Education

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

SW Worth, Microsoft

SNIA Legal Notice

Education SNIA

- The material contained in this tutorial is copyrighted by the SNIA.
- Member companies and individuals may use this material in presentations and literature under the following conditions:
  - Any slide or slides used must be reproduced without modification
  - The SNIA must be acknowledged as source of any material used in the body of any document containing material from these presentations.
- This presentation is a project of the SNIA Education Committee.

Abstract

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 other sessions.

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!

<u>Learning Objectives</u>

Understand what various groups mean by 'Green', especially as this term relates to storage network components and systems.

Understand some of the 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 - 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

Education SNIA

- "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" <u>differ</u> 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

Classic motivators: Fear, Guilt, Greed

Education SNIA

- "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 SOx/NOx, 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, i.e. no toner cartridges)
  - Integrated into OpEx *(maybe!)*
- End-stage: Removal, Recycling, Disposal
  - Integrated into CapEx or OpEx *(we hope!)*
  - *Alternative: dump these costs onto everyone else….*

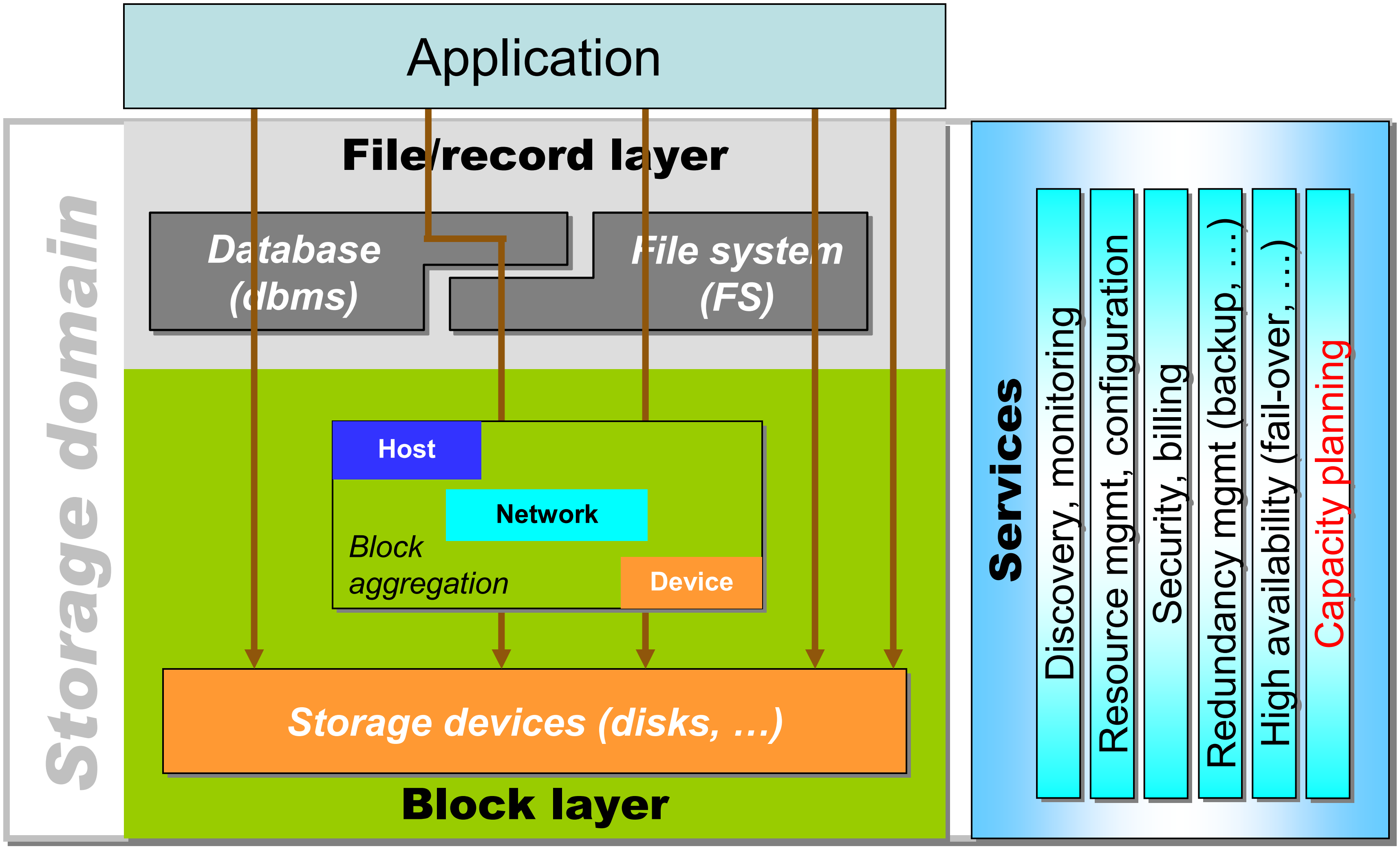
Power/Cooling Costs in the Datacenter

Education SNIA

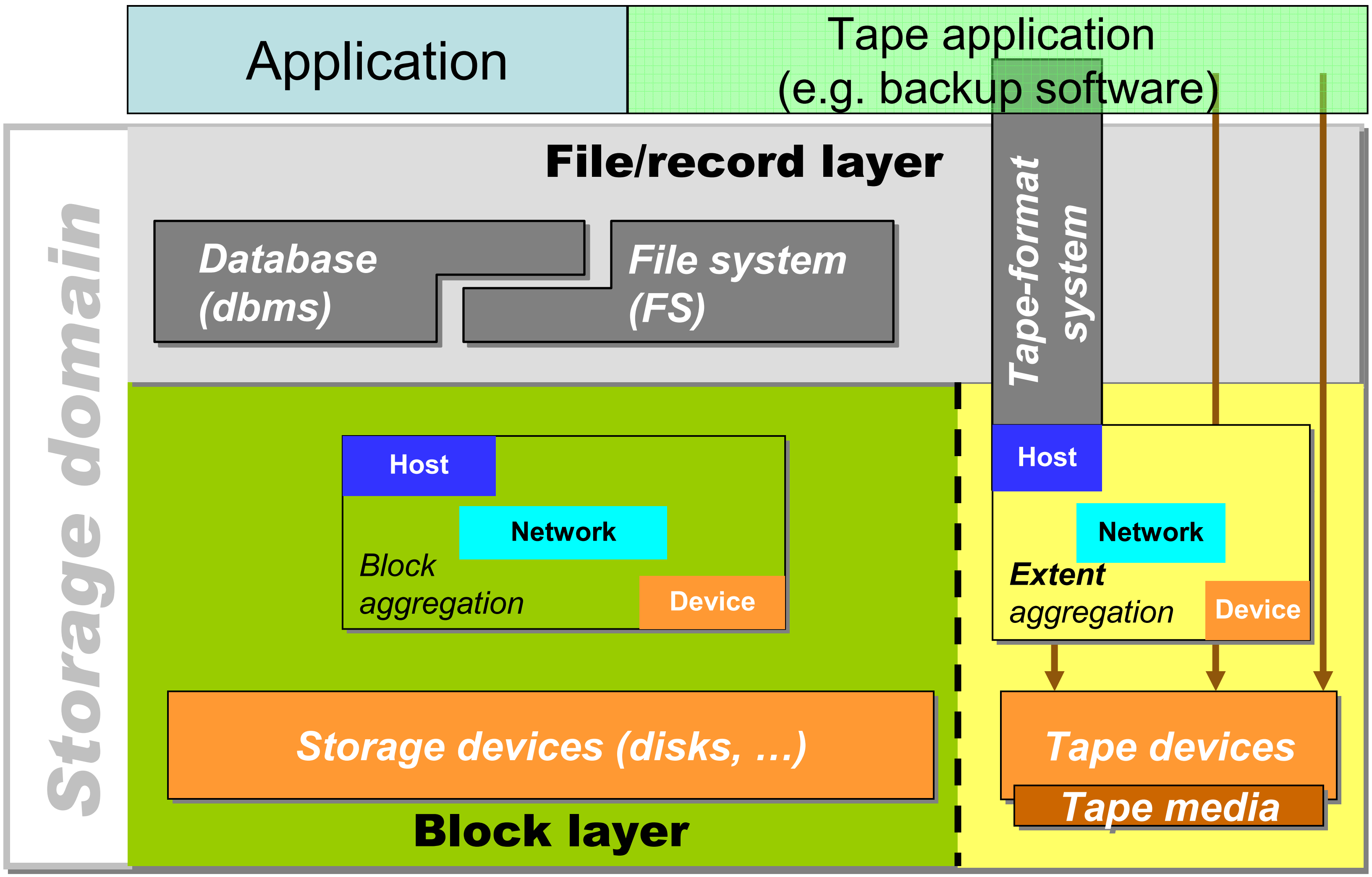
- How much is due to Storage?
  - It depends on Design and Workload (I/O profiles)!
  - Published studies range from <10% - >40%
  - "Rule-of-Thumb": 60% servers, 20% networking, 20% Storage (no consistent definition of Storage)
- Is your datacenter "typical", or unique?
  - Peak loads required for design
    - CapEx (Capital Expense) burden: Power/Cooling Equipment and Installation
    - 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 components could be affected?

SNIA Shared Storage Model



Is Tape dead?



Application
Tape application
(e.g. backup software)
Storage domain
File/record layer
Database
(dbms)
File system
(FS)
Tape-format
system
Host
Network
Block
aggregation
Device
Host
Network
Extent
aggregation
Device
Storage devices (disks, …)
Tape devices
Tape media
Block layer

Green Storage - 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

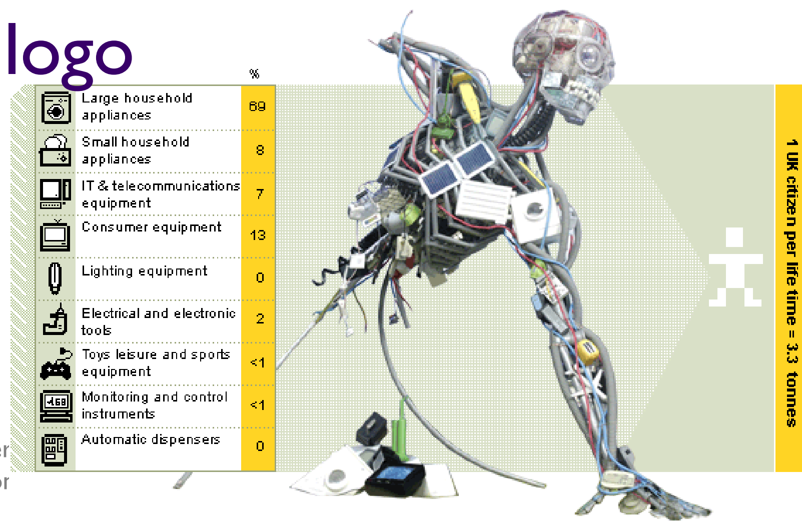
eWaste Reduction/Recycling

- 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)

WEEE:
Waste Electrical and Electronic Equipment

Education SNIA

- 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!



RoHS: Restriction of Hazardous Substances

Education SNIA

- 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 <u>component</u> level!)*
  - Mercury - Cadmium - Lead
  - Chromium VI - PBB - PBDE
- Unintended Consequences: reduced reliability?
  - EPA report (Aug-05) on lead-free solder!
  - RoHS <u>exemption</u>: 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?

- 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

Green Storage - 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

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

Education SNIA

- 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

Green Storage - Agenda

Education SNIA

- 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

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

- **Electricity cannot be stored effectively!**
- 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")

Education SNIA

U.S. Average 5.73

10 Most Expensive States

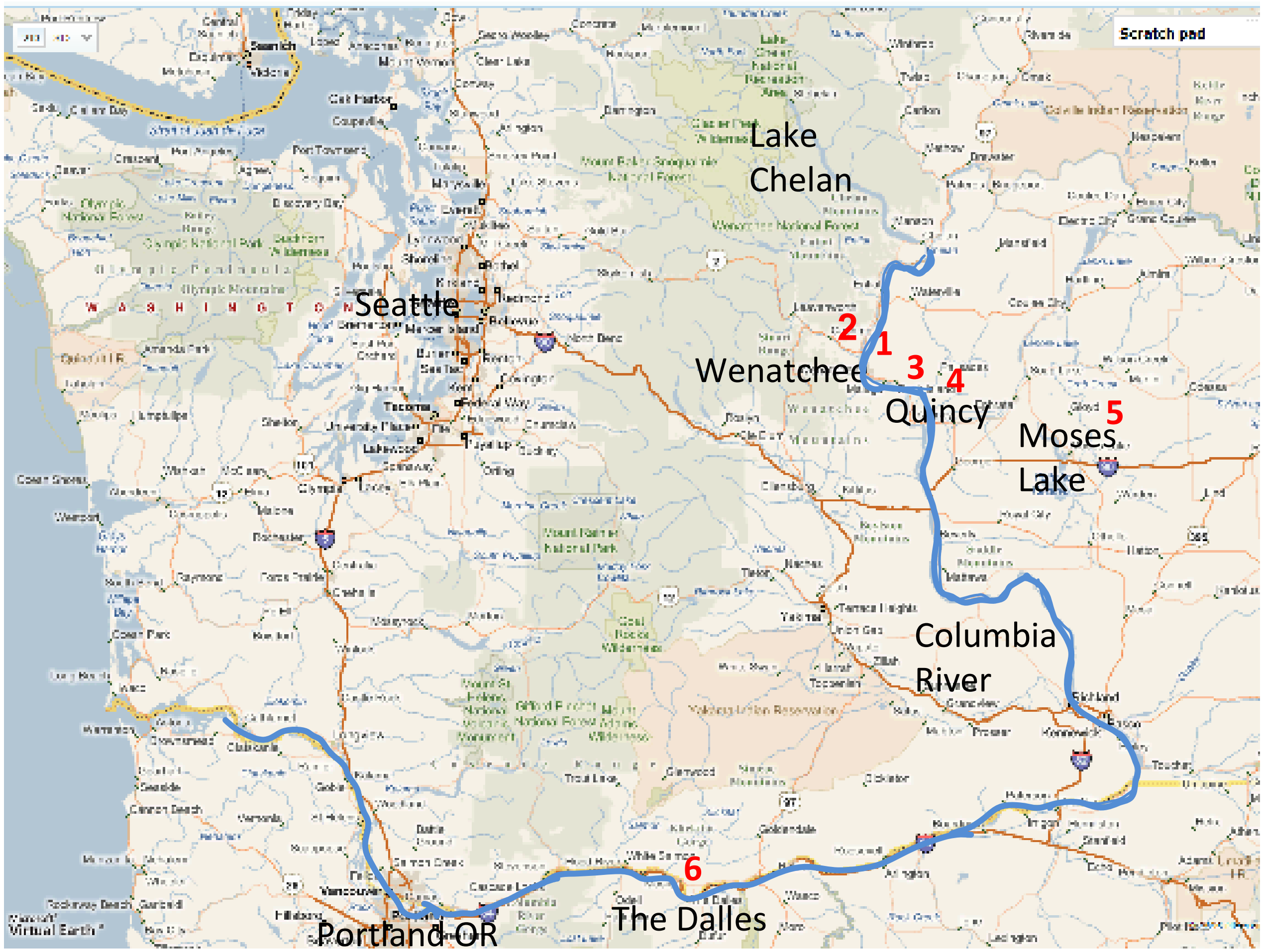
Rank	State	Price
1	HI	15.79
2	DC	14.13
3	NH	11.48
4	RI	10.01
5	NJ	9.76
6	CA	9.55
7	CT	9.40
8	AK	9.29
9	MA	9.22
10	NY	8.23

10 Least Expensive States

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?

Education 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!

Green Storage - Agenda

Education
SNIA

- 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

Datacenter: Design/Operation

Education SNIA

- 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=(Total Facility Power/IT Equipment Power)
    - DCiE (Datacenter Infrastructure Efficiency): DCiE=(1/PUE)
  - Metric for "Datacenter Productivity" (longer-term, strategic)
    - Datacenter Productivity = [Useful Work / Total Facility Power]
    - Definition problem: what is *"useful work"* for IT?

Model or Measure: Which is Better?

Education SNIA

- 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

Education SNIA

- REDUCE Performance whenever 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)

Green Storage - 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**

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

Education SNIA

- 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 of Optical
- **Move**: when energy/cooling costs or availability dominate TCO, you might consider moving to cheap energy/cooling with adequate WAN bandwidth
  - Columbia River datacenters?

Increase 'effective' Data Density

- 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

Education SNIA

- 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 plus **OpEx for Power/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

Education SNIA

- JBOD: **N**umber of disks scales to data capacity
  - **Cost of Power/Cooling = N x single disk cost**
- RAID 0 = data striping, disks required = **N**
- RAID 1 = mirroring, disks required = **2xN**
  - **RAID 0+1 or RAID 1+0, power/cooling=2xN**
- 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

Education SNIA

- 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

Education SNIA

- 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

Q&A / Feedback

Education SNIA

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

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

SNIA Education Committee

SNIA Green Storage Task Force
Clod Barrera
Rick Bauer
David Black
LeRoy Budnik
Deborah Johnson
Erik Riedel

Appendix

Education SNIA

- 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?

Green Storage - Appendix

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

Electricity Supply in the U.S.

Education SNIA

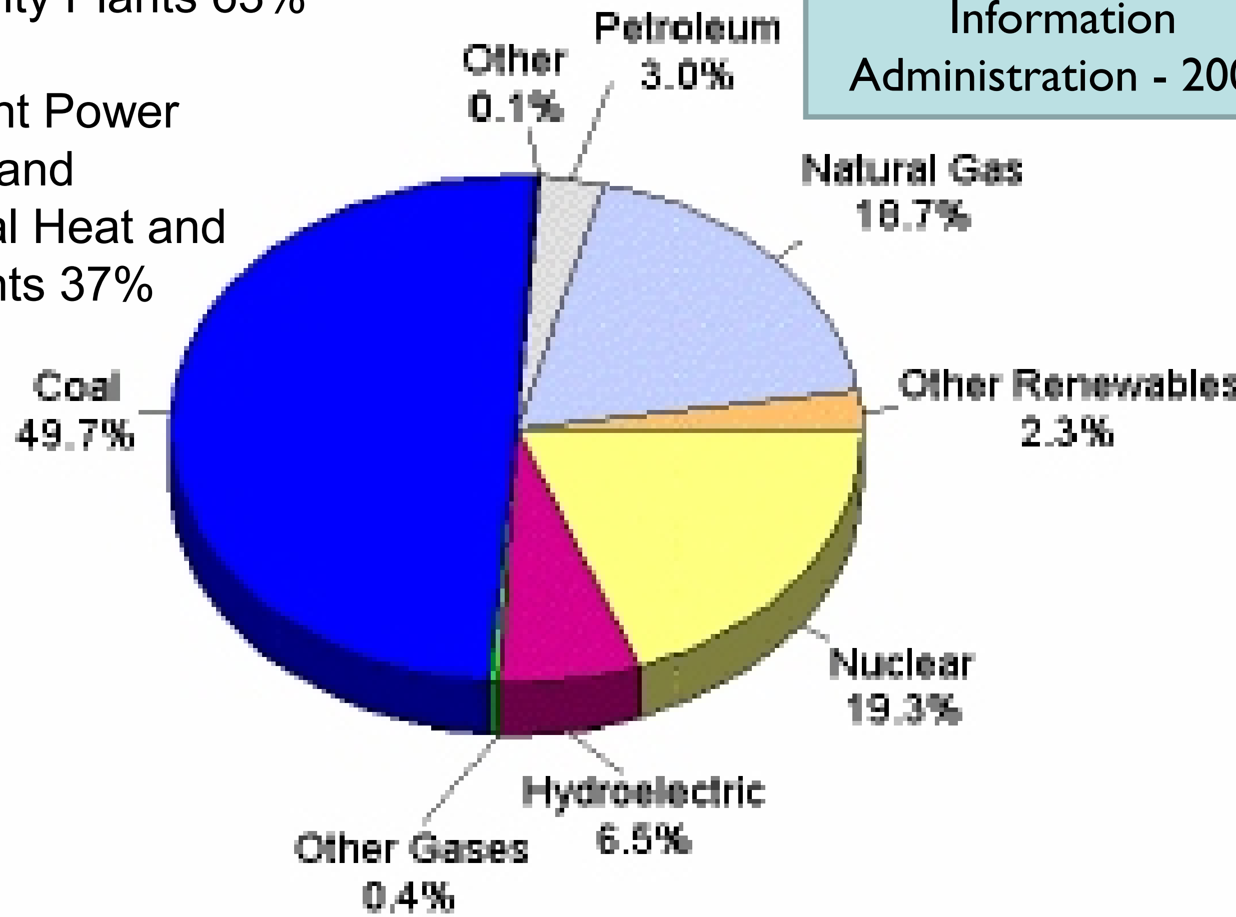
- System Reliability and Flow 'Control'
  - North American Electric Reliability Corp.
  - ISO (Independent System Operator) for each region controls "Congestion", Ancillary Services, etc.
- Generation, Transmission, Distribution
  - Regulated monopolies → Deregulation (partial)
- Pricing: What you buy,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

Electric Power Generation by Fuel Type

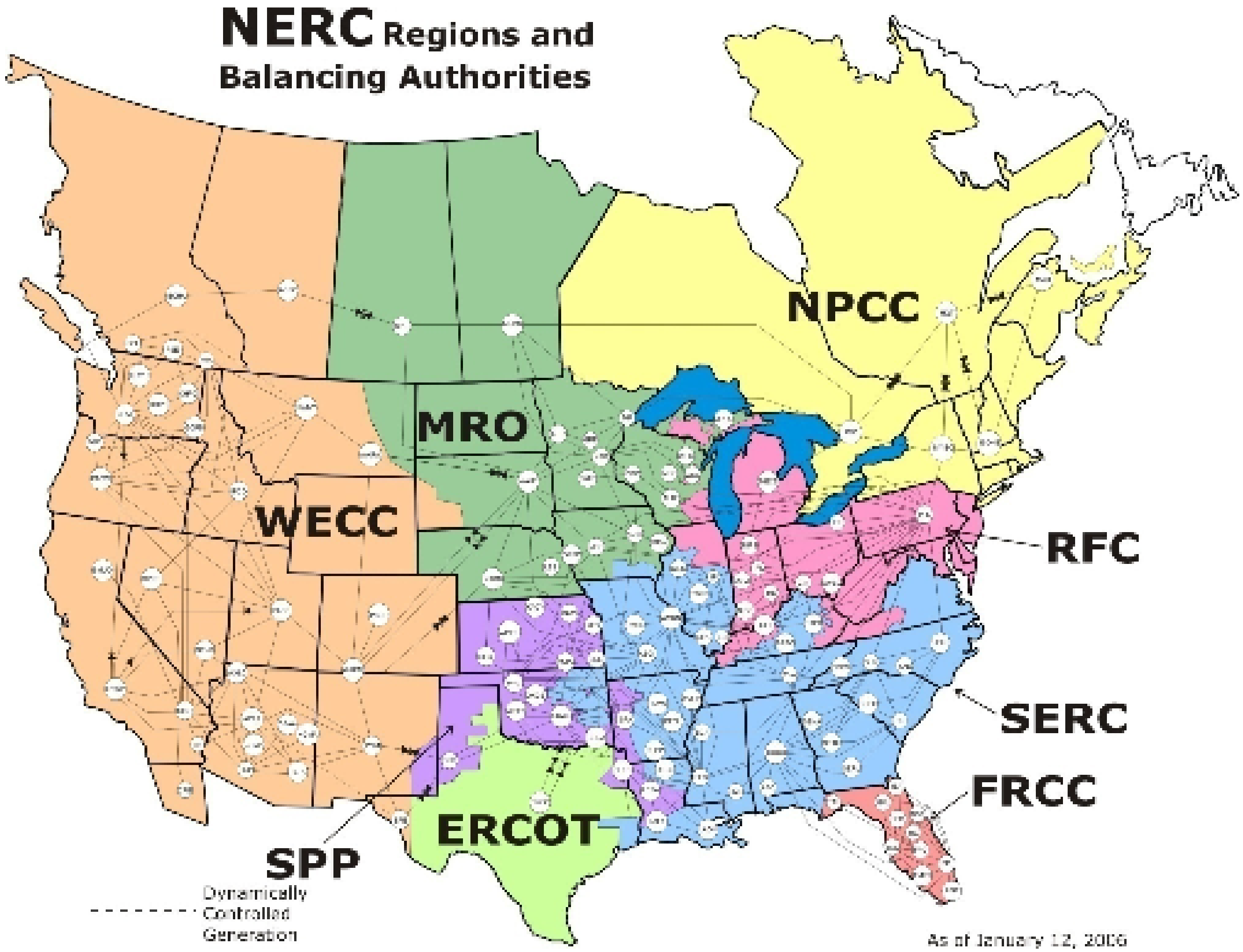
Total = 4,055 Billion kWh
Electric Utility Plants 63%

Independent Power Producers and Commercial Heat and Power Plants 37%

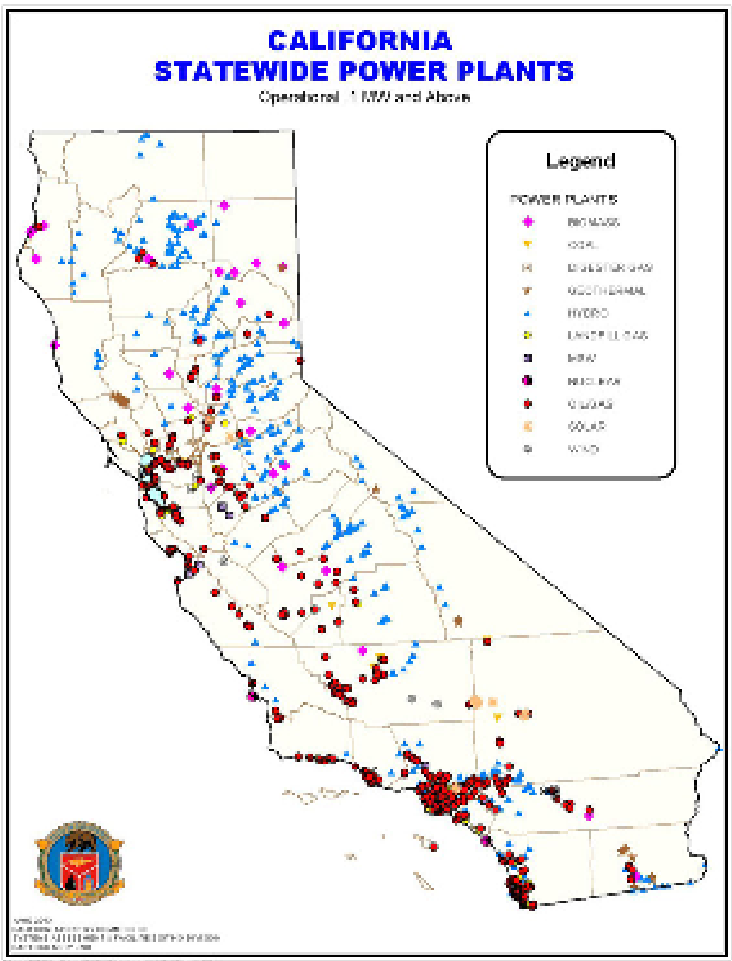
Data from U.S. Energy Information Administration - 2005

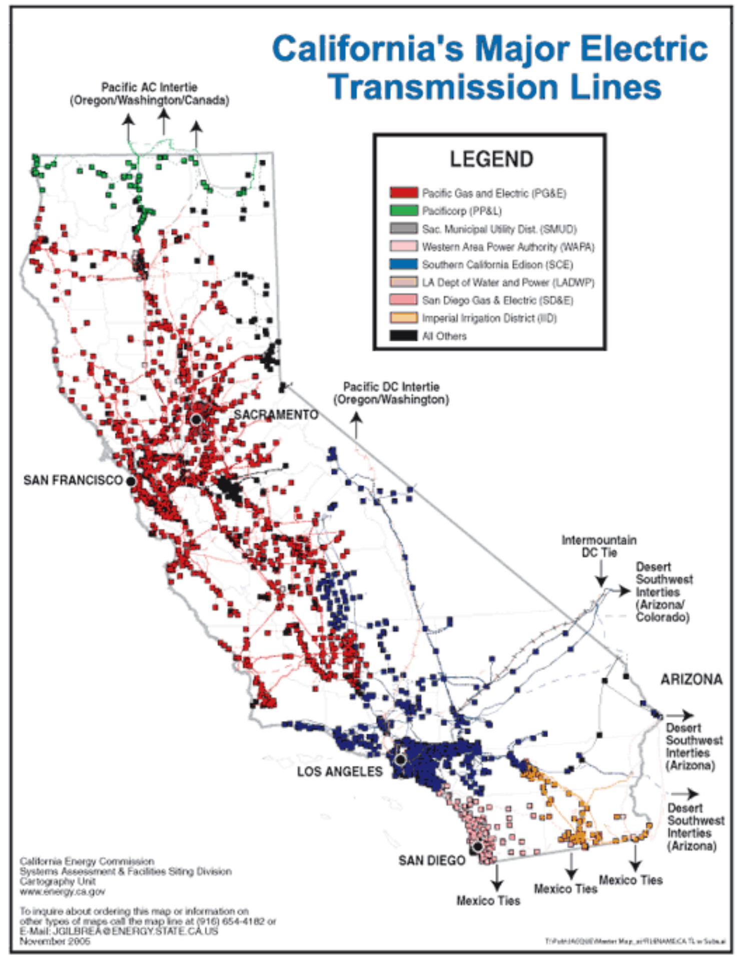


NERC: Electric Reliability org



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

Education SNIA

- 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 <u>wholesale</u>
  - Distribution (**“DisCo”** – a ‘natural’ monopoly which moves power to retail customers
  - Meters are everywhere throughout the system

Electricity Supply in the U.S. – other factors

Education SNIA

- 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)