Session 2a

Casey

High-Megawatt Converter Technology Workshop
January 24, 2007

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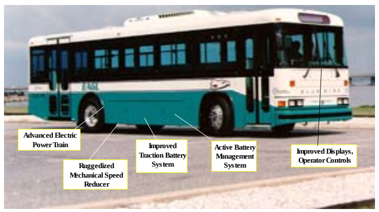
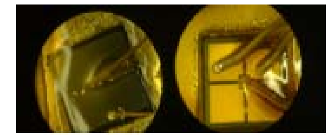
SatCon?
SatCon Highlights
Technology … Applications … Products

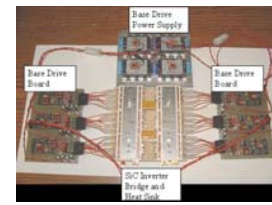
Technology

Today

- 200 Employees
- 3 Divisions







2003 Subsidiary Corporations

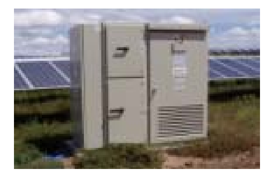
BEACON 1997

WEC/NG 1999

InverPower 2001

Patriot - 1992

FMI & HiComp 1998



Magmotor 1997

1985 MIT-DRAPER

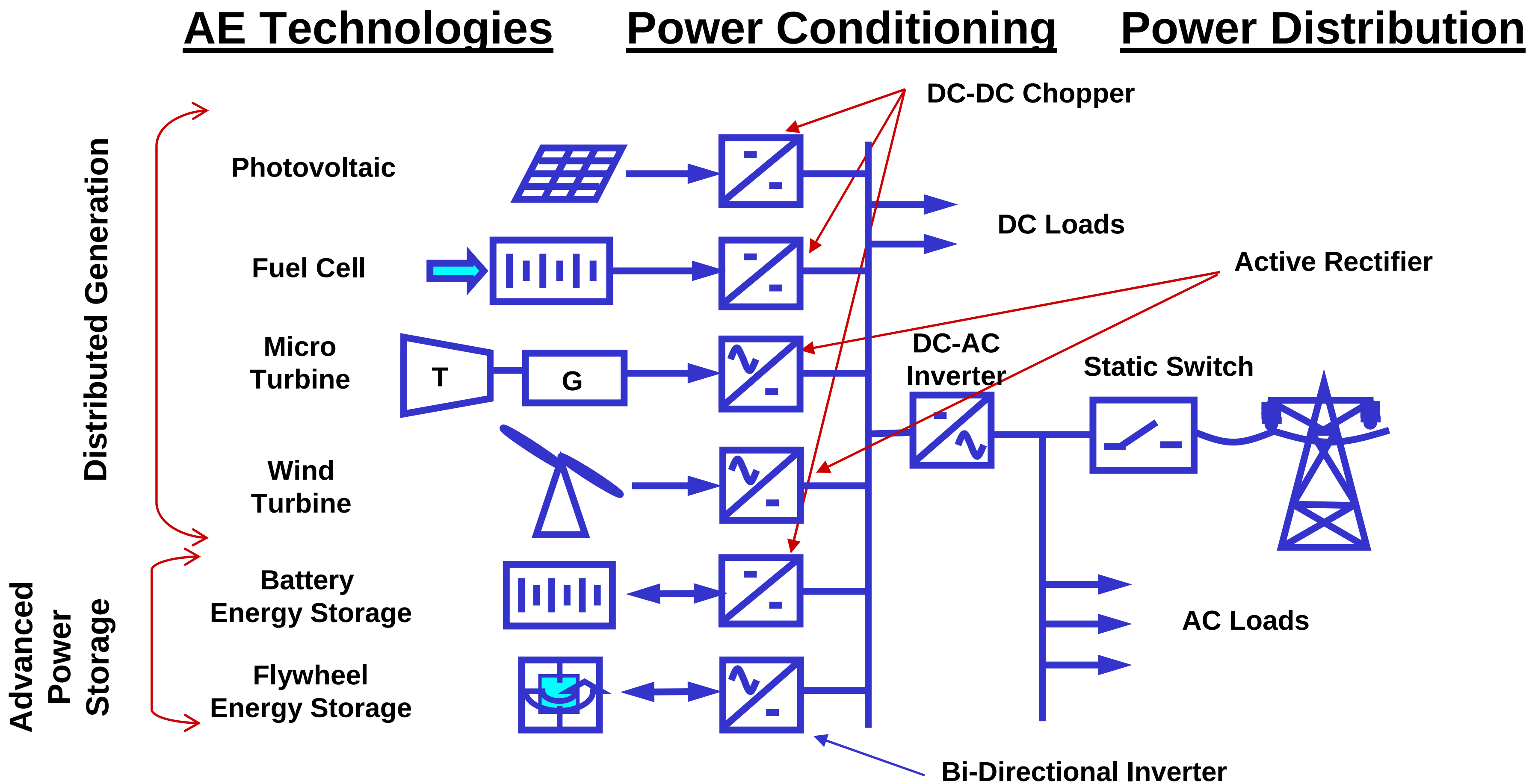
Applications

Energy Storage | *Renewable Energy* | *Distributed Energy* | *Grid Support*

Technology Development

- MIL-38534 Class K
- Outdoor Electronics with 5+ year Warranty
- R&D, e.g. SiC Applications WORK

SatCon's Focus is Grid Electronics – getting electrons on and off the Grid, reliably, efficiently, enhancing Power Q, improving System Dynamics



. . . Systems Integration Key to Meeting Requirements of AE Power Plant

Solar Inverter Product Line

POWERGATE™




30kW ←------------------------------→ ***500kW***

- Highest efficiency listed for approved CEC inverters in its power rating
- First 100 kW inverter shipped for European market
- Only 500kW solar inverter rated by the California Energy Commission

❖Additional Inverter Applications

Fuel Cells, Wind, …



300kW ←------------------------------→ ***3MW***

As Resource (Wind, PV, FC …) Penetration grows it becomes Integral to Grid Stability and Control, SO …

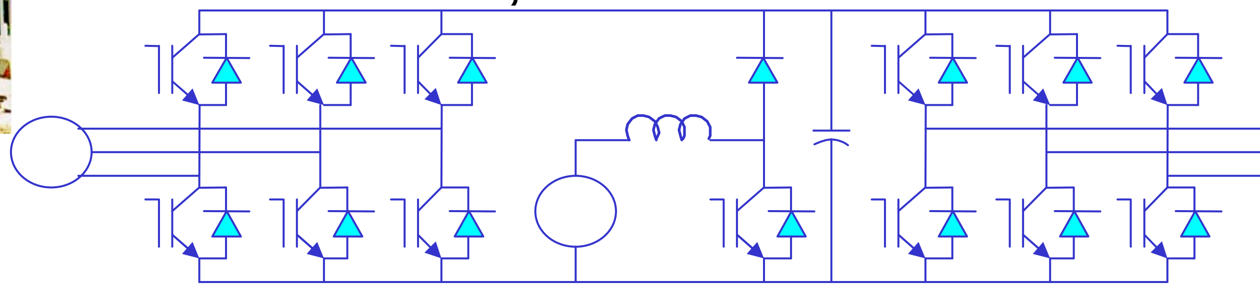
•Customer interface electronics, inherently destabilizing?

•Renewable resource potentially at odds with grid

•**Or**, could enhance, P, Q, dP/dt, nf, ABC

SVR/DVR

STS



BES

RUPS/CPS

RTD

DG

UPS

IEEE1547
UL1741
CEC Rule 21
519
…
IEC

Inverter is the Glue

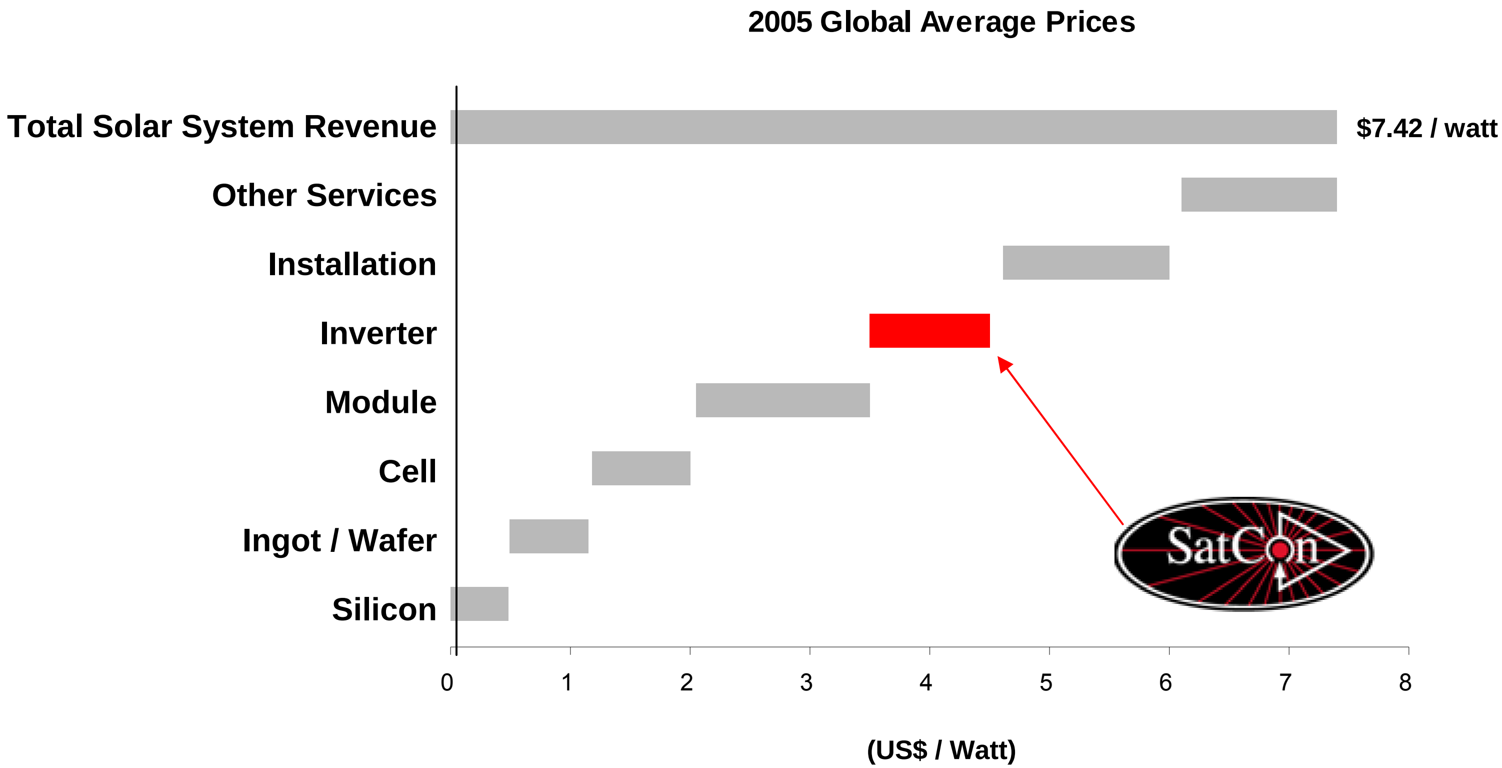
- Cost
- Performance
  - Power quality
  - Overload
  - …
- Reliability

- A Grid Inverter is not just a motor drive

- Could be much more than a thermal power plant

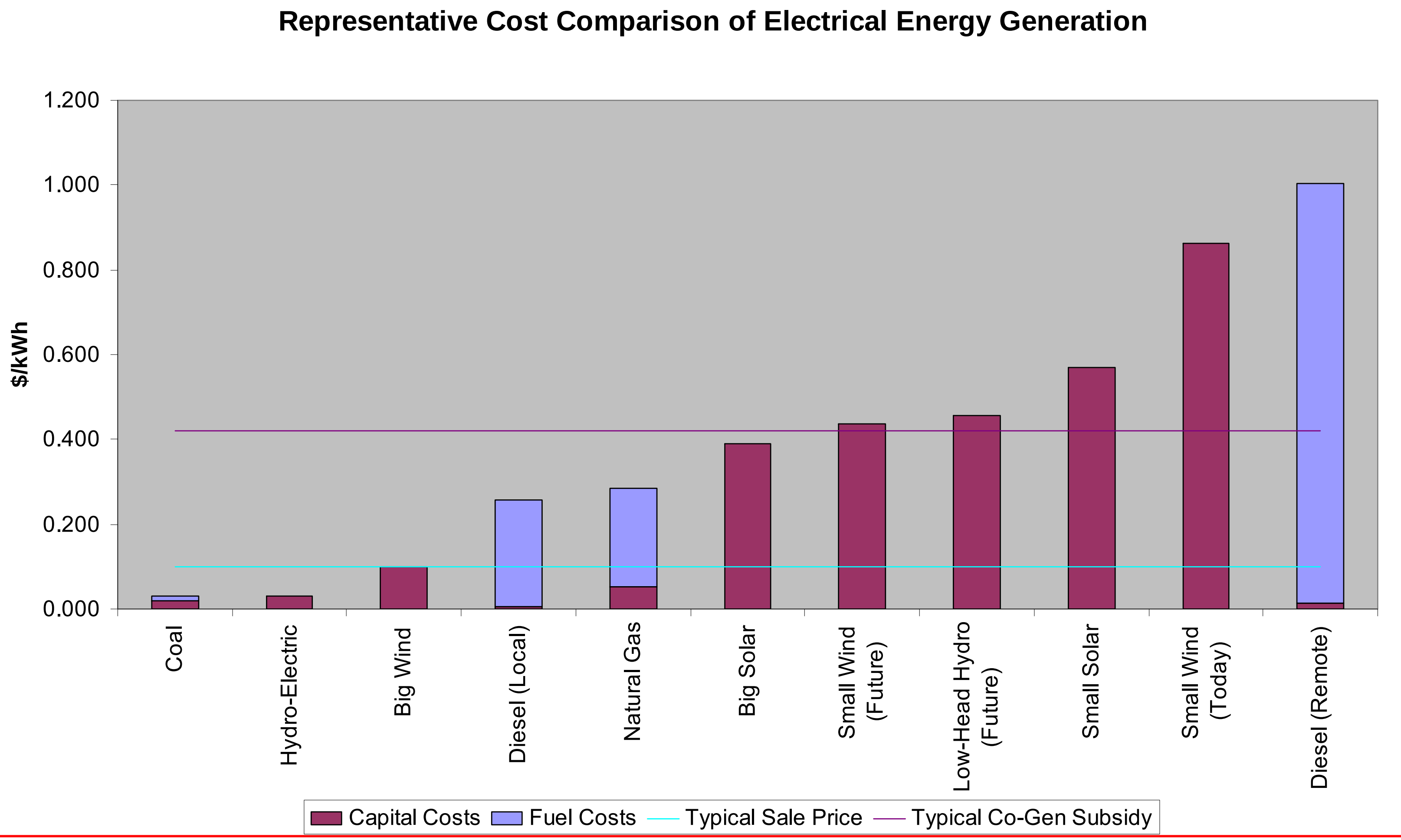
Inverters' Role in the Solar Value Chain

- Inverters make the solar power useful
- Represents approximately 7% to 10% of system cost



Source: CLSA report July 2005.

Economic Analysis



(Some) Grid Technology Developments

- Materials
  - Composites, e.g. cable
    - Replaces steel core conductor
    - 2x rating
    - eliminates sag caused by load, ambient
    - fewer structures along right-of-way
    - Reduces line losses
    - Eliminates bi-metallic corrosion, fatigue iss
  - Super conductors?
- Devices
  - Silicon Carbide (devices + related)
    - solid state breakers
    - HV, HT Electronics
- Distributed sensing
  - temp, volt, I,
- Communications
- Nuclear
- Demand side control
- Micro-grid
- Storage
- Efficiency (technology)?
- Improvments (FC, PV, Wind, ...)
- EV/HEV
- Biofuels, synthetic, cellulostic, ...
- Off-Shore Wind
- Storage, Storage, Storage, ...
-

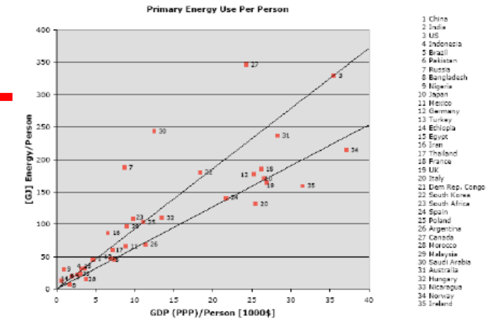
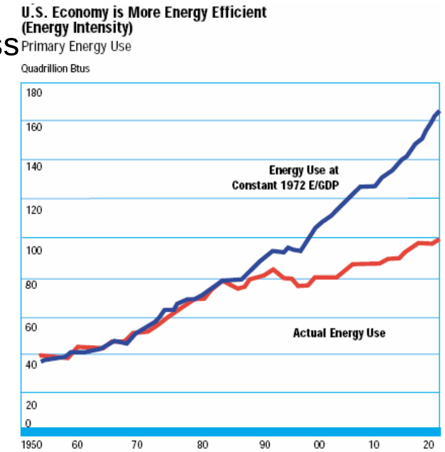


Figure 1.1 Energy use (in gigajoules) vs. GDP (on a purchasing power parity basis) for selected countries on a per capita basis. Data from the International Energy Agency. Upper line indicates ratio for the US; lower line indicates ratio for Japan and several Western European countries.



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.

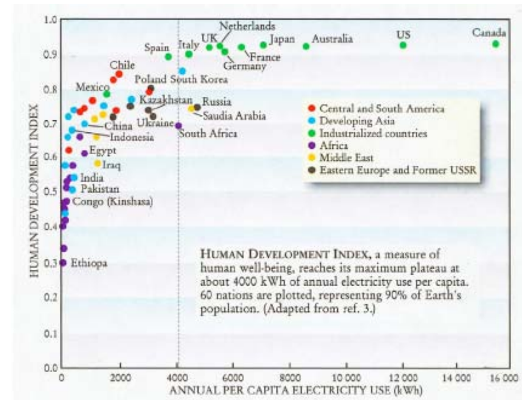
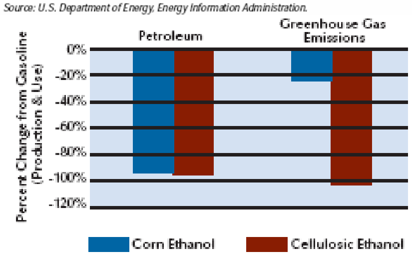
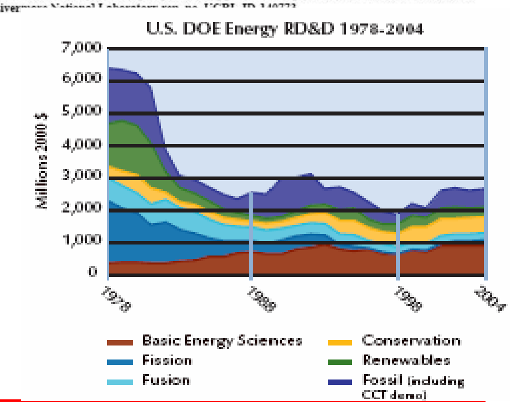


Figure 1.2. Human development index vs. per capita electricity use for selected countries. Taken from S. Benka, *Physics Today* (April 2002), pg 39, and adapted from A. Pasternak, Lawrence Liver

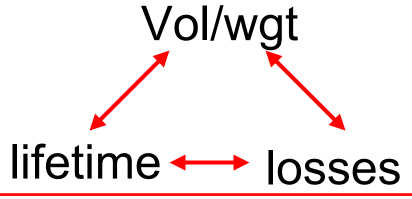


Data Source: Lynd, Greene, and Sheehan, 2004



Si → Si/SiC → SiC

	Silicon SOA	Hybrid Si/SiC Design	Full SiC Design
Size/Density/Efficiency	10 -- 100 W/in^3 (16 W/in^3 for SSIM)	15 -- 150 W/in^3 (25 W/in^3 for SSIM) (70% Vol., 50%Switching, ~75%P)	35 -- 350 W/in^3 (80 W/in^3 for SSIM) (30% Vol., 20%P)
Cooling	80°C max. liquid or 25 °C Air	80°C max. liquid or 25 °C Air	>100°C liquid or 40-50 °C Air
Response Time	10 ms for 5.6 kHz with V and I loops	5 ms for 10 kHz with V and I loops1mS for 100kHz with dead-beat control	50 µS for 100kHz with dead-beat control
High Temperature Design	Si limits entire system to < 125°C	Si limits entire system to < 125°C	Partial High-Temperature design then eventually complete High-Temperature design if needed (analog degradation)
Overload Capability	100-500 ms	2+ seconds	10+ seconds
Robustness/Reliability	10-20,000 hr. MTBF	20-50,000 hr. MTBF	50-100,000 hr. MTBF



Optimize Key Metric
$
Range
LCC
Life
…

Realizing Potential of Wide Band Gap

- Power Circuits
- Power Components, active and passive (SiC)
- Signal Electronics
- Control
- Software
- Thermal Management
- Mechanical Design & Packaging

Full benefit comes from addressing all areas

SiC devices are NOT drop in replacements

?

Is the performance acceptable?
Are the devices reliable?
Are they consistent (matched)?
What are the next hurdles?

$ $ $ $

Materials
⇓
Devices
⇓
Package
⇓
Drive
⇓
Sense
⇓
Control
⇓
•
•
•
System

Applications

?

Some Cost Considerations

Assume: SiC will reach 3x Si, diode is ½ of active, LC product goes down by 4, choose L or C

	Today's Si Design	Hybrid Si/SiC-1	Hybrid Si/SiC-2
Semiconductors	4.11	6.81	6.81
Magnetics	9.83	4.91	2.455
Filter Caps	1.7	0.85	1.7
Heatsinks + Hardware	2.4	1.2	1.2
Fans	1	1	1
Sum (% of total parts cost)	19.04	14.77	13.165

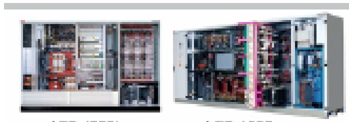
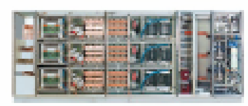
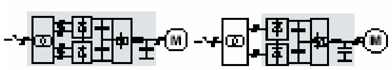
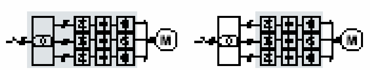
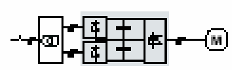
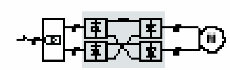
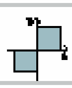
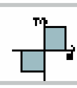
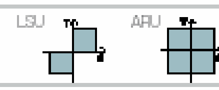
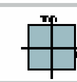
Percentage Costs for Si/SiC Inverter

1% increase, 2% improvement round-trip efficiency
For the 100kW Inverter, feeding a 200kWHr battery, once per day charging cycle 2kWHr saving of off-peak energy, 2KWHr of peak electrical energy.
German feed in tariff for PV as an indicator (~55 c€/kWh) we could argue that the 1% of efficiency is worth US $1/day, or with a 20% return on investment approximately $1,800
on the order of 10% of the parts cost of the inverter and so the increase in cost of the semiconductors in moving to a hybrid Si/SiC IGBT module is easily justified in savings due to improved efficiency
Or CEC have put a monetary value on KW capability of up to $3.50/watt and so the 1% efficiency improvement would have a direct monetary value in a subsidy situation of up to $3,500. Could be more for roundtrip and with 2 stage

Other factors: EMI, Snubbers, metal, MOVs, Electrolytics!, …

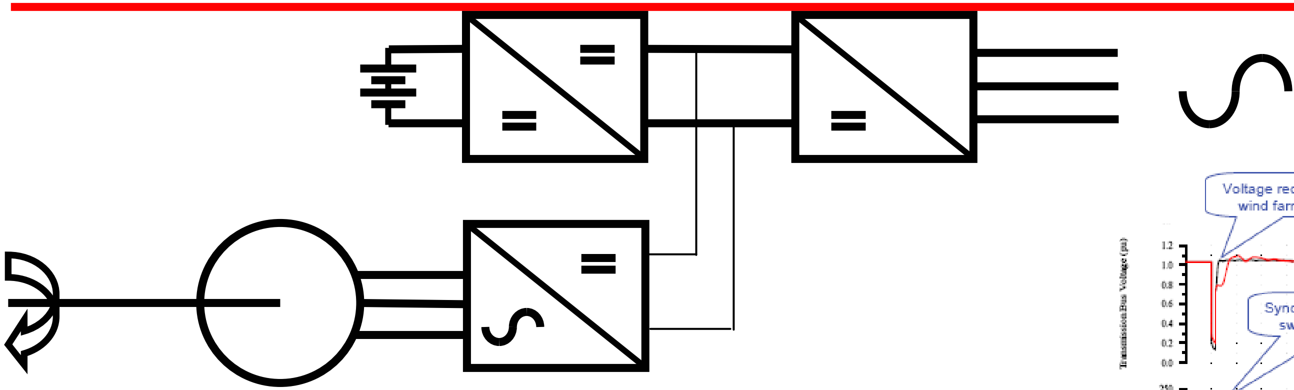
Medium Voltage Drives Today

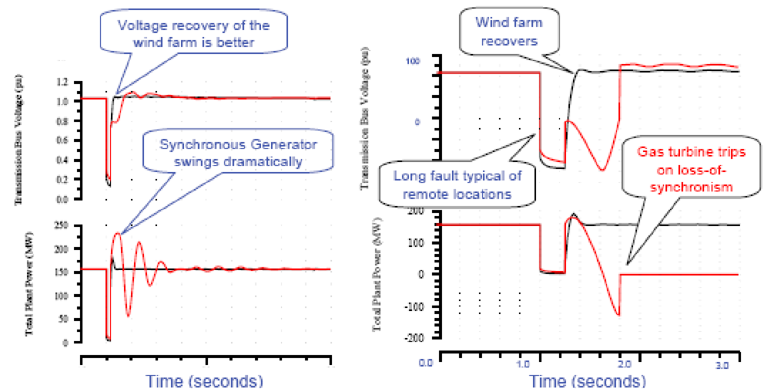
ABB, NishiShiba, Siemens, …

VSI-NPC Voltage Source Inverter Neutral-Point Clamped	VSI-MF Voltage Source Inverter Multilevel-Fuseless	VSI-NPC Voltage Source Inverter Neutral-Point Clamped	LCI Load Commutated Inverter
Pumps, fans, conveyors, extruders, mixers, compressors, grinding mills, suitable for retrofit of existing motors	Compressors, extruders, pumps, fans, grinding mills, conveyors, marine propulsion, bar and rod mills, blast furnance blowers, gas turbine starters	Pumps, fans, conveyors, extruders, compressors, grinding mills, marine propulsion, rolling mills, mine hoists	Compressors, pumps, fans, blast furnace blowers, pump storage plants
 ACS 1000i ACS 1000	 ACS 5000	 ACS 6000	 MEGADRIVE-LCI
			
Air (A) / Water (W)	Air (A) / Water (W)	Water (W)	Air (A) / Water (W)
A: 315 kW – 2 MW W: 1.8 – 5 MW	A: 2–7 MW W: 5–24 MW	W: 3–27 MW	A: 2–31MW W: 7–72MW / higher on request
Diodes: 12/24-pulse rectifier	Diodes: 36-pulse rectifier	Diodes: 12/24-pulse rectifier (LSU) or IGCT: Active rectifier (ARU)	Thyristors: 6/12/24-pulse rectifier
IGCTs: 3-level VSI, sinusoidal output	IGCTs: 5-level VSI-MF, 9-level output waveform	IGCTs: 3-level VSI, 5-level output waveform	Thyristors: 6/12-pulse inverter
2.3/3.3/4.0/4.16 kV Optional: 6.0/6.6 kV with step-up transformer	6.0–6.9 kV Optional: 4.16 kV	3.0–3.3 kV Optional: 2.3 kV	2.1–10 kV
66 Hz (optional 82.5 Hz)	75 Hz (higher optional)	75 Hz (Twin: 250 Hz)	60Hz (optional 120Hz)
> 45Hz (max. 1:1.5)	> 30Hz (lower optional)	> 6.25Hz (max. 1:5)	Customized
			
* Sinusoidal output * Constant network power factor over whole speed range * DTC (Direct Torque Control) * Fuseless	* Constant network power factor over whole speed range * DTC (Direct Torque Control) * Fuseless	* Constant network power factor over whole speed range * Optimized pulse pattern to minimize network harmonics (with IGCT) * DTC (Direct Torque Control) * Multi-motor drives with common DC bus * Fuseless	* Soft start of large synchronous motors and generators * Fuseless

Voltage, frequency, performance tradeoff

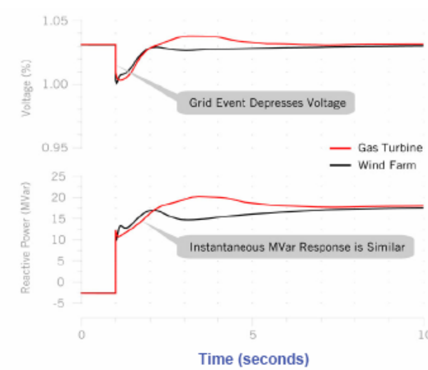
Fully Rated Inverter provides Many Possibilities





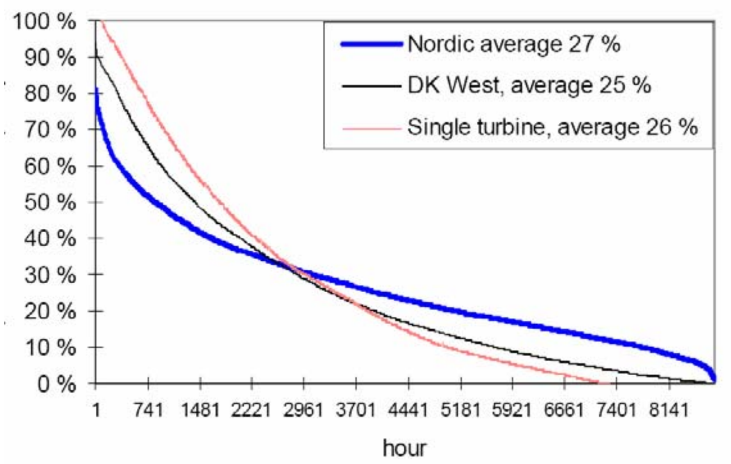
- Controllable (remotely)
- Supply Real Power, P, regulate battery

- Reactive power, Q, ($|P + jQ| < S_{INV}$)



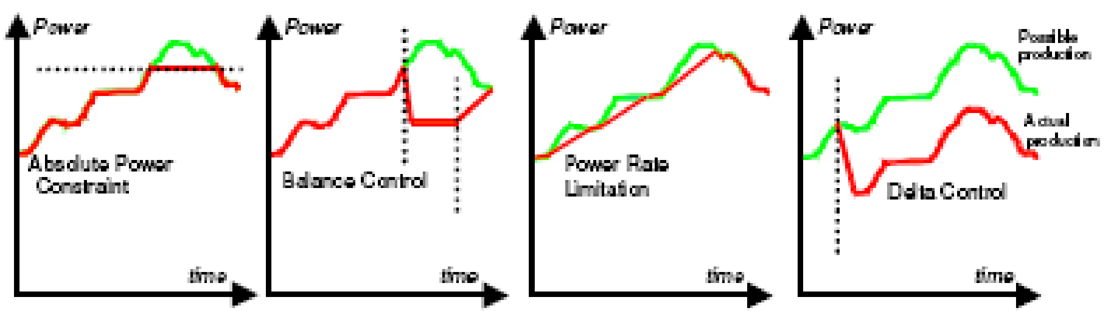
- Active Damping (stabilizing)
- Fault Clearing
- Rapid Dynamics
- Unbalanced, non-linear sourcing
- Active Filtering, harmonic cancellation
-
- **NOT an Electrical Machine!!**
-

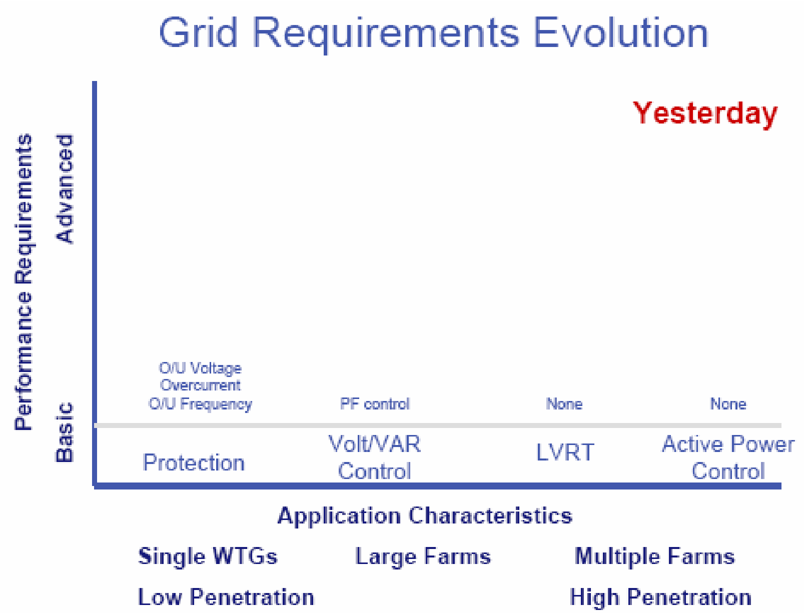
Increasing Penetration of Renewables

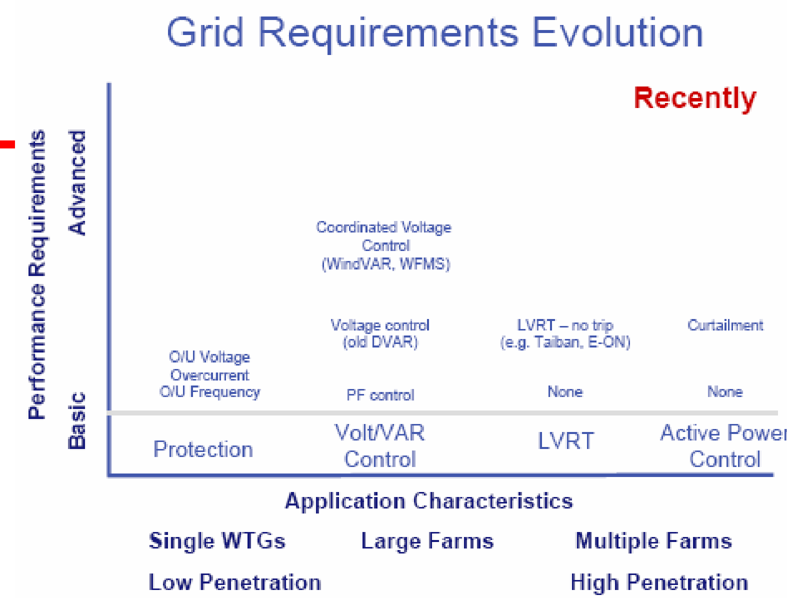


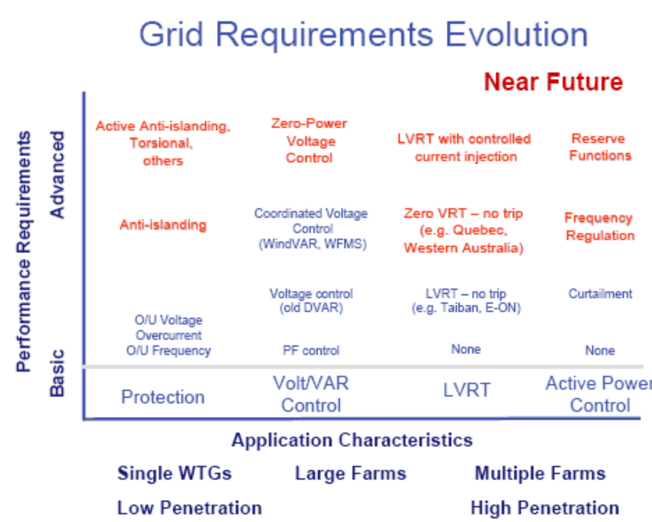
Denmark

- 14% of Electrical Energy
- New Control Regs.







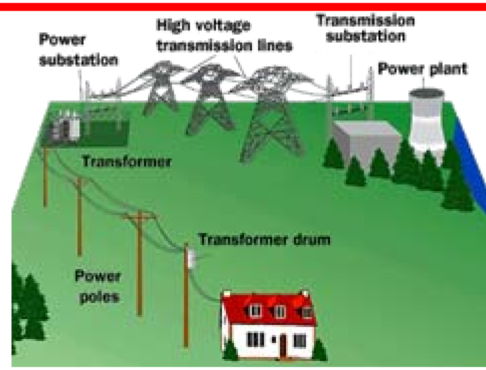


Harmonization?
Electronic Capability?

Power Distribution Options -- Battle

Thomas Edison and Joseph Swan

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



Move it at HV

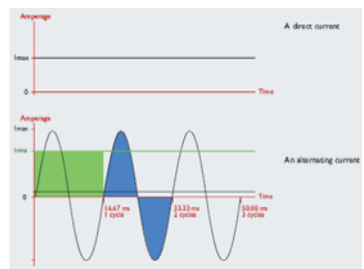
AC won (pre-electronics)
•Transformer isolation
•Impedance (V) transformation
•Grounded Secondary (safety)
•AC → DC, easy

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

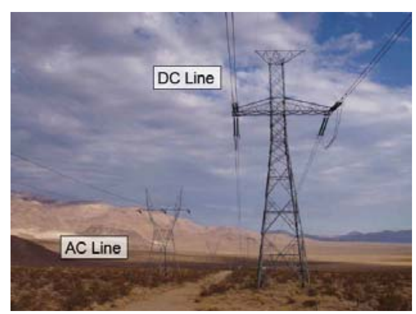
But
•Skindepth
•ϕ Imbalance
•Reactive power
•Peak to RMS

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

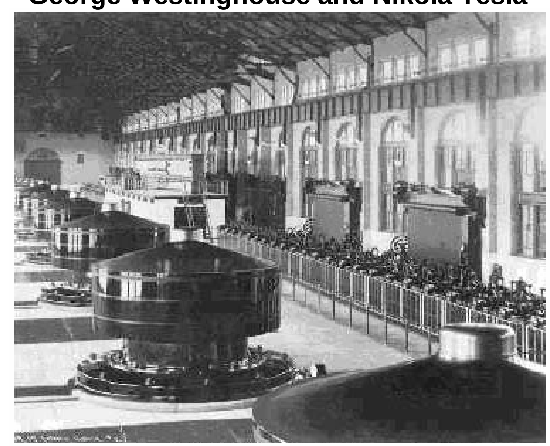
Edison was missing what?
Loads Today?
Sources Today
Storage?



Today, DC wins for T



George Westinghouse and Nikola Tesla

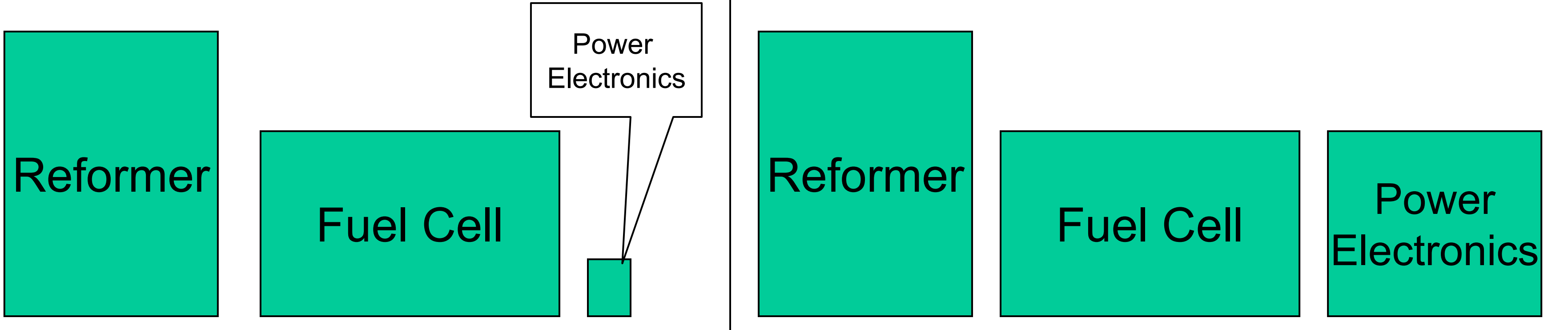


Adams Hydroelectric Plant
Niagara Falls 1895
Westinghouse, Tesla, Stanley

FC → dc/dc → HVDC ?

Power Electronics Can Provide the Solution - but at what cost?

Who is doing the System Design…?



The Vision

The Reality

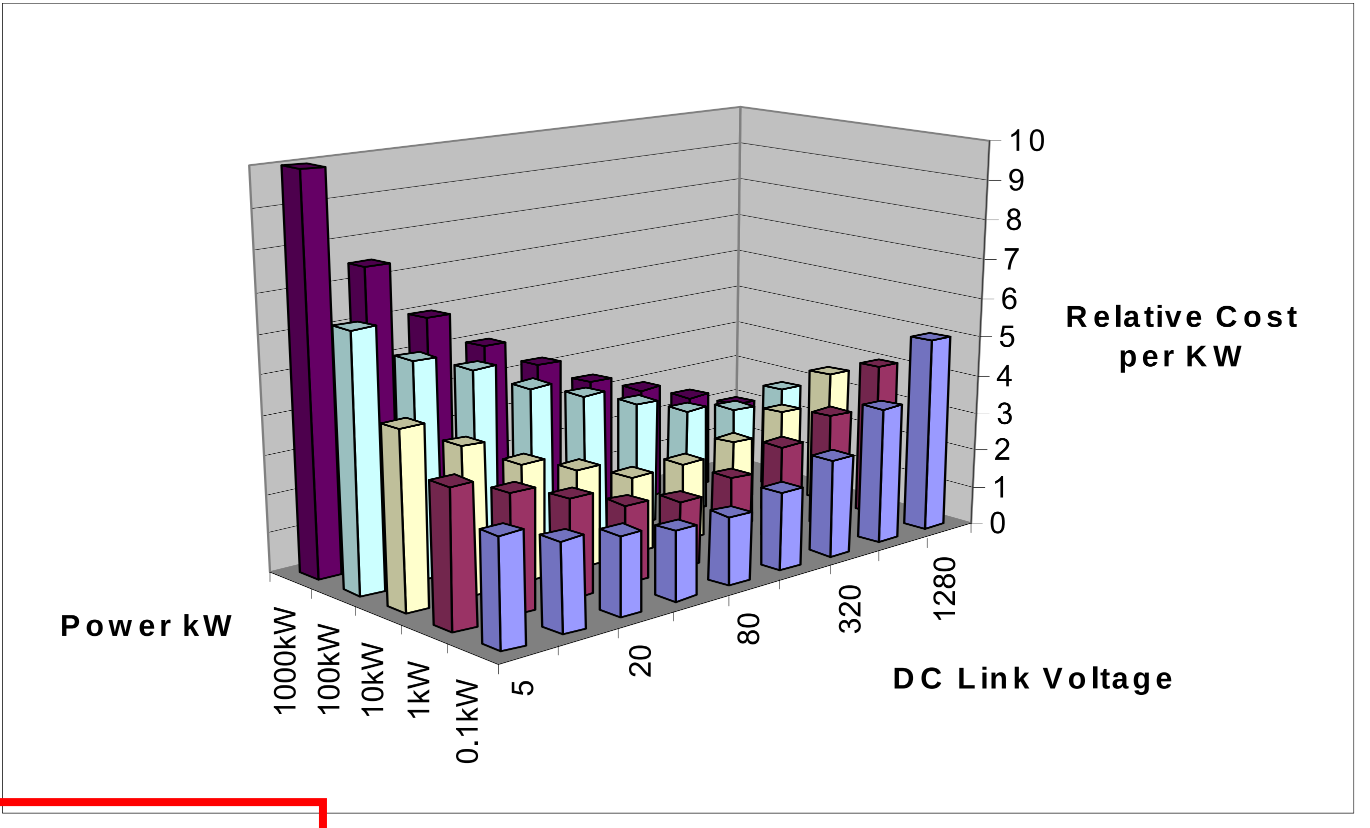
"Power Electronics is just a Commodity"

System Design and Specification are driving the Power Electronics Cost

FROM FC2000

Power Level and Circuit Topology define a balance of voltage and current that gives minimum cost

For a conceptual converter topology the curves might look like this:-



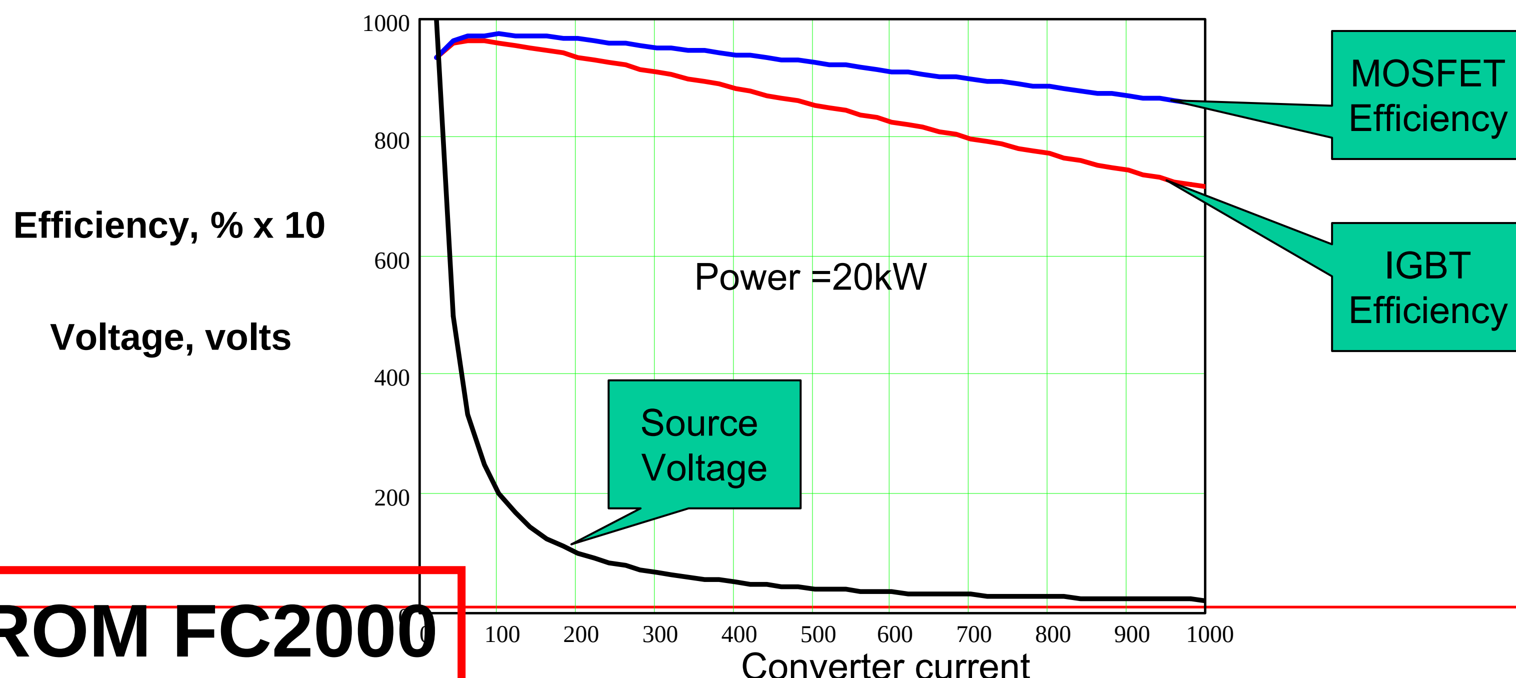
FROM FC2000

300V to 800V best for 10kW to 100kW power range, 800V and higher best for higher powers

Some general principles:-

Higher voltage semiconductor devices switch slower
Conversion frequencies must be lower at high voltages

High efficiency is difficult to achieve economically when power is the product of low voltage and high current



FROM FC2000

"Power Quality" is multi-dimensional – some attributes are more important to some users

- Necessary to meet load-specific power quality:
  - Harmonic content
  - Transient performance
  - Frequency tolerance
  - Load Circuit Protection
- Stand alone systems may not be required to beat/meet all utility characteristics
  - Saves components
  - Simplifies design
  - Reduces overall cost of system
- Smart Load and Non Invasive Load Monitoring
  - Intelligent control in place of grid imitation

FROM FC2000

Don't judge distributed power electronics $/kW costs based on motor drives

Motor drives are the most power dense and hence lowest $/kW of all DC/DC and DC/AC power conversion equipment - they have the lowest passive component count.

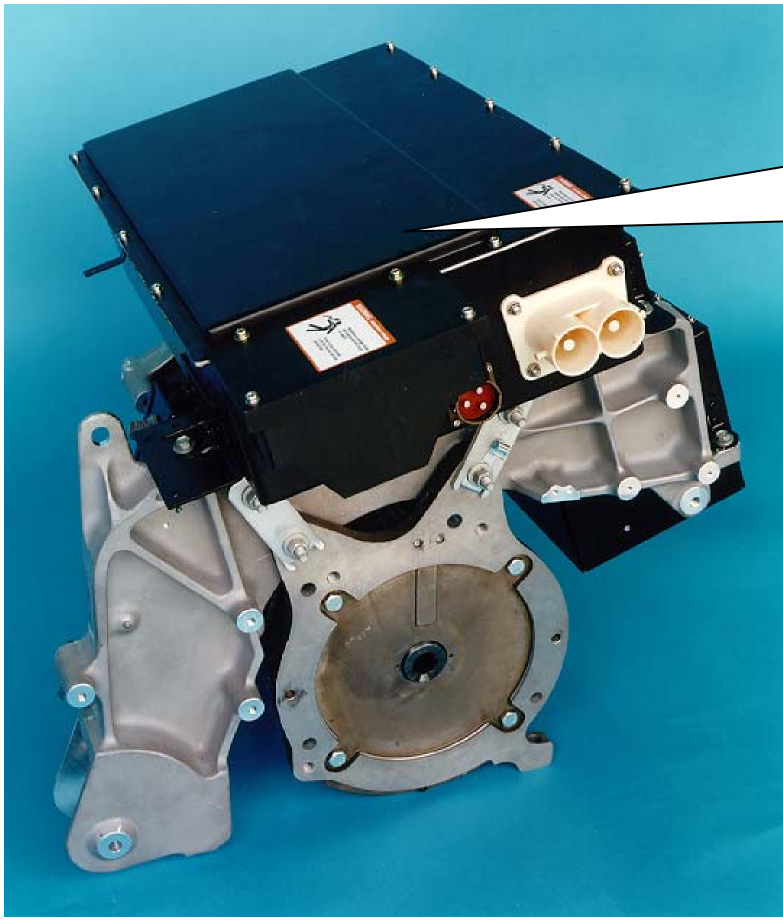
Typical numbers for very high power density designs:

DC/DC or DC/AC Power Converter	7kW/liter
DC/AC 3Φ Motor Drive	28kW/liter

In high volume production cost follows power density (& weight) so that cost expectation for DC/DC & DC/AC Power Converters should be 3 to 4 times the $/kW of motor drive converters.

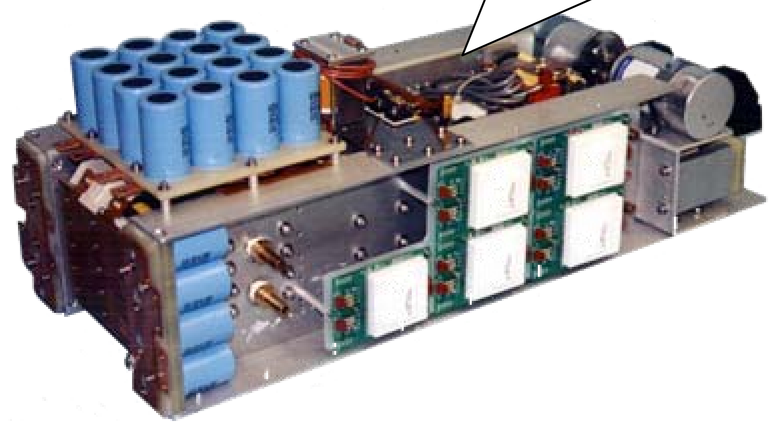
FROM FC2000

Hardware confirms the power density ratio



100kW motor drive inverter
1.3 ft^3, 56lb
DC input 320V

15kW Fuel Cell Converter
1.5 ft^3, 65lb
DC input 48V/48V



FROM FC2000

Big Inverters

- $200/kW?
- Extended Warranty?
- Performance?
- Research? -devices (SiC, GaN, … . Packaging, gate drives, control, passives, ….

  overload capability

  topology? Device dependent, say truly symmetric, bi-directional IGCT, 10kV+, building blocks, resonant transformers (isolation?), step-up to 25kV? CSI, …