High-Megawatt Power Converter Technology R&D Roadmap Workshop

Workshop Goals

Roadmap Vision; State-of-the-art grid connected inverter specifications, and goals, for future value added high-megawatt grid connected inverters

Why? Bigger Inverters, Faster Inverters, More and More Inverters ….

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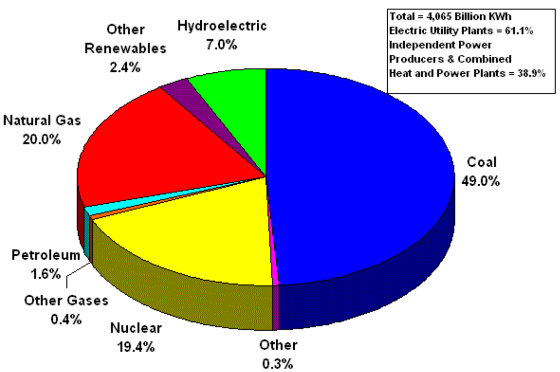
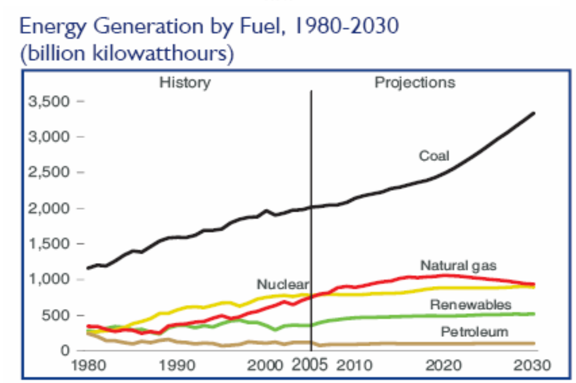
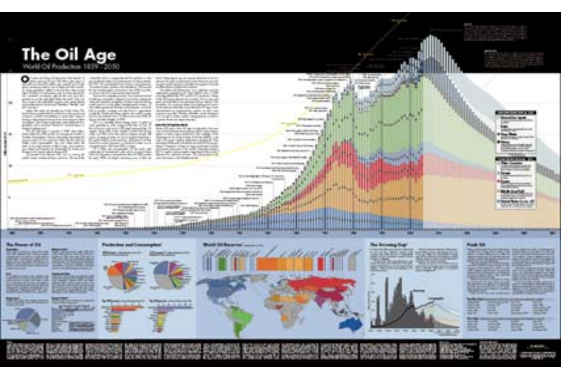
April 8, 2008

Environmental Factors and Increased Electrification







- Oil age is finite (cost, supply, security, environmental impact)
- Increasing Development
- Increasing Electrification

so renewables and Clean technologies

consider Wind

Cheap	**Erratic/Unpredictable**
Clean	**Remote**
	Destabilizing
	Low Utilization Factor

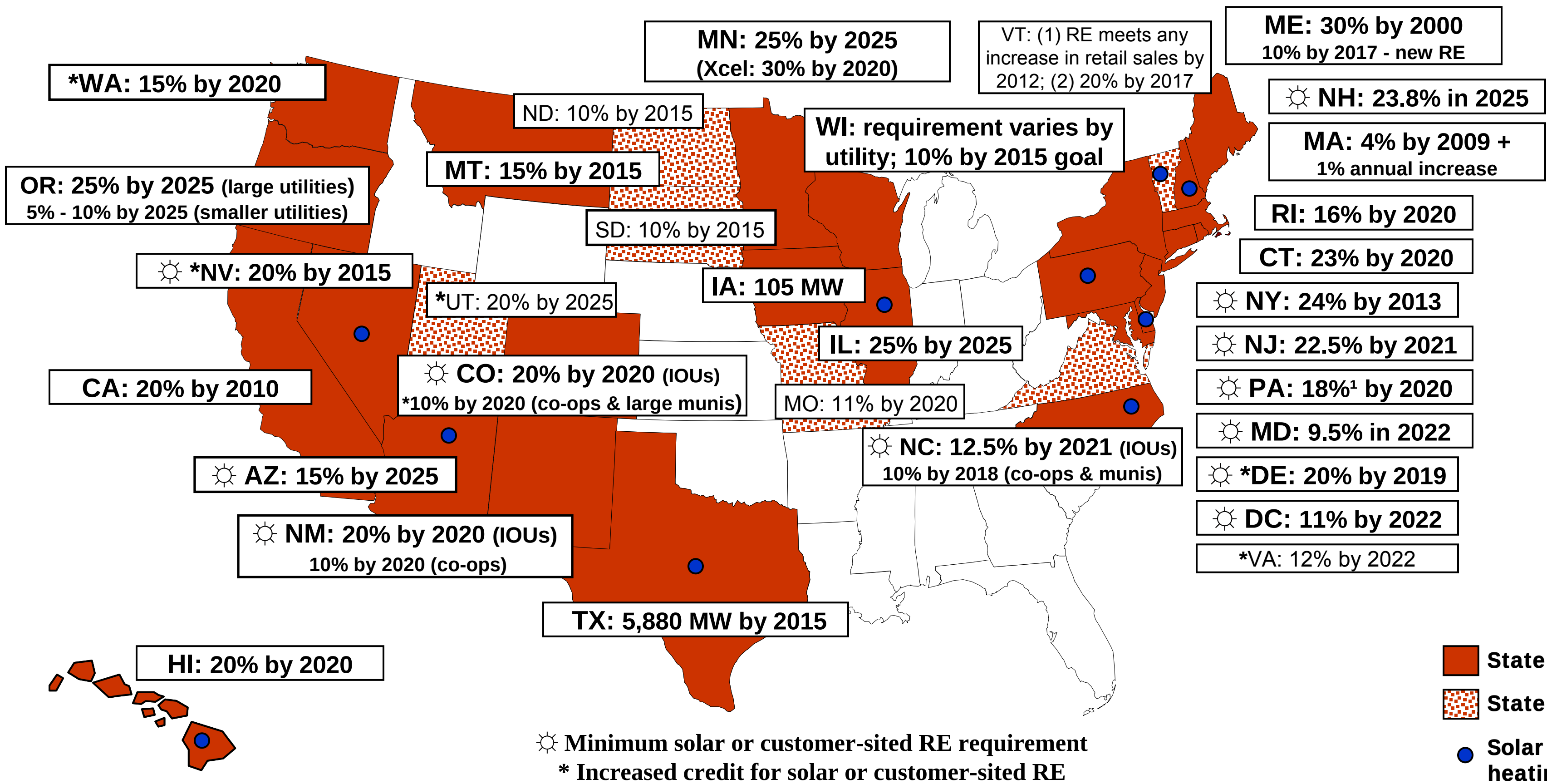
40% of US economy or 40Quads used to make 12.54Quads of Electricity in 2004 (100 Quads = 100 exajoule (100.10^{18}J))

Storage is the obvious answer, Integrated Storage

RPS Requirements becoming the Driver Despite Uncertainty over ITCs

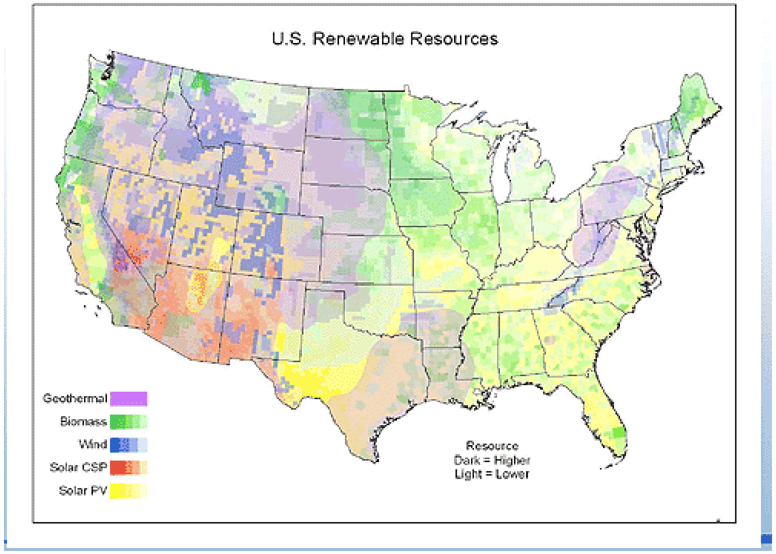
DSIRE: www.dsireusa.org **March 2008**

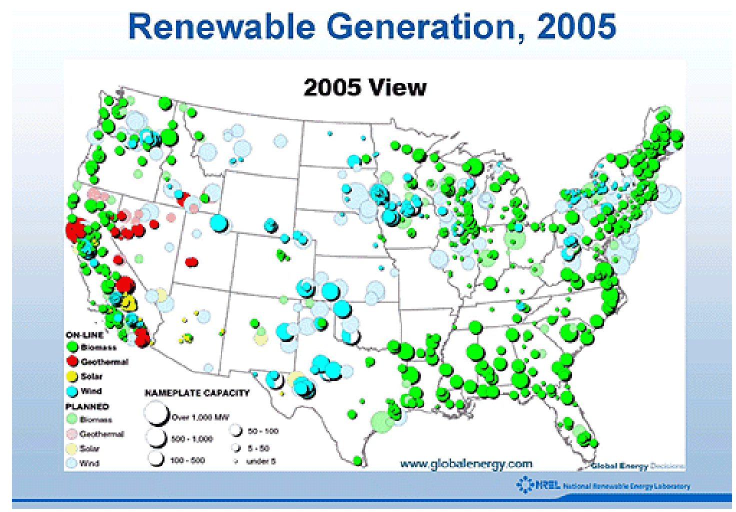
Renewables Portfolio Standards



☼ Minimum solar or customer-sited RE requirement
* Increased credit for solar or customer-sited RE
[1] PA: 8% Tier I / 10% Tier II (includes non-renewables)

Inverters Role in DER





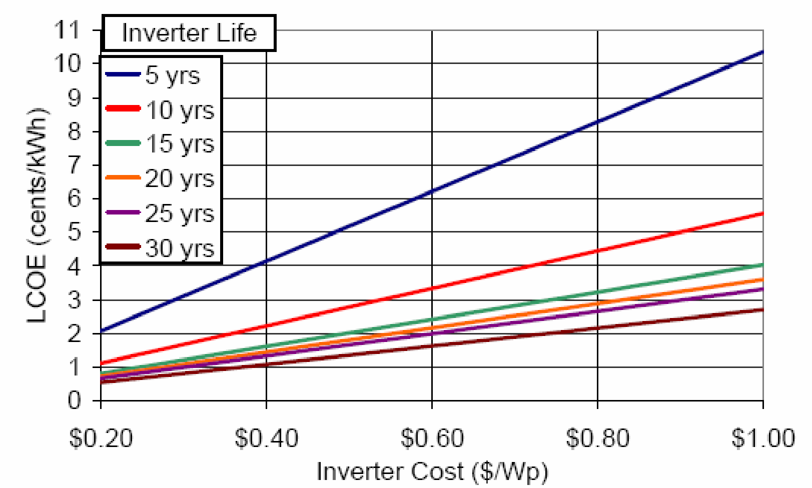
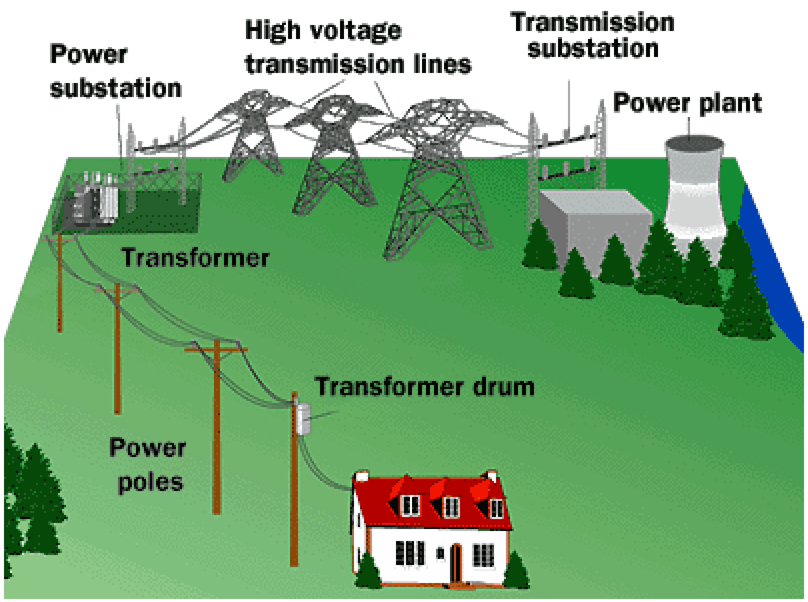


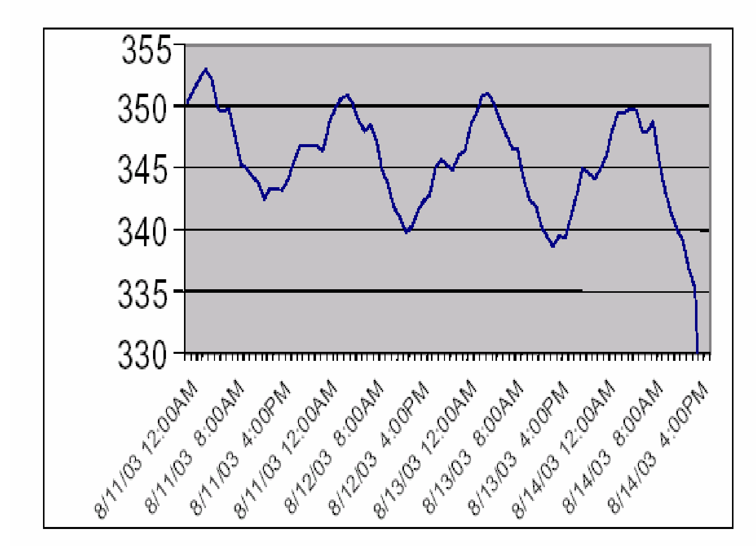
Figure 11. Contribution of Inverter Cost and Replacement to Energy Cost.

Primary Inverter Function and Focus

- **Cost**
- **Reliability (10+ year warranties …)**
- **Availability (Reliability, MTTR, …)**
- **Efficiency**
- **Volume and Weight**
- **Other Performance metrics?**

Why did the lights go out?
Isn't this the age of the electron?





First Energy – Vegetation + Heat

- Grid is a beautiful thing
- Energy moves at the speed of light
- Rugged Electro-mechanical generators
- Spinning "reserve"
- Excess capacity (>15% is critical) **SIZED FOR**
- Low Impedance – typically 5% of rating at PCC
    - Fault clearance
    - Overload
- ac – Simple Impedance Transformation, and Isolation

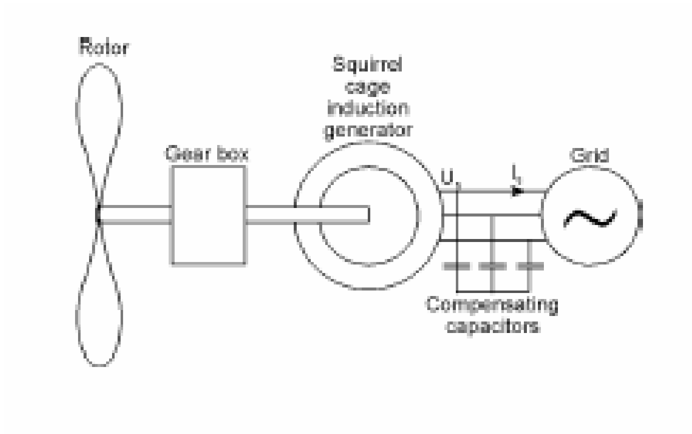
BUT, grid is,

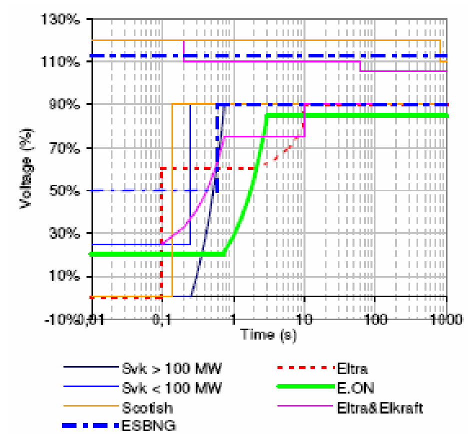
- **Slow**
    - **Response (Prime Movers, Controls)**
    - **Fault clearing, protection, coordination**
- **Smart Grid? Smart "slow" Grid still a slow grid. (load shedding is only relatively quick response)**

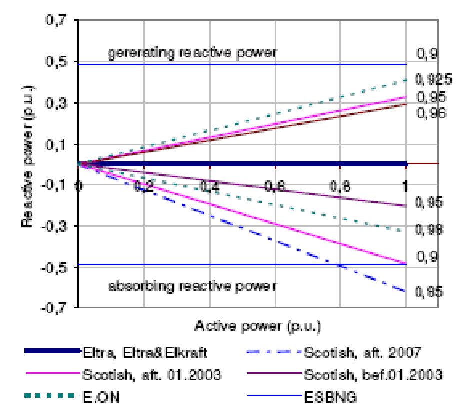
Grid Interconnection of DG

- Generators still most cost effective
- Power Electronic nature of Inverters brings great suspicion, (constant P characteristic, fast response,), hence some characteristics of regs (1547, …)
- Inverters can do much more that get the green e^-s on and off the grid. With storage can form microgrid, with control from utility can offer anciliary services, …
- Standards can inhibit technology (anti-islanding, tight trip points, … witness Wind and LVRT)

Wind -- Induction Generator Technology had poor PF and Ride-Thru







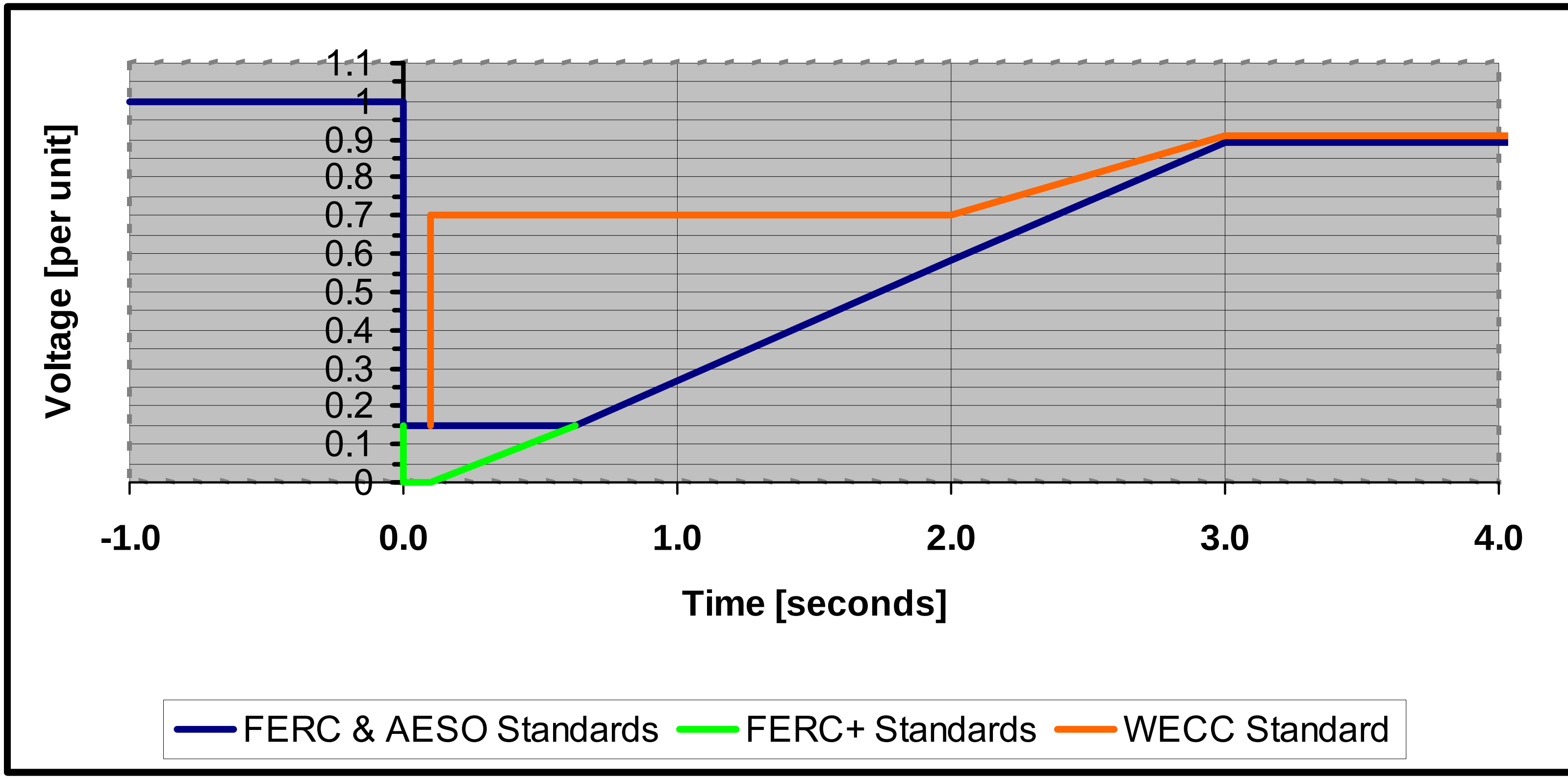
LV Ride-Through (LVRT) Requirement

- FERC, AESO, WECC Standards
- Substation LVRT Device / Equipment Solutions

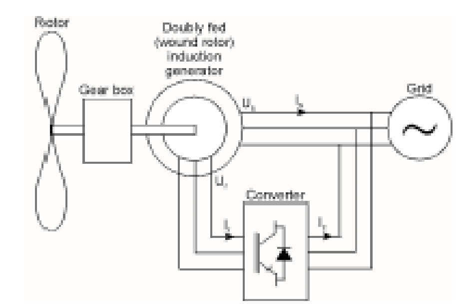
Reactive Power Compensation Requirement

- FERC, AESO, Manitoba Hydro Standards
- Substation VAR Management Equipment Solutions

FERC, AESO, WECS LV "Ride-Through" Curves



Ride-Through – no trip
– synched?
– impedance?



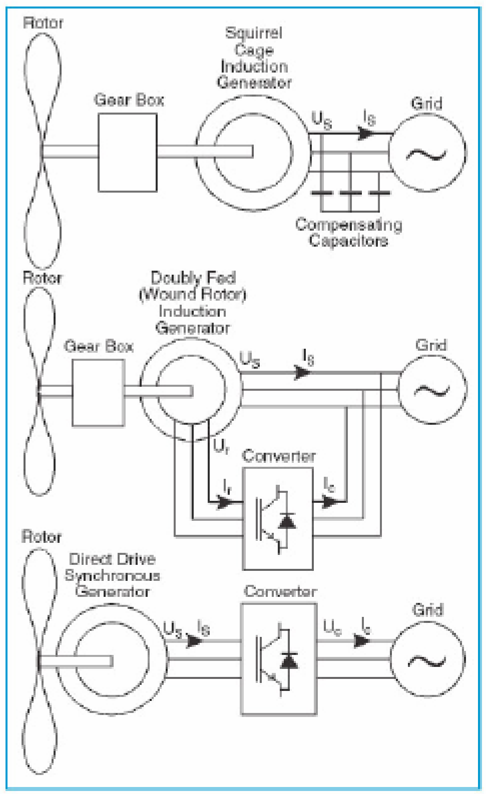
Doubly-Fed Machine can sink
or sources VARs, with high bandwidth control

Wind Generator and Power Backup/Storage Developments

Past

Present

Future



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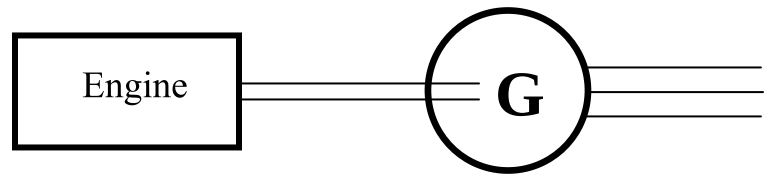

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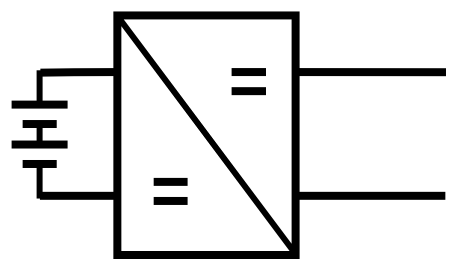
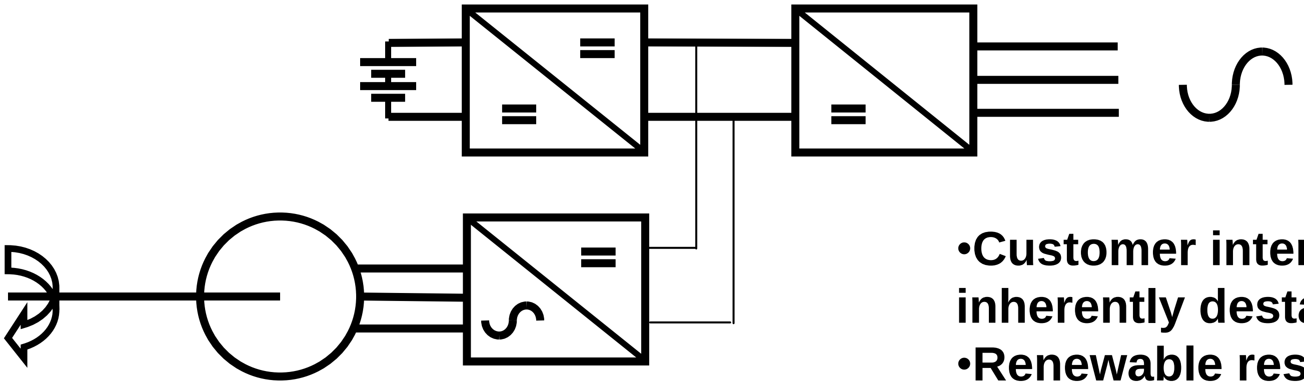


Fully Rated Inverter provides Many Possibilities



- Customer interface electronics, inherently destabilizing?
- Renewable resource potentially at odds with grid
- Or, can enhance, P, Q, dP/dt, nf, ABC
- Controllable (remotely)
- Supply Real Power, P
- Reactive power, Q, ($|P + jQ| < S_{INV}$)

- Active Damping (stabilizing)
- Fault Clearing
- Rapid Dynamics
- Unbalanced, non-linear sourcing
- Active Filtering, harmonic cancellation
-
- NOT an Electrical Machine!!
-

Some Advanced Inverter Features

- Dispatchable Real Power
- Dispatchable Reactive Power (voltage support)
- Controllable Harmonic Cancellation
- Phase Balancing (imbalance)
- Controllable Inertia
- Controllable Trip Points
- Permissive Utility Controlled Islanding

(Some) Grid Technology Developments

- Materials
    - Composites,
    - Super conductors?
- HVDC
- Devices
    - Silicon Carbide (devices + related)
        - solid state breakers
        - HV, HT Electronics
- Distributed sensing and control (smartgrid)
    - temp, volt, I,
- Communications
- Nuclear
- Demand side control
- Micro-grid (SDS + storage)
- Storage
- Efficiency (technology)?
- Improvements (FC, PV, Wind, ...)
- EV/HEV
- Biofuels, synthetic, cellulostic, ...
- Off-Shore Wind
- Storage, Storage, Storage, ...
- More Electronics, Faster, Better Control ...
- Higher Reliability Power Electronics
    - Prognostics

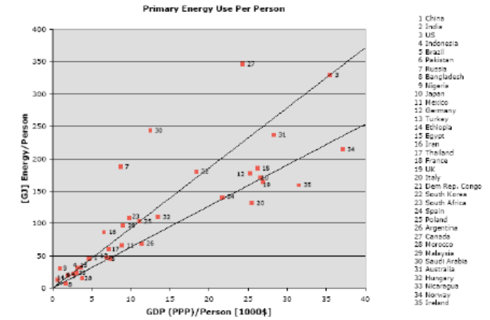


Figure 1.1 Energy use (in gigajoules) vs. GDP (on a purchasing power parity basis) for selected countries on a per capita basis. Data from the International Energy Agency. Upper line indicates ratio for the US; lower line indicates ratio for Japan and several Western European countries.

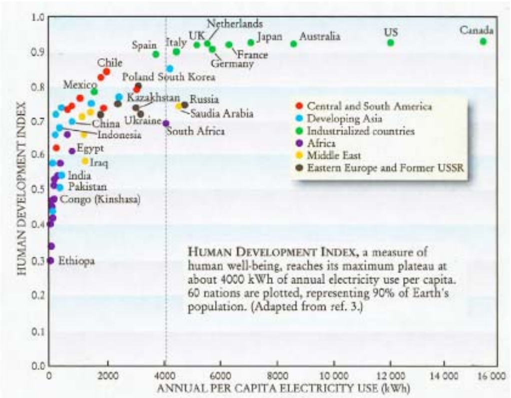
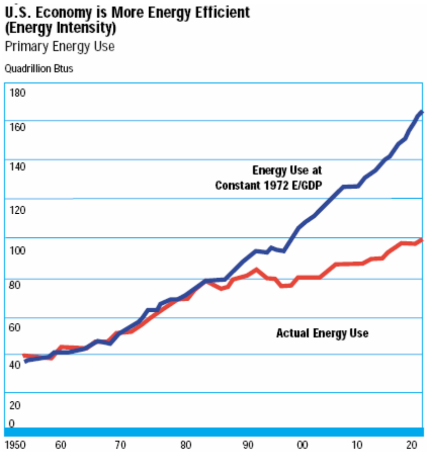
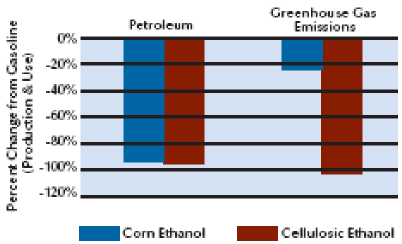


Figure 1.2. Human development index vs. per capita electricity use for selected countries. Taken from S. Benka, *Physics Today* (April 2002), pg 39, and adapted from A. Pasternak, Lawrence Liver...

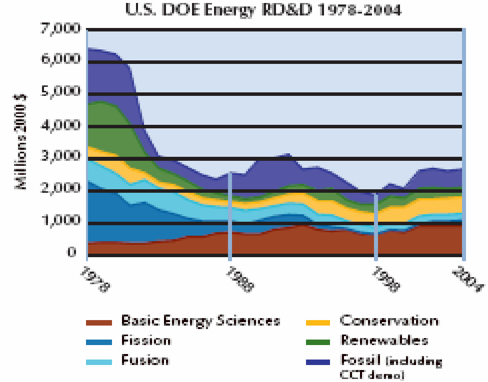


Improvements in energy efficiency since the 1970s have had a major impact in meeting national energy needs relative to new supply. If the intensity of U.S. energy use had remained constant since 1972, consumption would have been about 70 quadrillion Btus (74 percent) higher in 1999 than it actually was.

Source: U.S. Department of Energy, Energy Information Administration.



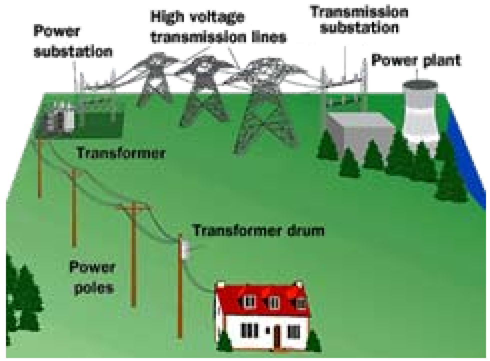
Data Source: Lynd, Greene, and Sheehan, 2004



Power Distribution Options -- Battle

Thomas Edison and Joseph Swan

Pearl St, NY, 1882
Edison
85 Customers, 400 Lamps



Move it at HV

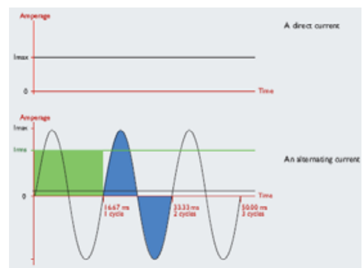
AC won (pre-electronics)
•Transformer isolation
•Impedance (V) transformation
•Grounded Secondary (safety)
•AC → DC, easy

$$d = \sqrt{\frac{2\rho}{\omega\mu}}$$

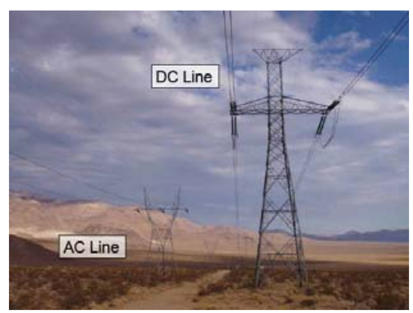
But
•Skindepth
•ϕ Imbalance
•Reactive power
•Peak to RMS

d or δ, 60Hz
Cu 8mm
Al 10mm
SiFe 0.1mm

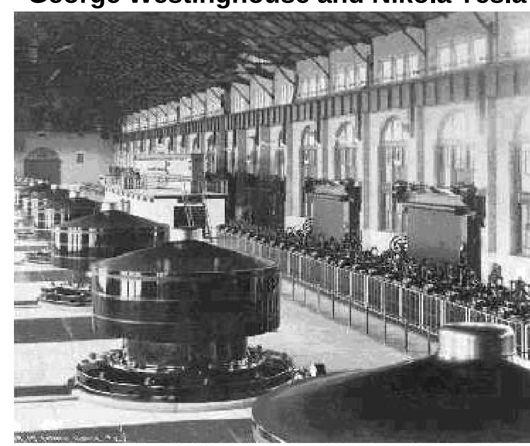
Edison was missing what?
Loads Today?
Sources Today
Storage?



Today, DC wins for T

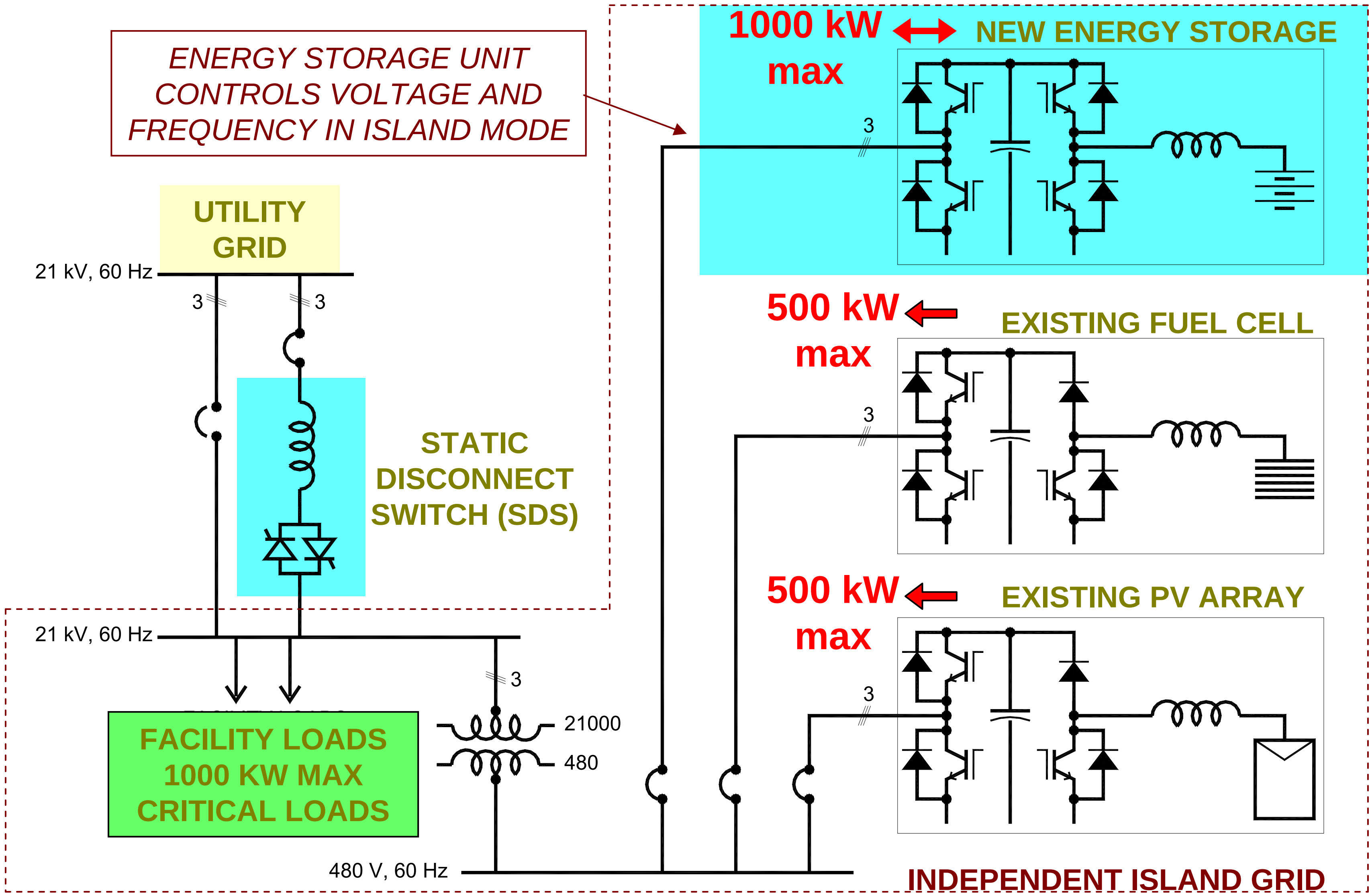


George Westinghouse and Nikola Tesla



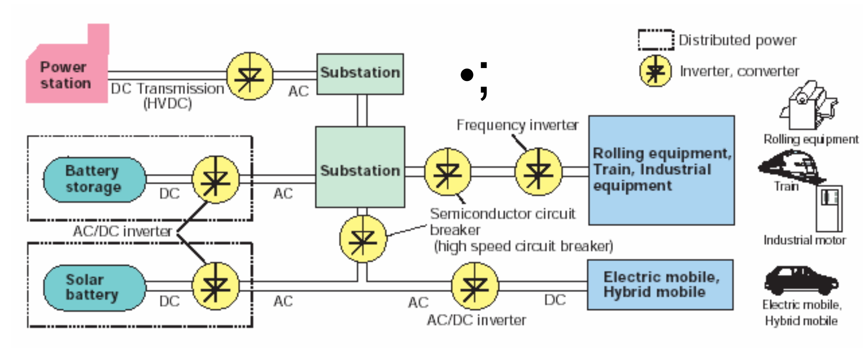
Adams Hydroelectric Plant
Niagara Falls 1895
Westinghouse, Tesla, Stanley

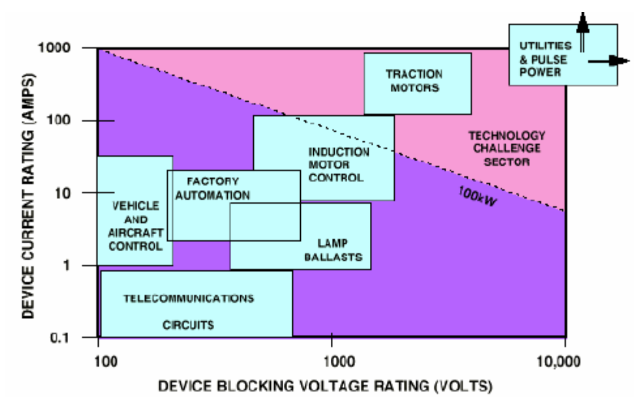
Adding Energy Storage and a SDS Allows Existing DG Units to Support an Island Grid (μGrid)



Some Potential SiC (WBG) Impacts on Grids, Mini-Grids, Power Systems

- **Relaying** (electromechanical is 6-10 cycle, solid-state for LV, MV, HV)
  - Isolation (SSR)
  - Protection
  - Fault clearing
  - Fault limiting (SSCL)
- **Transmission Electronics** (MV, HV)
  - FACTS
  - VARS, (SVAR, DVAR)
  - DVR
  - STS
- **Grid electronics** (storage, renewables, PQ)
  - Volume
  - Weight
  - Efficiency
  - Reliability
  - Cost
  - Overload capability
  - Voltage/Power Application Range
- **Solid State Suppression**
  - Spikes
- **Solid State Transformers** (HF Link)





New Switch Capabilities enables new Applications

Hi-T, Hi-Rad, Hi-V, Hi-f

Big Inverters

- $200/KW? $100/KW?
- Extended Warranty? 10+ years
- Performance? 5KHz switching? 97%? 2sec overload?
- Research?
  - devices (SiC, GaN, … . Packaging, gate drives, control, passives, ….
  - Passives
  - STORAGE
  - Protection (relays, contactors)
  - Communication and Controls for Utility Inverters
  - Controls of Hybrid Power Systems and MicroGrids

SatCon Multi-Input, Single-Stage, 2.4 MW, 13.8 kV, Inverter