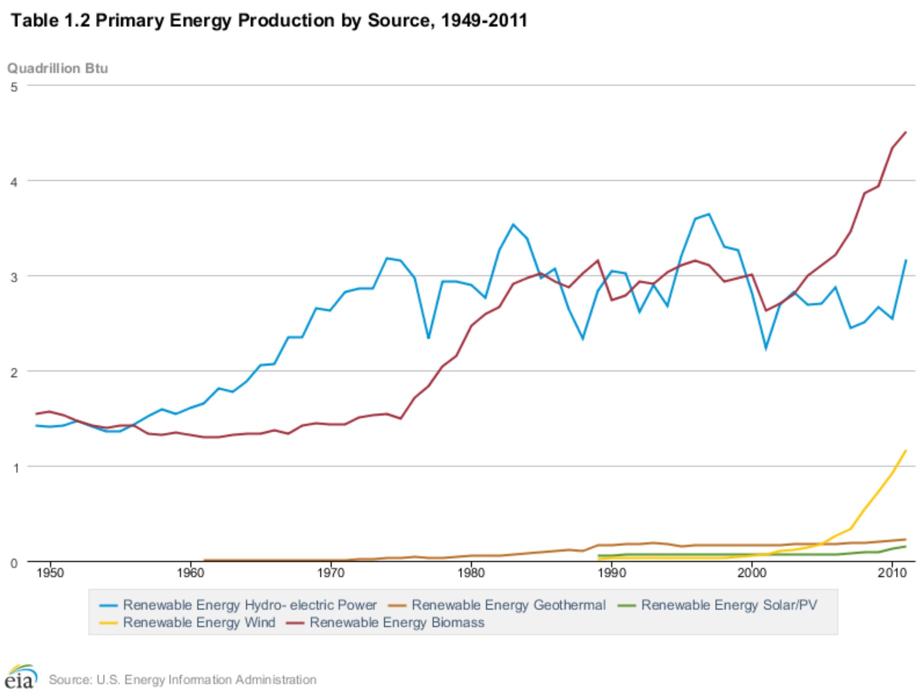
Renewable Energy Integration in Smart Grids

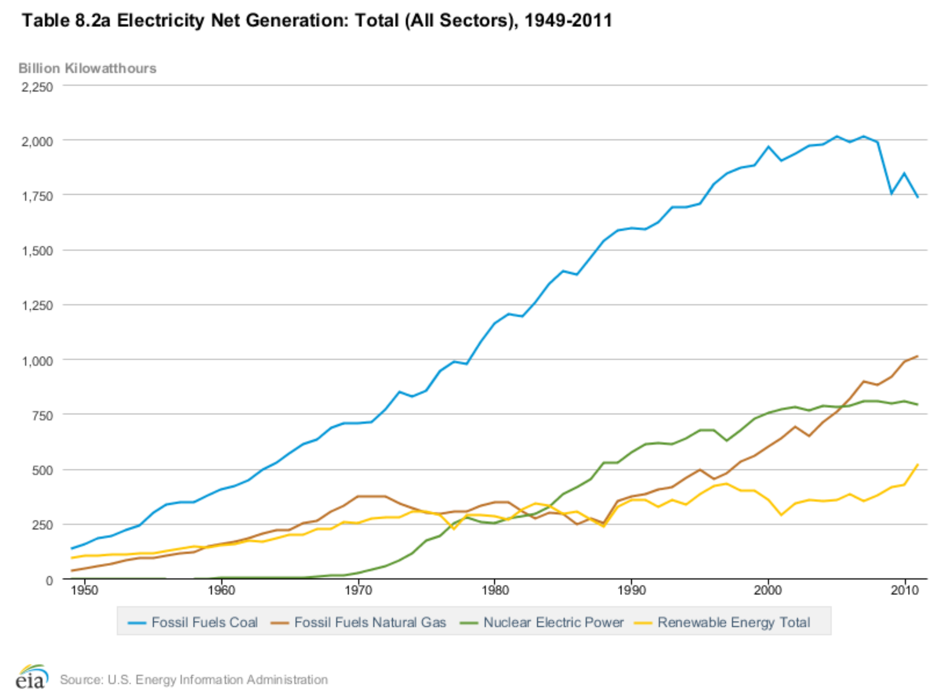
Jagannathan (Jug) Venkatesh
CSE 291 – Smart Grid Seminar

Overview

- Renewable Energy
- Renewable Energy Sources
- Grid Integration
- Renewable Energy Issues
- Renewable Energy Research
  - Storage
  - Integration
  - Prediction

The Big Picture

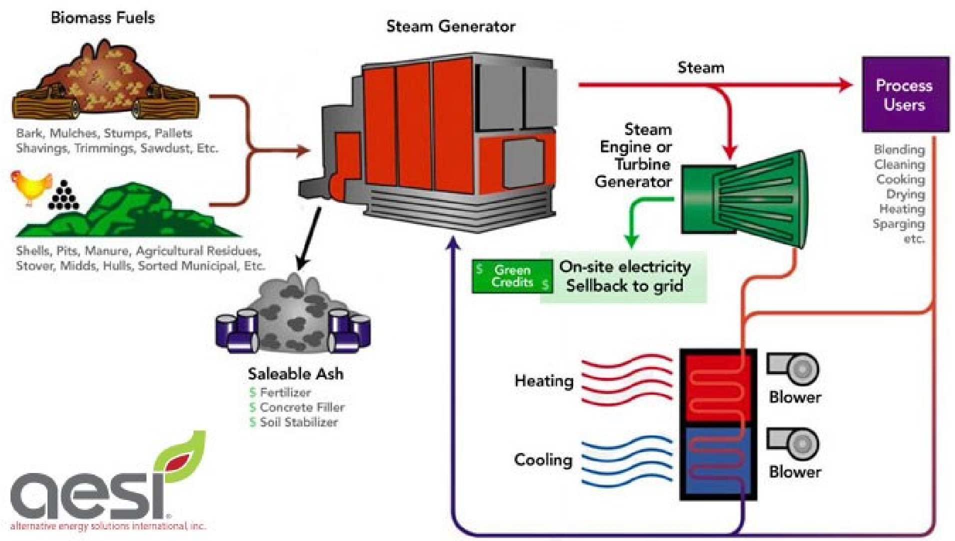


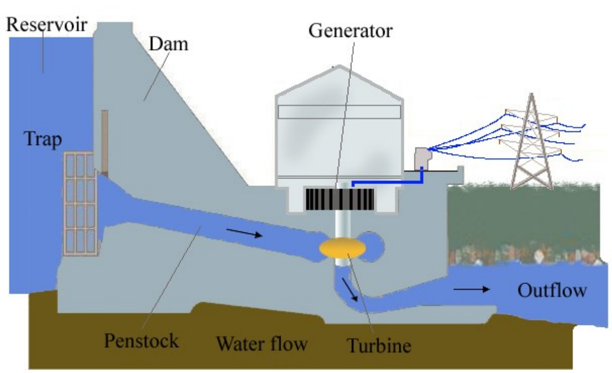


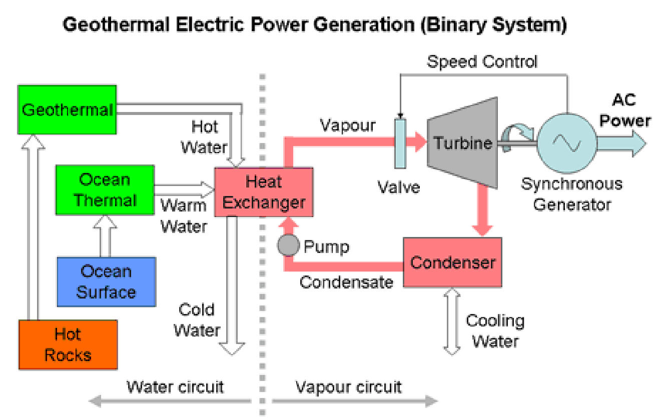
- Renewable energy use growing
  - 13% of total electricity in 2000 → 34.2% in 2012 (not including biogas)
  - >2x growth in annual electrical energy output since 2010

Renewable Energy Sources

- Types
  - Solar-electric
  - Wind
  - Hydroelectric
  - Fuel Cell/Biomass
  - Solar-heat
  - Geothermal
- Uses
  - Direct-electric
  - Heat/combustion electric



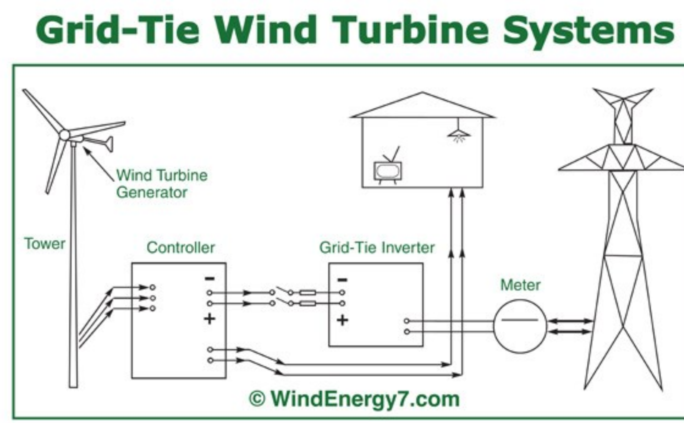


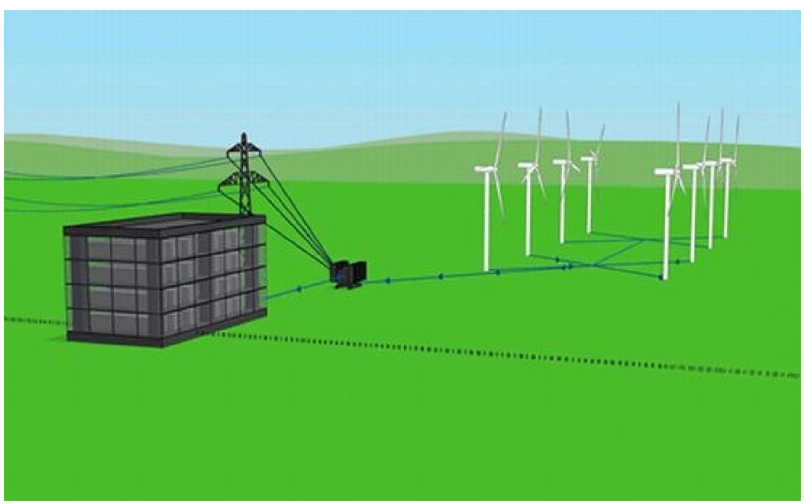


[1] http://www.nationalatlas.gov/articles/people/a_energy.htm

Renewable Energy at the Load

- Load-level, distributed generation
  - Solar[2]:
    - Grid Tie
    - Off-grid
    - Battery backup
  - Varying costs: $5000-$25000





- Wind:
  - 400-6000W commercially available systems
  - Capital costs: $500-10k turbine costs[3]
  - Additional inverter, regulator, transmission costs

[2] http://www.wholesalesolar.com/grid-tie-battery-backup.html
[3] http://bergey.com/wind-school/residential-wind-energy-systems
[4] R. Miller, "Wind-Powered Data Center Planned," Data Center Knowledge, 20 July 2009. [Online]. Available: http://www.datacenterknowledge.com/archives/2009/07/20/wind-powered-data-center-planned/.

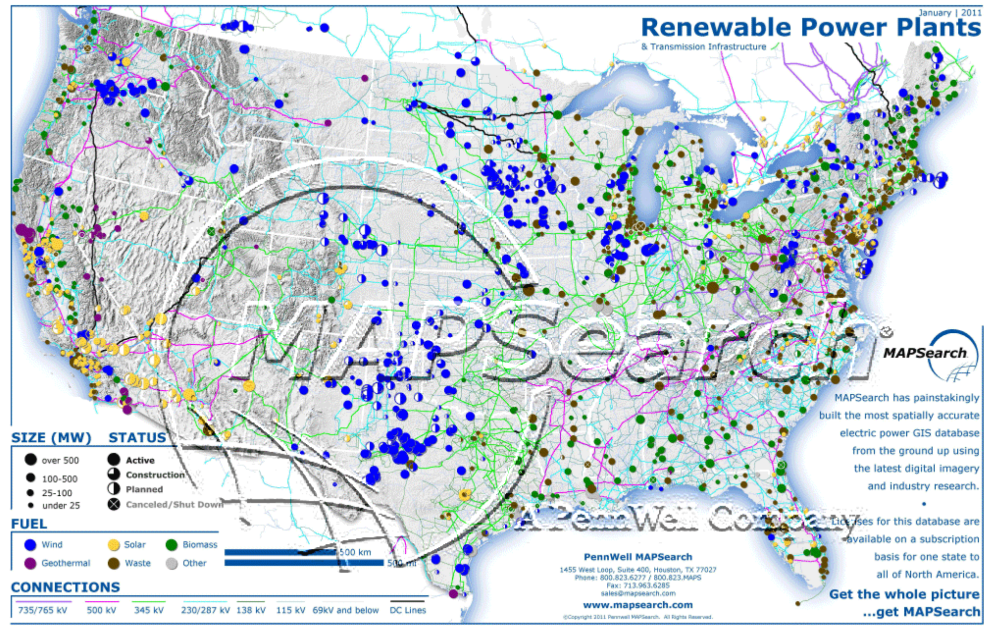
Renewable Energy at the Utility

- Larger sources
- Combined Heat & Power (CHP)

- Decoupled from grid, separated by:
  - Storage elements
  - Inverters (intermediate, grid-tie)
  - Converters (step-up or step-down)

- Voltage and Phase control
  - Physical control (sluice control, turbine resistance, heat exchanger flow control)
  - Electrical buffering (storage, flywheels, inversion)

  - Varying cold-start & ramp-up times
    - Sub-second control (solid-state inverters) to several-hours ahead (CHP cold-start)

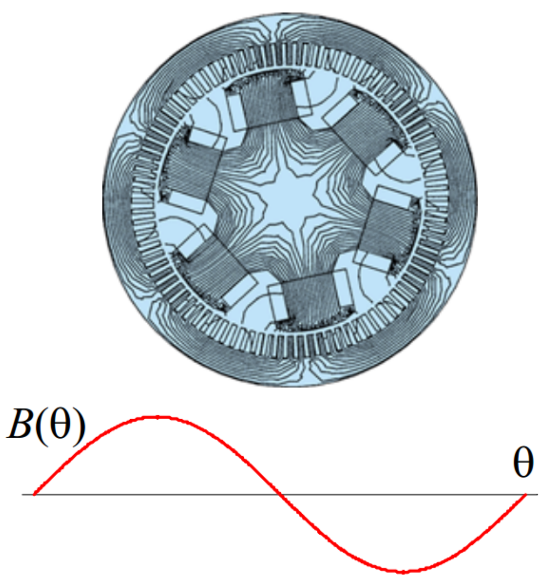


[5] http://www.mapsearch.com/gis-asset-data/renewable-energy-gis-data.html

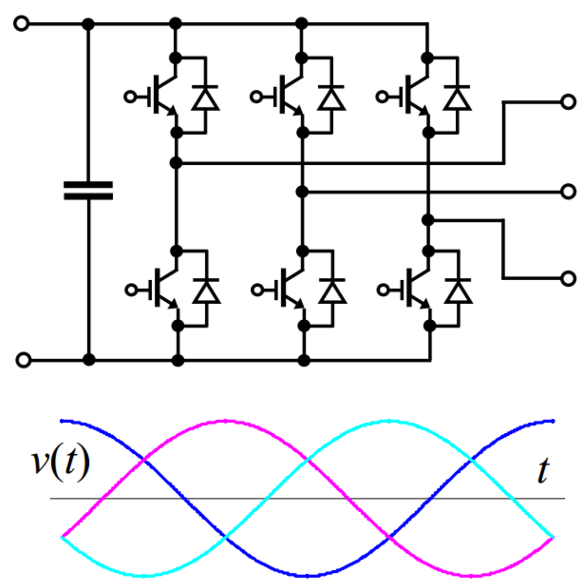
Grid Integration – AC Generators

- Found in wind turbines, smaller hydroelectric, etc. – sources that are turbine-connected.
- Progression:
  - One-phase AC output from generator, with **fine control** (turbine speed, current, excitation)
  - Switching semiconductor or capacitor-based *Voltage Source Converter (VSC)* with further **grid adjustment control** (semiconductor switching speed, current)
  - Three-phase grid output

Synchronous Generator



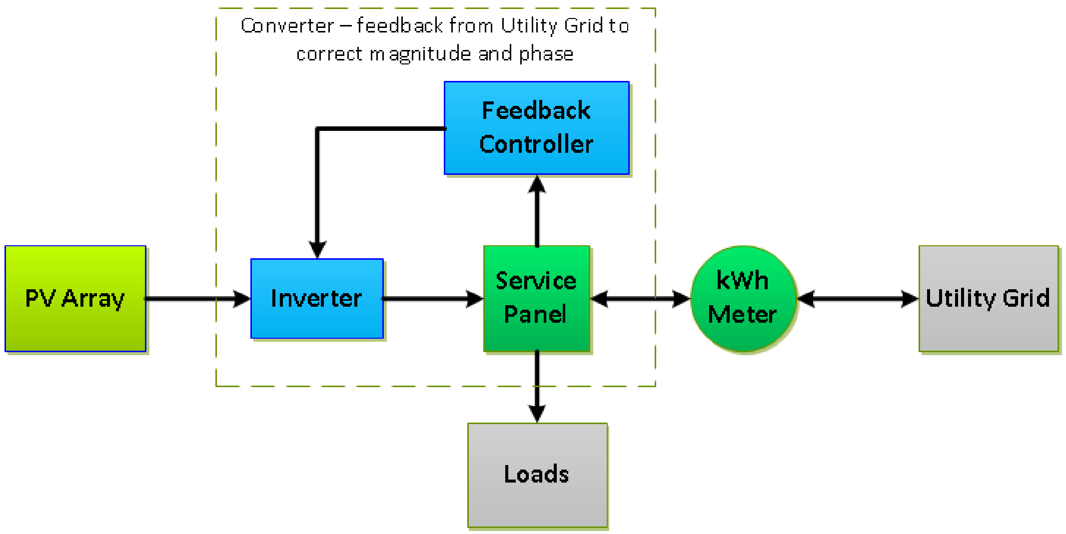
PWM VSC Converter



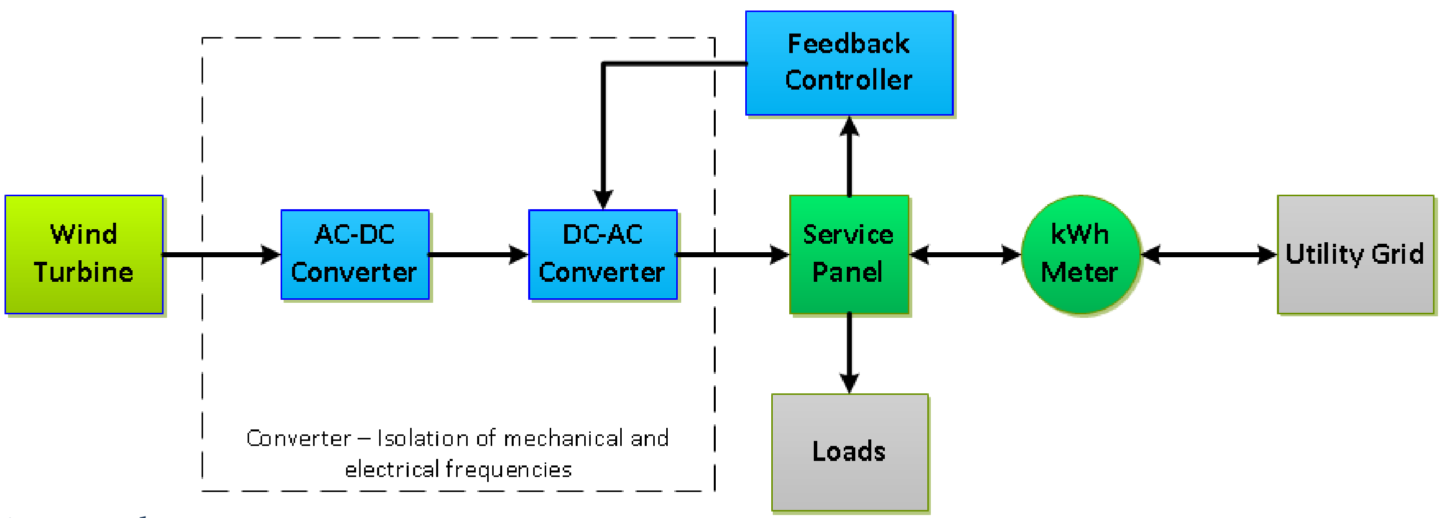
[6] http://www.rpi.edu/cfes/news-and-events/Seminars/06%20Sun.pdf

Grid Integration – Load-level

Solar:

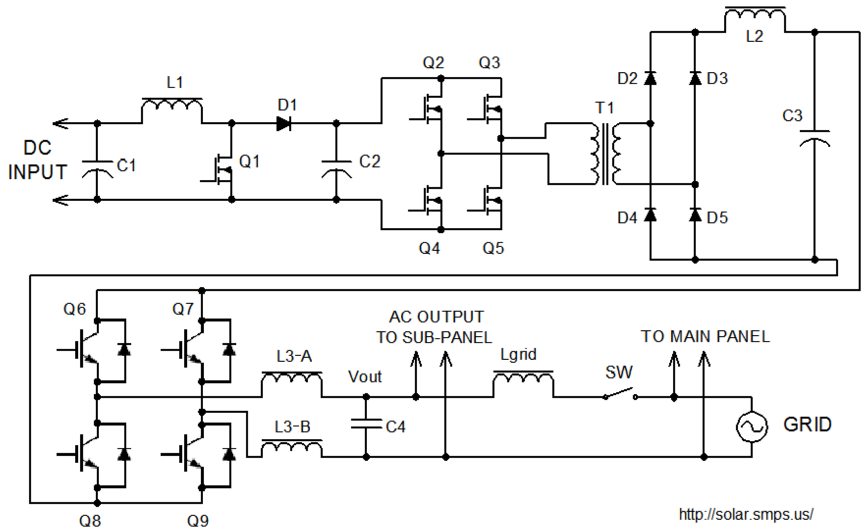


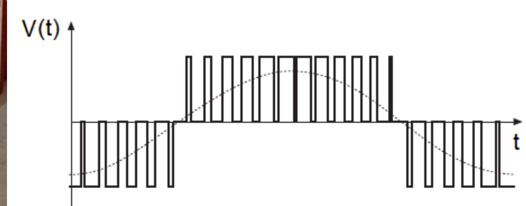
Wind:



Grid Integration – Grid-tie Inverter

- Single- or 3-phase, synchronous inverter, to allow connection back into the grid
  - Seamless integration with utility power in grid-connected loads:
    - Pull from the grid when local renewables are insufficient
    - Push back into the grid at overcapacity (net metering, etc.)
  - Grid connect/disconnect response time: ~100ms



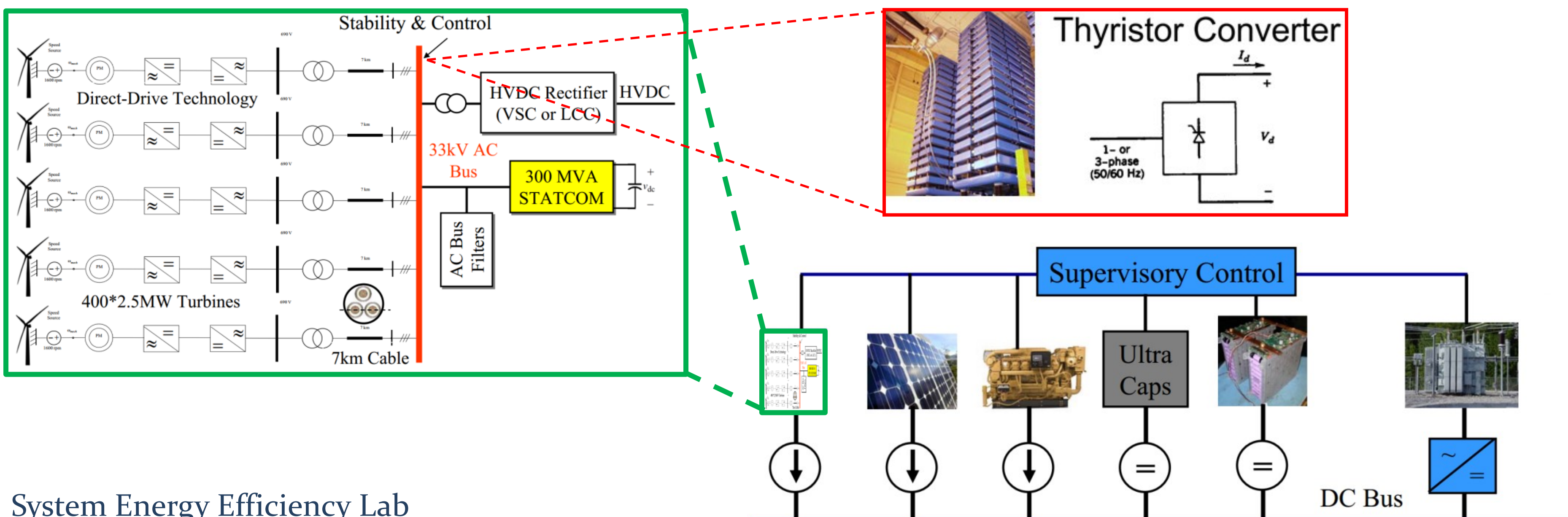


PWM to Synthesize Sinusoidal Output

[7] http://solar.smps.us/grid-tie-inverter-schematic.html

Grid Integration – High-Voltage DC

- Direct-drive offshore wind + HVDC
  - Efficient for offshore, due to long distances and HV generation
  - Conversion downstream for grid integration or:
  - (potentially) direct use for DC Micro Grids
  - **Thyristors**: solid-state “switch” to connect HVDC to AC Grid



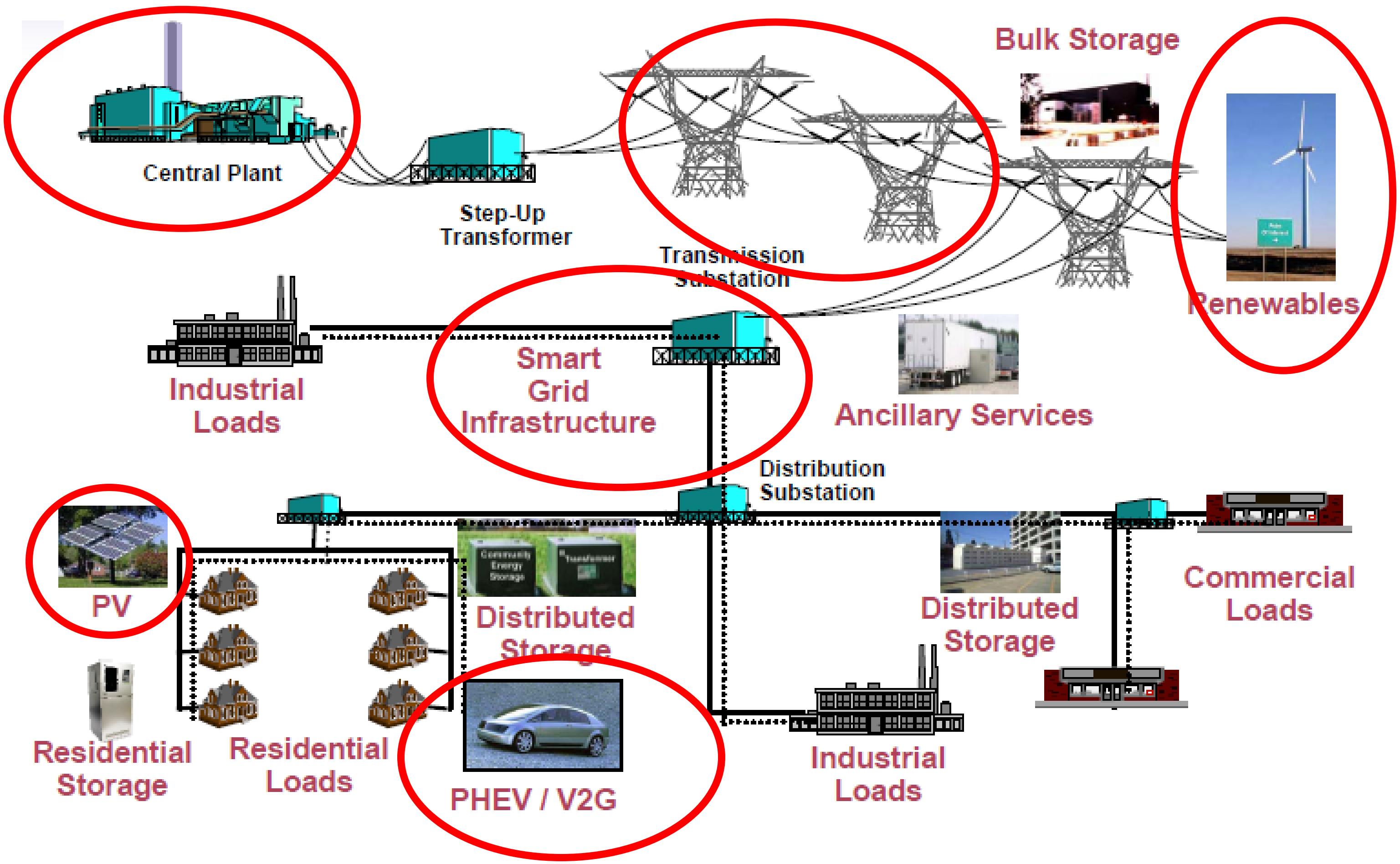
Renewable Energy Issues

- **Efficiency**:
  - Solar: up to 16%
  - Wind: up to 40%, realistically 20% **capacity factor**.
  - Biofuel: 20%, though up to 80% (best CHP generation)
  - Turbine-based generation suffers additional generator efficiency
- **Variability**!
  - Try to mitigate with storage (next section) or prediction
  - Grid-tied integration for immediate use
- **Distribution & Transmission**:
  - Grid accountability for distributed integration
  - Reverse power-flow support
  - Variability = secondary predictive supply/demand issues for utility providers

Energy Storage and Its Applications in Grid

Baris Aksanli
CSE 291 – Smart Grid Seminar

Energy Storage in Grid

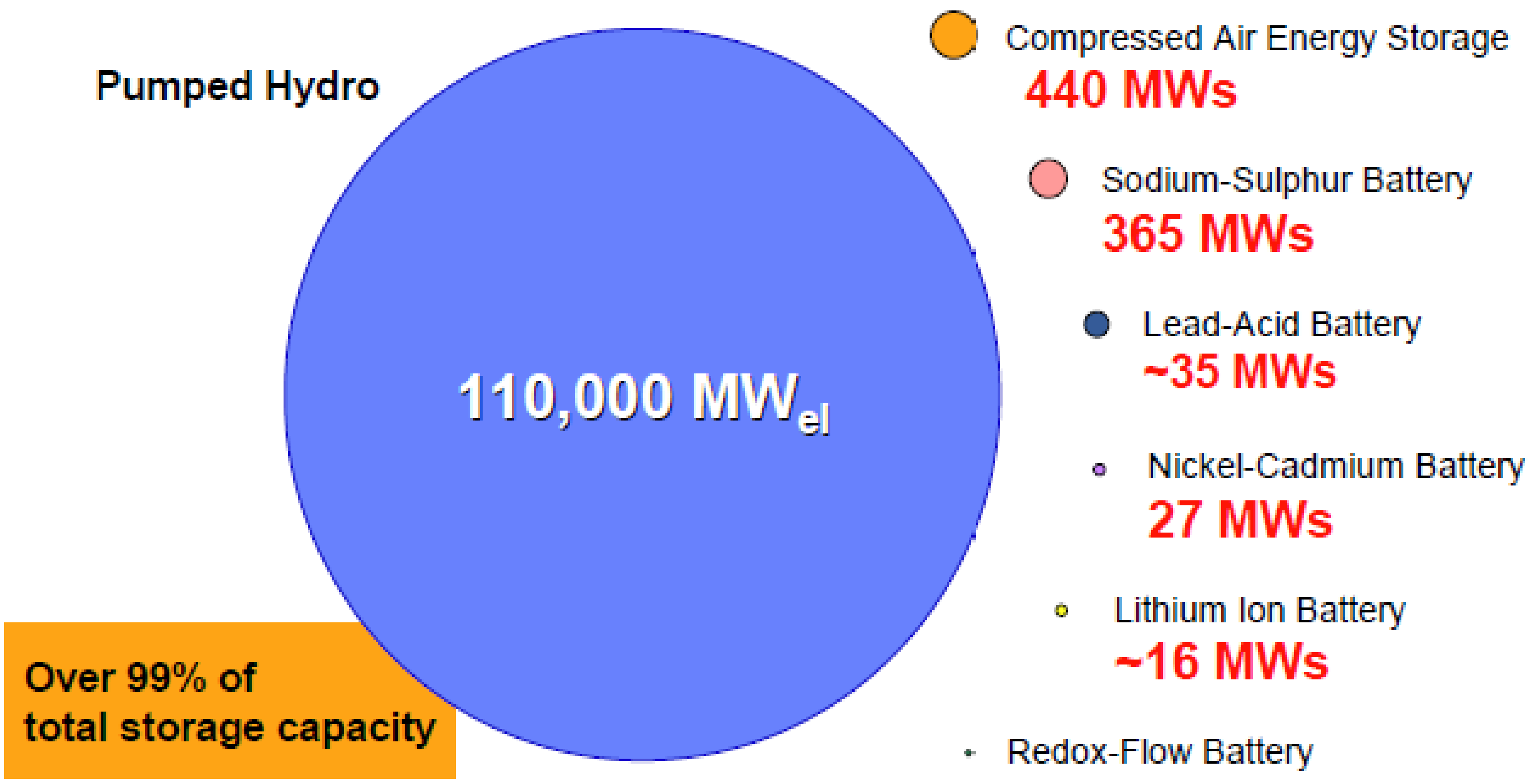


Source: EPRI

Energy Storage Technologies

- Mechanical
  - Pumped hydro, compressed air, flywheel
- Electromagnetic
  - Super-capacitors
- Chemical
  - Fossil fuel, biomass
- Thermal
  - Heat pump
- Electrochemical
  - Batteries

Market Share of Energy Storage Devices



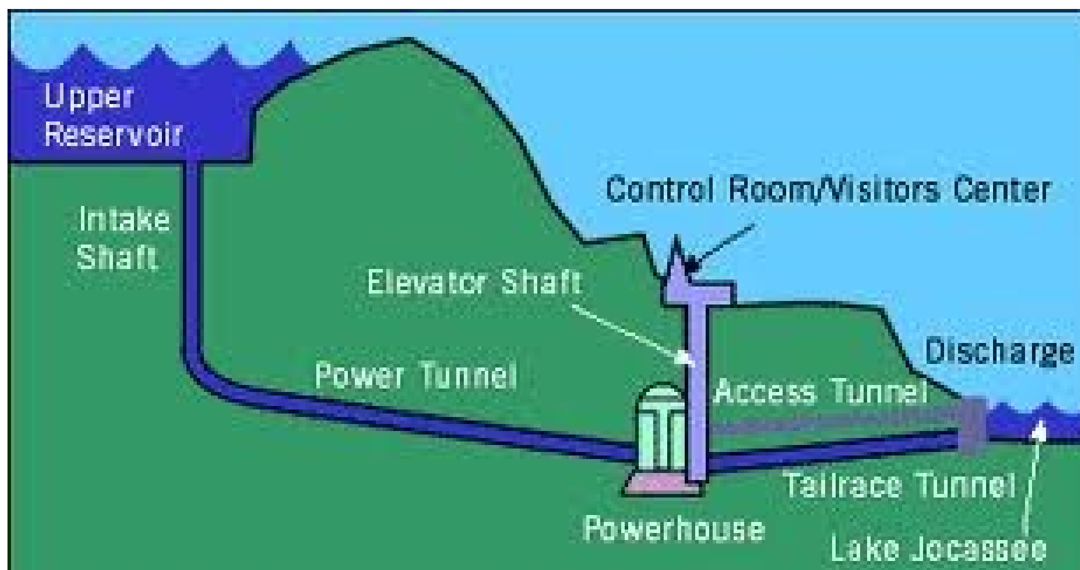
Source: Fraunhofer Institute, EPRI

Some Energy Storage Properties

1. Nominal discharge power
2. Discharge duration
3. Round-trip efficiency
4. Lifetime, i.e. "State-of-Health", performance
5. Energy and power density
6. Standby losses
7. Cost: Capital vs. operational

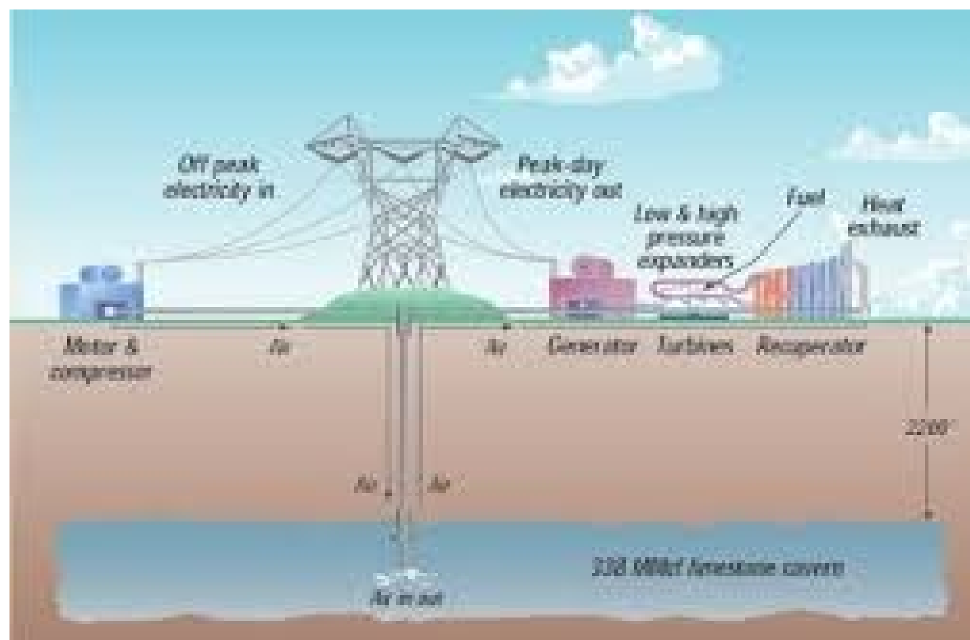
Pumped Hydro

- Operation
  - Use off-peak electricity to pump water to a reservoir at high elevation
  - When electricity is needed, water is released hydroelectric turbines into low reservoir
- Features
  - Siting is limited
  - Round-trip efficiency between 70% - 85%



Compressed Air Energy Storage (CAES)

- Operation
  - Use off-peak electricity to compress air & store in reservoir
    - Underground cavern
    - Aboveground vessel
  - When electricity is needed, compressed air is heated, expanded, and directed thru conventional turbine-generator
- Features
  - Efficiency < 70%
  - Siting is limited
  - Adiabatic CAES
    - Little or no fossil fuel



Batteries

- Lead-acid battery
  - Types
    - Flooded
    - Sealed (VRLA)
  - Applications
    - Starting/lighting/ignition
    - Industrial
      - Traction (Motive Power)
      - Stationary (UPS, backup)
    - Portable
  - Issues
    - Short lifetime cycle
      - Deep discharge and/or temperature issues

- Sodium sulfur battery
  - Operates at high temperature
  - High energy density
  - High efficiency, ~85
  - Inexpensive
  - Used for grid storage in USA and Japan
  - Other applications
    - Space applications
    - Transport and heavy machinery

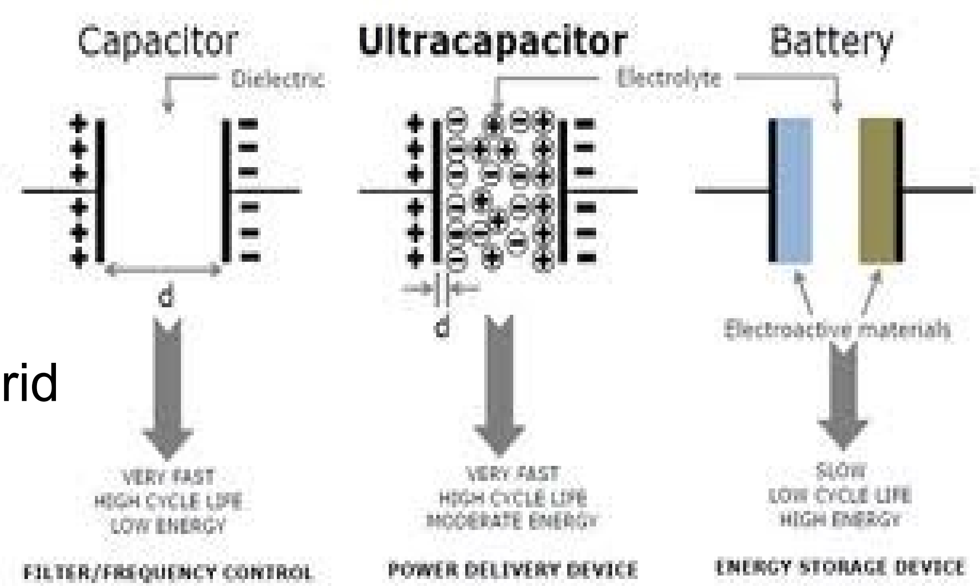
Batteries

- Lithium ion battery
  - Developed with many different materials
  - High energy density and efficiency, ~90%
  - Small standby loss
  - Applications
    - Consumer electronics
    - Transportation
    - Recently: Electric vehicle - Aerospace
- Nickel cadmium battery
  - Good cycle life
  - Good perf. at low temp.
  - Good perf. with high discharge rate
  - Expensive!
  - Memory effect
  - Environmental impact of heavy metal cadmium
  - Applications
    - Standby power
    - Electric vehicles
    - Aircraft starting batteries

Super-capacitors

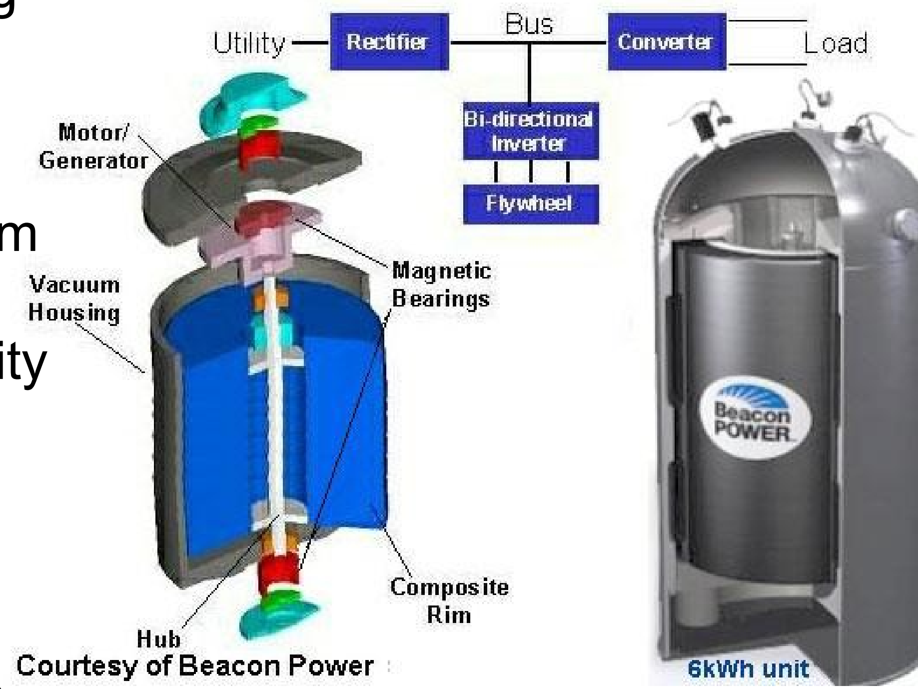
- Long life, with little degradation over hundreds of thousands of charge cycles
- Low cost per cycle
- Fast charge and discharge
- High output power but low energy density
  - Power systems that require very short, high current
- No danger of overcharging, thus no need for full-charge detection

- High self-discharge
- Rapid voltage drop
- Applications
  - General automotive
  - Heavy transport
  - Battery complement → Hybrid energy storage systems



Flywheel

- Operation
  - Store kinetic energy in a spinning rotor made of advanced high-strength material, charged and discharged through a generator
  - Charge by drawing electricity from grid to increase rotational speed
  - Discharge by generating electricity as the wheel's rotation slows
- Features
  - Limitations to energy stored
  - Primarily for power applications
  - High round-trip efficiency (~85%)



Source: Beacon Power

Application Classification

Storage Technologies	Main Advantages (relative)	Disadvantages (Relative)	Power Application	Energy Application
Pumped Storage	High Capacity, Low Cost	Special Site Requirement		●
CAES	High Capacity, Low Cost	Special Site Requirement, Need Gas Fuel		●
Flow Batteries: PSB VRB ZnBr	High Capacity, Independent Power and Energy Ratings	Low Energy Density	◐	●
Metal-Air	Very High Energy Density	Electric Charging is Difficult		●
NaS	High Power & Energy Densities, High Efficiency	Production Cost, Safety Concerns (addressed in design)	●	●
Li-ion	High Power & Energy Densities, High Efficiency	High Production Cost, Requires Special Charging Circuit	●	○
Ni-Cd	High Power & Energy Densities, Efficiency		●	◐
Other Advanced Batteries	High Power & Energy Densities, High Efficiency	High Production Cost	●	○
Lead-Acid	Low Capital Cost	Limited Cycle Life when Deeply Discharged	●	○
Flywheels	High Power	Low Energy density	●	○
SMES, DSMES	High Power	Low Energy Density, High Production Cost	●	
E.C. Capacitors	Long Cycle Life, High Efficiency	Low Energy Density	●	◐

● Fully capable and reasonable

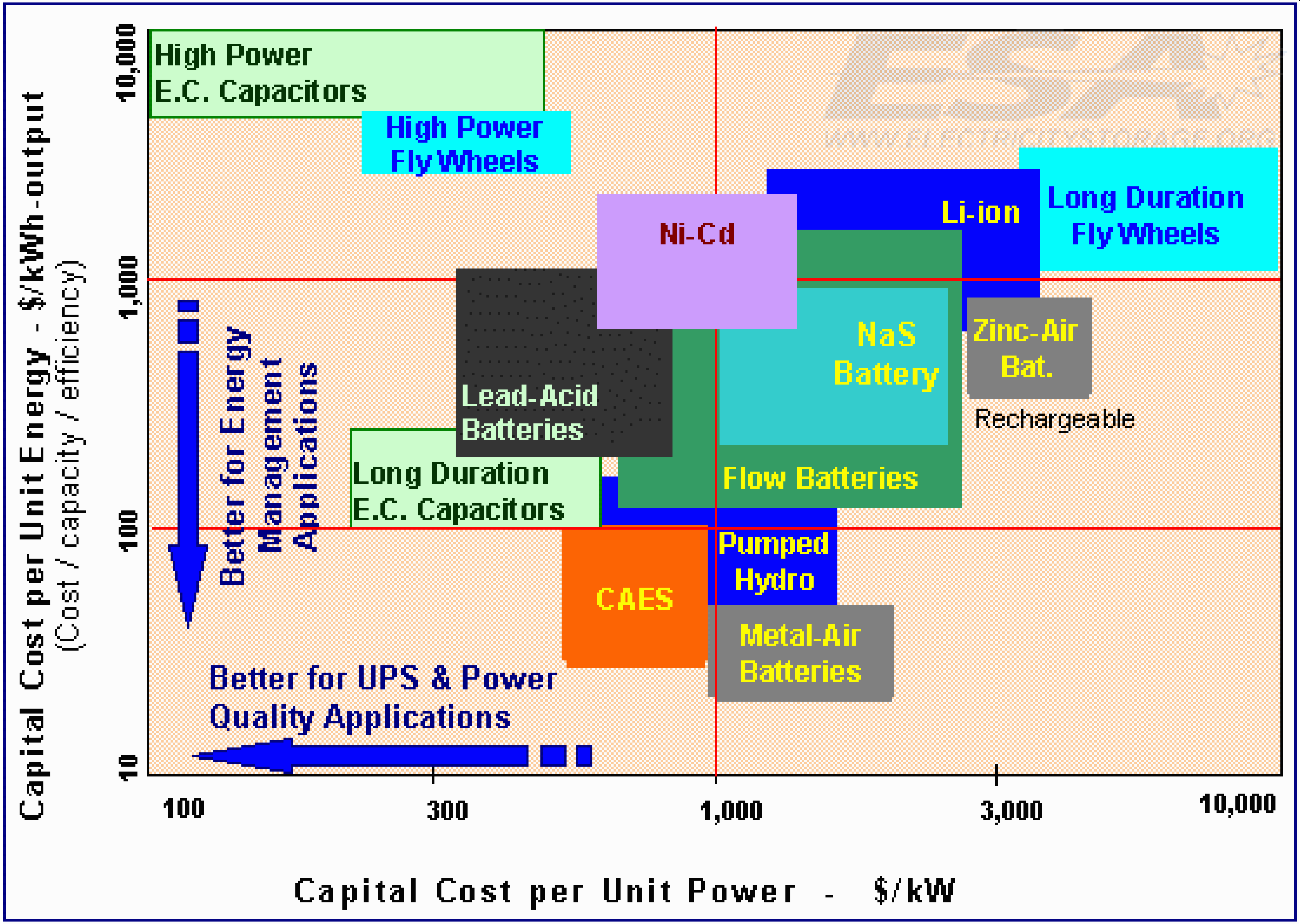
◐ Reasonable for this application

○ Feasible but not practical/economical

None Not practical or economical

Source: ESA

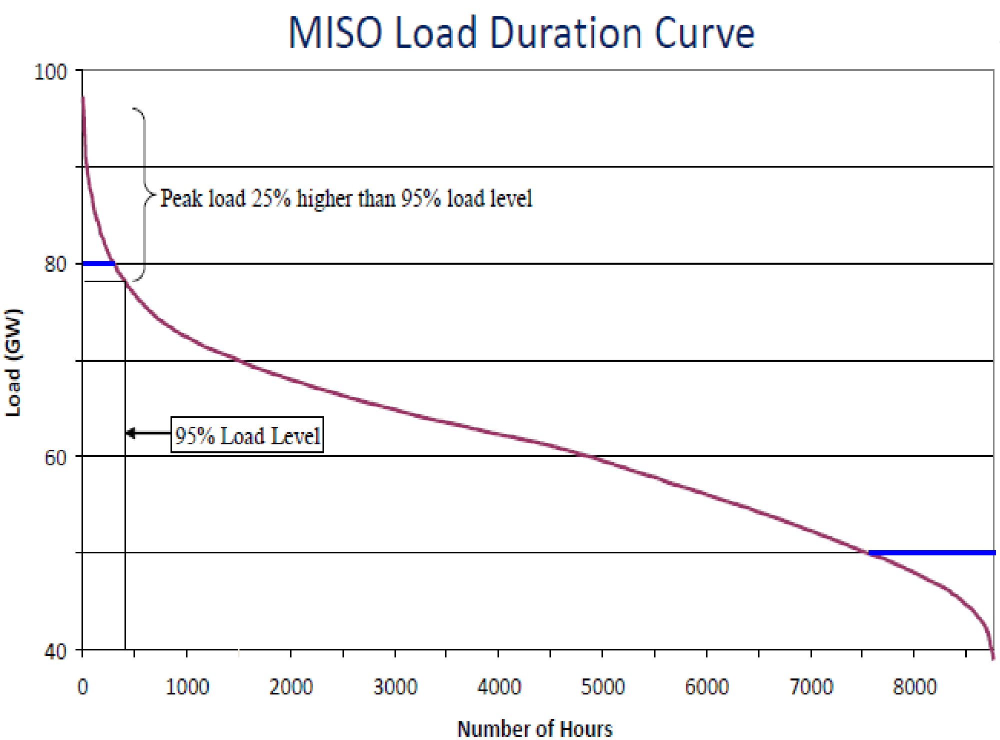
Capital Cost Comparison



Source: ESA

Electric Supply Applications

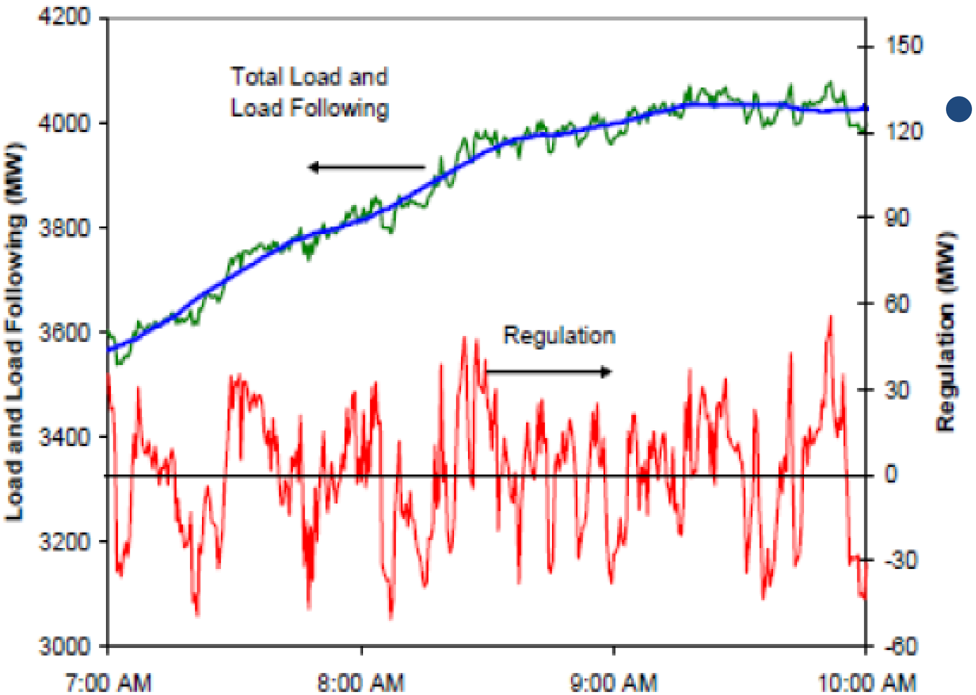
- Electric Energy Time Shift
  - When **inexpensive**: purchase energy from wholesale
  - When **expensive**: resell to market or offset need to buy



- Electric Supply Capacity (aka Asset Utilization)
  - Defer peak capacity investment
  - Provide system capacity/resource adequacy (offset need for generation equipment)

Energy storage will increase asset utilization for generation and transmission and reduce the number of "**peaker**" power plants

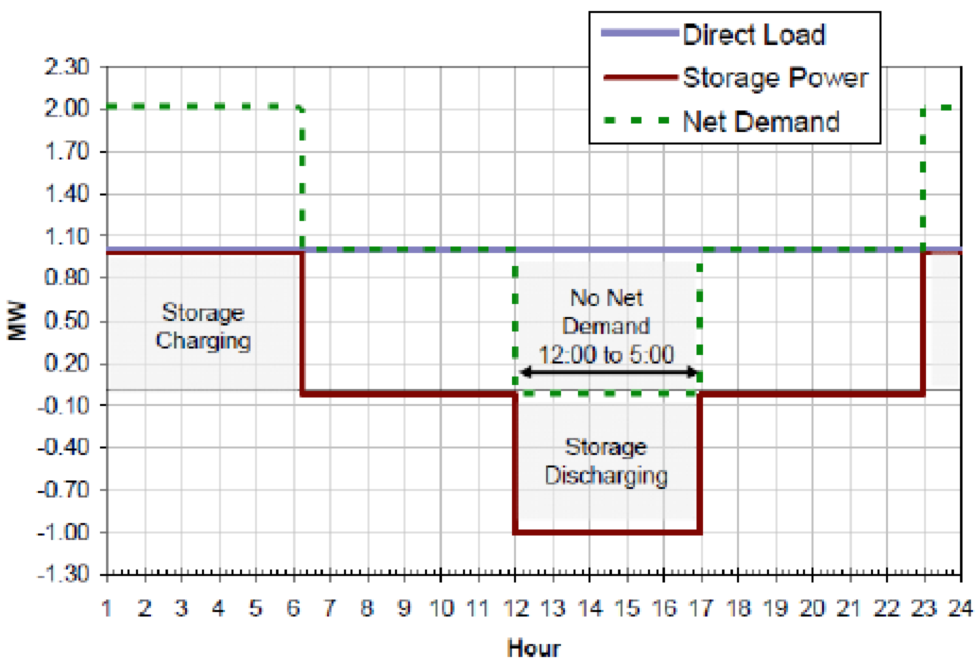
Ancillary Service Applications



- Area (frequency) regulation
  - Helps managing moment-to-moment variations within a controlled area
  - "interchange" flows between areas
- Load following
  - Helps grid to adjust its output level
  - Backup for grid to isolate the frequent and rapid power changes

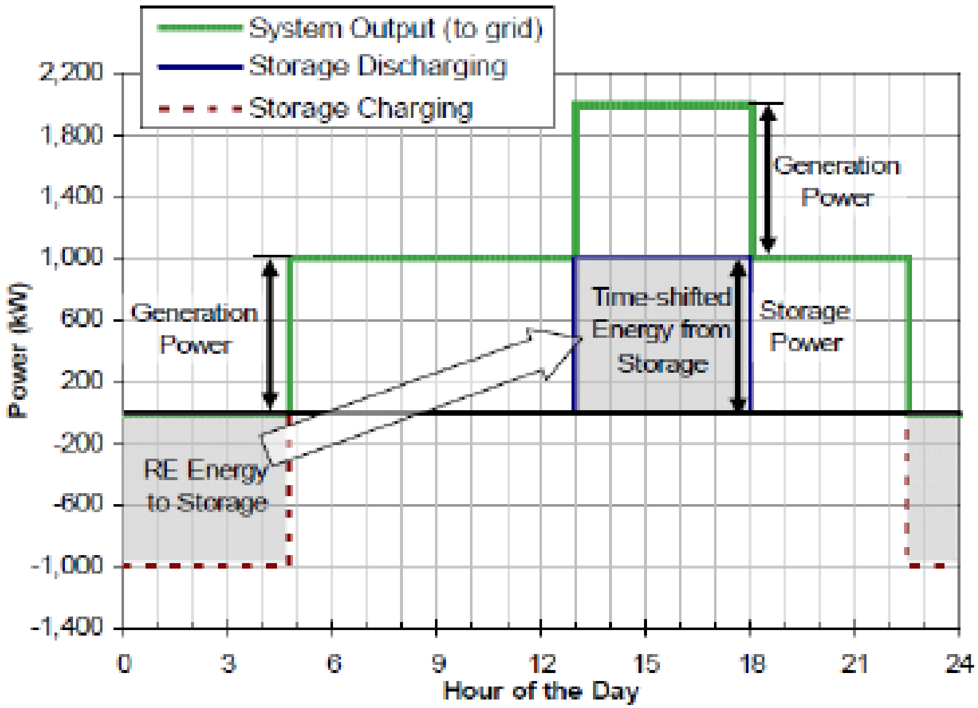
End-user Applications

- Time-of-use Energy Cost management
  - Discharge when the energy is more expensive
- Electric Service Reliability (UPS)
  - Provide energy outage management
- Electric Service Power Quality
  - Protect on-site loads downstream (from storage) against short-term events that affect the quality of power delivered



- Source: Sandia Lab (2010)

Renewable Energy Integration Applications

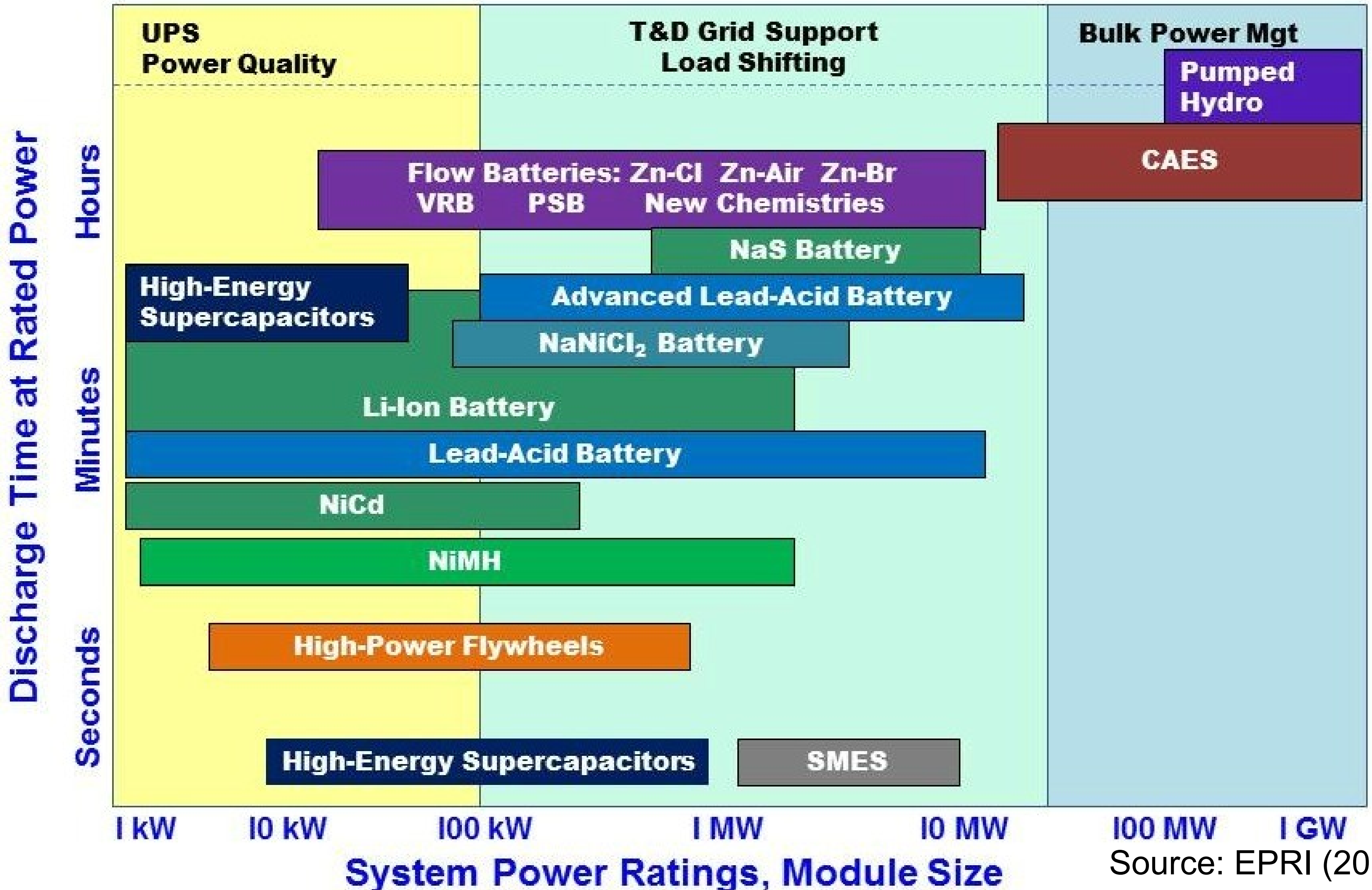


- Renewable Energy Time-shift
  - Charge using low-value energy
  - Discharge used by owner, sold on spot market or PPA
  - Enhance the value of energy to increase profits

Eg: Rokkasho Windfarm (JP), 51 MW Wind, 34 MW/7hr NaS Storage

- Renewable Capacity Firming
  - Use intermittent electric supply source as a nearly constant ***power*** source
- Wind Generation Integration
  - Improve power quality by reducing output variability
  - Backup when not enough wind energy

Storage Device vs. Application Domain



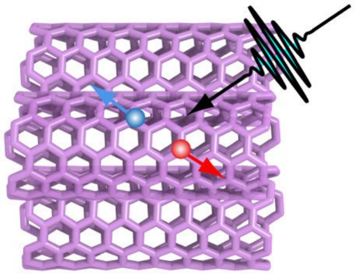
Source: EPRI (2010)

Current Research on Renewables and Energy Storage

System Energy Efficiency Lab
seelab.ucsd.edu

Renewable Energy Efficiency

- Very low efficiency, even compared to fossil-fuel generation
- Technology improvements:
  - **Solar:**
    - Multi-axis tracking and control[8]
    - Improved concentrator/CHP output (photovoltaic/thermal – PVT)[9]
    - Efficiency/yield improvements[10] and new PV cell types[11].

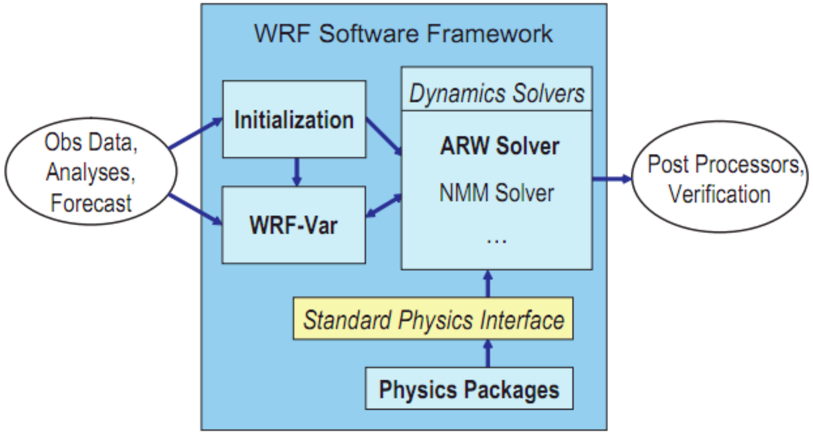


  - **Other Technologies:**
    - Improved efficiency/yield
    - Biological/cellular biofuel – re-engineer micro-organisms to generate *alkanes*, *alcohols*, *hydroxyl groups* as byproducts.
    - Wave and tidal stream generation – utility-scale
    - Nanotechnology filtration for refining/producing methanols

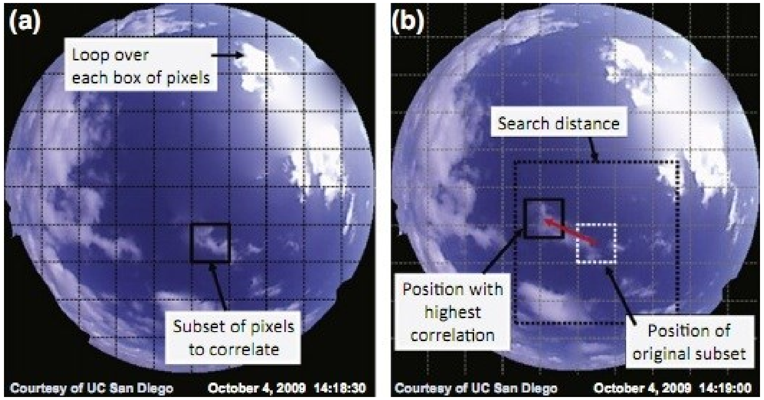
[8] Venkata et al. “Design and Development of an Automated Multi Axis Solar Tracker Using PLC”. 2013.
[9] Chow, T.T. “A review on photovoltaic/thermal hybrid solar technology”. 2011
[10] Jupe et al. "Increasing the energy yield of generation from new and renewable energy sources".
[11] http://news.yale.edu/2013/02/13/new-carbon-films-improve-prospects-solar-energy-devices

Variability Mitigation via Prediction

- **Numerical Weather Prediction[12] (<20% error):**
  - High-computation, data-intensive models to output different variables
  - Spatial prediction of variables
  - Succeeded by power prediction via other algorithms:
    - Time Series Analysis (TSA)
    - Machine-learning algorithms (ANN, MOS)

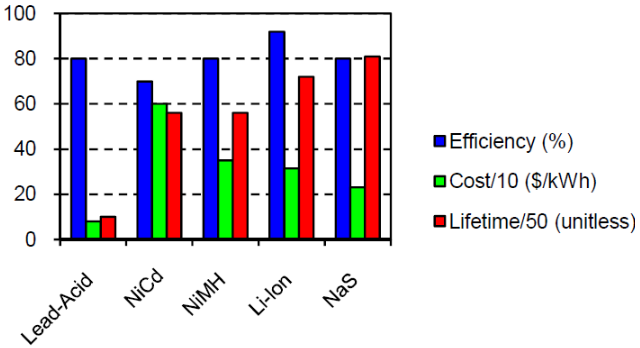


- **Direct Measurement[13] (<10% error)**
  - Cloud tracking for very granular (30s) prediction



[12] R. Marquez and C.F.M. Coimbra (2013) "Intra-Hour DNI Forecasting Methodology Based on Cloud Tracking Image Analysis" (2013)
[13] P. Mathieson, J. Kleissl, "Evaluation of numerical weather prediction for intra-day solar forecasting in the continental United States," 2011

Optimum Battery Chemistry Selection



SUMMARY OF RESULTS FOR ALL CHEMISTRIES CONSIDERED, 1% O&M FOR NAS

Feed-in Tariff (¢/kWh)	NaS O&M (%)	Capacities (MWh)	ROI (%)
8	1	27.8 NaS	6.39
50	1	40.1 Li-Ion	221
2	5	0	N/A
13	5	40.1Li-Ion	2.42

SENSITIVITY OF RESULTS TO BATTERY COSTS, 5% O&M FOR NAS, WITH 10-YEAR LIFETIME, 15CENTS/KWH FEED-IN TARIFF

Li-Ion Price ($/kWh) \ NaS Price ($/kWh)	50	100	150	200	250	300
50	363	363	363	363	363	363
100	175	175	175	175	175	175
150	316	91.5	91.5	91.5	91.5	91.5
200	316	141	46.2	46.2	46.2	46.2
250	316	141	61.5	17.6	17.6	17.6
300	316	141	61.5	17.6	Infeasible Region	

Li-Ion ROI (%) | NaS ROI (%)

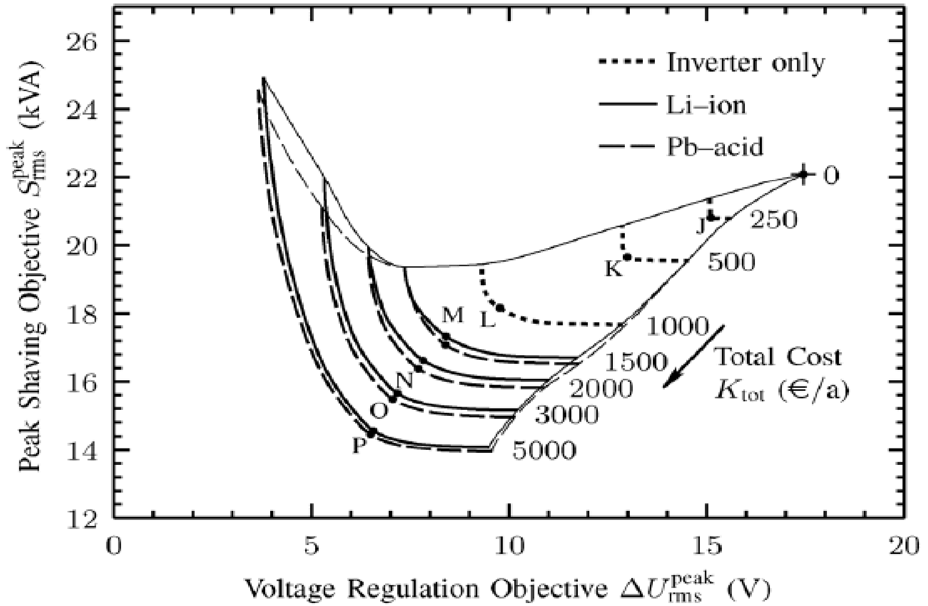
SUMMARY OF RESULTS FOR SINGLE TECHNOLOGY ONLY, 5% O&M FOR NAS, WITH 10-YEAR LIFETIME, 15CENTS/KWH FEED-IN TARIFF

Battery Chemistry Price Structure	Capacities (MWh) 3-level	Capacities (MWh) 2-level	ROI (%) 3-level	ROI (%) 2-level
Lead-acid	0	50	N/A	N/A
NiCd	0	0	N/A	N/A
NiMH	0	0	N/A	N/A
Li-Ion	20.5	20.5	32.9	15.2
NaS	16.9	16.9	49.6	20.9

- Barnes et al. “Optimal Battery Chemistry, Capacity Selection under Time of Use Pricing” IGST Europe 2011

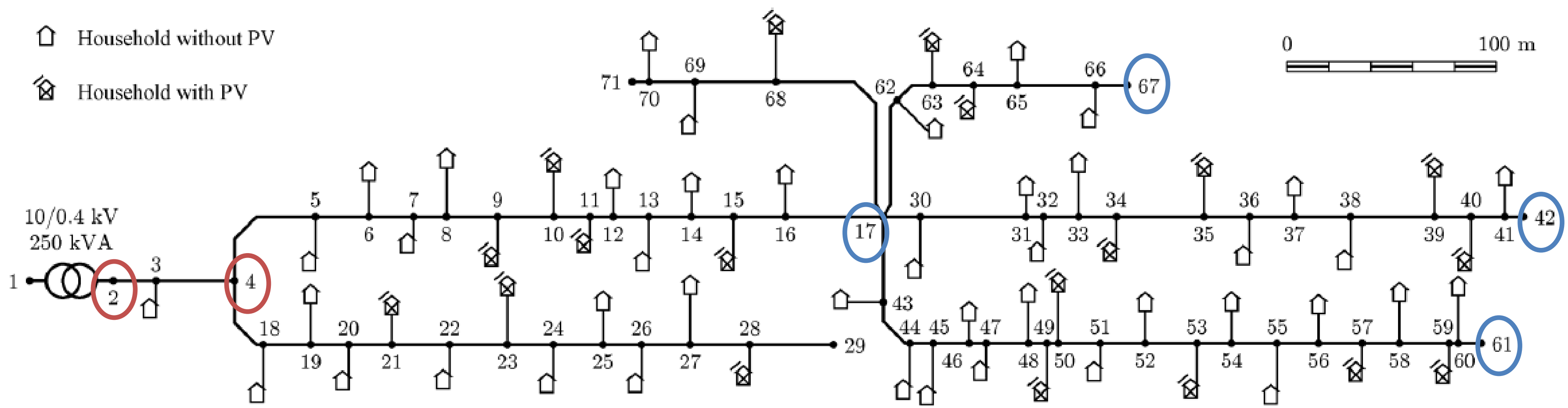
PV Integration

- Problems
  - Voltage regulation
  - Peak shaving
  - Cost of energy storage
  - Location



Pareto-optimal isocost trade-off curves between the objectives of peak shaving and voltage regulation, computed for two battery technologies, for multiple annual costs K_{tot}. The BESS is located at node 17.

- Tant et al. “Multiobjective Battery Storage to Improve PV Integration in Residential Distribution Grids”, IEEE Transactions on Sustainable Energy 2013



Schematic diagram of the semiurban feeder used in the scenario. Cable lengths are drawn to scale.

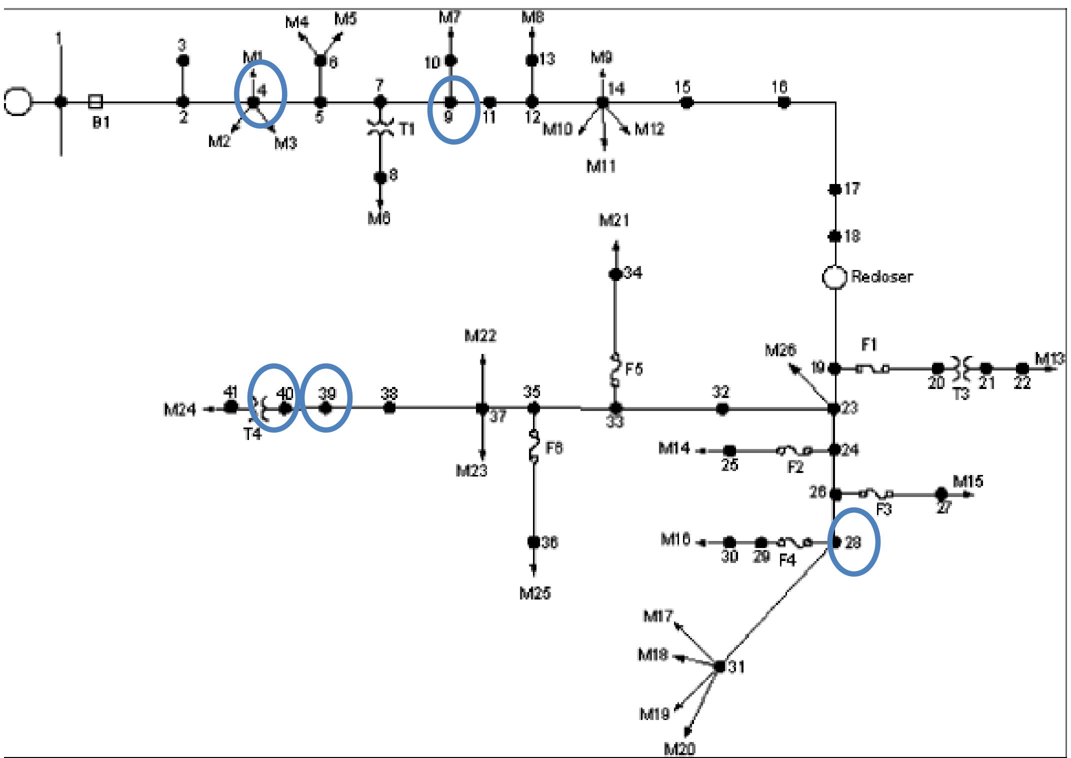
Wind Integration

- Problems
  - High variability
  - Large amount of instantaneous generation

- Atwa et al. "Optimal Allocation of ESS in Distribution Systems With a High Penetration of Wind Energy", IEEE Transactions on Power Systems 2010

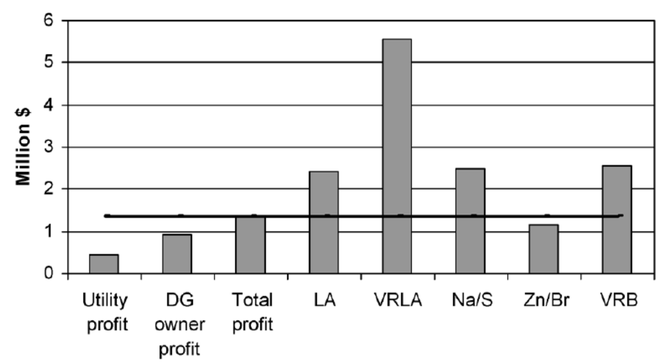
COST OF SPILLED ENERGY

Max amount of spilled power during the entire year P_{ESS}	6 MW
Max amount of spilled energy during a specific day E_{ESS}	40 MWh
Total annual spilled energy	7063.9 MWh
Total annual cost of spilled energy (million dollars)	0.92



OPTIMUM ALLOCATION OF ESS IN THE DISTRIBUTION SYSTEM

bus	MWh	MW
4	19.48	2
9	12.99	1.5
28	8.44	0.5
39	4.55	1
40	6.49	1

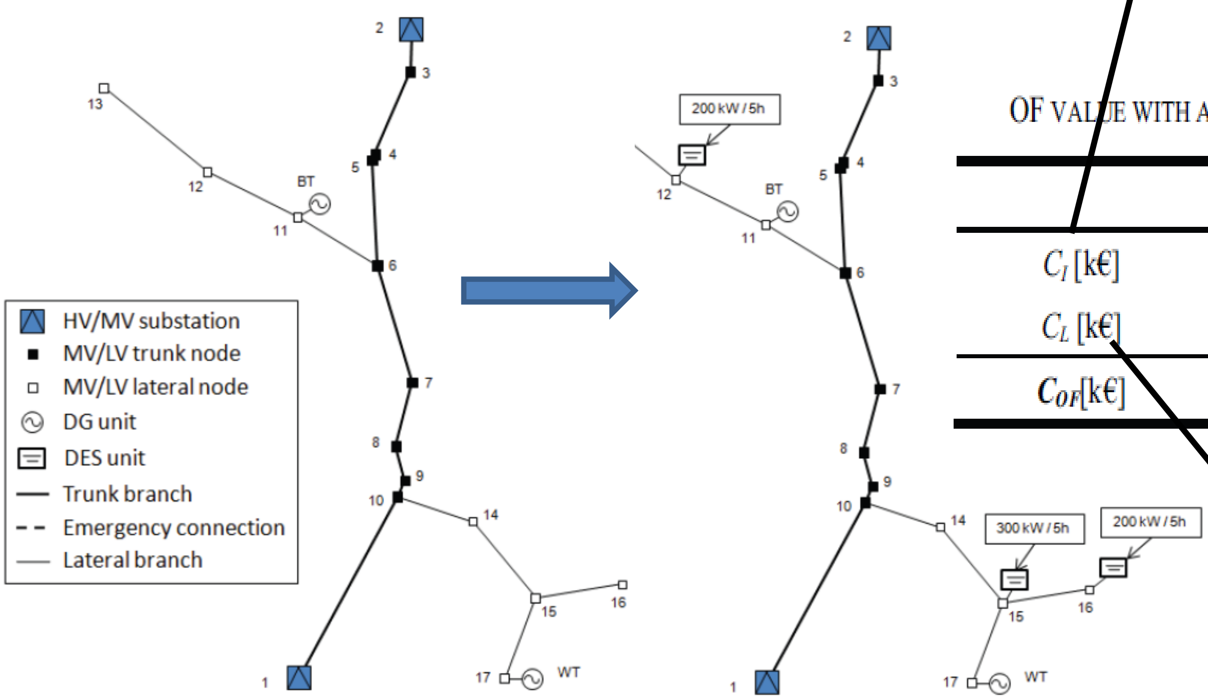


Total profit compared to the annual cost of different ESS technologies.

Grid Upgrade Deferring

- Problem
  - With more generation, the grid might need upgrades to keep up with the generation

- Celli et al. “Optimal Integration of Energy Storage in Distribution Networks”, PowerTech 2009



Infrastructure cost

Upgrade cost

Battery cost

OF VALUE WITH AND WITHOUT DES SITING AND SIZING OPTIMIZATION

	NO DES	WITH DES
C_I [k€]	75.7	20.1
C_L [k€]	469.3	421.7
C_{OF}[k€]	**545.0**	**466.2**

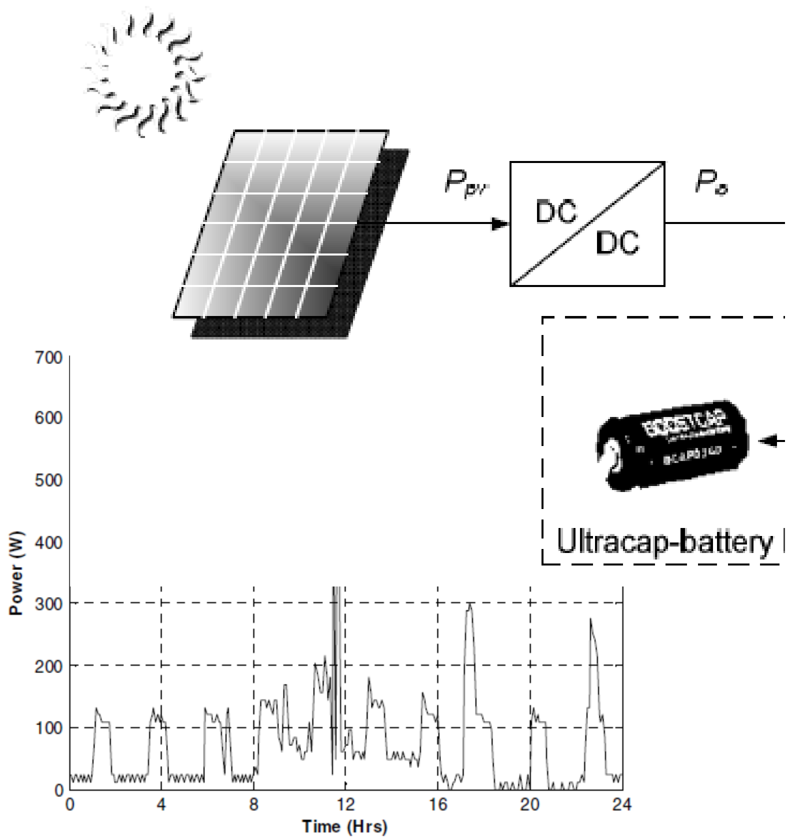
Cost of energy losses

Hybrid Storage Devices

- Battery + super-capacitors
  - Energy vs. power demand
  - Capacity planning along with PV

- Glavin et al. “Optimization of Autonomous Hybrid Energy Storage System for Photovoltaic Applications”, ECCE 2009

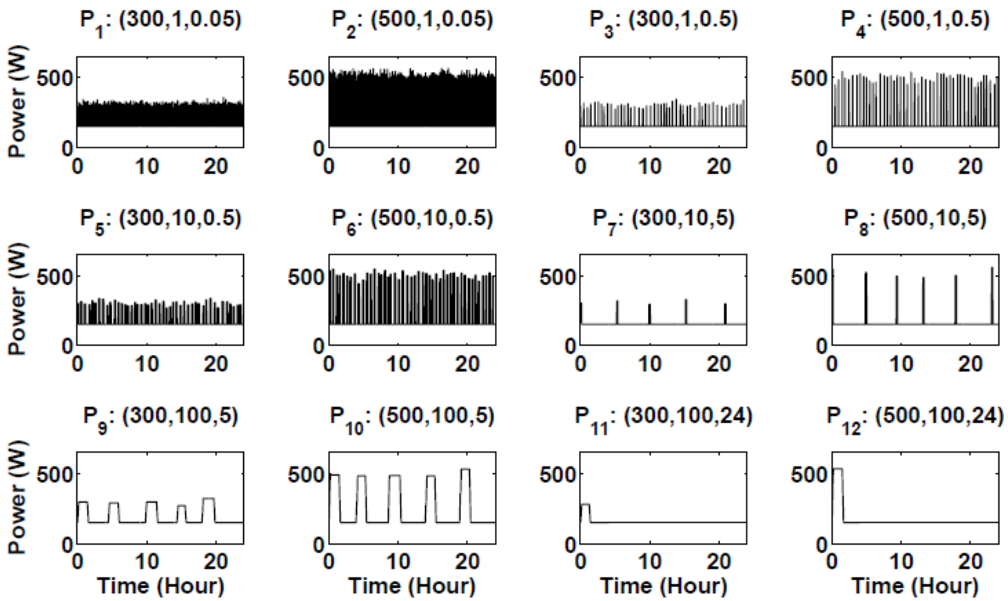
	Lead Acid Battery	Ultracapacitor
Specific Energy Density (Wh/kg)	10-100	1 – 10
Specific Power Density (W/kg)	<1000	<10,000
Cycle Life	1,000	> 500,000
Charge/Discharge Efficiency	70 – 85%	85 - 98%
Fast Charge Time	1 – 5hr	0.3 – 30s
Discharge Time	0.3 – 3hr	0.3 – 30s



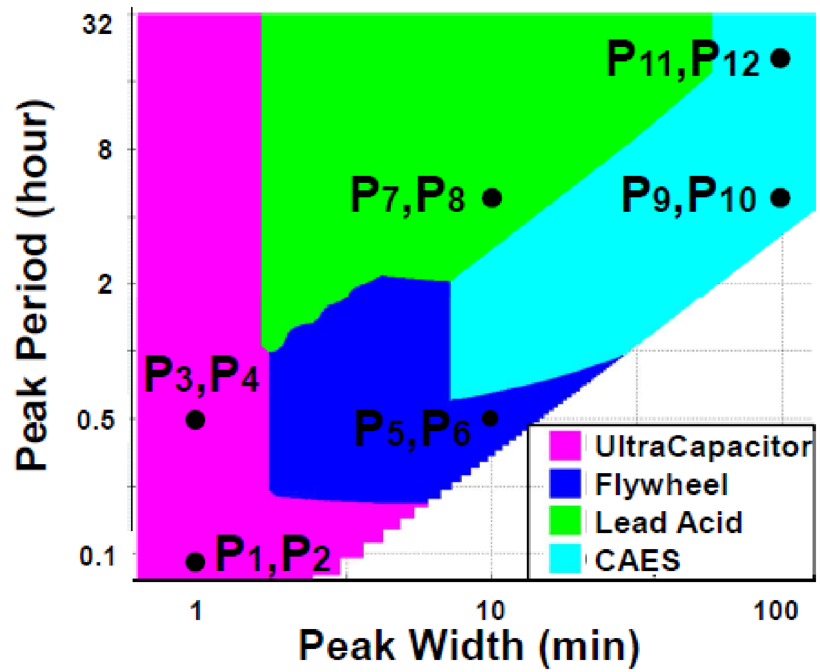
		No. of PV	No. of Battery	No. of ultracap.	LPSP	Cost
Constant Load	Under	4	3x5	0	0.55	€2,580
	Optim.	14	3x5	0	0	€6,330
	Over	16	8x5	0	0	€8,880
Peak Load	Under	10	2x5	5	0.22	€4,725
	Optim.	14	3x5	5	0	€6,585
	Over	16	6x5	15	0	€8,925
Pulse Load	Under	10	2x5	5	0.2	€4,725
	Optim.	13	3x5	5	0	€6,210
	Over	16	6x5	15	0	€8,925
Domestic Load	Under	39	4x5	100	0.1	€21,165
	Optim.	42	6x5	115	0	€23,775
	Over	45	7x5	265	0	€32,910

LPSP: Loss of power supply probability

Applicability of Storage Devices



Power demand building blocks with mean valu
of (h_{peak} watt, w_{peak} min, $\frac{1}{f_{peak}}$ hour)



- This research is specific for data centers but the main idea is applicable to different domains as well

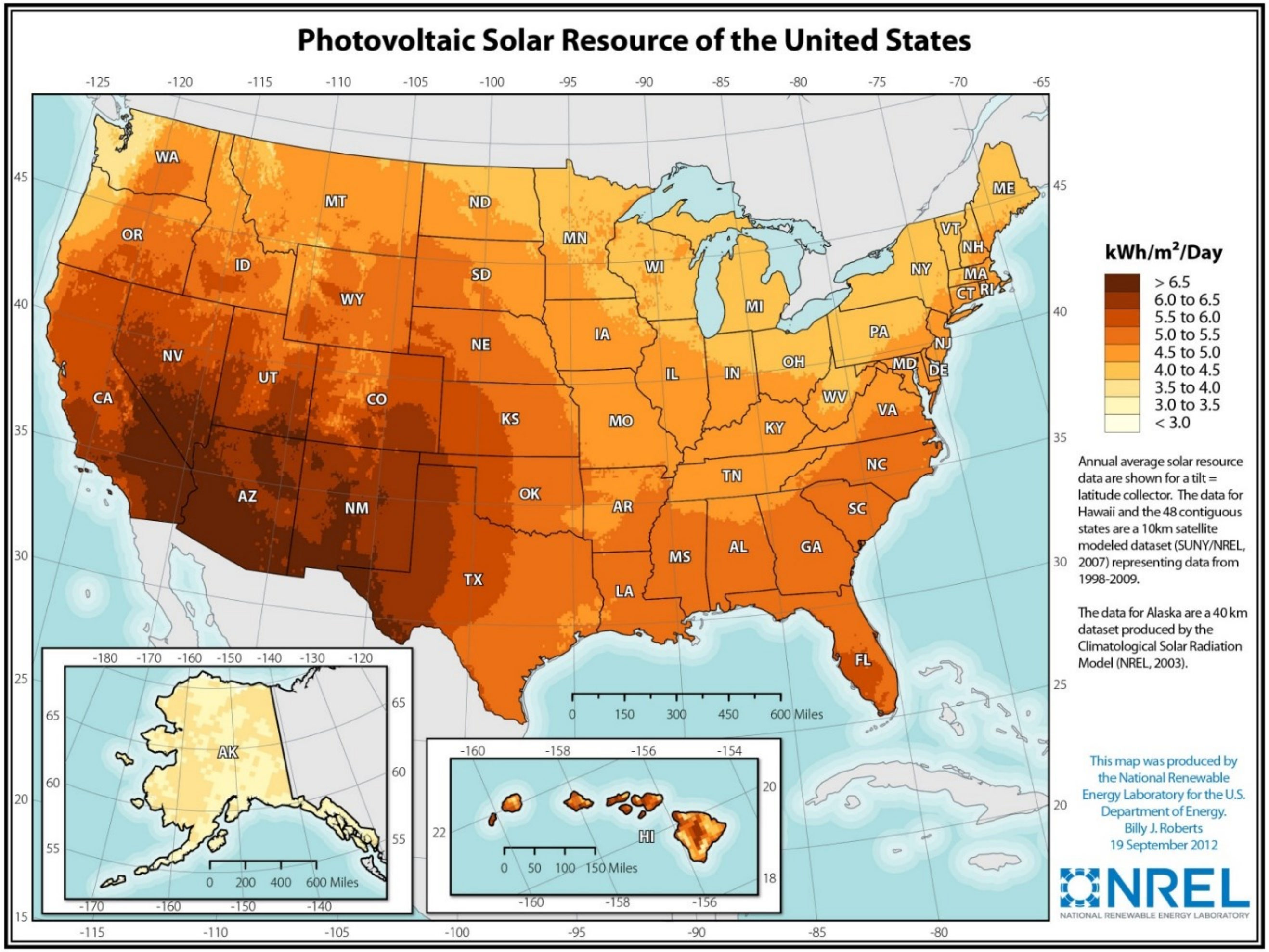
Wang et al. “Energy Storage in Datacenters: What, Where, and How much?”, SIGMETRICS 2012

Moving forward…

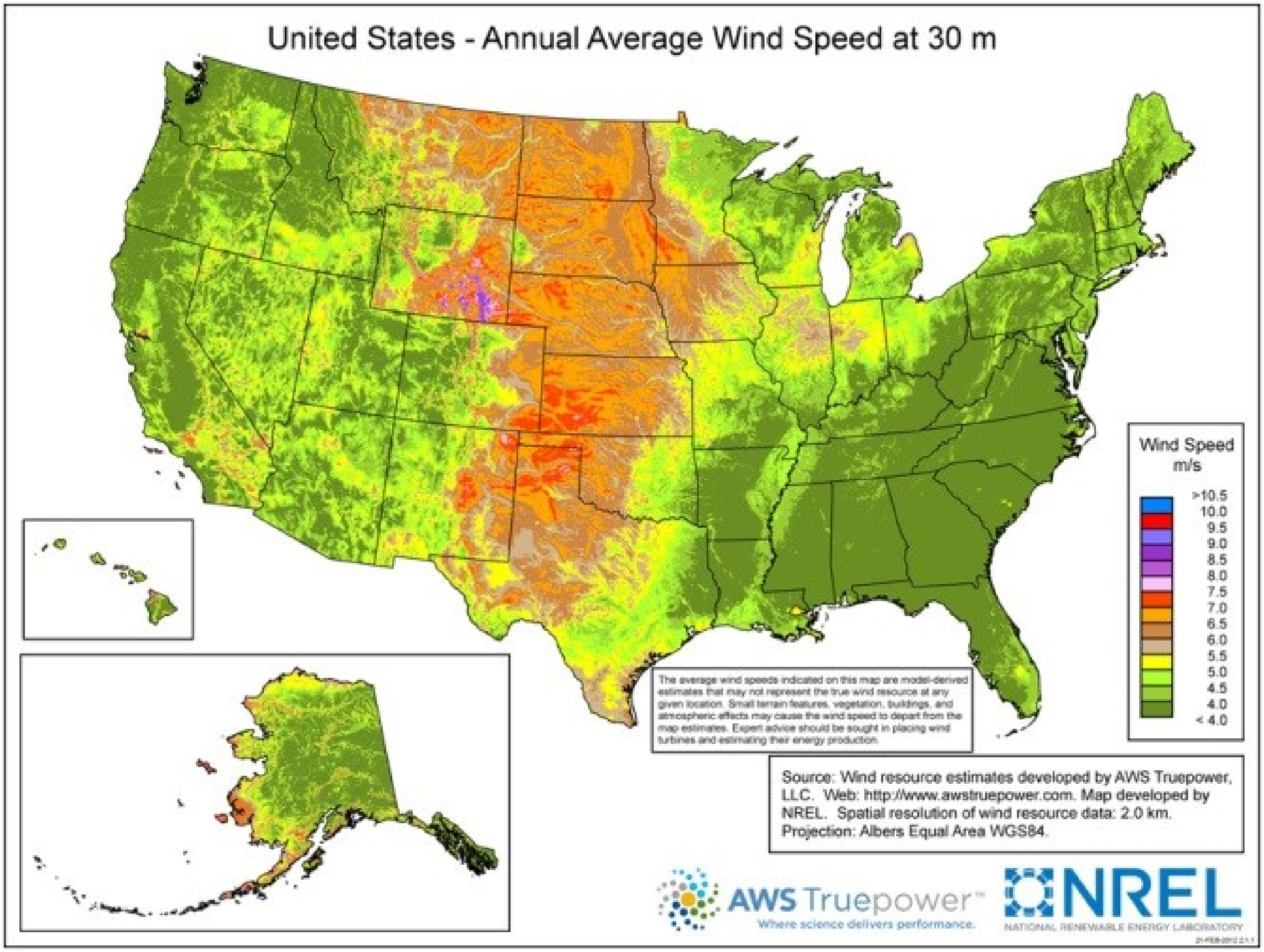
- Optimality of renewable sources + energy storage:
  - Type
  - Capacity
  - Configuration
- Energy Storage Implications on the Grid
- Prediction of loads/sources → more efficient grid use
- Energy distribution to loads/storage elements:
  - Pricing
  - Availability (home and utility)
  - Capacity
  - Load needs/rescheduling

Backup Slides

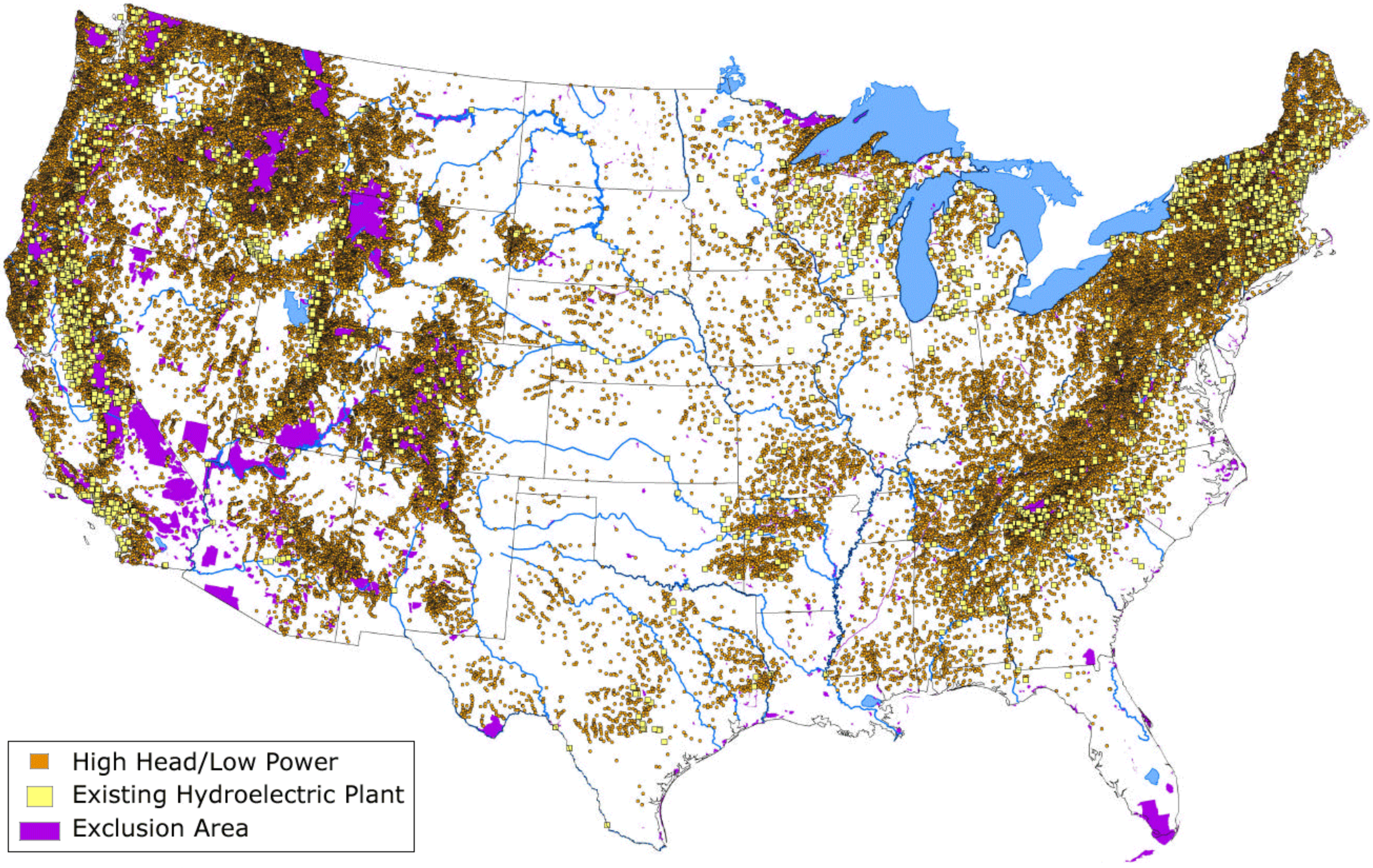
Solar-Electric Energy Potential



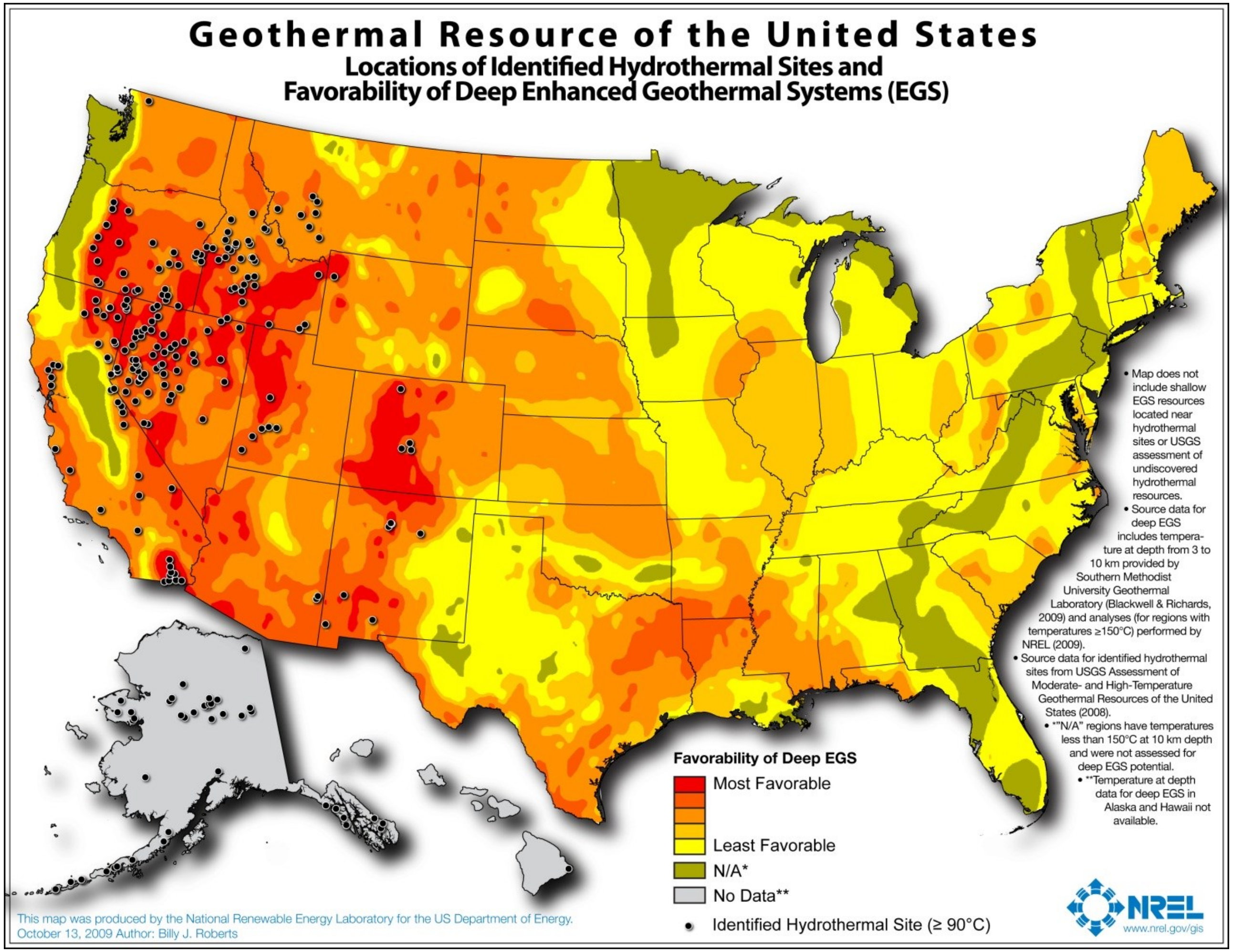
Wind Energy Potential



Hydroelectric Energy Potential



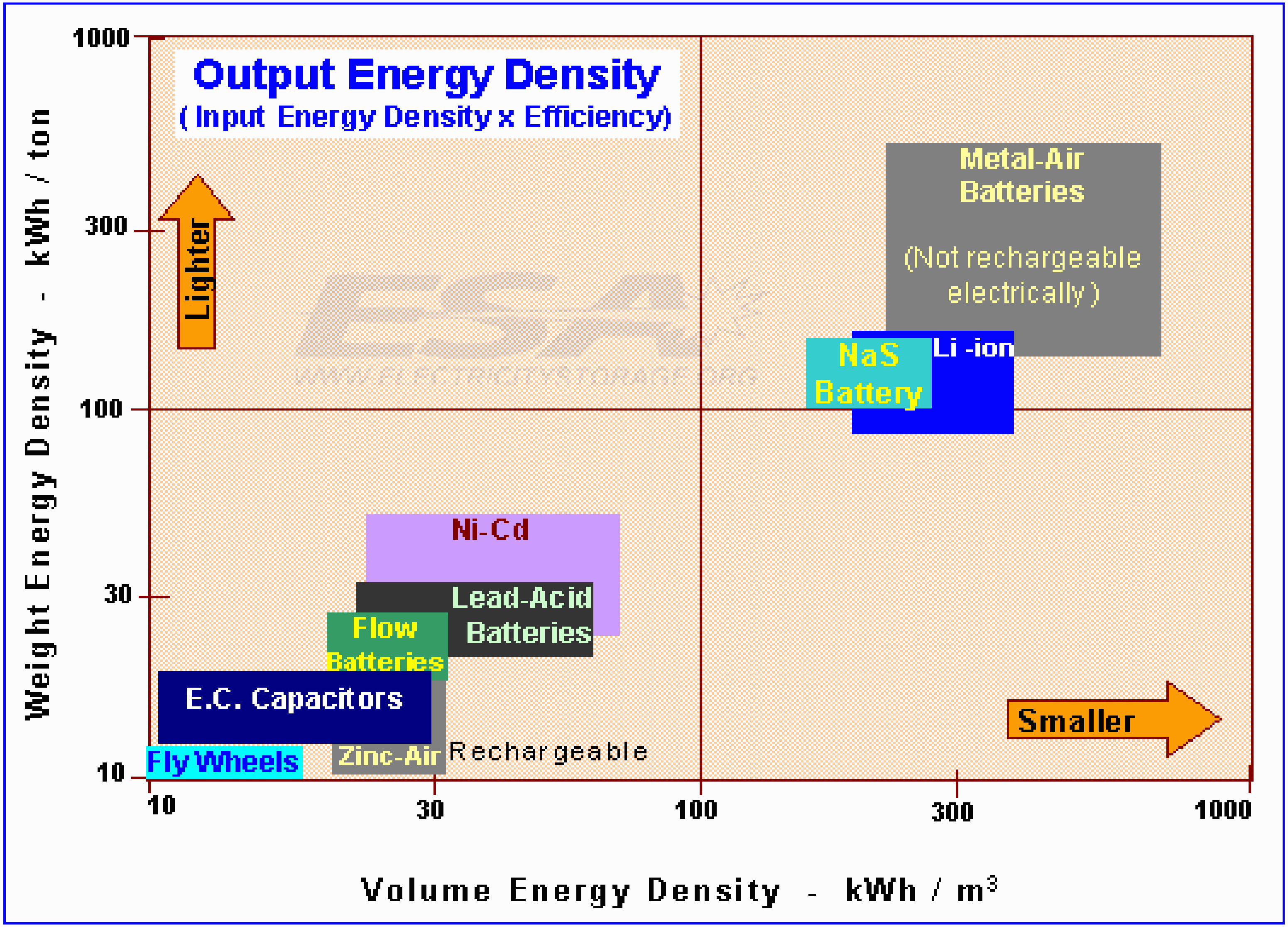
Geothermal Potential



Reasons for Energy Storage

- Smart Grid
- Increasing use of Demand Response
- Commonly available electricity price signals
- Regulatory incentives
- Transmission capacity constraints
- Increasing usage of electric vehicles
- Increasing usage of renewable energy sources
- Distributed energy sources
- Environmental concerns due to fossil-based fuel use
- Advancements in storage technology

Weight/Volume vs. Energy Density



Source: ESA

Application Classification

- **Power vs. Energy Application**
  - **Power**
    - High power output usually for a short periods of time (a few sec to a few min)
    - Capacitors (super-capacitors), flywheels, some batteries
  - **Energy**
    - Require relatively high amounts of energy, often for discharge duration of many minutes to hours
    - Pumped hydro, CAES, some batteries

- **Capacity vs. Energy Application**
  - **Capacity**
    - Storage used to defer or reduce the need for other equipment
    - Typically limited amounts of energy discharge throughout the year
  - **Energy**
    - Significant amount of energy stored and discharged throughout the year
    - Efficiency important or else energy losses will offset benefits

Energy Storage Applications in Grid

1. Electric supply
2. Ancillary services
3. Grid system
4. End-user/Utility customers
5. Renewable energy integration

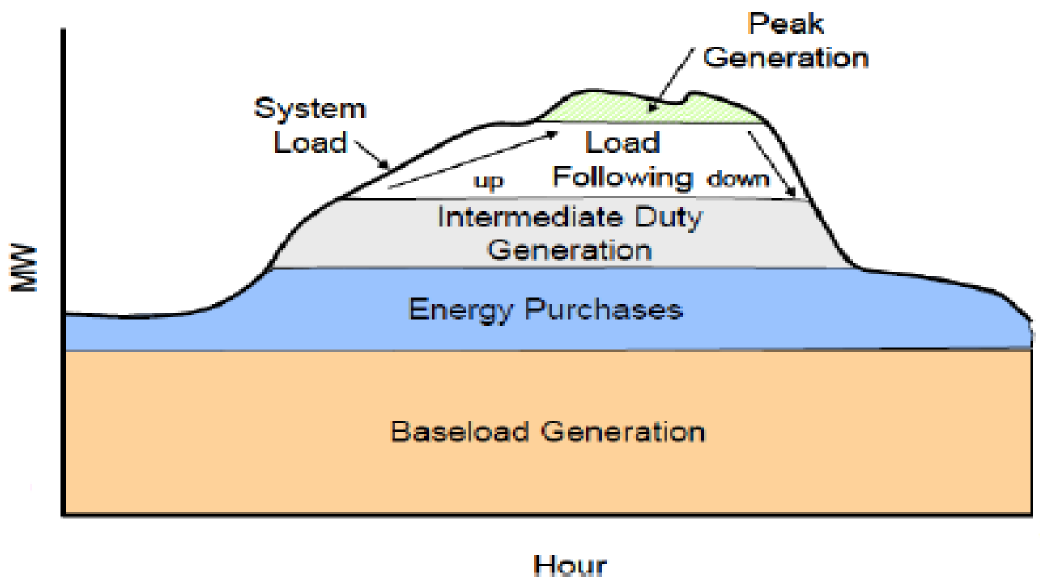
Source: Sandia National Lab (2010)

Ancillary Service Applications

- Load following
  - Helps grid to adjust its output level
- Area (frequency) regulation
  - Helps managing moment-to-moment variations within a controlled area and “interchange” flows between areas
- Electric supply reserve capacity
  - Increased reliability with more energy available
- Voltage support (Grid stabilization)
  - Maintain voltage levels within required stability

Ancillary Service Applications

- Load following
  - Helps grid to adjust its output level



When there are severe changes in total load associated with a region or a specific user, an electricity storage system can act as a buffer isolating the rest of the power grid from the frequent and rapid power changes.

Grid System Applications

- Transmission support
  - Compensate for electrical anomalies and disturbances in sub-second response
- Transmission congestion relief
  - Discharge during peak demand: reduce transmission capacity requirement
- Transmission and Distribution Upgrade Deferral
  - Small amount of storage can provide enough incremental capacity to defer the need for a large ‘lump’ investment in grid equipment
- Substation On-site Power
  - Provide power to switching components, communications, controls when grid is down

Energy Storage Challenges in Grid

- Relatively high cost per kW installed and cost of stored electricity
- Most technologies are not commercialized or mature
  - Financing of any 'new' technology is challenging
- Lack of regulatory rules
  - Inefficient electric energy and services pricing
  - Permitting and siting rules and regulation
- Limited risk/reward mechanisms between utility-customers and utility-third parties
- Existing utility biases: technologically risk averse