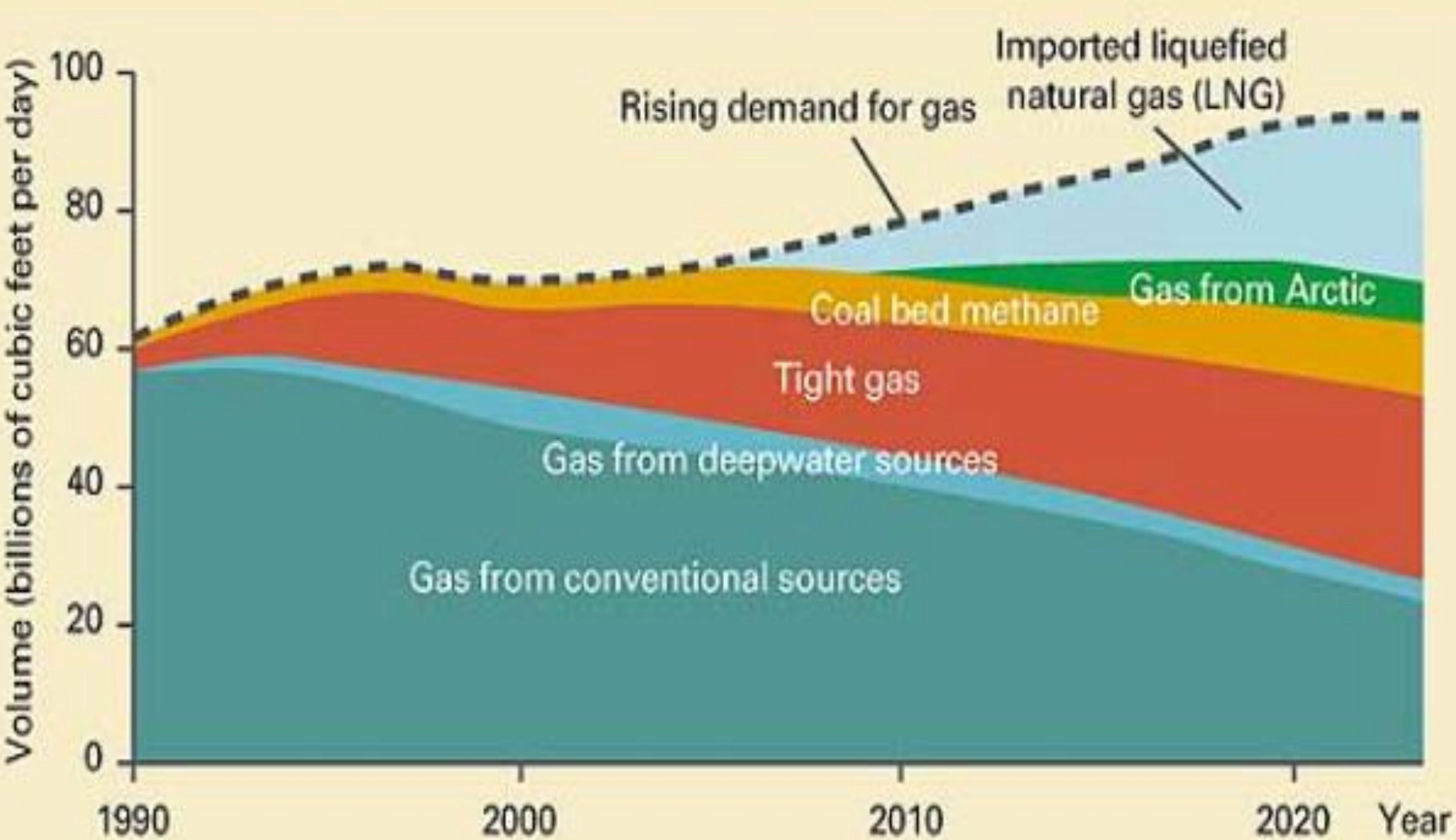
Need for pipelines slows shale gas



High volatility of natural gas price for power plants

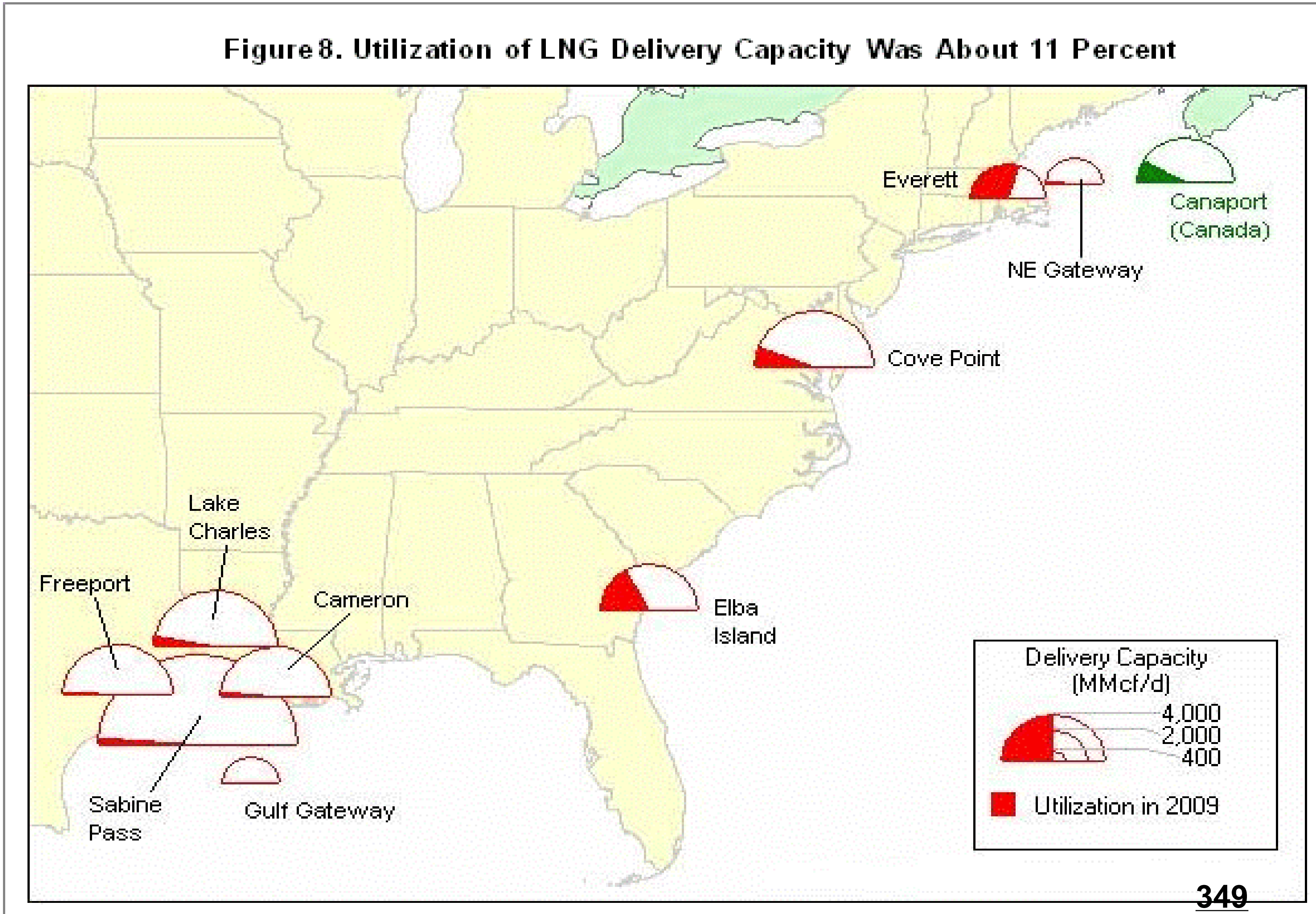


NATURAL GAS IN NORTH AMERICA – SUPPLY AND DEMAND



Demand for natural gas in North America and sources of gas supply. Source: CRA International

Liquid NG plants for importing NG



US natural gas supply in 2030 (NEIP)

- **Conventional natural gas production declines 2020-2030;**
- **Shale gas reserves are plentiful, but …**
- **…. cannot be ramped up to offset decline in conventional natural gas production;**
- **High natural gas price volatility in 2030 (like oil today).**

Implications:

- **Upward pressure on natural gas prices will nullify the economic benefits of amortized natural gas power plants;**
- **Use of natural gas for electricity will cause rise of home/business space and water heating costs;**
- **National standard of living will decrease.**

Conclusions

- **CAES can effectively be utilized to firm increases in wind and solar (PV) penetration;**
- **CAES can mitigate negative economic consequences of increasing natural gas consumption to support electricity generation from wind and solar (PV).**

16. Unconventional Gas: A Bridge to the Future?

Alfred Cavallo, *Energy Consultant*

In the late 1980s low natural gas prices made renewable energy extremely unattractive economically; storage technologies such as CAES were virtually forgotten. Some portrayed this in a positive sense, claiming that natural gas would be “a bridge to the future”, facilitating a smooth transition to renewable energy systems and technologies. However, nothing of the sort happened. Today, advances in drilling and rock fracturing technologies have allowed a large increase in unconventional natural gas production from low permeability organic-rich shale deposits; a vast new resource appears to be accessible. Once again, natural gas prices are low and once again natural gas is being termed a “bridging fuel” and a “game changer”. US proven gas reserves are now 250 Tcf, the highest they have been in 35 years, and US proven plus potential resources are now given as about 2,000 Tcf, or a 100 year supply at current production rates. However, while gas supplies appear to be abundant, natural gas prices are decoupled from supply over the intermediate and long term and are set by petroleum prices; typically the oil to gas price ratio on a per unit energy basis is about 1.5. Economic development in China and the Far East continues, with sales of automobiles rising rapidly; petroleum demand is expected to be supply constrained by the end of this decade. Crude oil prices will need to increase to bring supply in line with demand (to at least $150/barrel); this indicates natural gas prices around $17/million Btu (± 25%). Petroleum and natural gas price setting mechanisms will be reviewed and strategies proposed to deal with the current temporary low natural gas price environment.

Dr. Alfred Cavallo did his graduate studies at the University of Wisconsin in plasma physics, and worked for the Max Planck Institute, the French Atomic Energy Commission, and the Princeton Plasma Physics Laboratory in the experimental fusion program. He then moved to the Center for Energy and Environmental Studies at Princeton University, and developed the concept of transforming intermittent wind energy to a reliable power source that is technically and economically competitive with current generators. He has also done research on aerosols and radon risk assessment for the US Department of Energy. His current interests are resource constraints and energy policy.

Unconventional Gas: A Bridge to the Future?

Alfred Cavallo, Ph.D., Energy Consultant

Presented at

CAES Workshop: Integrating Wind-Solar CAES

Columbia University

October 20-21, 2010

Challenge to Wind/Solar/CAES

Natural Gas Prices Have Collapsed

- How to meet the payroll
- When to expect turnaround

HISTORY

1991

Natural Gas (NG) spot prices <$2/mmBtu

"Bridge to the (renewable energy) Future"

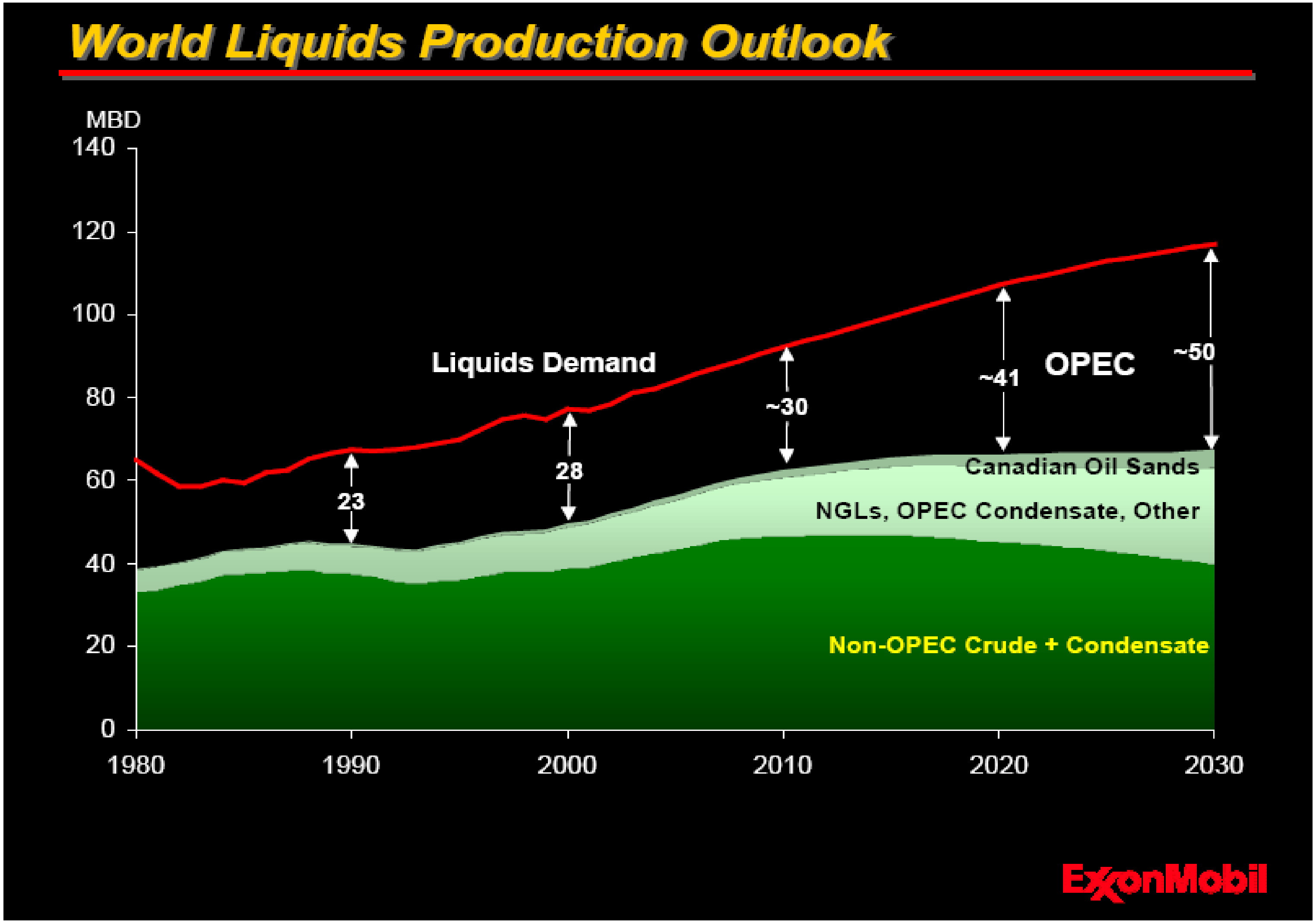
R/P = 60 years

Future belongs to (conventional) NG

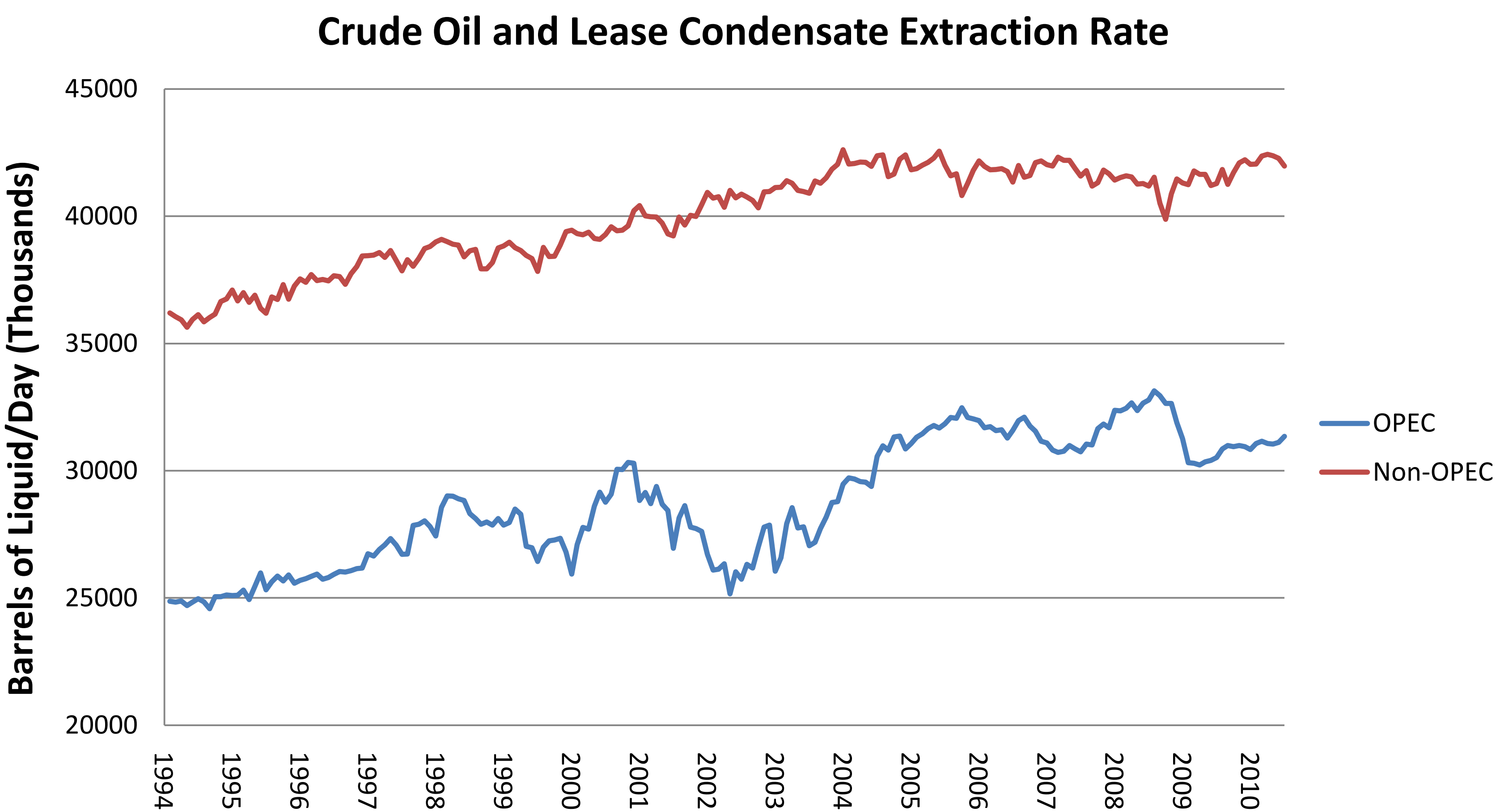
Renewables/storage nearly died in the US

Are We There Again??

If so, find the nearest watering hole…., return in 20 years


World Liquids Production Outlook
MBD
140
120
100
80
60
40
20
0
1980
1990
2000
2010
2020
2030
Liquids Demand
23
28
~30
~41
OPEC
~50
Canadian Oil Sands
NGLs, OPEC Condensate, Other
Non-OPEC Crude + Condensate
ExxonMobil

Non-OPEC Peak Production: 2004



Straws in Wind: China, India

- China: World's largest automobile market
- GM: largest market
- +10.9% China Oil Demand 01-08 2010 vs 2009; 8.51 Mb/d average (Platts Report 09-21-2010)
- China: **Net Importer of coal (5% consumption, $100/tn, >$3-$5/MBtu)**
- China: Electricity Demand: +11.5% (2010)
- India: 3.1 Mb/d, overtakes Japan

World Energy Outlook

- China: 1.3 billion people, 13 billion barrels of oil/year (bpy) required for European standards (current: 3.3 billion bpy)
- World : 6.5 billion people: 65 billion bpy.
  - Current extraction: 31 billion barrels/year
- OPEC to raise oil prices so demand and supply in balance ($150-$200/b)

WHEN?

(can you survive until this happens??)

WHAT DO OIL COMPANIES THINK?

- "We believe that world [oil] demand will be constrained by supply by the end of this decade and *we want to be in a position to take maximum advantage of this situation*…."

  Patrick de la Chevardière, CFO Total S.A.

  Interview, Don Stowers, Ed., OGFJ, April 2010, p17

  Discussion of recent JV with Chesapeake for Barnett shale gas

Enter, Stage Right

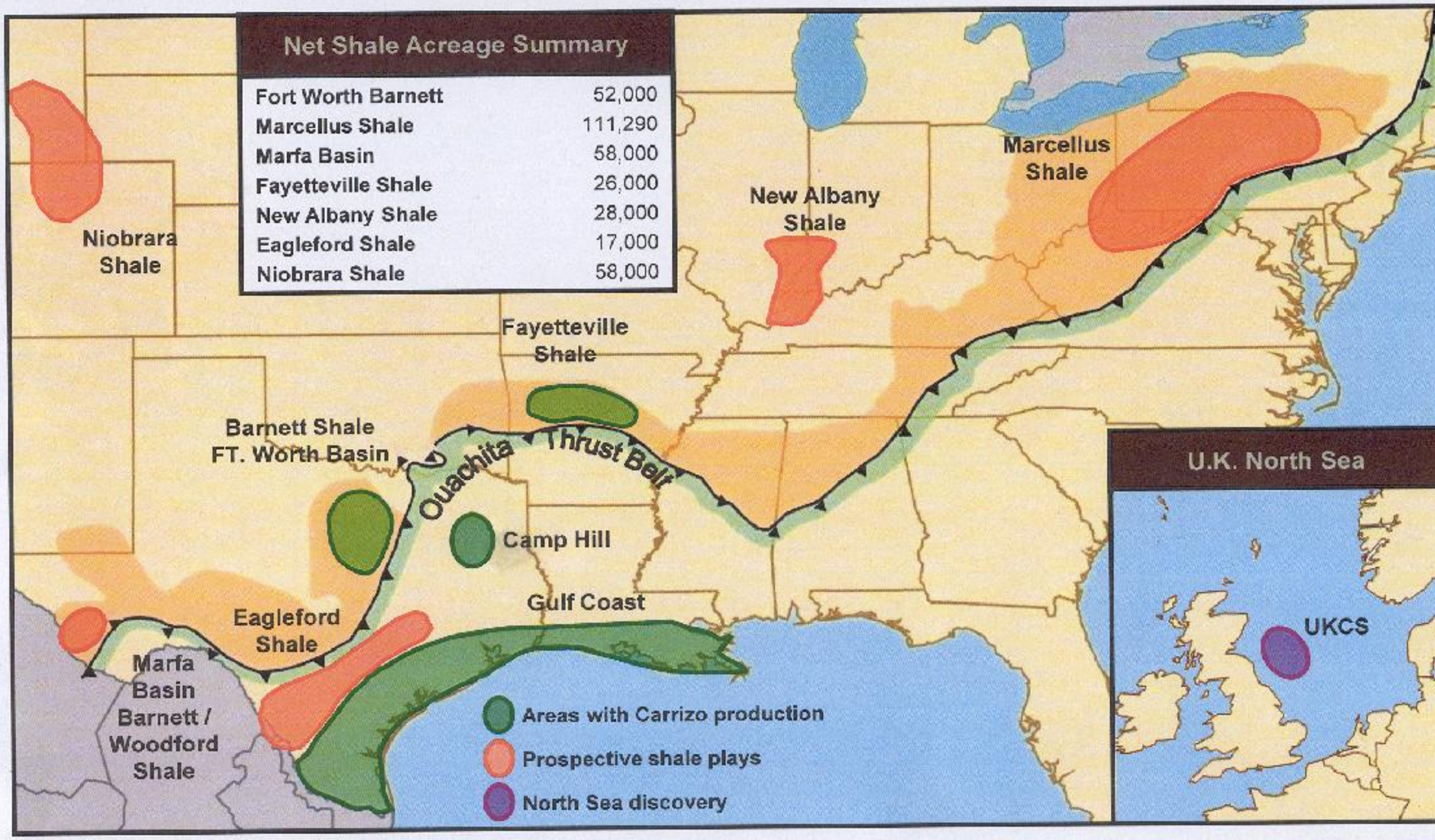
- Shale Gas, “a bridging fuel”

HOW MUCH GAS IS THERE?

- BE CAREFUL!!!!!
- Example: EIA 1999 Proven+Undiscovered NG Resources: 1281 Tcf (R/P=60 years)
- By 2005, production was declining, and increased imports from Canada and then LNG were proposed to cover the shortfall.
- There is a large new resource available
- **AT WHAT PRICE??????**

Operating Profile

CARRIZO



Net Shale Acreage Summary

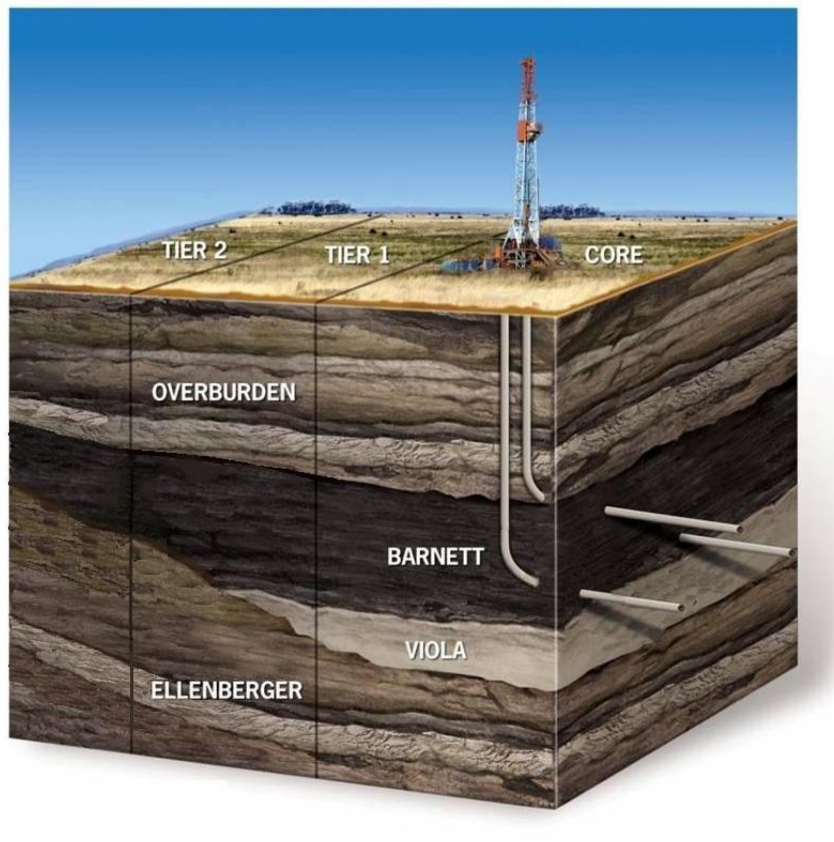
Fort Worth Barnett	52,000
Marcellus Shale	111,290
Marfa Basin	58,000
Fayetteville Shale	26,000
New Albany Shale	28,000
Eagleford Shale	17,000
Niobrara Shale	58,000

Barnett Shale (Texas) Lateral Wells

Source: Carrizo Oil and Gas, Inc.

- **Downspacing & Stacked Laterals**
- **Continue monitoring industry results from sub-500 ft. spacing**
- **Carrizo 250 ft. stagger stack performance encouraging**
- **Have drilled 3 additional downspace wells at UTA; completion in progress**

- **Re-Fracs**
- **Carrizo Tier 1 horizontal re-frac results: incremental reserves 600 Mmcfe; F&D cost of $0.70/Mcfe**



Horizontal Shale Gas Wells

10,000-12,000’ depth, 6500’ length

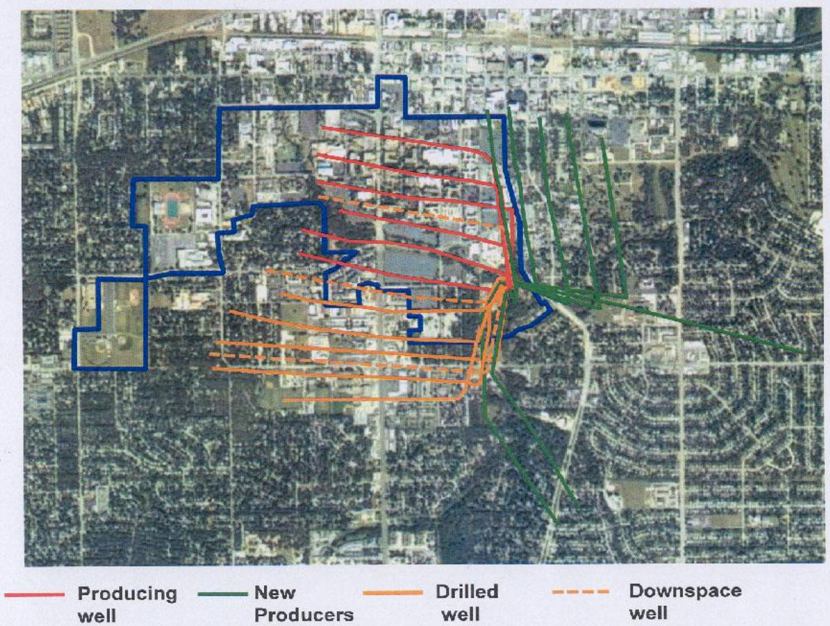
Source: Carrizo Oil and Gas Inc

University of Texas - Arlington

Urban Drilling

CARRIZO

- 400 acre lease; 2,500 acre “Halo”
- 22 wells drilled in initial development plan
- 22 wells capable of producing 70 Mmcfd gross (50 Mmcfd net)
- 8 final wells currently cleaning up
- Producing wells are highest rate CRZO Barnett wells drilled to date
- Infrastructure supports rapid expansion



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Enabling Technologies

- Horizontal (lateral) drilling
- 10-20 stages of fracturing (fracking) per well
- Better fracturing fluids (“slickwater”)
- Many other techniques and technologies
  - 3 dimensional seismic surveys
  - MWD, LWD (Measure, Logging While Drilling,…)
  - Petrophysical studies
  - Stimulation analysis

Now 15-35% recovery vs 2% ten years ago

(OGJ, 27 Sept 2010 , p22)

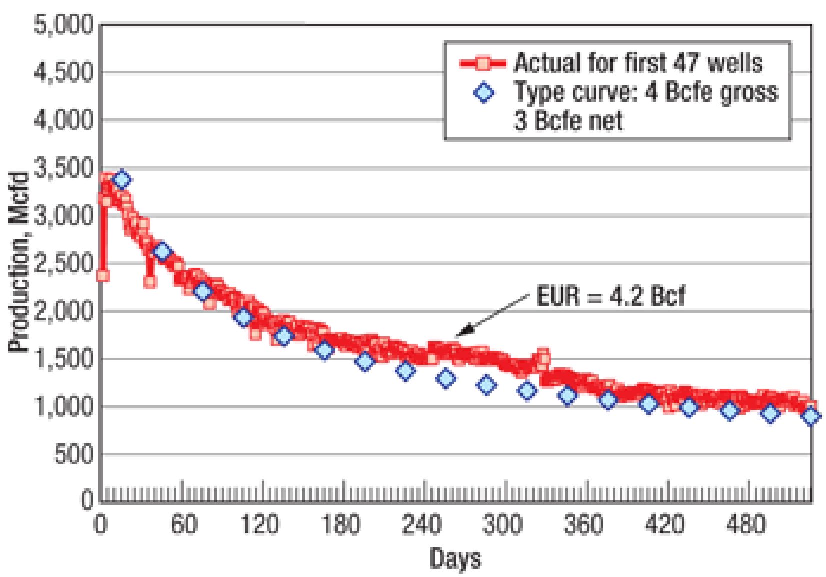
Barnett (Texas) Shale Gas Economics

Source: Carrizo Oil and Gas, Inc.

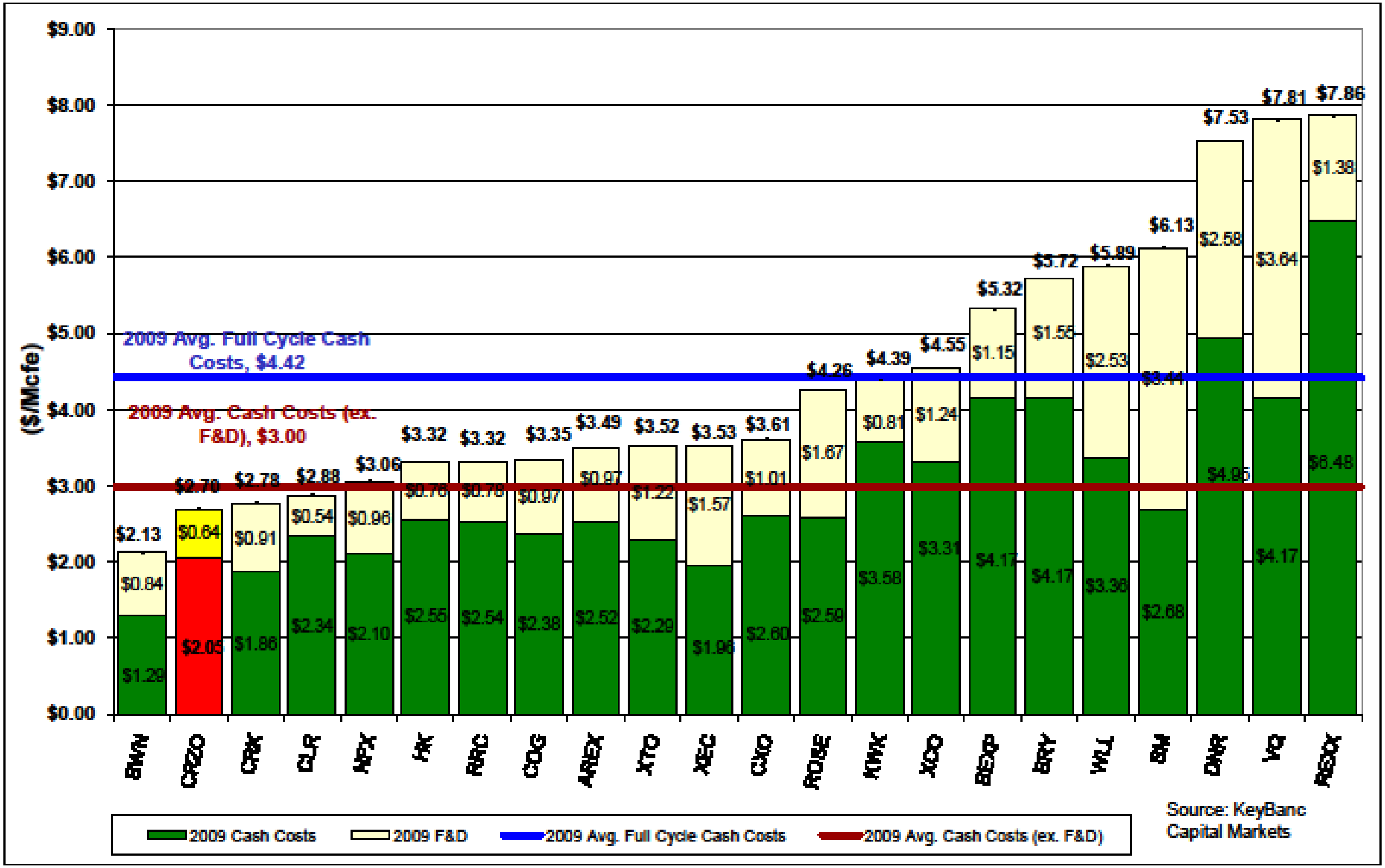
Shale Gas Well Economics		
	All In	Well Only
Land (45 ac@$8k)	0.4MM	
3-D Seismic	0.03MM	0.03MM
Total Well Cost	$3M	$3M
Net Reserves	3 Bcf	3 Bcf
F&D Cost	$1.14/Mcf	$1.0/Mcf
IRR: $8 NYMEX	65%	79%
$6 NYMEX	36%	46%
$4 NYMEX	13%	17%
Undiscounted Payback @$6 NYMEX	2.3 years	1.9 years

Shale Gas Well Performance

- 60% decline first year
- 1 Bcf extracted in two years



F&D and Cash Operating Costs



Source: KeyBanc Capital Markets

Natural Gas Hedge Positions
Carrizo Oil and Gas, Inc

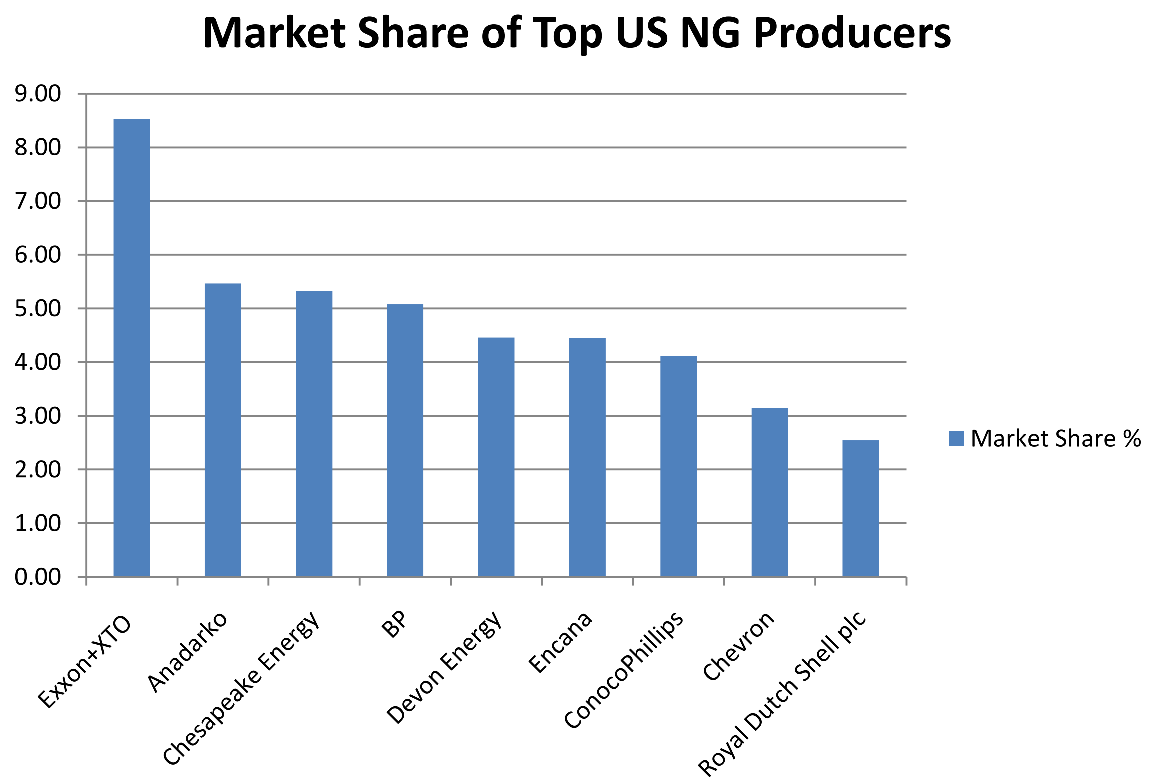
Natural Gas Hedging Contracts	Volume (MMcf)	Daily Volume (Mcfed)	Effective Price ($/MMBtu)	%of 2009 Q4 Production
1 Q Swaps and Collars	6,210	69	6.10	65
2 Q Swaps and Collars	5,773	63	5.52	61
3 Q Swaps and Collars	5060	55	5.75	54
4 Q Swaps and Collars	4876	53	5.94	52
2010	21,879	60	5.83	58
2011	11,765	32	6.32	31
2012	7,963	22	6.52	21

What to expect: Business Darwinism

- Deep Pockets will win
- Weak firms (unhedged, and/or primarily gas) must produce to pay salaries, fulfill lease terms, forced into bankruptcy or merger
- Large firms control extraction rates (off-the-record understanding)
- Prices INCREASED to levels acceptable to producers (decoupled from production costs)

US Natural Gas Market Structure

- Top 9 Companies: 43% of US natural gas market



Merger and Acquisition Activity, 2010

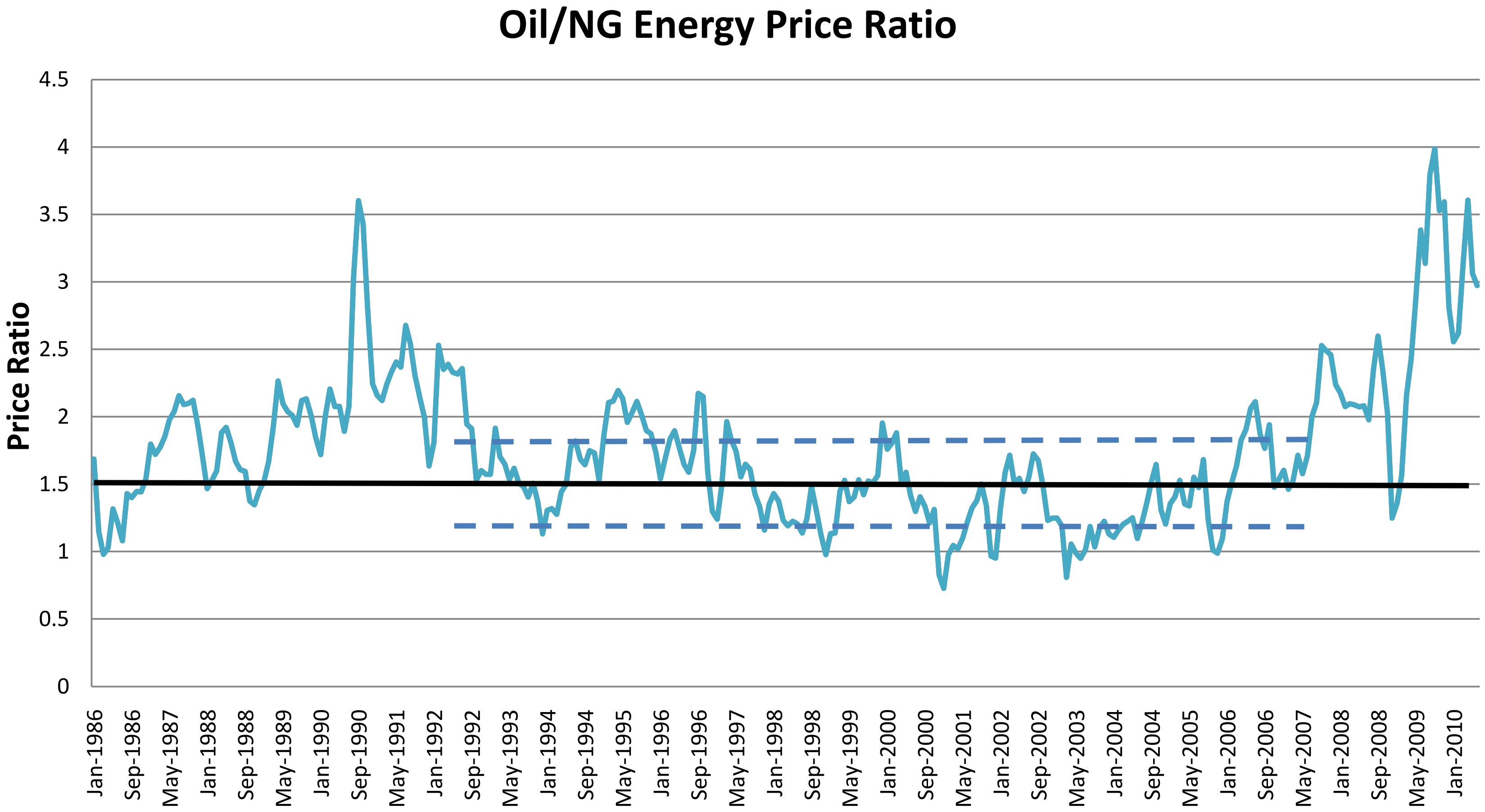
- Exxon+ XTO ($1/mcfe)
- First half 2010 M&A ($21 Billion) = 2009+2008 M&A ($0.60/mcfe – FIRE SALE)
- "…gas weighted independents with a weak balance sheet and/or hedging position are beginning to look increasingly vulnerable to larger players."

Wood Mackenzie, September 2010

Joint Ventures, Other

- Statoil (Norway), Talisman (Canada) buy Eagle Ford Shale in $1.3B JV deal (10-11-2010); $4/mcfe breakeven
- CNOOC (China) pays $1.1B cash, $1.1B drill carry to enter Eagle Ford Shale with Chesapeake
- Chesapeake sells Barnett shale assets to Barclays for $1.15 billion (VVP, volumetric production payment)

NG Expected Price: \$Oil/(1.5±0.3)



How will this evolve?

- Intermediate Term (5-10 years): OPEC will increase oil prices ($150-$200/b).
- Short term gas: 2010-2011: desperation M&A activity: late 2012, spot prices increase to historic norms (Oil/Gas Price ratio = 1.5)
- BUT merchant plants are also hedging so that low electricity prices may continue to put pressure on renewable energy and CAES

!!!BEWARE!!!

- Highly fluid, volatile situation
- Cannot take chances: low gas/electricity prices could last through 2012 or even beyond
- Minimize risk
- INSURE PROJECTS ARE PROFITABLE
  - compression costs known and locked in
  - Offload risk as much as possible
    financial engineering as important as conventional engineering

17. Potential Risks Associated with Underground CAES

S.J. Bauer, T.W. Pfeifle, *Sandia National Laboratories*

Presently, salt caverns represent the only proven underground storage used for CAES, but not in a mode where renewable energy sources are supported. Reservoirs, both depleted natural gas and aquifers represent other potential underground storage vessels for CAES, however, neither has yet to be demonstrated as a functional/operational storage media for compressed air.

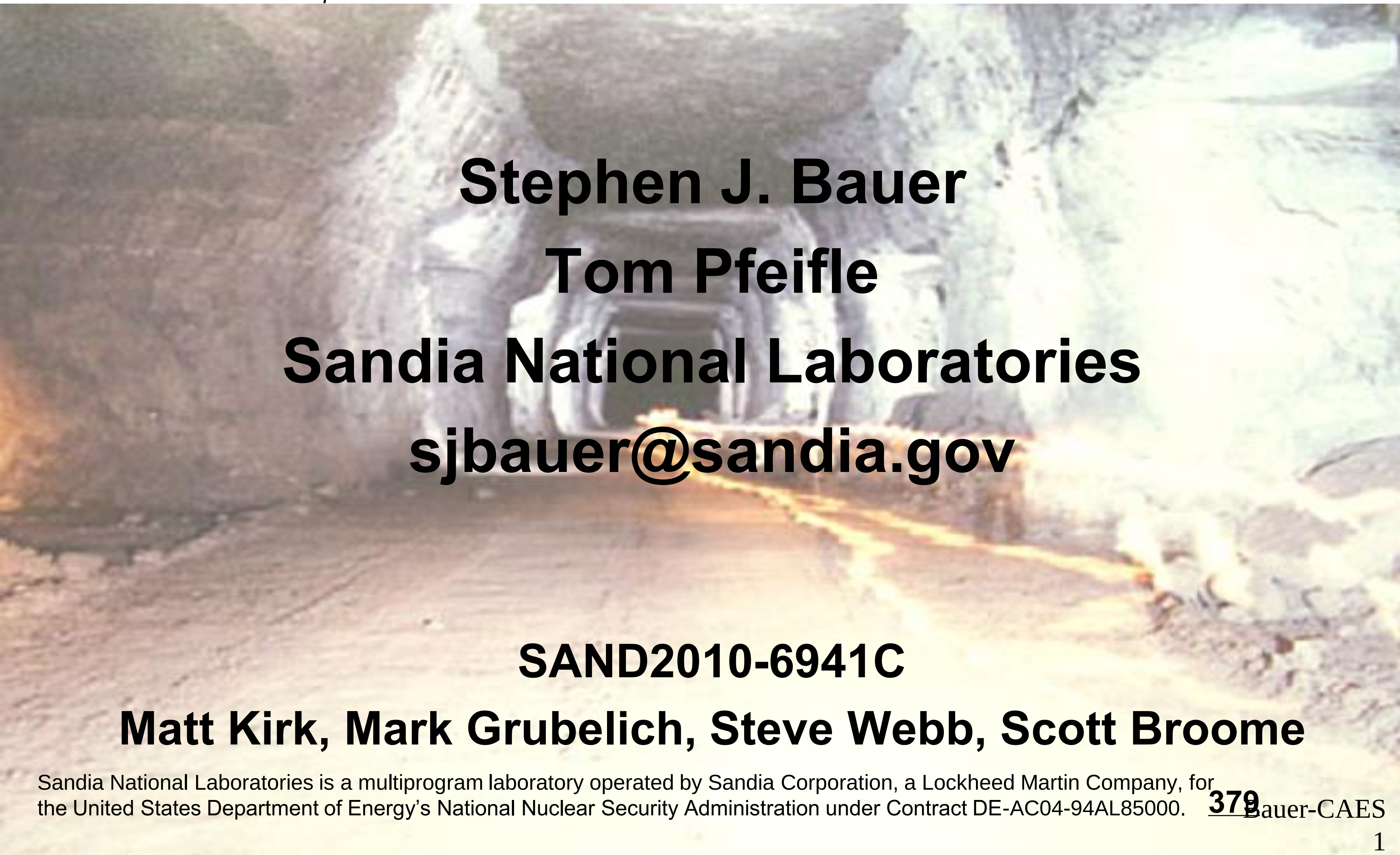
Renewable support using CAES implies that the storage "container", may experience small irregular pressure cycling, subjecting the storage media to repeated stress changes. These repetitive stress changes could degrade the mechanical integrity of salt (cavern storage), as well as sedimentary rock (reservoir storage). Also, air (containing O_2), may affect the composition and function of the microbial community in subsurface storage (aquifer) reservoirs. The impact will be strongest in reducing environments, particularly if the formation contains pyrite and little carbonate mineral mass. This impact has the potential to negatively affect groundwater quality and the long-term efficiency of the CAES facility. Furthermore, air introduced into a depleted natural gas reservoir presents a situation where ignition/explosion potential in a depleted natural gas reservoir may exist.

We will present the results of initial studies that begin to address these potential underground risks to CAES: experimental deformation of salt in cyclic loading, assessment of biologic growth potential in an aquifer resulting from air cycling, and assessment of ignition/explosion potential in a depleted reservoir from air cycling associated with CAES.

Stephen Bauer of Sandia National Laboratories manages the Geomechanics Lab, where pressures of 150ksi, temperatures of a few hundred degrees C, fluid flow through capabilities, and a 10 order of magnitude strain rate range are used to simulate many in situ earthen conditions. Steve has worked on lab and field testing as well as analyses projects addressing underground storage of natural gas, hydrogen, crude oil, air, and radioactive waste in hard rock, salt and reservoirs (sedimentary rock).

Potential Underground Risks Associated with CAES

Geomechanics Research Department



Stephen J. Bauer

Tom Pfeifle

Sandia National Laboratories

sjbauer@sandia.gov

SAND2010-6941C

Matt Kirk, Mark Grubelich, Steve Webb, Scott Broome

Sandia National Laboratories is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under Contract DE-AC04-94AL85000.

Background Facts

Geomechanics Research Department

1- CAES in geologic media has been proposed to help "firm" renewable energy sources (wind and solar) by providing a means to store energy when excess energy was available, and to provide an energy source during non-productive renewable energy time periods. Such a storage media may experience hourly (perhaps small) pressure swings.

2- Salt caverns represent the only proven underground storage used for CAES, but not in a mode where renewable energy sources are supported.

3- Reservoirs, both depleted natural gas and aquifers represent other potential underground storage vessels for CAES, however, neither has yet to be demonstrated as a functional/operational storage media for CAES.

Some Risks We Studied

Geomechanics Research Department

1-Air (containing $\mathbf{O_2}$), **may affect the composition and function of the microbial community** in subsurface storage (aquifer) reservoirs.

2- A**ir** introduced **in**to **a depleted natural gas reservoir presents a situation where ignition/explosion potential** may exist.

3- The combination of **intrinsic rock properties** (porosity and permeability) important to fluid flow and **well field construction** (number, diameter , spacing of boreholes) are used to determine needed air mass flow rates: Facility Cot are a direct result of this marriage.

4-**Repetitive stress changes** could degrade the mechanical integrity of salt (cavern storage), as well as sedimentary rock (reservoir storage).

Specific Problems Studied

Geomechanics Research Department

1-Potential Microbial and Chemical Impact of CAES in a Sandstone, M. Kirk

2-Assessment of Ignition/Explosion Potential in a Depleted Hydrocarbon Reservoir from Air Cycling Associated with CAES, M. Grubelich

3-Flow Analysis Parametric Study: S. Webb

4-Material Degradation (T-M-C-H effects) Due to Cyclic Loading, SJ Bauer and ST Broome

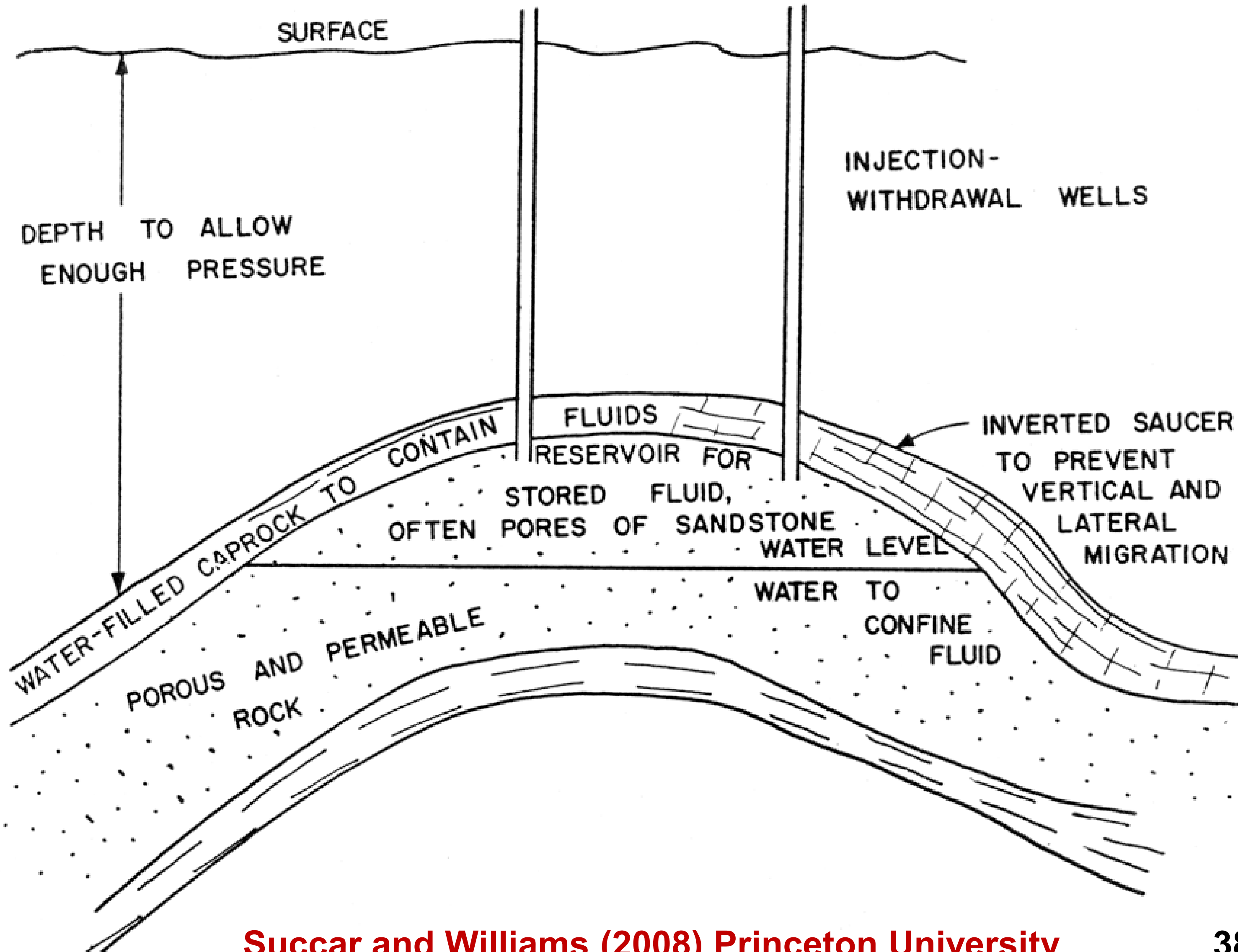
Potential Microbial and Chemical Impact of CAES in a Sandstone

Matthew Kirk

Geochemistry Department

Compressed Air Energy Storage

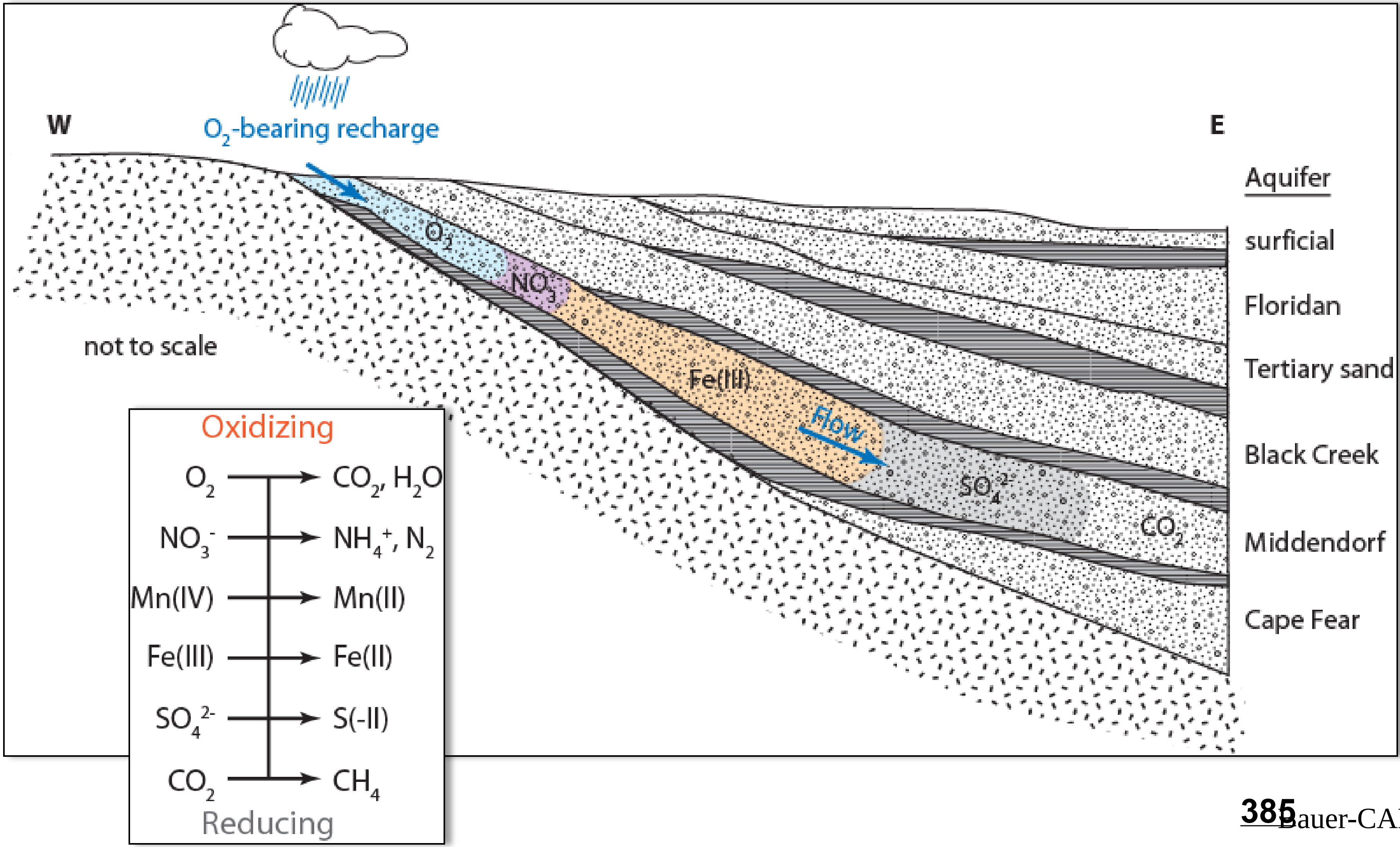
Geomec



Succar and Williams (2008) Princeton University

Groundwater Microbiology

Example: Middendorf coastal plain aquifer, South Carolina



Conclusions: Potential Microbial and Chemical Impact of CAES in a Sandstone

- Sandstone evaluated in a reducing environment
- Microbial Fe(II) and Mn(II) oxidation will become favorable
- Pyrite oxidation could lead to considerable changes in pH, salinity, and mineralogy
- Microbiology and mineralogy changes would impact porosity

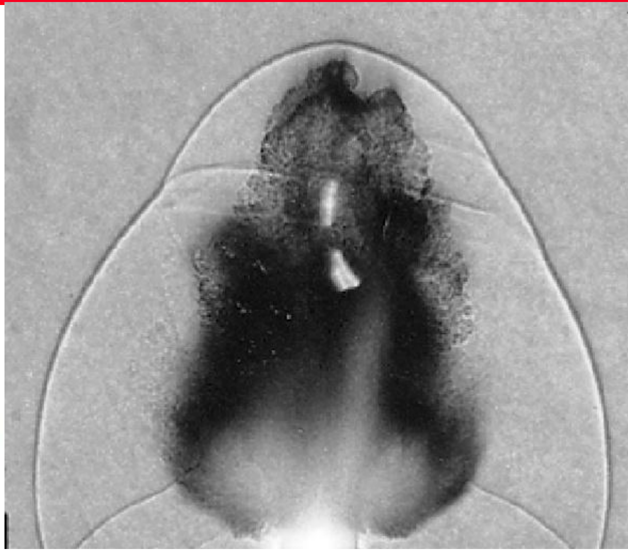
Considerations for Explosion Potential for CAES in a Depleted Natural Gas Reservoir

Geomechanics Research Department

Mark Grubelich

Fuel, Oxygen & Ignition Source

Geomechanics Research Department



Detonation, reaction proceeds at supersonic speeds (shock wave).

Combustion or Deflagration
10's to 100's of ft/sec reaction rates.

Results & Conclusions: Mitigation & Safety

Geomechanics Research Department

- Purge reservoir before use
- Low pressure air cycling below UFL to remove gas (~90 psi)
- In-situ gas monitor
- Never draw down air below the LFL (370 psi)
- Insure no surface breach if ignition occurs (sufficient overburden)
- Monitor NG content entering surface equipment
- Further study required
  - Buoyancy issues, etc.

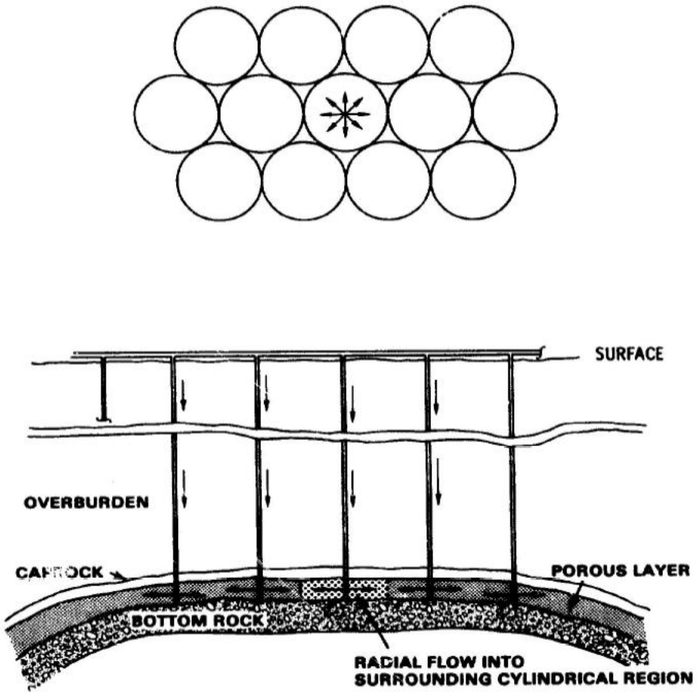
CAES Borehole Study: Steve Webb

Geomechanics Research Department

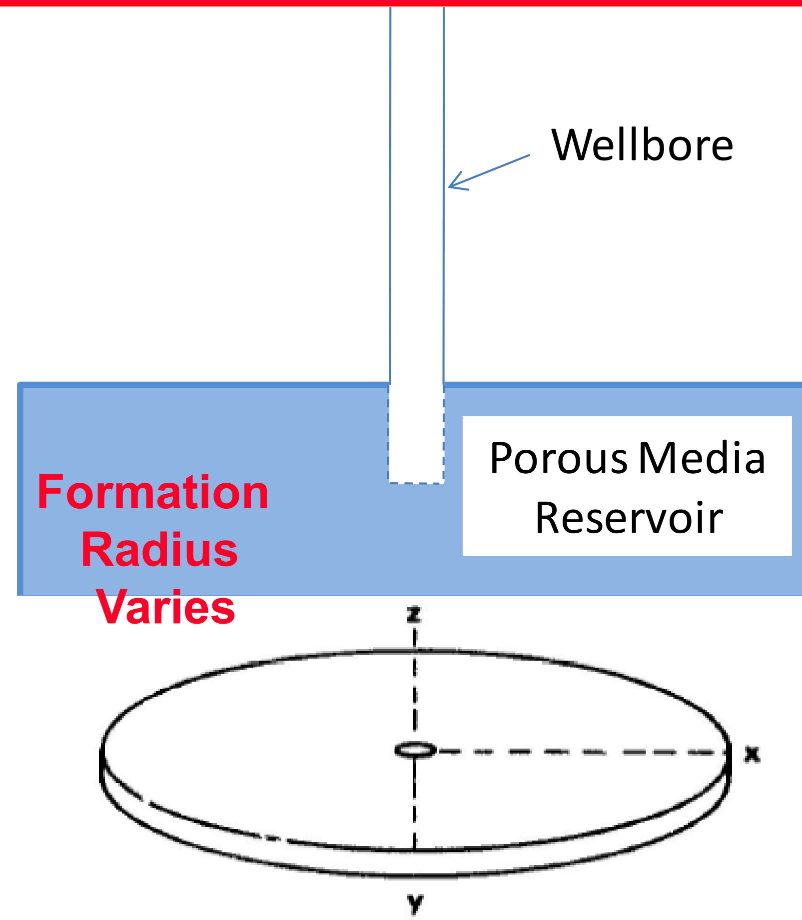
- **Objective**
  - **Look at Flow in Individual Boreholes**
  - **Simple 2-d Models**
  - **Estimate Number of Boreholes and CAES Footprint**
- **Assumptions**
  - **Representative Borehole/Formation Geometry**
  - **Include Two-Phase Behavior**
    - **Capillary Pressure and Relative Permeability**
    - **Bubble Formation**
    - **Air Injection and Withdrawal – 10 Weekly Cycles**

Study geometry views

Geomechanics Research Department



CAES Borehole Schematic
(from Smith and Wiles, 1979)

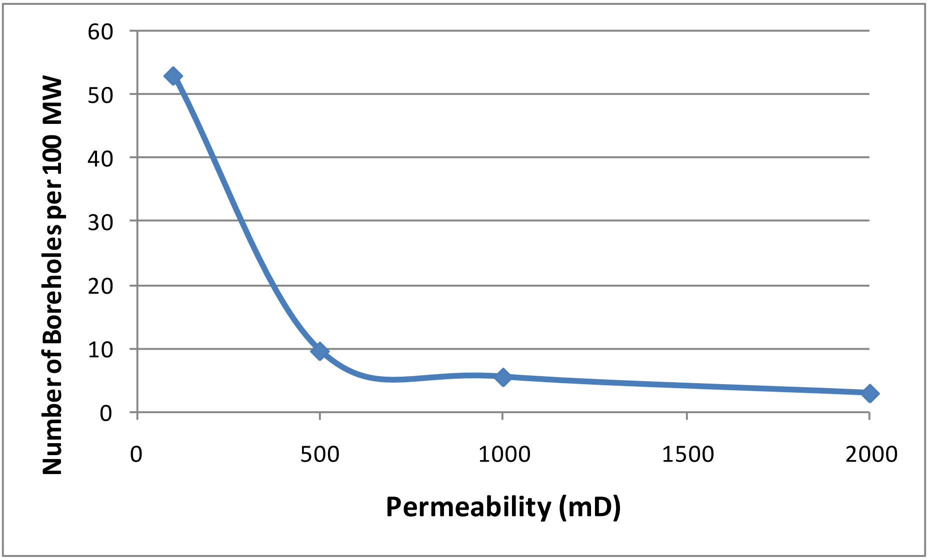


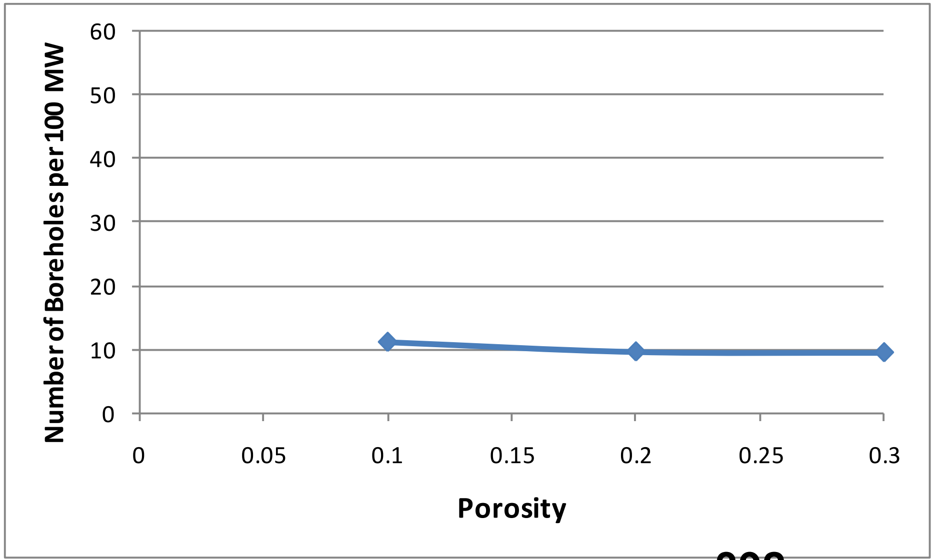
Representative Borehole/Formation Geometry

Conclusions

Geomechanics Research Department

- Permeability Variation Much More Important then Porosity Variation
- Procedure Can Quantify Differences Between Various Sets of Formation Parameters
    - Borehole Spacing, Number of Boreholes





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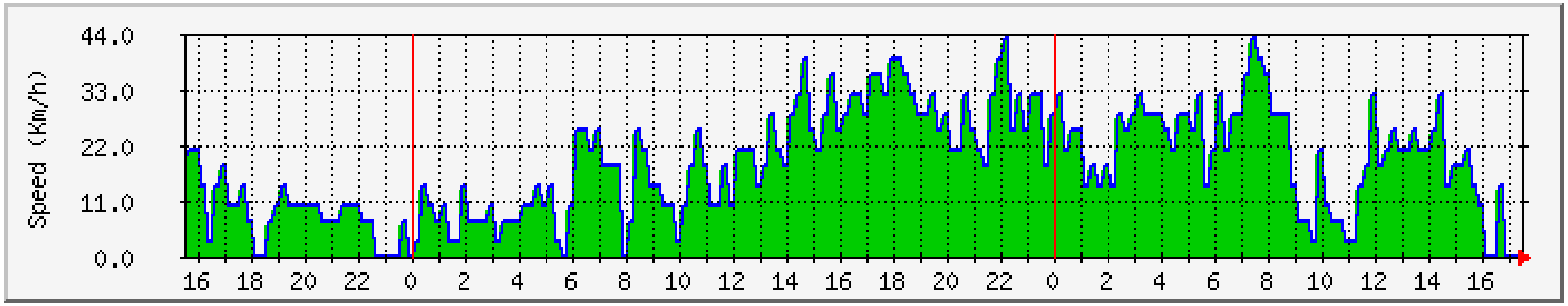
Material Degradation (T-M-C-H effects) Due to Cyclic Loading

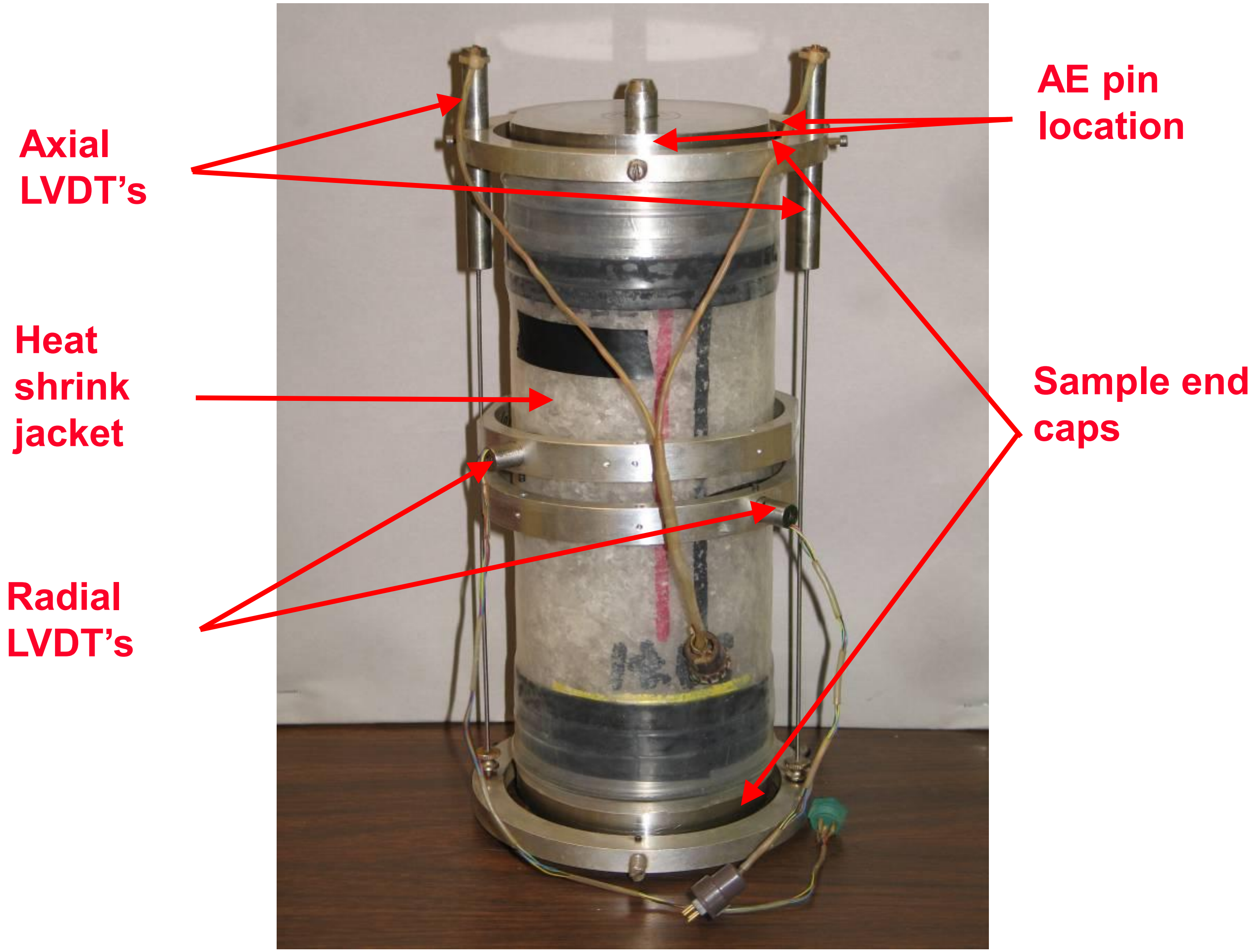
SJ Bauer and ST Broome



Hourly fluctuations in wind speed could translate to frequent pressurization/depressurizations of salt caverns

Test assembly

Geomechanics Research Department



Concluding Comments

- Preliminary cyclic tests completed on salt
- Change in volume strain observed
- Young's Modulus changes observed
- Acoustic emissions detected
- Cracks observed in thick sections
- Results consistent with previous work
- Implication that cyclic loading caused cracking at low differential stresses

Summary/Conclusions

1- Sandstone in a reducing environment could effect biologic and mineralogic changes that could lead to changes in porosity and permeability

2-Recommendations given for mitigation of potential use of a natural gas reservoir for CAES

3- Permeability variation much more important than porosity variation; procedure can help determine borehole spacing, number of boreholes (CO$T)

4-Salt strength observed to degrade in cyclic loading

Publications

Geomechanics Research Department

1- "*Potential Effects of Compressed Air Energy Storage on Microbiology, Geochemistry, and Hydraulic Properties of Porous Aquifer Reservoirs*", Kirk, Altman, and Bauer, SAND2010-4721

"*Potential Subsurface Environmental Impact of Compressed Air Energy Storage in Porous Bedrock Aquifers*" Env. Sci. & Tech. (in Prep, Kirk et al)

2- "*Considerations for Explosion Potential for CAES in a Depleted Natural Gas Reservoir*" , M. Grubelich

***3- "Borehole and Formation Analyses in Reservoirs to Support CAES Development"* , S. Webb**

4- "*Experimental Deformation of Salt in Cyclic Loading*", S. Bauer and S. Broome, Solution Mining Research Institute April 2010 SAND2010-1805


thanks
Questions?

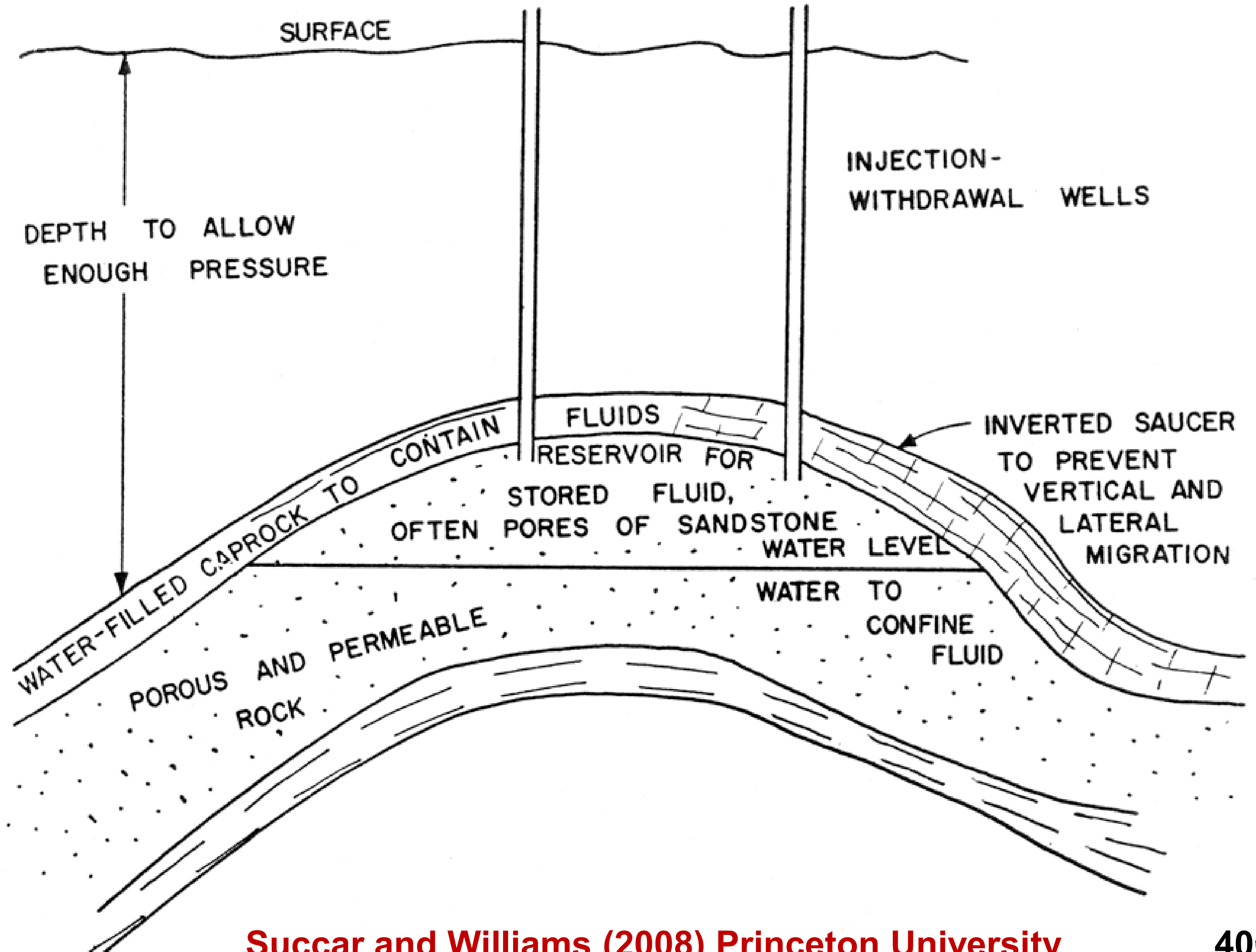
Potential Microbial and Chemical Impact of CAES in a Sandstone

Matthew Kirk

Geochemistry Department

Compressed Air Energy Storage

Geomec



Succar and Williams (2008) Princeton University

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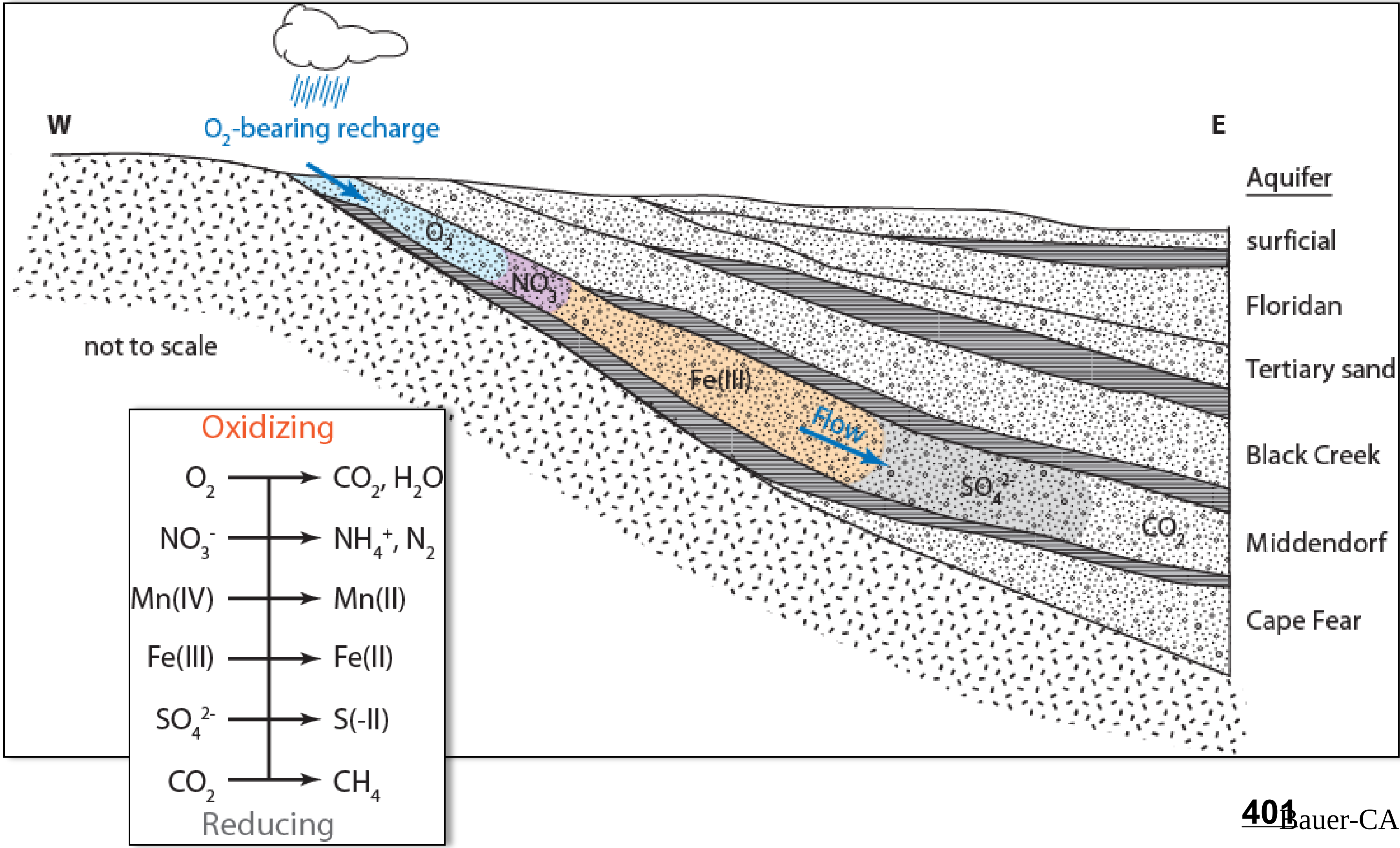
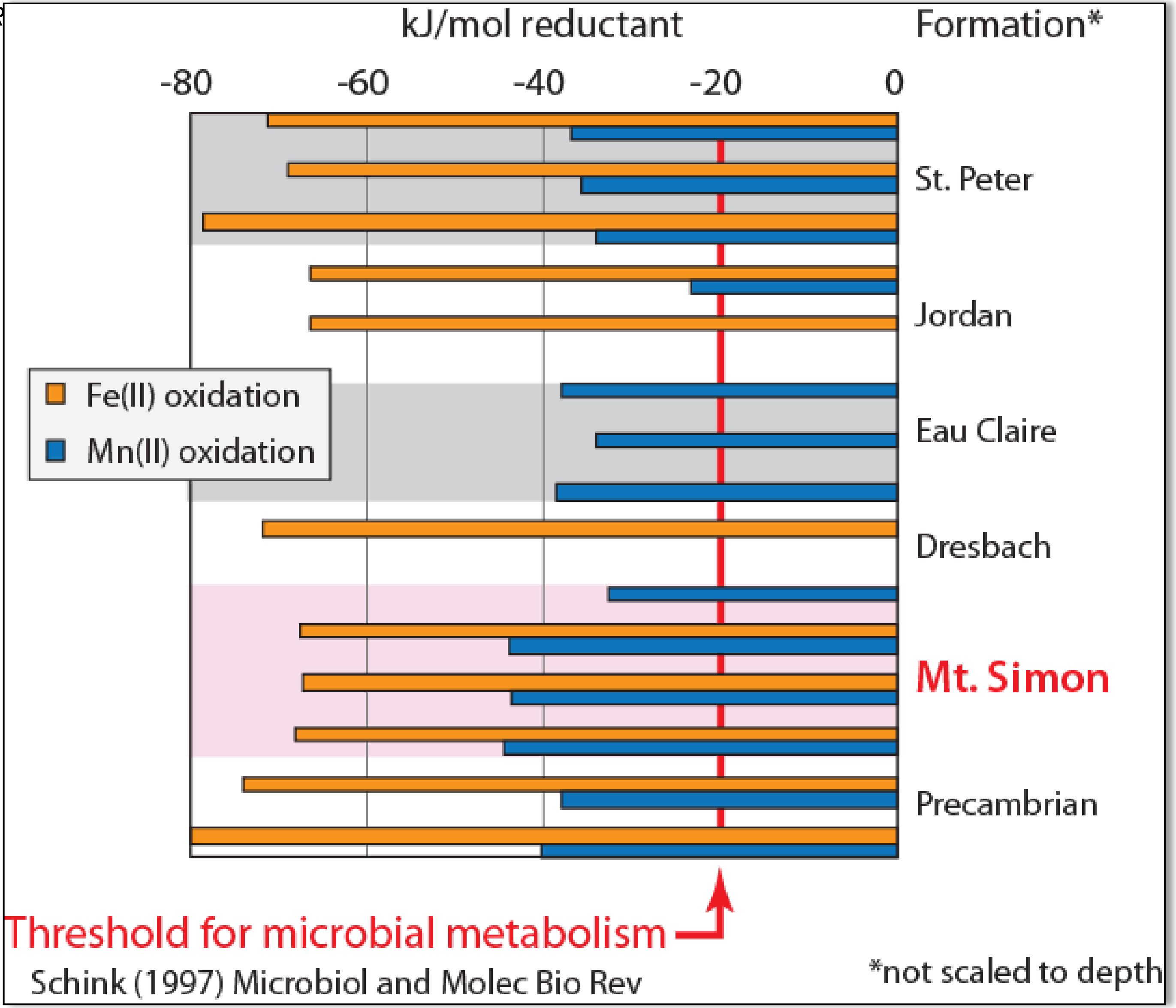
Groundwater Microbiology

Example: Middendorf coastal plain aquifer, South Carolina

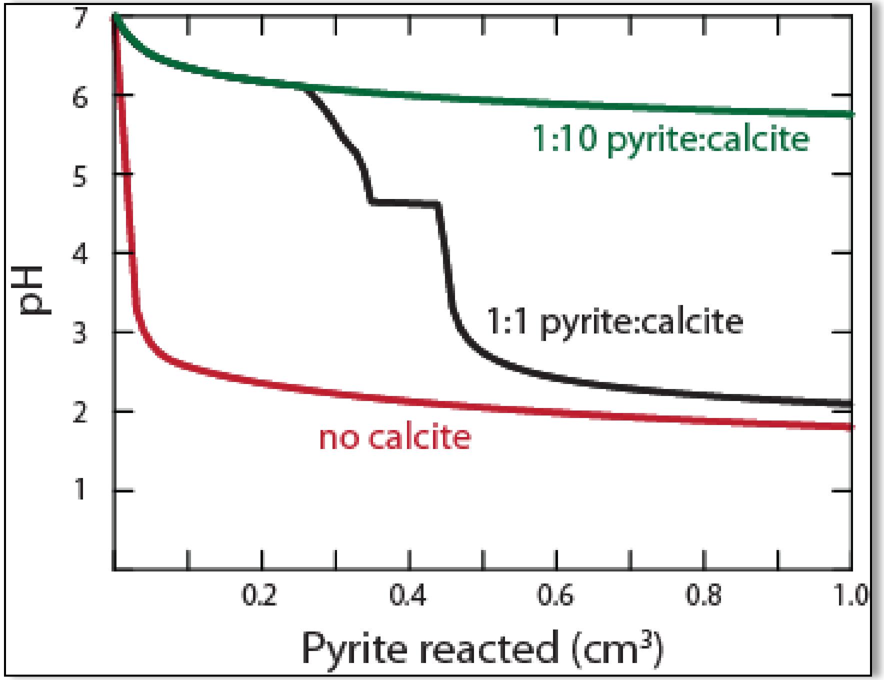


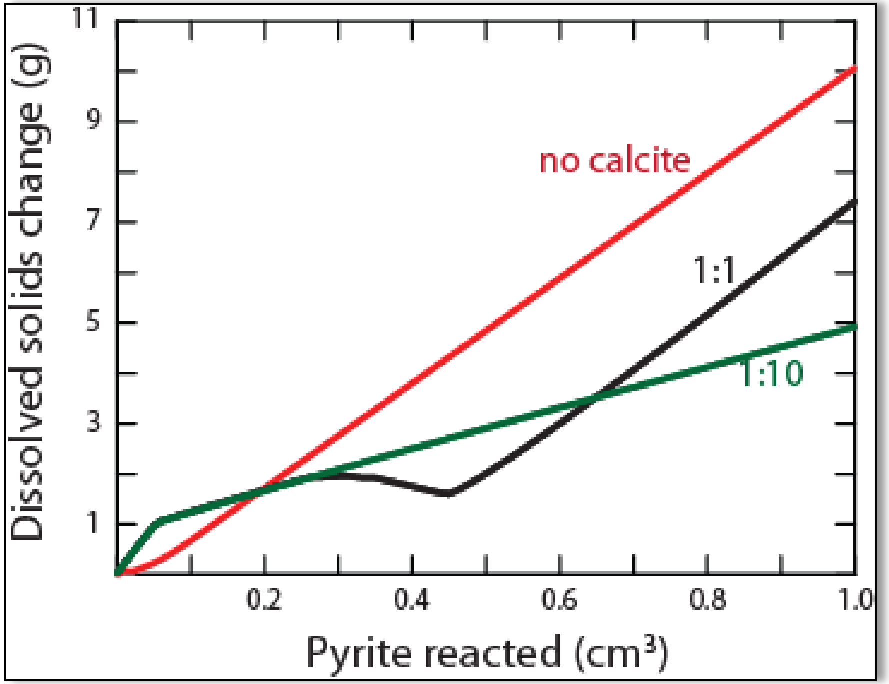
Metabolic energy available for Fe(II) and Mn(II) oxidation in the Mt. Simon



Effect of Pyrite Oxidation on Groundwater Composition

Geomechanics Research Department





Geochemist's Workbench reaction path model assuming 0.2 fO_2

- **no calcite:** pyrite + 3.75 O_2 + 3.5 H_2O → $Fe(OH)_3$ + 2 SO_4^{2-} + 4 H^+
- **with calcite:** pyrite + 2 calcite + 3.75 O_2 + 1.5 H_2O → $Fe(OH)_3$ + 2 SO_4^{2-} + 2 Ca^{2+} + 2 CO_2

Effect of Pyrite Oxidation on Porosity

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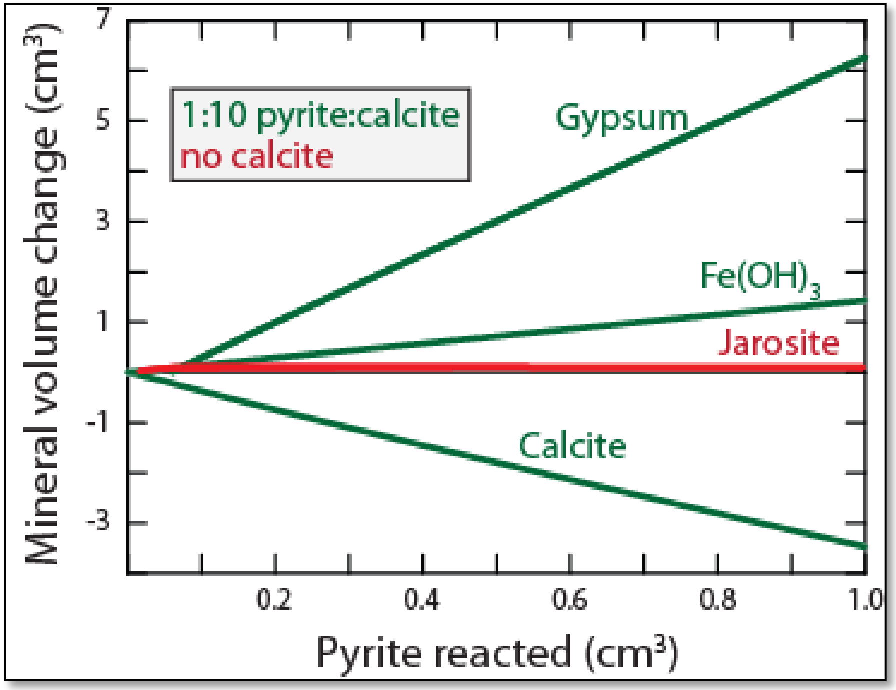
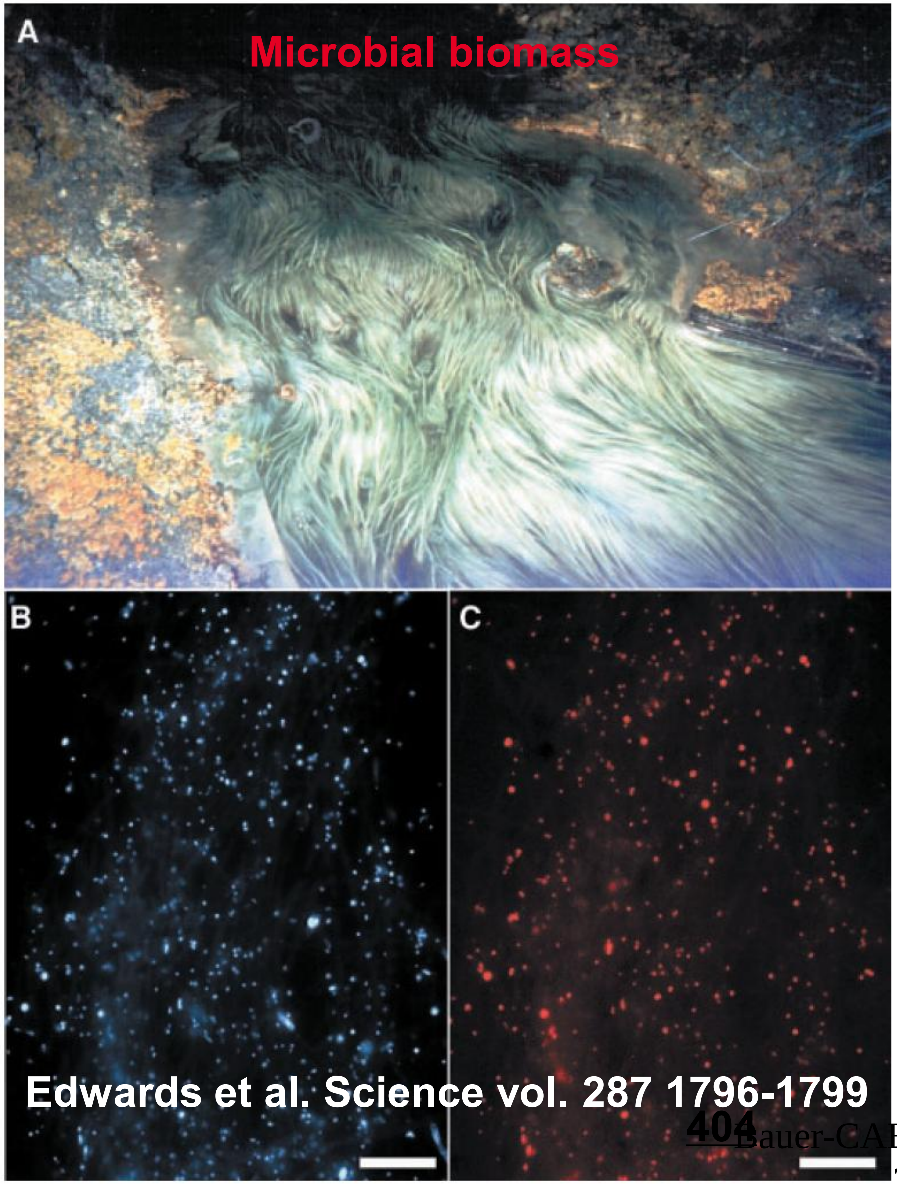
Mineral volume





Conclusions

- Sandstone evaluated in a reducing environment
- Microbial Fe(II) and Mn(II) oxidation will become favorable
- Pyrite oxidation could lead to considerable changes in pH, salinity, and mineralogy
- Microbiology and mineralogy changes would impact porosity

Considerations for Detonation Potential for CAES in a Depleted Natural Gas Reservoir

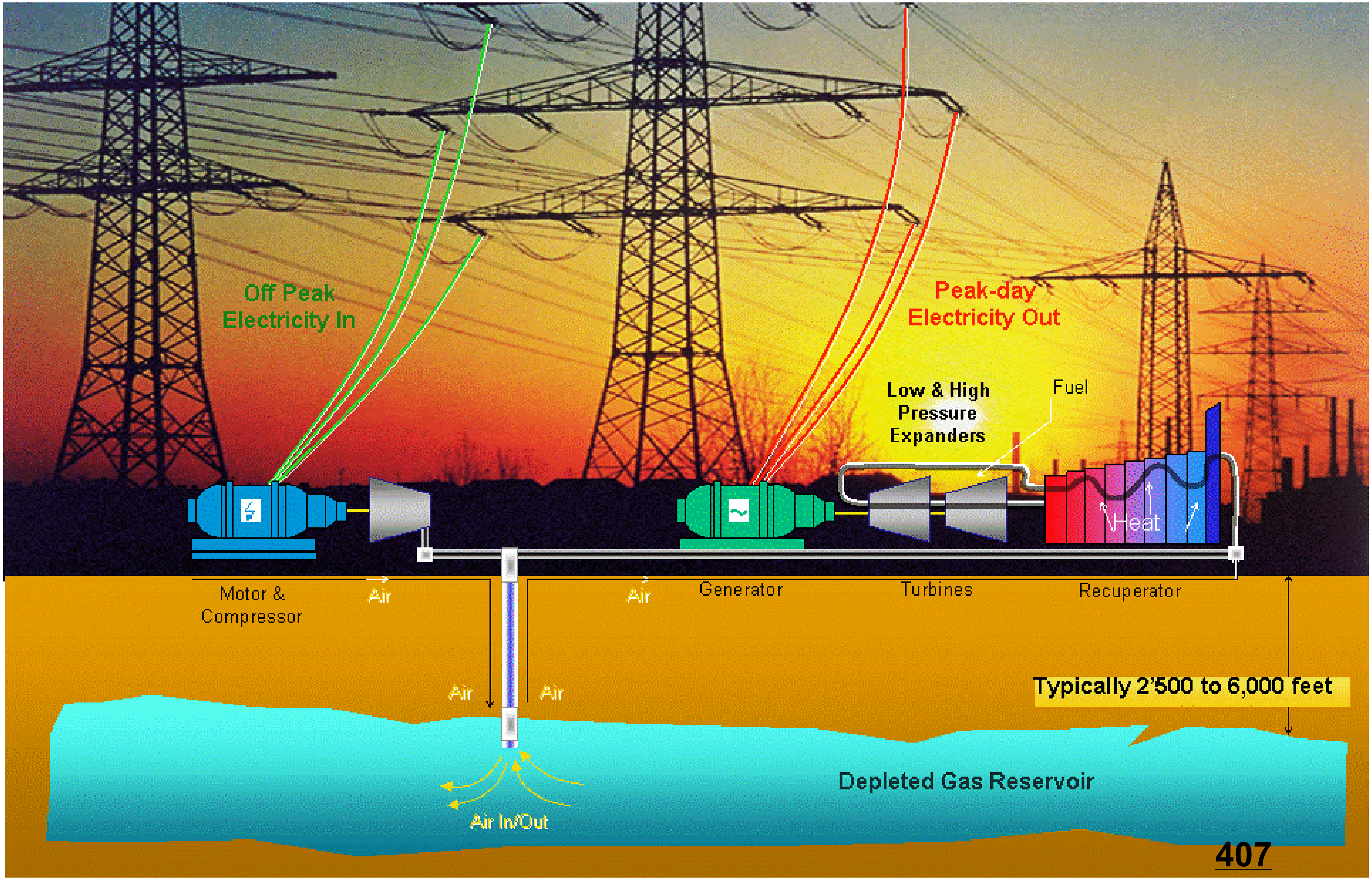
Geomechanics Research Department

Mark Grubelich

Geothermal Energy

Compressed Air Energy Storage

Geomechanics Research Department



Fuel, Oxygen & Ignition Source

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Detonation, reaction proceeds at supersonic speeds (shock wave).

Combustion or Deflagration
10's to 100's of ft/sec reaction rates.

Why worry?

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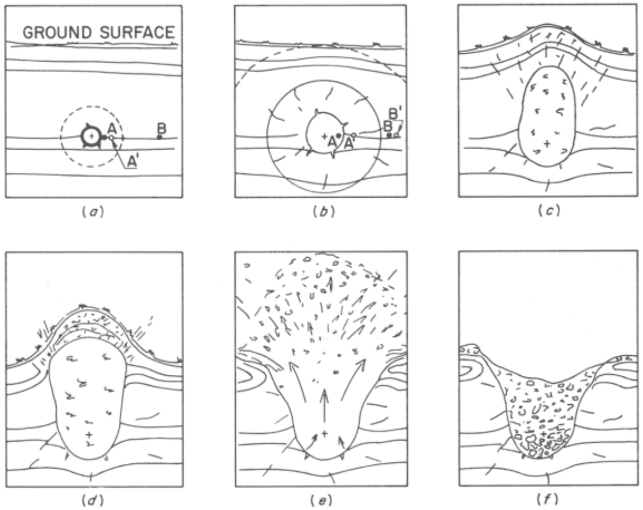
- **The pressure rise ratio for a confined deflagrating (unvented) fuel air mixture is ~9:1**
- **The peak pressure ratio for a detonating fuel air mixture is ~ 18:1**
- **Both events could be severe: (rough calculation in progress)**



Important Points

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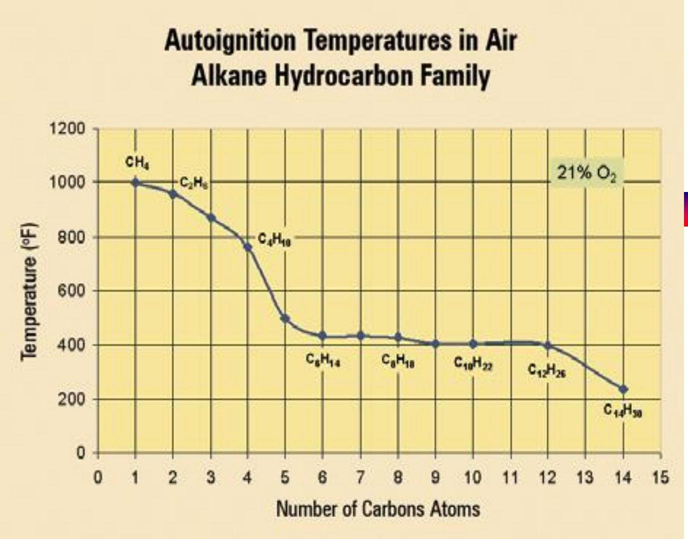

Depleted gas reservoir

- **What does depleted mean?**
- **At atmospheric pressure?**
  - **What is the residual natural gas composition?**
    - **Why is this important?**
      - **Heavy hydrocarbons change the ignition window and decrease the ignition temperature**

Natural gas composition

Component	Typical Analysis (mole %)	Range (mole %)
Methane	95.2	87.0 - 96.0
Ethane	2.5	1.5 - 5.1
Propane	0.2	0.1 - 1.5
iso - Butane	0.03	0.01 - 0.3
normal - Butane	0.03	0.01 - 0.3
iso - Pentane	0.01	trace - 0.14
normal - Pentane	0.01	trace - 0.04
Hexanes plus	0.01	trace - 0.06
Nitrogen	1.3	0.7 - 5.6
Carbon Dioxide	0.7	0.1 - 1.0
Oxygen	0.02	0.01 - 0.1
Hydrogen	trace	trace - 0.02

Table 6. — Limits of flammability of combustible vapors in air and oxygen at 25° C and 1 atm[1]

Combustible	Flammability limits, vol pct			
	Air		Oxygen	
	L_{25}	U_{25}	L_{25}	U_{25}
HYDROCARBONS				
Methane	5.0	15.0	5.0	61
Ethane	3.0	12.4	3.0	66
Propane	2.1	9.5	2.3	55
n-Butane	1.8	8.4	1.8	49
n-Hexane	1.2	7.4	1.2	[2]52
n-Heptane	1.1	6.7	.9	[2]47
Acetylene	2.5	100	≤2.5	100
Ethylene	2.7	36	2.9	80
Propylene	2.4	11	2.1	53
α-Butylene	1.6	10	1.8	58
Cyclopropane	2.4	10.4	2.5	60
Benzene	[2]1.3	[2]7.9	≤1.3	NA

Ignition Window

- **Lower Flammability Limit** **(aka Lower Explosive Limit, LFL or LEL)**
  - **Below the LFL the mixture of fuel and air lacks sufficient <u>fuel</u> to react**
  - **Above the LFL deflagration or detonation possible**
- **Upper Flammability Limit** **(aka Upper Explosive Limit, UFL or UEL)**
  - **Above the UFL the mixture of fuel and air lacks sufficient <u>air</u> to react.**
  - **Below the UFL deflagration or detonation possible**
- **~Ignition possible between 90 and 370 psi**
  - **Assuming well mixed conditions and starting at 1atmosphere NG**
  - **~Below 90 psi too rich and above 370 psi too lean**
  - **Example: Flight 800 center tank explosion**
    - **Lean on the ground & rich at cruise altitude**
    - **Above the LFL and below the UFL during climb**
    - **Ignition source present**
    - **Boom!**

Ignition Sources 0.3 mJ=0.0002 ft-lb= “not much”

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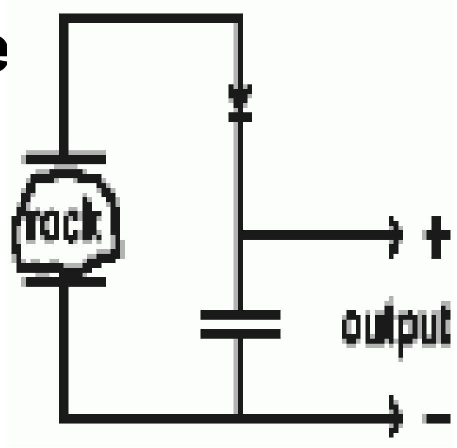
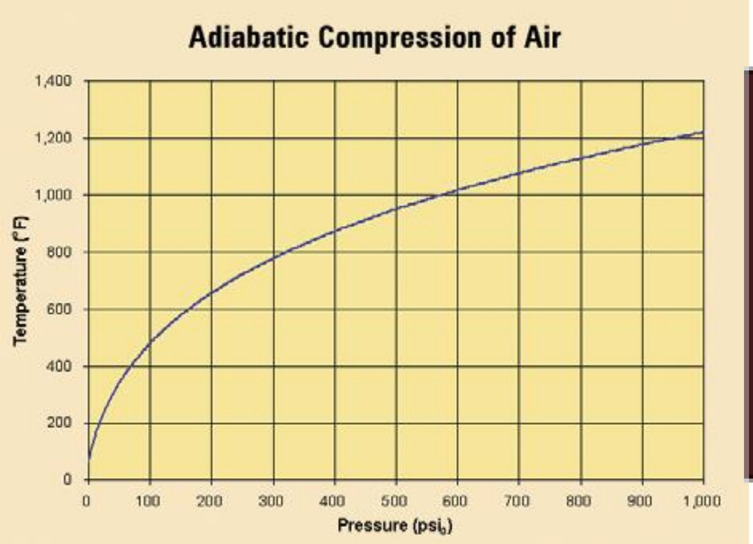
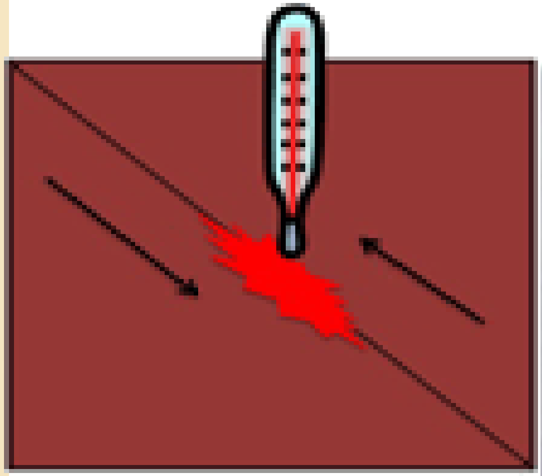
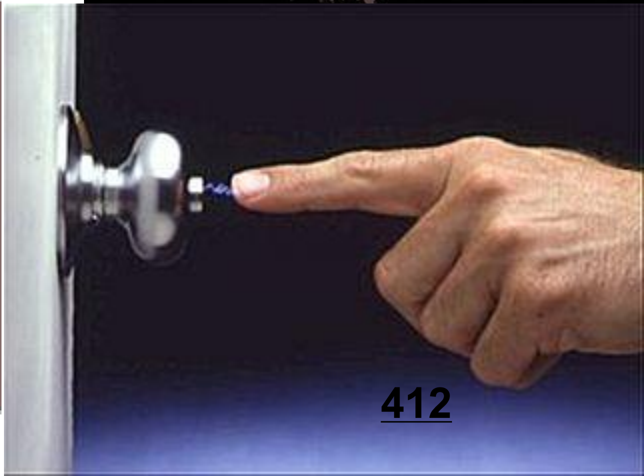
- **Adiabatic compression**
- **Piezo-electric discharge**
- **Static discharge**
- **Lightening strike**
- **Frictional heating**









Mitigation & Safety

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- Purge reservoir before use
- Low pressure air cycling below UFL to remove gas (~90 psi)
- In-situ gas monitor
- Never draw down air below the LFL (370 psi)
- Insure no surface breach if ignition occurs (sufficient overburden)
- Monitor NG content entering surface equipment
- Further study required
  - Buoyancy issues, etc.

CAES Borehole Study

Geomechanics Research Department

Stephen W. Webb

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company,
for the United States Department of Energy's National Nuclear Security Administration
under contract DE-AC04-94AL85000.

Objectives & Assumptions

- Objective
  - Look at Flow in Individual Boreholes
  - Simple 2-d Models
  - Estimate Number of Boreholes and CAES Footprint
- Assumptions
  - Representative Borehole/Formation Geometry
  - Include Two-Phase Behavior
    - Capillary Pressure and Relative Permeability
    - Bubble Formation
    - Air Injection and Withdrawal – 10 Weekly Cycles

Study geometry views

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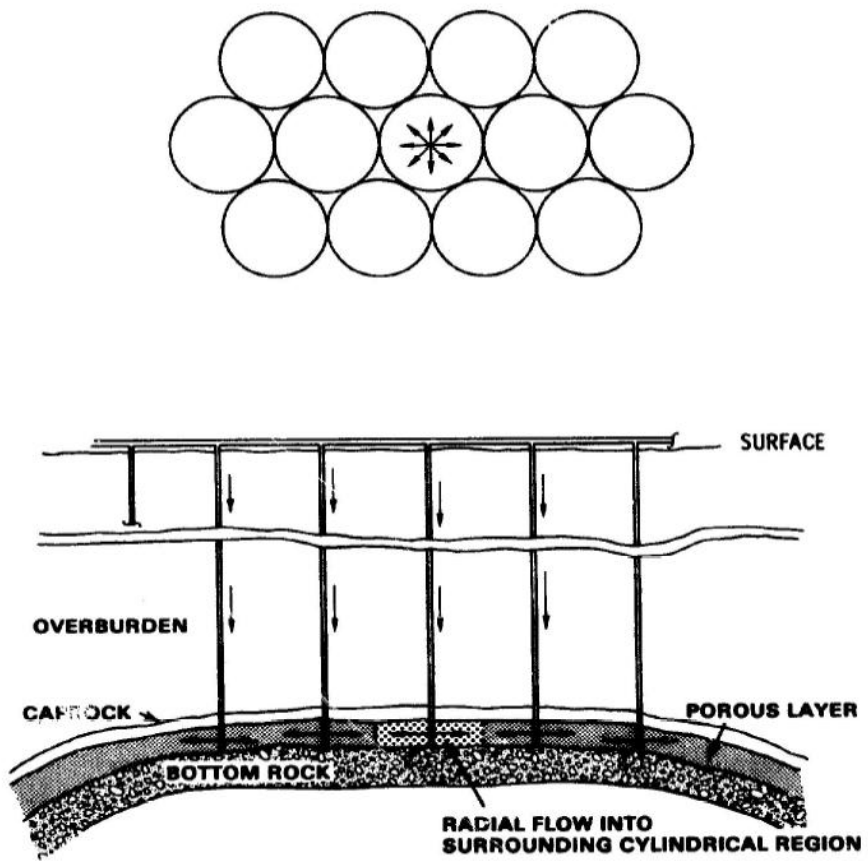

CAES Borehole Schematic (from Smith and Wiles, 1979)

CAES Borehole Study

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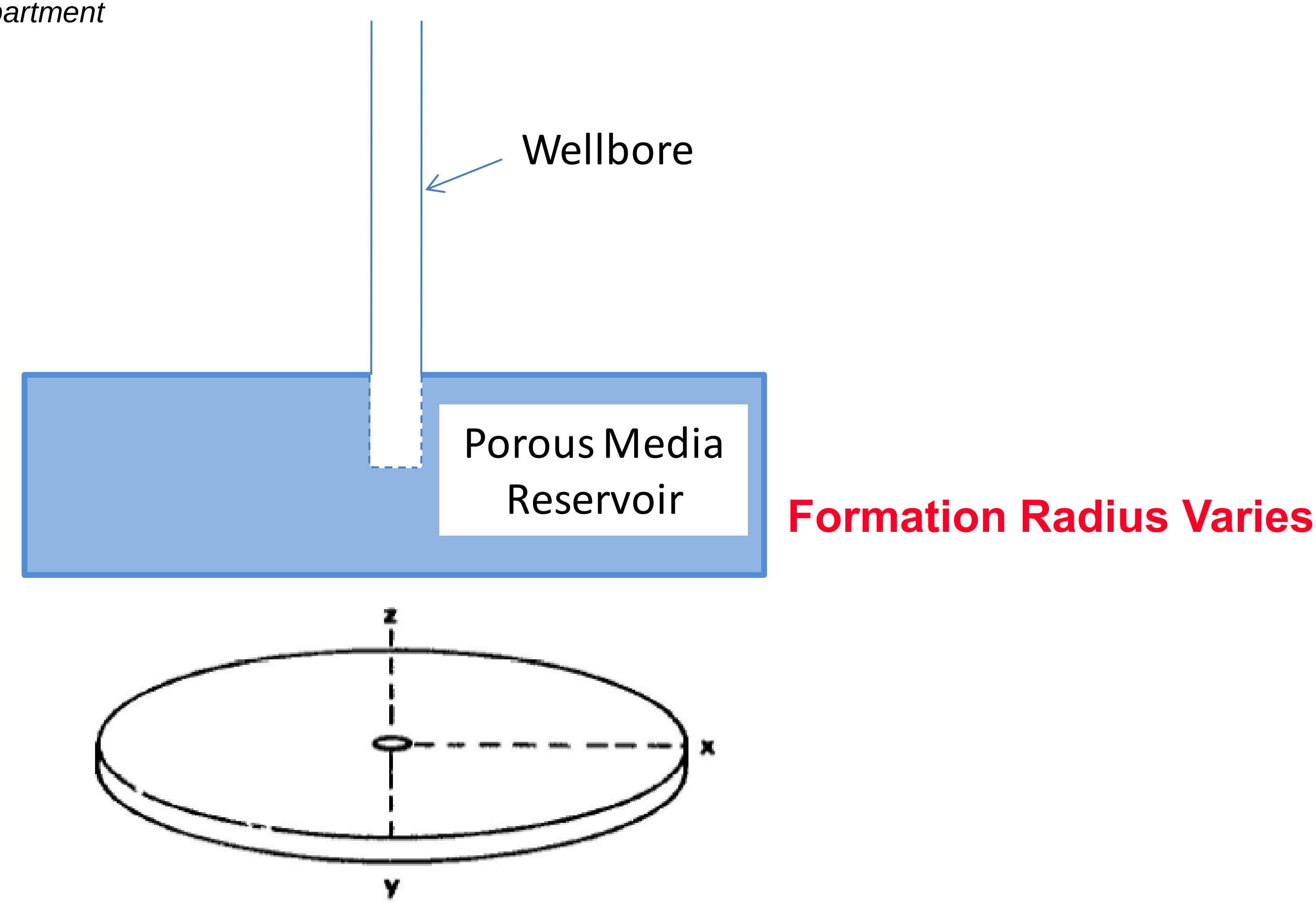

Representative Borehole/Formation Geometry

Study Parameters

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- Formation Height – 100 ft high
- Depth – 2000 ft
- Borehole Diameter – 7 inches
  - Partial Completion
- Permeability – 100 mD to 2000 mD (500 mD Nominal)
- Porosity – 0.1 to 0.3 (0.2 Nominal)
- Formation Radius - Varies
  - Based on P_{max} and P_{min} Values
- Mass Flows
  - See Cycle
- Two-Phase Characteristic Curves
  - Leverett J-Function Scaling

Air Pressure Considerations

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P_{min}

- Turbine Inlet Pressure = 45 bar (4.5 MPa)
- Pressure Drop to Surface = ~5 bar (0.5 MPa)
- Minimum Borehole Pressure = 5.0 Bar

P_{max}

- 0.6 x Lithostatic = 8.4 MPa
- Maximum Borehole Pressure = 8.4 MPa

Pressure Cycling Model

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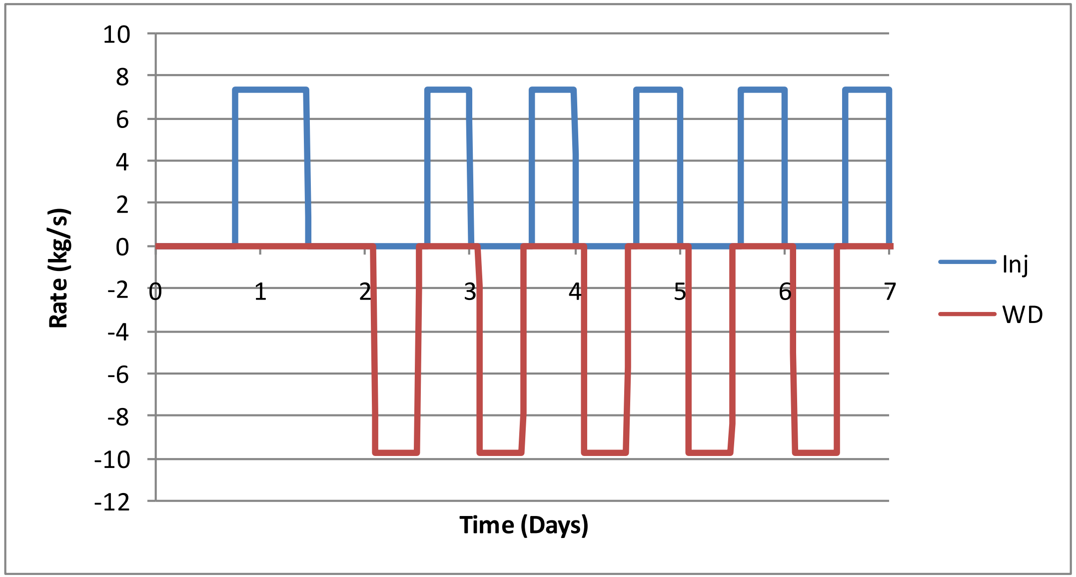
CAES Cycle

- Based on Smith and Liles (1979)
- 10% Mass Cycled Per Week
- 40% Air Added on the Weekend
- Mass Rates Based on Available Mass
  - » Function of Formation Radius, Porosity, Gas Saturation



Typical Cycle

Borehole pressure

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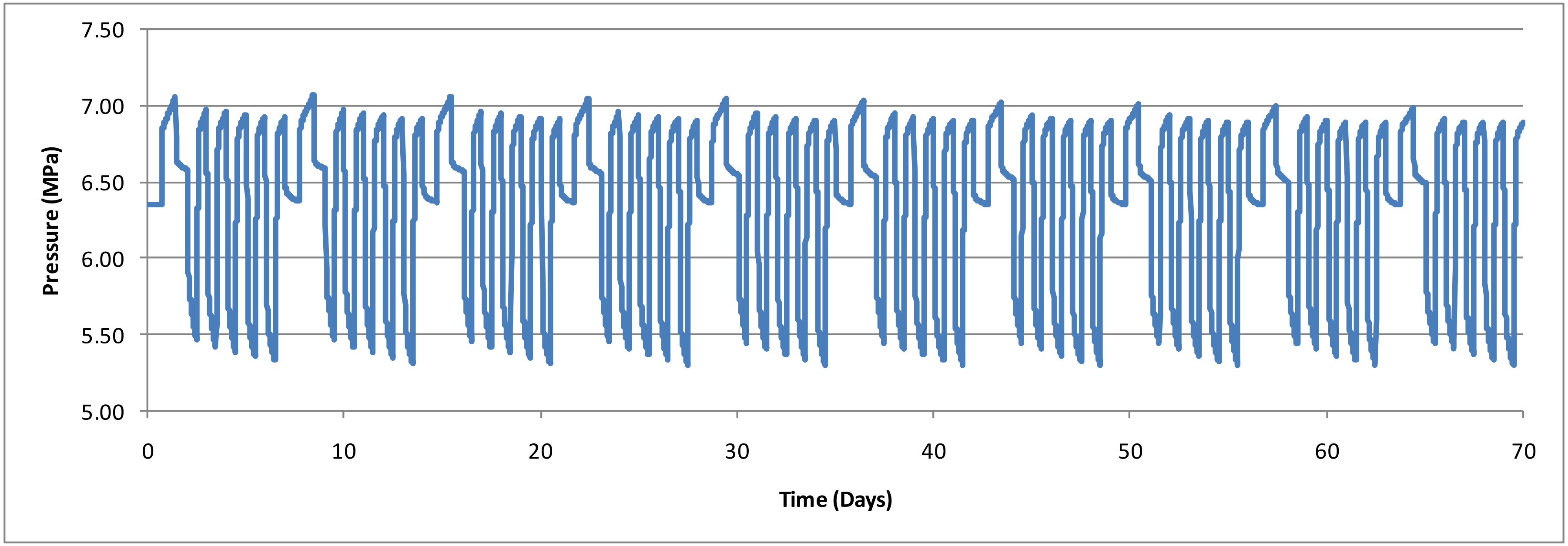
Typical Cycle Results for Borehole Pressure

– **After Formation of Bubble**



Procedure for Given Permeability and Porosity

- **Formation Radius Increase**
  - **Mass Rates Increase – Larger Available Mass in Formation**
  - **P_{max} Increases**
  - **P_{min} Decreases**
- **Optimum Formation Radius and Mass Flow Rate When P_{max} and/or P_{min} Met**

CAES Borehole Study

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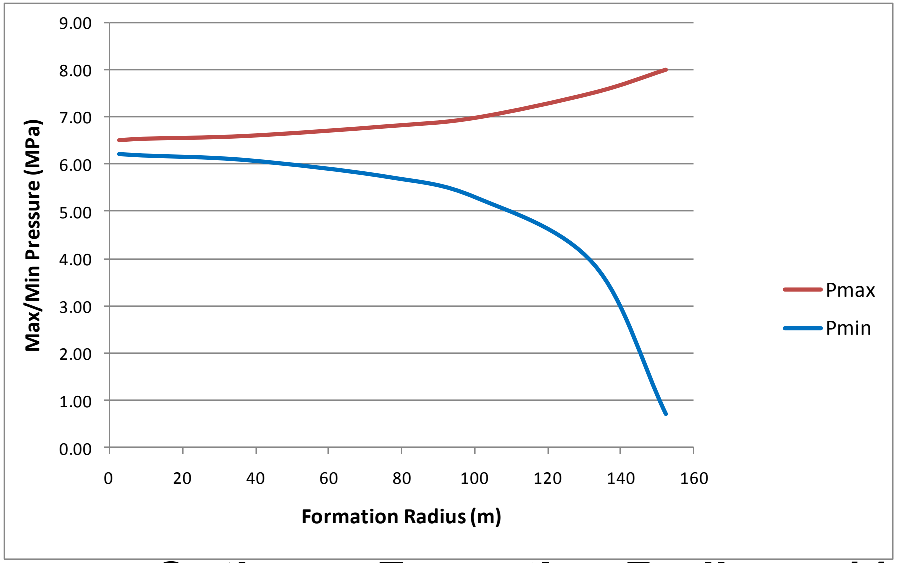
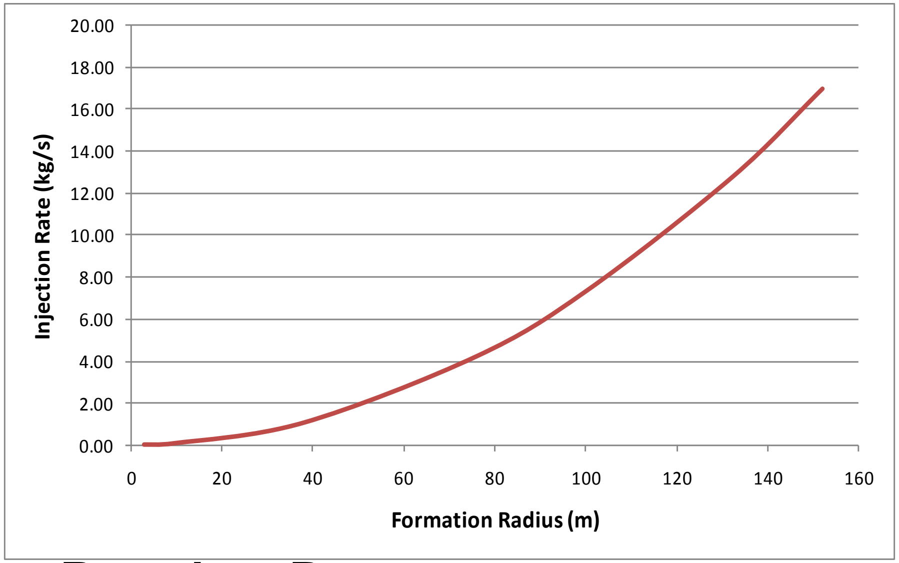
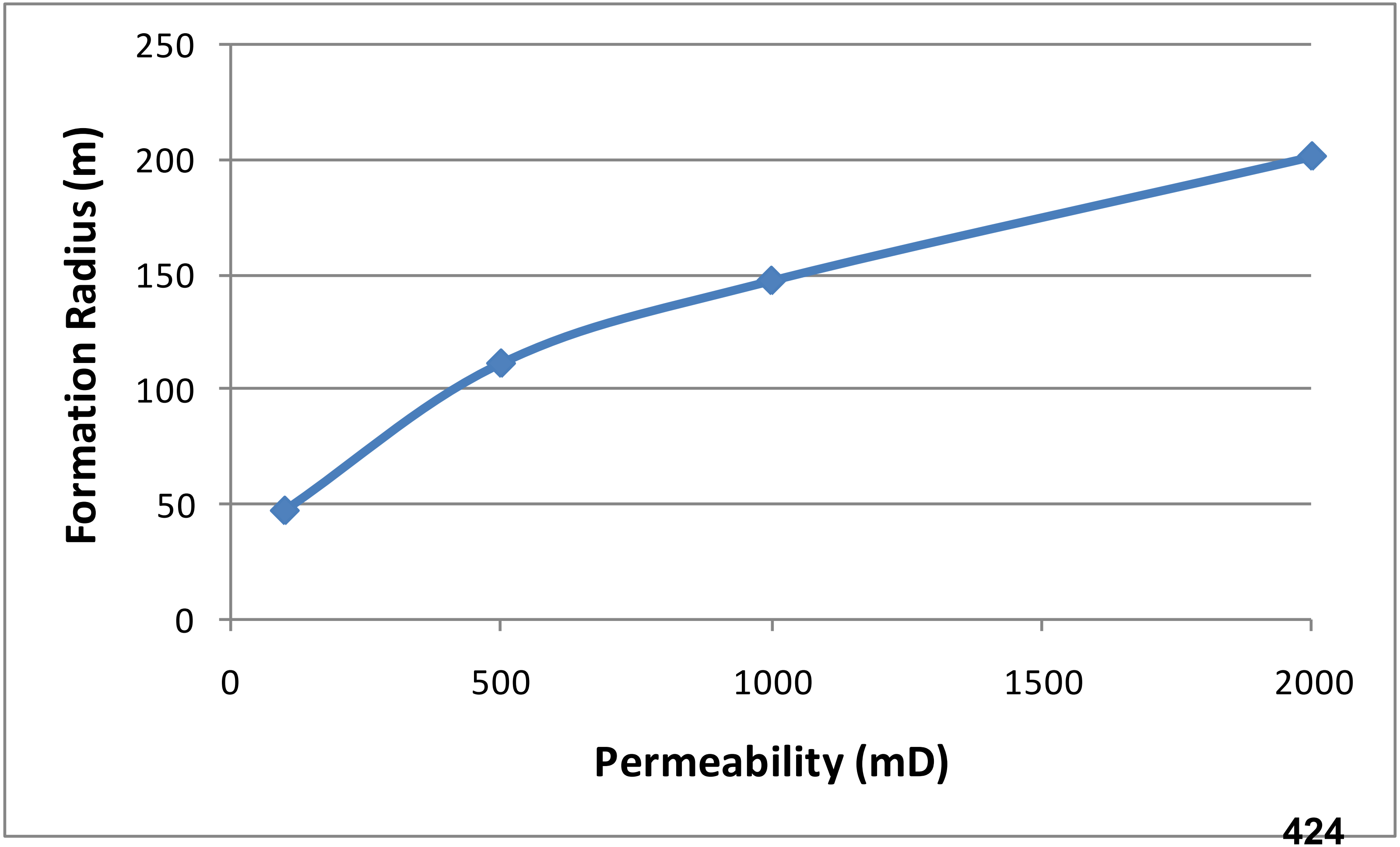
Typical Results (k = 500 mD, ϕ = 0.2)





Optimum Formation Radius = 111 m Based on P_{min}

Permeability Variation



Porosity Variation

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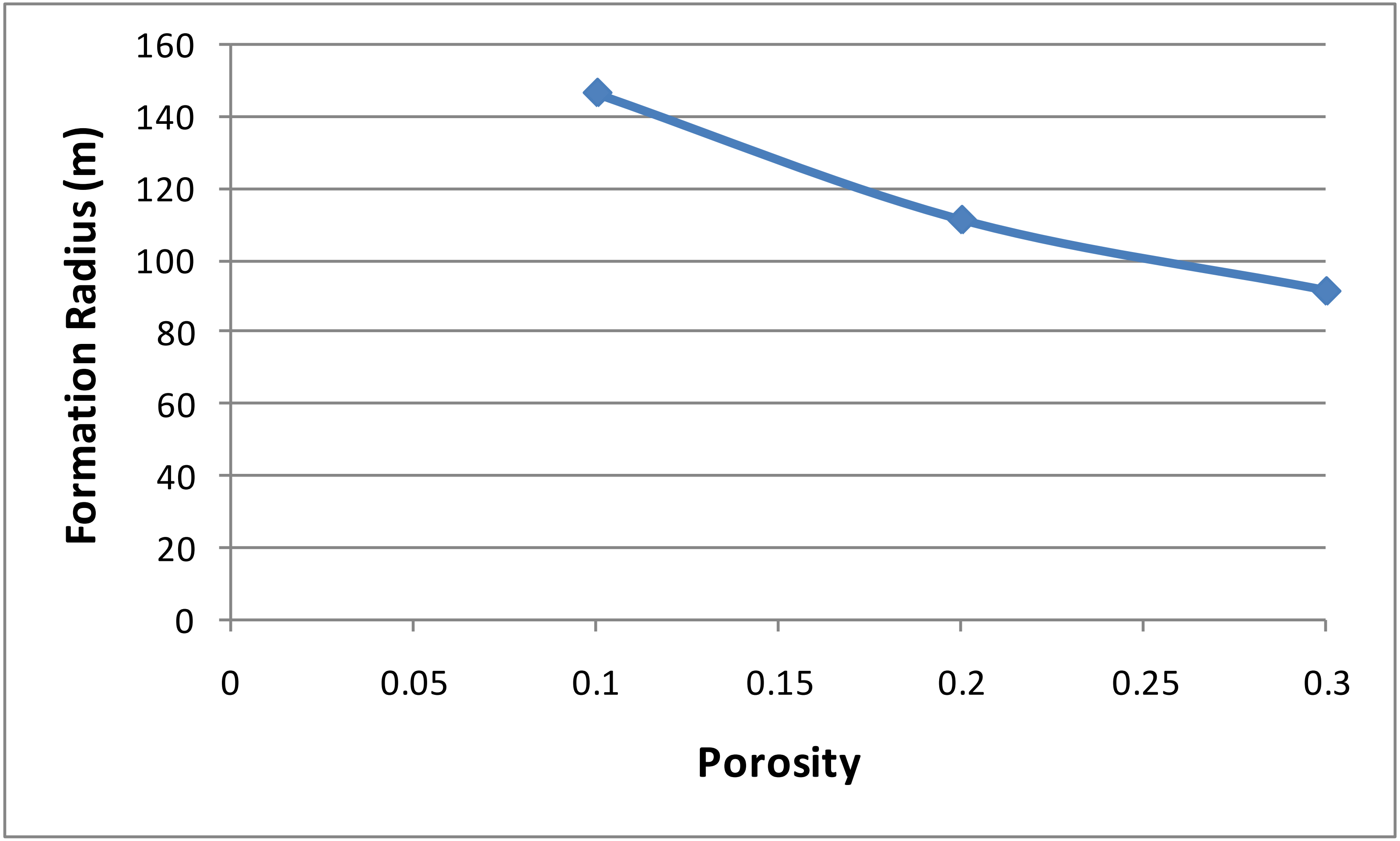
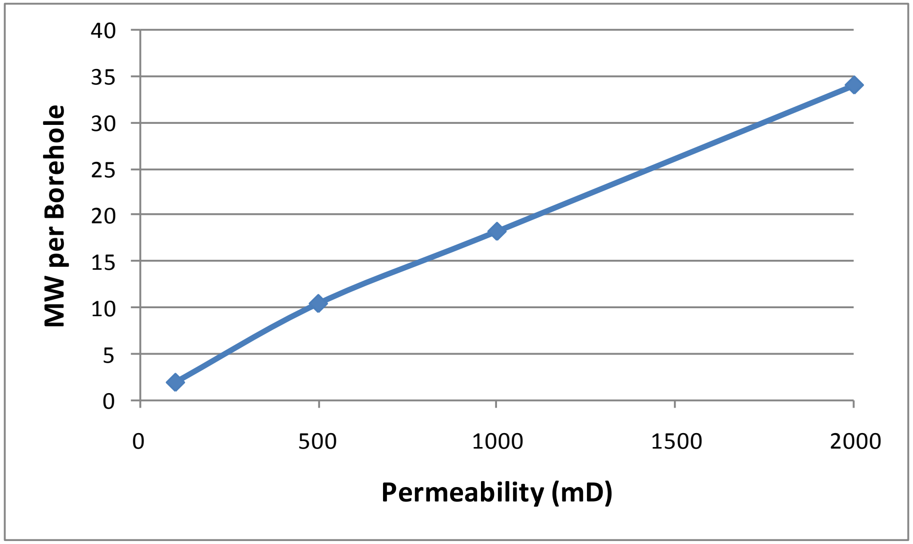
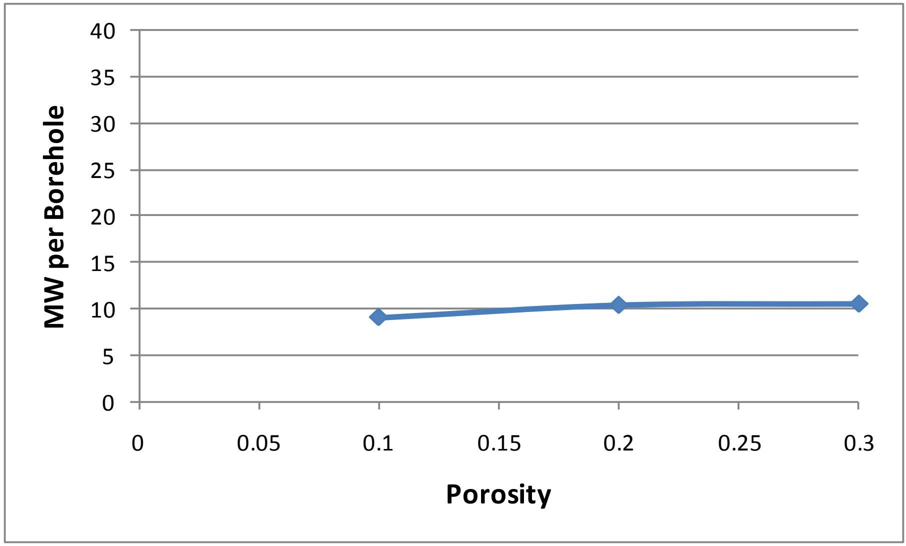


Permeability/Porosity vs. Power

Using Typical Turbine Parameters

Based on Iowa CAES Power Density (~5 MW/m^3)
Scaled by Formation Pressure (Succar, 2008)





Number of Boreholes vs Permeability & Porosity

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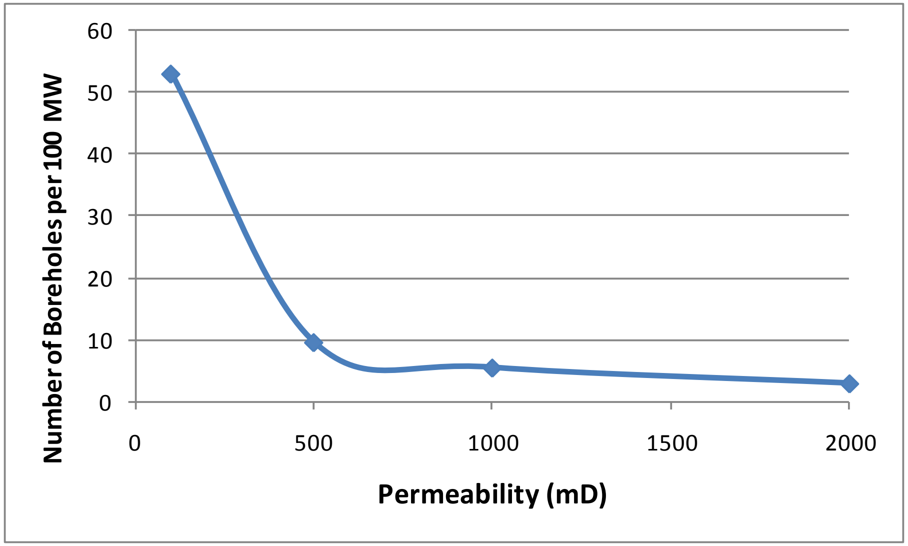
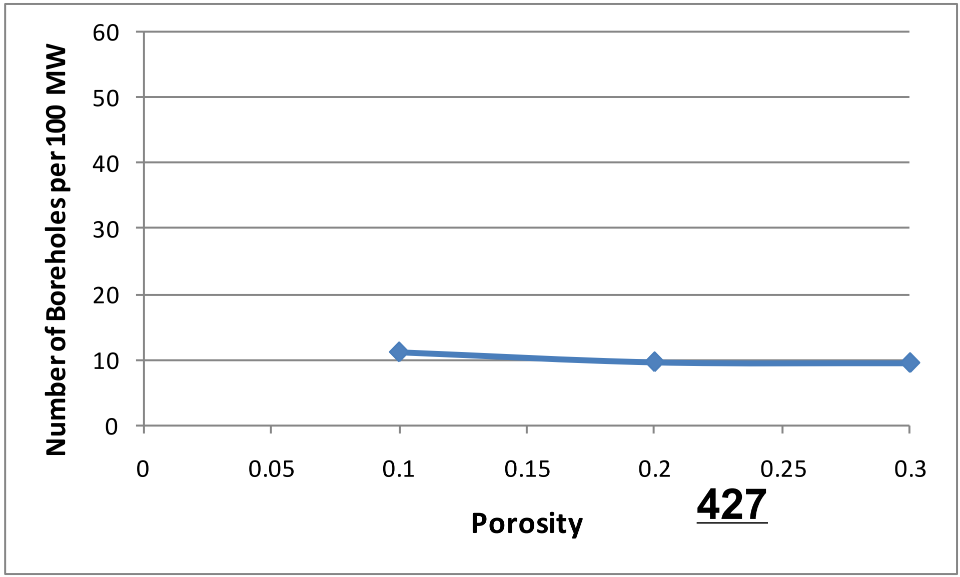




Conclusions

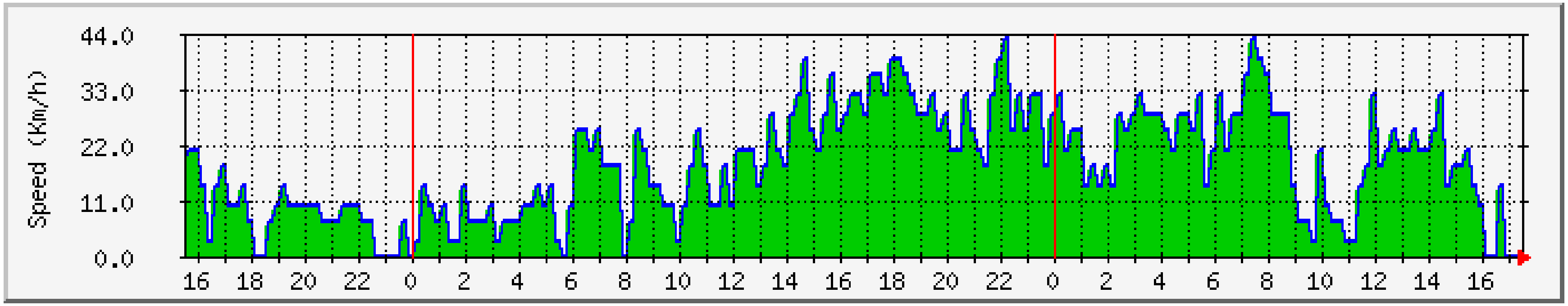
- Permeability Variation Much More Important then Porosity Variation
- Procedure Can Quantify Differences Between Various Sets of Formation Parameters
  - Borehole Spacing, Number of Boreholes
- Borehole Arrays Will Be Investigated in the Future

Background :
Experimental Deformation of Salt in Cyclic Loading

Geomechanics Research Department

SJ Bauer and ST Broome

Compressed air energy storage



Hourly fluctuations in wind speed could translate to frequent in pressurization/depressurizations of salt caverns

Background : Variable Resource

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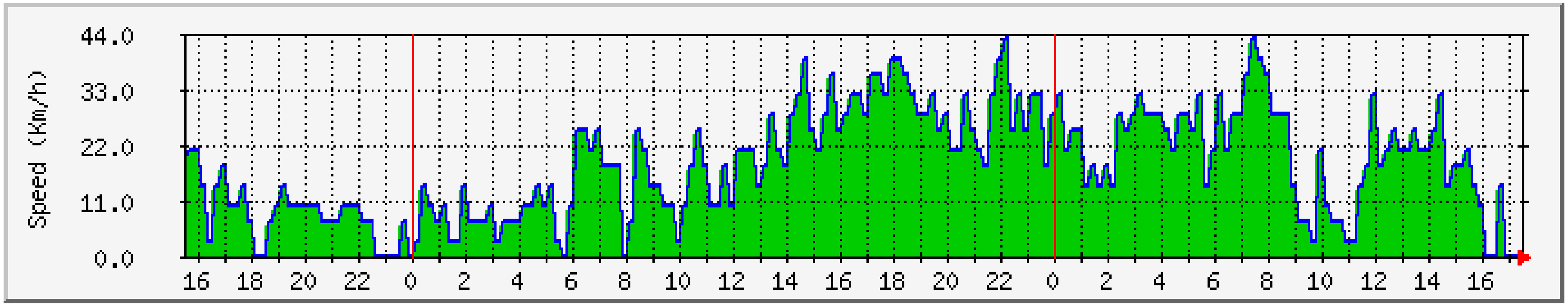
Compressed air energy storage



Hourly fluctuations in wind speed could translate to frequent in pressurization/depressurizations of underground formations

Dilatant behavior of salt determined from quasi-static tests and stress states for this study

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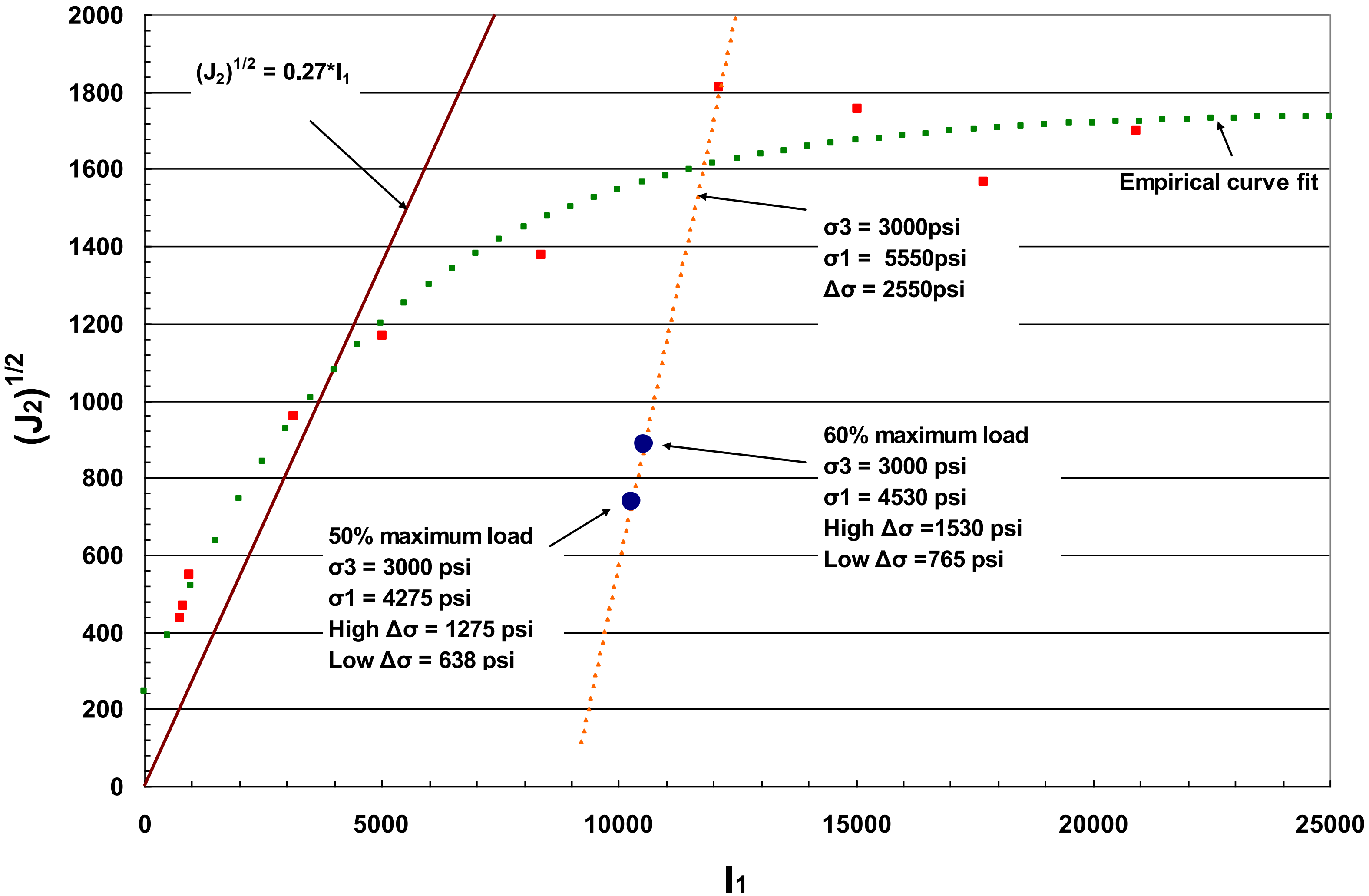

Test assembly

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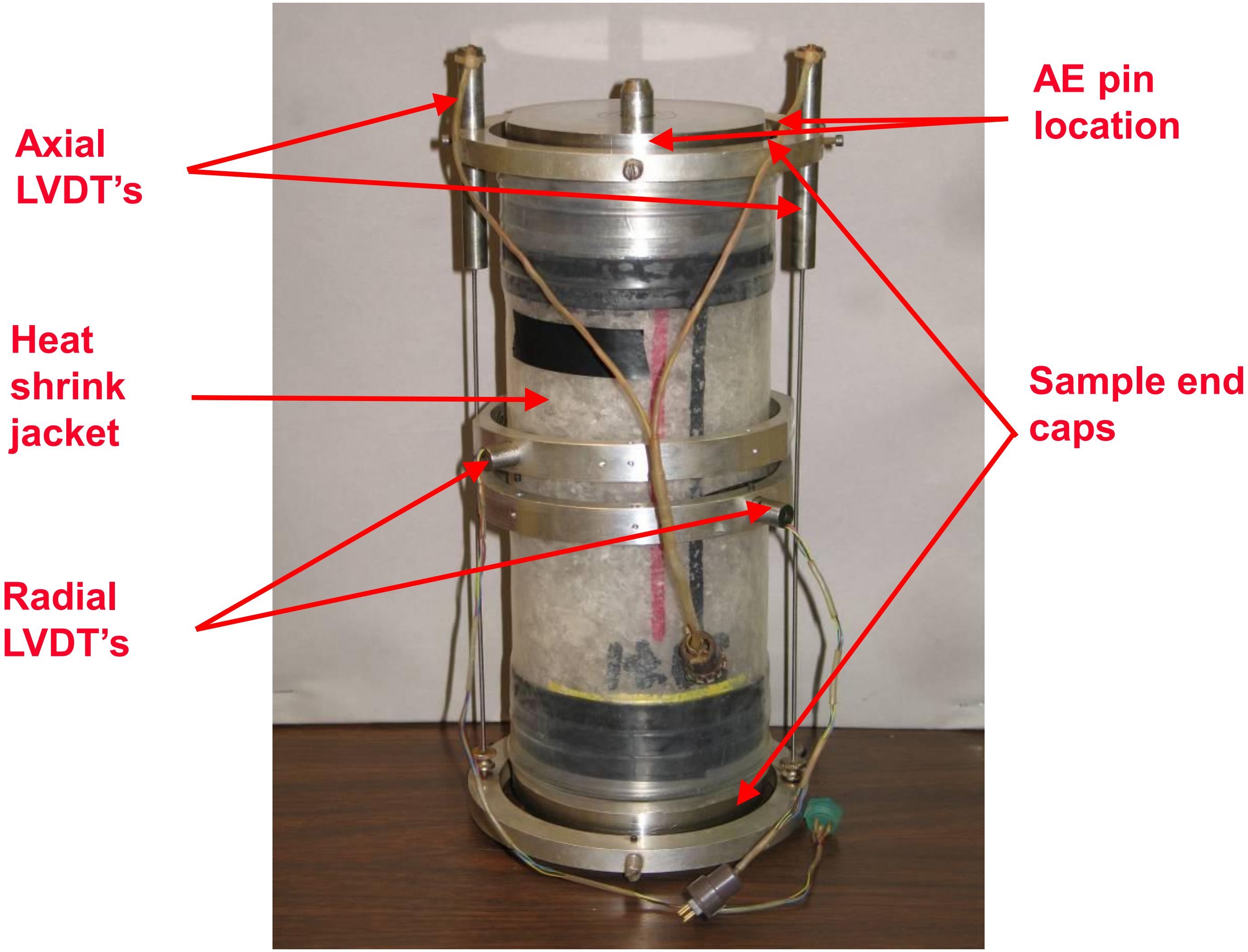
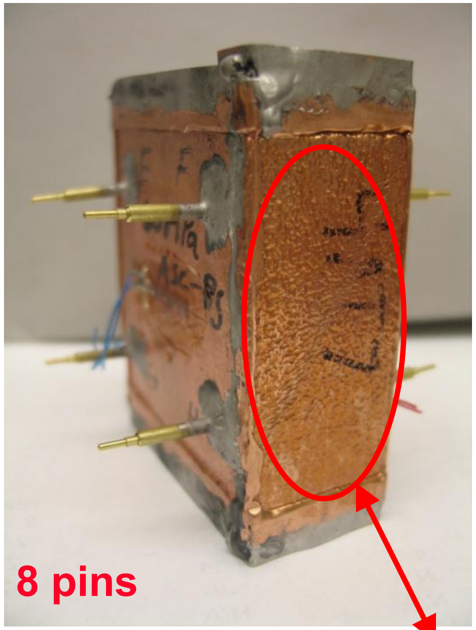
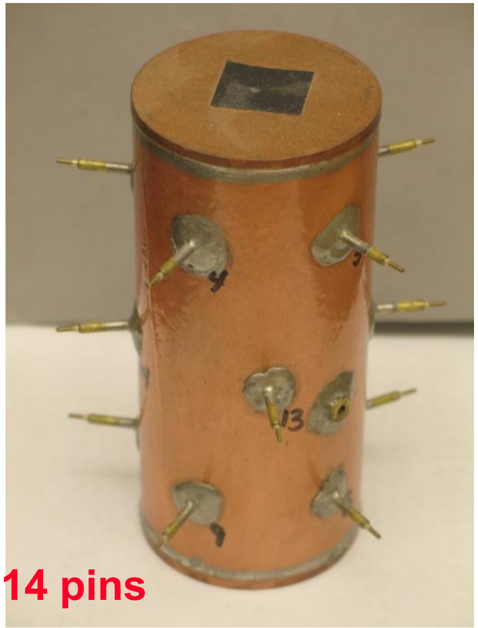


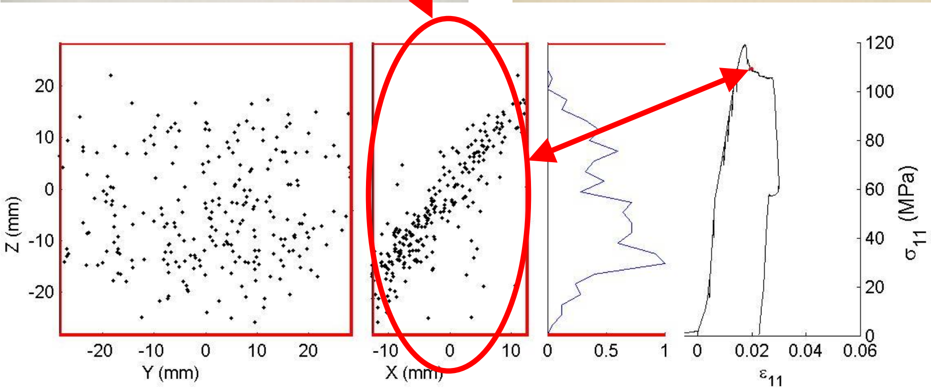
Acoustic Emissions System

Geomechanics Research Department

- **Sample rates up to 25 MHz**
- **Typically acquire 3000 samples/event**
- **Tailor a discriminator to only sample events of a given criteria**
- **60 dB amplifier**
- **Location of events is possible with many pins**







Differential stress versus axial strain, Test 3.

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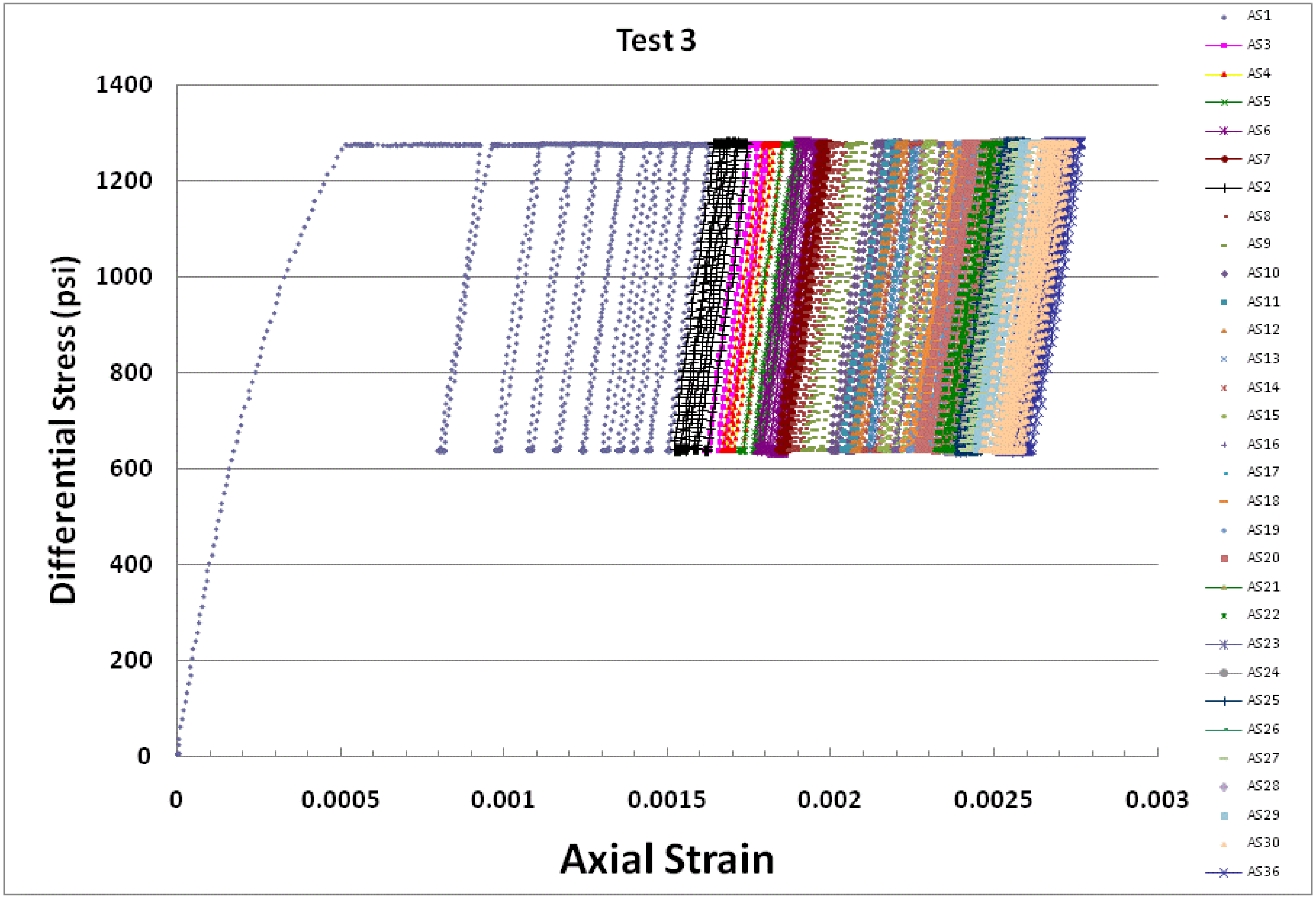

Test data

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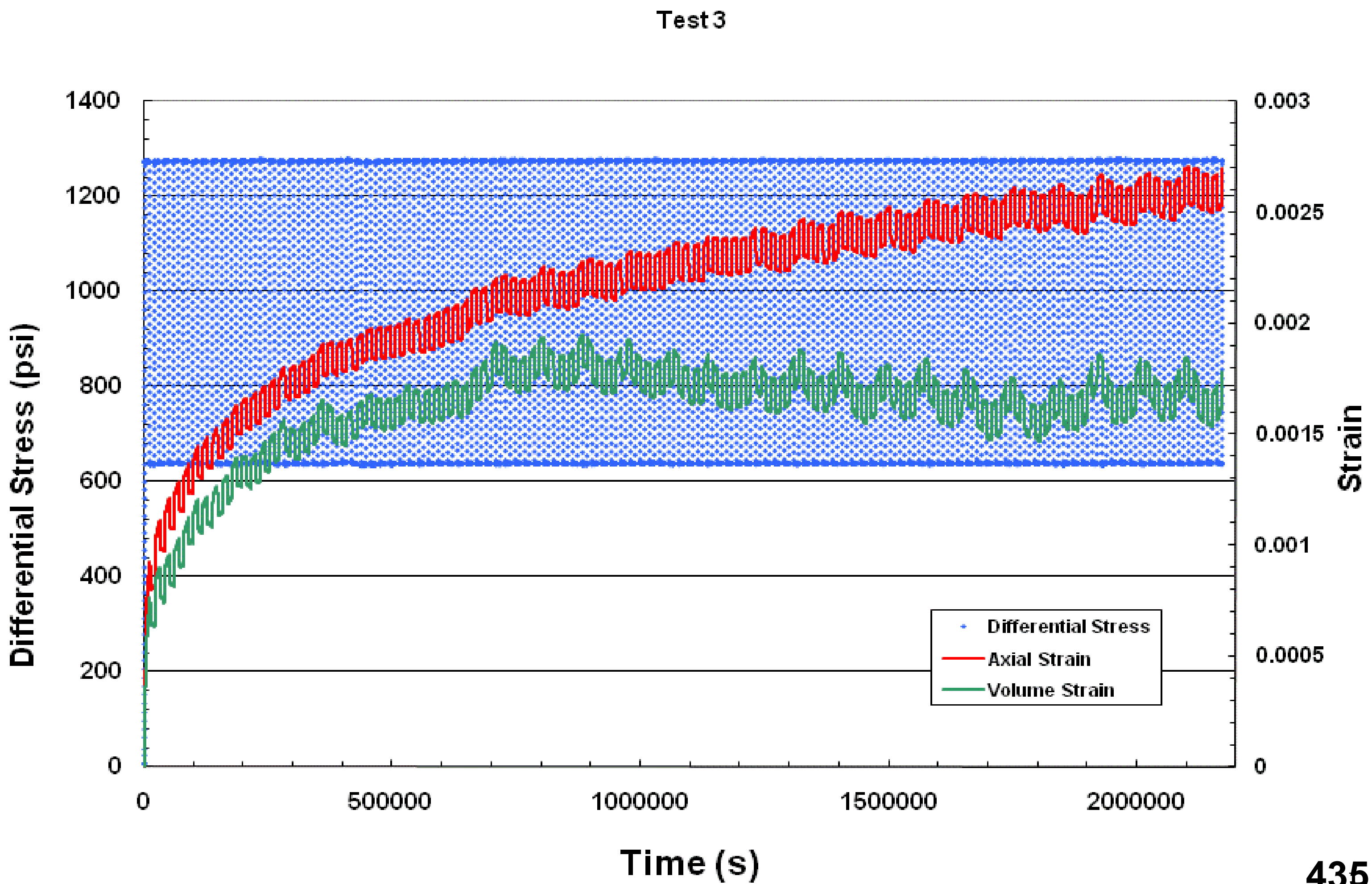
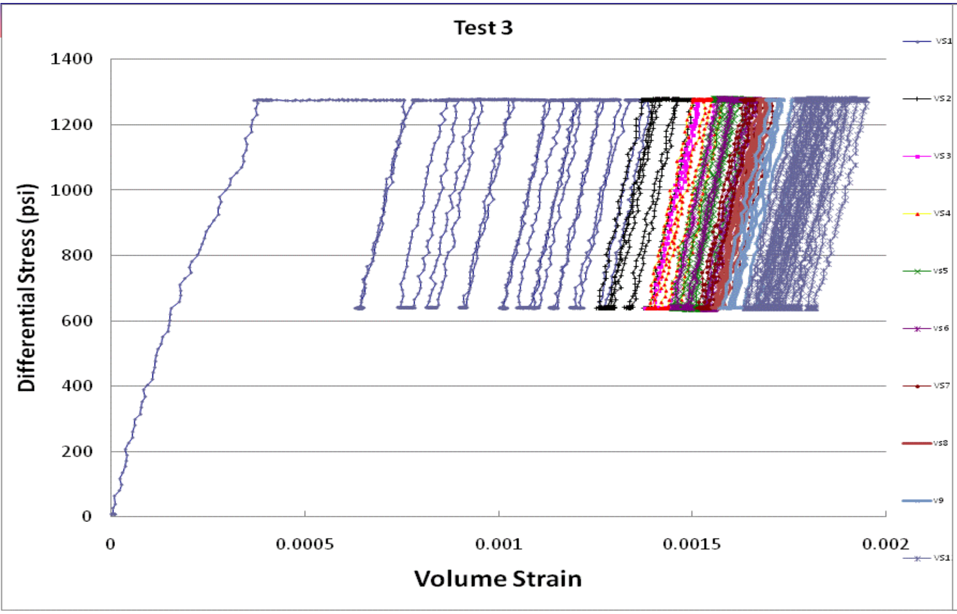
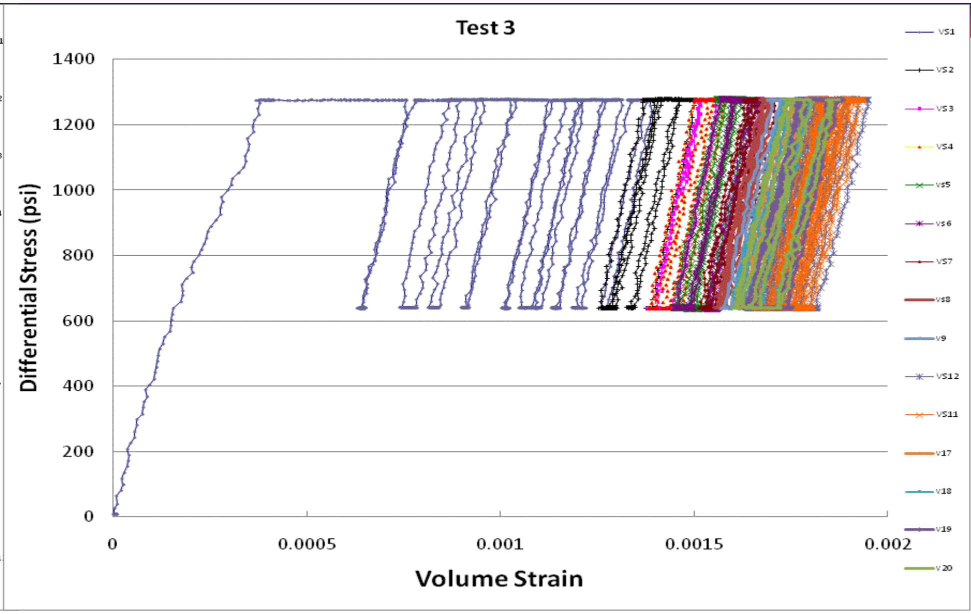
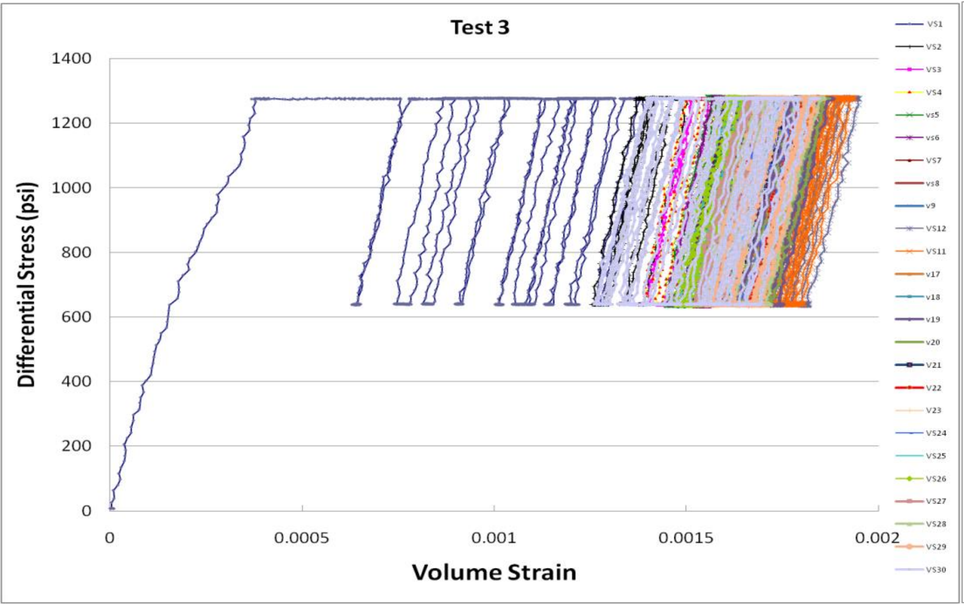
Differential stress, axial and volume strain versus time, Test 3.

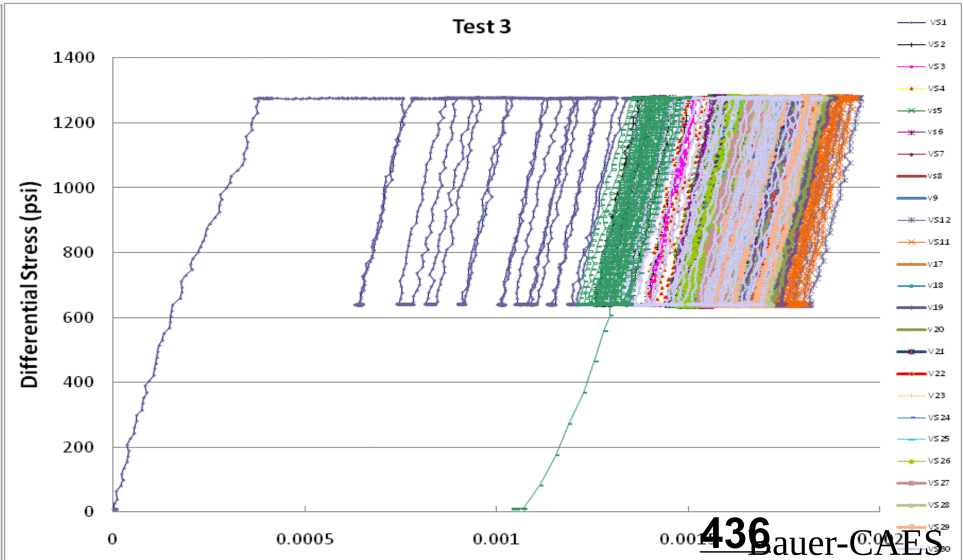


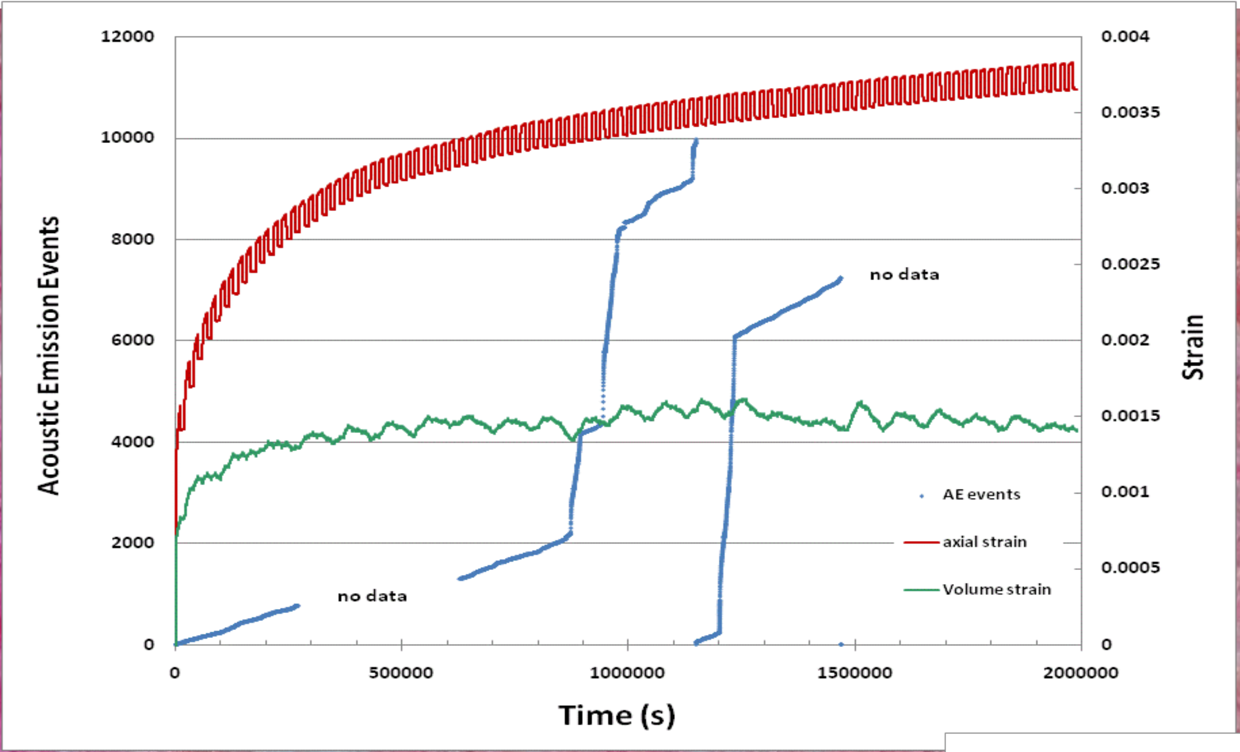
Differential stress versus volume strain, Test 3





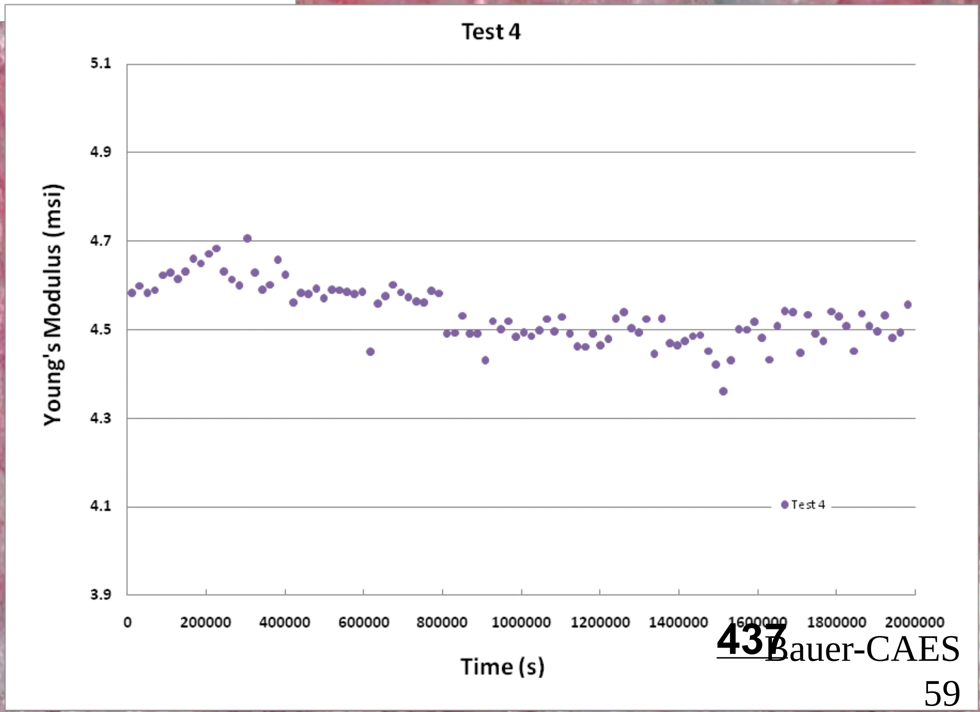






Acoustic emission events and strain versus test time.

Young's Modulus versus test time



Concluding Comments

- Preliminary cyclic tests completed on domal salt
- Test methods developed, some improvements needed
- Change in volume strain observed
- Young's Modulus changes observed
- Acoustic Emissions detected
- Cracks observed in thick sections (not yet quantified)
- Results consistent with previous work
- Implication that cyclic loading caused cracking at low differential stresses

Summary/Conclusions/Risk

1- Sandstone in a reducing environment could effect biologic and mineralogic changes that could lead to changes in porosity and permeability

2-Recommendations given for mitigation of potential use of a natural gas reservoir for CAES

3- Permeability Variation Much More Important then Porosity Variation;
Procedure Can help Determine Borehole Spacing, Number of Boreholes (Co$t)

4-Salt strength observed to degrade in cyclic loading

Supporting Publications

1-"*Potential Effects of Compressed Air Energy Storage on Microbiology, Geochemistry, and Hydraulic Properties of Porous Aquifer Reservoirs*", SAND2010-4721 M. Kirk, S. Altman, and S. Bauer

2-"*Potential subsurface environmental impact of compressed air energy storage in porous bedrock aquifers*" J. Env. Sci. & Tech. (in Prep, Kirk et al)

3- *"Considerations for Detonation Potential for CAES in a Depleted Natural Gas Reservoir"* White paper; M. Grubelich

4- "*Borehole and Formation Analyses in Reservoirs to Support CAES Development*" SAND report, S.Webb

5- "*Experimental Deformation of Salt in Cyclic Loading*": SAND2010-1805 SJ Bauer & ST Broome , Solution Mining Research Institute 4/2010


thanks
Questions?

18. On the Use of Large-scale Multi-physics Modeling to Address Potential Vulnerabilities Associated with Air/Gas Mixtures in CAES

Nick Simos, *Brookhaven National Laboratory*

We present an overview of modeling for addressing the CAES vulnerability in natural gas/air systems and discuss the results of complex simulations of extreme scenarios in CAES systems. By relying on advanced capabilities in analyzing large-scale complex systems which involve gas mixtures enclosed in a multitude or rock formations and the ability to simulate explosion- and/or detonation-type events through the use of multi-physics formulation, the resilience of the overall CAES system to intense but extremely rare events will be assessed. In particular, through a detailed representation of the air/gas mixture volume and the surrounding rock in the finite element space and the use of arbitrary Lagrangian-Eulerian formulation which enables the mechanics at their interface different scenarios are analyzed to assess the consequences on the cavern walls. Given the great variability in rock properties that exist between different sites of CAES systems, the rock failure potential as a function of the type is assessed. Realistic scenarios which do not involve the potential combustion or even explosion within the gas/air mixture such as the sudden drop of pressure in the reservoir as a result of uncontrolled or unplanned release, which will constitute a dynamic event, are also being evaluated.

Dr. Simos joined the Nuclear Energy Department at Brookhaven National Laboratory in 1989 and promoted to scientist in 1993 studying seismic safety of nuclear installations. In 1996 he moved to Los Alamos and the accelerator for tritium production. In 1999 he joined the Spallation Neutron Source project in charge of beam collimation. He is a member of the Neutrino Factory collaboration and the Long Baseline Neutrino Experiment leading the experimental effort on high-power accelerator targets. He has been principal investigator on vulnerability of critical infrastructure for DHS. He currently holds a joint appointment with the Photon Science Directorate.

On the Use of Large-scale Multi-physics Modeling to Address Potential Vulnerabilities Associated with Air/Gas Mixtures in CAES

N. Simos, Ph.D., P.E

Nuclear Science Dept. & Photon Science Directorate
Brookhaven National Laboratory

MOTIVATION

Use of depleted natural gas reservoirs in CAES (aquifers or caverns)

Air/gas mixtures and potential consequences
Flammability/explosion ➔ above ground or within air bubble

Desire to operate at higher pressures than "discovery pressure"
Rapid withdrawal ➔ consequences on host rock

While large-scale events with serious consequences are highly unlikely, it is desired to address the complex problem and deduce operational limitations

Goal is to formulate a process based on state of the art of multi-physics simulations of realistic/anticipated scenarios that will be able to establish operating thresholds for site-specific field conditions and desired operating parameters in CAES

What's at Issue

Concerns identified in past CAES-related scoping studies:

Surface explosion in gas/air mixtures (particularly in 1st full air bubble injection) explosion in air-bubble very remote

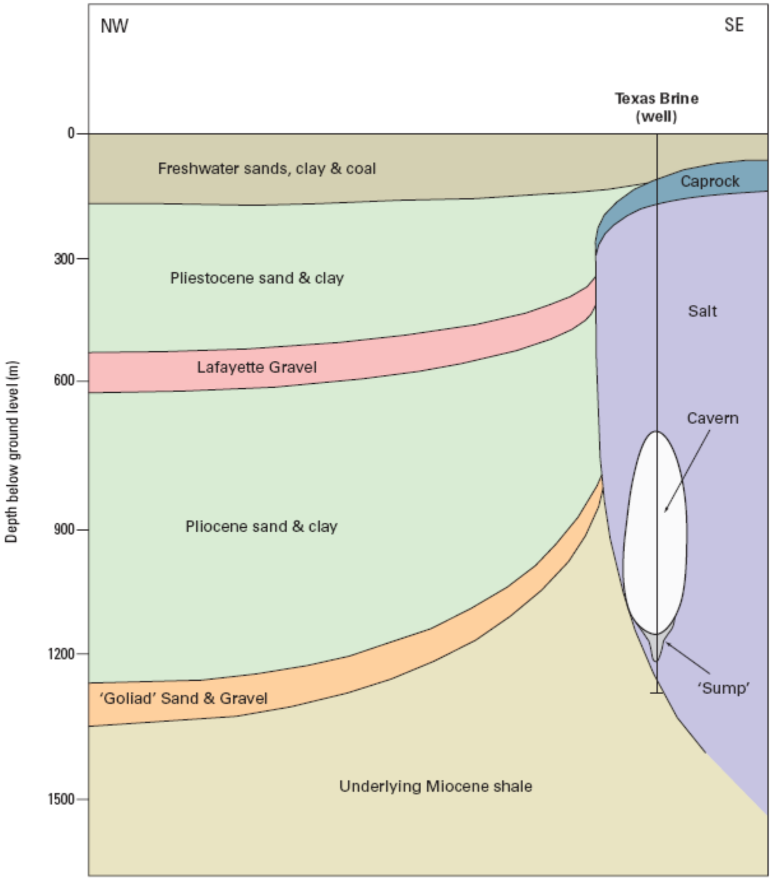
(what do we know from other types of storage)

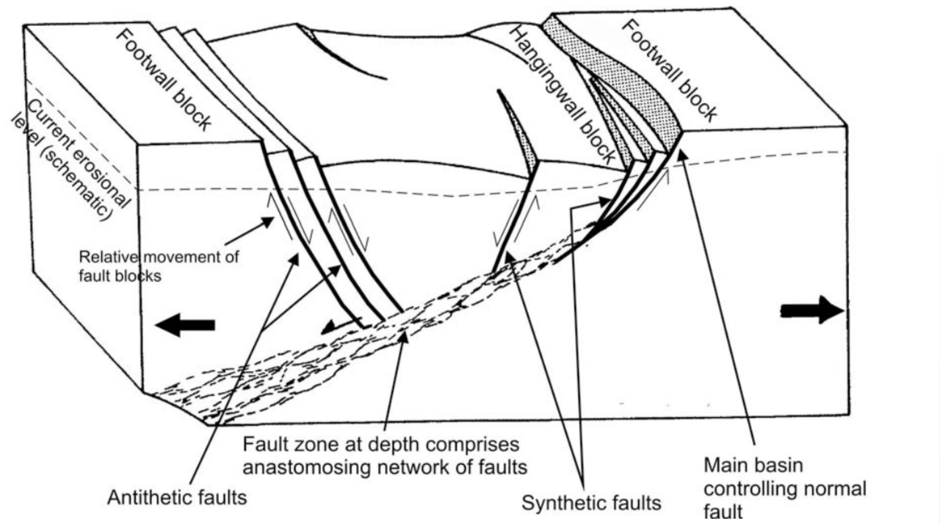
Sudden depressurization and the initiation of transient in the host rock possibly aiding gas/air mixing

Higher operating CAES pressures to make CAES more economical

desire to operate beyond the original host rock pressures

(above coupled with need to be closer to population centers)





What can go wrong?
Inadequate site characterization,
Higher operating pressures than rock has experienced,
creep underestimation,
presence of anomalous zones

Use of Multi-Physics/ALE Formulation Vulnerability Assessment

Need to solve the problem at the appropriate scale

Multitude of physics/constitutive relations

host salt bed (non-linear, creep)

porous, saturated strata/permeability and fluid flow

Fluid (gas) and rock interaction (pressure boundary interface, fluid flow across interface)

Combustion/explosion of air/gas mixtures (surface and/or air bubble) and shock generation

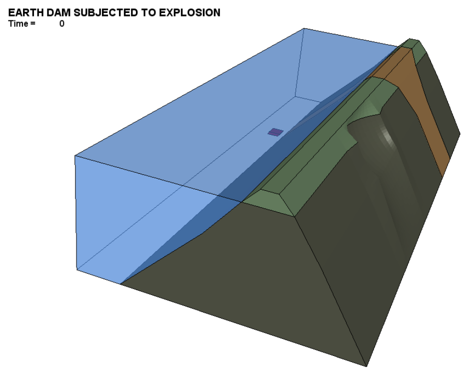
Dynamic response of the host rock due to events leading to rapid depressurization

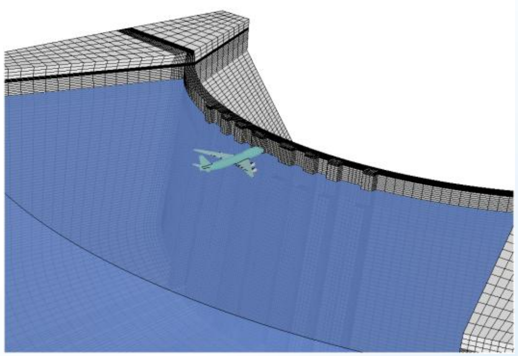
To address these interconnected issues the multi-physics, non-linear code LS-DYNA and its Arbitrary Lagrangian-Eulerian (ALE) formulation is used

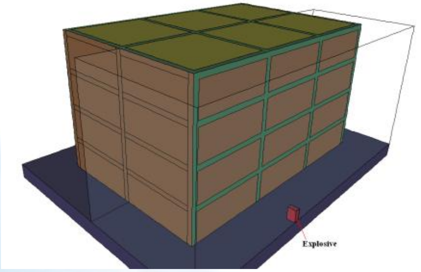
Vulnerability Studies - Background

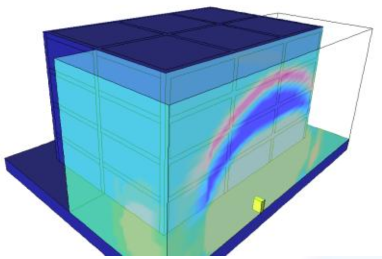
Past studies involving vulnerability of infrastructure

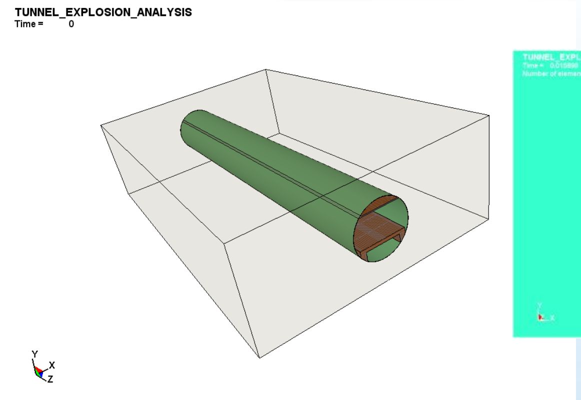
- WIPP Facility and the study of long term creep in salt formation
- DHS/NATO/US NRC studies on installations, dams and other critical infrastructure

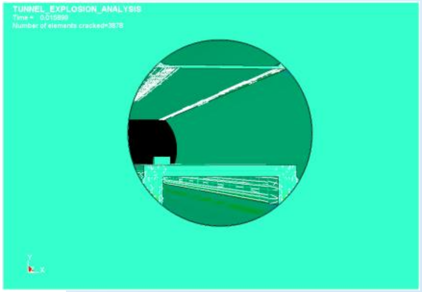












Applying Multi-Physics/ALE Formulation to CAES

Large Scale 3-D Model that captures

Behavior of salt
Behavior of rock (which can fracture)
Treatment of gases (equation of state, flow, and coupling with the multi rock layers)

Fluid (gas) and rock interaction

Injection and flow of compressed air into aquifer strata (or rock fluid displacement)

Darcy's Law and fluid flow in porous medium $\boldsymbol{q} = \frac{-\boldsymbol{\kappa}}{\mu}(\nabla P - \rho g \hat{\mathbf{e}}_z) \quad v = \frac{q}{\phi}$

q=Darcy discharge flux, φ=porosity, υ=pore velocity

Biot's dynamic equations of induced waves in porous media

Theory of propagation of elastic waves in fluid-saturated porous solid.
Low-frequency (1) and high-frequency (2) range.

$$\frac{\vartheta\tau_{xx}}{\vartheta x} + \frac{\vartheta\tau_{xy}}{\vartheta y} = \varrho\ddot{u}_x + \varrho_f\ddot{w}_x \qquad \frac{\vartheta\tau_{yx}}{\vartheta x} + \frac{\vartheta\tau_{yy}}{\vartheta y} = \varrho\ddot{u}_y + \varrho_f\ddot{w}_y$$

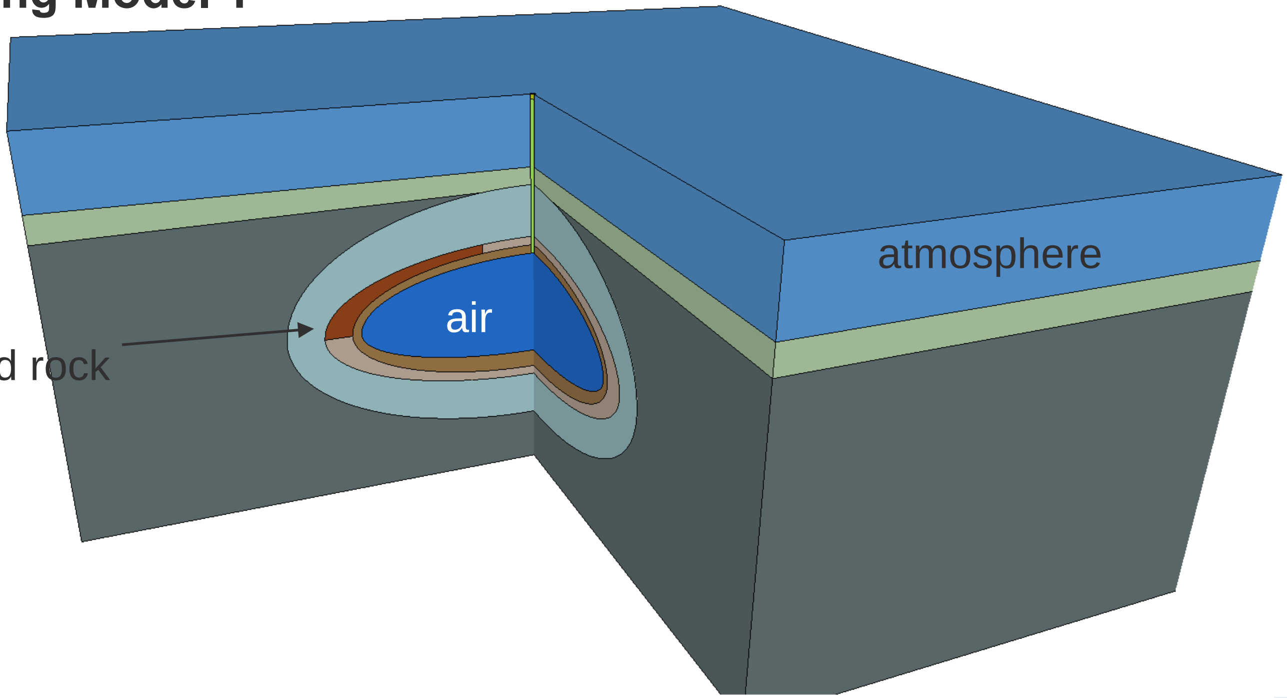
$$-\frac{\vartheta p_f}{\vartheta x} = \varrho_f\ddot{u}_x + \frac{1}{f}\varrho_f\ddot{w}_x + \frac{\eta}{k}\dot{w}_x \qquad -\frac{\vartheta p_f}{\vartheta y} = \varrho_f\ddot{u}_y + \frac{1}{f}\varrho_f\ddot{w}_y + \frac{\eta}{k}\dot{w}_y$$

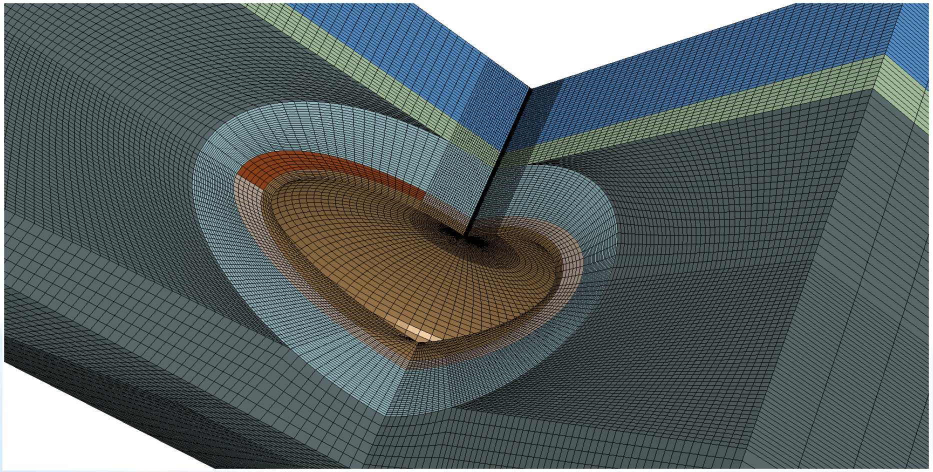
$$p_f = -\alpha M\left(e_{xx} + e_{yy}\right) - M\left(\frac{\vartheta w_x}{\vartheta x} + \frac{\vartheta w_y}{\vartheta y}\right)$$

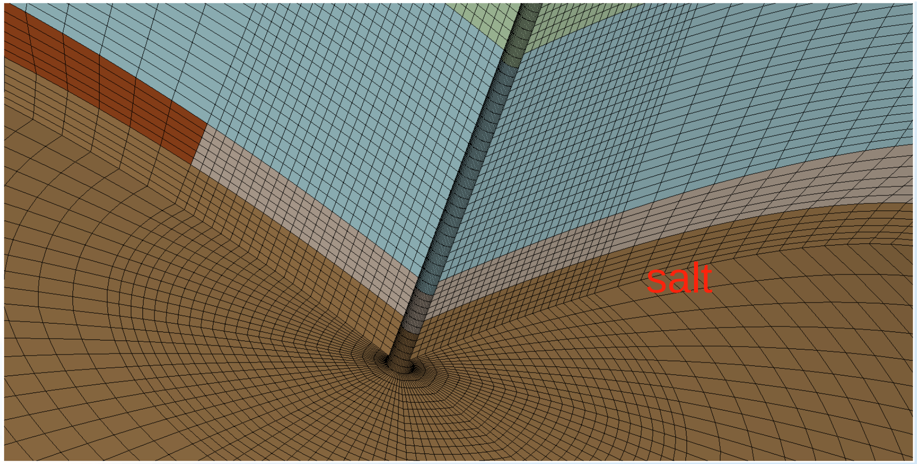
On-going work to formulate a 3-D porous material model based on a 2-D Biot equations formulation for porous media

CAES Working Model 1

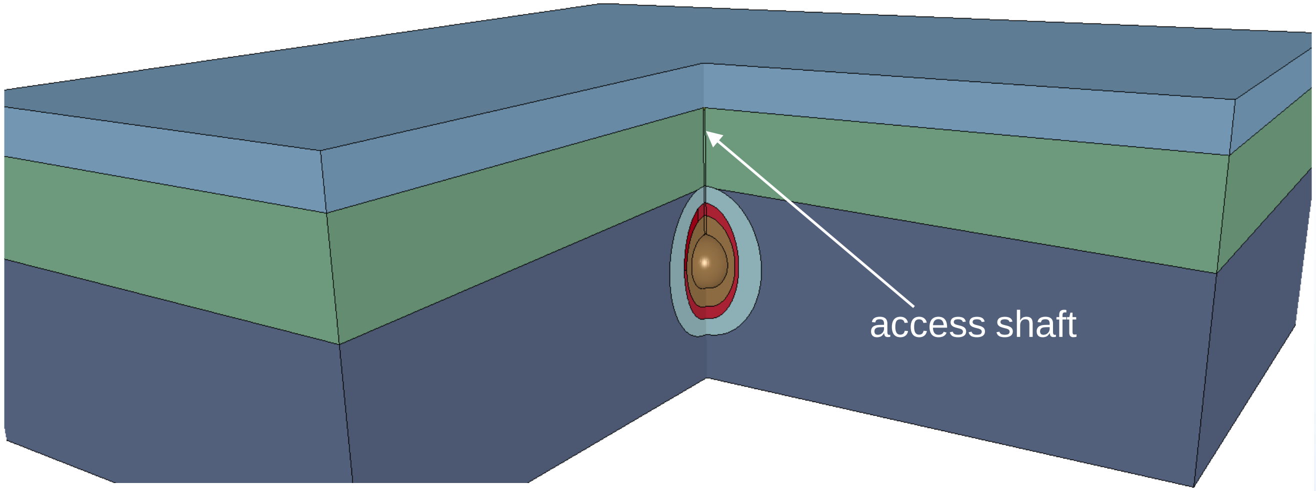
1km x 1km surface space
Cavern Width = 400m
Cavern Height = 130 m

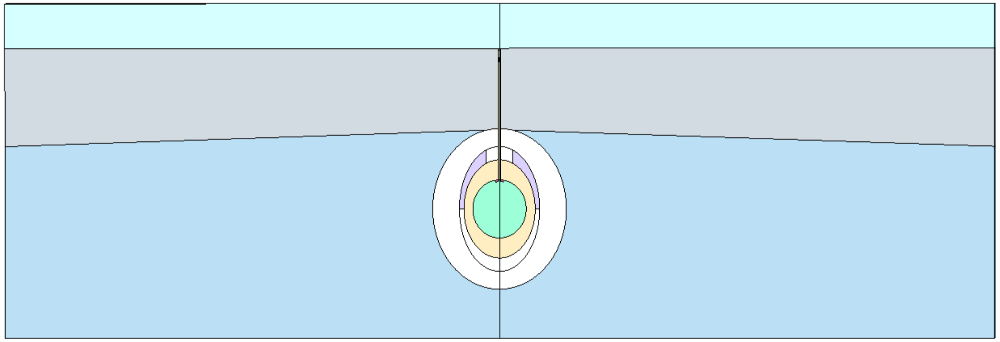


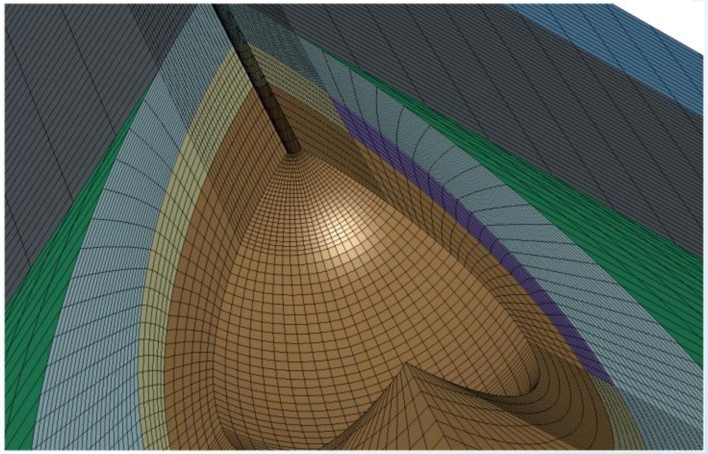




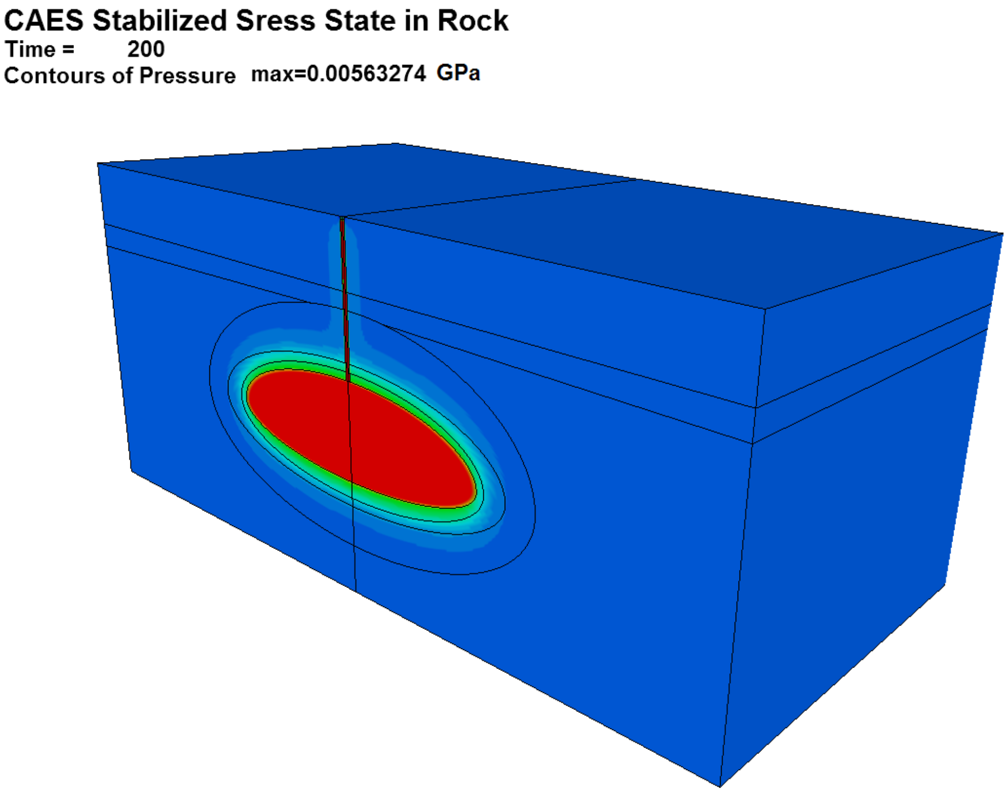
CAES Vulnerability Working Model 2

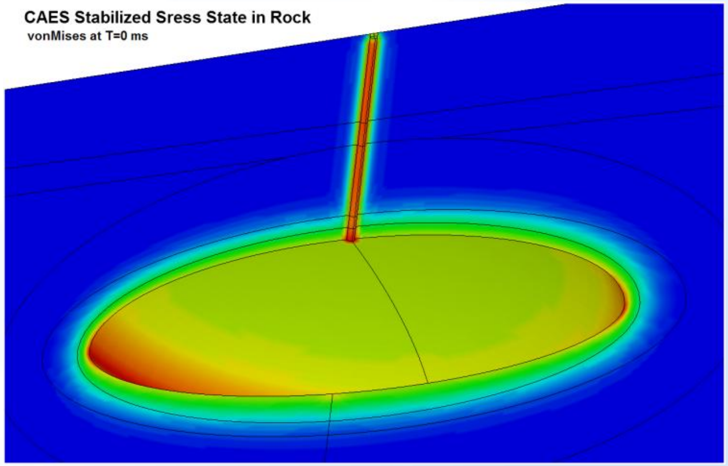






Initial Rock Stress – Site at Equilibrium with Cavern Pressure





Vulnerability Assessment – Formulated Problems

Surface Explosions of Air/Gas Mixtures and Implications on Safety Valves (valve breach leading to uncontrolled de-pressurization)

Explosions within the air bubble (even though remote possibility) and potential of surrounding rock failure and surface subsidence

Impact of rapid depressurization with interfaces of low/high pressures at depth and at the surface

Air injection process (not an obvious vulnerability problem)

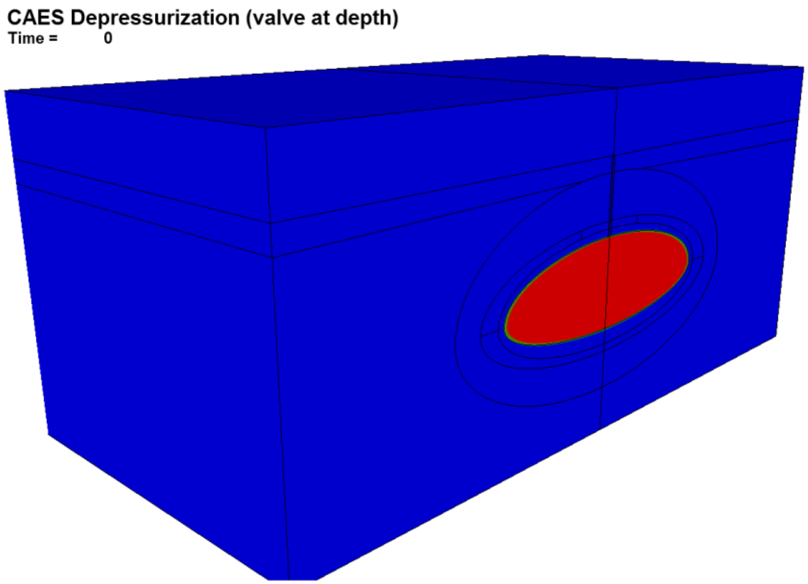
- aquifer (flow and pressure accumulation within the porous rock at depth
- cavern

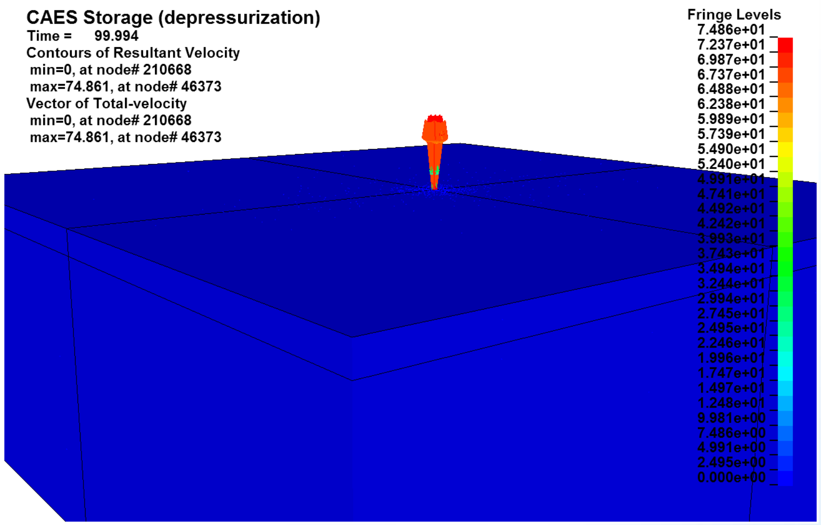
Presented are example cases (not reflecting an actual CAES configuration) used to explore the potential of the ALE formulation in addressing vulnerability scenarios associated with CAES

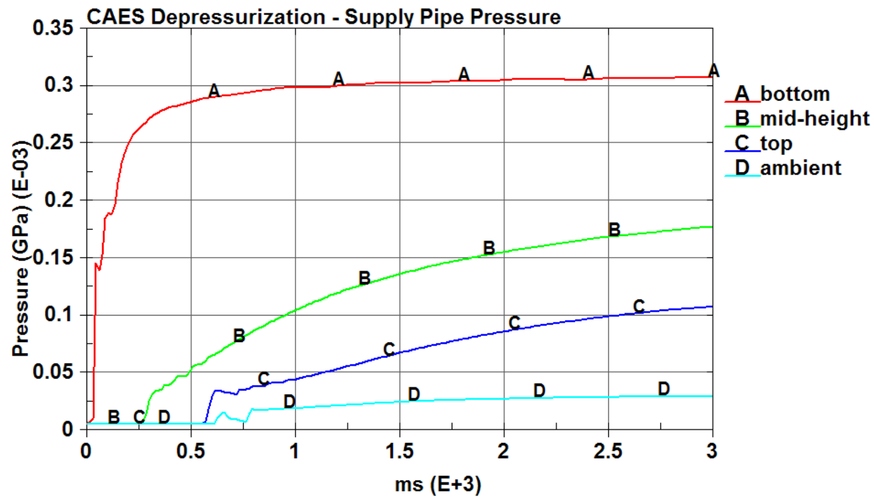
Rapid Depressurization (withdrawal) Scenario

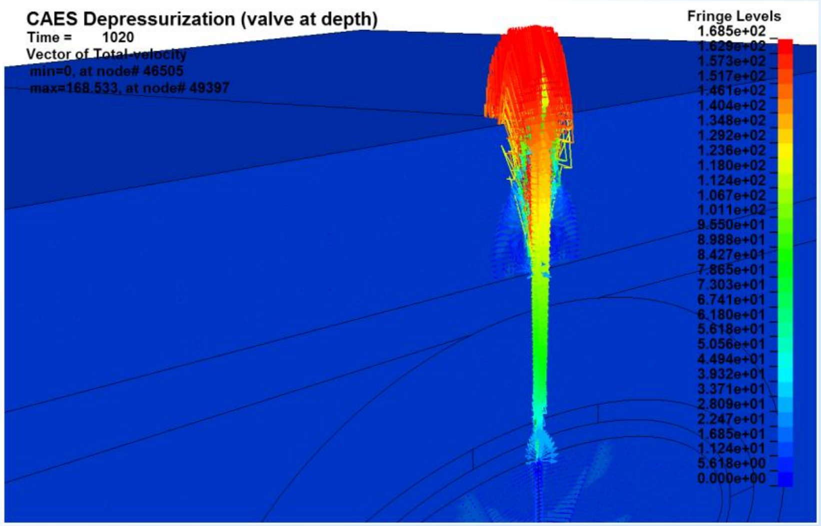
i. high/low pressure interface at depth
ii. Interface at top

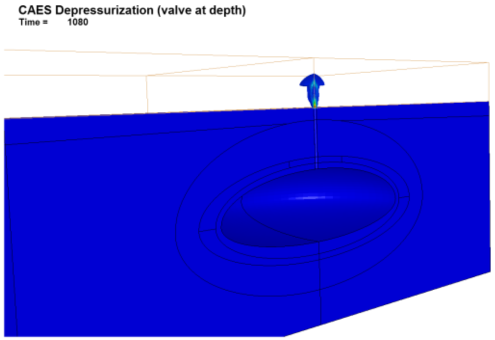
High/low pressure interface at depth: Studies for up to 110 bar compressed air pressure in cavern

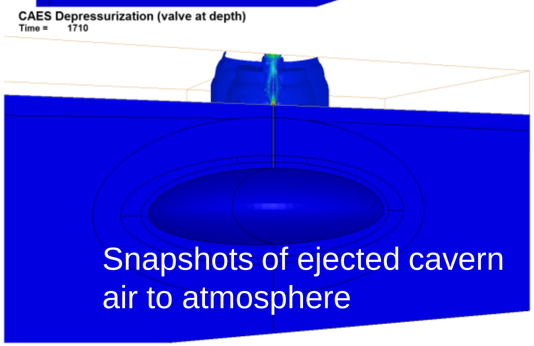


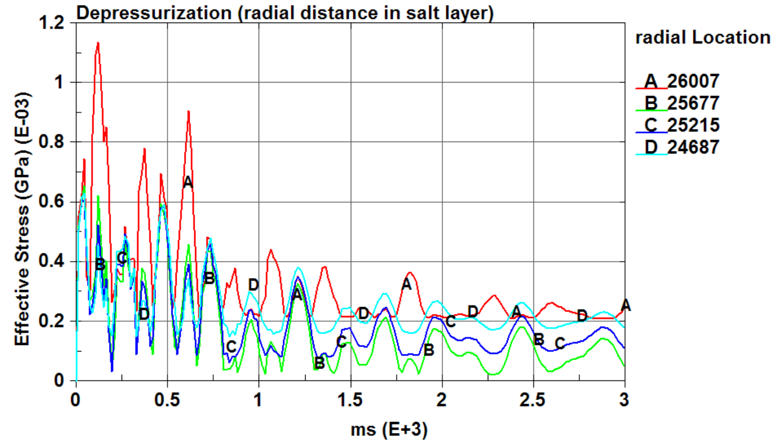


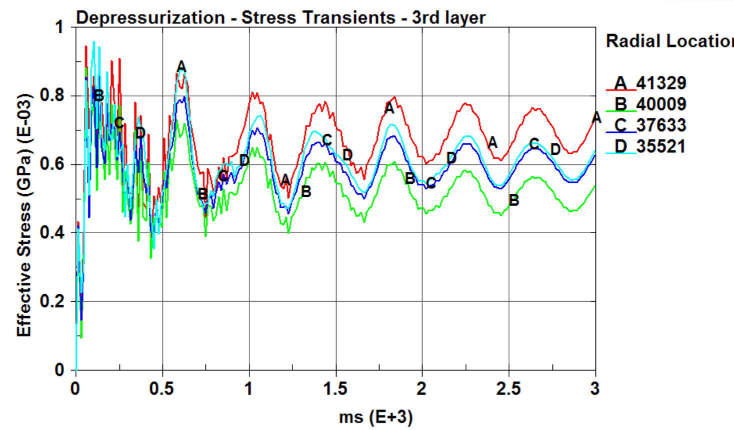


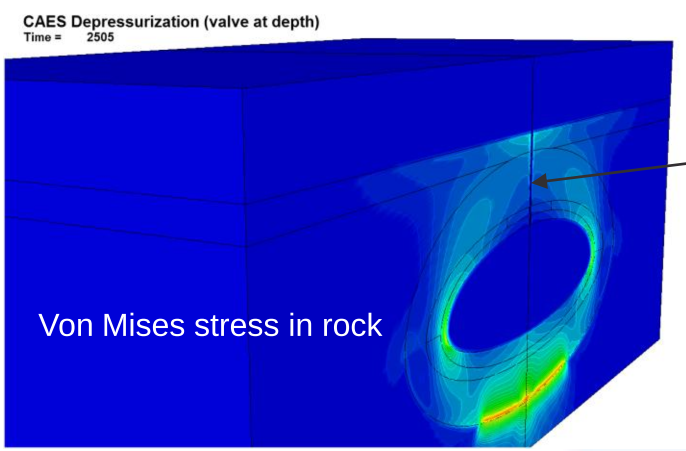


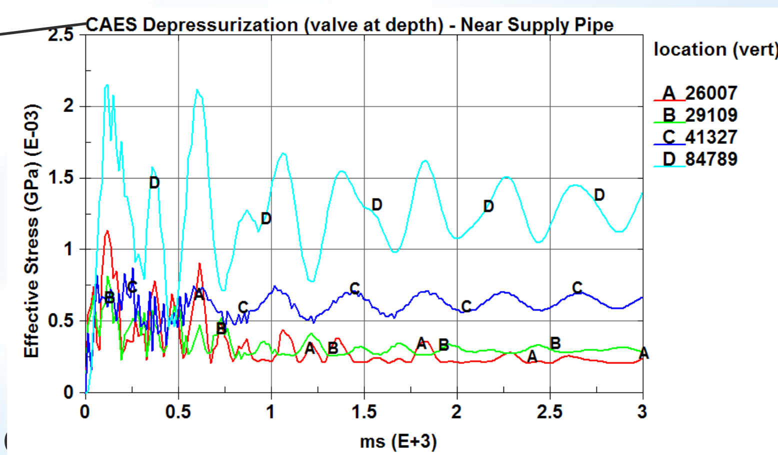

CAES Depressurization (valve at depth)
Time = 1080


CAES Depressurization (valve at depth)
Time = 1710
Snapshots of ejected cavern air to atmosphere

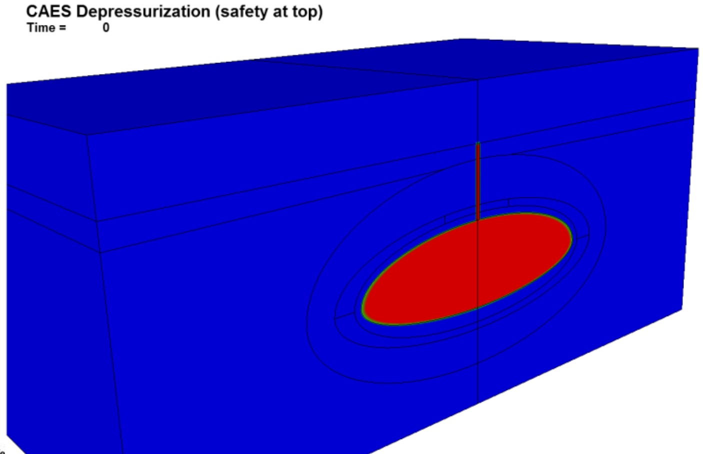

Depressurization (radial distance in salt layer)
Effective Stress (GPa) (E-03)
ms (E+3)
radial Location
A 26007
B 25677
C 25215
D 24687
0
0.2
0.4
0.6
0.8
1
1.2
0
0.5
1
1.5
2
2.5
3

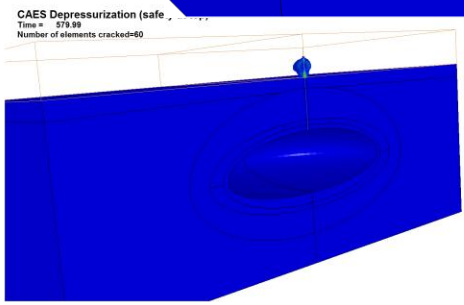

Depressurization - Stress Transients - 3rd layer
Effective Stress (GPa) (E-03)
ms (E+3)
Radial Location
A 41329
B 40009
C 37633
D 35521
0
0.2
0.4
0.6
0.8
1
0
0.5
1
1.5
2
2.5
3

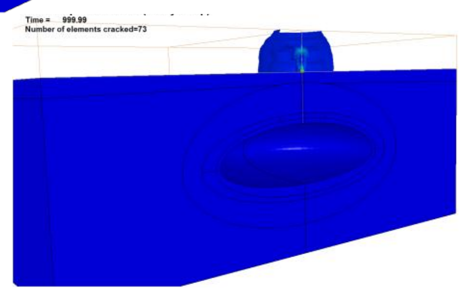

CAES Depressurization (valve at depth)
Time = 2505
Von Mises stress in rock

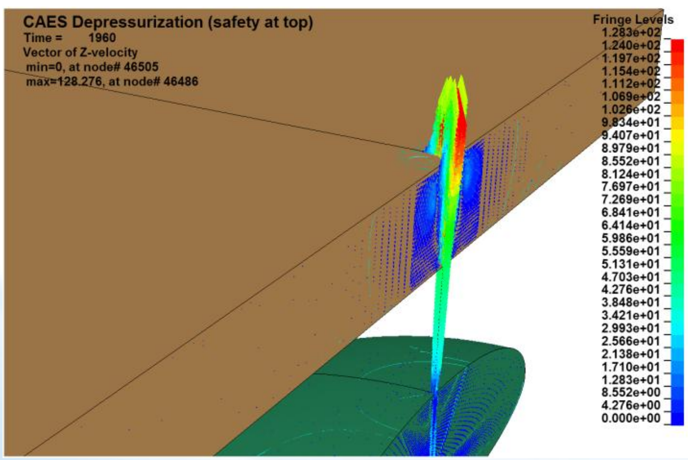

CAES Depressurization (valve at depth) - Near Supply Pipe
Effective Stress (GPa) (E-03)
ms (E+3)
location (vert)
A 26007
B 29109
C 41327
D 84789
0
0.5
1
1.5
2
2.5
0
0.5
1
1.5
2
2.5
3

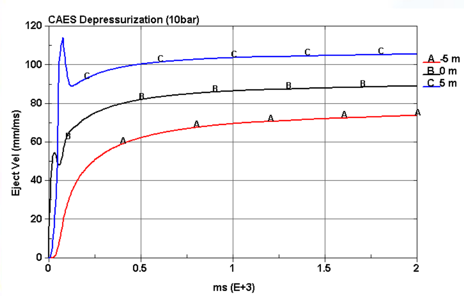
Rapid Depressurization Scenario (Safety at ground level)

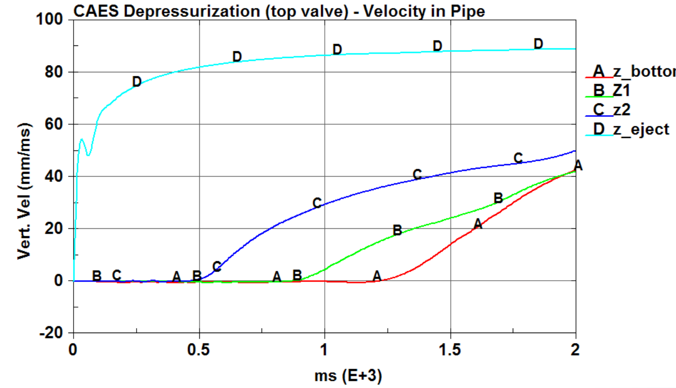


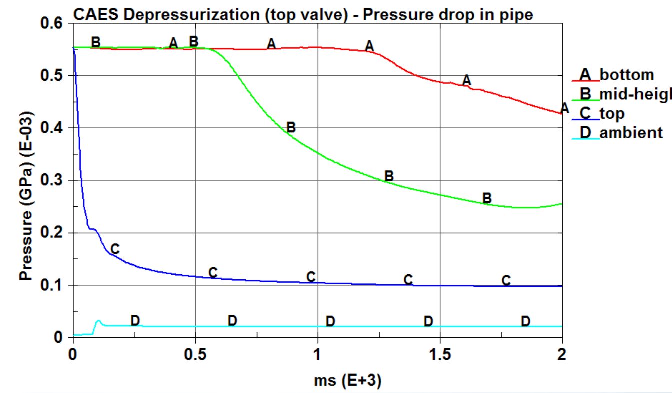


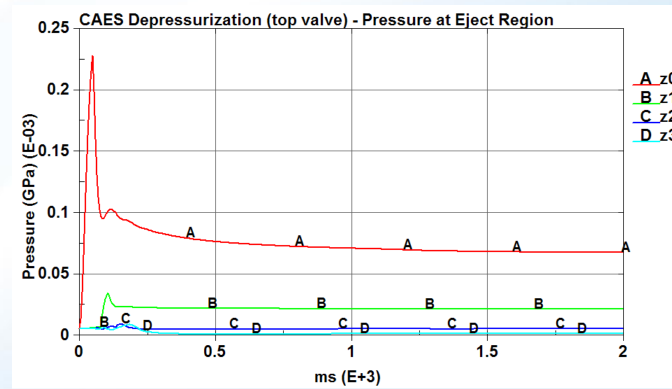






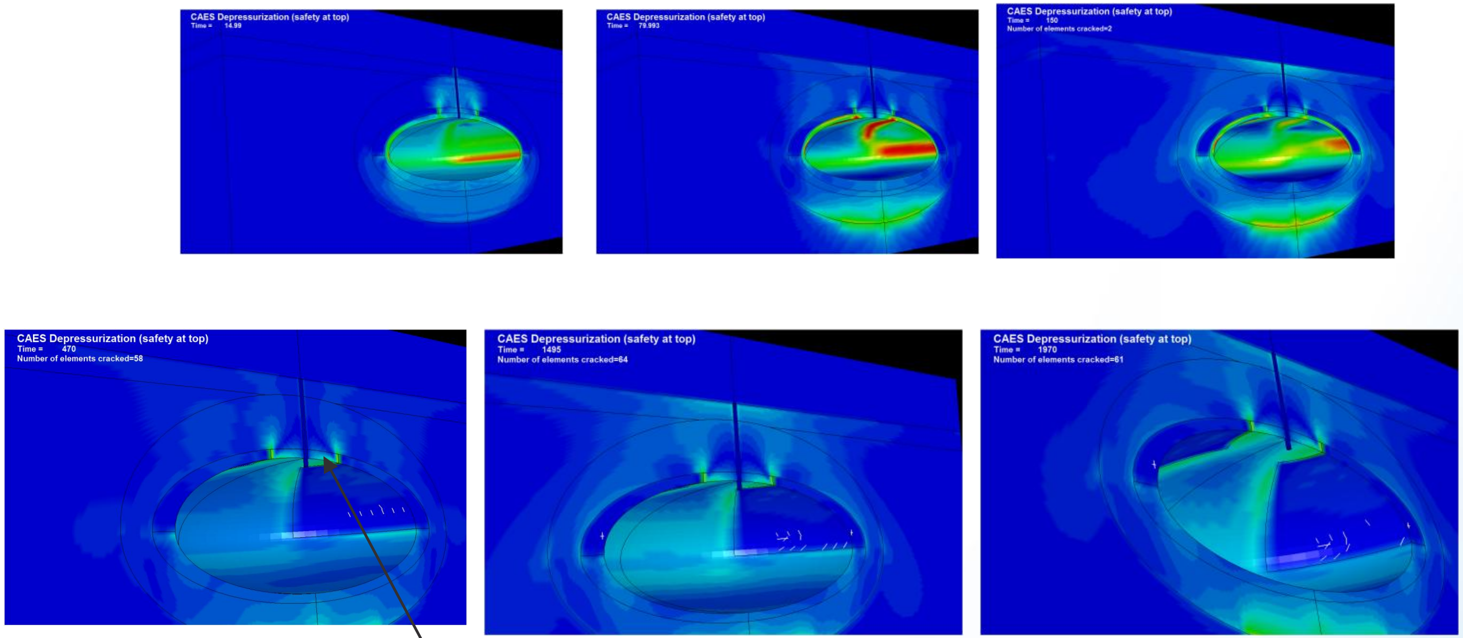


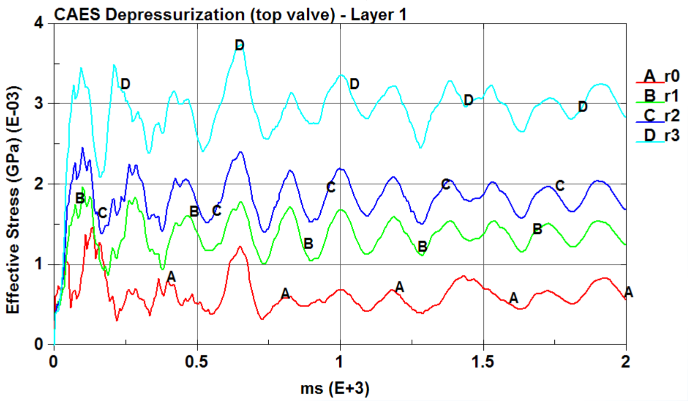


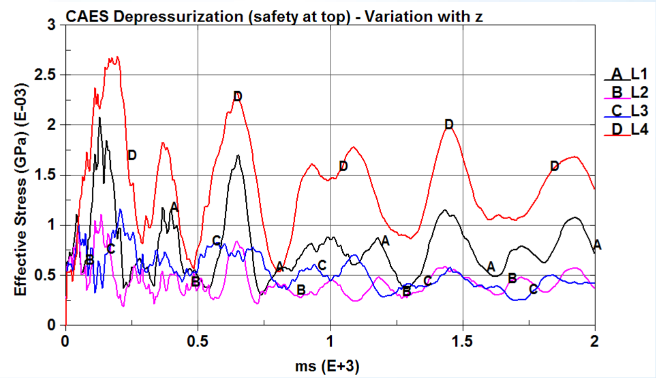


Rapid Depressurization Scenario (Safety at ground level)

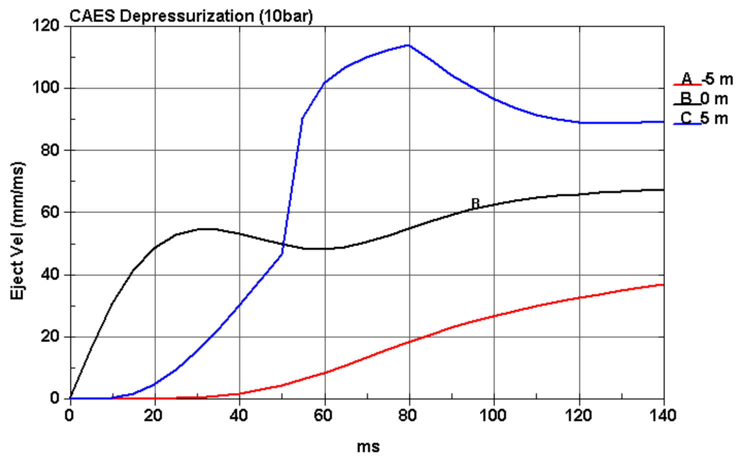
Effective stress evolution in rock strata due to depressurization and the formation of cracks in rock

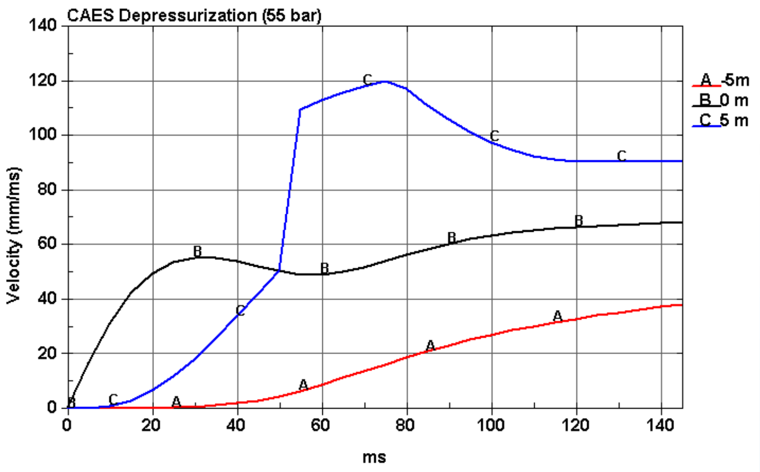


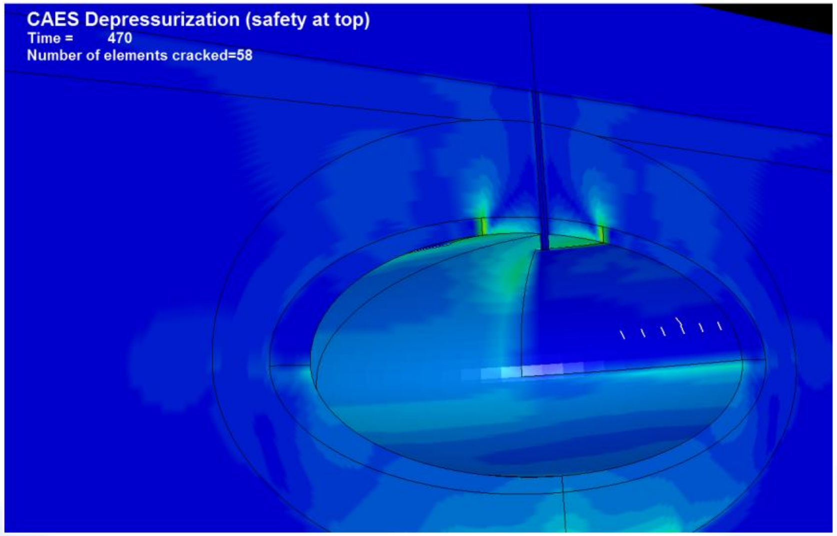


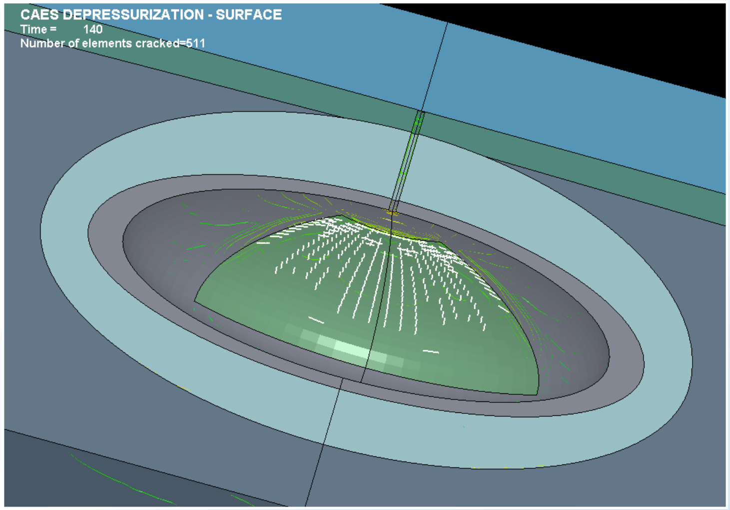


Rapid Depressurization Scenario (Safety at ground level)

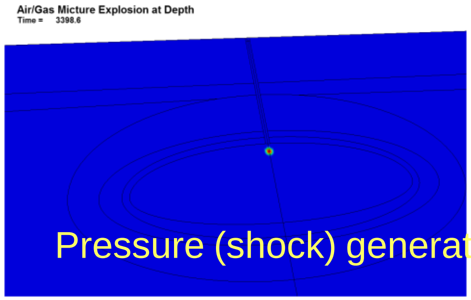


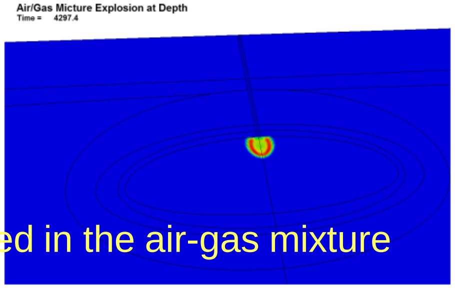


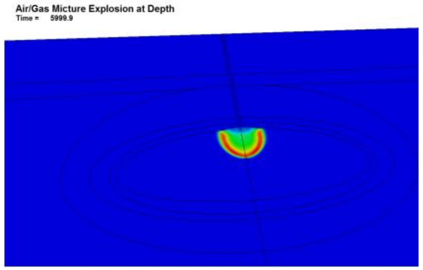


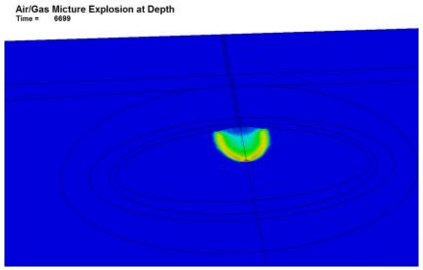


Explosion Scenarios

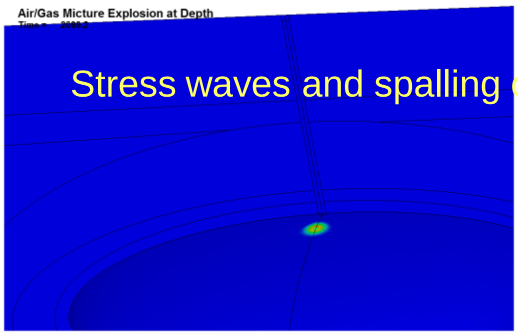


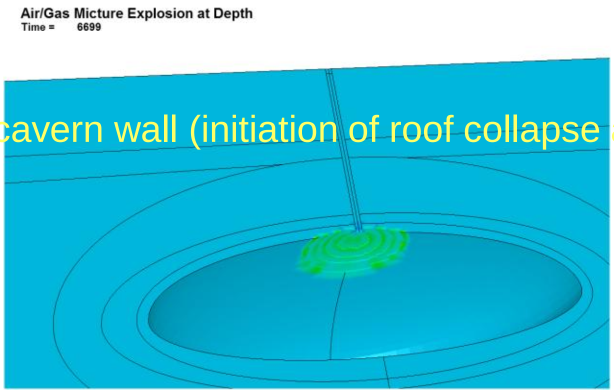


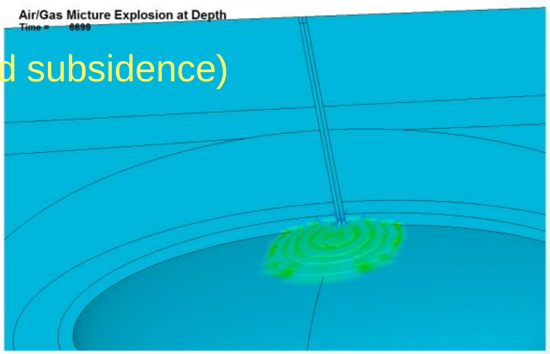




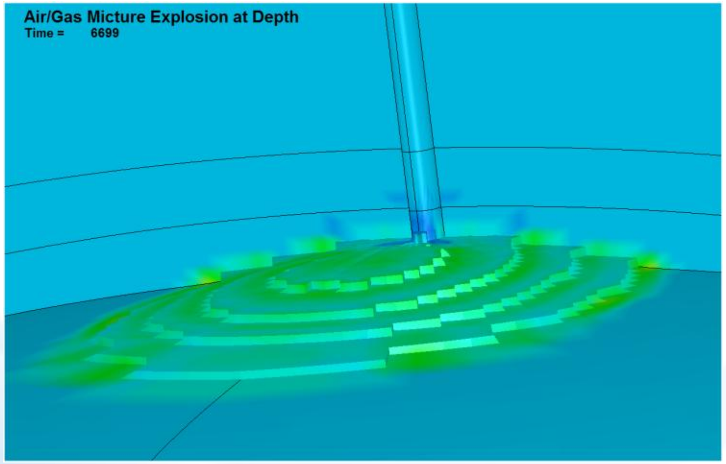
Pressure (shock) generated in the air-gas mixture

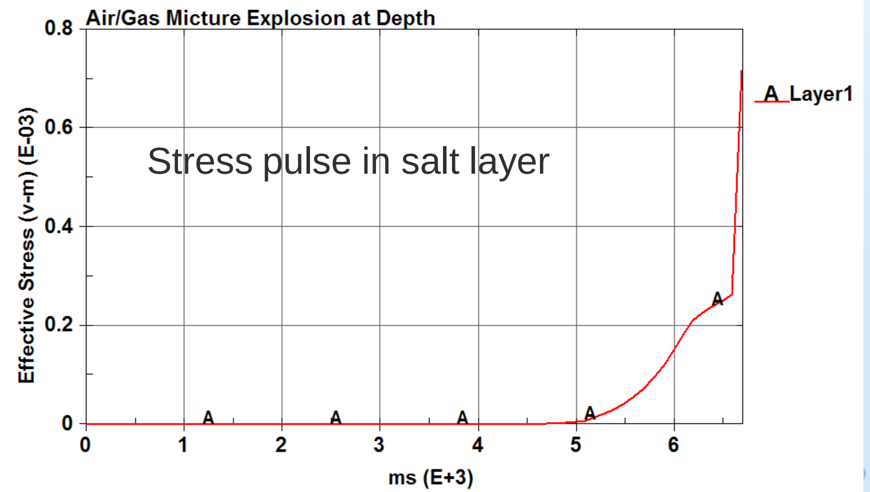






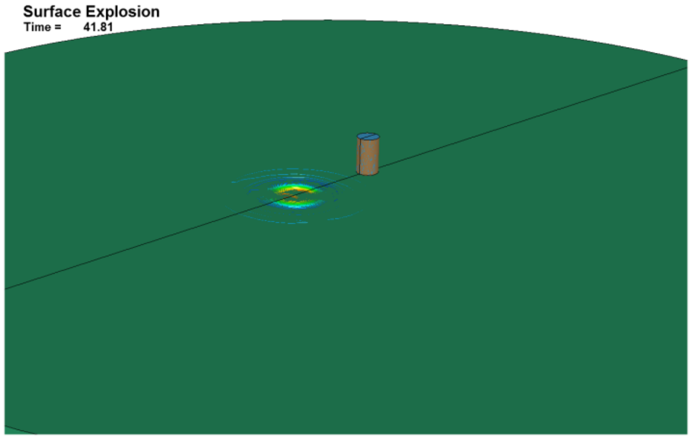
Stress waves and spalling of cavern wall (initiation of roof collapse and subsidence)

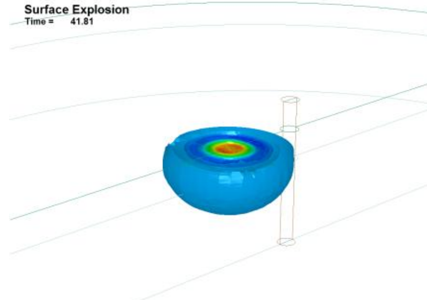


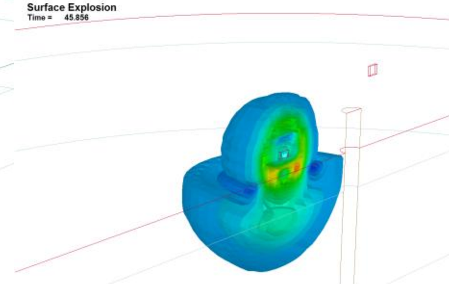


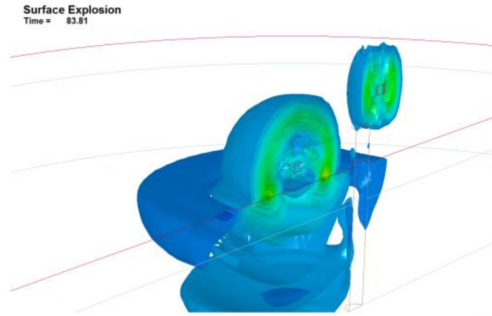
Stress pulse in salt layer

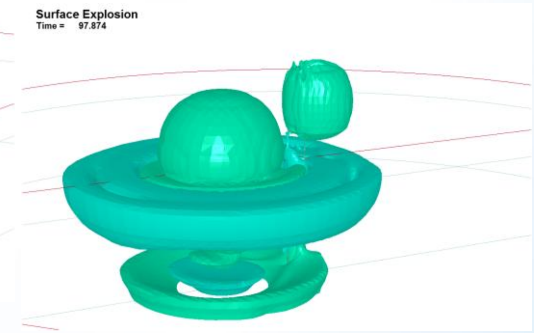
Explosion of air/gas mixture above ground (near supply pipe)

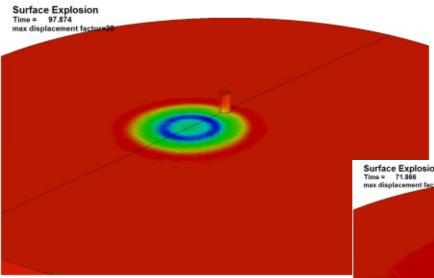


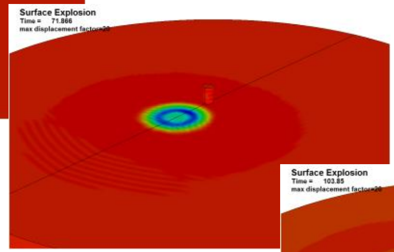


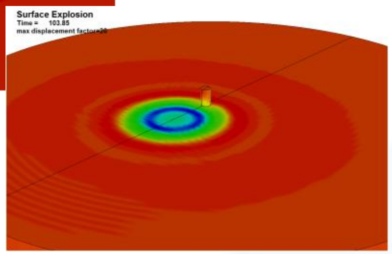




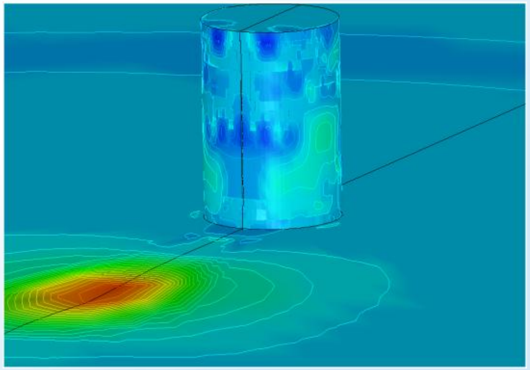








Depending on mixture breaching of the steel pipe can occur

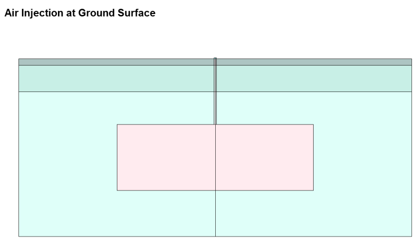


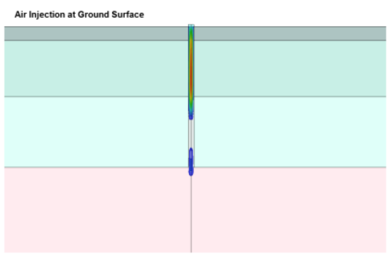
Pressurization Scenario (injection)

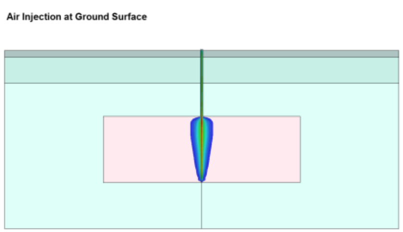
Injection into cavern (treatable problem ➔ fluid flow and pressurization ➔ rock loading)

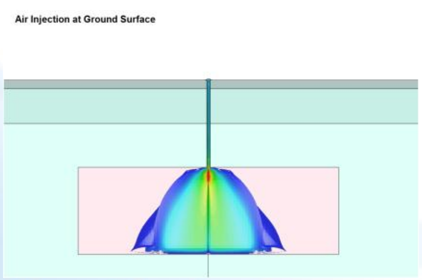
Injection into porous rock (aquifer) and its numerical treatment an ongoing effort

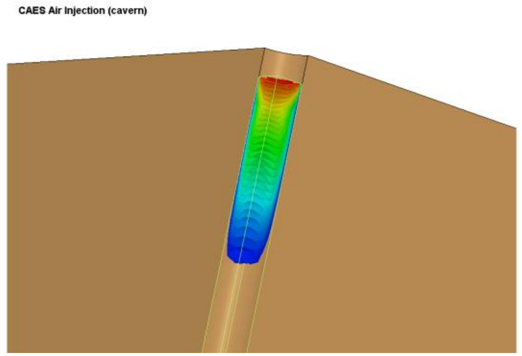
Start of injection

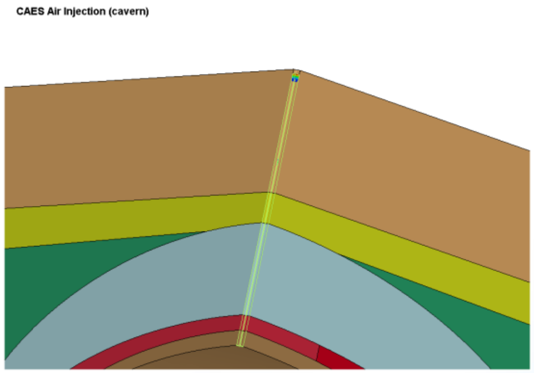


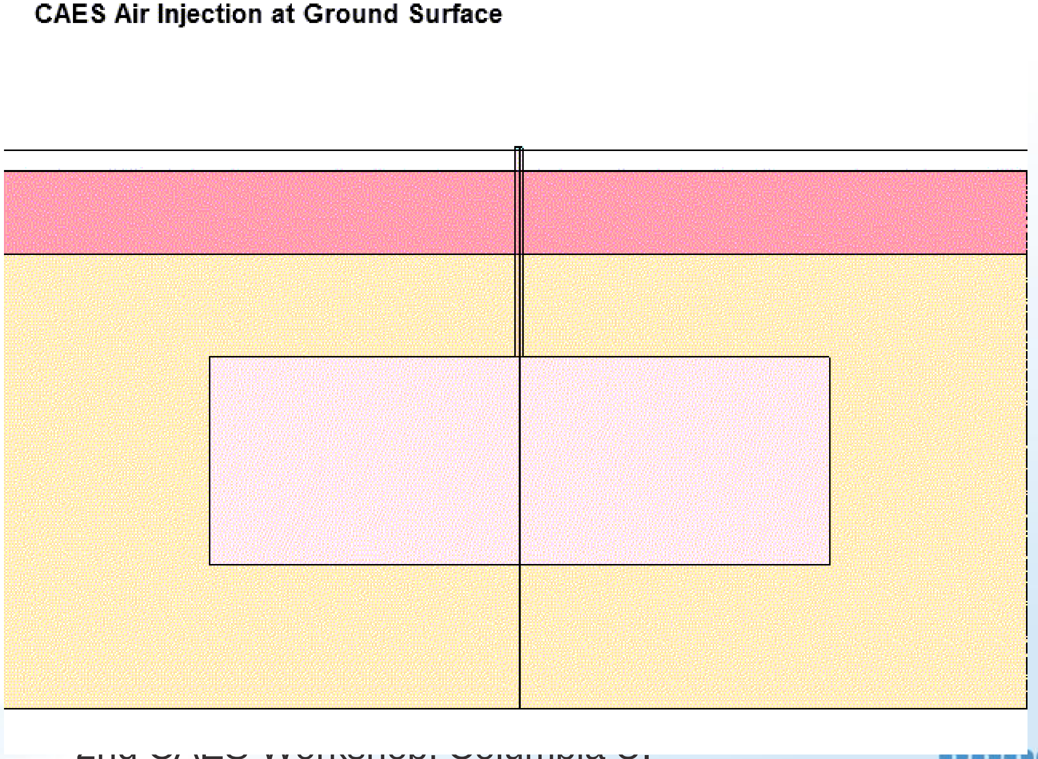






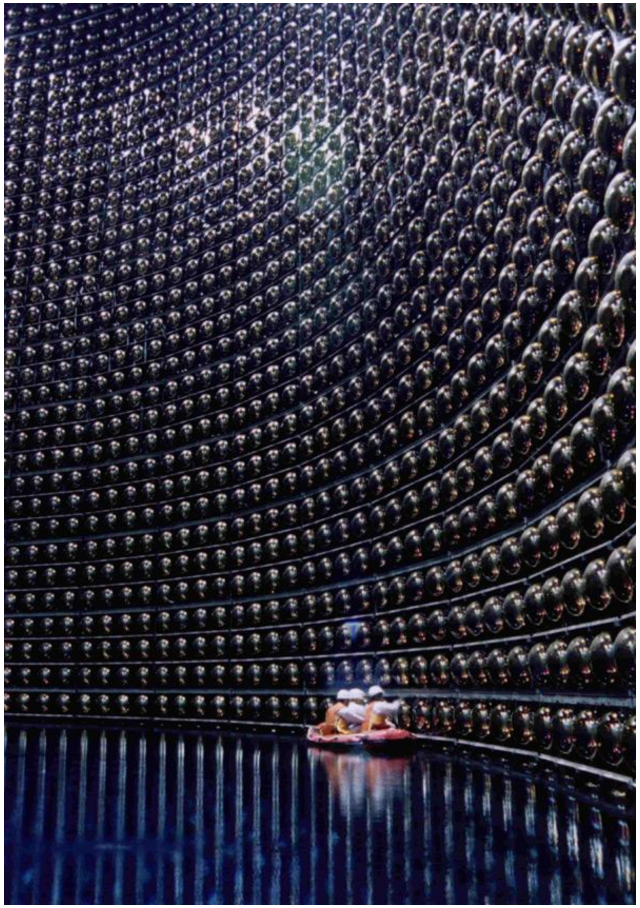


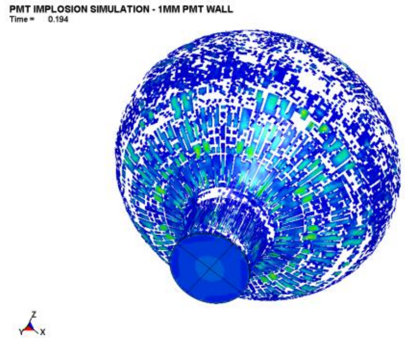


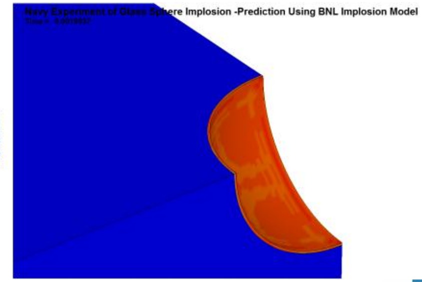


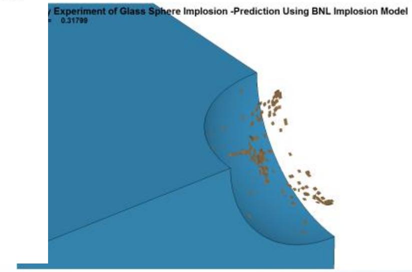
Use of ALE formulation to verify a NAVY implosion test

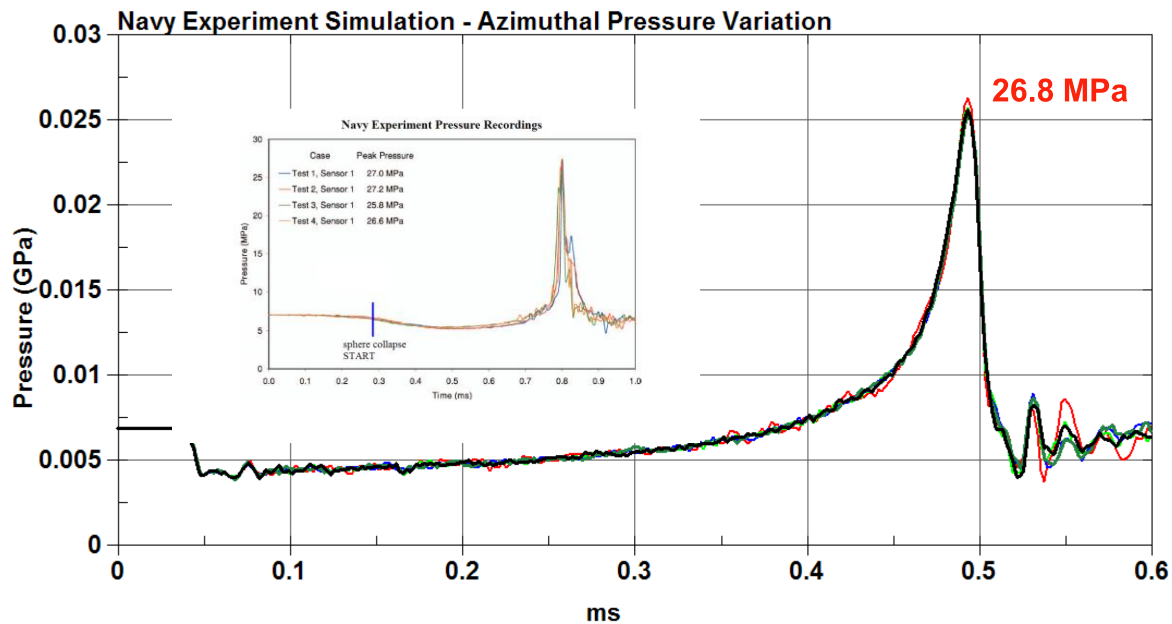
Study shows that the simulated complex processes can predict the test











Relevant study:
Large, deep underground cavern filled with water and thousands of phototubes
The issue is implosion and domino effect (it happened)

Summary

- A simulation process of the complex processes that may take place in an CAES vulnerability related scenario has been formulated
- Process is based on multi-physics, highly non-linear, Lagrangian-Eulerian formulation which has been proven in recent studies to accurately predict large scale events
- A number of postulated scenarios in CAES have been tested in the simulation space for proof-of-principle
- Complex processes of flow in porous rock linked to CAES are being developed to enhance the current capabilities
- Realistic scenarios on actual CAES systems and vulnerability based on site-specific rock parameters and operating pressures will be analyzed in the near future to assess operating limits.

19. Use of Carbon Dioxide as a Cushion Gas for CAES

Curtis M. Oldenburg, Lehua Pan, *Lawrence Berkeley National Laboratory*

We are investigating the advantages of using carbon dioxide (CO_2) as the cushion gas for CAES. Carbon dioxide compresses non-linearly and acts like a super-cushion when the reservoir is operated around the critical pressure and near the critical temperature. This behavior allows the storage of more air (working gas) for a given reservoir size. Furthermore, an operator could receive payments for sequestering CO_2 under the various cap-and-trade or carbon tax policies under consideration that are aimed at lowering CO_2 emissions from fossil-fuel power plants and other industrial facilities. To provide the foundation for future studies of the use of CO_2 as a cushion gas, we have modeled the coupled hydrologic and two-phase flow aspects of standard aquifer CAES including coupled reservoir and wellbore flow. We simulated the initial fill with air of a two-dimensional radial CAES reservoir to create the working and cushion gas bubble. Subsequently we modeled the physical processes in the reservoir and wellbore of the operation of the system using the same operational parameters as an existing cavern system. Results to date show the reservoir-wellbore system limits deliverability unless relatively large-diameter wells are used. Liquid saturation changes very little during production and injection cycles, but there is slow bleed-off of pressure as the bubble expands against the infinite aquifer over time

Curt is a Staff Scientist and Geologic Carbon Sequestration Program Lead in the Earth Sciences Division at Lawrence Berkeley National Laboratory. His area of expertise is numerical model development and applications for coupled subsurface flow and transport processes. He has worked at LBNL for 20 years in the areas of geothermal reservoir modeling, and vadose zone hydrology. For the last ten years, Curt has worked in three main areas of geologic CO_2 storage, (1) CO_2 injection for enhanced gas recovery, (2) near-surface leakage and seepage processes, and (3) CO_2 leakage risk assessment.

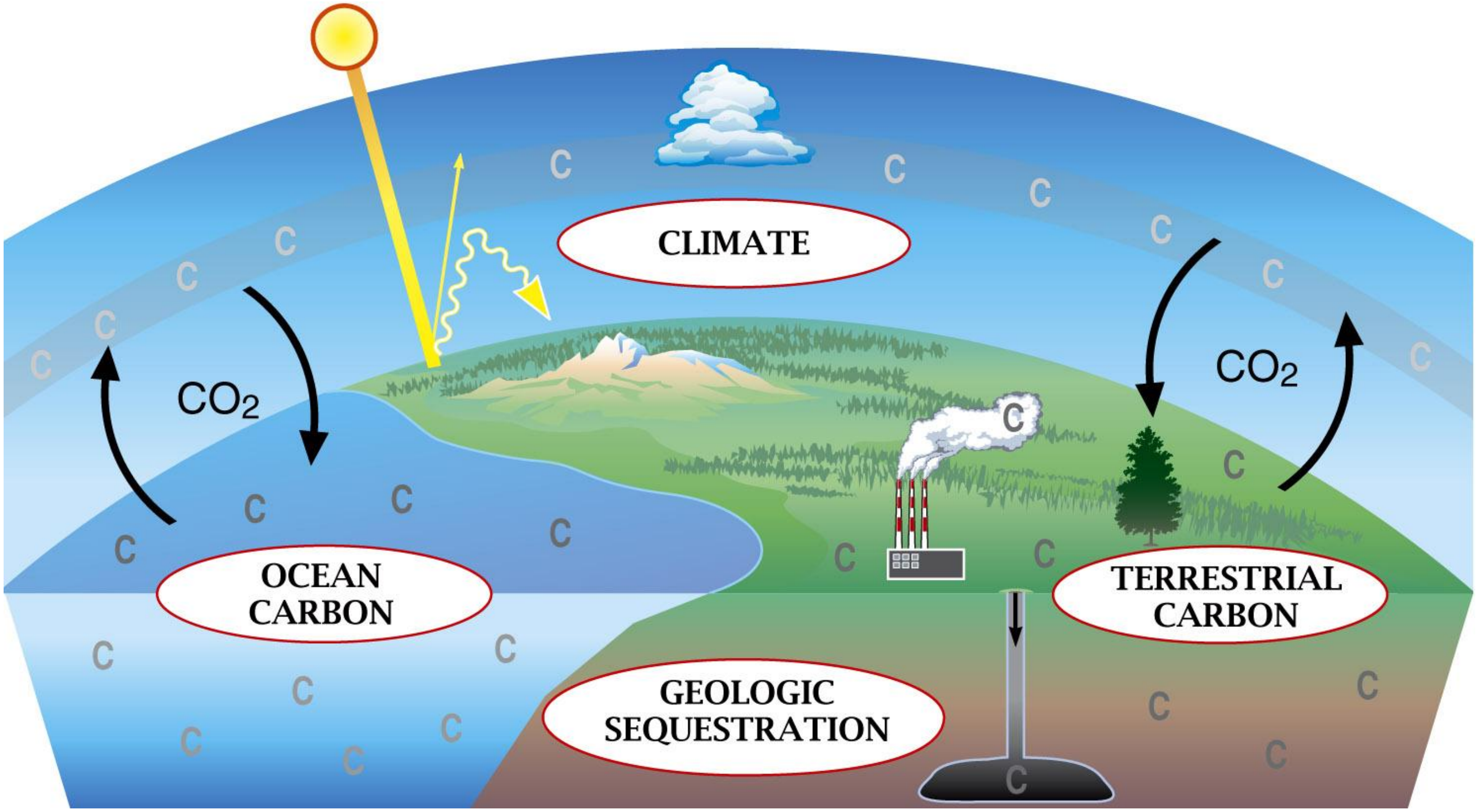
Use of CO_2 as a Cushion Gas for Compressed Air Energy Storage

Curtis M. Oldenburg
Lehua Pan

Earth Sciences Division
LBNL

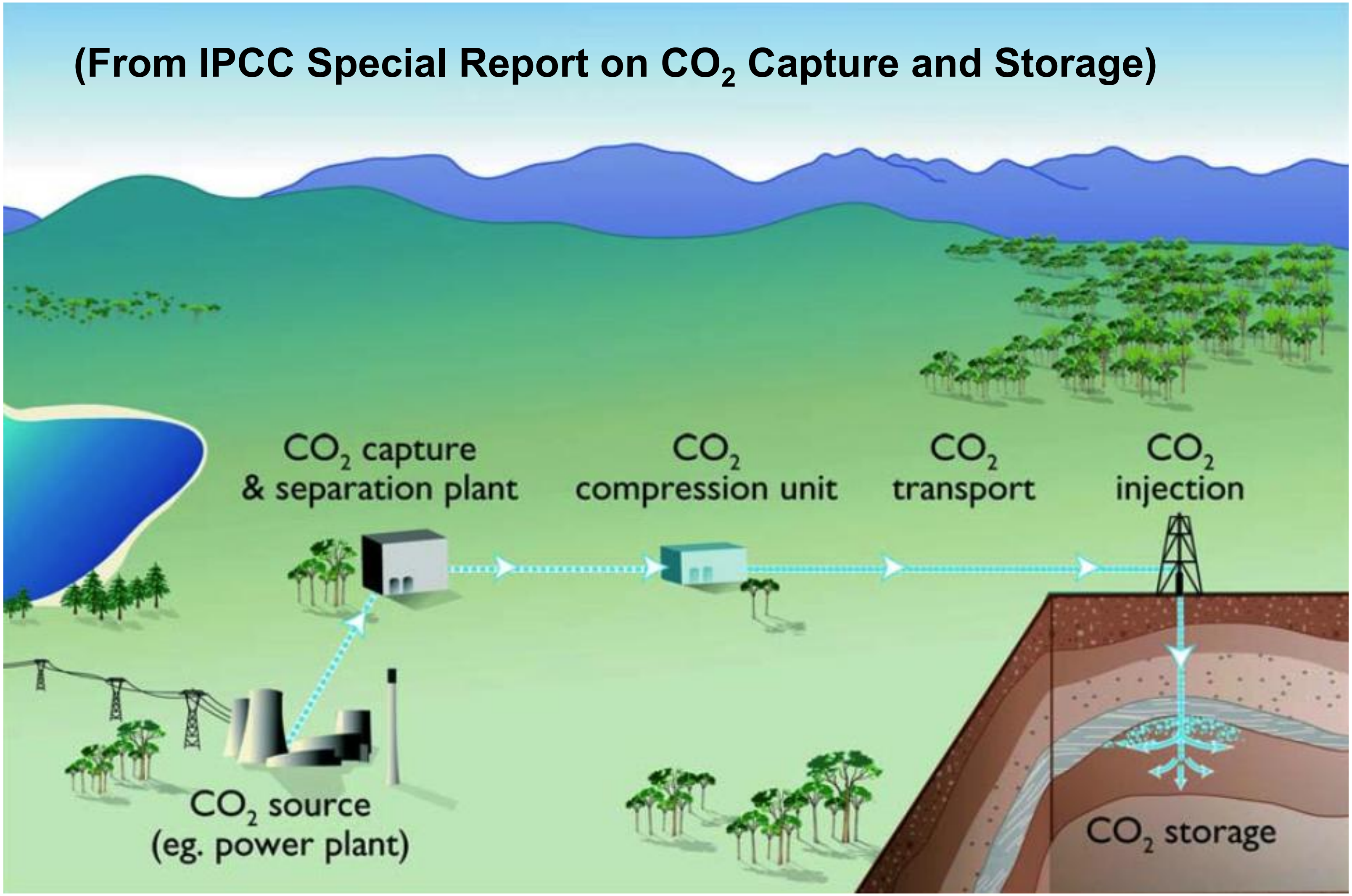
October 20, 2010

2nd Compressed Air Energy Storage Conference and Workshop
Columbia University



Source: Margaret Torn (LBNL)

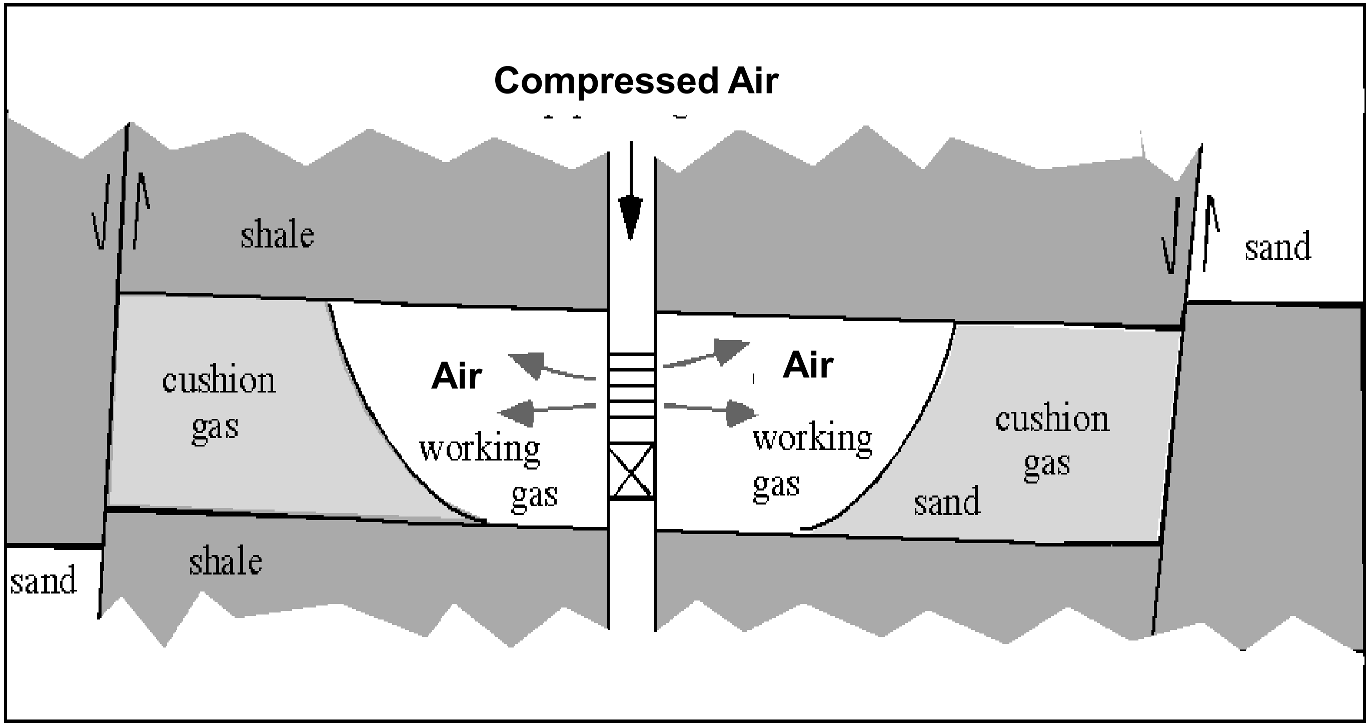
Carbon Capture and Storage (CCS)



(From IPCC Special Report on CO_2 Capture and Storage)

Cushion and Working Gas

• Production of air from the reservoir relies on presence of a cushion gas (gas that is not produced, but whose pressurization drives working gas out of reservoir).

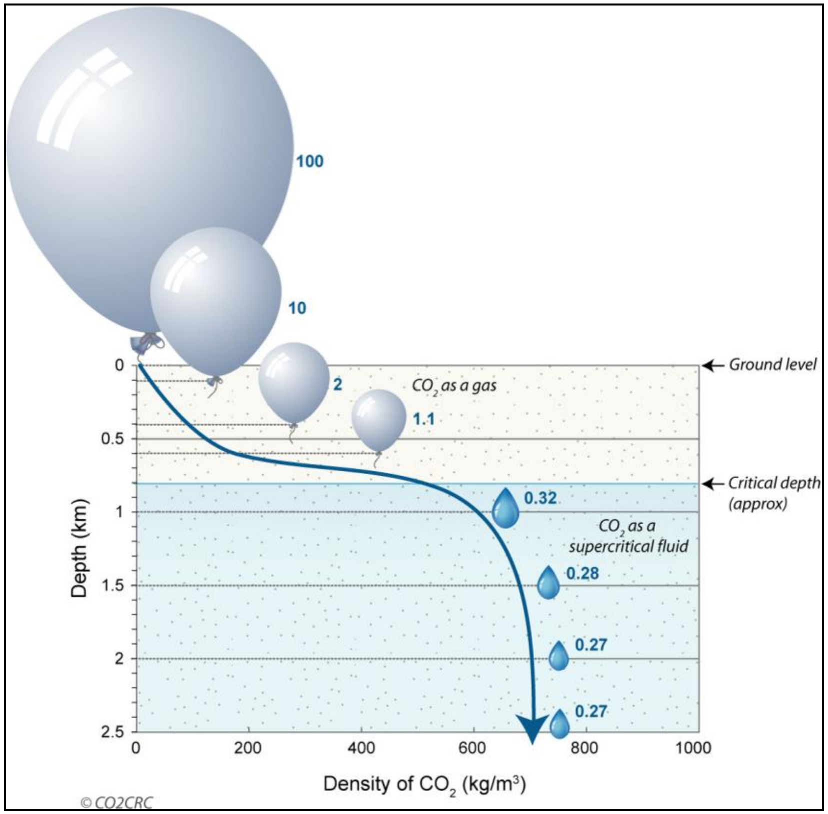


Oldenburg, C.M., *Energy&Fuels*, *17*(1), 240–246, 2003.

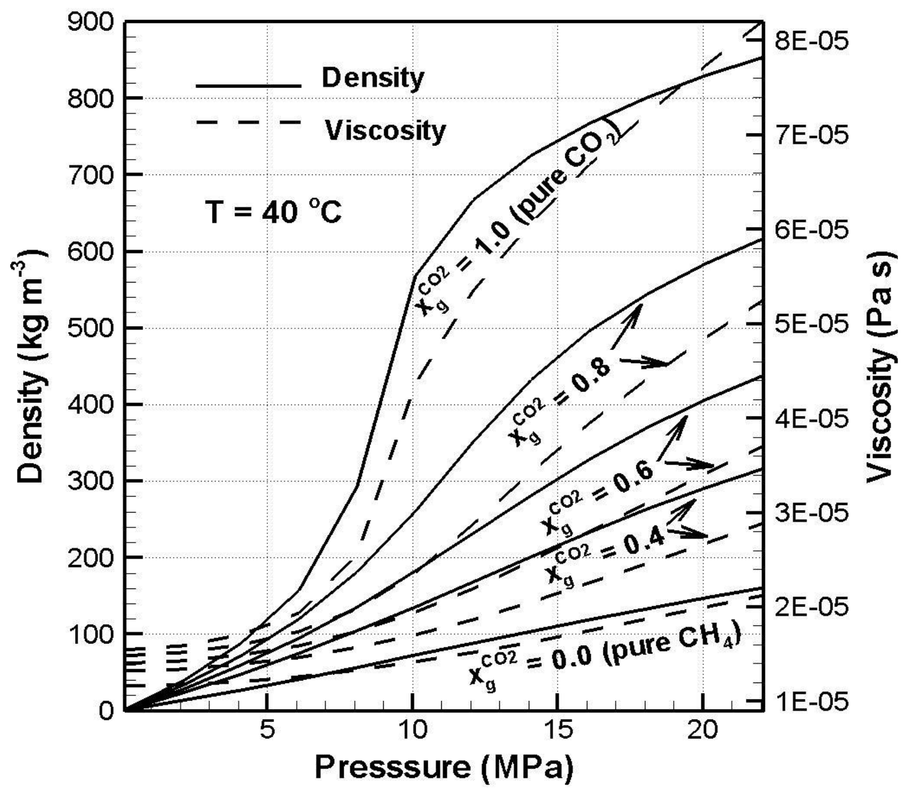
Enhancement of CAES Using CO_2

- CO_2 around its critical pressure behaves like a super-cushion

Oldenburg, C.M., *Energy&Fuels*, *17*(1), 240–246, 2003.

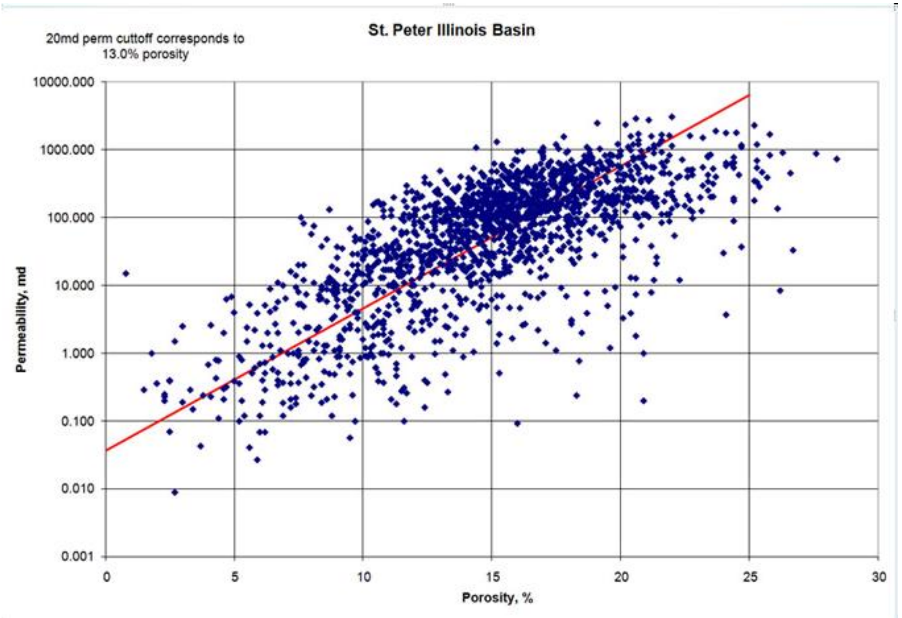


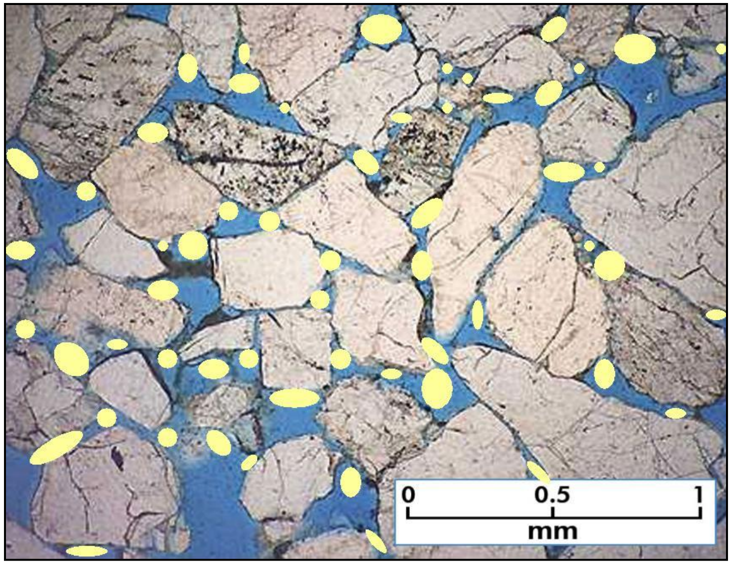
Source: The Australian Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC)



Aquifers ≠ Caverns

- Pore space (porosity)
- Permeability
- Two-phase flow
- Capillary forces (wetting phase, non-wetting phase)
- Relative permeability

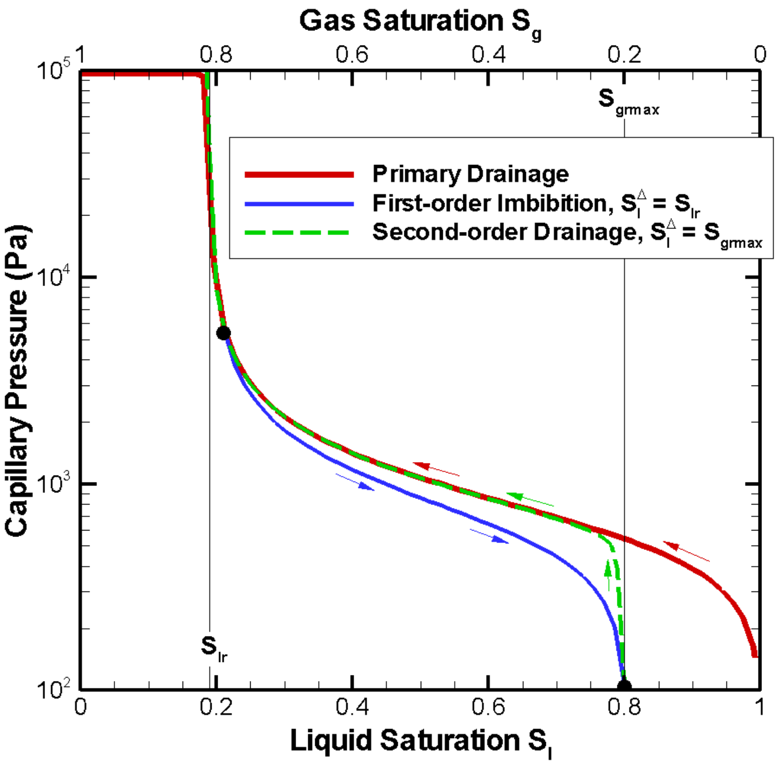


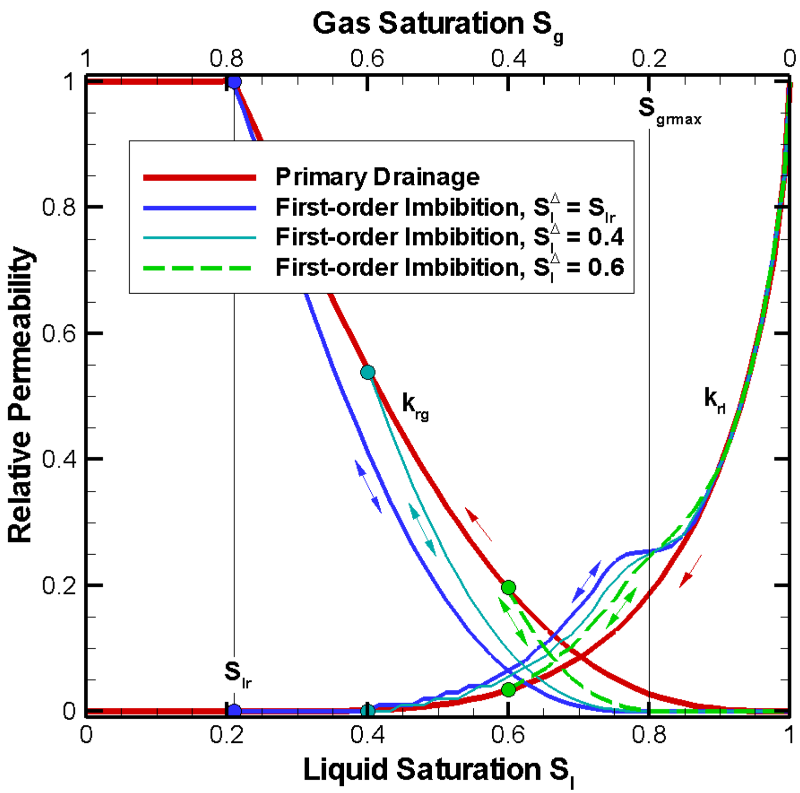


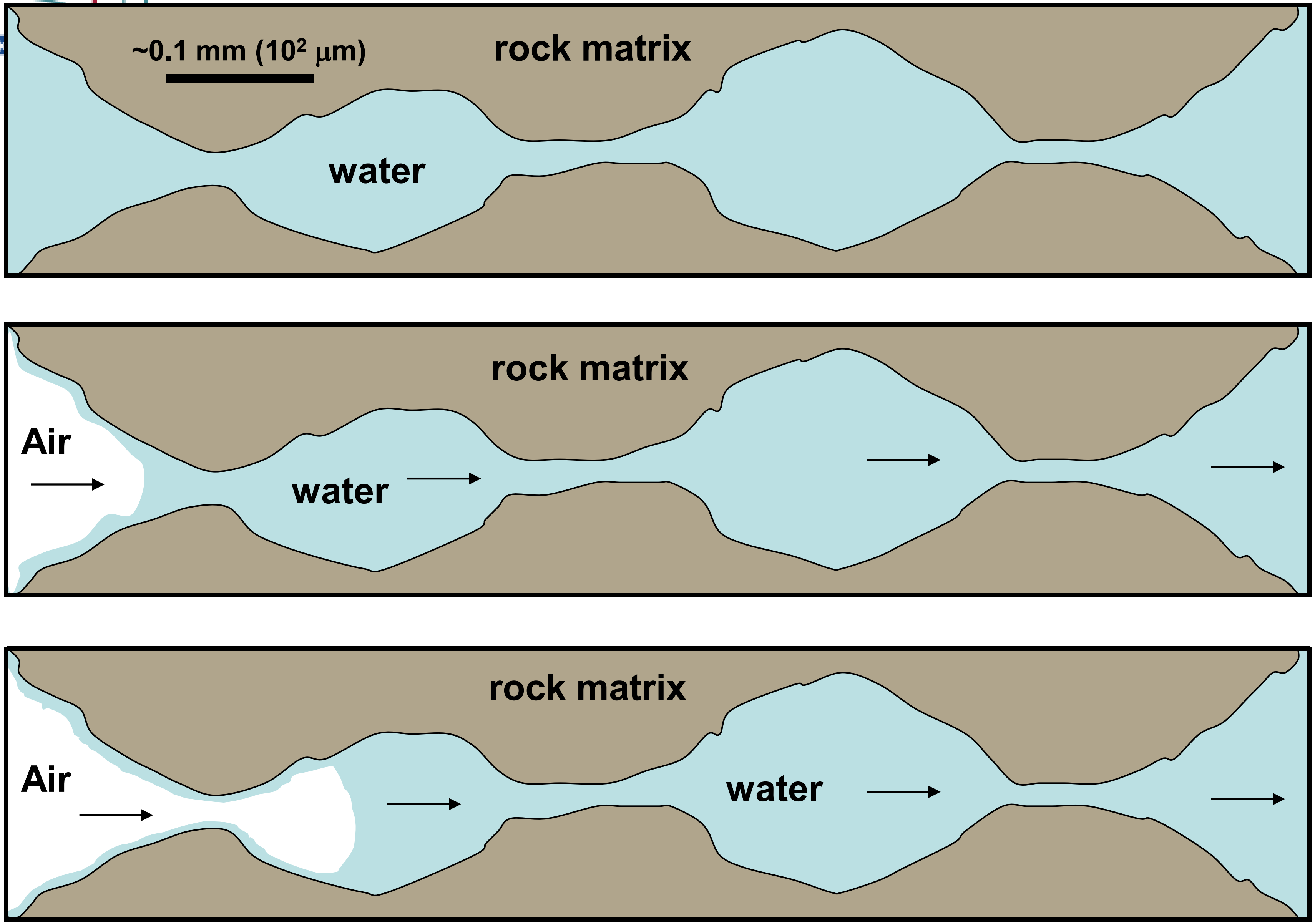
Source: John Beyer (LBNL)

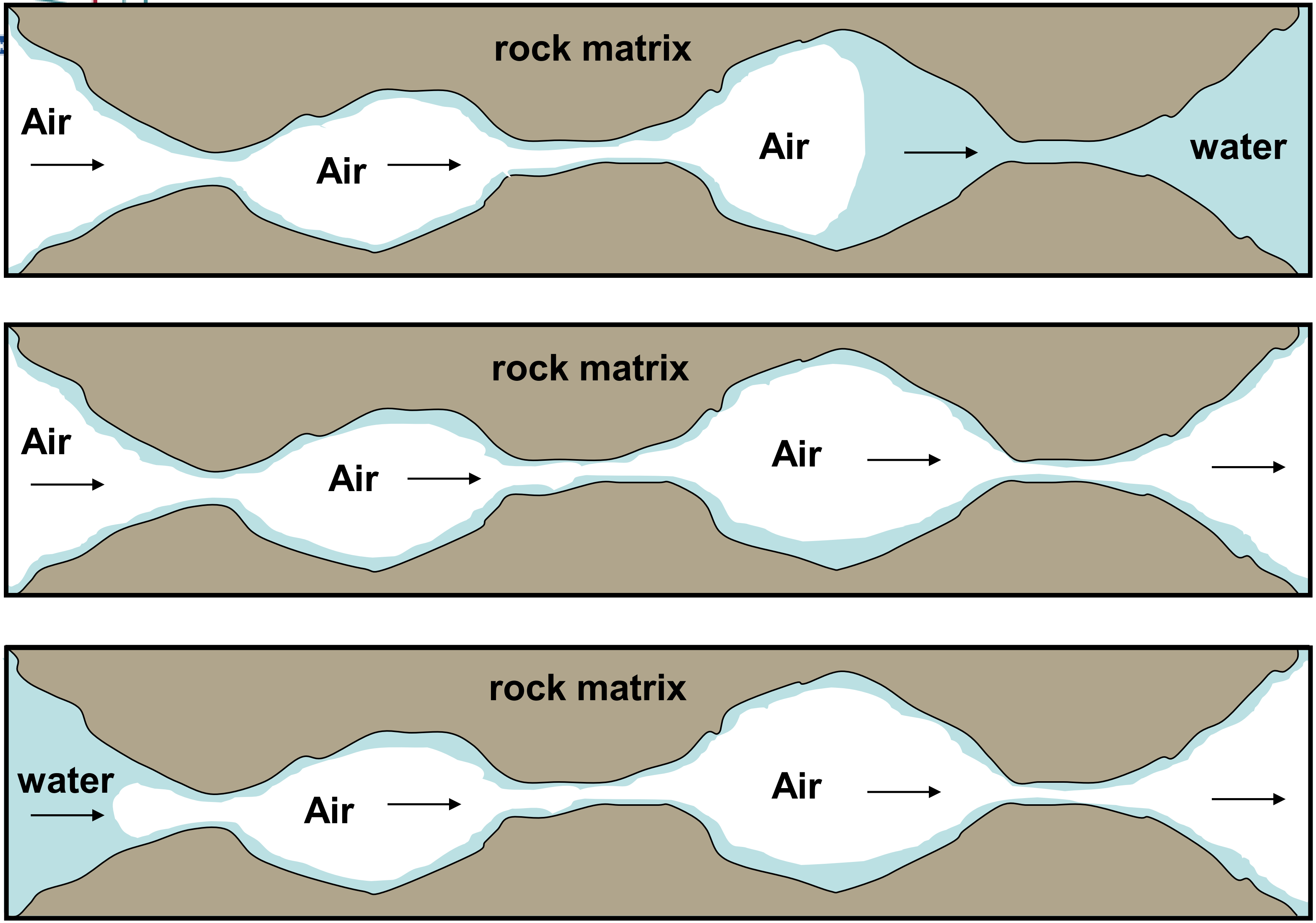
Source: Leetaru et al. http://knoxstp.com/reservoir.htm

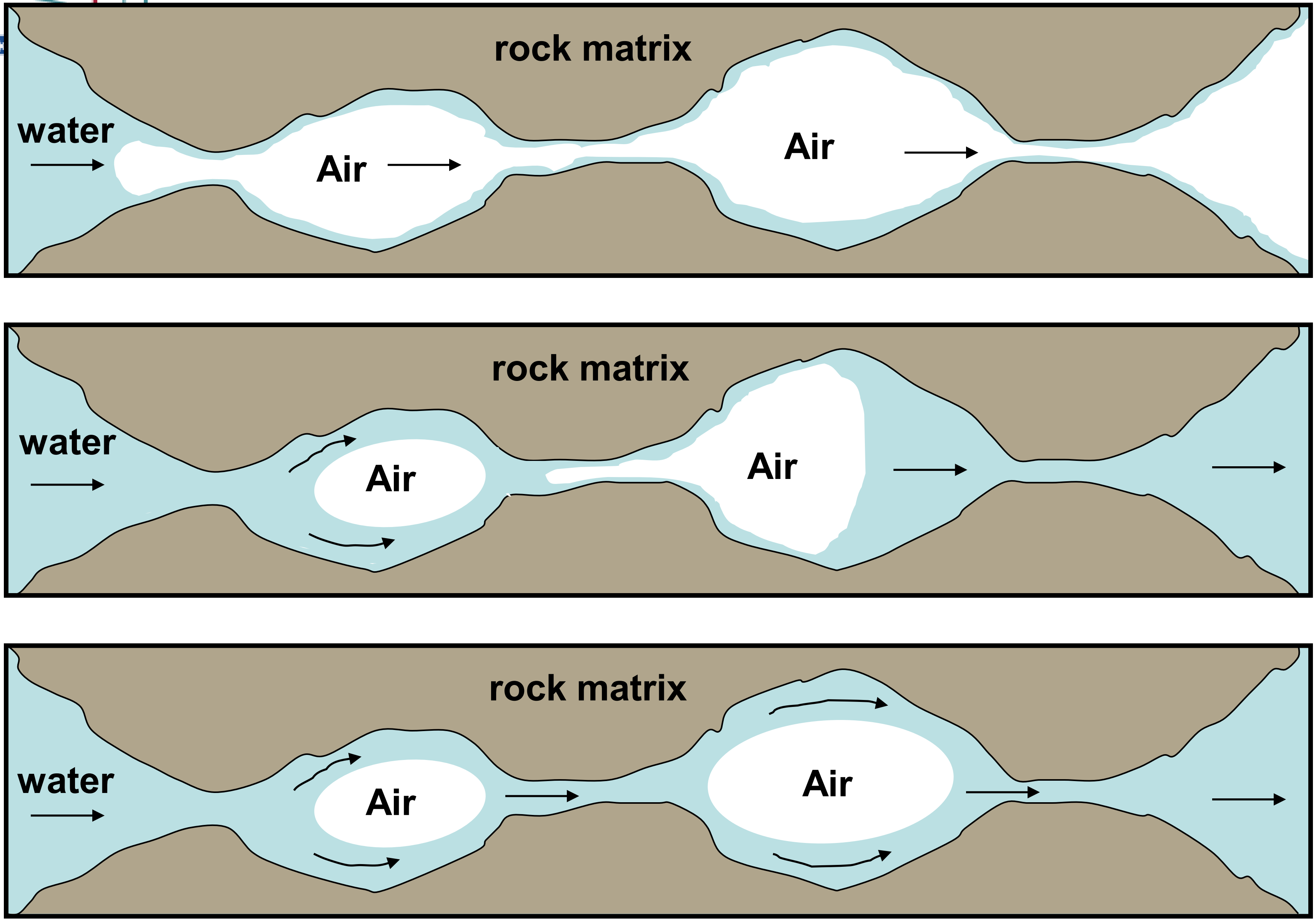
P_{cap} and k_{rel} Curves





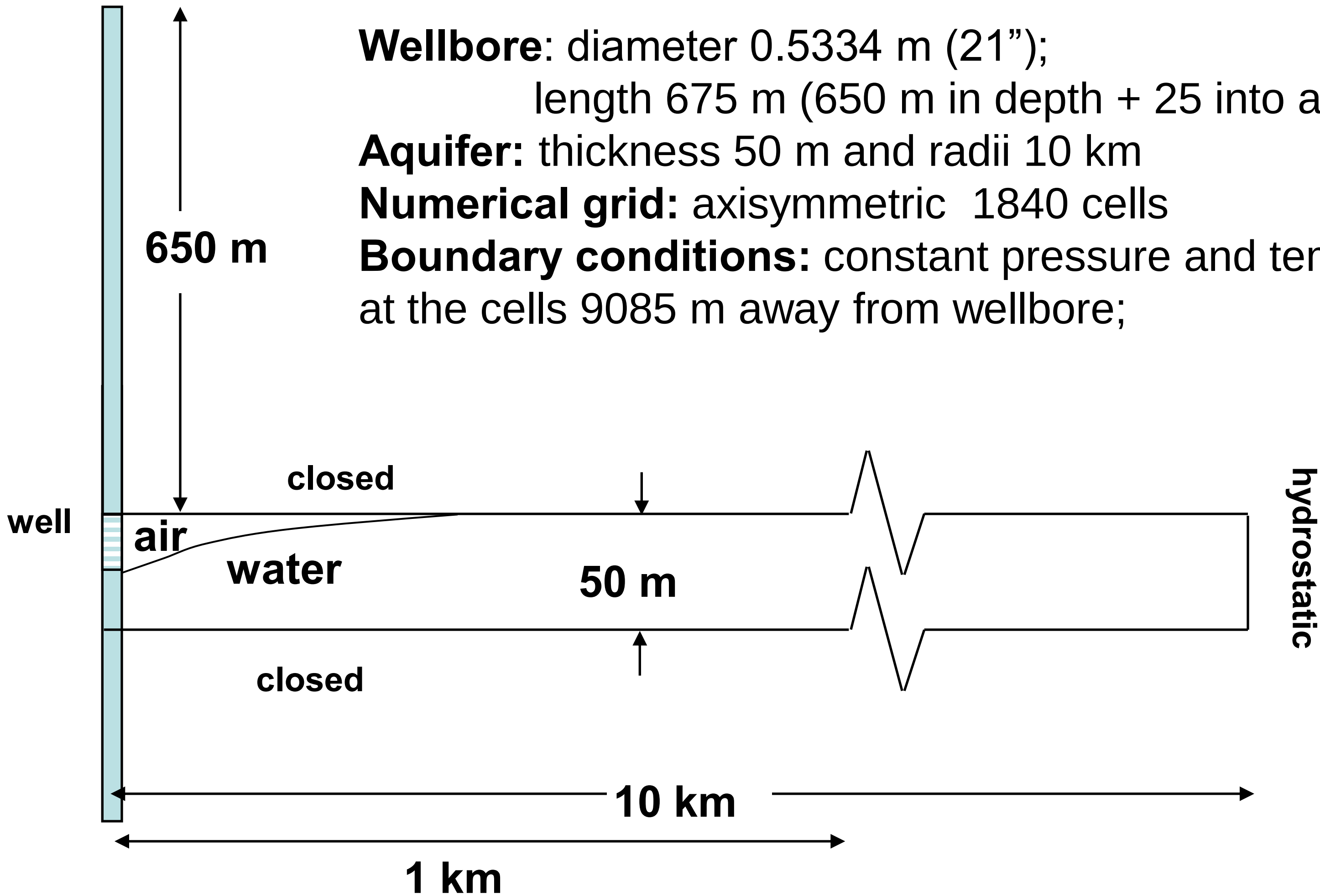

~0.1 mm (10² μm)
rock matrix
water
rock matrix
Air
water
rock matrix
Air
water


rock matrix
Air
Air
Air
water
rock matrix
Air
Air
Air
rock matrix
water
Air
Air


rock matrix
water
Air
Air
rock matrix
water
Air
Air
rock matrix
water
Air
Air

Simulation of Aquifer-CAES

Wellbore: diameter 0.5334 m (21”);
length 675 m (650 m in depth + 25 into aquifer);
Aquifer: thickness 50 m and radii 10 km
Numerical grid: axisymmetric 1840 cells
Boundary conditions: constant pressure and temperature at the cells 9085 m away from wellbore;



The TOUGH Codes

- TOUGH: Transport Of Unsaturated Groundwater and Heat

multidimensional	1D, 2D, 3D
multiphase	liquid, gas, NAPL
multicomponent	water, air, VOC, radionuclides
nonisothermal	heat
flow and transport	multiphase Darcy law
fractured-porous media	dual-ϕ, dual-k, MINC, ECM

EOS: Accurate description of thermophysical properties

http://esd.lbl.gov/TOUGH2/

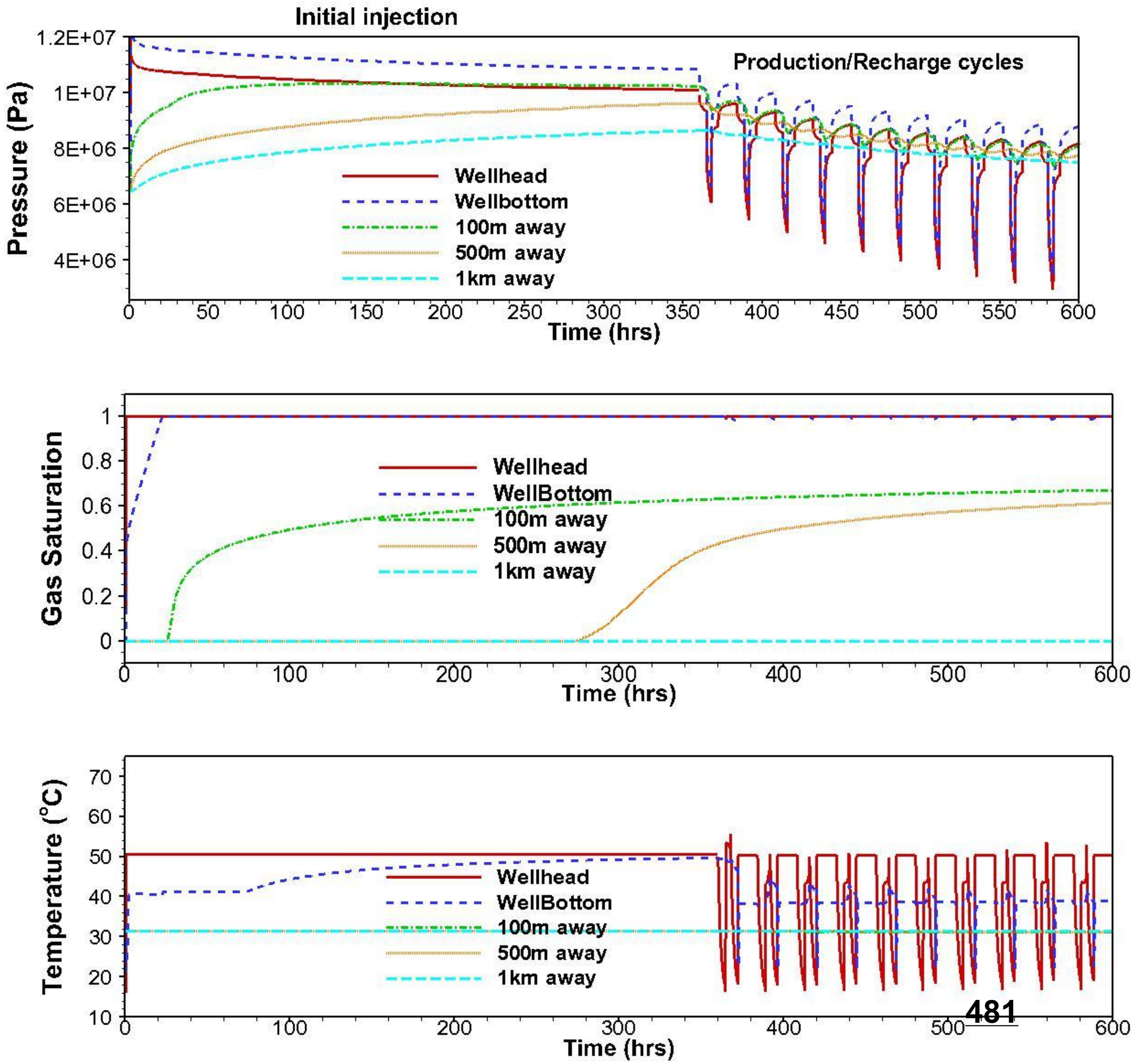
http://esdtools.lbl.gov/gaseos/

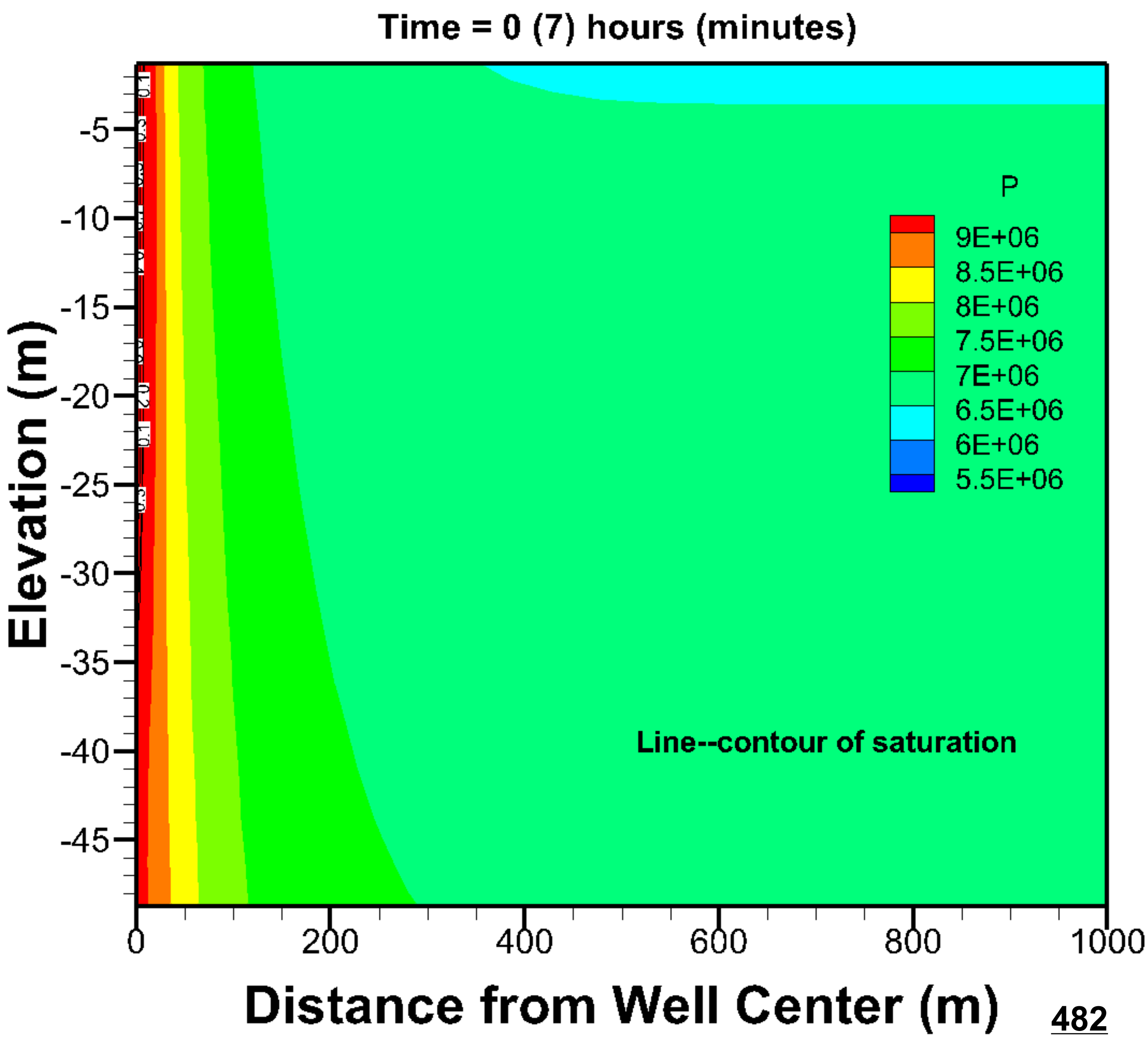
Simulation of Aquifer-CAES (modeled after the Huntorf caverns)

Simulation: TOUGH2 with Drift-Flux Model for wellbore flow = T2Well*
Initial fill: 54 kg/s for 15 days (total of 30 times working gas by mass)
Production: 3 hours at 208.5 kg/s (half of total rate for two caverns)
Recharge: 12 hours at 54 kg/s (half of total rate for two caverns)
Initial condition: hydrostatic pressure and natural geothermal gradient (25^{o}C/km)
Boundary conditions: constant pressure and temperature at the cells 9085 m away from wellbore; wellhead is prescribed injection (air) rate with enthalpy of 0.13005E+06 J/kg or production (mass) rate.

Schedule:
During initial filling stage: continue injection of 54 kg/s air
During production/recharge cycle: 4.5 hrs shut-in, 3 hrs production, 4.5 hrs shut-in,
12 hrs recharge per each day

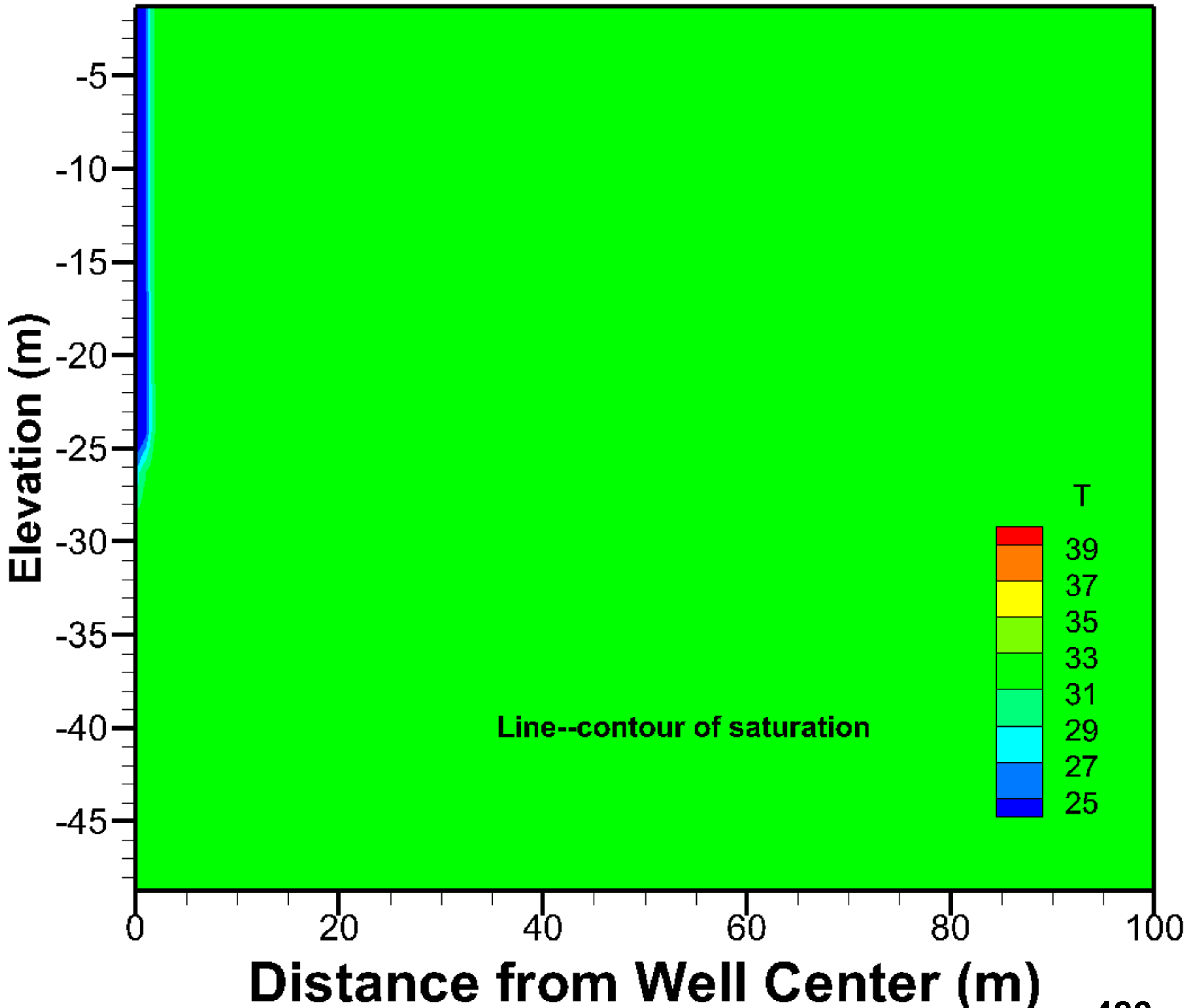
***Pan, L., C.M. Oldenburg, Y.-S. Wu, and K. Pruess, Wellbore flow model for carbon dioxide and brine, *Energy Procedia*, GHGT9 conference, Nov. 16-20, 2008, Washington DC. LBNL-1416E.**


Initial injection
Production/Recharge cycles
Pressure (Pa)
1.2E+07
1E+07
8E+06
6E+06
4E+06
Wellhead
Wellbottom
100m away
500m away
1km away
0
50
100
150
200
250
300
350
400
450
500
550
600
Time (hrs)
Gas Saturation
1
0.8
0.6
0.4
0.2
0
Wellhead
WellBottom
100m away
500m away
1km away
0
100
200
300
400
500
600
Time (hrs)
Temperature (°C)
70
60
50
40
30
20
10
Wellhead
WellBottom
100m away
500m away
1km away
0
100
200
300
400
500
600
Time (hrs)

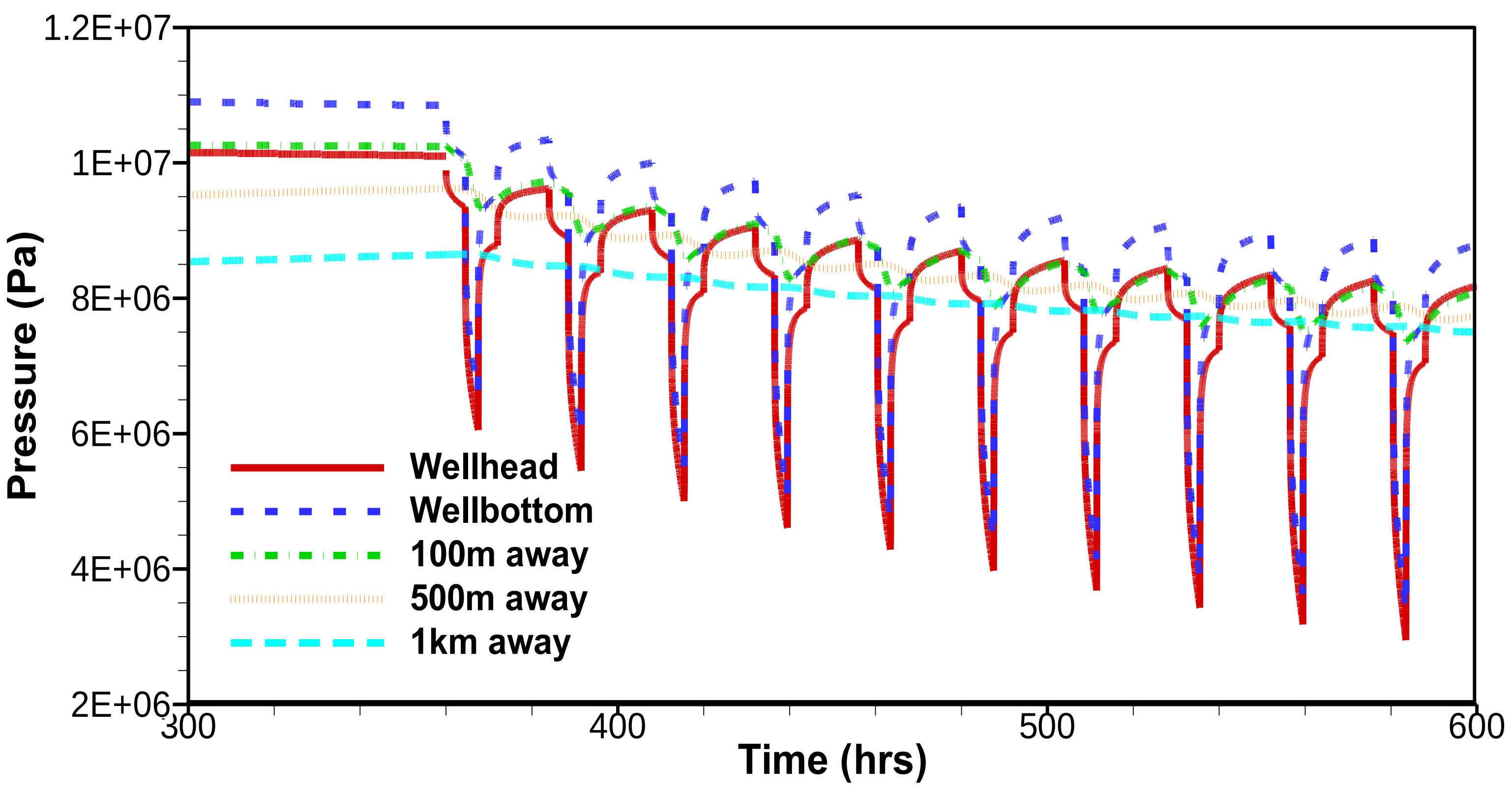


Time = 0 (7) hours (minutes)
P
9E+06
8.5E+06
8E+06
7.5E+06
7E+06
6.5E+06
6E+06
5.5E+06
Line--contour of saturation
Elevation (m)
-5
-10
-15
-20
-25
-30
-35
-40
-45
Distance from Well Center (m)
0
200
400
600
800
1000

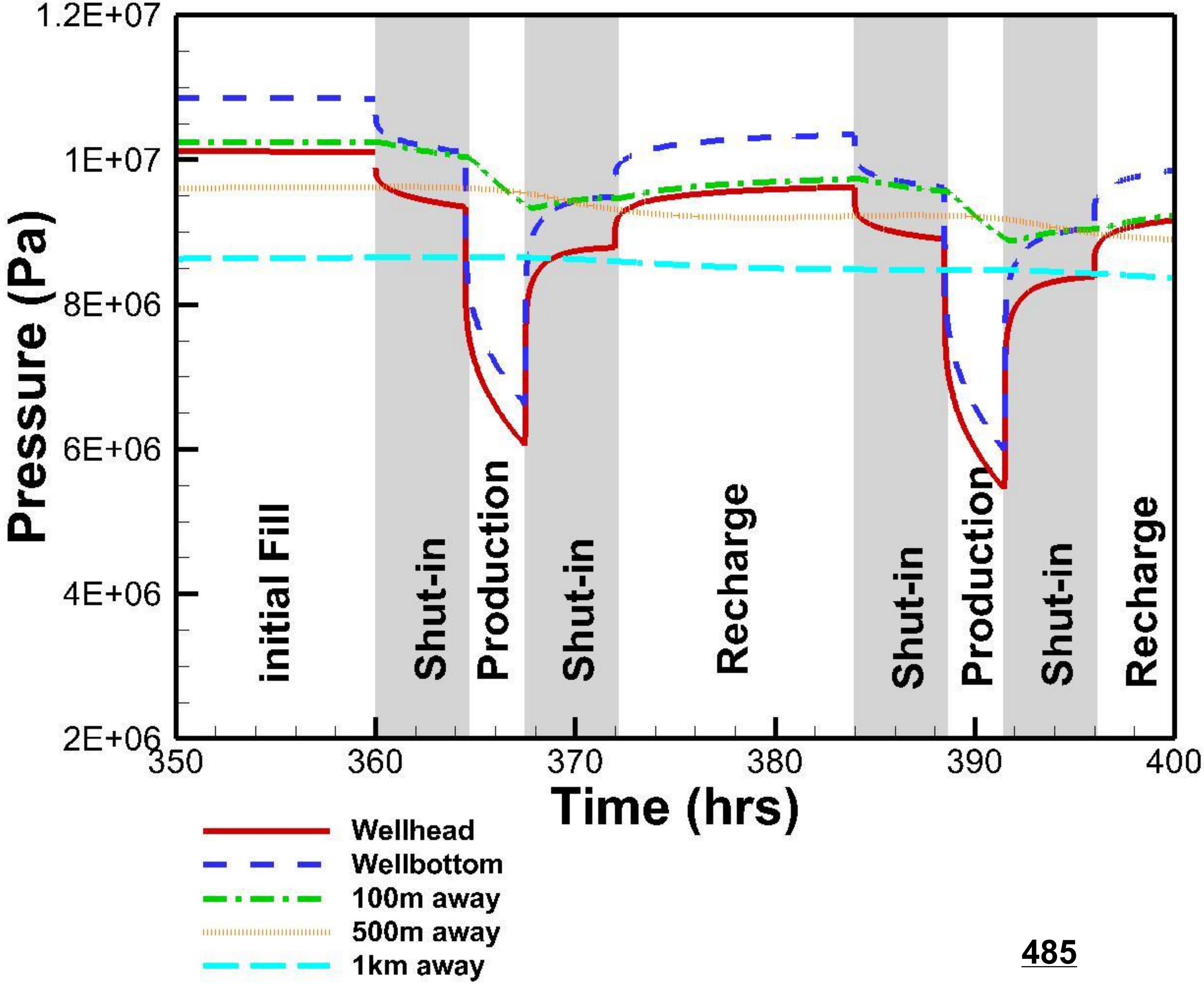
Time = 0 (7) hours (minutes)

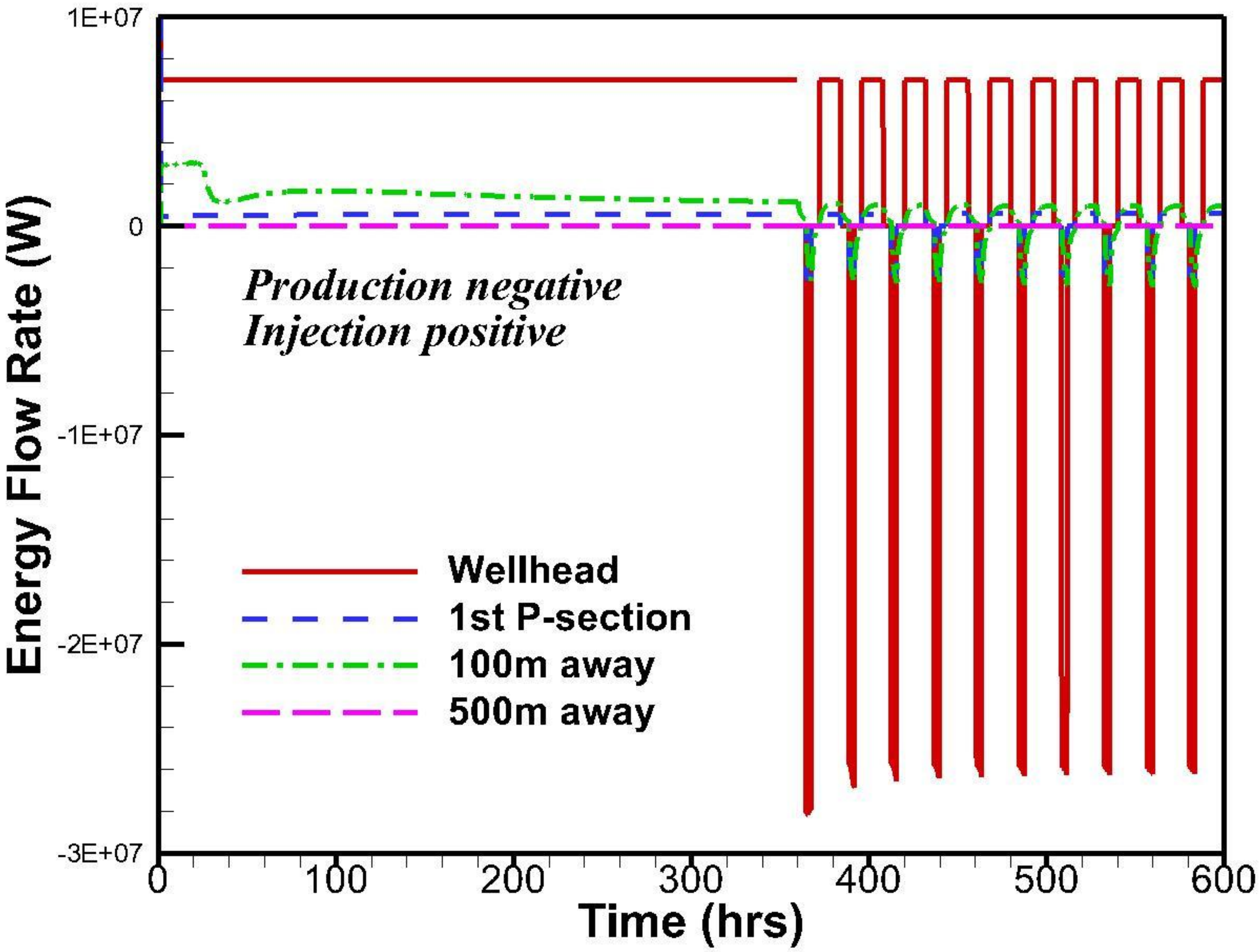


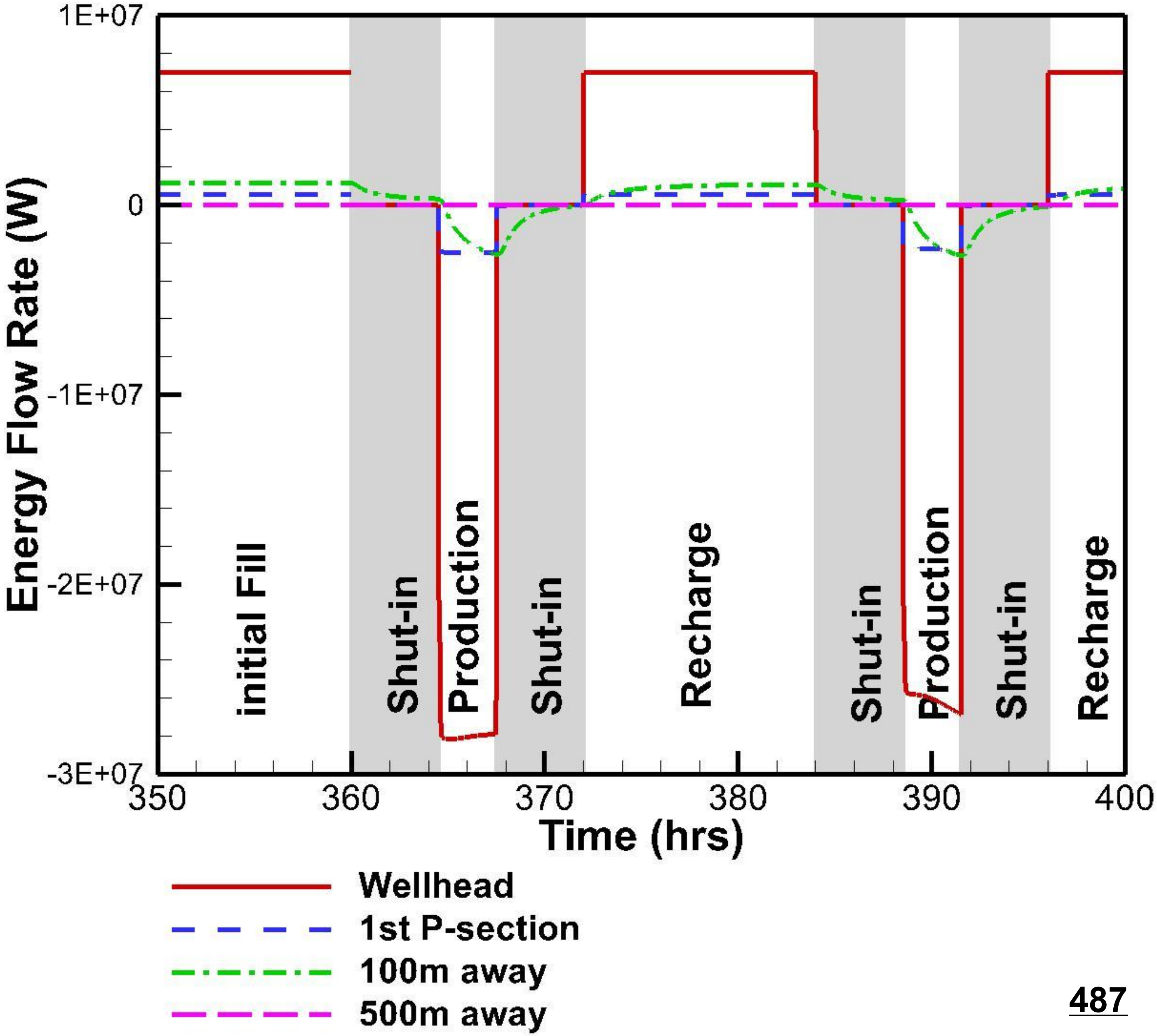
Pressure (during production & recharge cycles)



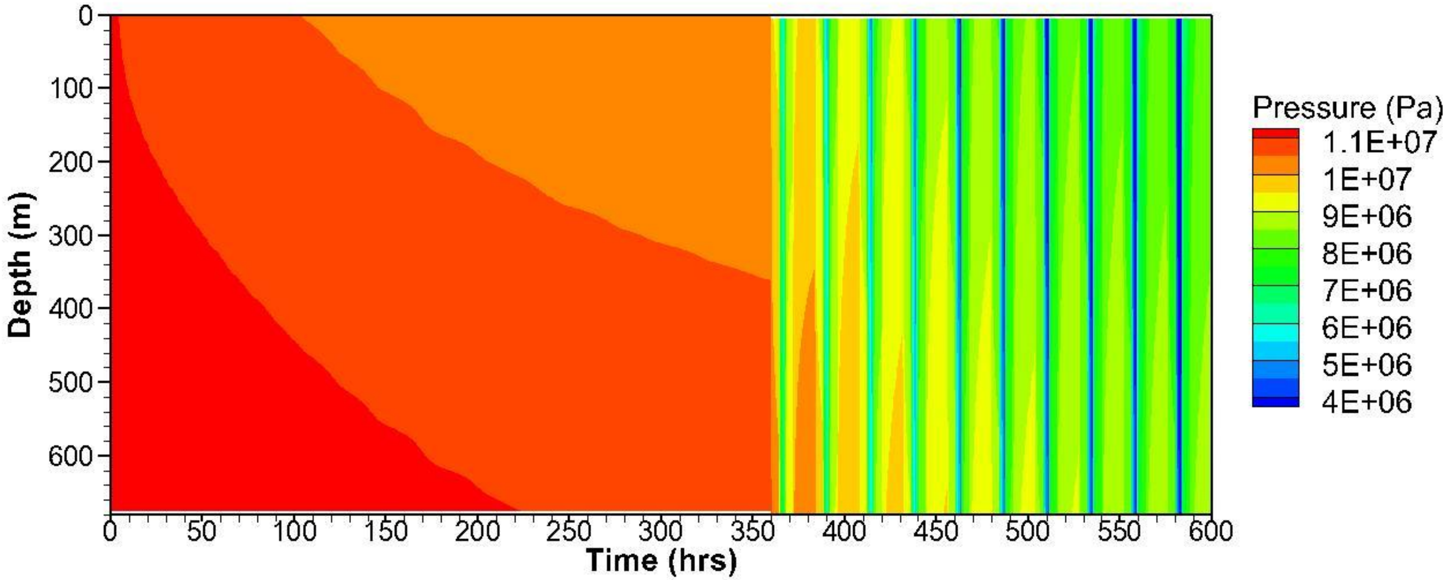
Working mass 1/30
3 hrs Production at 208.5 kg/s
12 hrs Recharge at 54 kg/s
Recharge surplus per cycle 8.1e4 kg

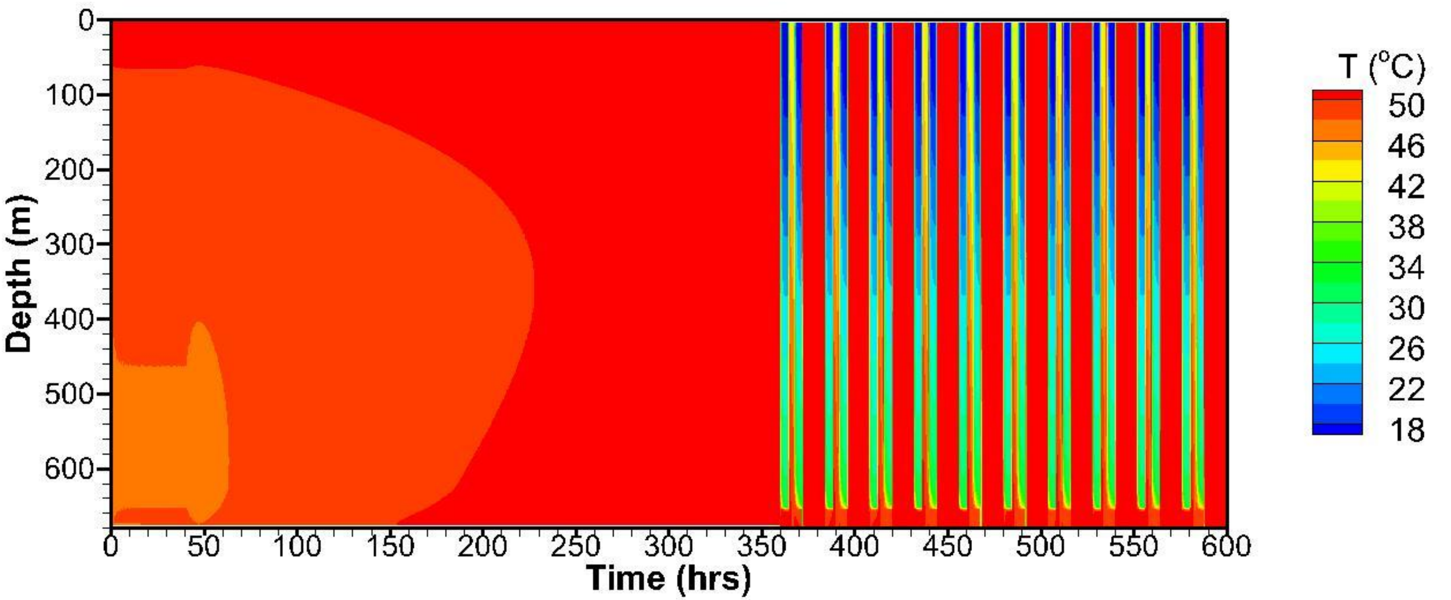

1.2E+07
1E+07
8E+06
6E+06
4E+06
2E+06
Pressure (Pa)
350
360
370
380
390
400
Time (hrs)
initial Fill
Shut-in
Production
Shut-in
Recharge
Shut-in
Production
Shut-in
Recharge
Wellhead
Wellbottom
100m away
500m away
1km away

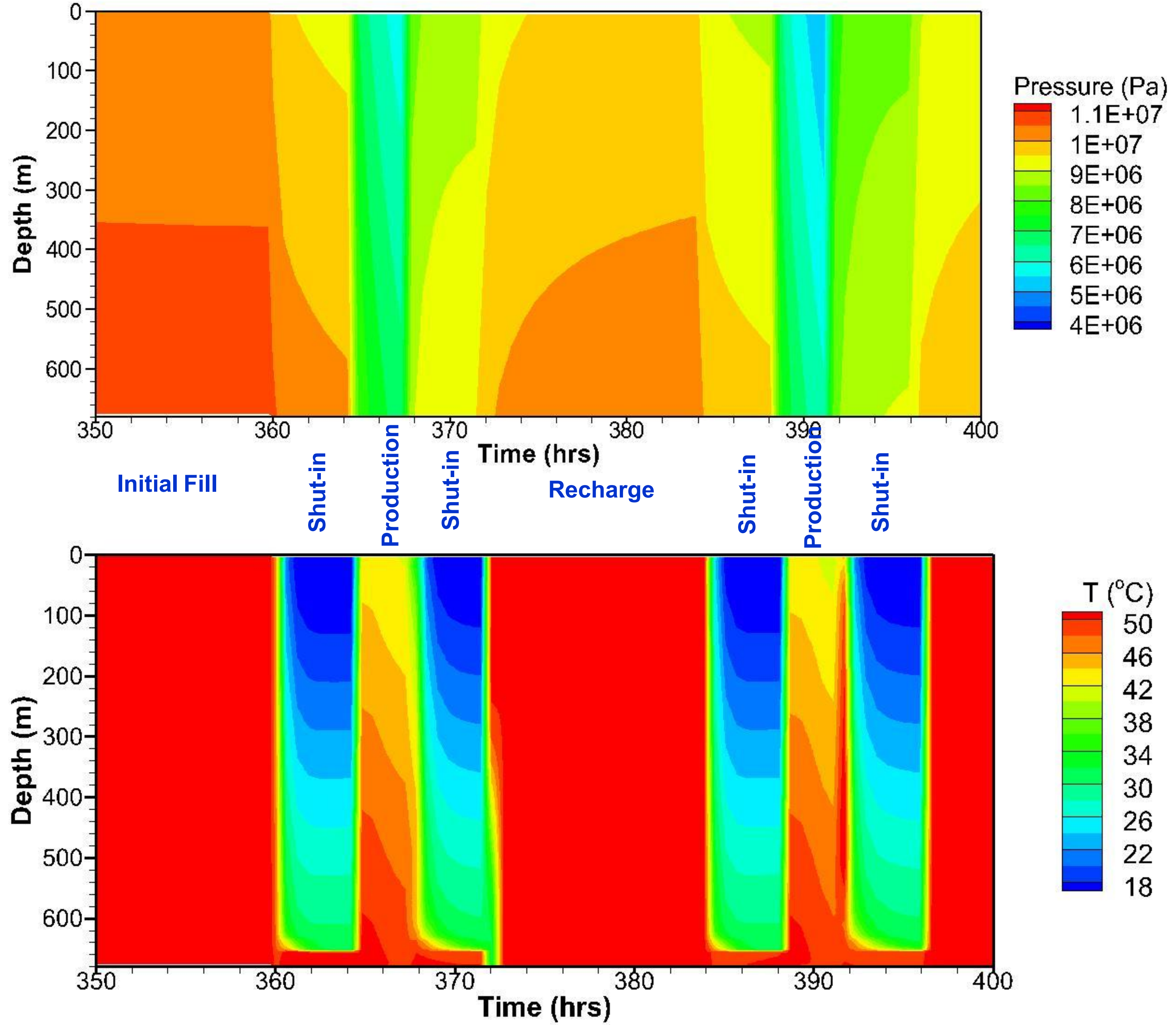

1E+07
0
-1E+07
-2E+07
-3E+07
0
100
200
300
400
500
600
Time (hrs)
Energy Flow Rate (W)
Production negative
Injection positive
Wellhead
1st P-section
100m away
500m away



Energy Flow Rate (W)
1E+07
0
-1E+07
-2E+07
-3E+07
350
360
370
380
390
400
Time (hrs)
initial Fill
Shut-in
Production
Shut-in
Recharge
Shut-in
Production
Shut-in
Recharge
Wellhead
1st P-section
100m away
500m away


Pressure (Pa)
1.1E+07
1E+07
9E+06
8E+06
7E+06
6E+06
5E+06
4E+06
Depth (m)
Time (hrs)


T (°C)
50
46
42
38
34
30
26
22
18
Depth (m)
Time (hrs)


Pressure (Pa)
1.1E+07
1E+07
9E+06
8E+06
7E+06
6E+06
5E+06
4E+06
Depth (m)
Time (hrs)
Initial Fill
Shut-in
Production
Shut-in
Recharge
Shut-in
Production
Shut-in
T (°C)
50
46
42
38
34
30
26
22
18
Depth (m)
Time (hrs)

Conclusions

- Climate change motivates CCS and increased use of renewables.
- Renewables need energy storage (e.g., CAES) to meet baseload requirements.
- CCS can potentially be coupled with CAES.
- Price on carbon would subsidize CAES project.
- CAES could benefit by super-cushion properties of CO_2.
- Initial simulations of coupled wellbore-aquifer CAES support the concept.

Acknowledgments

This work was supported in part by the Office of Science, U.S. Department of Energy, and by the Assistant Secretary for Fossil Energy (DOE), Office of Coal and Power Systems, through the National Energy Technologies Laboratory (NETL), and by Lawrence Berkeley National Laboratory under Department of Energy Contract No. DE-AC02-05CH11231 .