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

Renewable Energy at the Load

- Load-level, distributed generation
  - Solar\(^\text{[2]}\):
    - Grid Tie
    - Off-grid
    - Battery backup
  - Varying costs: $5000-$25000

- Wind:
  - 400-6000W commercially available systems
  - Capital costs: $500-10k turbine costs\(^\text{[3]}\)
  - Additional inverter, regulator, transmission costs

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)

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
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

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

Pumped Hydro

- Compressed Air Energy Storage: 440 MWs
- Sodium-Sulphur Battery: 365 MWs
- Lead-Acid Battery: ~35 MWs
- Nickel-Cadmium Battery: 27 MWs
- Lithium Ion Battery: ~16 MWs
- Redox-Flow Battery: < 3 MWs

Over 99% of total storage capacity

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

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

Source: ESA
Capital Cost Comparison

![Diagram comparing capital costs of various energy storage technologies, categorized by their energy density and cost per unit power.](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)

"peaker" power plants 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
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

[^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”.
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

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\(^{[12]}\) 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," 2013
Optimum Battery Chemistry Selection

Summary of results for all chemistries considered, 1% O&M for NaS

<table>
<thead>
<tr>
<th>Feed-in Tariff (¢/kWh)</th>
<th>NaS O&amp;M (%)</th>
<th>Capacities (MWh)</th>
<th>ROI (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>1</td>
<td>27.8 NaS</td>
<td>6.39</td>
</tr>
<tr>
<td>50</td>
<td>1</td>
<td>40.1 Li-Ion</td>
<td>221</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>0</td>
<td>N/A</td>
</tr>
<tr>
<td>13</td>
<td>5</td>
<td>40.1 Li-Ion</td>
<td>2.42</td>
</tr>
</tbody>
</table>

Summary of results for single technology only, 5% O&M for NaS, with 10-year lifetime, 15 cents/kWh feed-in tariff

<table>
<thead>
<tr>
<th>Battery Chemistry</th>
<th>Capacities (MWh)</th>
<th>ROI (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Price Structure</td>
<td>3-level</td>
<td>2-level</td>
</tr>
<tr>
<td>Lead-acid</td>
<td>0</td>
<td>50</td>
</tr>
<tr>
<td>NiCd</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>NiMH</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Li-Ion</td>
<td>20.5</td>
<td>20.5</td>
</tr>
<tr>
<td>NaS</td>
<td>16.9</td>
<td>16.9</td>
</tr>
</tbody>
</table>

PV Integration

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

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

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.

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


### Cost of Spilled Energy

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Max amount of spilled power</td>
<td>6 MW</td>
<td></td>
</tr>
<tr>
<td>during the entire year $P_{ESS}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max amount of spilled energy</td>
<td>40 MWh</td>
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</tr>
<tr>
<td>during a specific day $E_{ESS}$</td>
<td></td>
<td></td>
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<tr>
<td>Total annual spilled energy</td>
<td>7063.9 MWh</td>
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<tr>
<td>Total annual cost of spilled</td>
<td>0.92</td>
<td></td>
</tr>
<tr>
<td>energy (million dollars)</td>
<td></td>
<td></td>
</tr>
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</table>

#### Optimum Allocation of ESS in the Distribution System

<table>
<thead>
<tr>
<th>bus</th>
<th>MWh</th>
<th>MW</th>
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<tbody>
<tr>
<td>4</td>
<td>19.48</td>
<td>2</td>
</tr>
<tr>
<td>9</td>
<td>12.99</td>
<td>1.5</td>
</tr>
<tr>
<td>28</td>
<td>8.44</td>
<td>0.5</td>
</tr>
<tr>
<td>39</td>
<td>4.55</td>
<td>1</td>
</tr>
<tr>
<td>40</td>
<td>6.49</td>
<td>1</td>
</tr>
</tbody>
</table>
Grid Upgrade Deferring

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


### Infrastructure cost

<table>
<thead>
<tr>
<th></th>
<th>Without DES</th>
<th>With DES</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_I$ [k€]</td>
<td>75.7</td>
<td>20.1</td>
</tr>
<tr>
<td>$C_L$ [k€]</td>
<td>469.3</td>
<td>421.7</td>
</tr>
<tr>
<td>$C_{of}$ [k€]</td>
<td>545.0</td>
<td>466.2</td>
</tr>
</tbody>
</table>

Cost of energy losses
Hybrid Storage Devices

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


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

LPSP: Loss of power supply probability

<table>
<thead>
<tr>
<th></th>
<th>No. of PV</th>
<th>No. of Battery</th>
<th>No. of ultracap.</th>
<th>LPSP</th>
<th>Cost</th>
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<tbody>
<tr>
<td><strong>Constant Load</strong></td>
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<td></td>
<td></td>
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</tr>
<tr>
<td>Under</td>
<td>4</td>
<td>3x5</td>
<td>0</td>
<td>0.55</td>
<td>€2,580</td>
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<tr>
<td>Optim.</td>
<td>14</td>
<td>3x5</td>
<td>0</td>
<td>0</td>
<td>€6,330</td>
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<td>Over</td>
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<td>8x5</td>
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<td>0</td>
<td>€8,880</td>
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<td><strong>Peak Load</strong></td>
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<td></td>
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<tr>
<td>Under</td>
<td>10</td>
<td>2x5</td>
<td>5</td>
<td>0.22</td>
<td>€4,725</td>
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<tr>
<td>Optim.</td>
<td>14</td>
<td>3x5</td>
<td>5</td>
<td>0</td>
<td>€6,585</td>
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<tr>
<td>Over</td>
<td>16</td>
<td>6x5</td>
<td>15</td>
<td>0</td>
<td>€8,925</td>
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<td><strong>Pulse Load</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Under</td>
<td>10</td>
<td>2x5</td>
<td>5</td>
<td>0.2</td>
<td>€4,725</td>
</tr>
<tr>
<td>Optim.</td>
<td>13</td>
<td>3x5</td>
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<td>Over</td>
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<td><strong>Domestic Load</strong></td>
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<td>Under</td>
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<td>7x5</td>
<td>265</td>
<td>0</td>
<td>€32,910</td>
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</table>
Applicability of Storage Devices

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

Moving forward…

- Optimality of renewable sources + energy storage:
  - Type
  - Capacity
  - Configuration
- Energy Storage Implications on the Grid
- Prediction of loads/sources $\rightarrow$ 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

Photovoltaic Solar Resource of the United States

- Annual average solar resource data are shown for a tilt—latitude collector. The data for Hawaii and the 48 contiguous states are a 10km satellite modeled dataset (SUNY/NREL, 2007) representing data from 1998-2009.
- The data for Alaska are a 40km dataset produced by the Climatological Solar Radiation Model (NREL, 2003).

This map was produced by the National Renewable Energy Laboratory for the U.S. Department of Energy. Billy J. Roberts 19 September 2012
Wind Energy Potential

United States - Annual Average Wind Speed at 30 m

The average wind speeds indicated on this map are model-derived estimates that may not represent the true wind resource at any given location. Variations in topography, atmospheric conditions, and other factors can cause the wind speed to differ from the map estimates. Expert advice should be sought in placing wind turbines and estimating their energy production.


System Energy Efficiency Lab
seelab.ucsd.edu
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