



Education

Green Storage I: Economics, Environment, Energy, and Engineering

SW Worth, Microsoft

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Abstract for “Green Storage I”

Even non-geeks are becoming aware of the environmental impacts (especially energy costs) associated with data storage. Discussions of “Green Storage” require understanding of fundamental concepts common to all components of a datacenter. This SNIA Tutorial covers the concepts of Economics, Environment, Energy, and Engineering that are necessary to participate in the dialogue, whether you are a manager or a hands-on I.T. professional. Wherever possible, the examples used refer to Storage, but detailed focus on Storage components and technologies is left for Part II.

We start with definitions of “Green” used by various groups, covering various motivations for making “Green” decisions for your organization. This requires some economic theory, but you will be rewarded with a new-found ability to explain “Cap-and-Trade” management of Carbon and “SOx” (Sulfur Oxides, not Sarbanes-Oxley!) at cocktail parties. This leads naturally to coverage of various environmental regulations and initiatives (e.g. ROHS, WEEE, Energy Star) that affect manufacturers and end-users of storage components or computers. We will quickly review basic engineering topics relevant to understanding 'Green', including stuff you may have successfully avoided, such as environmental chemistry, thermodynamics, energy vs. power, and heat transfer. (Examples include conversion losses, AC and DC power choices, and power supply efficiency.) Since much of the focus in I.T. is on energy costs, we'll spend some time understanding energy supply and pricing (focused on the U.S. market), and provide some negotiating alternatives for dealing with your friendly energy suppliers. We will review current problems in data center design, including increasing computational and storage density and the resulting energy and cooling issues. All of this will come together to help guide your design process towards a better allocation of capital expenses (CapEx) and operational expenses (OpEx) to lower your TCO.

Bottom-line: After this session you will be armed with the knowledge you need to be part of the Green decision-making process for your datacenter, so those pesky server-geeks don't dominate the discussion!

Learning Objectives

- ◆ Understand what various groups mean by 'Green', especially as this term relates to storage network components and systems.
- ◆ Understand factors that should (or will) motivate your interest in 'Green' storage, including regulation, competition, and TCO.
- ◆ Understand why 'OpEx' (Operating expenses) can outweigh 'CapEx' (Capital expense) in TCO models, and how 'Green' factors increasingly influence OpEx.

Green Storage I - Agenda

- **Overview, Motivation, and Definitions**
- eWaste Reduction/Recycling: RoHS, WEEE, etc.
- Fundamentals of Energy and Cooling
- Electricity Pricing in the United States
- Datacenter Design and Operation
- Storage Components and Technologies

Overview and Definitions

- “Green” ~ = Reduction of (Waste + Energy Use)
 - ◆ Gov’t. (EPA, EU, Kyoto), Green Grid, Vendors, etc.
- Classic motivators: Fear, Guilt, Greed
 - ◆ Constraints, Competition, and ProfitMax/CostMin
 - ◆ Strategy (CapEx) vs. Tactics (OpEx)
- How does “Green” differ from normal economic considerations, e.g. efficiency, optimization?
 - ◆ Rationalize decisions by including “**externalities**” Widen scope of action across org boundaries, time
- “Green” effects on Storage decisions

- ▶ “Fear”: Constraints (Regulations, Physical limits)
 - ◆ Do what you are forced to do by Gov’t. Regulations
 - ◆ Do what you can within physical limits
 - › E.g. WAN latency, Disk rotation speed
- ▶ “Guilt”: Competitive and ‘Moral’ aspects
 - ◆ Keeping up with industry, responding to non-economics
- ▶ “Greed”: Profit Maximization / Cost Minimization
 - ◆ Strategy → Capital Expenses (CapEx)
 - ◆ Tactics → Operational Expenses (OpEx)
 - ◆ TCO (Total Cost of Ownership) integrates CapEx and OpEx

Externalities

- Problem: some important inputs or outputs (e.g. Carbon) have unclear prices or owners
 - ◆ Some factors are effectively Zero-cost to the decision-maker, but are not cost-free to larger group affected
 - ◆ This leads to non-optimal decisions and behavior
 - › ‘Tragedy of the commons’
 - › Classic solutions: Government mandates (Regulation)
 - › Separate accounting system, e.g. for Carbon “Footprint”
 - › Unintended Consequences
- Pigouvian taxes
- Coase’s Theorem: Property Rights, Negotiation
 - ◆ Examples: Cap-and-Trade SO_x/NO_x, Carbon offsets

“Green” effects on Storage

- “TCO” (Total Cost of Ownership) now combines with Externalities to affect purchase decisions
 - ◆ In most cases Externalities will evolve to provide clear pricing signals (e.g. RoHS, WEEE)
- Expand scope of decision-criteria and constraints to include (at least) entire datacenter
 - ◆ Servers, Networking, and Storage
 - ◆ People: widen their decision-boundaries, -constraints
 - ◆ Facilities managers, especially power and cooling
- Unintended Consequences: reduced reliability?

Three Stages of Product “Life”

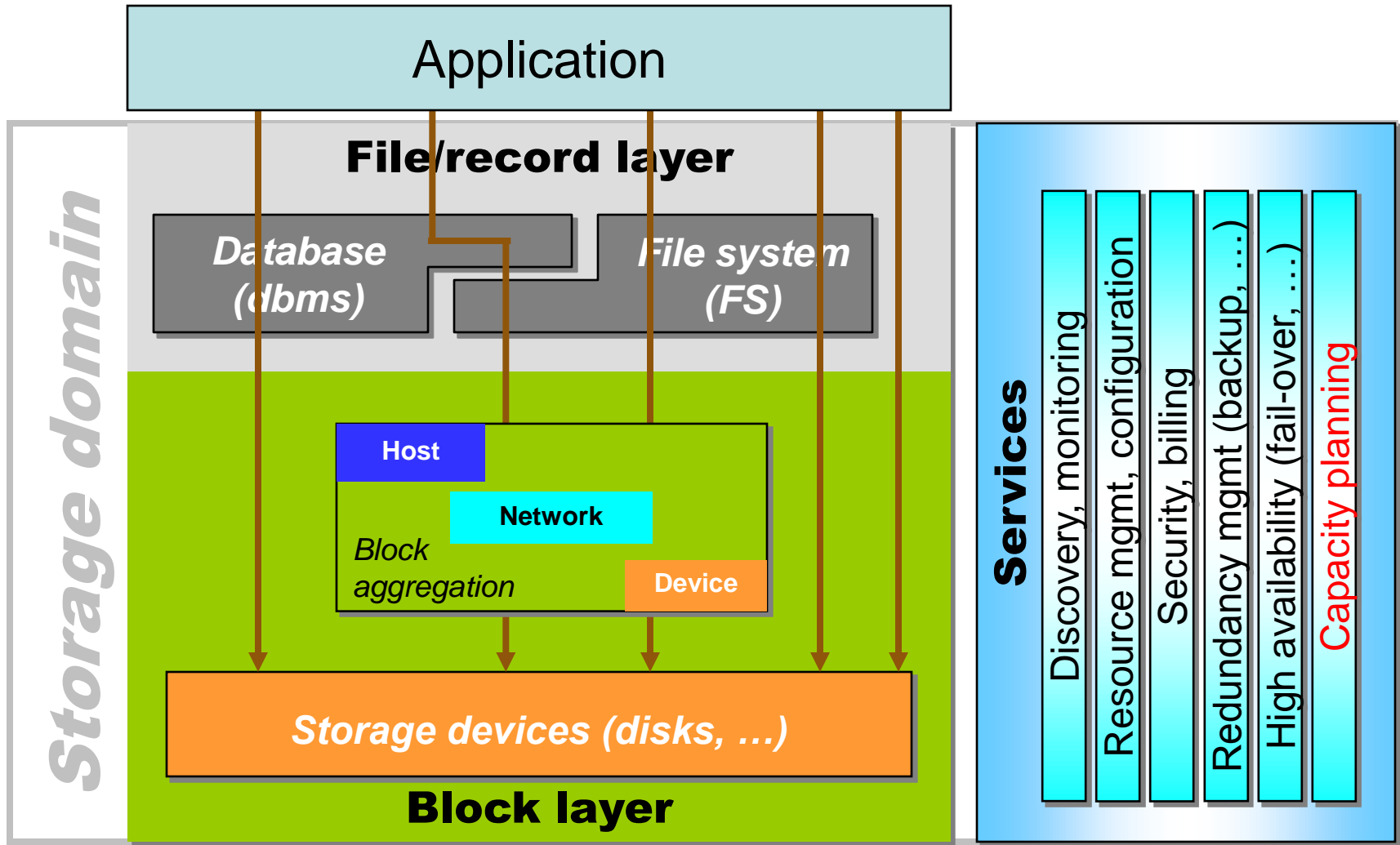
- Birth: Product Creation to Delivery
 - ◆ Integrated into CapEx (*probably*)
- Life: Power, Cooling, and “Other” Environmental Impacts during Productive Life
 - ◆ Storage: dominated by Power/Cooling
 - › Few consumable supplies, except Tape cartridges
 - ◆ Integrated into OpEx (*maybe!*)
- End-stage: Removal, Recycling, Disposal
 - ◆ Integrated into CapEx or OpEx (*we hope!*)
 - ◆ *Alternative: dump these costs onto everyone else....*

Power/Cooling Costs in Datacenters

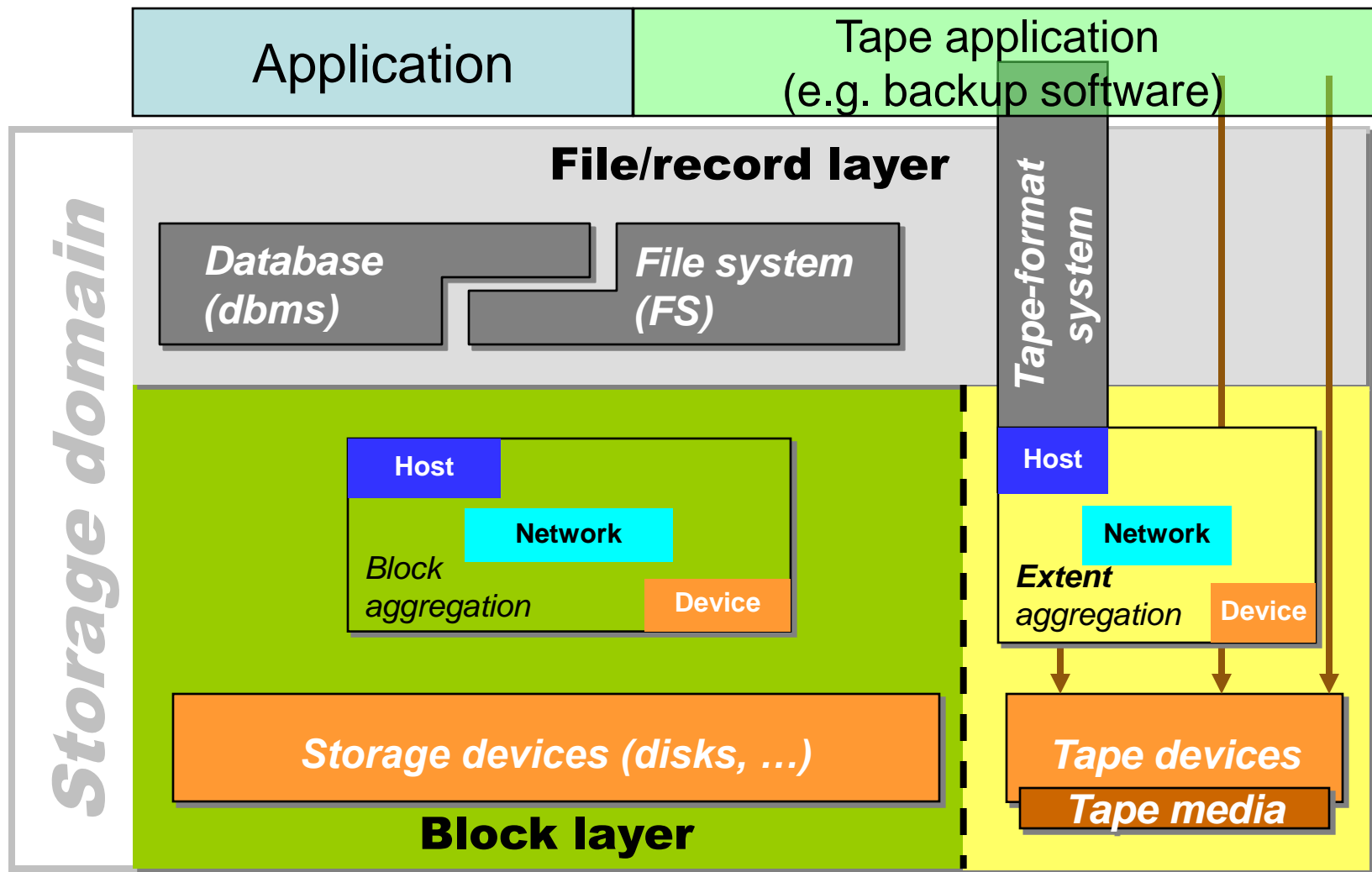
- How much is due to Storage? (*Proportion is increasing!*)
 - ◆ It depends on Design and Workload (I/O profiles)!
 - ◆ Published studies range from <10% - >40%
 - ◆ “Rule-of-Thumb”: 60% servers, 20% networking, 20% Storage (but no consistent definition of ‘Storage’)
- Is your datacenter ‘typical’, or unique?
 - ◆ Peak loads required for design
 - › CapEx (Capital Expense): Power/Cooling Equipment and Installation
 - Can overwhelm space charges, even Energy Costs
 - › Watch for “Demand” charges (Peak 15-min. of 3 Months!)
 - ◆ Time-weighted I/O for Energy/Cooling
 - › = OpEx (Operations Expense) = Majority of TCO?

What Storage aspects could be affected?

SNIA Shared Storage Model



Is Tape dead, or is it the answer?



Green Storage - Agenda

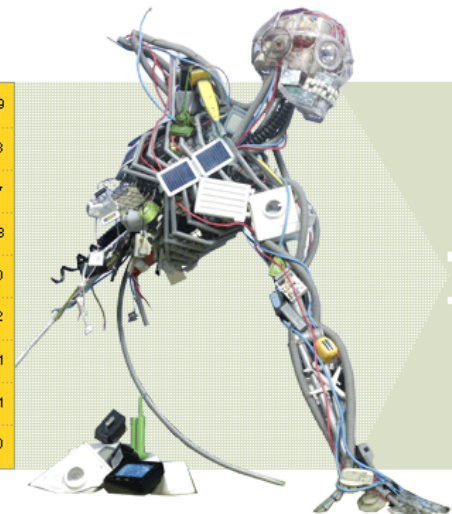
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- Fundamentals of Energy and Cooling
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- Government regulations (“Directives”) that may affect storage vendors (and their customers).
 - ◆ Useful site for US businesses:
www.buyusa.gov/europeanunion/commerce_docs.html
- WEEE
- RoHS, China-RoHS
- Packaging and Pkg Waste
- Halogens (in plastics)
- Basel Convention/Basel Ban (Transboundary Wastes)

- European Community directive 2002/96/EC
 - ◆ Conformance from Aug-05
- Increase reuse, recycling, recovery
- Reduce landfill and incineration
- Financed by manufacturers and vendors
 - ◆ Users can return WEEE without charge
 - ◆ “Take It Back” programs
- Look for the “Wheelie-Bin” logo
 - ◆ Recycle, don’t dispose!



	%
 Large household appliances	69
 Small household appliances	8
 IT & telecommunications equipment	7
 Consumer equipment	13
 Lighting equipment	0
 Electrical and electronic tools	2
 Toys, leisure and sports equipment	<1
 Monitoring and control instruments	<1
 Automatic dispensers	0



1 UK citizen per life time = 3.3 tonnes

RoHS: Restriction of Hazardous Substances

- European Directive 2002/95/EC, effective Aug-06
- RoHS restricts the use of certain hazardous substances in various types of new electronic and electrical equipment. (*Note: at a component level!*)
 - ◆ Mercury - Cadmium - Lead
 - ◆ Chromium VI - PBB - PBDE
- Unintended Consequences: reduced reliability?
 - ◆ EPA report (Aug-05) on lead-free solder!
 - ◆ RoHS exemption: lead solder for Servers and Storage!
 - › Due to a clear trade-off on reliability and performance



“China-RoHS”

- Chinese Ministry of Information Industry Order #39 Management Methods for Controlling Pollution by Electronic Information Products, in effect on March 1, 2007.
 - ◆ [SJ/T 11363-2006 Requirements for Concentration Limits for Certain Hazardous Substances in Electronic Information Products](#)
- Similar restricted substances as RoHS
- Split timetable for labeling and conformance
- Different/Fewer(?) exemptions
- ➔ Ask an expert if you think you are affected!

WEEE/RoHS – U.S. and Rest of World? **SNIA**

➤ United States

- ◆ Vendors have almost universally adopted RoHS since most do business in Europe
- ◆ EPA regulations and recommendations (e.g. Pb-free)
- ◆ Proposed federal legislation
- ◆ Several States have some regulations
 - › California – “Electronic Waste Recycling”
- ◆ Many vendors will “take it back” or take trade-ins

➤ Canada/Australia RoHS

➤ Asia (Japan JGPSSI), Korea/Taiwan RoHS

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Energy and Cooling: Fundamentals

- Laws of Thermodynamics
- Heat Transfer
 - ◆ Conduction, Convection, Radiation
- Example: how data-center cooling works
 - ◆ Types of Cooling (Air vs. Liquid)
- Energy Conversion, Transmission, Storage
 - ◆ AC/DC and DC/AC conversion losses
 - ◆ Voltage step-down and step-up conversion losses
- Units of Measurement: Energy vs. Power
- Systems of Measurement: SI vs. US

Laws of Thermodynamics

- First Law: Energy cannot be created or destroyed, it only changes form.
- Second Law: Entropy increases. (Efficiency of energy conversion to a useful form is $< 100\%$.)
- Alternate Formulations:
 - ◆ **You can't win, you can't even break even, and you can't get out of the game....**
 - ◆ *“Nullium Prandium Gratium”* (or “TANSTAAFL”)
- NO: you cannot power your datacenter using the waste heat to generate electricity to run the site!

Heat Transfer

➤ Heat (Cooling):

- ◆ Conduction:

- › thermal glue/grease between CPU and cooling fins

- ◆ Convection

- › Cooling fluid circulated past hot components
- › Note: “fluid” could be air or liquid, but liquid has a lot more capacity to move heat

- ◆ Radiation

➤ Newton’s Law of Cooling

- ◆ Rate varies with Temperature Difference

➤ Phase Change: Solid-Liquid; Liquid-Gas

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Electricity prices are variable (10^2) (at least at the wholesale level)

- **Electricity cannot be stored effectively!**
 - ◆ Few exceptions: Pumped Water Storage, Compressed Air
- **Prices vary with DEMAND (local and regional)**
 - ◆ Weather (Hot, Cold, or Both), Supply disruptions
 - ◆ Time-dependent: Daily, Weekly, Seasonally
 - ◆ Economic conditions – general, regional
- **Prices vary with SUPPLY (local and regional)**
 - ◆ CapEx: plant construction (NIMBY), maintenance
 - ◆ OpEx: Fuel costs dominate – swings are wild (10^2)
- **Electricity Transmission congestion/losses increase cost; hard to build new lines (NIMBY)**

State Electricity Prices, 2005 (cents/kWh – “Industrial”)

U.S. Average 5.73

10 Most Expensive States

10 Least Expensive States

Rank	State	Price
1	HI	15.79
2	DC	14.13
3	NH	11.48
4	RI	10.01
5	NJ	9.76
6	CA	9.55
7	CT	9.40
8	AK	9.29
9	MA	9.22
10	NY	8.23

Rank	State	Price
42	VA	4.46
43	NE	4.43
44	IN	4.42
45	ND	4.32
46	WA	4.27
47	UT	4.24
48	WY	3.99
49	ID	3.91
50	WV	3.85
51	KY	3.60

Move your datacenter to cheap power? SNIA



Energy costs on the Columbia River are about **\$0.02/kWh** for Datacenters.

Ample fiber (WAN) bandwidth is available (www.noanet.net)

The area is also seismically inactive and in a 500-year flood zone.

Result: Construction!

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Datacenter: Design/Operation

- ◆ Datacenter: Design and Operation
 - ◆ CapEx and OpEx
 - ◆ Traditional focus on Servers: Power and Cooling
 - ◆ Trends in Conservation and Optimization
- ◆ Size matters (for Power and Cooling equipment)!
 - ◆ Undersized means less density for IT gear
 - › Some datacenters are limited by Electric Company
 - › Choice: run out of space, or pay more rent
 - › May even constrain modern Storage equipment
 - ◆ Oversized means excess CapEx, and inefficiencies

Facilities vs. I.T. in the Datacenter

- Who represents I.T. to the Facilities staff?
 - ◆ Right now, the whole conversation is about Servers!
 - ◆ Try to find “Storage” mentioned in any recent article on power/cooling problems in the datacenter....
 - ◆ Try to find “Storage” mentioned in any Utility program.
 - ◆ Can you show that Storage is significant to the power/cooling load (*via modeling or measuring*)?

- Organizational differences (who owns what?)
 - ◆ Do you talk with your Facilities managers?
 - ◆ Do your decisions affect each other? (YES!)
 - ◆ When will you start planning together?

Datacenter Options: (Mech, Elec, Plumbing)

- Convert from AC to DC distribution
 - ◆ Can be partial conversion (DC arrays available)
- Run at higher voltage (240 vs. 120)
- Increase Power Supply efficiency
 - ◆ 80 PLUS program (www.80plus.org/servers.htm)
- Operate Cooling effectively
 - ◆ Leverage sensors, Follow basic rules (hot/cold aisles?)
 - ◆ Computational Fluid Dynamics (get some help!)
- Run Generator-testing for Peak-shaving
 - ◆ Negotiate with your power supplier for discounts

The Green Grid

- What is “The Green Grid”? www.thegreengrid.org
- Green Grid metrics (*measured at the meter*)
 - ◆ What amount of Power (and Cooling) goes to do “useful IT work”? (The rest is “overhead”, from an IT viewpoint)
 - ◆ Overall Datacenter (short-term, tactical)
 - › PUE (Power Usage Effectiveness)
 - $PUE = (\text{Total Facility Power} / \text{IT Equipment Power})$
 - › DCiE (Datacenter Infrastructure Efficiency): $DCiE = (1 / PUE)$
 - ◆ Metric for “Datacenter Productivity” (longer-term, strategic)
 - › Datacenter Productivity = $[\text{Useful Work} / \text{Total Facility Power}]$
 - › Definition problem: what is “*useful work*” for IT?

Model or Measure: Which is Better?

- Modeling: some info is required!
 - ◆ Accurate manufacturer data by Component and Product (Frame)
 - ◆ Stand-by Power vs. Full-load – CRUD analysis
 - ◆ Knowledge of I/O workload
 - › Well-known benchmark(e.g. SPC, SNIA-IOTTA) – vary replay
 - › YOUR unique workload traces (time-weighted and Peak)
- Measurement issues (Reality validates Modeling)
 - ◆ Actual *in-situ* workloads (“normal” and Peak) – can use traces
 - ◆ Actual Energy usage from Power Meter
 - › Watts or Kwh (what you pay for!), not Amps
 - › Must be adequate to fit your Storage device (>30 Amp?)
 - › See your Facilities Mgr, or a consultant for help
- SNIA Green Storage Technical Working Group projects

Datacenter: Proposals and Solutions **SNIA**

- ▶ **REDUCE Performance when possible**
 - ◆ “Underclocking”: reducing performance-state of CPU reduces power/cooling needs for **Servers**
 - › Out-of-band mgmt (BMC) = no OS tuning
 - › Management via OS gives more granular control
- ▶ **What is the equivalent for **Storage**?**
 - ◆ TAPE or Optical? (trade-off response time vs. energy)
 - ◆ Disk drives and RAID arrays
 - › Slower/Larger drives where possible (Design choice vs. Dynamic)
 - › Power off selected drives: MAID (Massive Array of Idle Disks)
 - › Spin-down
 - ◆ **Solid-State Storage**

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Storage-specific Power/Cooling data

- Each component of a Storage system has Power and Cooling requirements
 - ◆ Understand “Idle” (stand-by) vs. “Loaded” (R/W)
 - ◆ Label ratings are usually peak power required
 - › If you design using this data, your power/cooling equipment will be (grossly) over-built (Bad!), and CapEx will suffer.
 - › Operating equipment below its rated temperature offers little (no?) benefits (except for Operators!)
 - ◆ Some manufacturers offer better data or design info
 - ◆ If you really want to know, you have to instrument in order to get real measurements.
 - ◆ Or, you could wait to see what SNIA comes out with...

Disk-specific Power/Cooling

- Operational envelope
 - ◆ Perform as designed
 - ◆ No clear effects on MTBF or TCO of variation within design temperature range
- Rotational speed of Disks
 - ◆ Buy slower disks, if you don't mind the latency
 - ◆ Variable-speed disks?
- Use appropriate RAID levels
 - ◆ Disks may be 'free', but power/cooling are NOT!
- Max Disk Utilization (OpEx: per disk, not per GB)

Key Strategies: Energy/Cooling

- Understand Usage vs. Demand and Other charges!
- Are you sure that Storage is a significant contributor?
- ➔ **Increase Utilization** (Storage Resource Mgmt helps)
 - ◆ **Thin Provisioning, Dynamic LUN Grow/Shrink**
- Consolidate (possibly change storage architecture)
- Trade Response Time (Latency+Throughput) for Reduced Power. i.e. Use Lower-tier Disk, VTL, Nearline, MAID, or Off-line Tape or Optical
- **Move:** when energy/cooling costs or availability dominate TCO, you might consider moving to cheap energy/cooling with adequate WAN bandwidth
 - ◆ Columbia River, West Texas, Canada datacenters?

- Metric: kW/GB vs. kW/disk – Which is correct?
- Store less stuff; delete when approved: Classify → ILM, HSM
- Location: Tiered Storage (SSD, SAS/FC, SATA, Tape, Optical)
- Increase effective Data Density on Disks (or Tape)
 - ◆ Lossless Compression
 - ◆ File de-duplication (Single-instance)
 - ◆ De-duplication (Factoring, Common Blocks)
- Trade-offs on Reliability, Performance
 - ◆ Single-copy of data?! (RPO, RTO)
 - ◆ Unpack/Inflate penalty may be incurred
 - ◆ Hotspots? – spread data across disks

RAID level vs. Power/Cooling

- RAID (*Redundant Array of Independent Disks*), a family of techniques for managing multiple disks to deliver desirable cost, data availability, and performance characteristics to host environments.
- Despite capacity cost reductions exceeding Moore's Law, RAID is not 'free' – extra disks add CapEx and infrastructure costs
- plus **OpEx for Energy/Cooling**
- Compare RAID levels against equivalent JBOD (“Just a Bunch of Disks” = Capacity only)

What Affects Storage Energy Use?

RAID Definitions



Standalone



Cluster



Hot swap



RAID 0



RAID 1



RAID 5



RAID 0+1



RAID level vs. Power/Cooling

- JBOD: **Number of disks scales to data capacity**
 - ◆ **Cost of Power/Cooling = $N \times$ single disk cost**
- RAID 0 = data striping, disks required = **N**
- RAID 1 = mirroring, disks required = **$2 \times N$**
 - ◆ **RAID 0+1 or RAID 1+0, power/cooling= $2 \times N$**
- RAID 5 = parity RAID, parity check data is distributed across the RAID array's disks.
 - ◆ disks required = **$N+1$**
- RAID 6 = various methods to tolerate two concurrent disk failures; disks required = **$N+2$**

Storage Energy Use for other redundancy methods using Erasure Codes

- Erasure codes transform data from n blocks across multiple $(n+m)$ blocks, such that recovery is possible with up to m failures.
 - ◆ See Jim Plank's Usenix-FAST tutorial:
<http://www.cs.utk.edu/~plank/plank/papers/FAST-2005.pdf>
 - ◆ Parity, as used in some RAID-levels is a optimal erasure code
 - ◆ Most complex erasure codes are less efficient than simple or DP parity, so the power/cooling costs are for **N+M** disks.
- Erasure codes can be very useful across distributed nodes with unreliable network connections
- **This could allow you to place some nodes into areas of lower energy cost!**
 - ◆ This lower cost could overcome the energy cost of extra nodes

Resources and Links

- Lots of info available, but little is storage-specific
- Consultant\$ and other paid expert\$
 - ◆ Useful when dealing with gov't. regulations
- WEEE/ RoHS – lots of online tutorials
- The Green Grid is emerging as a resource for power and cooling issues (datacenter focus).
 - ◆ Likely they will look to SNIA for Storage expertise
- Government agencies and Industry orgs
 - ◆ EPA Energy Star program

- Please send any questions or comments on this presentation to SNIA: trackgreenstorage@snia.org.

**Many thanks to the following individuals
for their contributions to this tutorial.**

- SNIA Education Committee

SNIA Green Storage Initiative

Wayne Adams

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Deborah Johnson

Erik Riedel

SW Worth

Alan Yoder

- Metrics for Power/Cooling for Storage
- Primer on Electric Power in the United States
 - ◆ Generation, Transmission, Distribution
 - ◆ Pricing: What you buy, Variable factors
 - › Geographic variations

Storage-specific Metrics

- What are the appropriate metrics for Storage?
 - ◆ Energy (kWh) per 'Unit' of Storage (MB, GB, TB)?
- **Table** of Storage Operations vs. Energy-cost for each type of Storage technology
- Devices: Flash, Disk, Tape, Optical
- Operations: CRUD + periodic Validation of Data or other Maintenance Op (e.g. Re-tensioning tape)
 - ◆ Blocks vs. Files?

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Electricity Supply in the U.S.

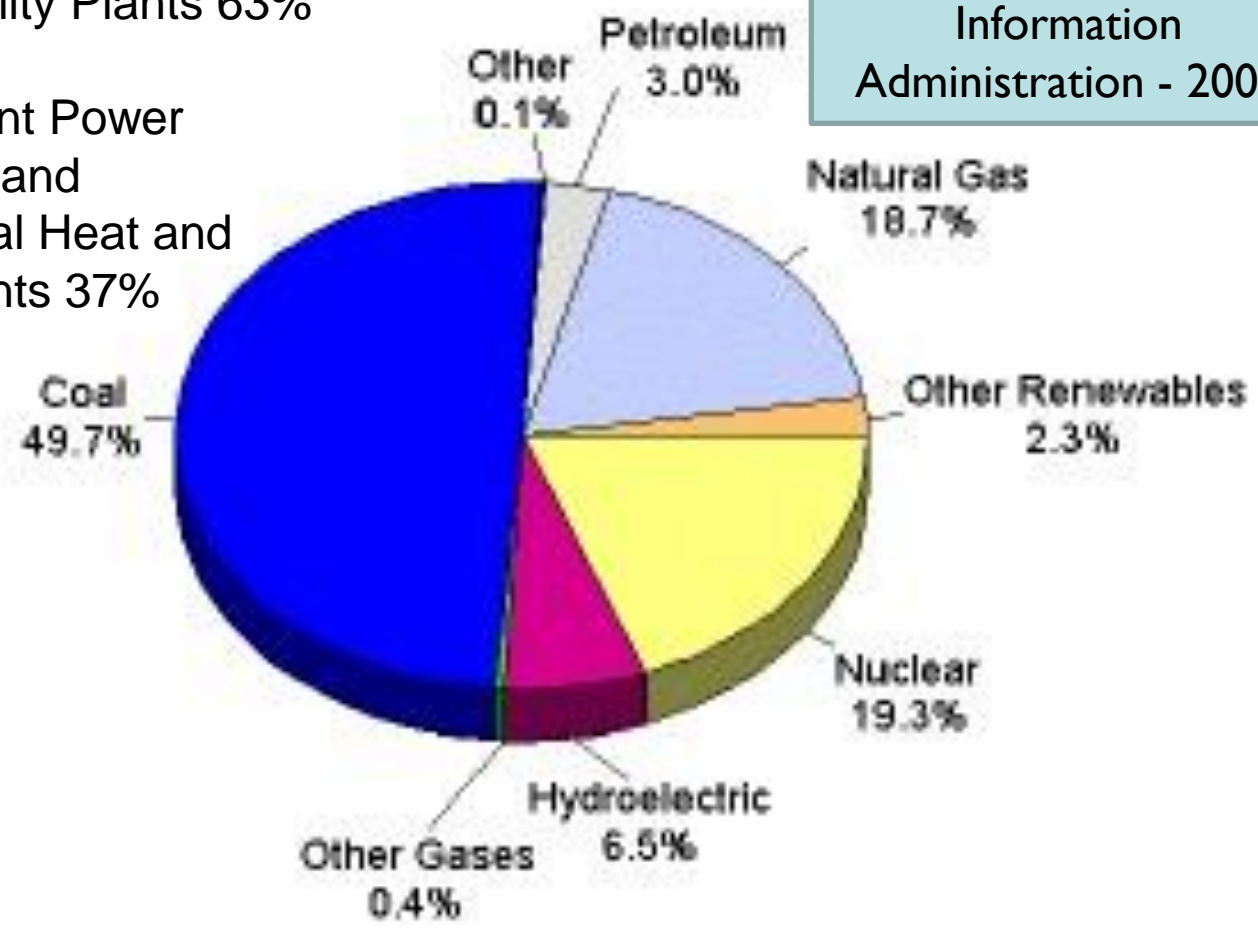
- System Reliability and Flow ‘Control’
 - ◆ North American Electric Reliability Corp.
 - ◆ ISO (Independent System Operator) for each region controls “Congestion”, Ancillary Services, etc.
- Generation, Transmission, Distribution
 - ◆ Regulated monopolies → Deregulation (partial)
- Pricing: What you buy, Variable factors, Geographic variations, Roles of Regulators, ISOs
- Metering:
 - ◆ **Energy** kWh or MWh (at multiple points in system)
 - ◆ **Demand** (peak, to compensate for infrastructure)

Electric Power Generation by Source SNIA

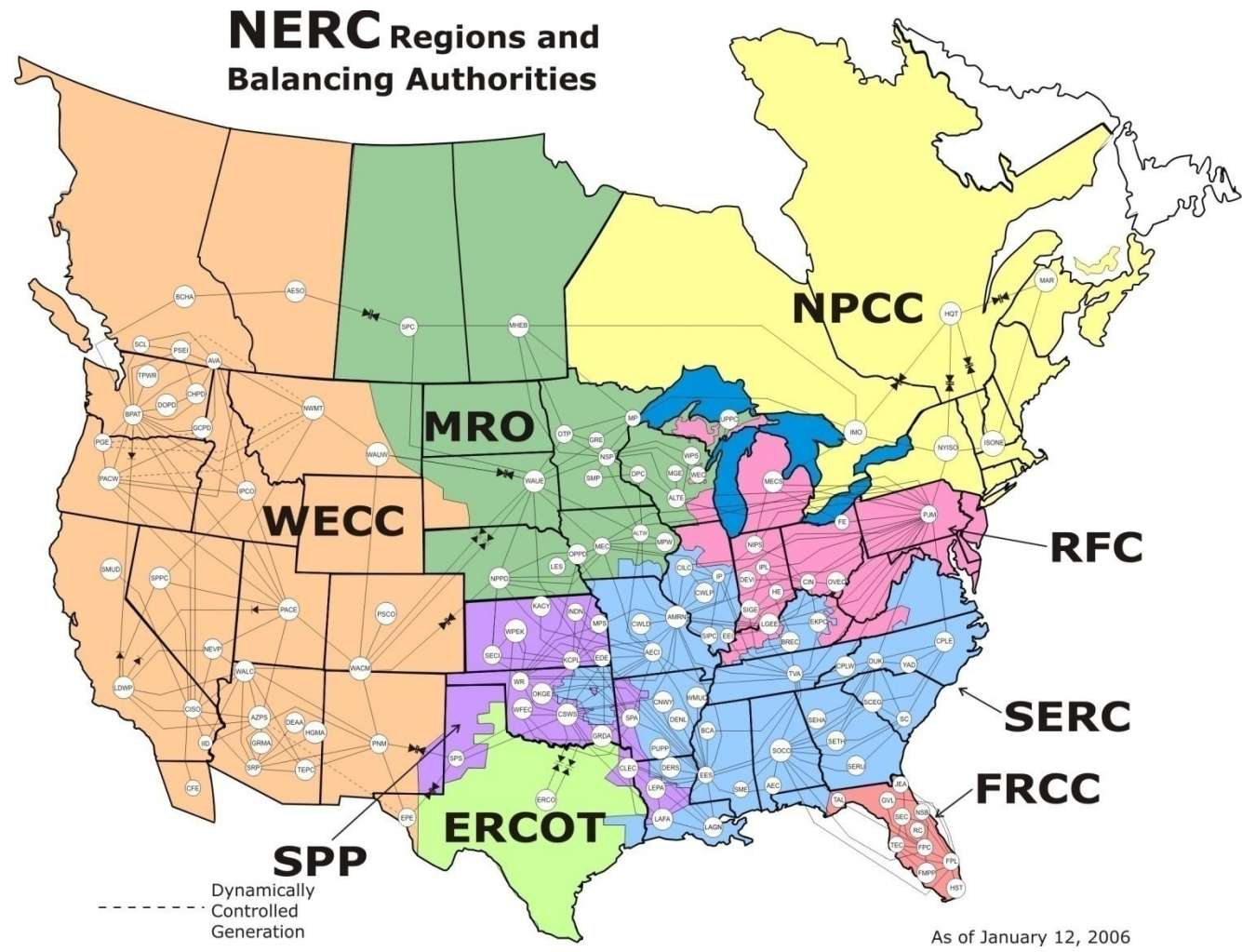
Total = 4,055 Billion kWh
Electric Utility Plants 63%

Independent Power
Producers and
Commercial Heat and
Power Plants 37%

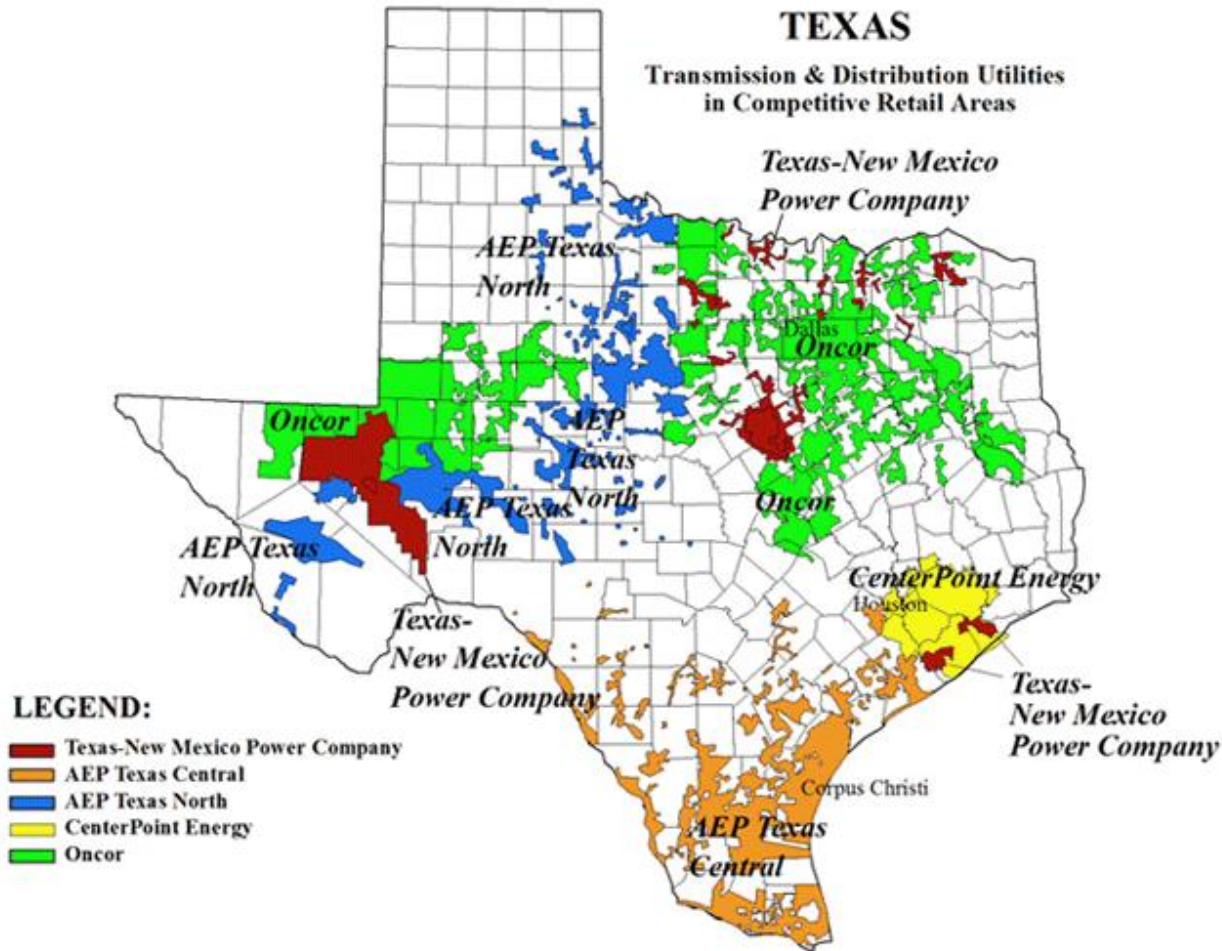
Data from U.S. Energy
Information
Administration - 2005



NERC: Electric Reliability org

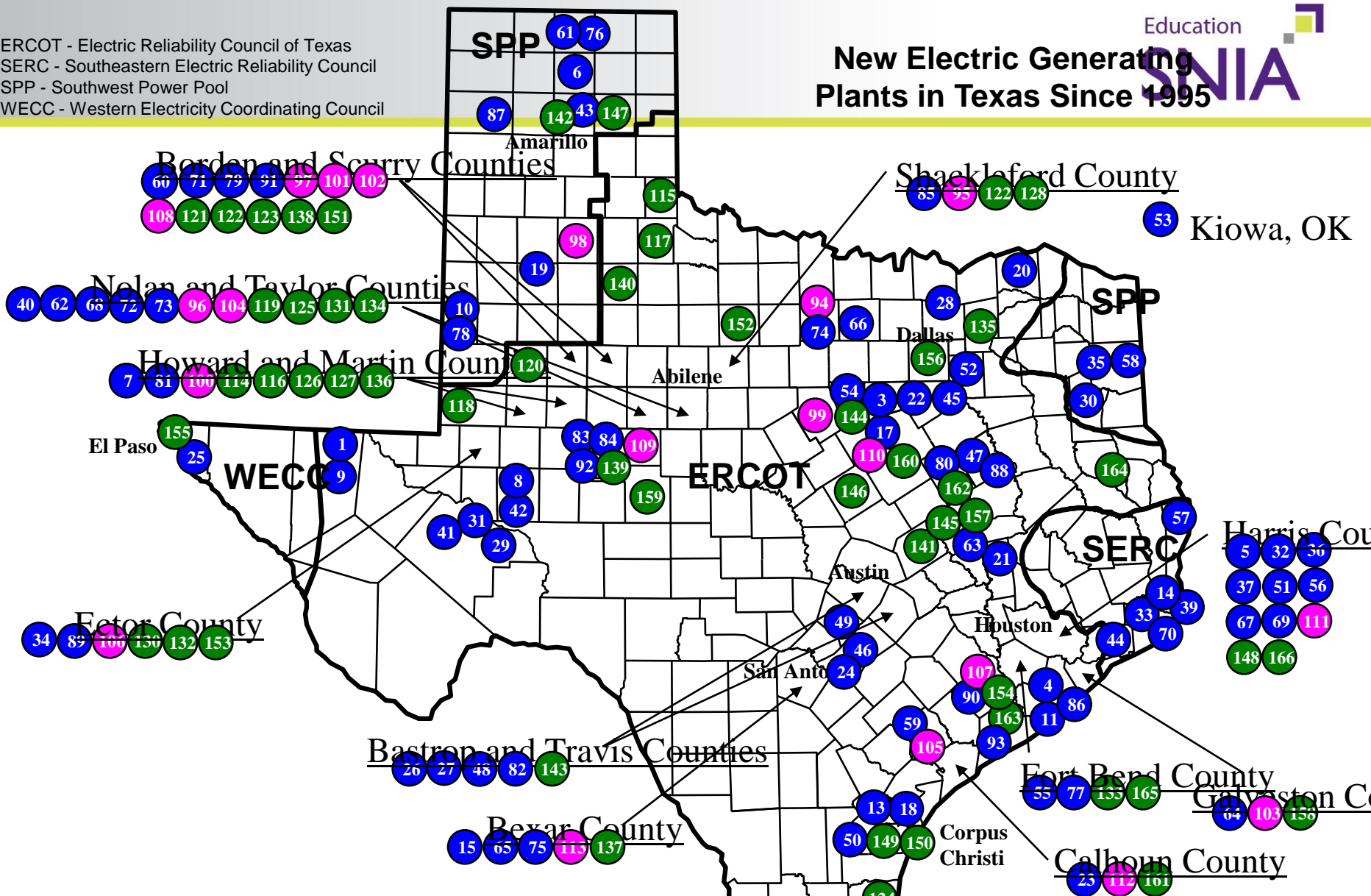


- ERCOT and PUCT slides go here
 - ◆ and/or in Pricing section
- <http://www.ercot.org/>
- <http://www.puc.state.tx.us/>



ERCOT - Electric Reliability Council of Texas
 SERC - Southeastern Electric Reliability Council
 SPP - Southwest Power Pool
 WECC - Western Electricity Coordinating Council

New Electric Generating Plants in Texas Since 1995

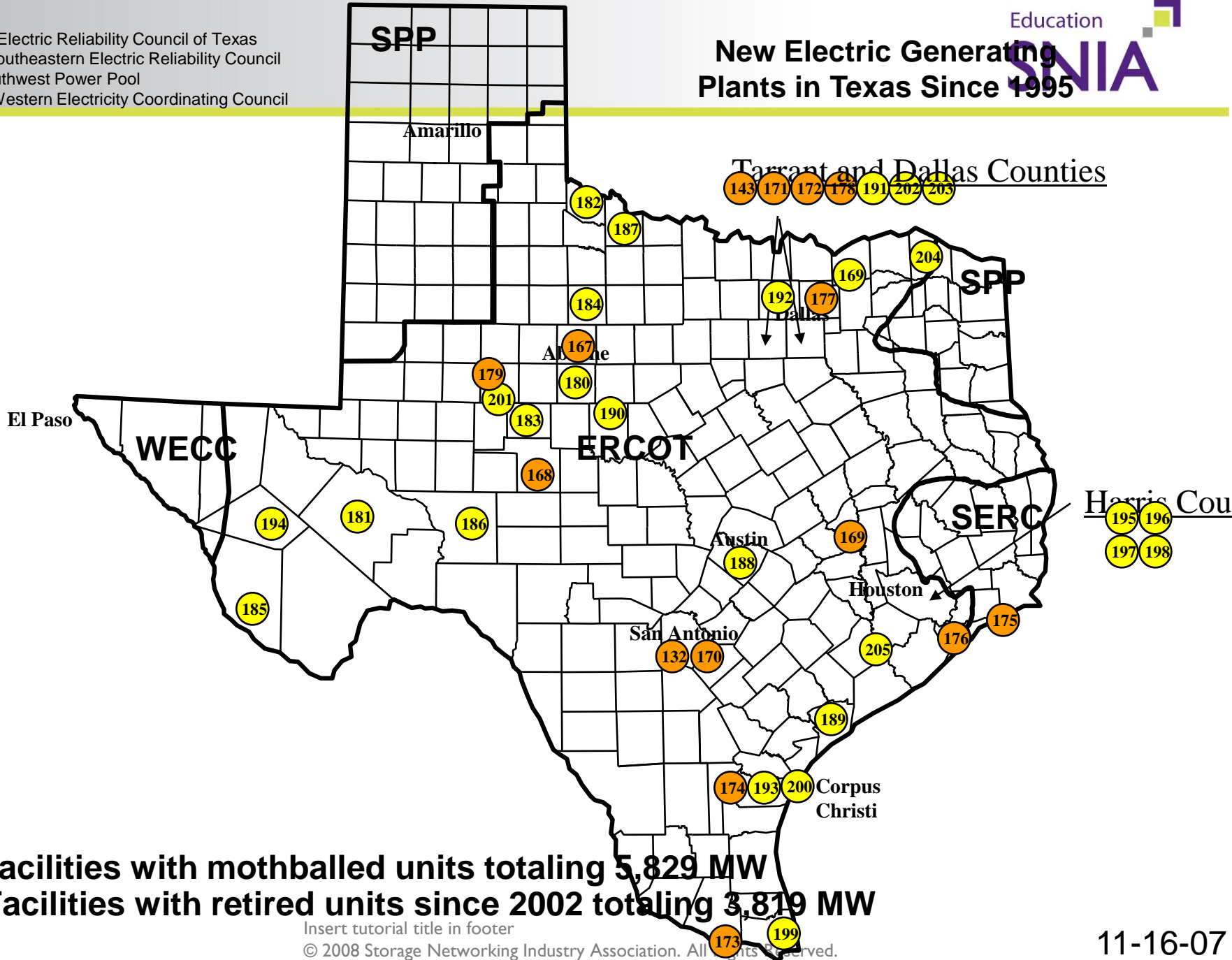


- Generation projects completed since 1995 totaling 37,063 MW
- Generation projects under construction totaling 1,133 MW
- Generation projects announced totaling 25,756 MW

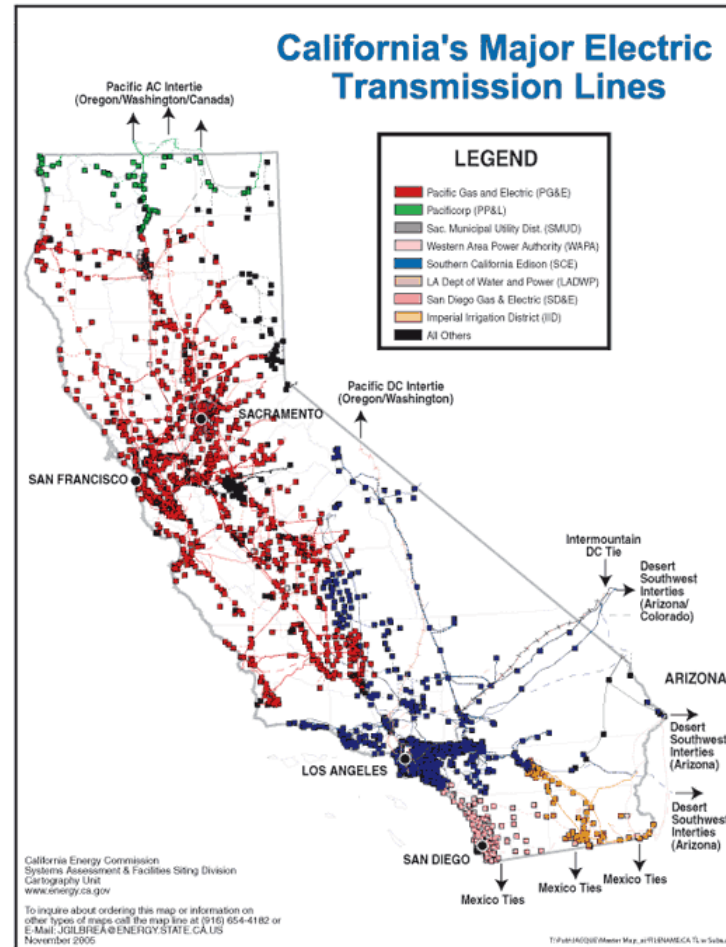
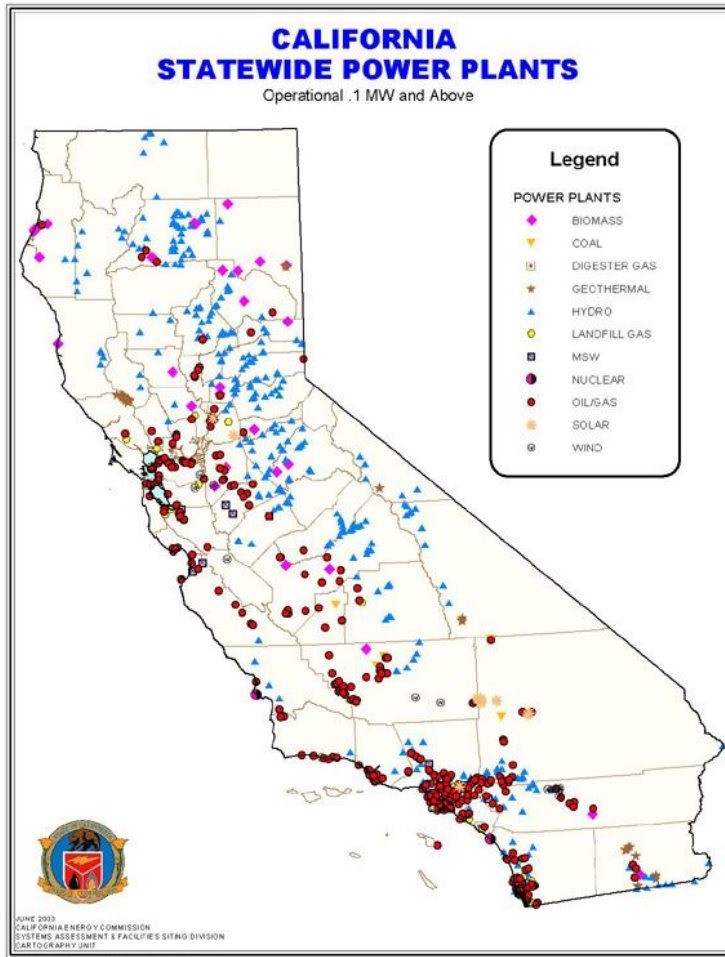
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ERCOT - Electric Reliability Council of Texas
 SERC - Southeastern Electric Reliability Council
 SPP - Southwest Power Pool
 WECC - Western Electricity Coordinating Council

New Electric Generating Plants in Texas Since 1995



Calif. Generation; Transmission Interconnects



www.energy.ca.gov/maps/

Electricity Supply in the U.S.

- Integration

- ▶ Traditional vertically-integrated monopolies
 - ◆ Generate (shared with “IPPs”), Transmit, and Deliver power to everyone in their monopoly service territory
 - ◆ Heavily regulated by federal (FERC), state (PUC/ PSC), and almost every other level of gov’t.
 - ◆ Emphasis on efficient allocation of Capital with very long time horizon, then recovery from “rate-base”
 - ◆ Emphasis on operational reliability and system security, but getting squeezed by regulators
 - ◆ Customer-service metrics overseen by regulators
 - ◆ IT focus on SCADA, Meter/Billing, Property Records

Electricity Supply: Deregulation

- Deregulated Segments (U.K. model, NY, CA)
 - ◆ Generation (“**GenCo**” or “**IPP**”) – generates power from Coal, Nuclear, Natural Gas, Hydro, Oil, “Other”
 - › Some “Green” generation: Wind, Tidal, Geothermal, Bio-mass, or Hydro(!?!?)
 - ◆ Transmission (“**TransCo**” or **ISO**) – aggregates supply and “ancillary services” from GenCos and IPPs via Auctions, and moves power to wholesale
 - ◆ Distribution (“**DisCo**” – a ‘natural’ monopoly which moves power to retail customers
 - ◆ Meters are everywhere throughout the system

- Interchanges, Power Pools, and “Reliability Councils” (e.g. ERCOT)
- NYMEX – transparent open-auction pricing of standardized “bundles” at major delivery points (e.g. Oil, NatGas, Coal, Electricity-PJM)
- GenCo: long-term contract pricing to DisCos and Large End-Users (may be distributed locations)
- Fuel Adjustment pricing (may be volatile!)
- IPP: Independent Power Producer
- ISO as maintainer of reliability and open auction

Electricity prices are variable (at least at the wholesale level)

- **Electricity cannot be stored effectively!**
- **Prices vary with DEMAND (local and regional)**
 - ◆ Weather (Hot, Cold, or Both)
 - ◆ Time-dependent: Daily, Weekly, Seasonally
 - ◆ Economic conditions – general, regional
- **Prices vary with SUPPLY (local and regional)**
 - ◆ CapEx: plant construction (NIMBY), maintenance
 - ◆ OpEx: Fuel costs dominate – swings can be wild
- **Electricity Transmission congestion/losses increase cost; hard to build new lines (NIMBY)**