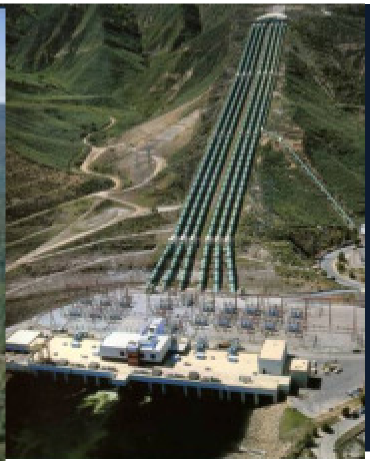
Understanding Pumped Storage Hydropower

Michael Manwaring, HDR Engineering
Chair, NHA Pumped Storage Development Council

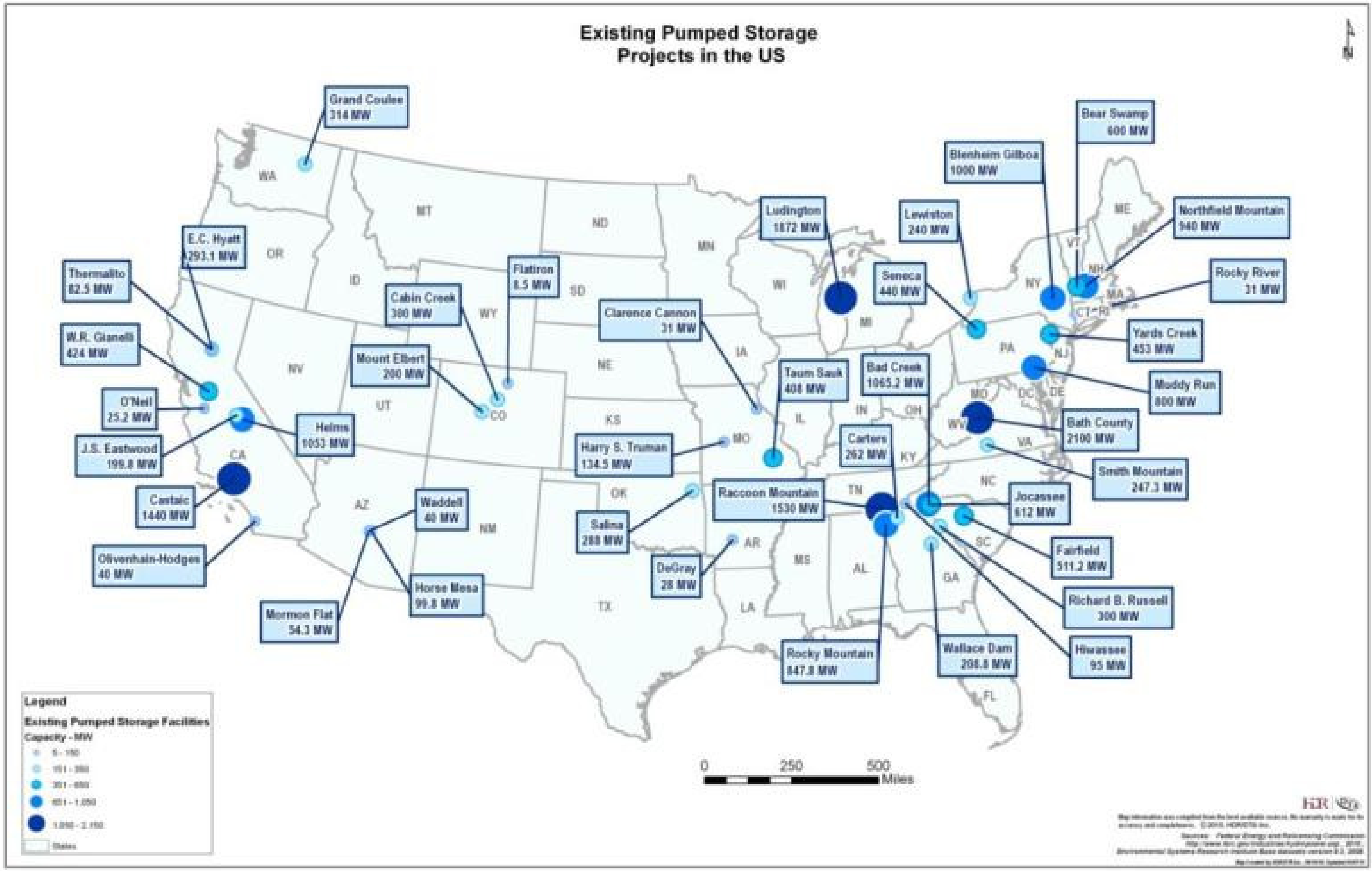


November 2012

Presentation Agenda

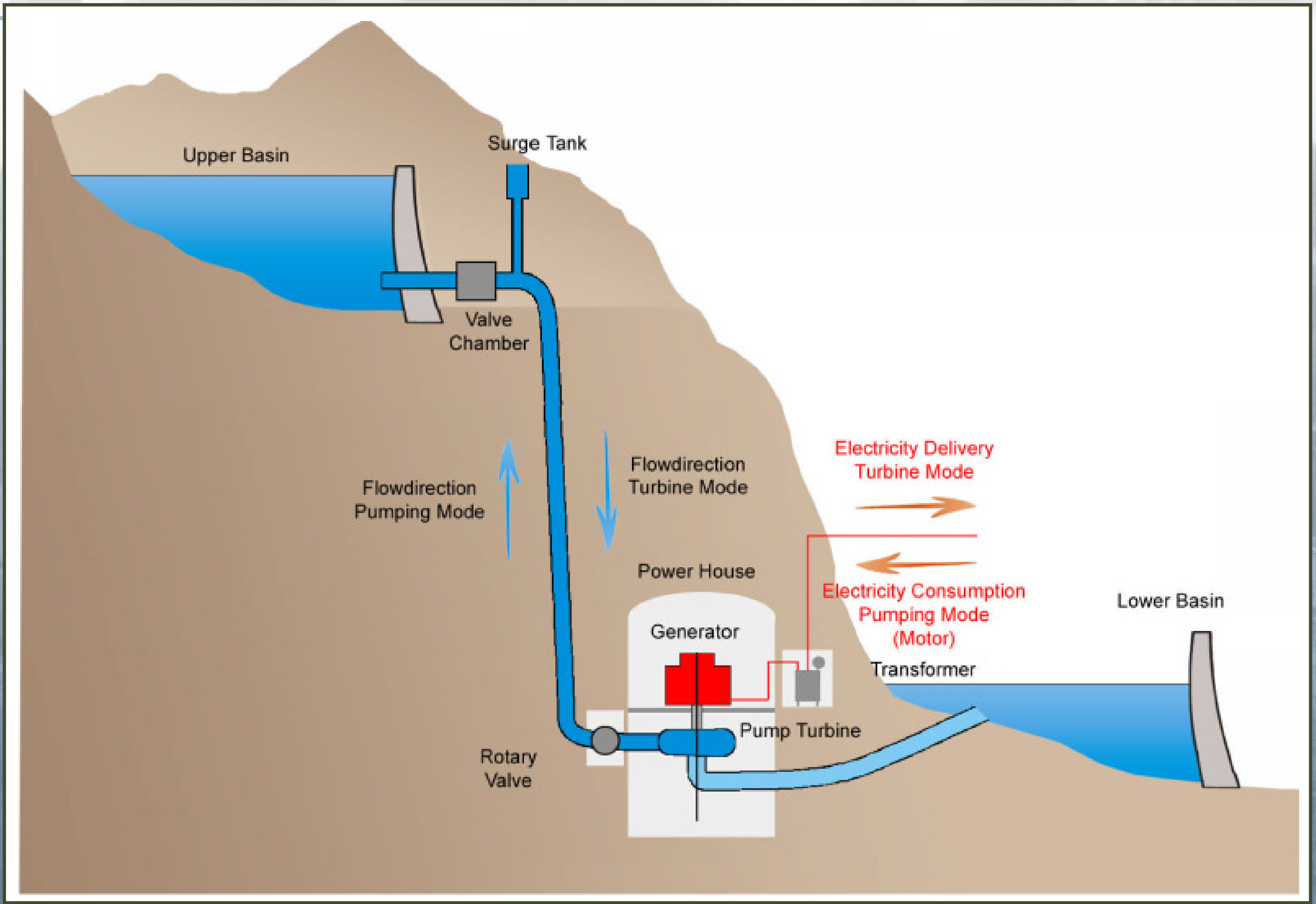
- General Overview – Historic Perspective
- Variable Renewable Energy Integration
- Siting a Pumped Storage Project
- Water Resource Needs
- Transmission Needs & Siting
- Overview of Markets

Existing U.S. Pumped Storage Projects

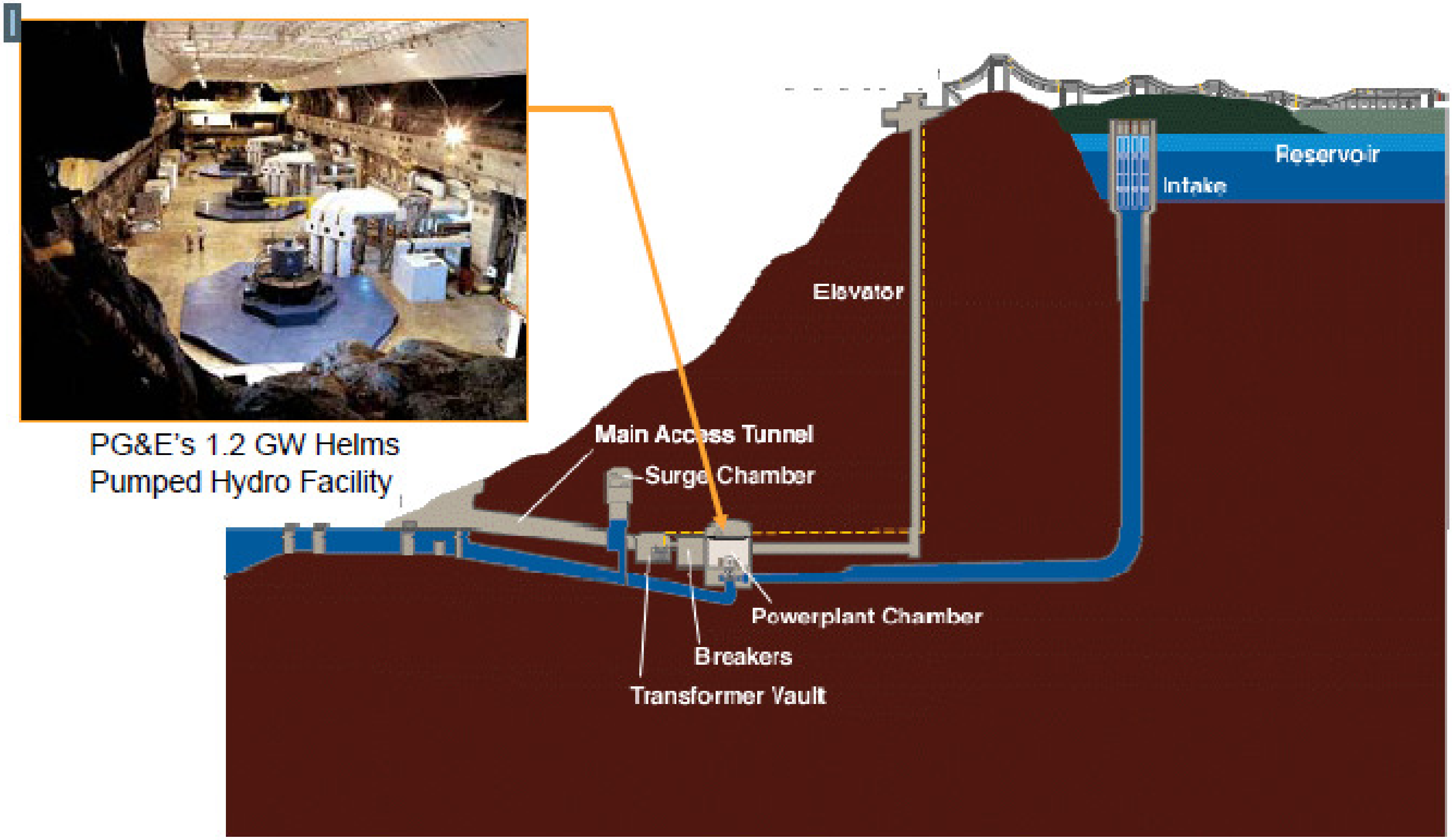


Jocassee & Bad Creek Pumped Storage Projects (Duke, South Carolina)

Pumped Storage Project Design Scheme



Pumped Storage Project Design Scheme



PG&E's 1.2 GW Helms
Pumped Hydro Facility

Overview: Challenges to Develop Pumped Storage

Projects are Capital Intense

- Licensing ($millions) → Construction/Operation ($billions)

Markets Limitations:

- Valuing services pumped storage and conventional hydropower provide (missing revenue streams)
- Level playing field for all energy storage technologies
- Regional differences in generation and energy storage needs
- Pumped Storage's role in energy security for domestic electric grid

Regulatory:

- Need for streamlined licensing for low-impact pumped storage projects (off-channel or closed-loop projects)

Pumped Storage Hydropower

Smallest U.S. Plants

- Flatiron (CO) – 8.5 MW (Reclamation)
- O'Neil (CA) – 25 MW

Largest U.S. Plant

- Rocky Mountain (GA) – 2100 MW
- Ludington (MI) – 1870 MW

First Pumped Storage Project

- Switzerland, 1909

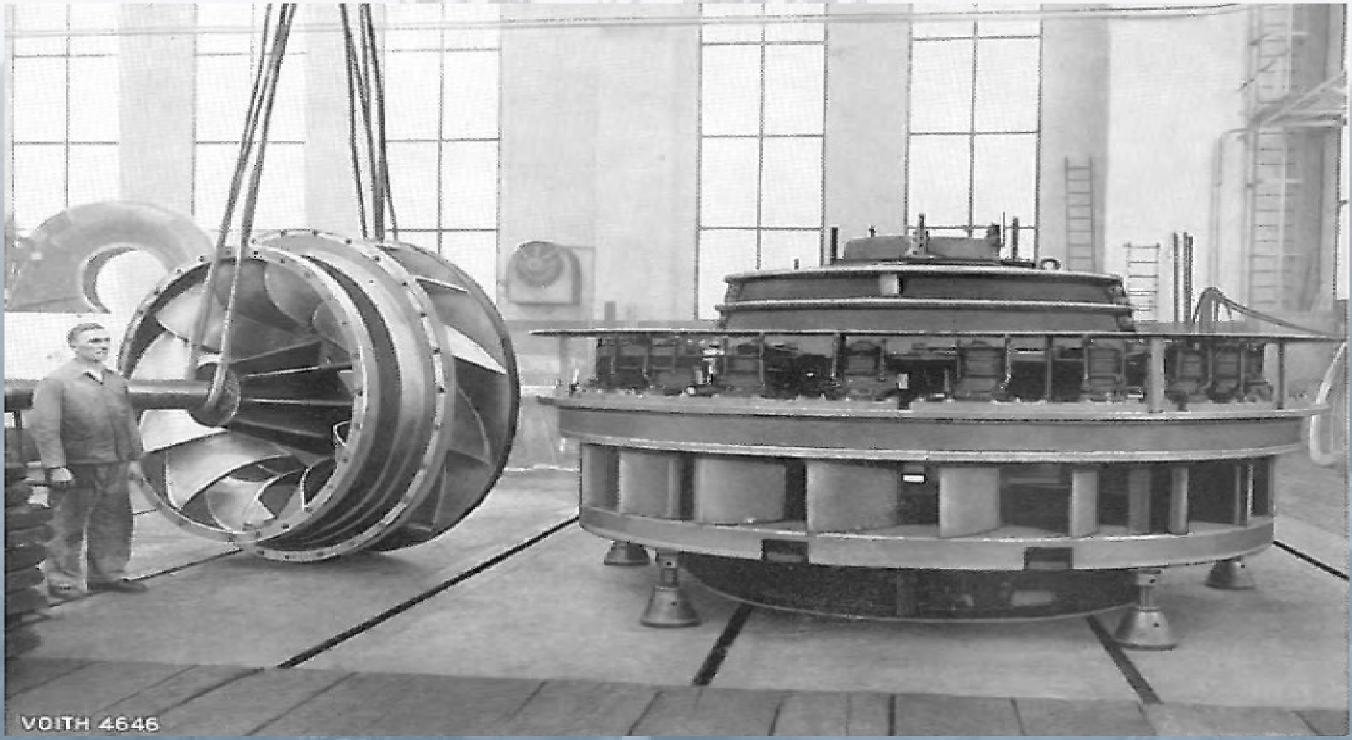
First U.S. Pumped Storage Project

- Connecticut, 1930s - Rocky River (now 31 MW)

Most Recent U.S. Pumped Storage Project

- California, 2010 - Olivenhain-Hodges (40 MW)

Pumped Storage Hydropower Development



Early reversible pumped storage unit 1937

Flatiron Powerplant - One 8.5 MW PS Unit (Reclamation, Colorado)

Rocky Mountain Pumped Storage Project – 760 MW (Oglethorpe Power, Georgia)

Why Pumped Storage Being Developed (Again)?

Support Increased Variable RE Generation

- DOE Goal of 20% Wind Penetration

Provides balancing, reserves and grid stability

- Remains a fundamental grid component

Most economical means of Energy Storage

- Plant design life of 50 to 100 years
- Other technologies design life - ??

Proven technology with major advancements

- Adjustable/Variable Speed
- Closed Loop Projects – minimal environmental impacts

Olivenhain-Hodges Pumped Storage Project - 40 MW (San Diego County Water Authority, California)

Where/Why is Pumped Storage Being Developed?

Europe is building Pumped Storage because:

- Significant integration of wind and solar
- Lack of access to natural gas for fast regulation/response
- Established markets/tariff structures for revenue
- Markets developing to “value” ultra-fast response

China is building Pumped Storage because:

- Want to self supply wind (over 42 GW in 2010)
- Transmission constraints limit grid integration

Japan built Pumped Storage because:

- Nat’l sponsorship to promote grid reliability (Island = self supply)
- Post Fukashima development

Where is Pumped Storage Being Developed?

Region	Total MW	% Total MW
Europe	5,297	33%
Asia (Excluding China & India)	4,250	26%
China	3,480	22%
India	900	6%
Middle East	1,368	8%
Russia	856	5%
Total	**16,151**	**100%**

PS Projects Under Construction, By Region, Outside of N. America

Country	Total MW	% Total MW
China	3,480	22%
Japan	3,450	21%
Switzerland	1,900	12%
South Africa	1,368	8%
Portugal	1,211	7%
Spain	1,027	6%
Austria	959	6%
India	900	6%
Russia	856	5%
South Korea	800	5%
Luxembourg	200	1%
Total	**16,151**	**100%**

PS Projects Under Construction, By Country, Outside of N. America

Okinawa Yanbaru Seawater Pumped Storage Project (Japan)

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- General Overview – Historic Perspective
- **Variable Renewable Energy Integration**
  - Maximizing RE Value
- Siting a Pumped Storage Project
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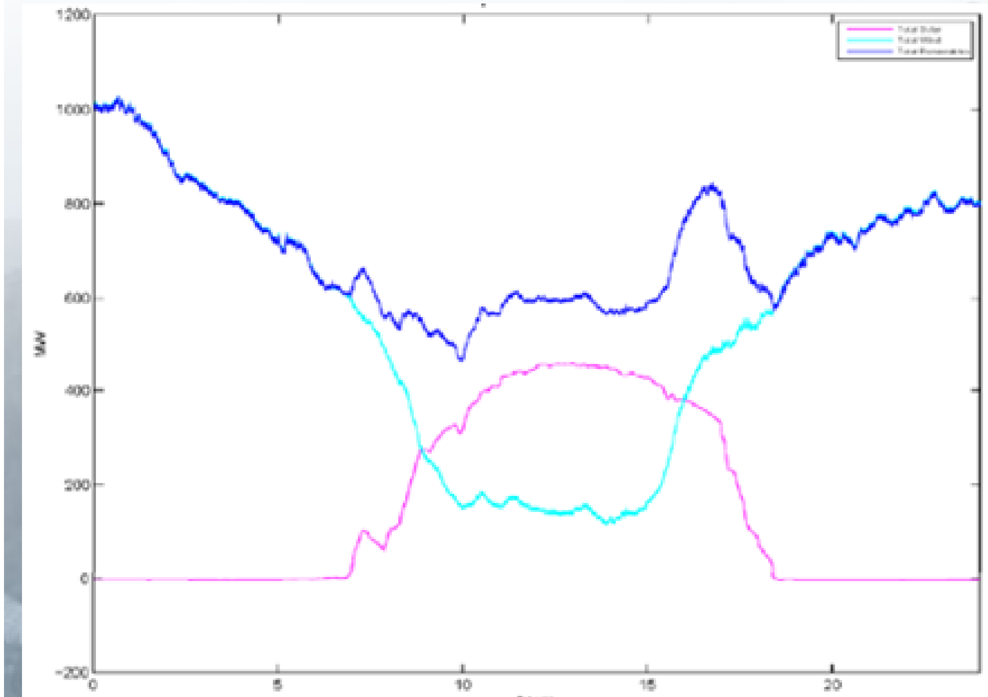
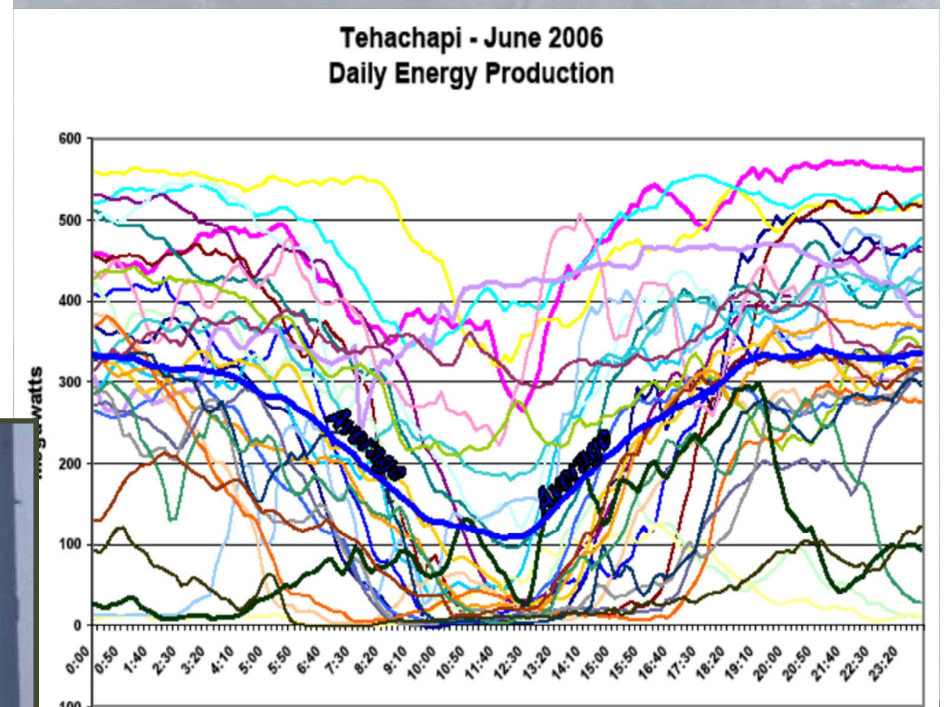
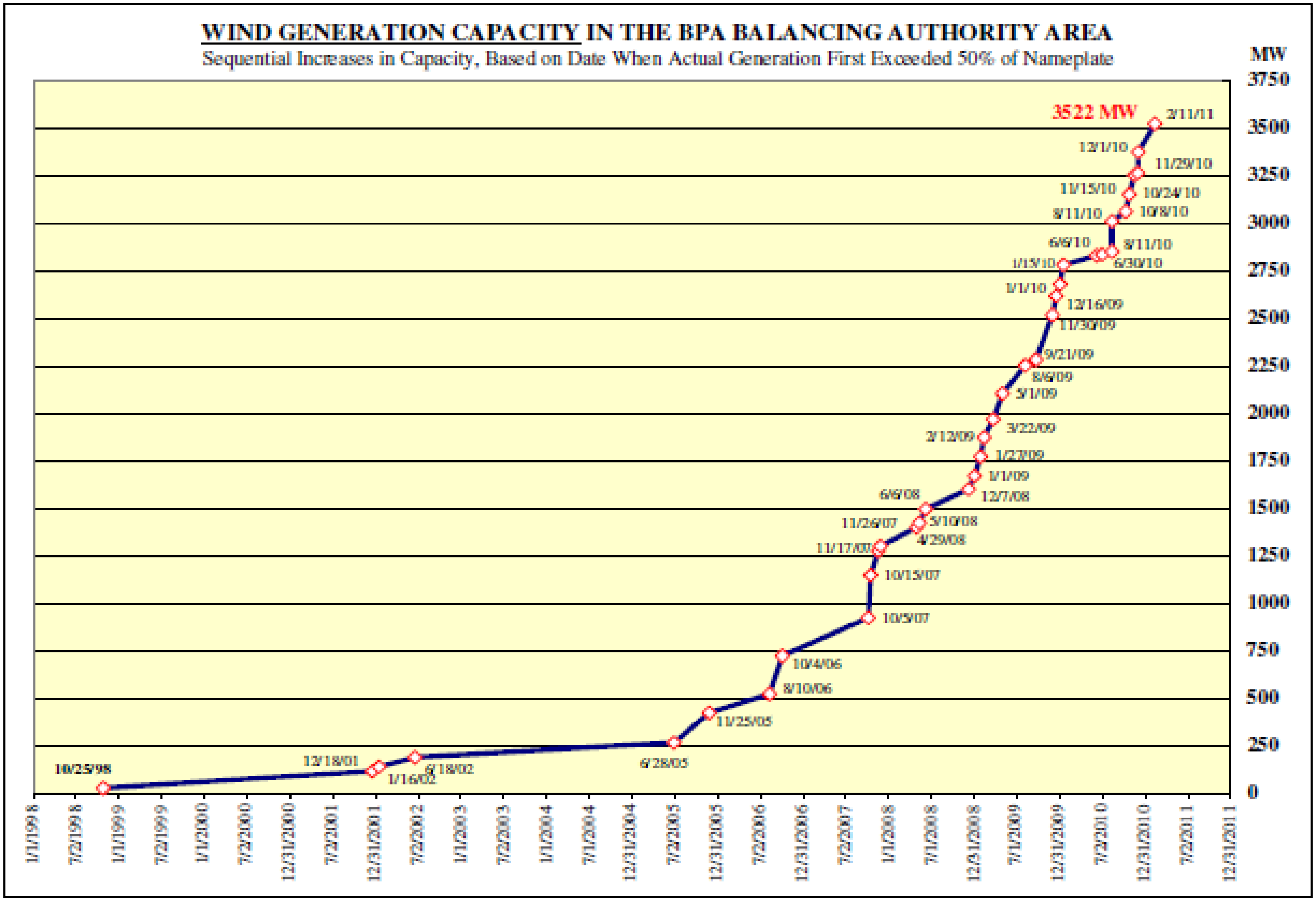
Variable Renewable Energy Integration Support





Variable Renewable Energy Integration Support



WIND_InstalledCapacity_current.xls 3/15/2011

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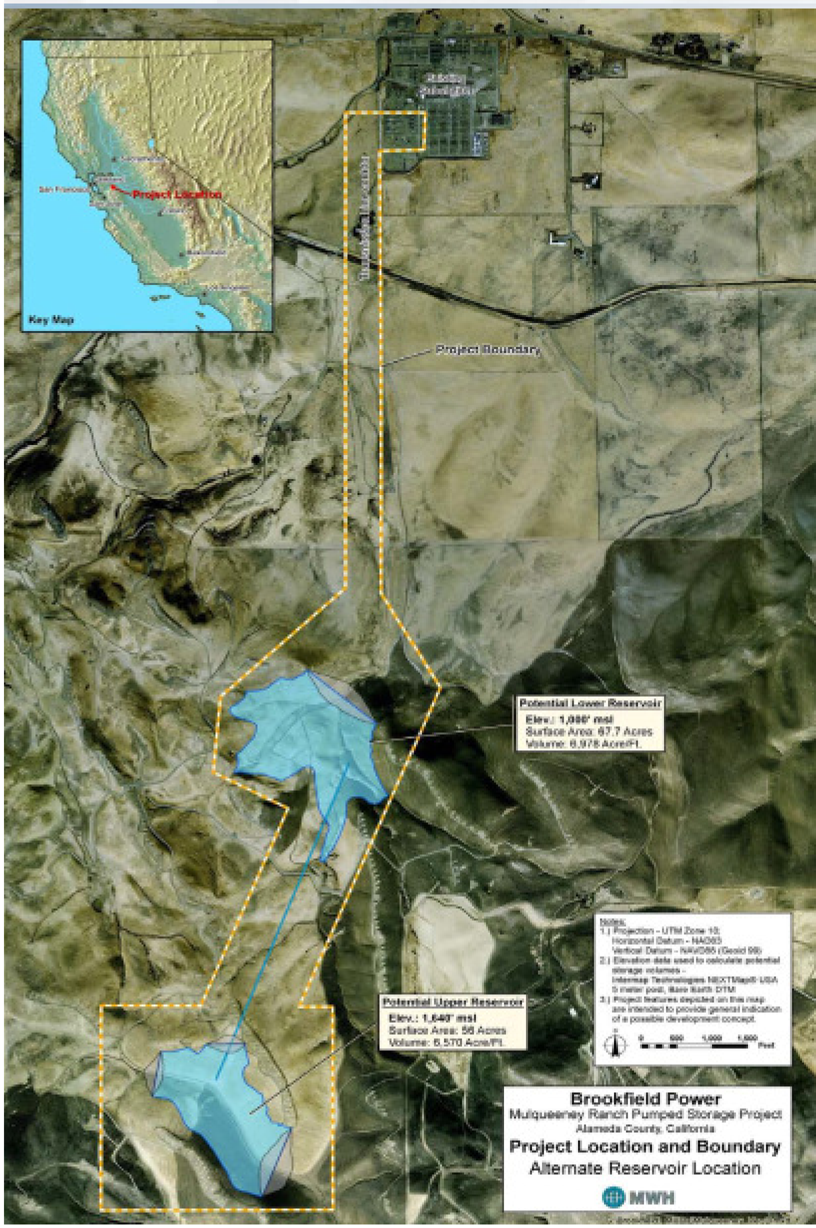
Siting a Pumped Storage Project

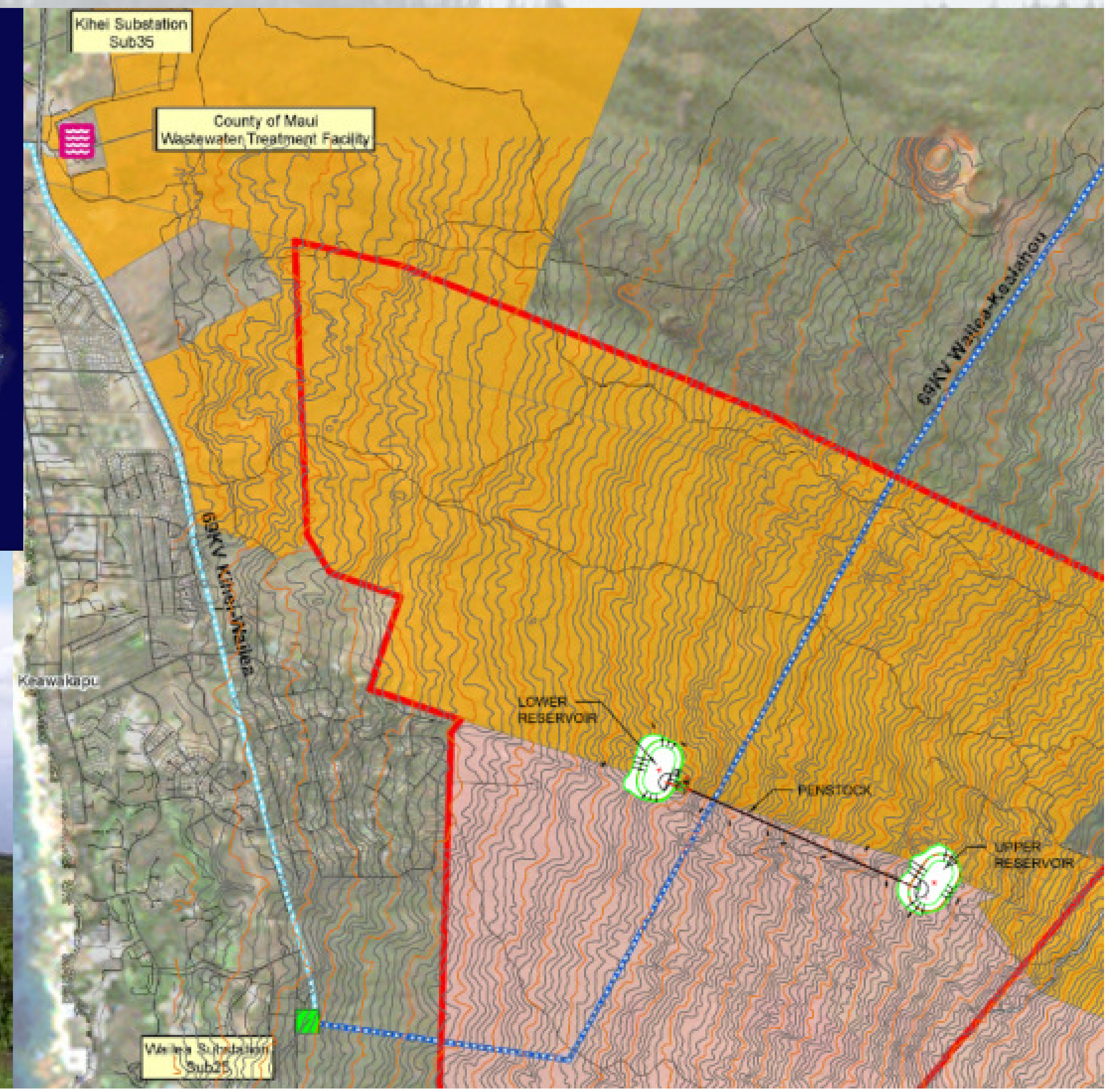
General Steps for

- Physical Evaluation
  - Elevation (head)
  - Availability to water (surface, ground or treated)
  - Geology (seismic and underground conditions)
  - Access to roads, transmission, etc.
- Regulatory
  - FERC Preliminary Permit
  - PAD and Environmental Studies
  - License Application
  - NEPA, CWA, ESA, etc.

Siting a Pumped Storage Project



Siting a Pumped Storage Project



Red Mountain Bar Pumped Storage Project (TID-Conceptual Design, California)

Agenda

- General Overview – Historic Perspective
- Variable Renewable Energy Integration
- Siting a Pumped Storage Project
- **Water Resource Needs**
  - Surface or Groundwater
  - Open or Closed Loop
  - Seasonal Management
- Transmission Needs & Siting
- Overview of Markets

Ludington Pumped Storage Project – 1870 MW (Consumers/DTE, Michigan)

Water Resource Needs

Surface Water – “Open Loop”/Stream Diversion

- Traditional PS project design
  - Issues: ESA, water temps, minimum flows, fish passage

Groundwater/Treated Water – Closed Loop

- New design to minimize Environmental impacts
  - Make-up water needed
  - Removes aquatic species issues
  - Potential avian issues with heavy reservoir fluctuations

Seasonal Management

- Concern with Open Loop
  - Minimum flows, drought tolerance, water temperatures

Castaic Pumped Storage Project (LADWP/DWR, California)

John Key's Pump-Generating Plant (BPA, Washington)

Agenda

- General Overview – Historic Perspective
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- Siting a Pumped Storage Project
- Water Resource Needs
- **Transmission Needs & Siting**
- Overview of Markets

Transmission Needs & Siting

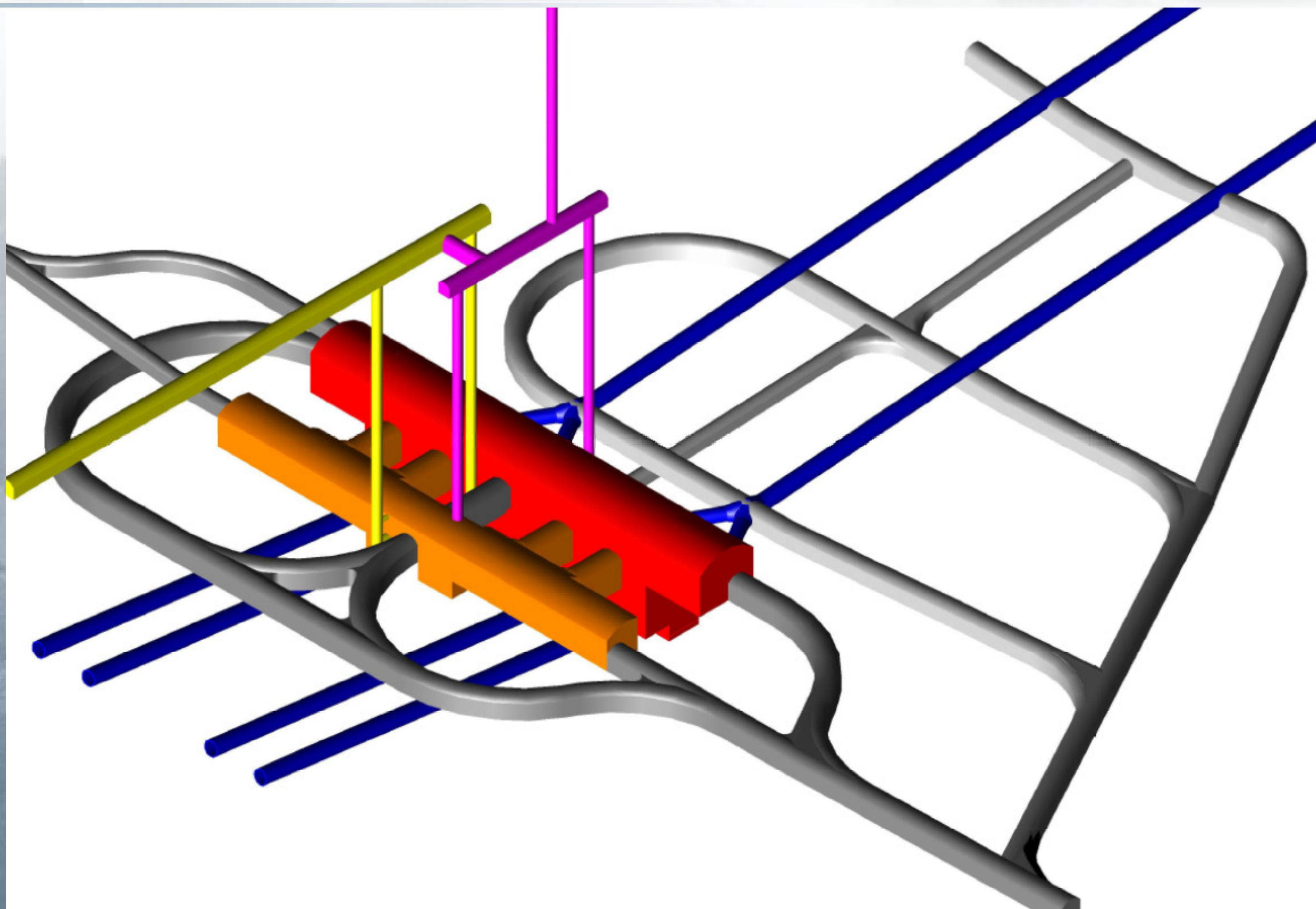
Transmission Line Information

- Size Information
  - Typically range from 230 kV to 500 kV
- Length
  - Cost: $2M/mile so length is important
- Interconnection Study Needs
  - Typically occur after License Application ready
  - Most States don't have PS-specific forms
  - PS projects can occur significant costs ($$$)

Powerhouse and Substation Considerations

- Surface or Subsurface
  - Design of tunnels/surface shafts are important

Conceptual Pumped Storage Underground Powerhouse and Tunneling Scheme



Raccoon Mountain Pumped Storage Project (TVA, Tennessee)

Agenda

- General Overview – Historic Perspective
- Variable Renewable Energy Integration
- Siting a Pumped Storage Project
- Water Resource Needs
- Transmission Needs & Siting
- **Overview of Markets**
  - **Market Barriers**
  - **Market Opportunities**

Overview of Markets

Market Opportunities

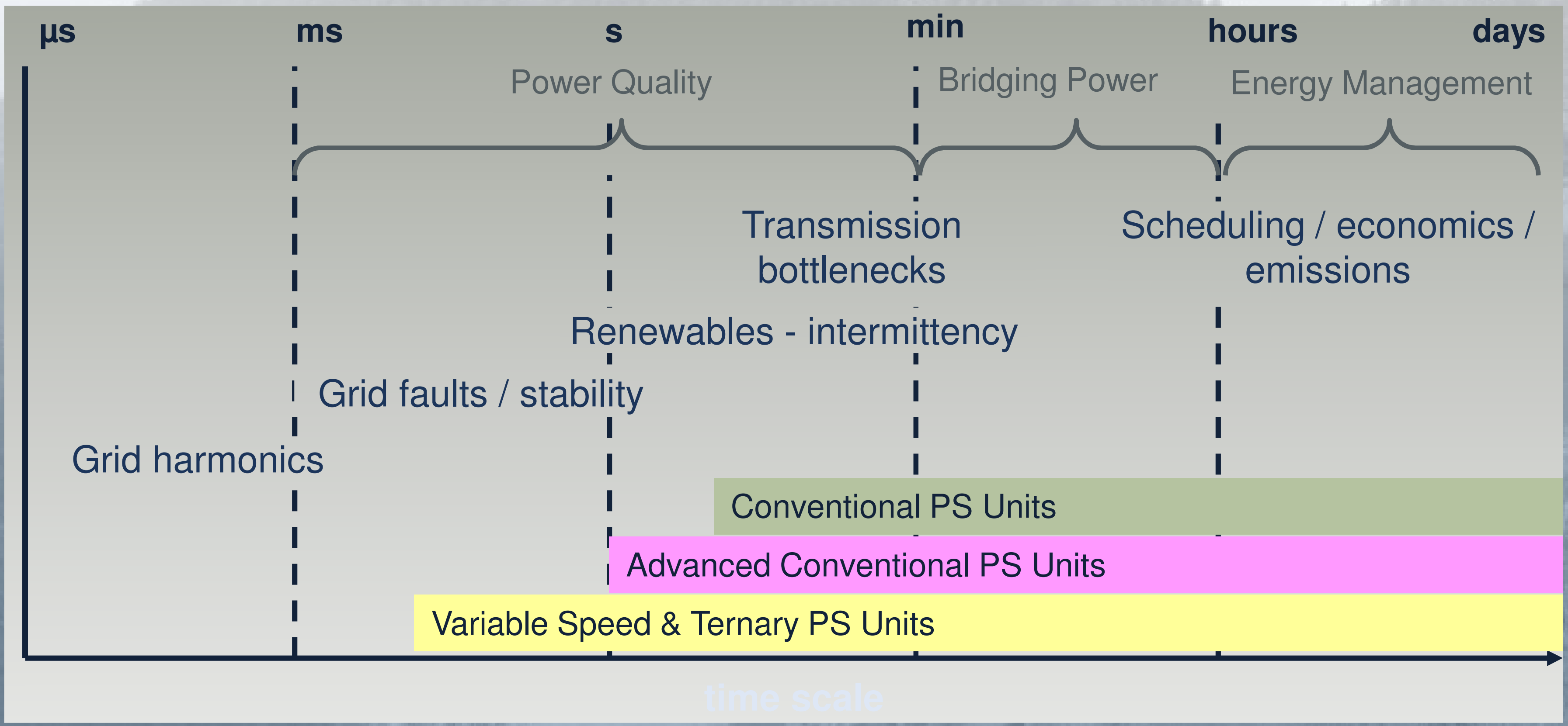
- Transparent Prices for Energy and Ancillary Services
- Energy Storage Technologies Treated Equally (almost)
- Energy Market (Regional)
  - Arbitrage, Day-ahead hourly, Hour ahead, 15 or 5-minute
- Ancillary Services Market (Regional)
  - Frequency Regulation
  - Spinning and Non-Spinning Reserves
  - Voltage Support/Reactive Power
  - Black Start
  - Capacity
  - Customer Energy Management (Demand Side)
- Shorter FERC Licensing Timeline (development)

Ancillary Services PS Can Provide

Ancillary Services are products (other than energy) necessary to support capacity and the transmission of energy from resources to loads, while maintaining reliable operation and power quality of the Electric Grid.

- Frequency Regulation – instantaneous balancing of the grid
- Spinning Reserves – able to very quickly provide inc. or dec. support
- Non-Spinning Reserves – able to start and ramp up to provide inc. or dec. support
- Voltage Support/Reactive Power – maintain balance on a regional level
- Black Start – ability to restart remotely in the event of an outage
- Load Following and Peak Shaving
- T&D Facility Deferral
- Customer Energy Management – Demand side

Electric Grid Power Control Issues and Pumped Storage Solutions

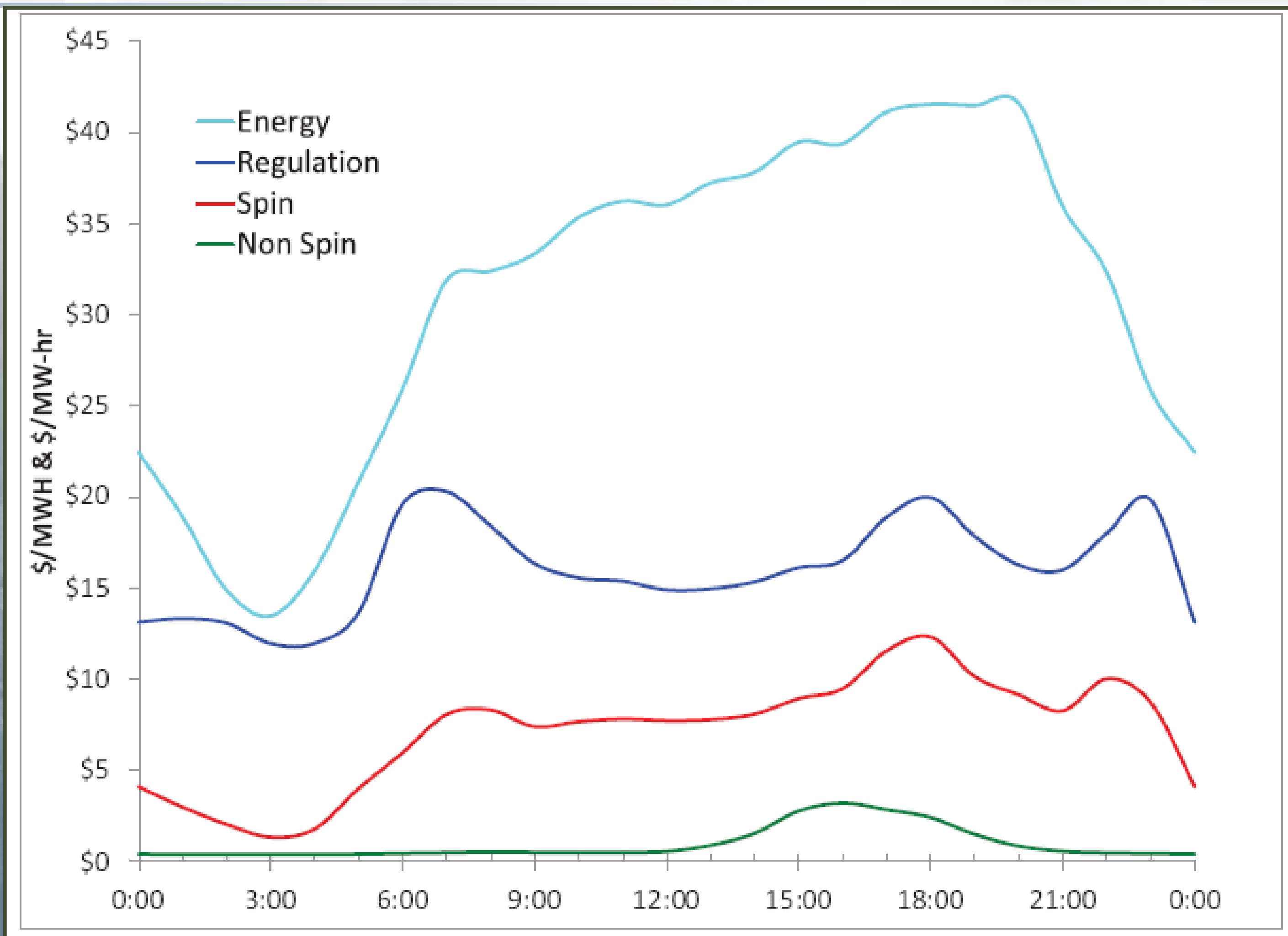


CA ISO - Ancillary Service Markets (Trend shows market is "Recovering")

	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
	CAISO Annual **Average** and Maximum Ancillary Service Prices ($/MW-hr)									
Regulation	**26.9**	**35.5**	**28.7**	**35.2**	**38.5**	**26.1**	**33.4**	**12.6**	**10.6**	**16.1**
(up+down)	111	164	166	188	399	421	618	500	124	120
Spin	**4.3**	**6.4**	**7.9**	**9.9**	**8.4**	**4.5**	**6.0**	**3.9**	**4.1**	**7.2**
	250	92	125	110	225	400	400	416	66	48
Non-Spin	**1.8**	**3.6**	**4.7**	**3.2**	**2.5**	**2.8**	**1.3**	**1.4**	**0.6**	**1.0**
	92	92	129	125	110	400	399	416	66	35
Replacement	**0.90**	**2.9**	**2.5**	**1.9**	**1.5**	**2.0**	**1.4**			
	80	55	90	36	70	175	244			

Courtesy of Kirby Consulting (www.consultkirby.com)

Ancillary Service Markets (Varies by Time of Day)



Courtesy of Kirby Consulting (www.consultkirby.com)

Ancillary Service Markets
(Trend shows decrease in value)

	2002	2003	2004	2005	2006	2007	2008	2009	2010
	Annual Average $/MW-hr								
California (Reg = up + dn)									
Regulation	26.9	35.5	28.7	35.2	38.5	26.1	33.4	12.6	10.6
Spin	4.3	6.4	7.9	9.9	8.4	4.5	6.0	3.9	4.1
Non-Spin	1.8	3.6	4.7	3.2	2.5	2.8	1.3	1.4	0.6
Replacement	0.90	2.9	2.5	1.9	1.5	2.0	1.4		
ERCOT (Reg = up + dn)									
Regulation		16.9	22.6	38.6	25.2	21.4	43.1	17.0	18.1
Responsive		7.3	8.3	16.6	14.6	12.6	27.2	10.0	9.1
Non-Spin		3.2	1.9	6.1	4.2	3.0	4.4	2.3	4.3
New York (east)									
Regulation	18.6	28.3	22.6	39.6	55.7	56.3	59.5	37.2	28.8
Spin	3.0	4.3	2.4	7.6	8.4	6.8	10.1	5.1	6.2
Non Spin	1.5	1.0	0.3	1.5	2.3	2.7	3.1	2.5	2.3
30 Minute	1.2	1.0	0.3	0.4	0.6	0.9	1.1	0.5	0.1
New York (west)									
Regulation	18.6	28.3	22.6	39.6	55.7	56.3	59.5	37.2	28.8
Spin	2.8	4.2	2.4	4.9	6.0	5.4	6.2	4.2	4.4
Non Spin	1.4	1.0	0.3	0.6	0.9	1.6	1.7	1.7	0.9
30 Minute	1.2	1.0	0.3	0.4	0.6	0.9	1.1	0.5	0.1
MISO (day ahead)									
Regulation								12.3	12.2
Spin								4.0	4.0
Non Spin								0.3	1.5
New England (Reg +"mileage")									
Regulation			54.64	30.22	22.26	12.65	13.75	9.26	7.07
Spin					0.27	0.41	1.67	0.71	1.75
10 Minute					0.13	0.34	1.21	0.47	1.15
30 Minute					0.01	0.09	0.06	0.08	0.42

Courtesy of Kirby Consulting (www.consultkirby.com)

Overview of Markets

Market Challenges/Barriers

- Deregulation – long-term system planning
- No long-term markets (spot/day-ahead only)
  - No project financing without long-term contracts
  - Some important benefits aren't recognized
    - PS & Large Hydro stabilize energy prices
    - Grid Security/Reliability
    - Portfolio Optimization – other products are more efficient
    - Transmission Line Deferral (new or upgrades)
    - RE Energy "Recycling" (optimize use of wind & solar)
- Regulated Transmission vs Competitive Generation
- Natural Gas – similar services and low cost (today)

Overview: Challenges to Develop Pumped Storage
NHA "Asks" of FERC and ISOs/PUCs

Markets Needs:

- Valuing services pumped storage and conventional hydropower provide (missing revenue streams)
- Level playing field for all energy storage technologies
- Regional differences in generation and energy storage needs
- Pumped Storage's role in energy security for domestic electric grid

Regulatory Needs:

- Need for streamlined licensing for low-impact pumped storage projects (off-channel or closed-loop projects)
- Reconcile Regulated transmission & Competitive generation
  - Markets: "We need it but cannot help pay for it"

Goldisthal Pumped Storage Project (Vattenfall , Germany)

Questions?

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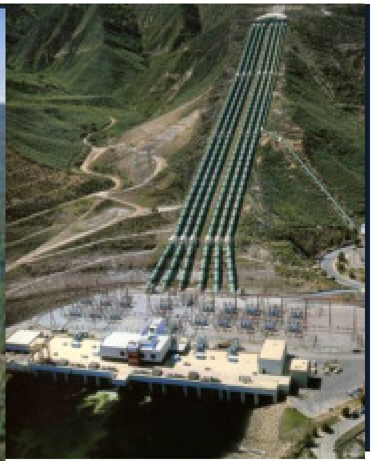

November 2012

Extra Slides

Michael Manwaring – HDR Engineering
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How does pumped storage hydro compare with other storage technologies?

Source: Alstom Power & HDR

	Energy Storage Technology	Operating principle	System output	Backup time / Reaction time	Cycle efficiency	Energy density	Applications
Batteries	Conventional (Li-ion,Ni-Cd,Pb)	Static liquid or solid electrodes/anode materials	100 kW – 10 MW	min - hours / seconds	70 - 90% Li-ion: 95%	Li-ion: 290 Ni-Cd: 150 kWh/m^3	Transportation UPS Power quality Load leveling
Batteries	Flow Cell/Advanced (VRB, ZnBr,NaS)	Two electrolytes are separately stored	100 kW – 10 MW	min - hours / seconds	60 - 80%	VRB: 6 NaS: 42 kWh/m^3	Load leveling Renewables storage
Kinetic	Flywheels	Massive rotating cylinder stores/delivers energy via motor/generator mounted on stator	5 kW – 3 MW	sec - min / seconds	95%	2 kWh/m^3	Voltage/Frequency stabilization Power quality Transportation
Potential	CAES	Off-peak electricity used to compress air	10 MW – 200 MW	hours / minutes	65-75%	6 kWh/m^3	Energy Arbitrage Renewables Integration
Potential	Pump Storage	Off-peak electricity used to pump water to storage lake	100 MW – 2000 MW	days / seconds - minutes	75 - 85%	5 kWh/m^3	Energy Arbitrage Renewables Integration Grid Reliability Ancillary Services
Electrical	Super Capacitors	High surface area electrode materials used to enhance capacitors to higher power/energy	< 1 MW	milliseconds / milliseconds	95%	6 kWh/m^3	Power quality
Chemical	Bulk Hydrogen (concept)	Hydrolysis with surplus electricity to obtain H_2 Bulk storage H_2, H_2 direct use + turbining	500 MW - 1000 MW	days-months/ minutes	35 - 40%	2700 kWh/m^3	Mobility, Chemistry, Electrification with turbine-generator

Developmental Challenges in the U.S.

CHANGING REGULATORY LANDSCAPE – GRID IMPACTS

Once Through Cooling Rule (EPA 316b)

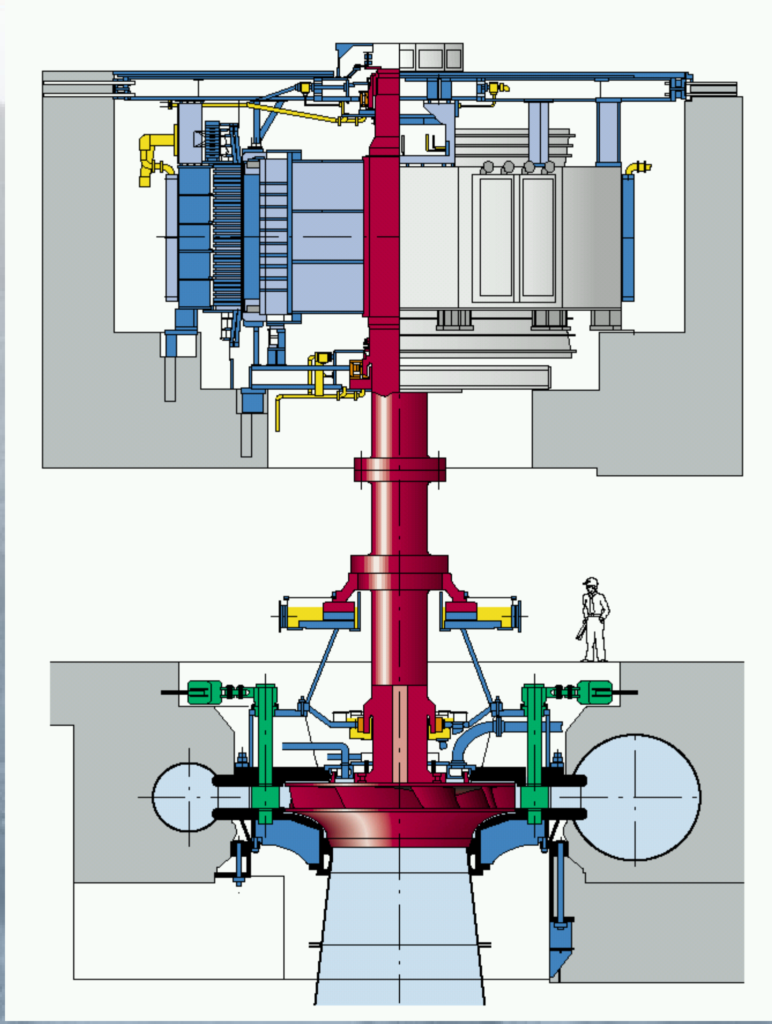
- Retirement of Older Fossil Generating Plants
  - Up to 22,000 MW (CA Alone)
  - Up to 70,000 MW (Eastern U.S.)

Loss of System Inertia for Grid Stability

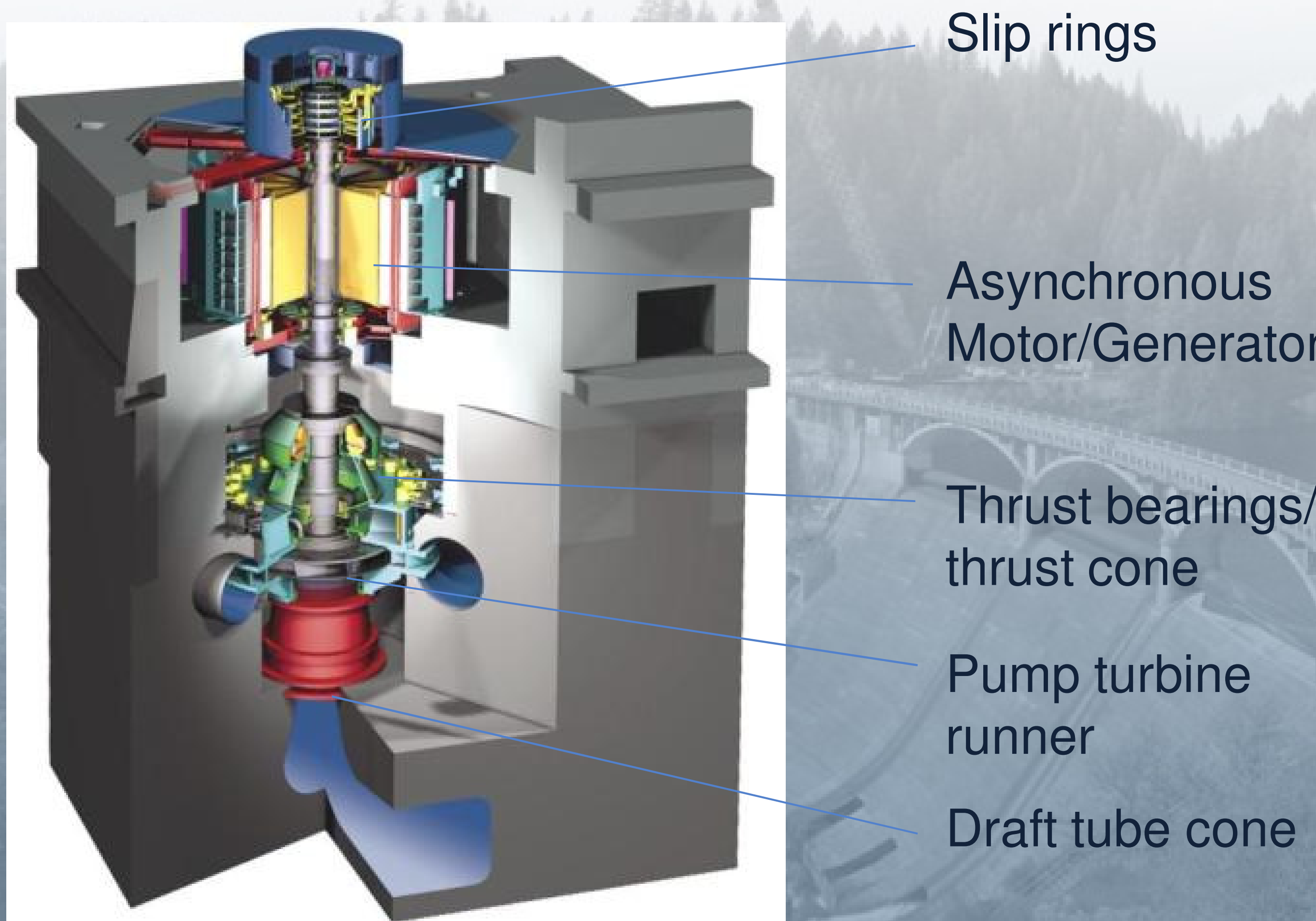
- "Rotating Copper"
  - Resources Not Replaced by Wind/Solar

Conceptual Pumped Storage Underground Powerhouse Turbine Scheme

Conventional Reversible Pumped Storage Unit



Components of Variable Speed Reversible Pumped Storage Unit



Pumped-Storage "Response" Time

Pumped Storage & Hydroelectric

- 10 to 59 MW .... 1% to 6% per second
- Above 60 MW .... 4% to 6% per second

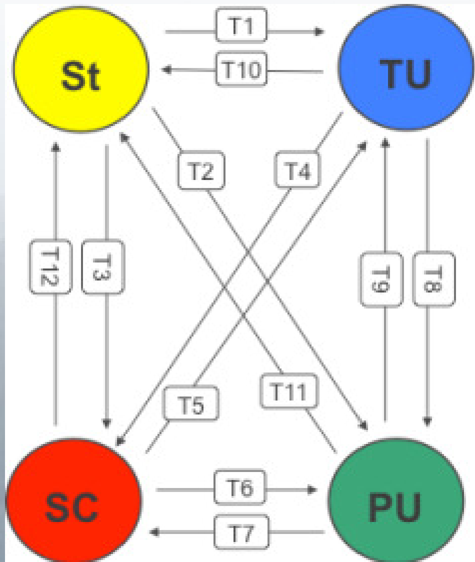
Combustion Turbines

- All sizes .... 55% per minute

Steam Units (all fuels)

- 10 to 50 MW .... 4% to 8% per minute
- 60 to 199 MW .... 3% to 8% per minute
- Above 200 MW .... 2% to 8% per minute

Mode change times for various Unit concepts -

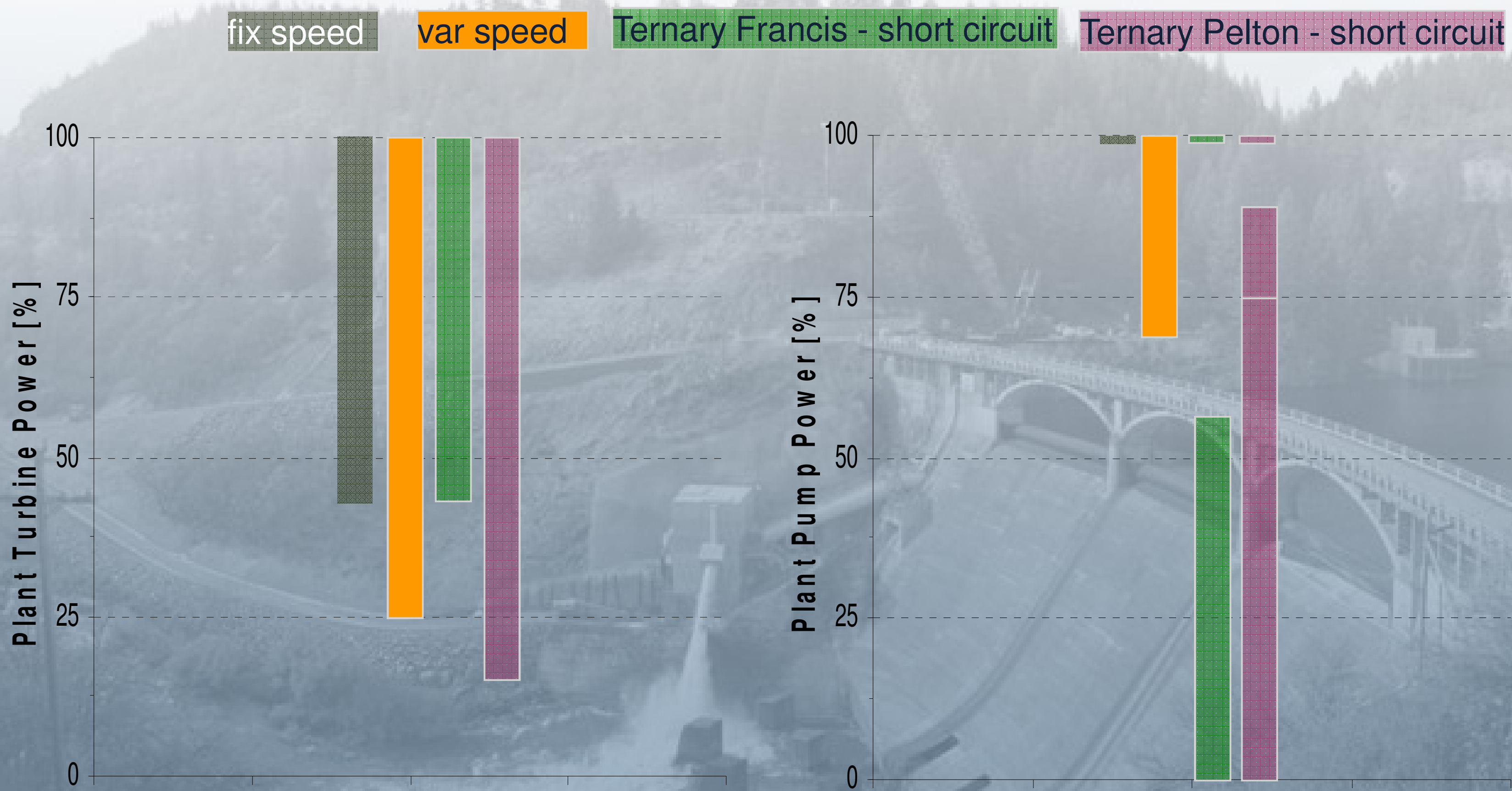


T	Pump Turbine Mode change			time [seconds] A	B	C	D	E
1	Standstill	→	TU-Mode	90	75	90	90	65
2	Standstill	→	PU-Mode	340	160	230	85	80
5	SC-Mode	→	TU-Mode	70	20	60	40	20
6	SC-Mode	→	PU-Mode	70	50	70	30	25
8	TU-Mode	→	PU-Mode	420		470	45	25
9	PU-Mode	→	TU-Mode	190	90	280	60	25

Reversible PT
A – advanced conventional (2012)
B – extra fast response conventional
C – VarSpeed,

Ternary set
D – with hydraulic torque converter + hydr. short circuit, horiz, with Francis Turbine
E – same as E but vertical with Pelton Turbine

Plant Regulation Capability for Various Types of Advanced Pumped Storage Solutions



Adjustable Speed Pumped Storage Fast Response Capabilities