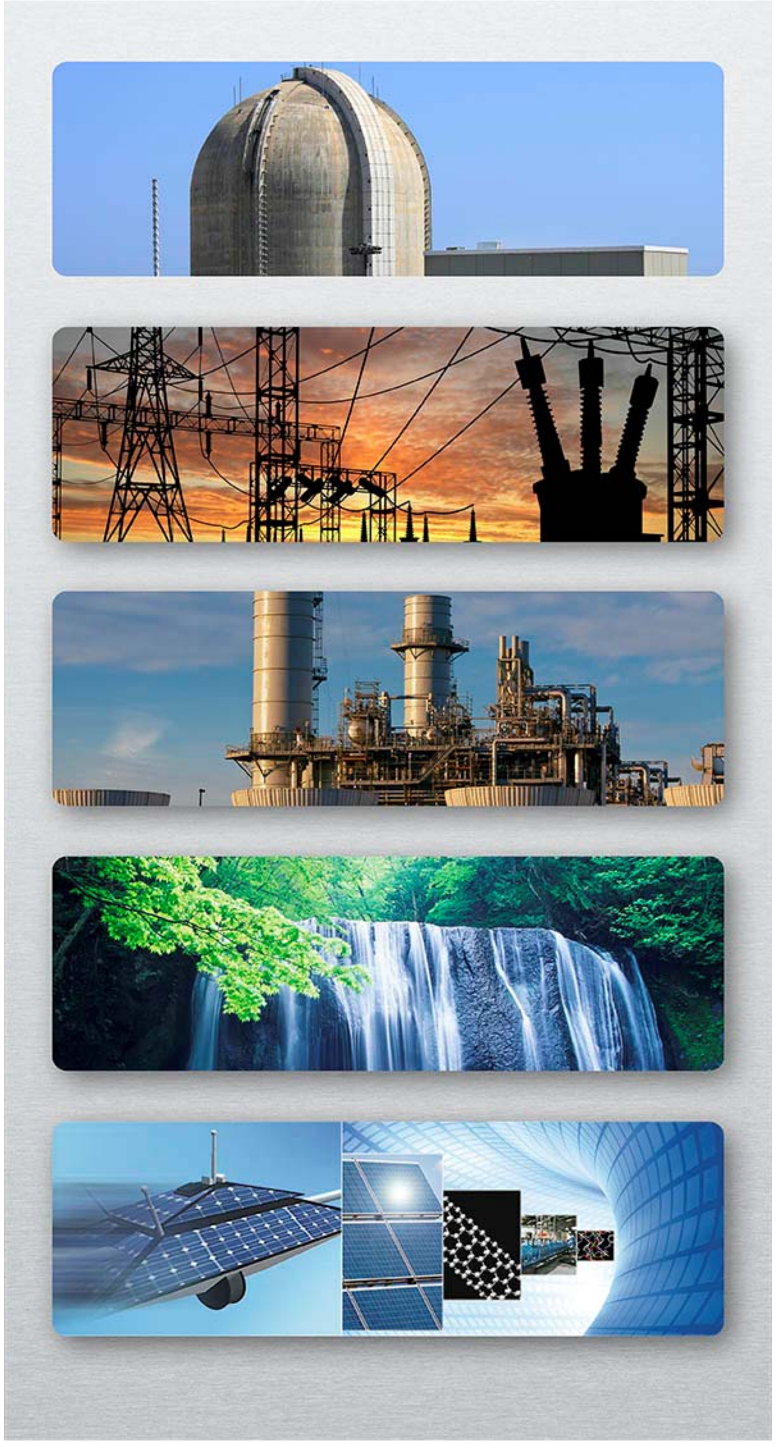


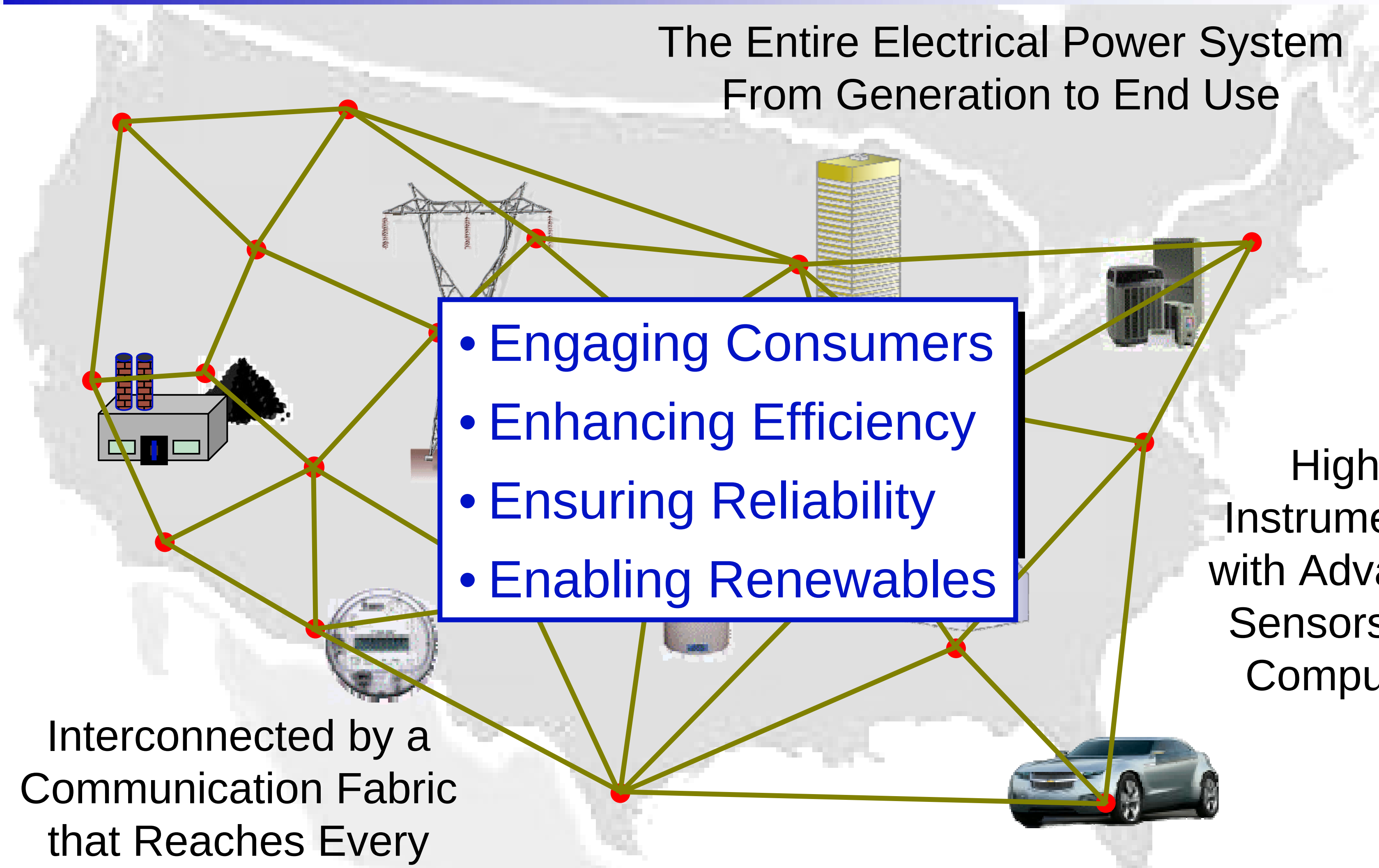
The Role of Power Electronics in the Future Smart Electric Grid

Dr. Ram Adapa
Technical Leader, EPRI
radapa@epri.com

IEEE Power Electronics Society
SCV Chapter Meeting

June 15, 2011

SMART Grid - Many Definitions – But All Pointing to:
Sensors…Two Way Communication…Intelligence…Response



The Entire Electrical Power System From Generation to End Use

- Engaging Consumers
- Enhancing Efficiency
- Ensuring Reliability
- Enabling Renewables

Highly Instrumented with Advanced Sensors and Computing

Interconnected by a Communication Fabric that Reaches Every Device

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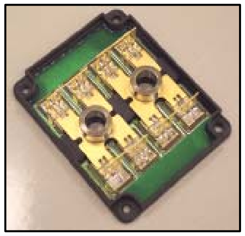
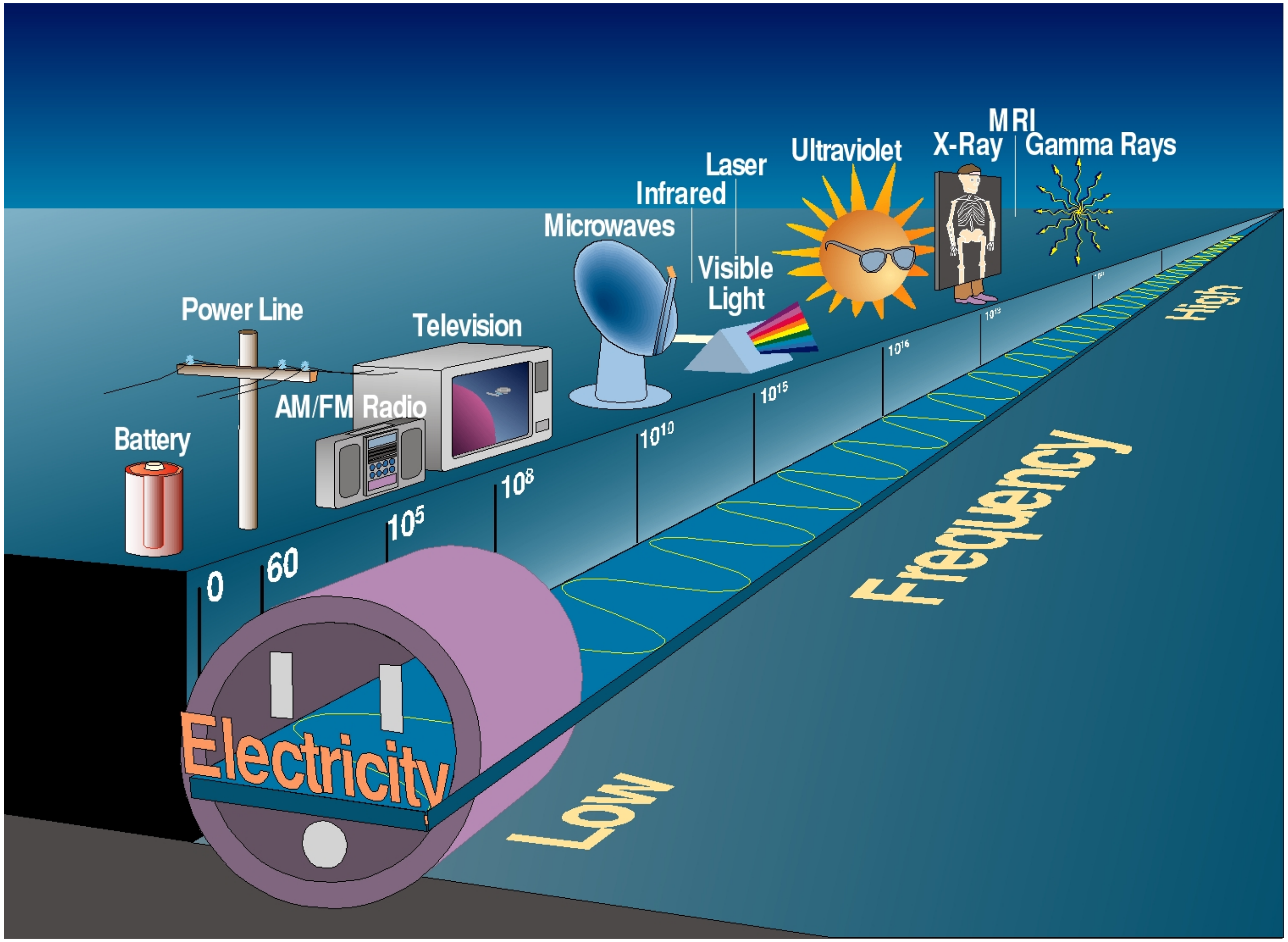
The Power Electronics Revolution – Opportunities



- Reduce energy use
- Enhance the functionality of the power system
- Enable the integration of renewables
- Facilitate the creation of a low-carbon energy future

Power Electronics – Gateway to the Electromagnetic Spectrum



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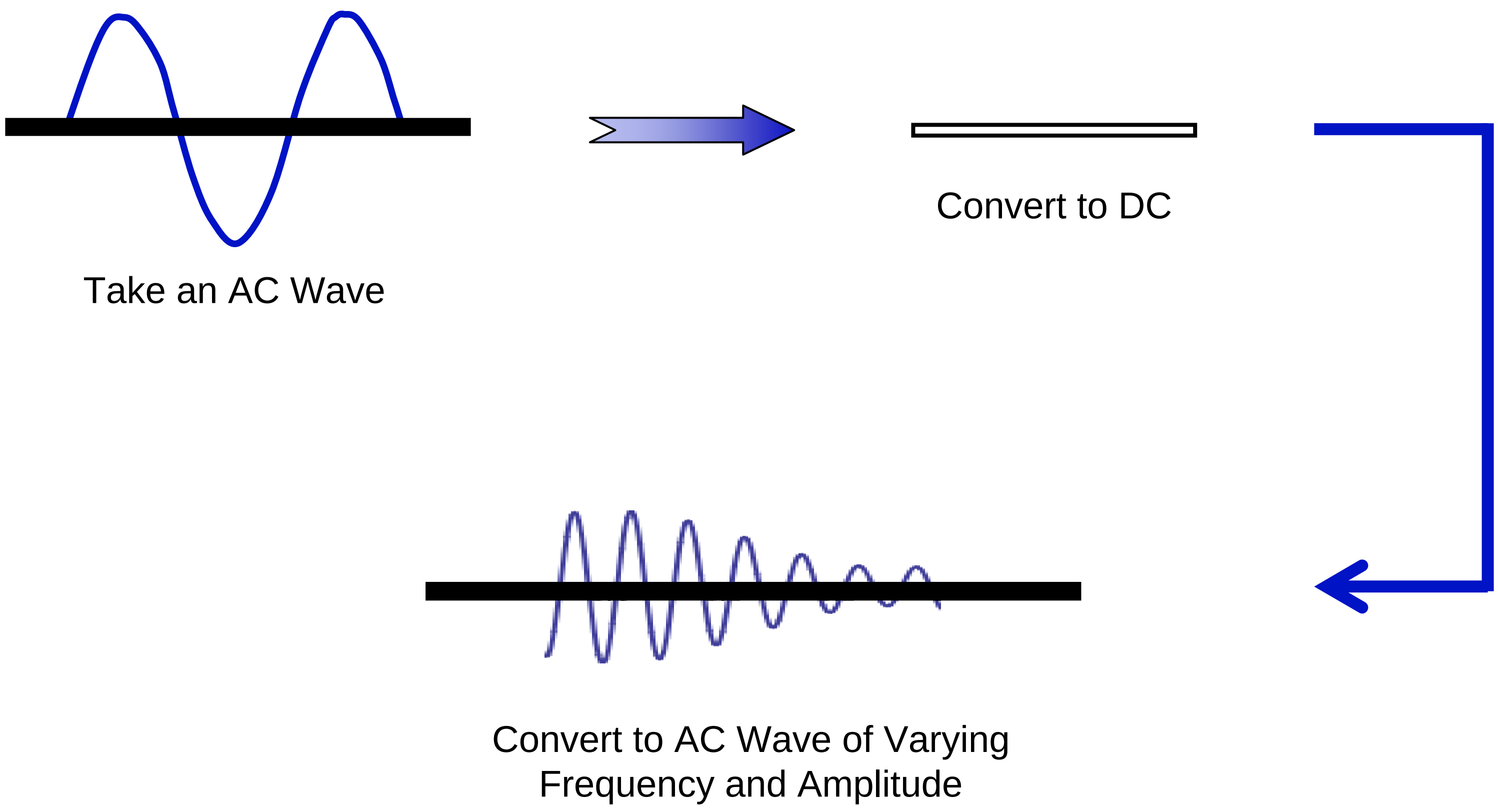
How Do Power Electronics Work?



Quantifying Energy Losses Along KCPL Electricity Value Chain

Generation — ~ 67% loss [1]

Transmission — ~ 1.5% loss [2]

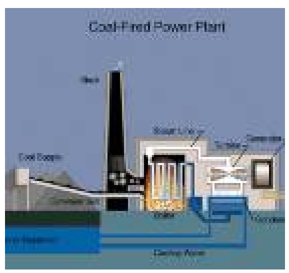
Distribution — ~ 3.7% loss [2]

~ 5.2% T&D loss [3]

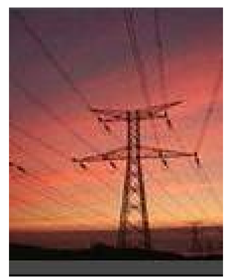
End-Use Utilization — ~ 88% loss (incandescent light example)

Coal

100



electricity ~ 33



electricity ~ 32.5

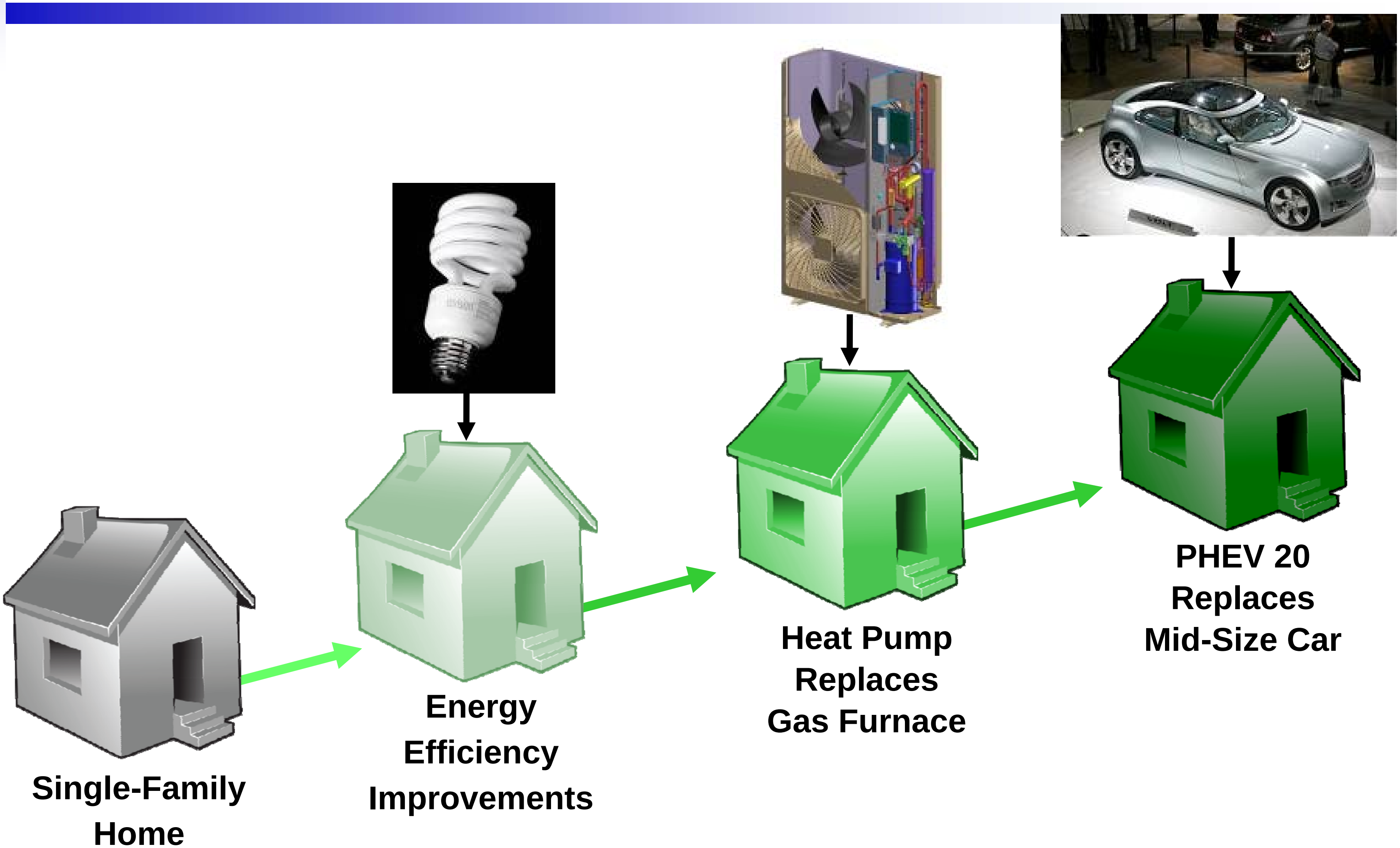
electricity ~ 31.3

[1] Based on weighted average efficiency of KCPL coal fleet, derived from 2006 data

[2] Source: KCPL (“Building the Delivery System of the Future”, November 2005)

[3] Compares favorably to national average estimates of 6 - 8 %

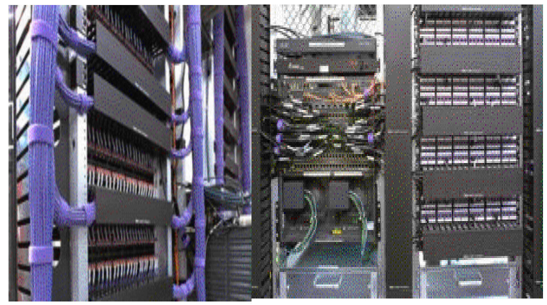
Using Power Electronics to Improve Energy Efficiency



Using Power Electronics to Improve Energy Efficiency

COMMERCIAL

Variable Refrigerant Flow Air Conditioning



Efficient Data Centers

LED Street and Area Lighting

RESIDENTIAL

Heat Pump Water Heaters

Ductless Residential Heat Pumps and Air Conditioners

Hyper-Efficient Residential Appliances

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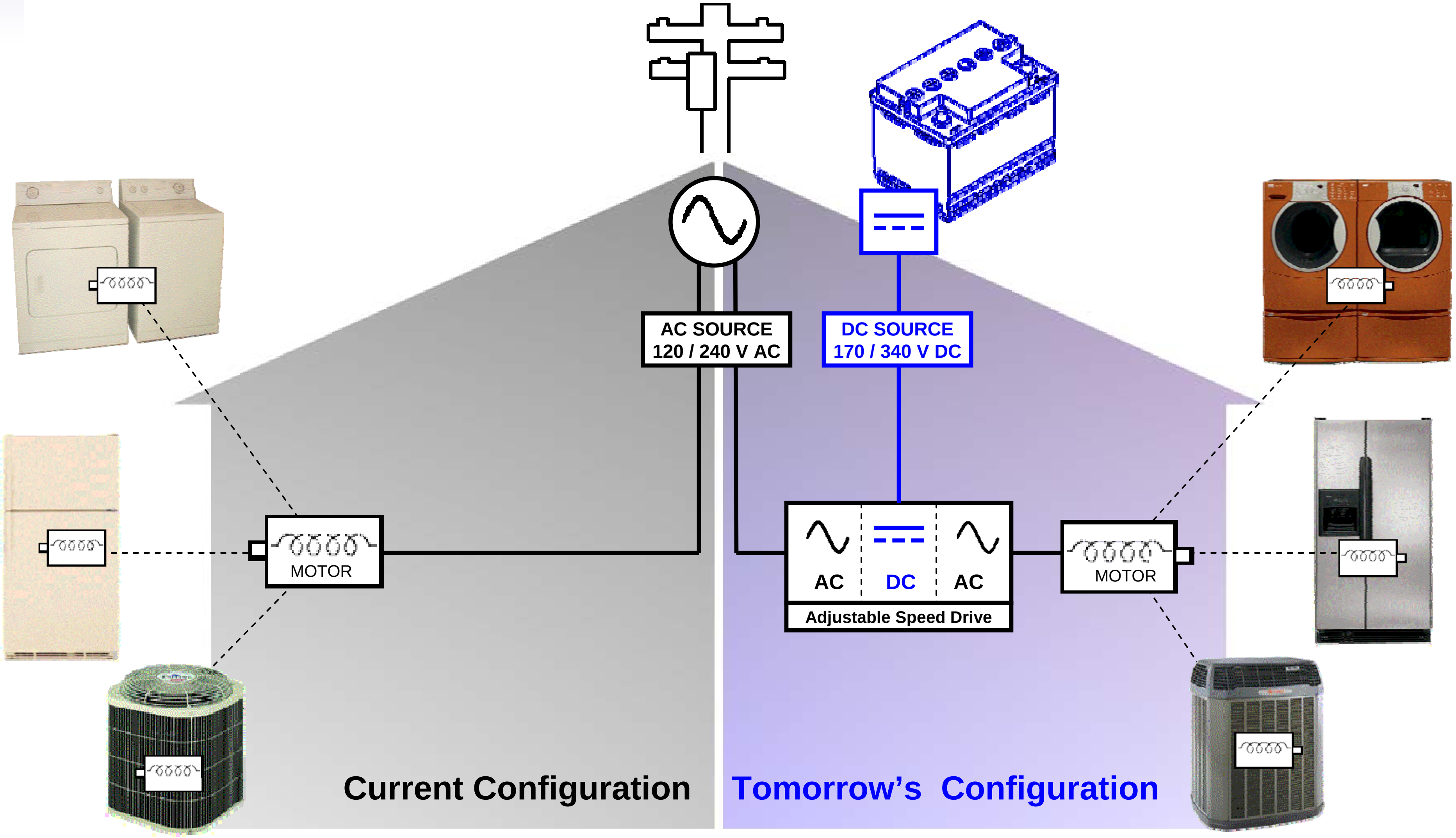
Example: Power Electronics in Appliances



Power Electronics: A Key Technology for Improving Energy Efficiency of ACs, Heat Pumps, Refrigerators, Washing Machines

TOSHIBA
DC Hybrid Inverter Controlled Heat Pump

FUJITSU
Comfort
Wall mounted Inverter models

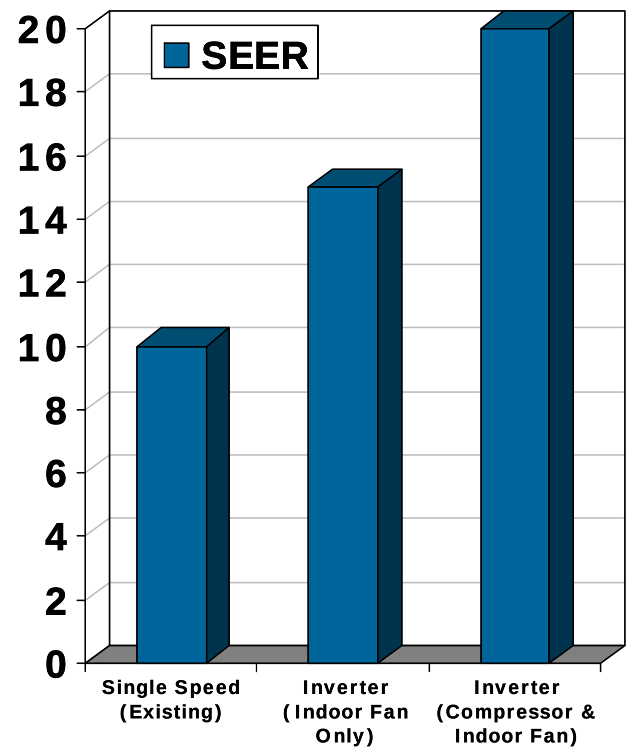
Hisense
Distribution Limited
CLIMATE CONTROL
Inverter
Innovation is life

MITSUBISHI HEAVY INDUSTRIES, LTD.
Inverter single & Multi-split systems

In Japan, up to 70 to 80% of air conditioning equipment is variable speed. By contrast, in the U.S., roughly 80% of the equipment sold today is 10 SEER (Seasonal Energy Efficiency Ratio), the minimum level allowed.

Variable-speed compressor and indoor fan reduces losses by constantly matching the heating and cooling requirement with motor speed.

In a washing machine, a variable-speed motor can provide a high-speed spin-cycle that extracts extra water.



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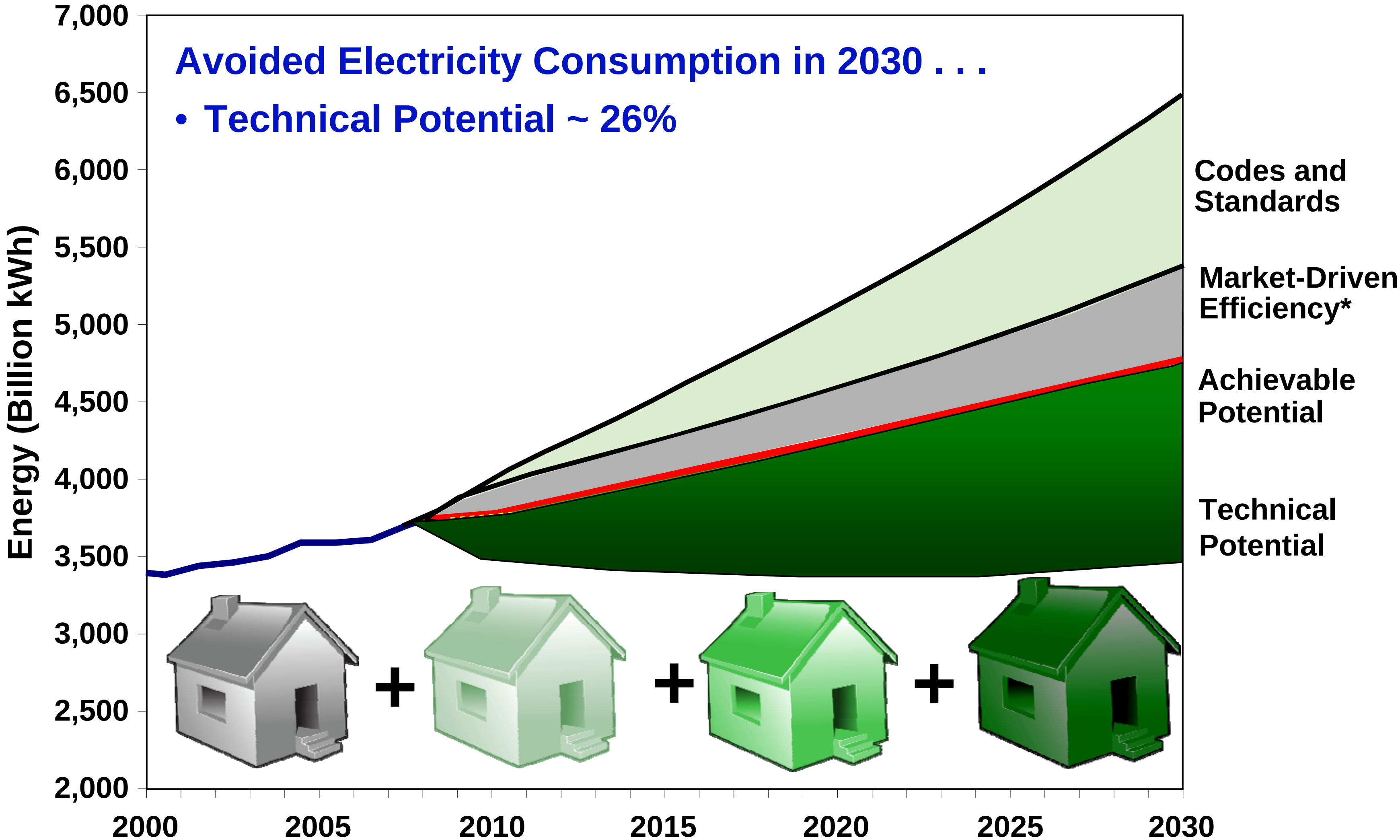
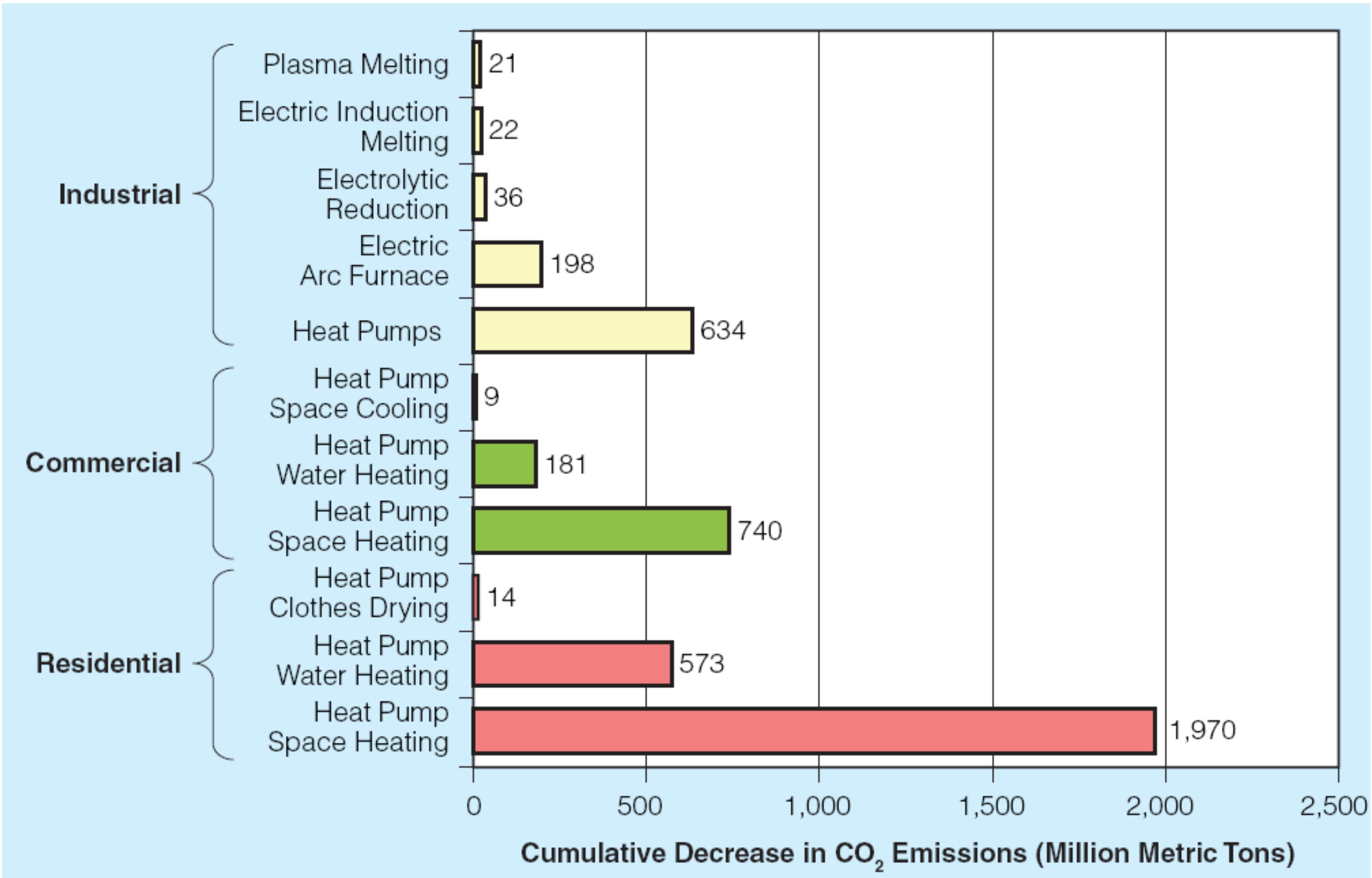
Power Electronics can Reduce Electricity Consumption
Technical Potential Electricity Savings



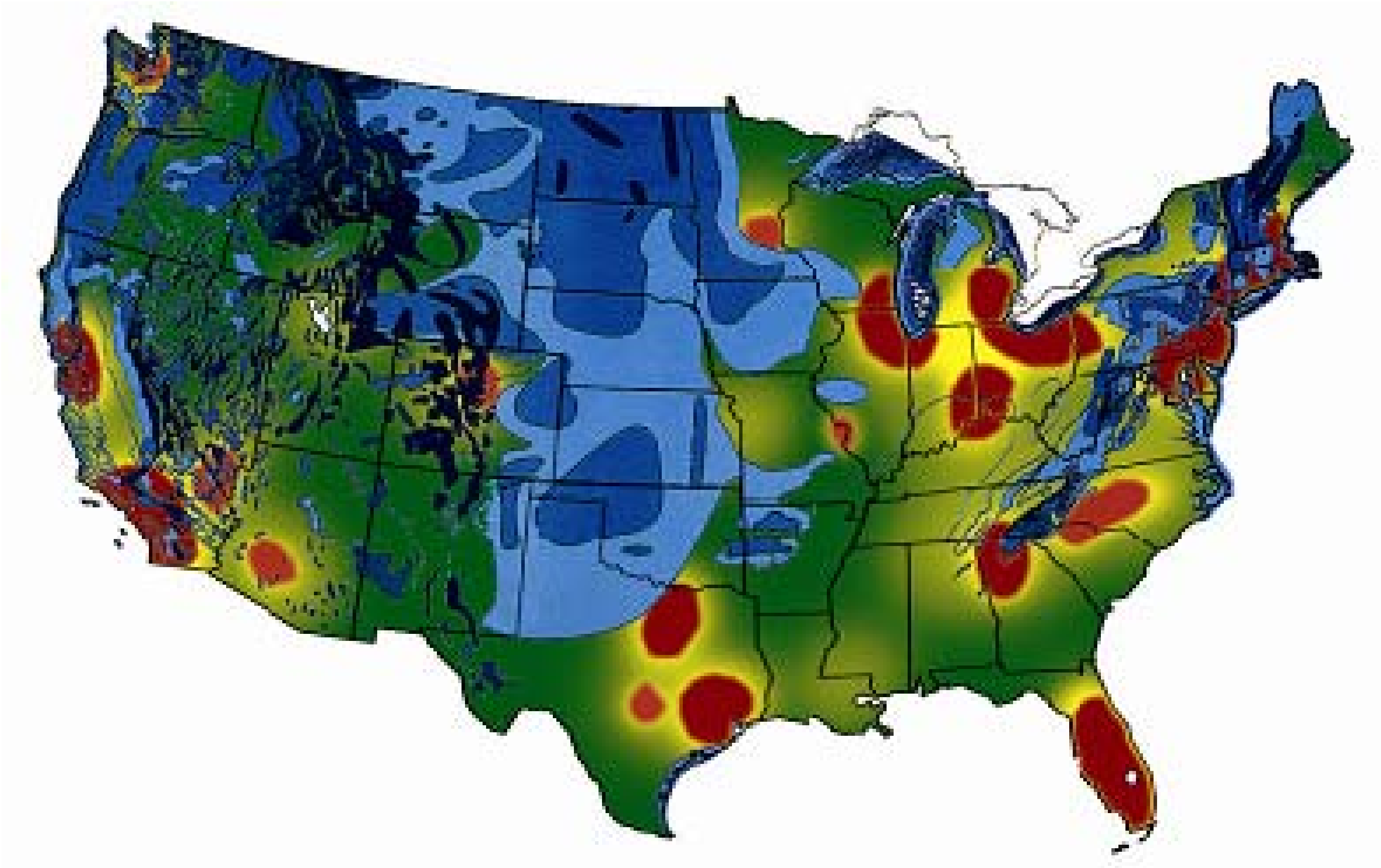
* Includes embedded impact of EE programs implicit in AEO 2008

Technical Potential

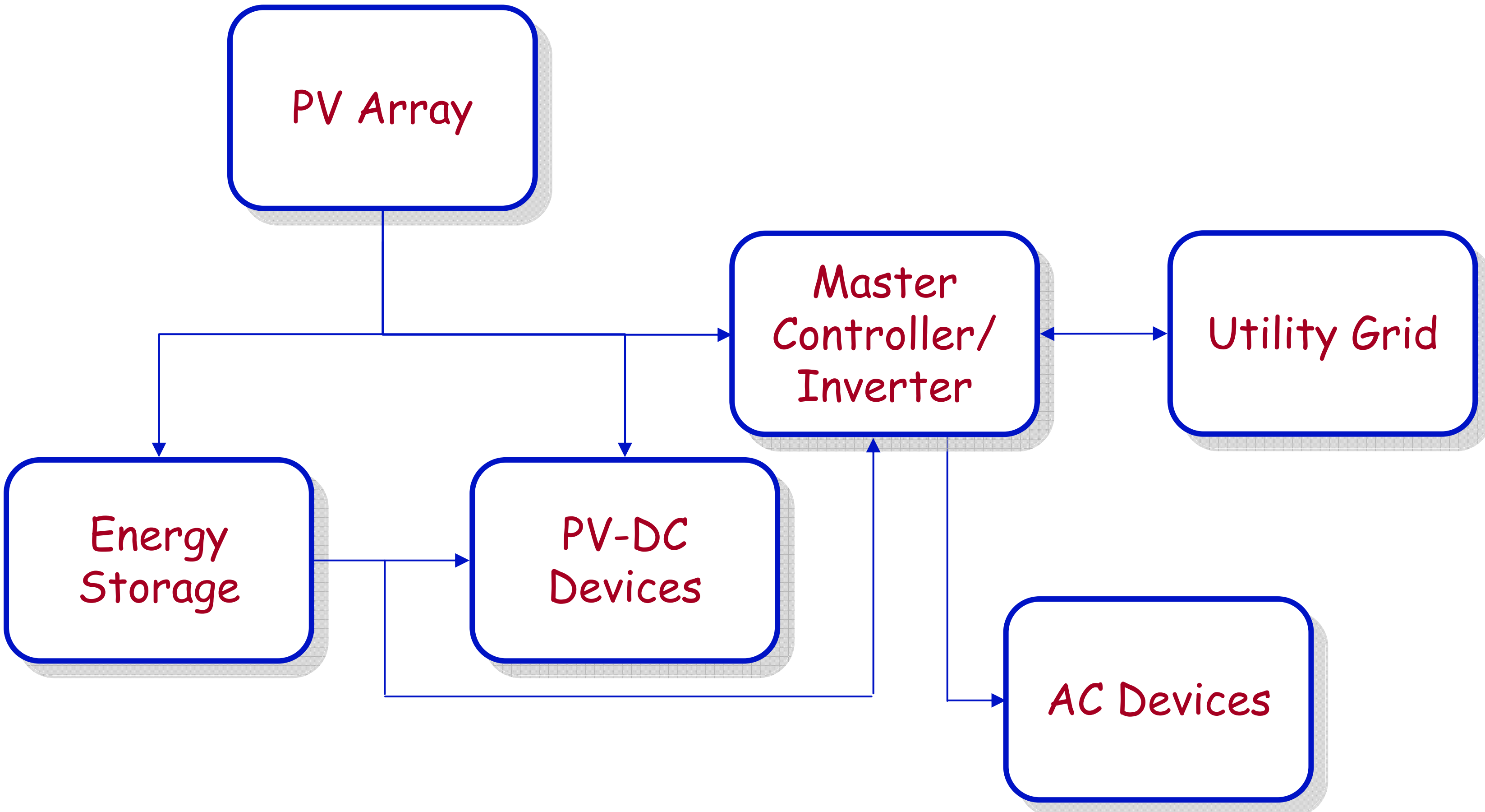


Cumulative Decrease in Energy-Related CO_2 Emissions Between 2009 and 2030 by Sector and Efficient Electric End-Use Technology

Power Electronics: Close the Gap Between Wind Resources & Population Density



Power Electronics: Enable Master Controllers



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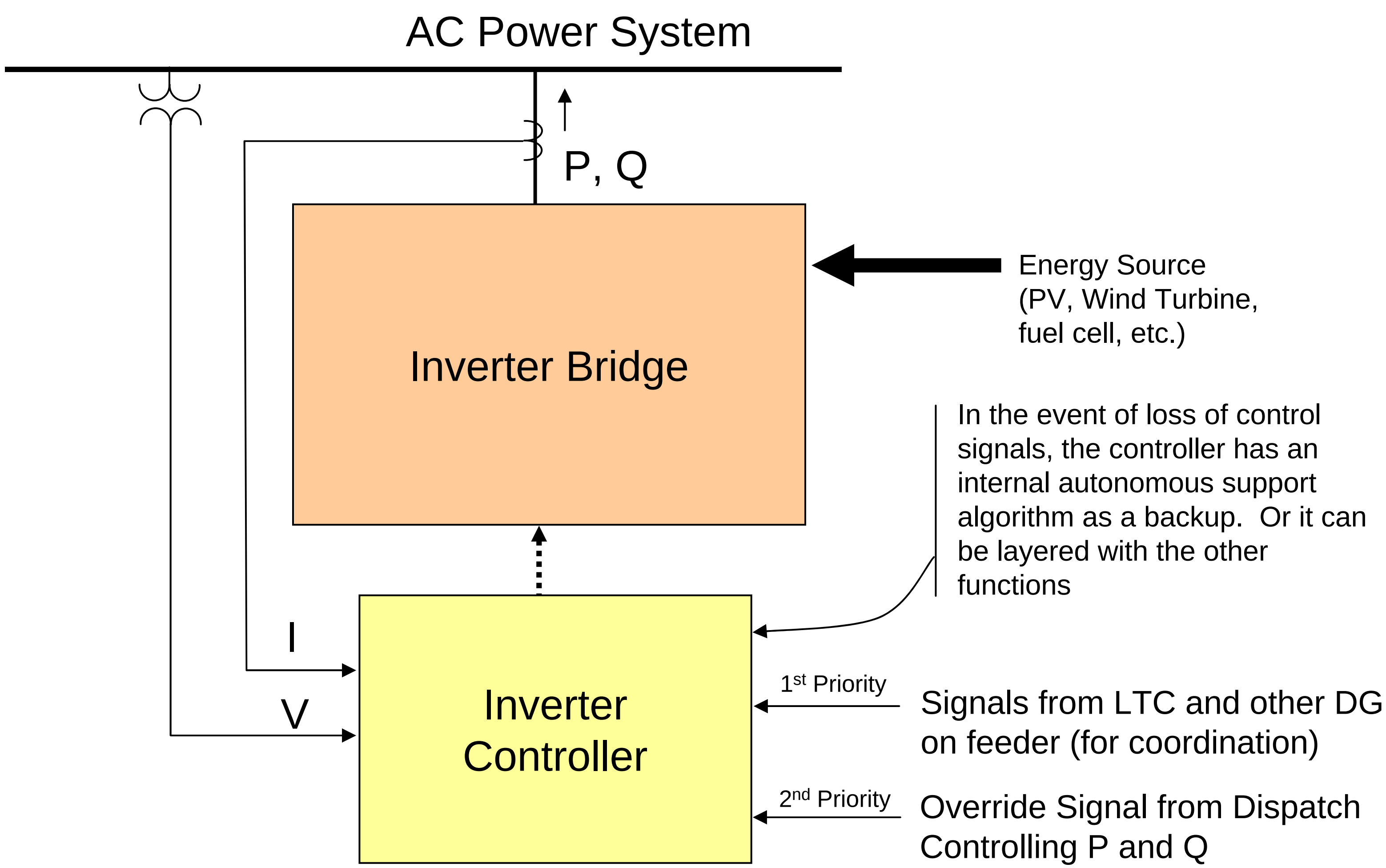
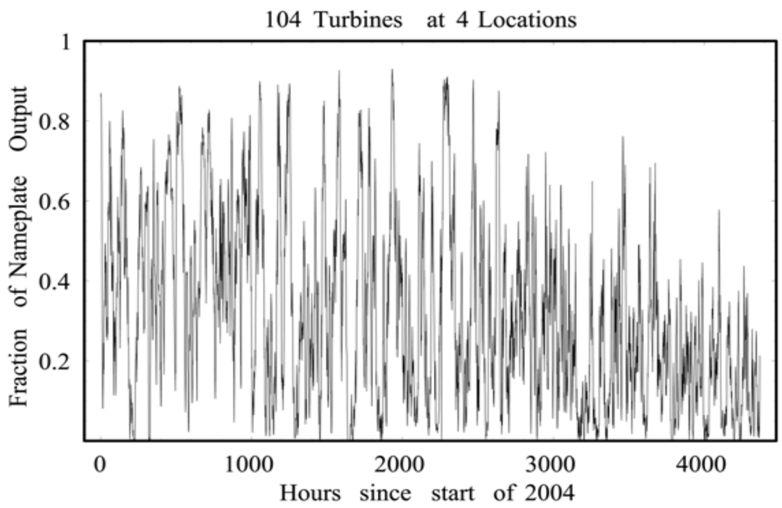
Expected Inverter Requirements for High Penetration



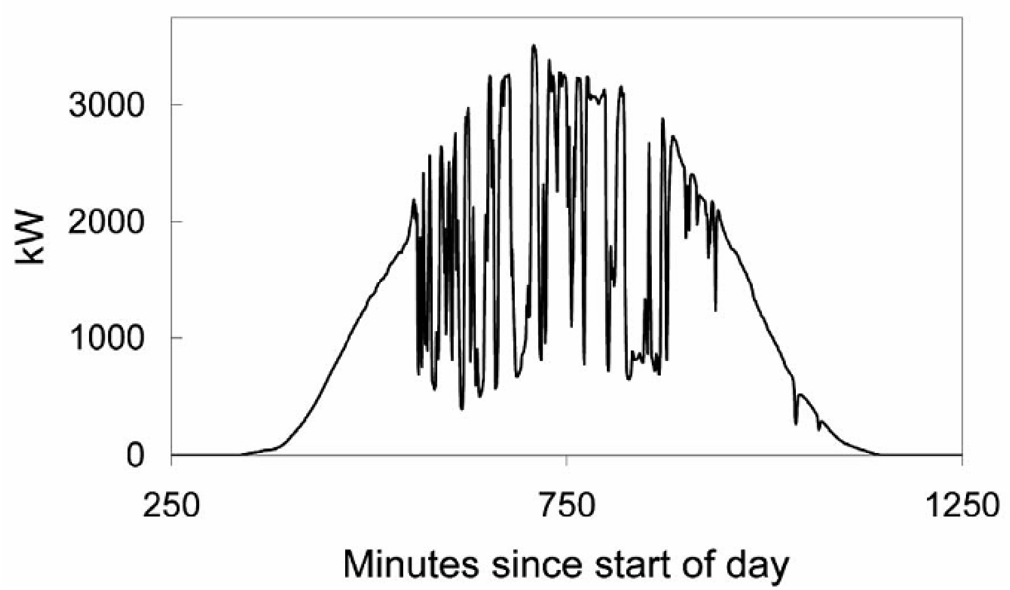
Example of Improved 10 kW Inverter Design & Packaging

Source: "PV Manufacturing R&D: Inverter Manufacturing Progress" by Dave Mooney & Rick Mitchell – NREL. Presented at the DOE Workshop on Systems Driven Approach To Inverter Research & Development, Maritime Institute, Baltimore, MD, April 23-24, 2003

Power Electronics Enable Renewables by Providing Dance Partners



Wind Intermittency

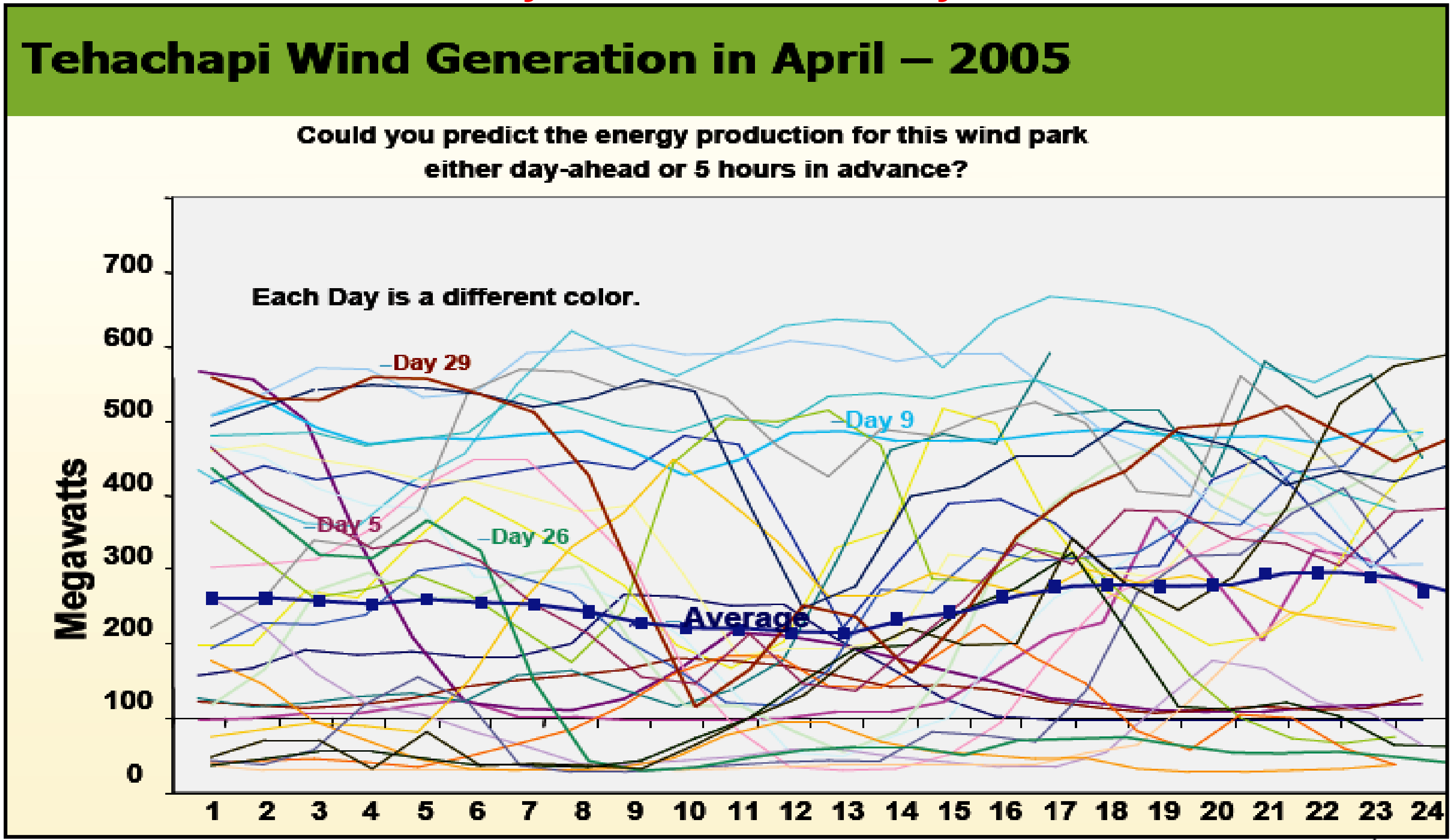


Solar Intermittency

Wind Variability and Predictability: A Challenge to Integrate into Grid

California Energy Policy Targets for Renewable Energy Penetration:

20% by 2010 & 33% by 2020



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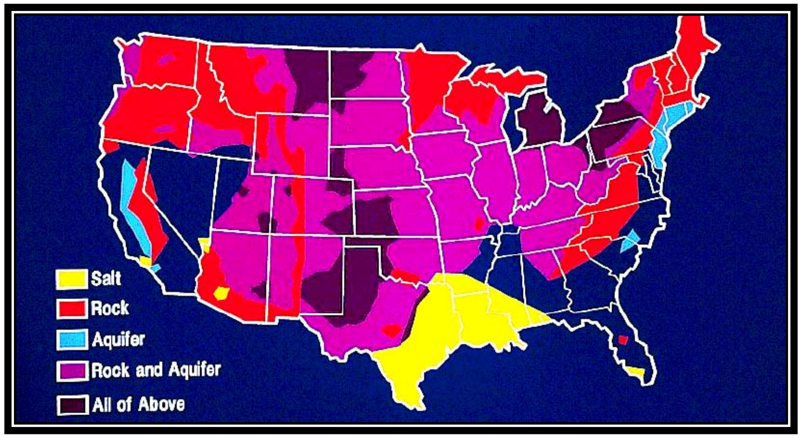
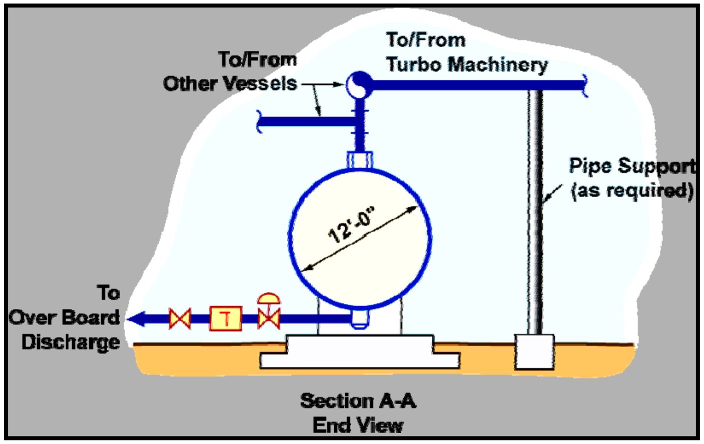
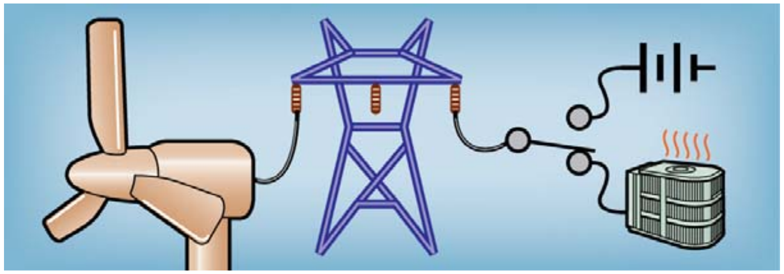
Examples: Dance Partners for Renewables



Compressed Air Potential



Above Ground CAES



Fast-Reacting Demand Response

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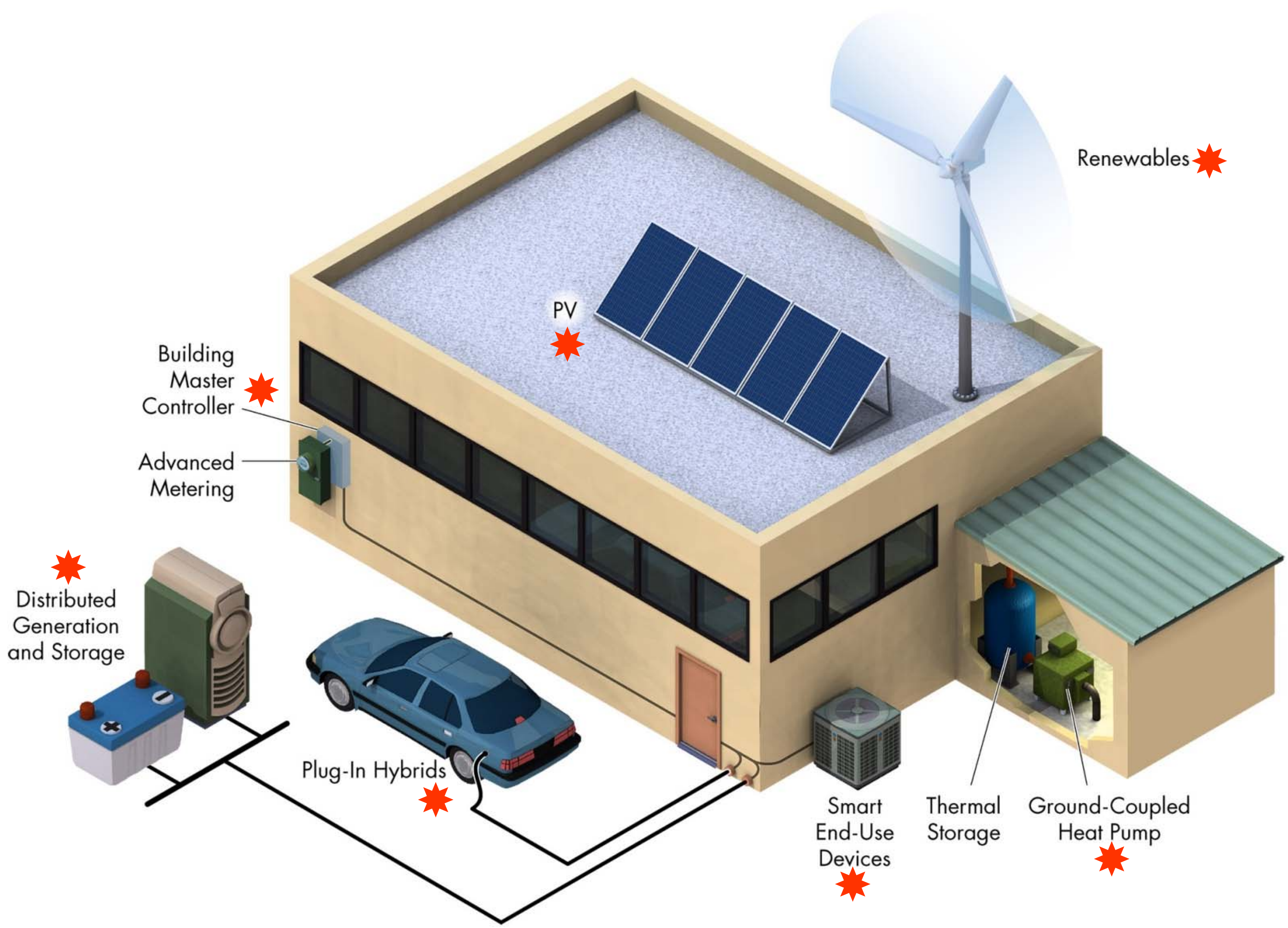
Power Electronics in Building-Level Local Energy Networks



✷ Power Electronics

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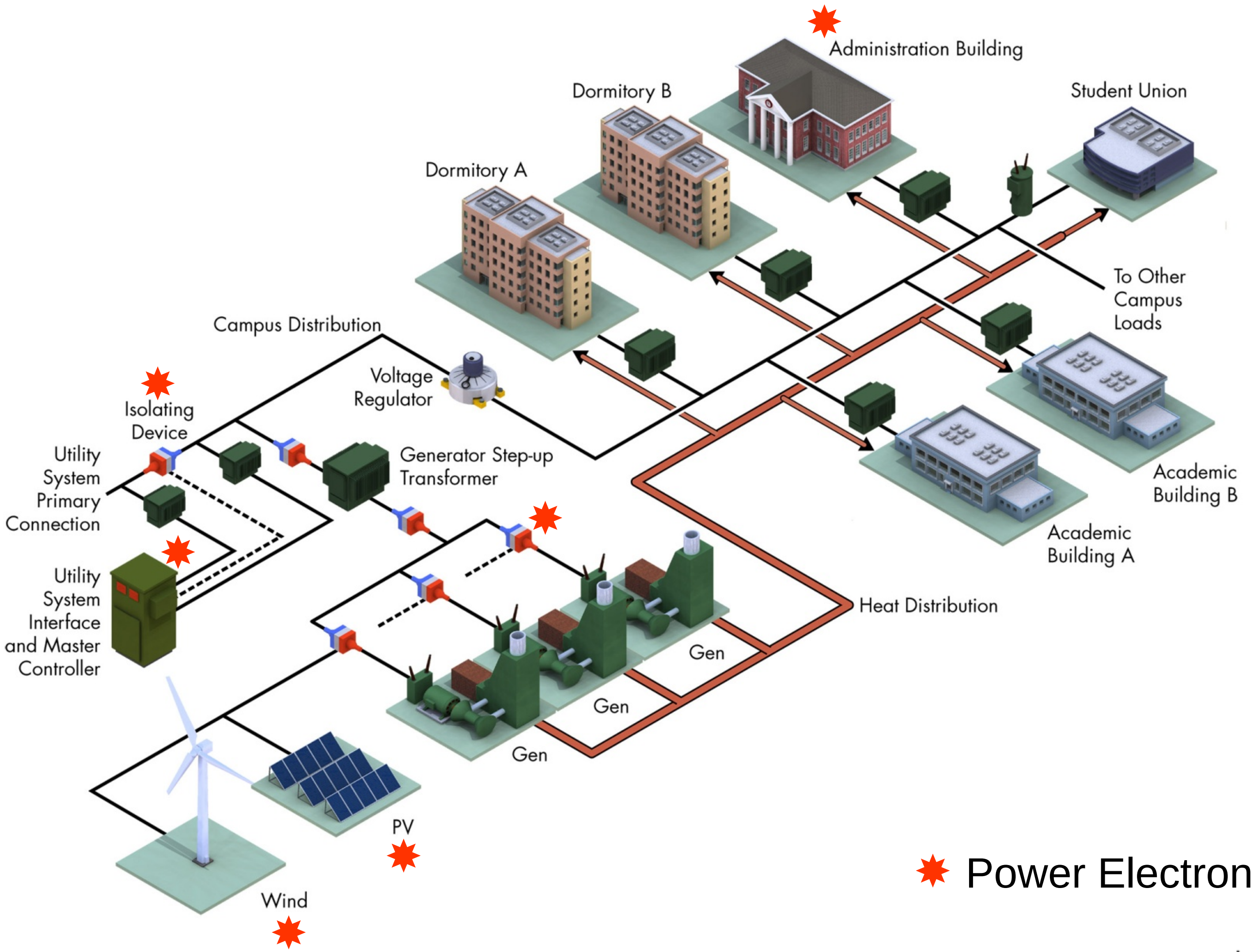
Power Electronics in Campus-Level Local Energy Networks



✸ Power Electronics

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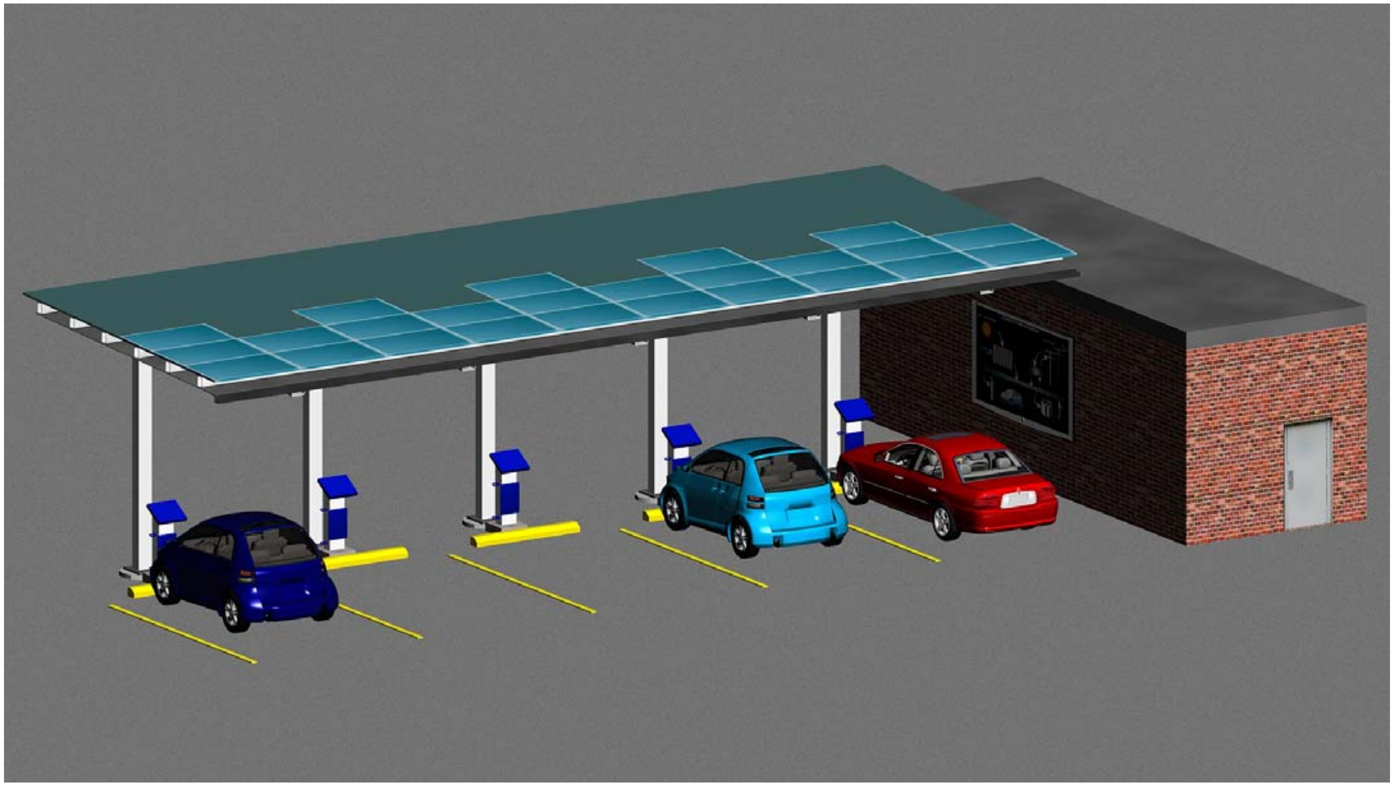
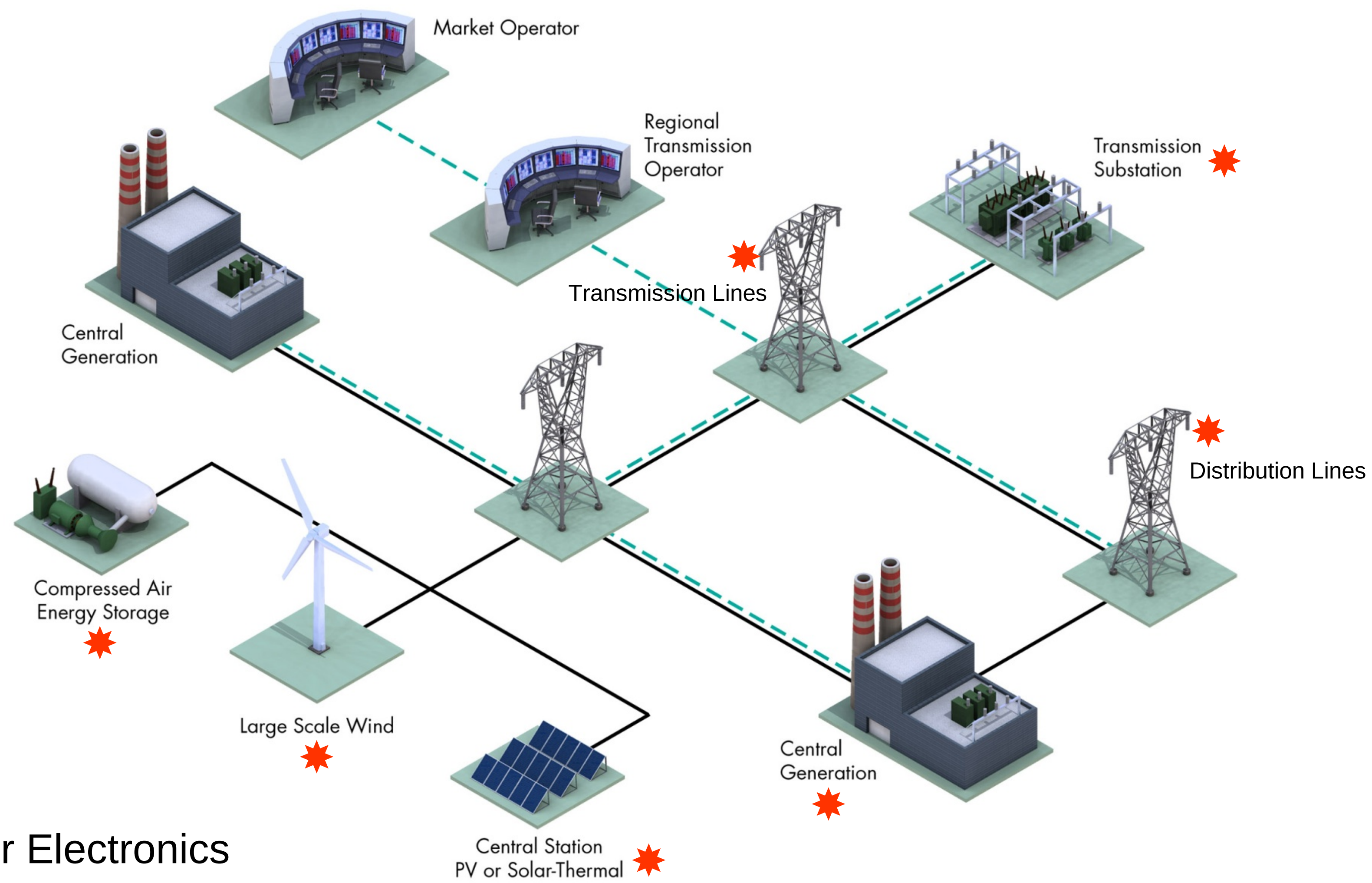
TVA/EPRI Solar Assisted EV Charging Stations

- Combines vehicle charging with solar power and battery storage along with smart grid interface
  - First of it's kind in U.S.



Power Electronics in Bulk Power Systems



✸ Power Electronics

Power Electronics will Enable the Intelligent Universal Transformer

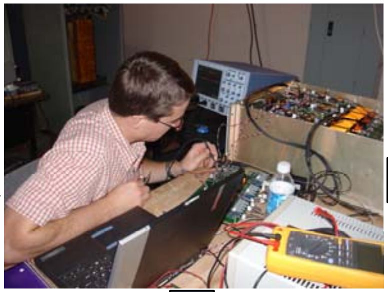
Core Technologies Needed

New State-of-the-Art Power Electronic Topology

New High-Voltage, Low-Current Power Semiconductor Device

Interoperable with Open Communication Architecture

All Solid-State Replacement for Distribution Transformers



Functions & Value

Traditional voltage stepping, plus…

New service options, such as DC

Real-time voltage regulation, sag correction, system monitoring, and other operating benefits

Other benefits: standardization, size, weight, oil elimination

Cornerstone device for advanced distribution automation (ADA)

Product Spin-offs

Emergency EHV / Recovery transformer replacement (substations)

Other power electronic applications

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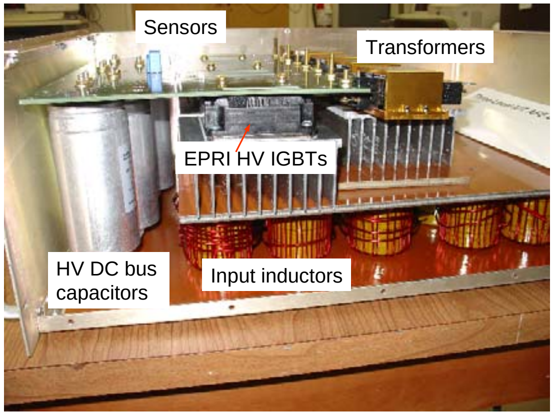
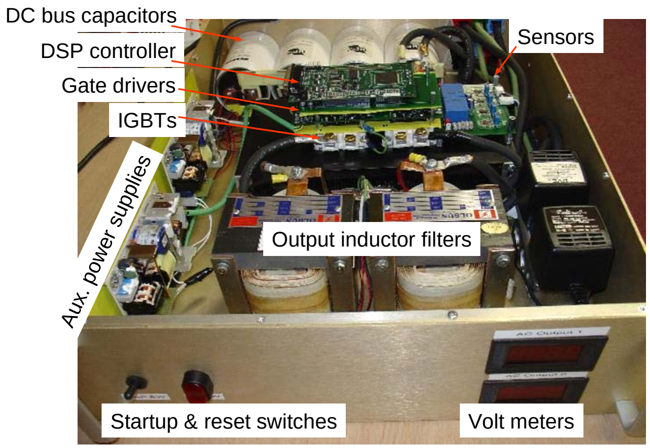
Enabling Core Technologies Needed for the IUT

- Advanced high-voltage, low-current power-electronic circuit topology

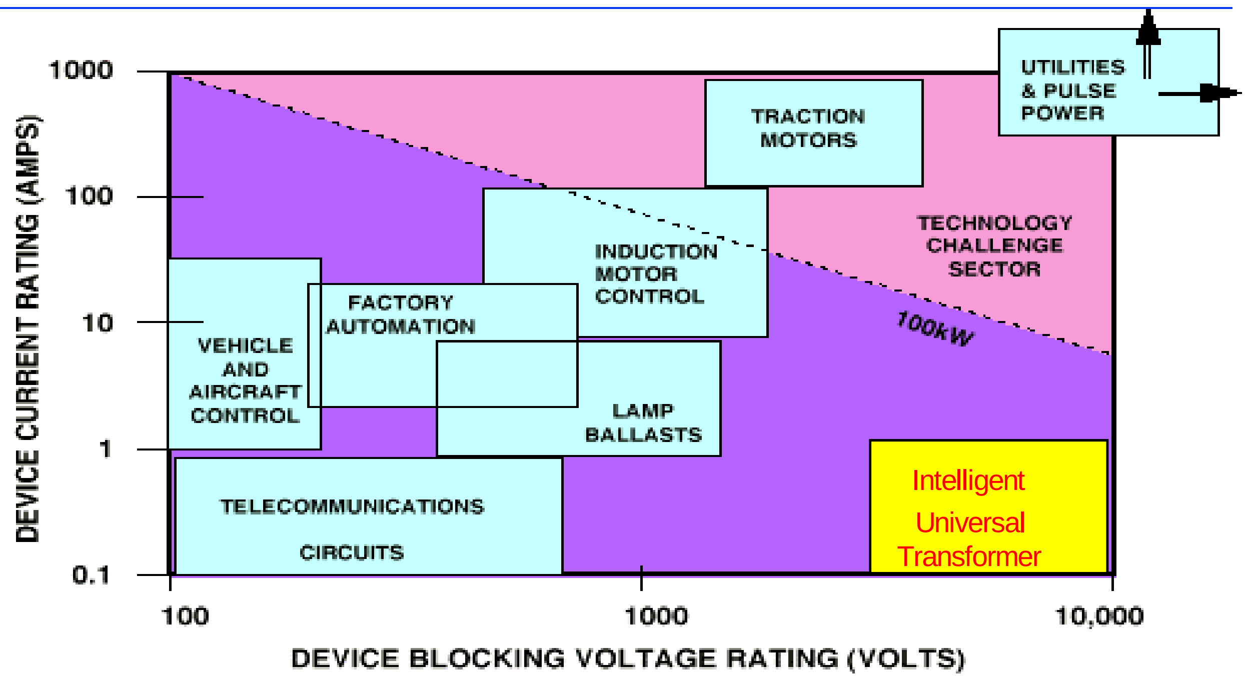




- New high-voltage, low-current power semiconductors (switches and diodes)

High-Voltage, Low-Current Power Semiconductor Devices

- A key feature of the IUT is the use of HV power electronics for interfacing to the distribution system.
- While development of HV power electronics devices such as the HV-IGBT (6.6kV) is driven by high power application (FACTS, Traction, Drives), the distribution transformer is relatively low power application.



IEEE Spectrum – January 2011 Issue
Top 11 Technologies of the Decade

1. SMART Phones
2. Social Networking
3. Voice Over IP
4. LED Lighting
5. Multi-core CPUs
6. Cloud Computing
7. Drone Aircraft
8. Planetary Rovers
9. *FACTS*
10. Digital Photography
11. Class-D Audio

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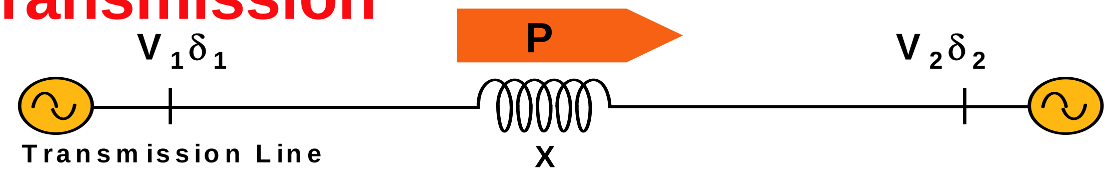
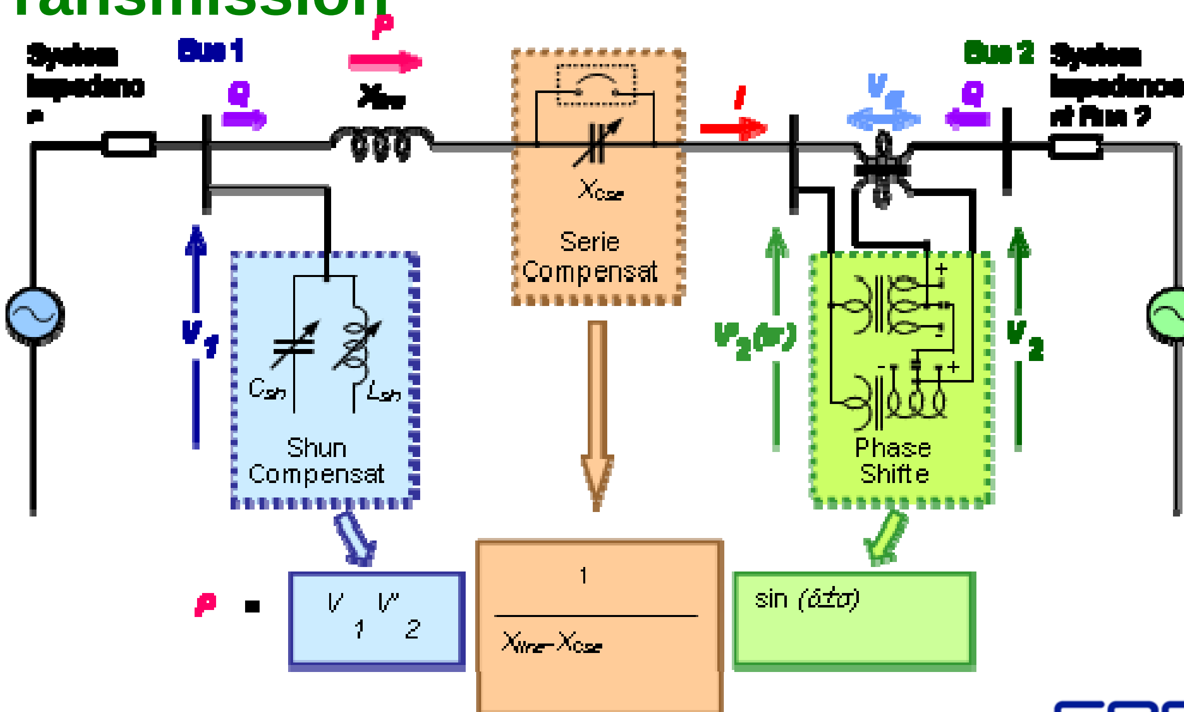
FACTS (Flexible AC Transmission Systems) – Expanding Laws of Physics

Passive Transmission



$$P = V_1 V_2 \; \frac{1}{X} \; \sin(\delta_1 - \delta_2)$$

Active Transmission



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FACTS Hardware

Traditional Technologies

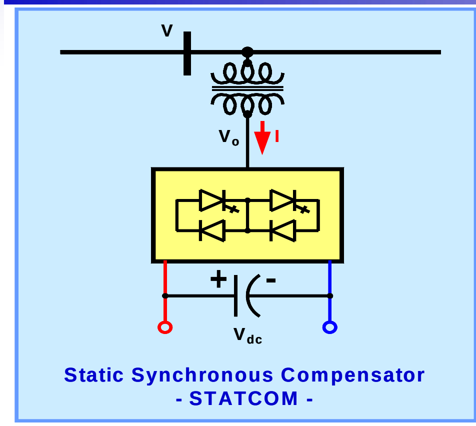
- Thyristor controlled reactors
- Thyristor switched reactors
- Thyristor switched capacitors
- Static Var Compensators (SVC)

"New" Technologies

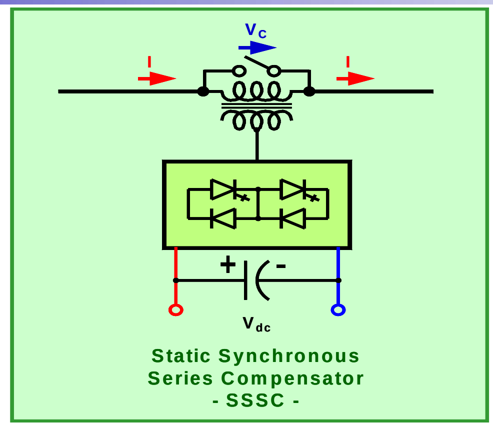
- Thyristor Controlled Series Compensation (TCSC)
- STATic synchronous COMpensator (STATCOM)
- Static Synchronous Series Compensator (SSSC)
- Unified Power Flow Controller (UPFC)
- Interphase Power Flow Controller (IPFC)

NanoMarkets Survey – Global FACTS installations from U.S. $330M this year to $775 M in 2017

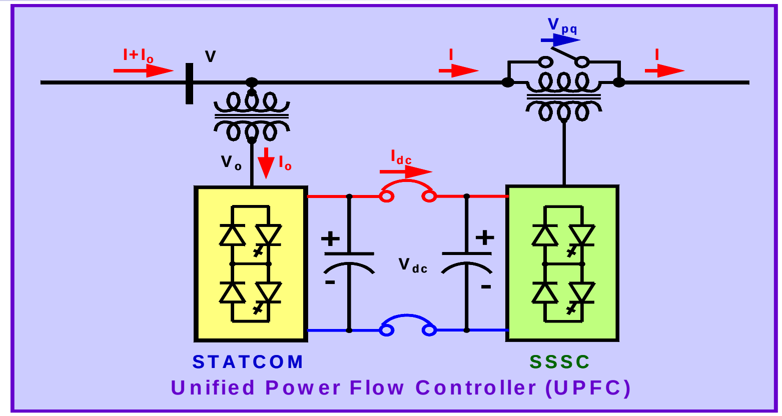
Transmission Applications of VSC



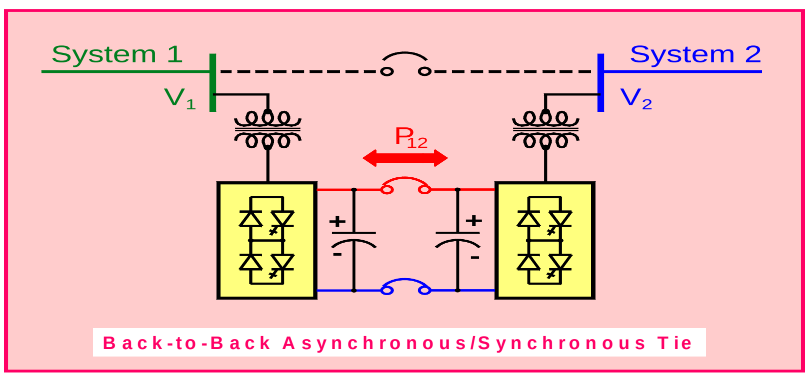
STATCOM
Voltage Control



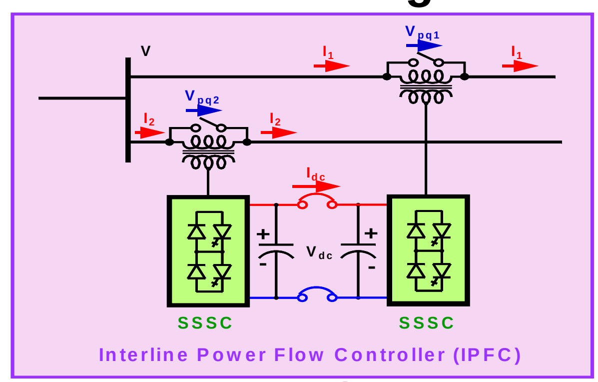
SSSC
Line Impedance Control



UPFC
Voltage, Line Impedance & Phase Angle Control

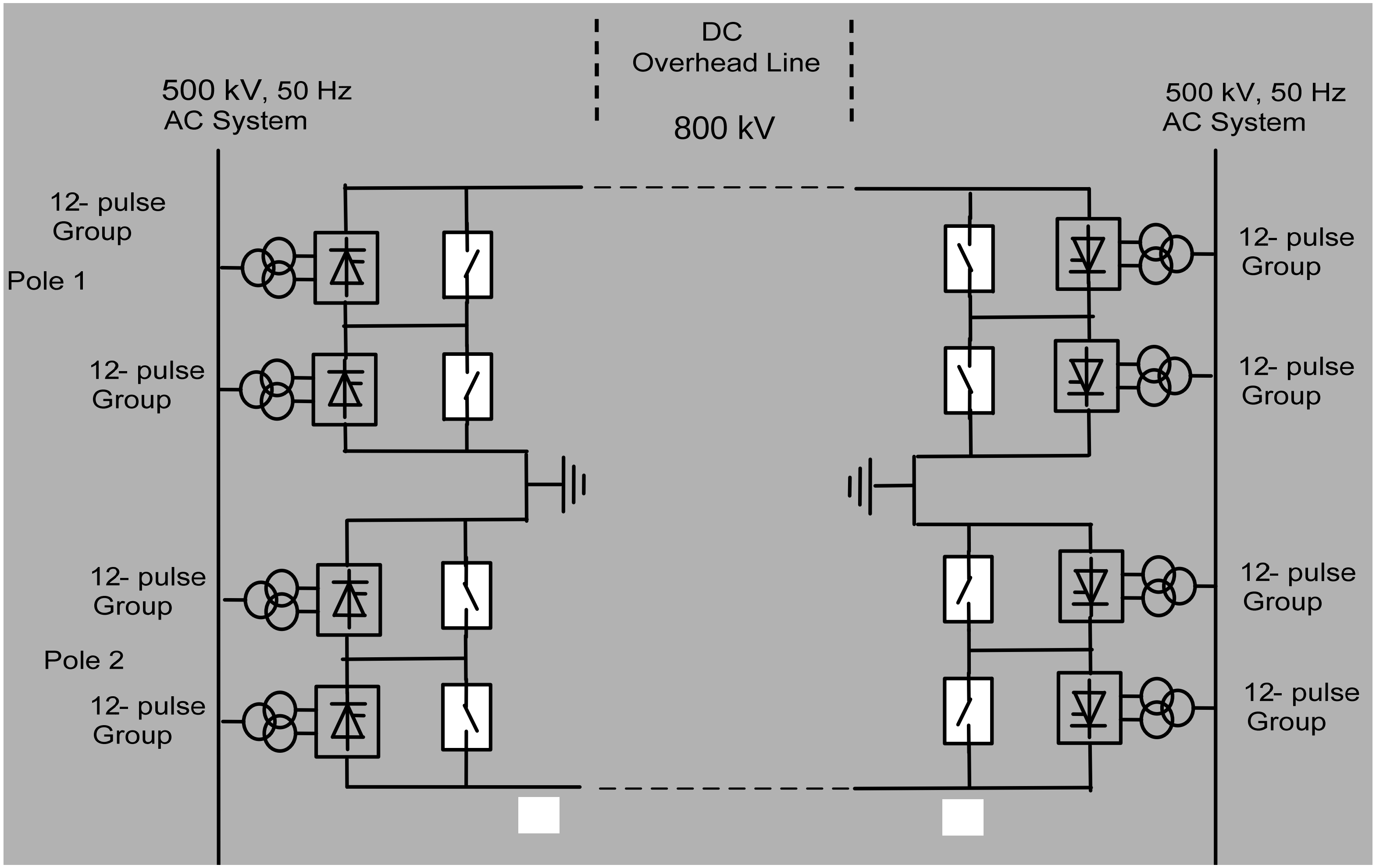


Back-to-Back
Voltage & Power Transfer Control

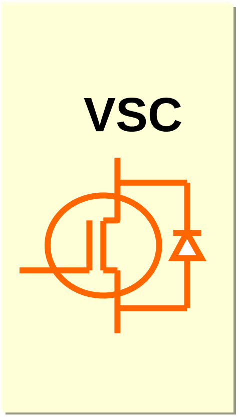


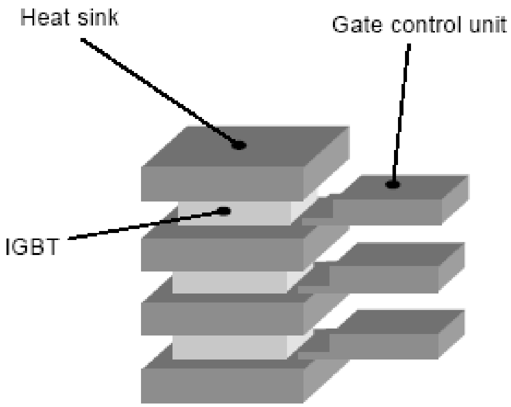
IPFC
Interline Power Exchange

Ultra HVDC Transmission
Schematic Arrangement of Converters



High Voltage Direct Current Transmission
Voltage Source Converters - Short History





- First introduced in 1997 with the 3MW, +/-10kVdc technology demonstrator at Hellsjön, Sweden
- In 2007 Cross Sound cable having a rating of 330 MW and ±150 kV dc & in 2010 Transbay Cable rated at 400 MW and +/- 200 kV
- Awarded projects not in operation yet –
  - France to Spain 320 kV, two bipoles (2x1000 MW), using underground extruded cable of 64 km (40 miles)
  - Skagerak 4 (one pole) at 500 kV, 700 MW by 2014 using DC submarine cable (140 km)+land cable(104 km) between Norway & Denmark .
- Most successful power device is IGBT which combines high impedance, low power gate input, with power handling capacity close to normal thyristors and transistors
- Vendors estimate is that the VSC technology in HVDC is ready for 1000 MW per pole. However current rating is limited by the IGBT switch off current of about 1200 Amps to 1800 Amps. And dc voltage is limited by cable at 320 kV though cable voltages are going higher.

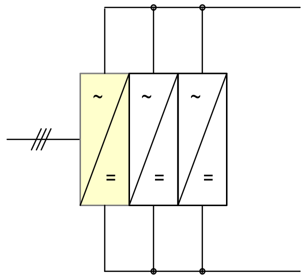
VSC

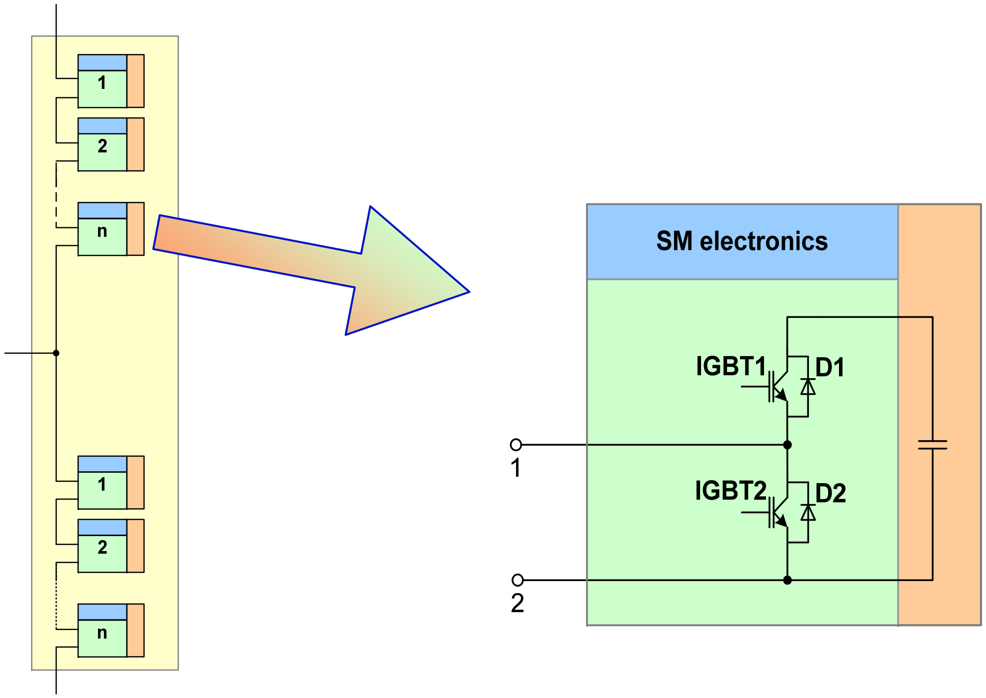
- Currently all the HVDC VSC systems are designed with solid extruded cables XLPE cables, with the exception of the Caprivi HVDC inter-connector in Namibia, where the technology is applied to an overhead line. The project is rated at 300 MW at 350 kV.

- The use of VSC is being expanded to overhead lines and dc voltage can be increased to higher levels (above 320 kV because there is no limit of dc cable voltage)

- One of the important applications of HVDC VSC converters is integration of off-shore wind farms using DC Grids.

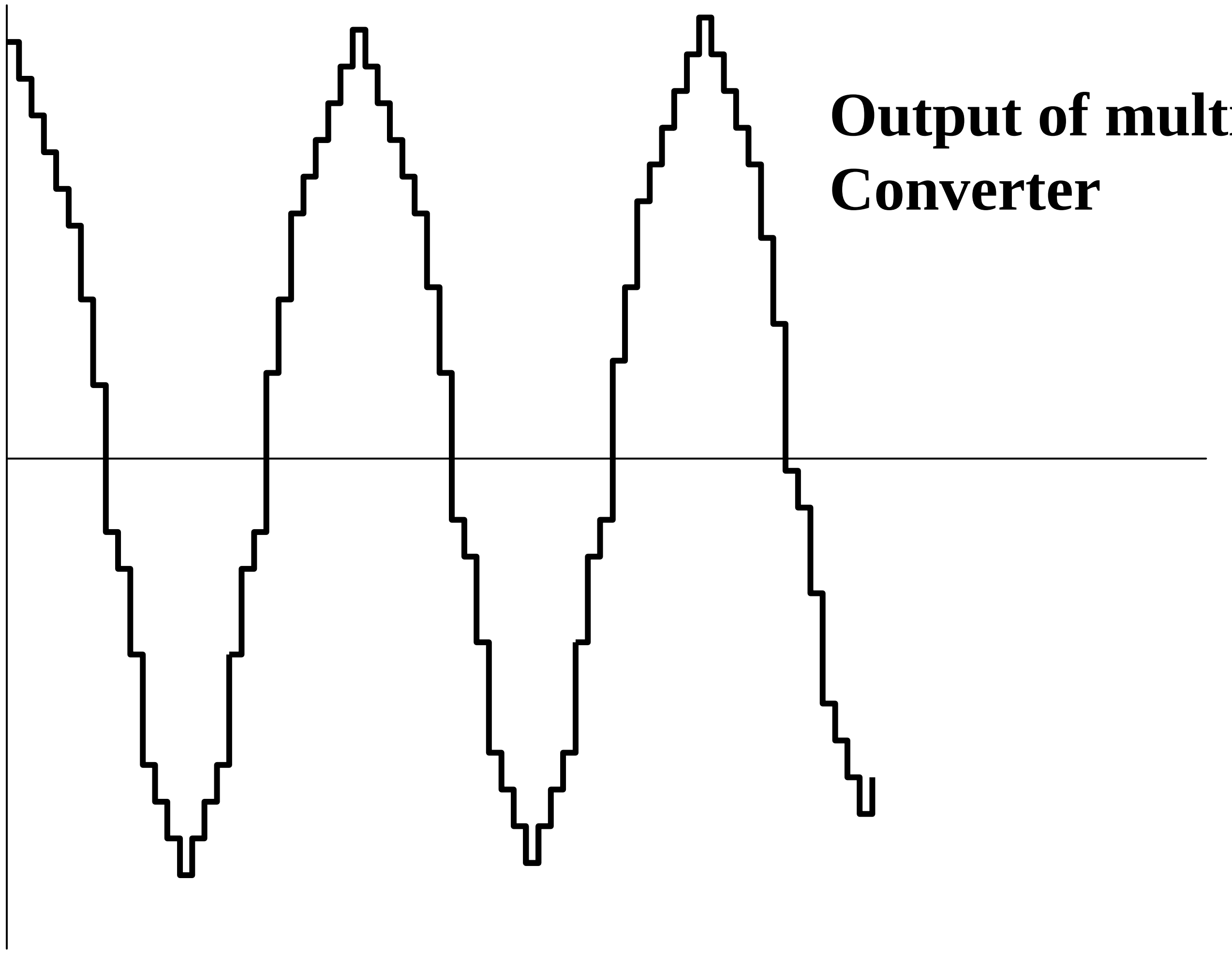
Recent new Topology (MMC)





• Modular Multi Level Converter. In this case the converter arms are constructed from identical sub-modules that are individually controlled to obtain the desired ac voltage.

VSC



Output of multi-module Converter

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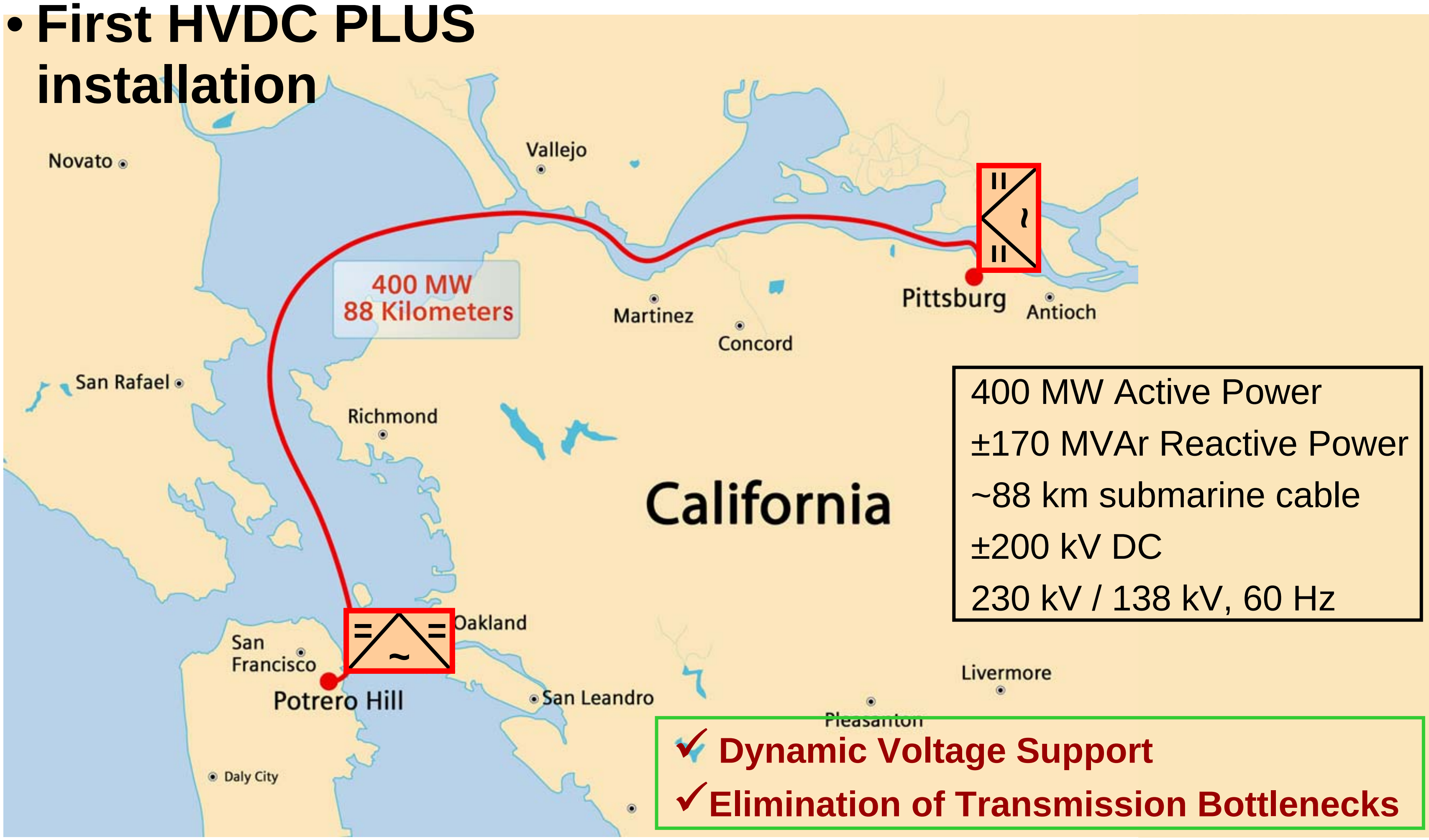
VSC vs. LCC

Function	LCC	VSC
Semi-Conductor Device	Thyristors currently 6 inch, 8.5 kV and 5000 Amps. No controlled turn off capability	IGBTs with anti-parallel free wheeling diode, with controlled turn-off capability. Current rating 4.5 to 6 kV and turn off current of 1200 Amps.
DC transmission voltage	Up to +/- 800 kV bipolar operation	Up to +/- 320 kV currently limited by HVDC cable if extruded XLPE cable is used. Up to +/- 350 kV with Overhead line, can go higher
DC power	Currently in the range of 6000 MW per bipolar system	Currently in the range of 600 to 1000 MW per pole
Reactive Power requirements	Consumes reactive power up to 60% of its rating	Does not consume any reactive power and each terminal can independently control its reactive power.
Filtering	Requires large filter banks	Requires moderate size filter banks or no filters at all.
Black start	Limited application	Capable of black start and feeding passive loads
AC system short circuit level	Critical in the design	Not critical at all

HVDC PLUS
Trans Bay Cable Project

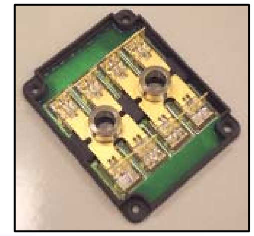
- **First HVDC PLUS installation**



400 MW Active Power
±170 MVAr Reactive Power
~88 km submarine cable
±200 kV DC
230 kV / 138 kV, 60 Hz

✓ **Dynamic Voltage Support**
✓ **Elimination of Transmission Bottlenecks**

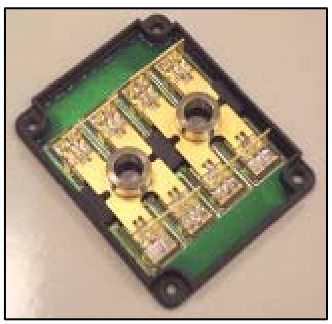
Advanced Power Electronics



Addresses fundamental research required for advances in PE materials

Silicon

- Widely available
- Low cost



Super GTO Switch
2007 R&D 100 Award

Silicon Carbide

- High operating temperature
- Lower switching losses

Silicon Carbide + Gallium Nitride

- Higher Temperature
- Higher Voltage
- Optical switching

New power electronics materials enable newer applications and benefits

Silicon-Based Converter Limitations

- Limited maximum blocking voltage
  - Solution: Series-connected devices
  - Solution: Multi-level converters
- Limited maximum switching frequency
  - Result: Larger passives
  - Solution: Multi-level converters
- Limited maximum operating temperature
  - Result: significant cooling capability needed

Disadvantages: cost, complexity, reduced reliability

Source: Grid-Connected Advanced Power Electronic Systems

Needed: Wide Bandgap Power Electronics Devices

Choices:

- Silicon Carbide (SiC)
- Gallium Nitride (GaN)
- AIN (Aluminum Nitride)
- Diamond

Only feasible options before 2030

Wide Bandgap Device Performance

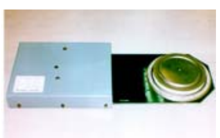
- Wide bandgap and high thermal conductivity allow high temperature operation with reduced cooling
- High saturation current velocity gives high current density
- High breakdown electric field increases maximum blocking voltage of devices
- High breakdown electric field and electron mobility give lower specific resistance for a given blocking voltage

Technical Innovations – Power Electronics

Thyristor

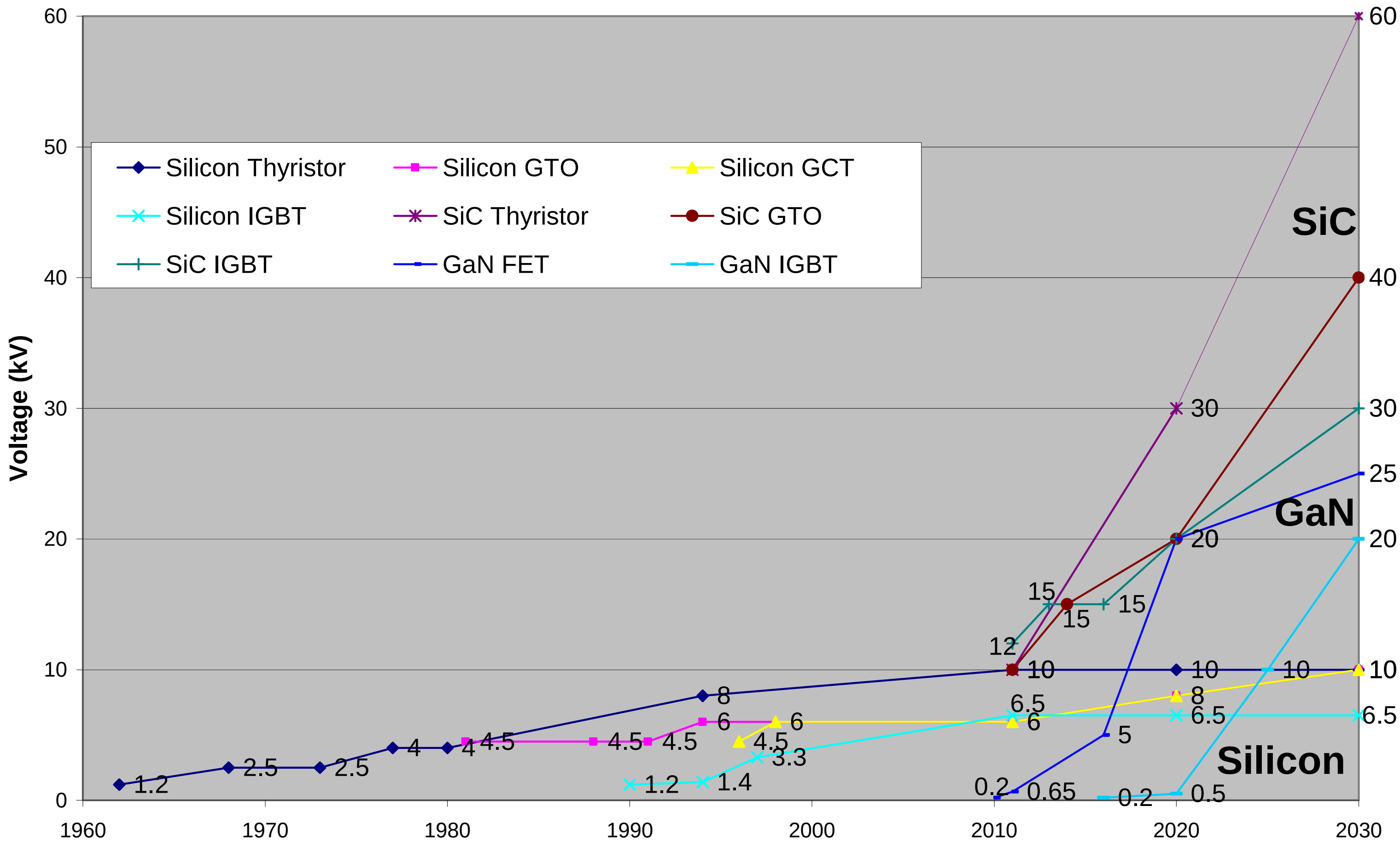
GTO

LTT



GCT

IGBT



ELECTRIC POWER RESEARCH INSTITUTE

Power Electronics
(EPRI Technical Innovation Program Overview)

The Challenge

- Increased penetration of variable generation and the growth in electric vehicles are driving industry needs to apply power electronic control to increase reliability and efficiency.
- Innovative power electronic technologies are needed to realize **SMART GRID** for real time monitoring and control

If Successful

- Technologies under investigation in this program have the potential to increase the existing asset utilization by >50% and/or reduce the equipment failures and thus increasing revenues or saving millions of dollars to the utilities

Timeline & Requirements

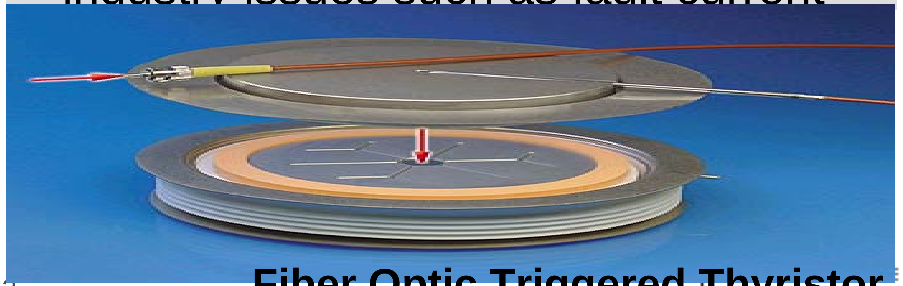
- A 7-10 year sustained TI effort is needed to enhance wide-band-gap based power electronics development and their application to the electric power industry
- Technologies are being transferred to base and supplemental programs for near-term deployment, beginning immediately

R&D Objective

- Fund innovative, game changing, higher risk ideas and technologies with high potential for performance and financial improvements to members

R&D Approach

- Leverage funding working with others such as DOE to develop wide-band-gap materials and their applications to electricity chain – generation, transmission, distribution, and end use
- Develop and demonstrate new concepts / approaches for smart transmission & distribution using power electronics to solve the present industry issues such as fault current



Fiber Optic Triggered Thyristor

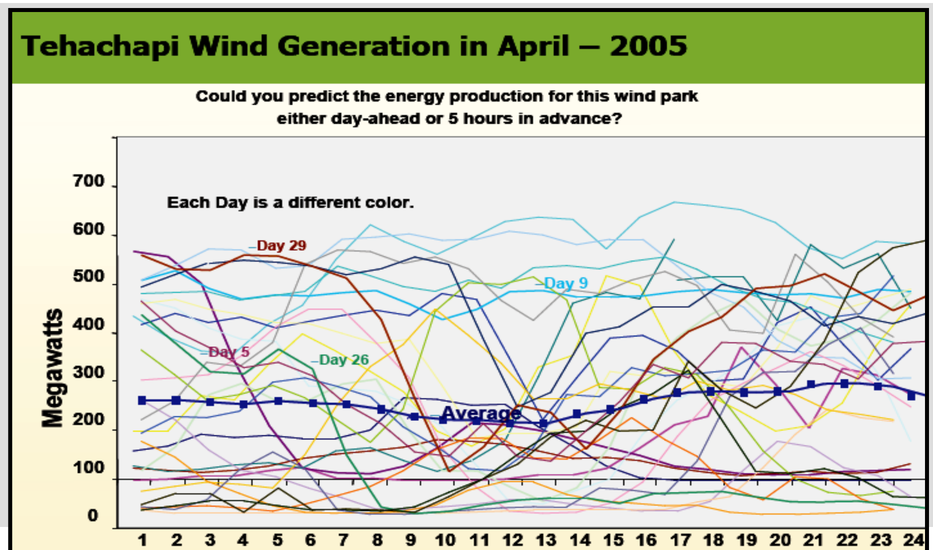
Power Electronics (Major R&D Gaps)

Power Electronics (PE) Devices

- Today's utility applications use PE devices based on silicon which are reliable and less costly compared to earlier mercury arc valves
- There is a need for high voltage and high power PE devices based on wide-band-gap materials such as SiC and GaN which can further reduce losses and increase system efficiency & reliability

Power Electronics (PE) Applications

- Smart grid needs not only smart meters but also smart PE controllers on the electric grid.
- Fundamental breakthroughs in PE applications are needed to develop solid state counterparts of most of the power equipment such as transformers, breakers, and fault current limiters so that new demands like renewable integration and electric vehicle charging are reliably met.



Research Objectives & Industry Value

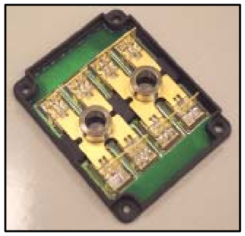
Objectives

- Advance the development of wide-band-gap PE materials such as SiC and GaN in terms of high power ratings so that they can be widely adopted for electric power applications
- Develop economic and technical solutions based on power electronics to address the challenges faced by EPRI members while integrating renewable resources and providing electric vehicle charging stations.
- Develop power electronic based controllers for SMART GRID implementation.
- Specific research focus:
  - Development of optically triggered GaN devices and other wide-band-gap materials
  - Development of novel technologies such as Solid State Fault Current Limiter using Silicon as well as wide-band-gap materials
- Technology breakthroughs resulting from the research will lead to pilot applications/demo projects supported by PDU Sector supplemental and base activities (e.g. EPRI Substations program offering the Solid State Fault Current Limiter project as a supplemental project starting 2012)

Value

- Research under this program can contribute to advanced power electronics technology which can enable a fully functional and controllable power system resulting in a ***<u>potential value in excess of $1 trillion over next 20 years.</u>***
- This program is designed to develop new power electronic devices / systems / controllers / applications that will:
  - Reduce power system losses and increase efficiency and reliability and thus reduce energy cost.
  - Make power grid more controllable and allow more power throughput
  - Allow increased penetration of renewables and electric vehicle charging stations
  - Increase the use of power electronics for the entire electric infrastructure - all the way from generation to the load centers.
- Technology evaluation studies will provide new approaches to evaluate technical and economic trade-offs for various power electronic and non-power electronic options, as well as solutions for meeting new power system demands.

Power Electronics Materials Current Projects

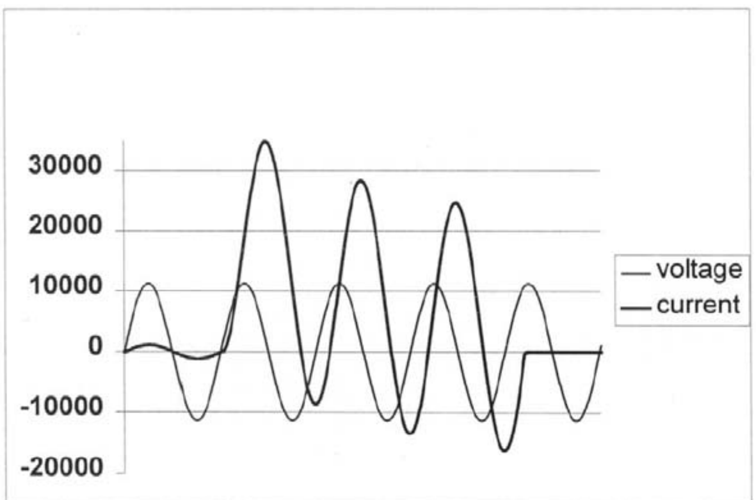


- Development of Super GTO-based Solid-State Fault Current Limiter
- Development of SiC Power Modules and Components
- Optically-Gated GaN Power Semiconductors
- Fundamental Power Electronics through GRid-connected Advanced Power Electronics (GRAPES) Consortium
- Development of EPRI Strategy for Power Electronics

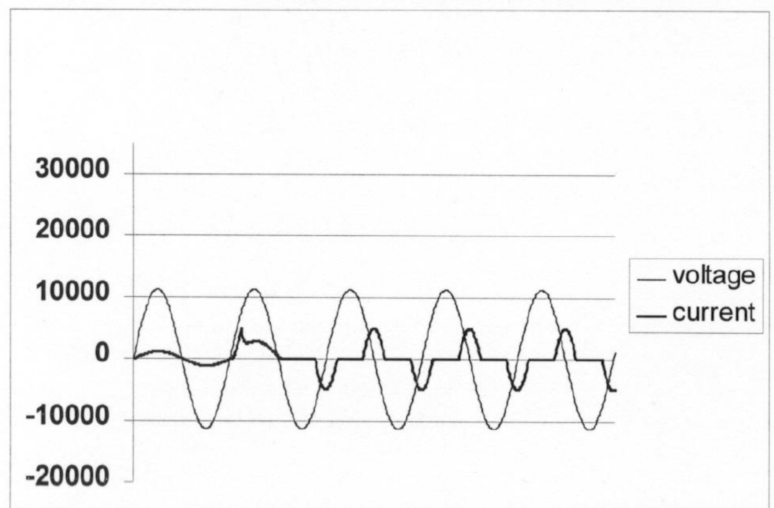
37.010 Solid State Fault Current Limiter

- Solid state devices – Improved performance, reduced cost
- Instantaneous (sub-cycle) current limiting

Single Line to Ground Fault
Conventional Breaker



Single Line to Ground Fault
SSCL with Current Limiting



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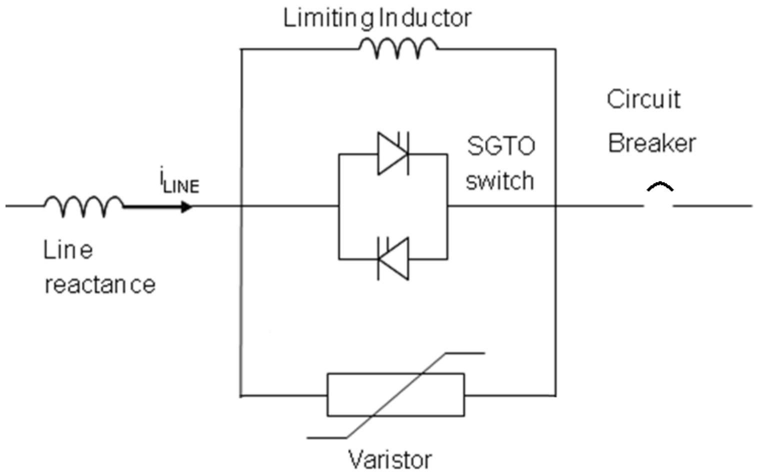
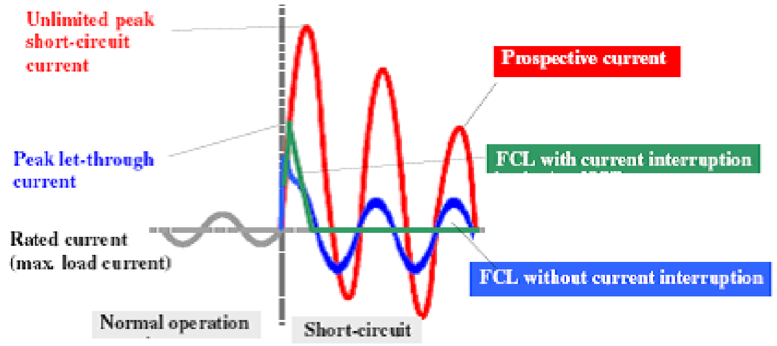
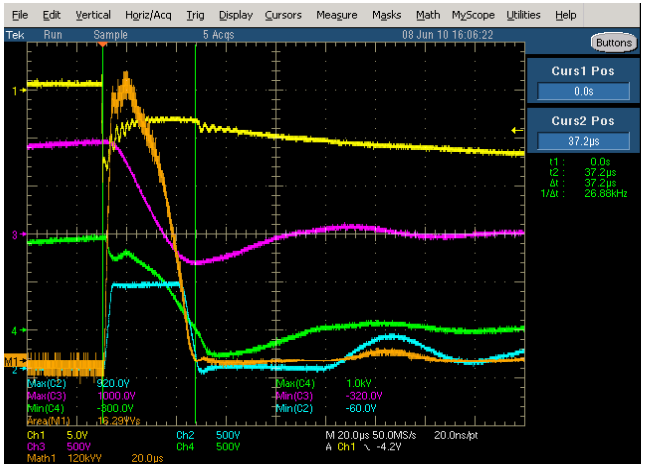
SSCL Operational Concept

- 15kV, 1200 Amp Distribution Class SSCL
- Current passes through SGTO modules in normal operation
- Drive modules off when detect fault event
- 2kV, 1000A turn off per block. Stack in series / parallel for increased voltage / current.
- Tune inductors for let-through current

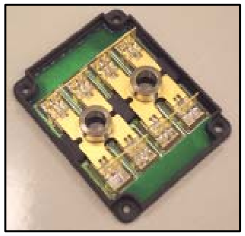






CV

GRid-connected Advanced Power Electronics (GRAPES) Consortium



What: Join basic research consortium to develop advanced power electronics materials and devices

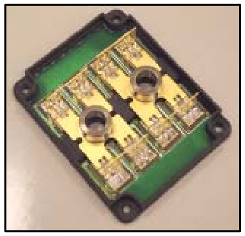
Why: Leverage research funding for basic science

How: Work with utilities (AEP, ConEd, Entergy, Southern), government (DOE, ORNL), and industry (GE, Eaton) to address basic research needs in power electronics

Status: Several new technologies in progress, including silicon carbide, gallium nitride

What's Next: Continue involvement into 2011 & beyond

Embedded PV Power Electronics



What: Develop power electronics approaches that are embedded into wafers, rather than discrete approach

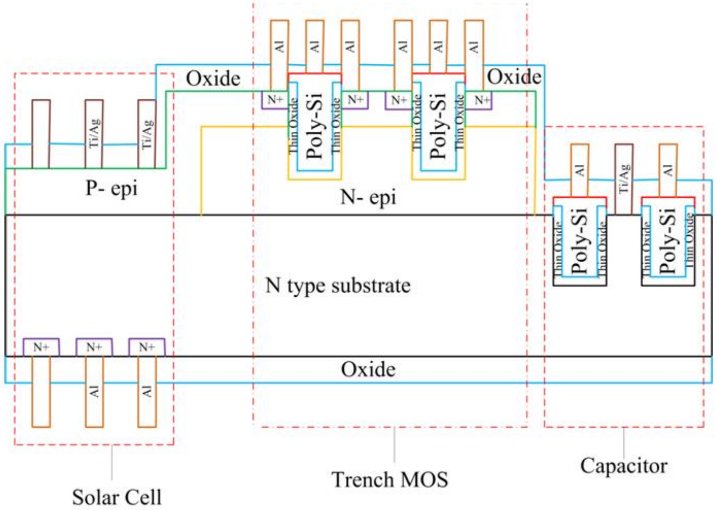
Why: Reduce cost of production and integration; improve safety, reliability, and operation

How: Electronics constructed directly into the substrate of photovoltaic silicon

Technical Challenges:
Advanced photolithography process to work with solar-grade silicon; N-type vs. P-type substrates; cost and durability

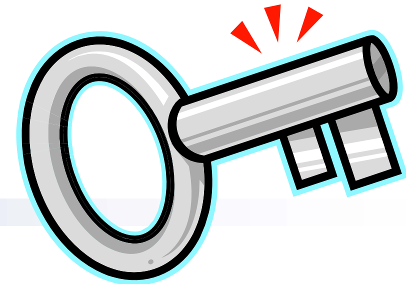
Status: Presently initiating project

What's Next: Initial investigation, testing



Others Are Interested Too!

In Conclusion



Power Electronics is key for:

- Future SMART Electric Grid
- Integration of renewables such as wind and solar with interconnections to the main grid
- Reducing system losses and increase efficiency
- Reducing carbon footprint
- Enhancing quality of life

Together…Shaping the Future of Electricity