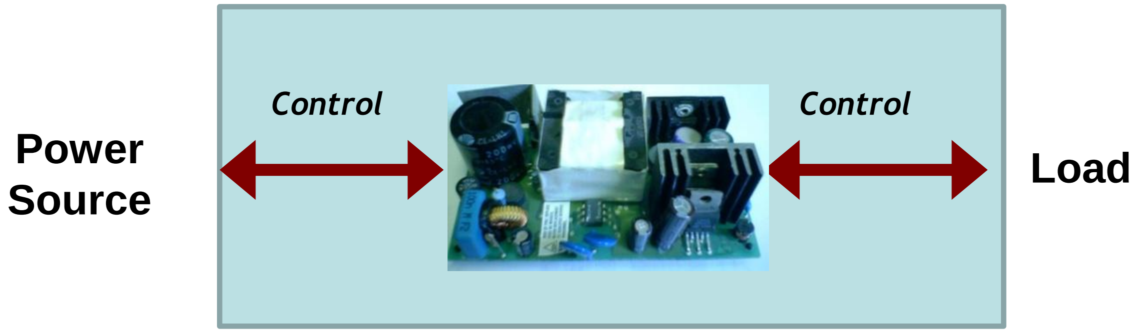
Power Electronics

Rajeev Ram, Program Director,
ARPA-E

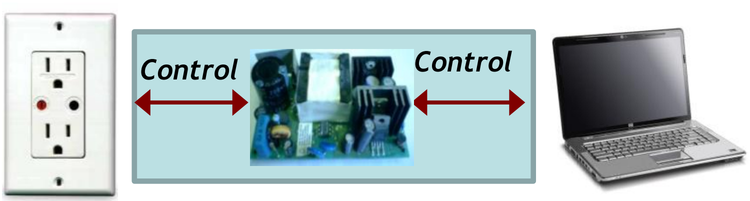
2010: 30% of all electric power flows through power electronics
2030: 80% of all electric power will flow through power electronics

What is Power Electronics?

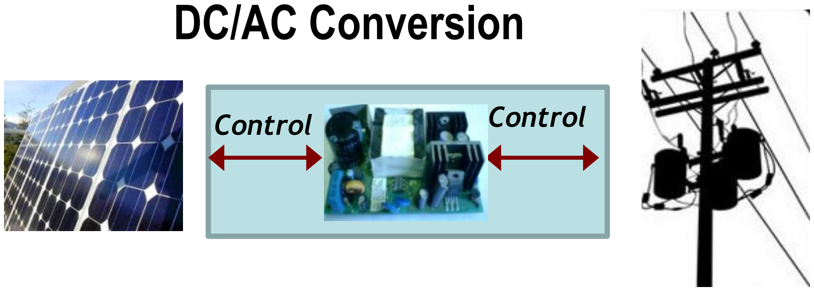
"The task of power electronics is to process and control the flow of electric energy by supplying voltages and currents in a form that is optimally suited to the load."



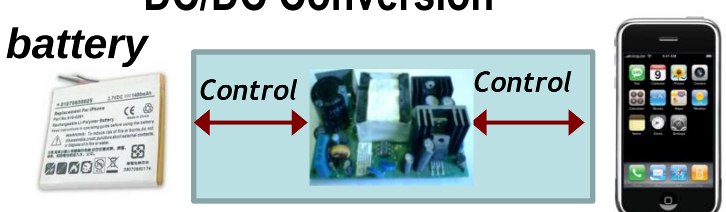
AC/DC Conversion



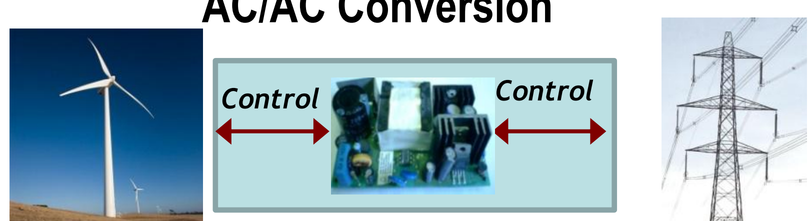
DC/AC Conversion



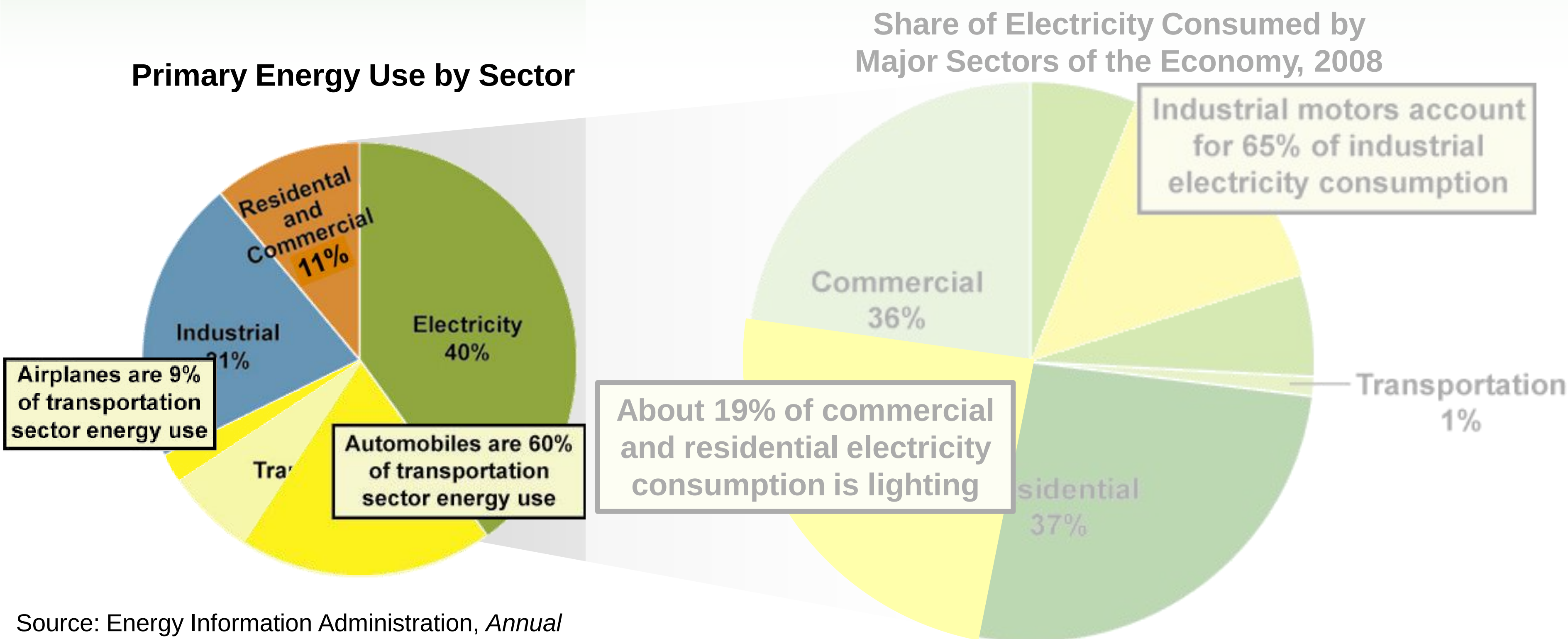
DC/DC Conversion



AC/AC Conversion



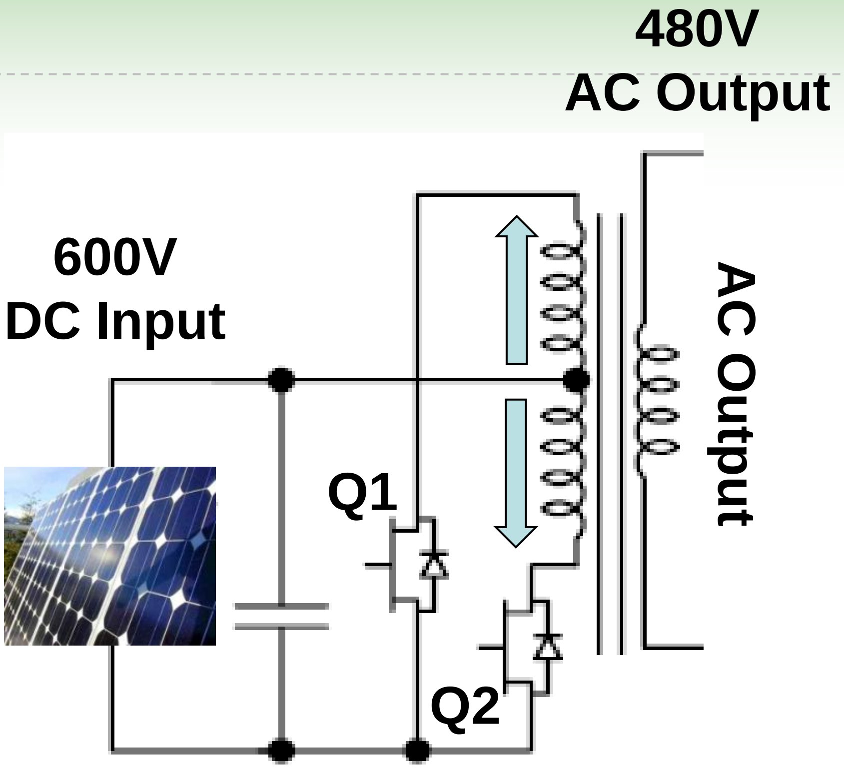
Agile Delivery of Electrical Power Technology (ADEPT)

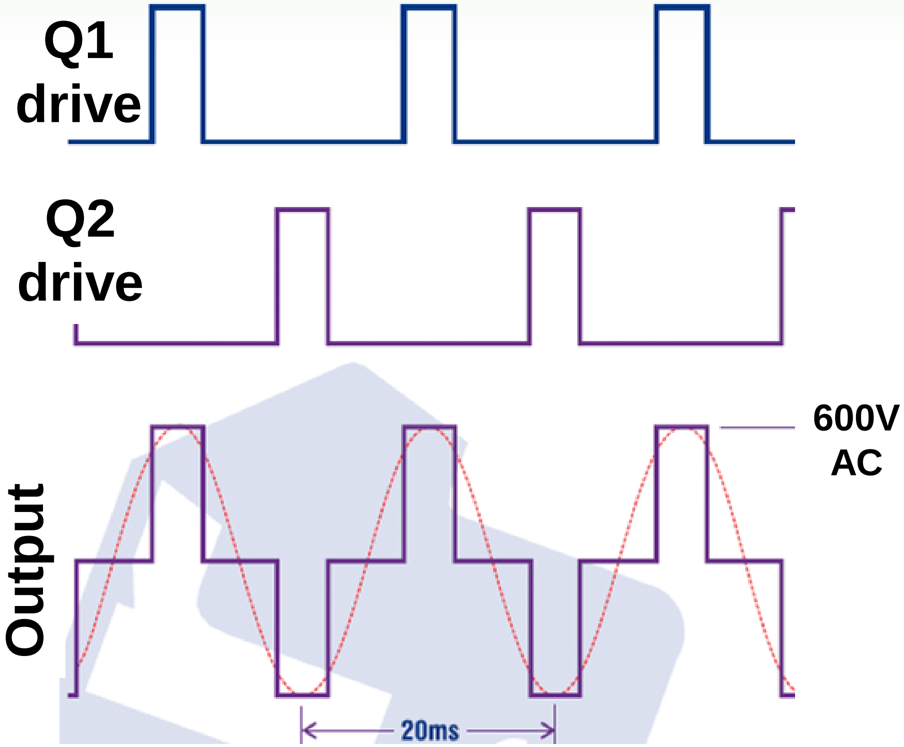


Source: Energy Information Administration, *Annual Energy Review 2008*

- **30-50% of cost for dimmable LED luminaire**
- **20% energy loss in industrial motors due to mechanical throttling**
- **20% of material cost for HEV is power electronics**
- **‘No bleed’ More Electric Airplanes give 41% reduction in non-thrust power**

One-slide Tutorial





- Switches convert DC to Distorted AC
- Inductors (L) and Capacitors (C) clean AC
- Transformer changes AC voltage level

Magnetics and Cost
– largest, most expensive part of the converter

>92% Dimmable LED Driver (comm. 37-50% of luminaire cost)

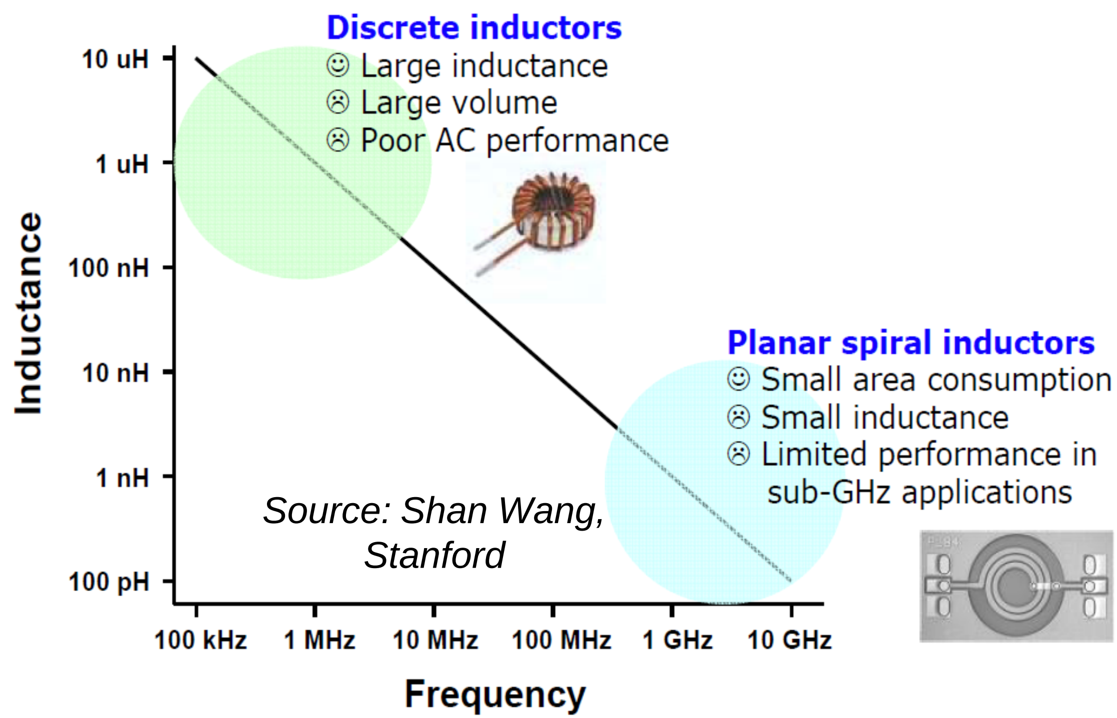
AC/DC Converter

Magnetics

1MW Photovoltaic Inverter ($0.2/W)

40%
Magnetics

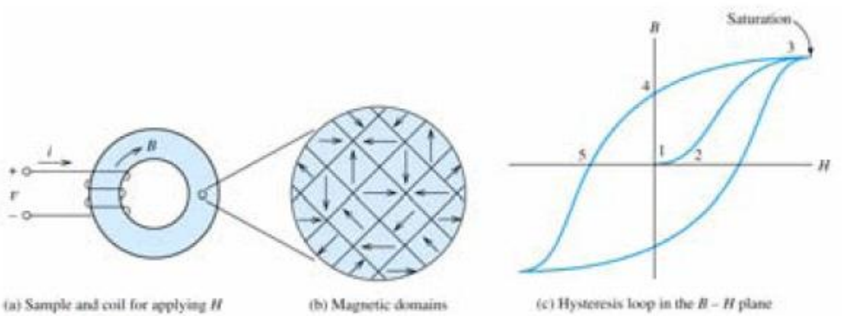
$Z = j\omega L$



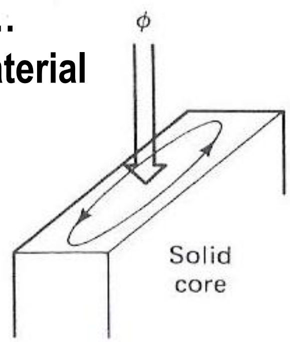
Limits to Scaling with Frequency & Power

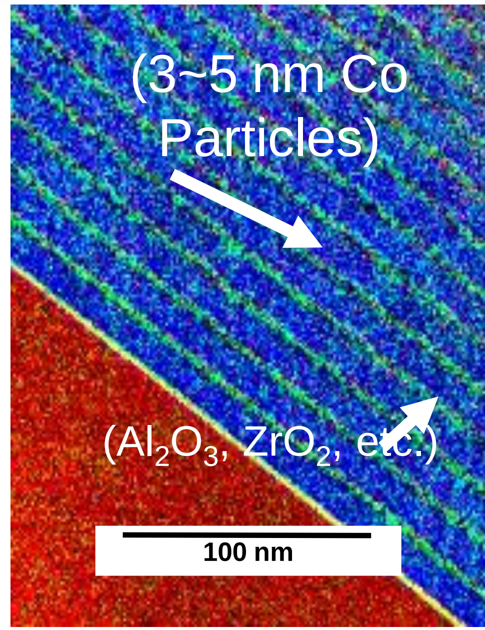
At hi-frequency, Loss Increases

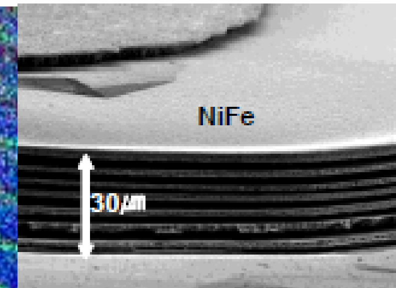
Energy lost in rotating recalcitrant domains…
requires soft magnets, low coercive fields

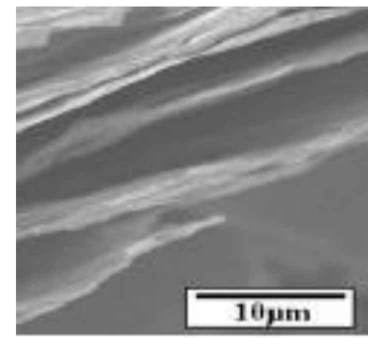


Energy lost induced electrical current…
requires electrically insulating material (>1 mOhm.cm)









- Ferromagnetic coupled particles or 2D flakes/laminates
- High resistivity (300 ~ 600 μΩ·cm) controls eddy-current loss

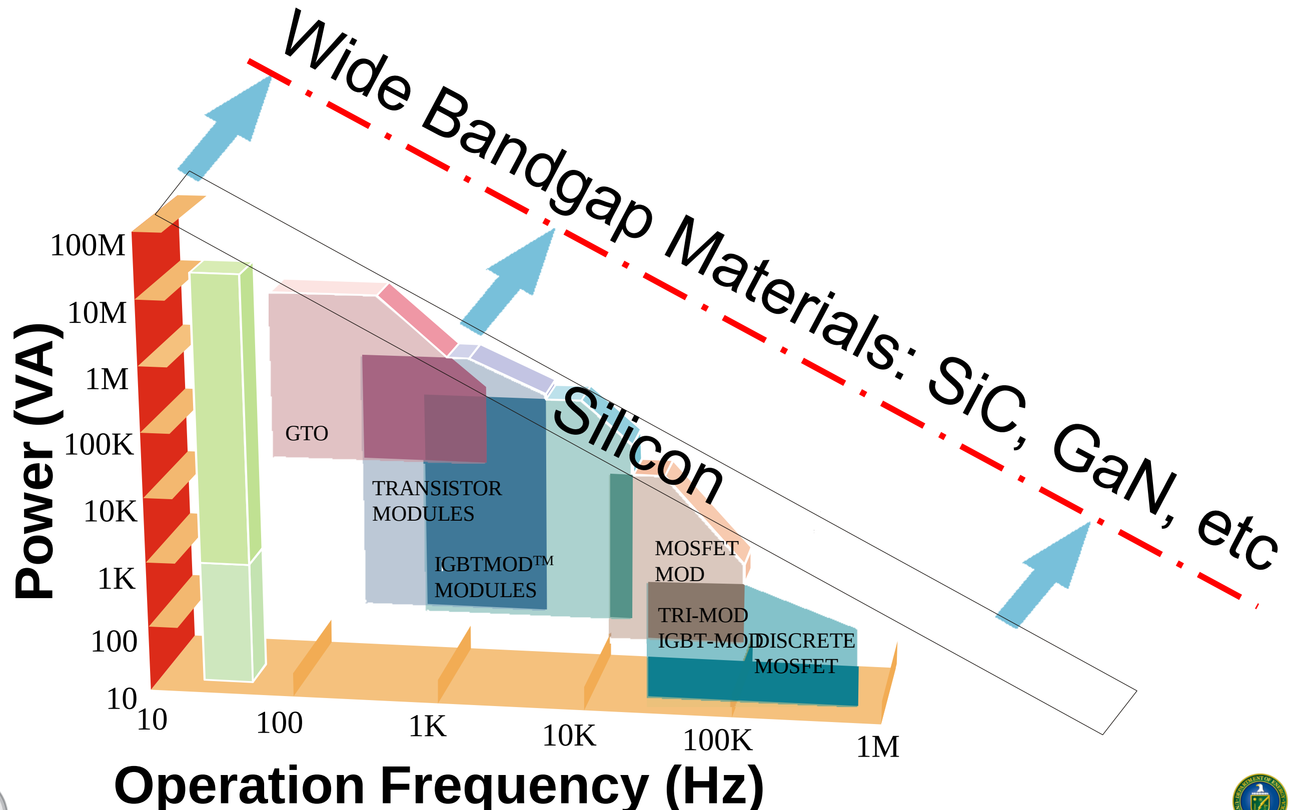
Miniature (Fast) Magnetics Needs Fast Switches

Bandgap (energy to 'free electron') increases

Breakdown voltage increases

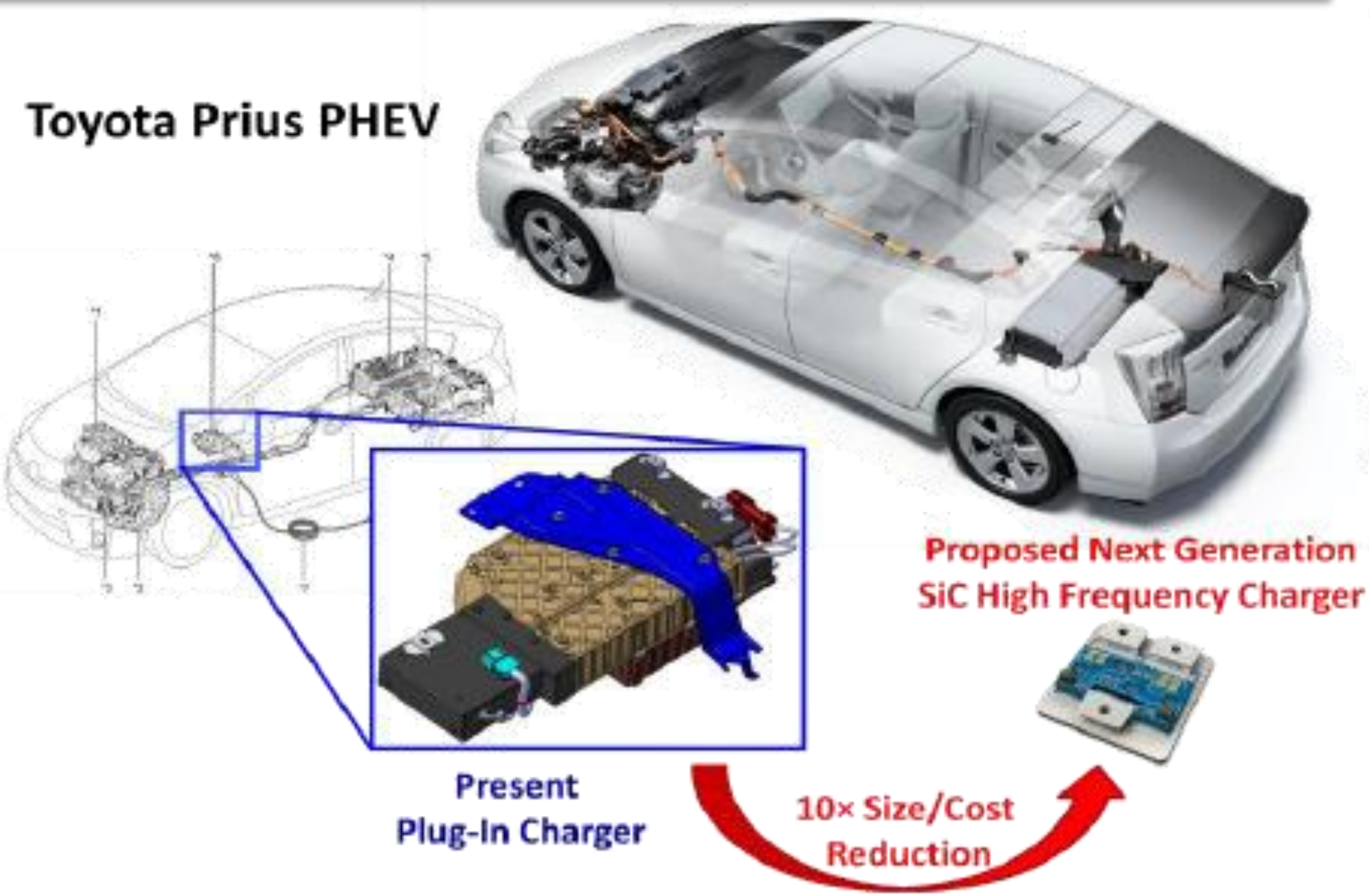
Drift region can be decreased

- Reduces transit time
- Increases frequency
- Reduces on-resistance



ADEPT Project Example: SiC IC Bi-Directional Battery Charger

Arkansas Electric Power International (APEI): $3.9 M, 3 years

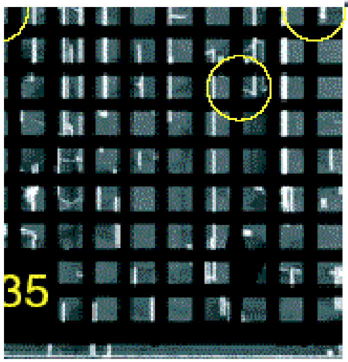


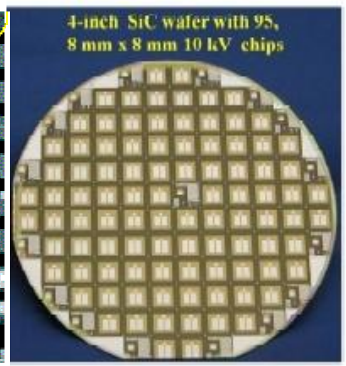
600V SiC IC with full CAD design environment

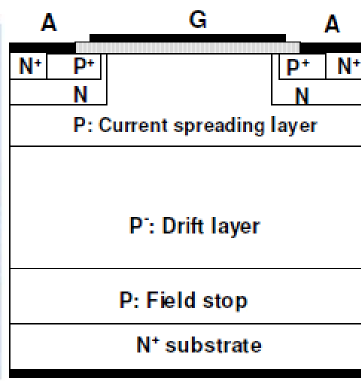
High temperature, air cooled packaged

ADEPT Project Example: 20kV & 0.4 MW Transistors for Solid-State Substations

Cree Inc.: $5.2 M, 2 years



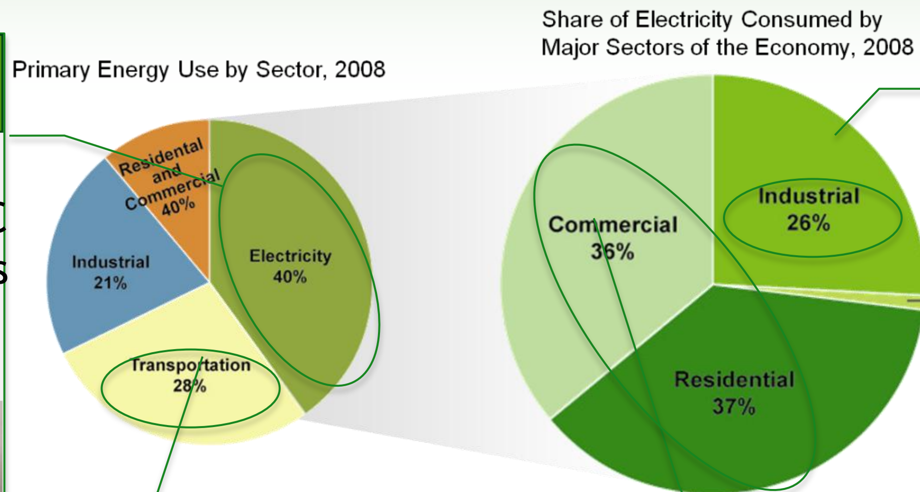




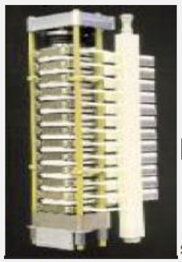
Improved SiC IGBTs
High voltage (20kV)
98% Efficient
50 kHz
Improved reliability & lifetime
High device yields

Improved technologies
50% reduction in total power conversion losses
100X reduction in high power transformer weight

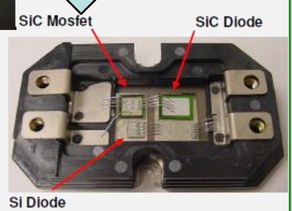
ARPA-E Supported Power Electronics Innovation



Distribution & Transmission

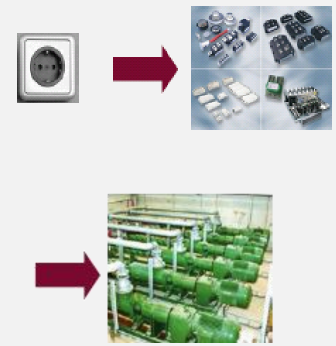


>13 kV, 50kHz SiC transistors



Industrial

Inverter drives motor



Lighting

Existing 25 W AC-DC SSL Driver

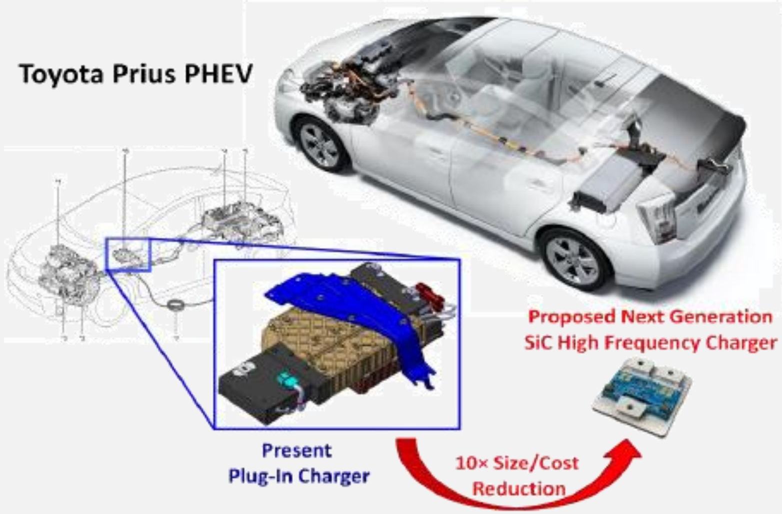
EMI Filter

Power Stage:

130 mm x 45 mm x 25 mm

300X reduction in power stage volume

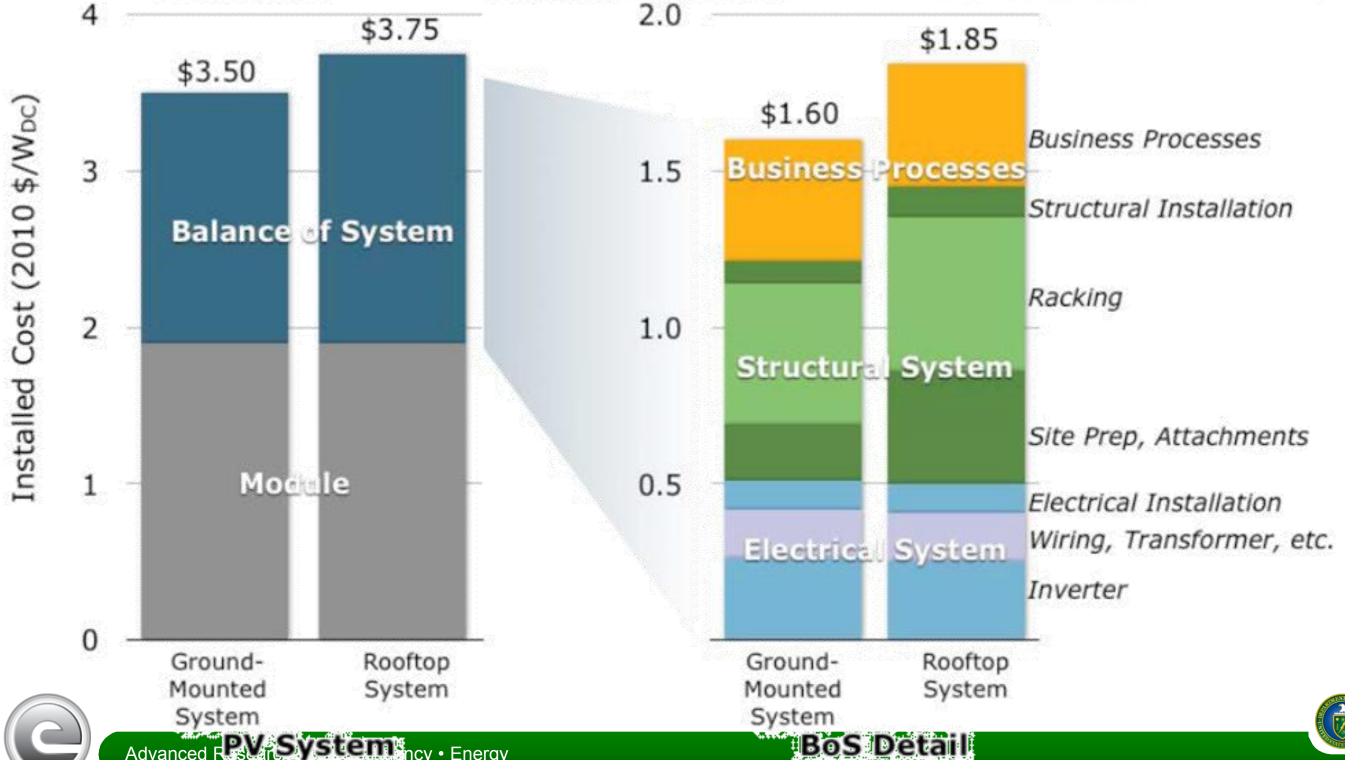
Automotive



Solar ADEPT

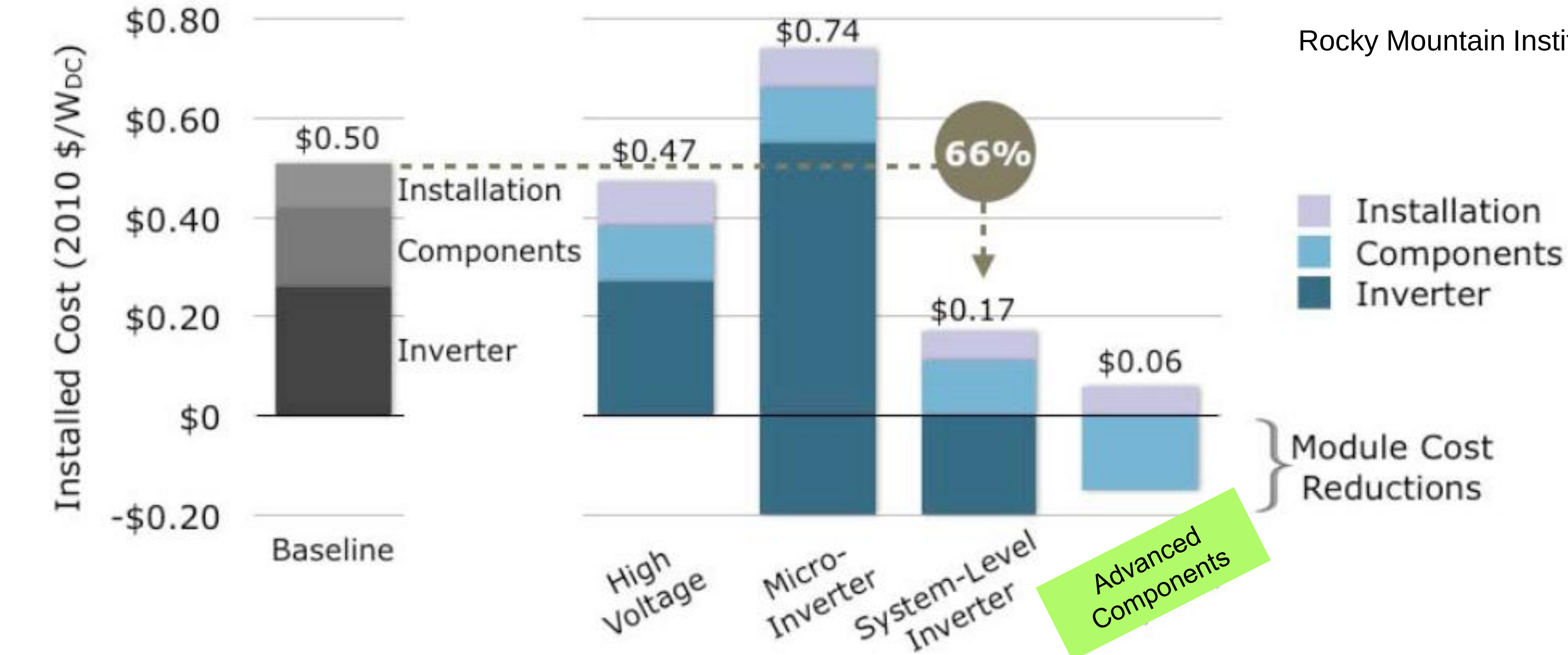
Agile Delivery of Electrical Power Technologies

Balance of System



Source: Rocky Mountain Institute

Power Electronics Additionality for BOS

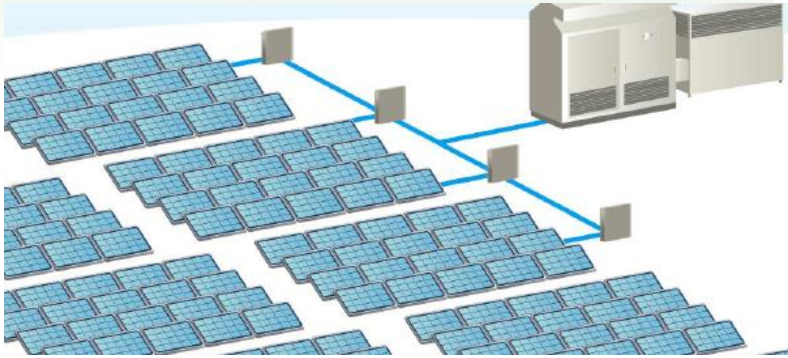


Rocky Mountain Institute, 2010

Reducing Module and BoS Costs

- Cell, Module electronics compensates materials variability
- Streamlined engineering and installation
- AC modules
- Lightweight central inverters

UTILITY SCALE SOLAR



Goal: Consolidate the number of inverters
20 MW installation will have
20 x 1MW inverters

Barrier: Longer wiring, limited by loss

Approach: Higher DC bus voltages
DC/DC boost converters at module string (w/ MPPT)

Goal: Improve power quality while delivering cost
high frequency electronics - improved EMI, reduced harmonics

Barrier: - Low loss, high-voltage switches and magnetics
- Utility 'ownership' of line frequency transformer

Approach: Wide-bandgap switches with advanced magnetic materials

COMMERCIAL ROOFTOP SOLAR

Goal: Module level MPPT (>98%)

Barrier: Cost & reliability

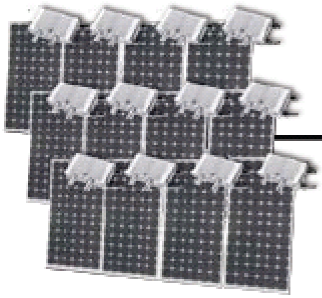
Approach: DC/DC or DC/AC module integrated converters

Goal: Light weight, roof-top inverter [controversial]
99%, 200-500kW, eliminates DC conduit and wiring

Barrier: High-frequency switches and magnetics
AC switches (for current drive architectures)

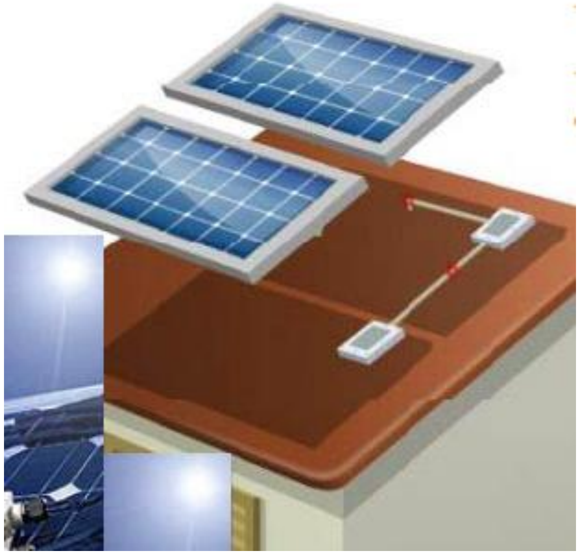
Approach: Wide-bandgap switches with advanced magnetic materials

MICROINVERTERS

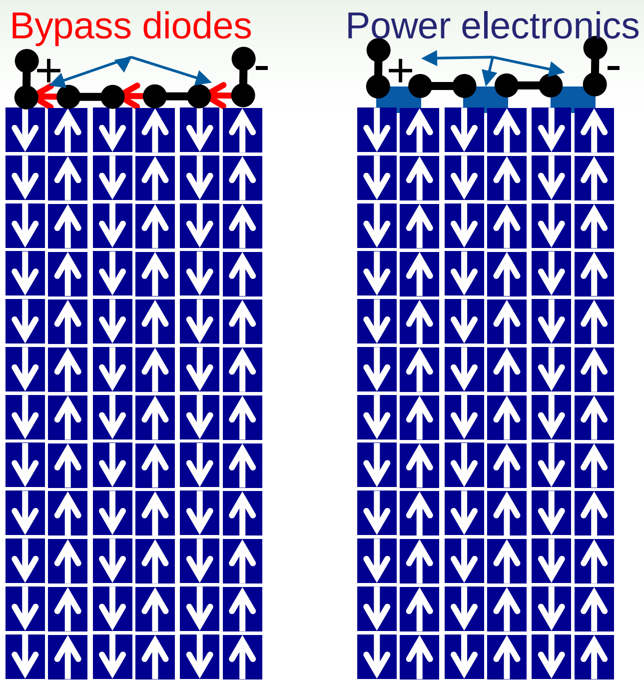


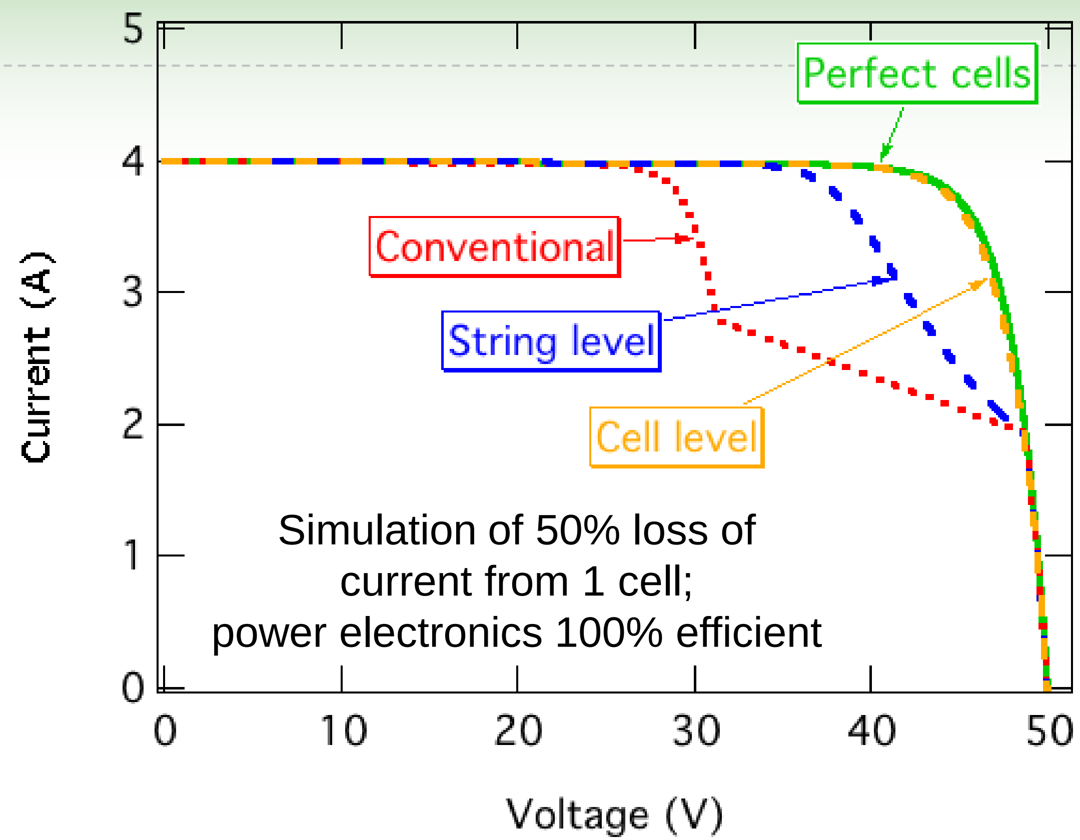
Barriers to adoption:

- Cost to Install
- Risk Averse Customers
- Cost to Maintain/Repair
  (multiple point of failure)



SUB-MODULE CONTROL





Goal: Improved yield without compromising cost ($1-2 per module) or reliability

Barrier: >99% efficient for improved yield + MPPT function for cost of a diode

Approach: Single chip DC/DC converter in Silicon

MULTISTAGE INVERTER

BASE CASE

1/10 the weight , 1/3 lower losses, ½ the manufacturing cost

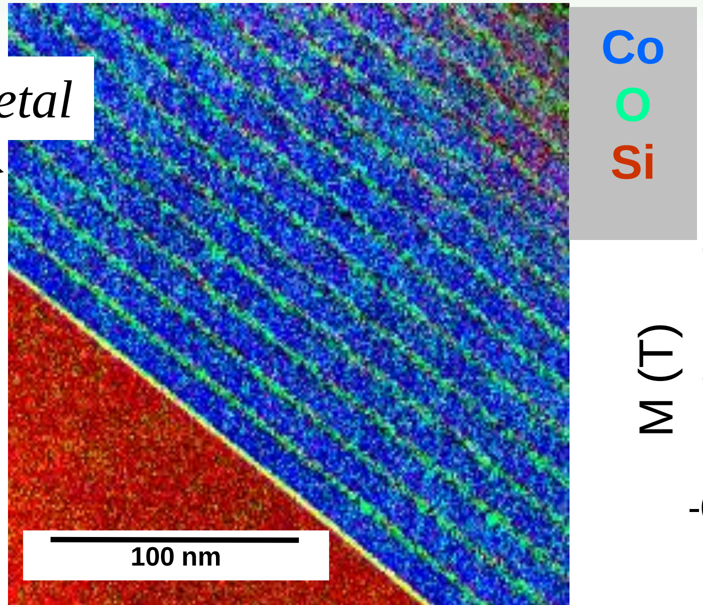
	Power (Watt)	Weight (lbs)	Lbs/kW	CEC Efficiency	Est. Mfg Cost
PVPowered	35K	1200	34	95.5%	$10K
SatCon Power Systems	30K	1204	40	95.0%	$10K
IDEAL POWER CONVERTERS	**30K**	**80**	**2.7**	**97.0%**	**<$5K**

Hi-voltage switches and hi-frequency transformer

SCALING NANOCOMPOSITE MATERIALS

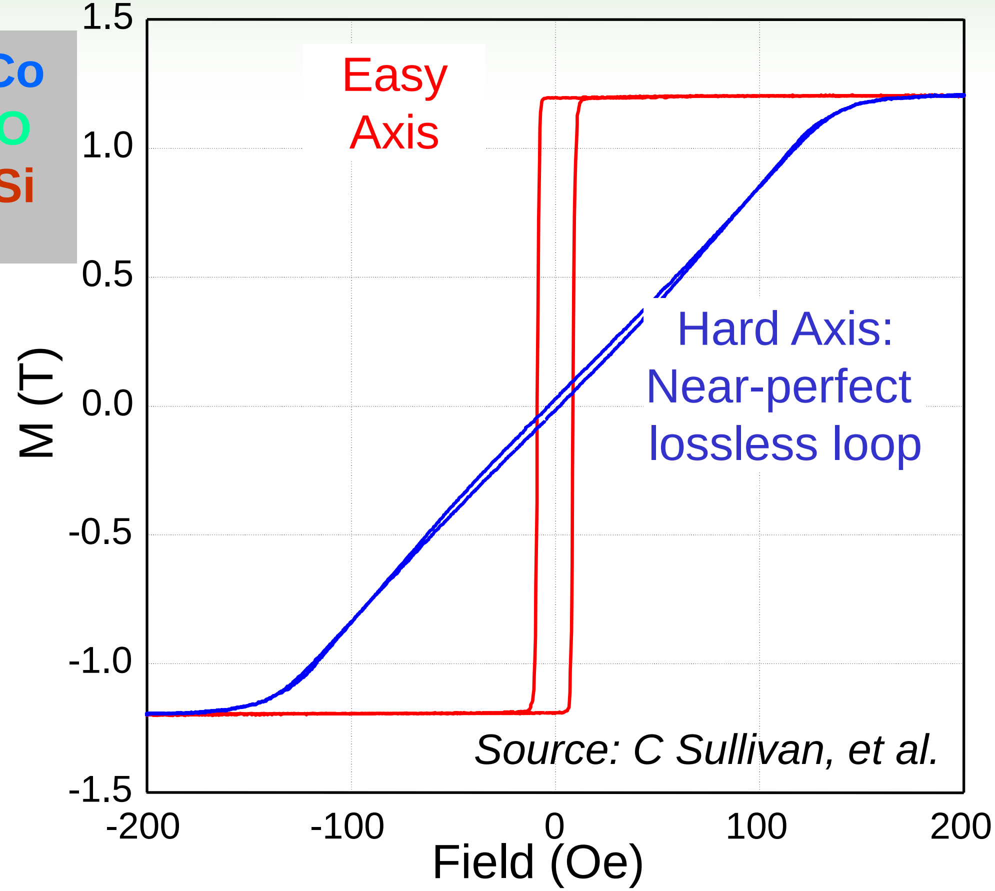
Magnetic Metal

(3~5 nm Co Particles)



Ceramic

(Al_2O_3, ZrO_2, etc.)



- Ferromagnetic (coupled particles)
- High resistivity (300 ~ 600 μΩ·cm) controls eddy-current loss

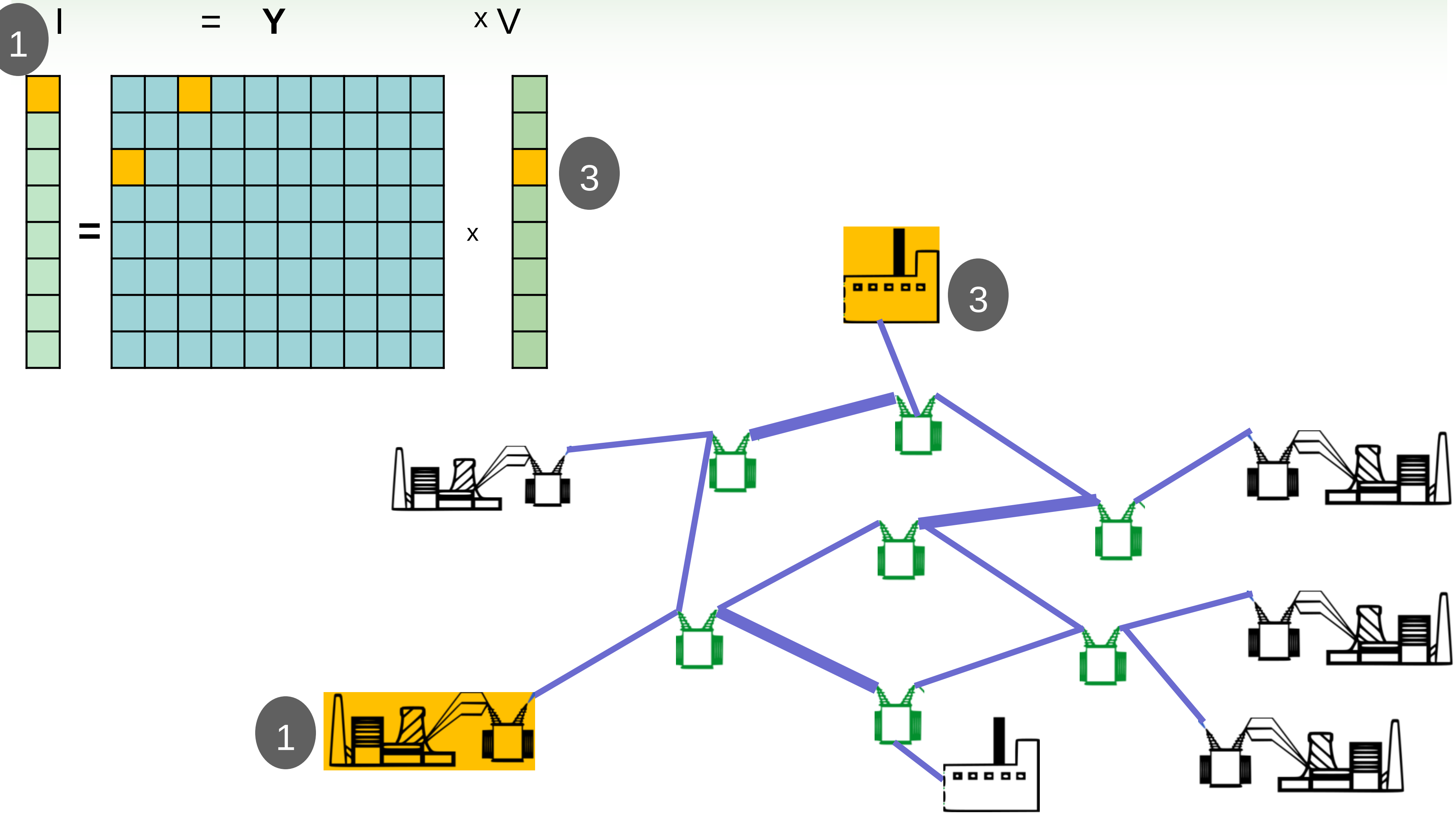
From micron thin-films to
mm scale inductors & transformers for 3 –
10 kW, 1 MHz

SOLAR ADEPT TARGETS

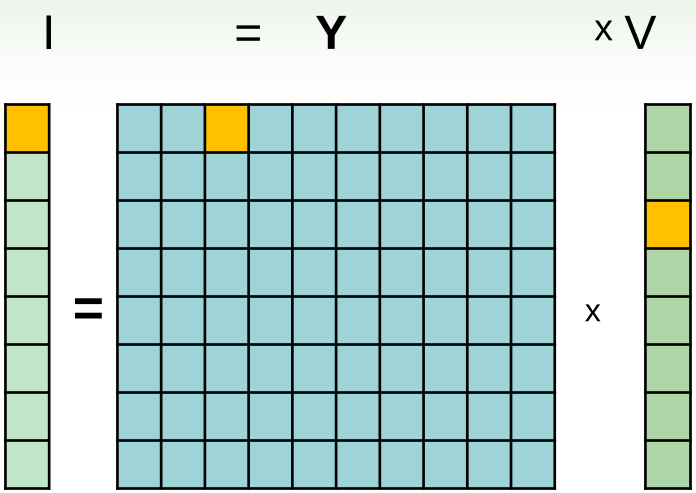
System Categories	Cost	Voltage & Power	CEC Efficiency	Size
Category 1 **Sub-module converter (Smart bypass)**	$0.05/W	>3 converters /module	>98% cell-to-AC MPPT	Single-chip DC/DC Inside Module Frame
Category 2 **Microinverter (Residential)**	$0.20/W	>600 V >250 W	>98% cell-to-AC	< 2 lbs Integrated: < 10 parts
Category 3 **Lightweight (Commercial)**	<$0.10/W	100kW	>98% cell-to-AC MPPT	< 50 lbs
Category 4 **Utility-scale Converters**	$0.10/W	> 2 MW scalable	>98% module-to-grid	< 1000 lbs

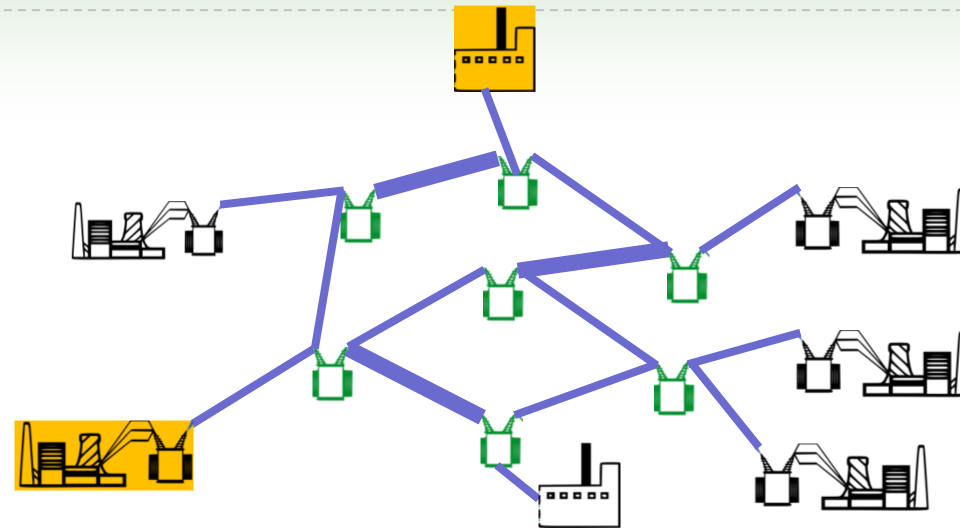
GREEN ELECTRICITY NETWORK INTEGRATION (GENI)

Designing Power Flow



Controlling Power Flow





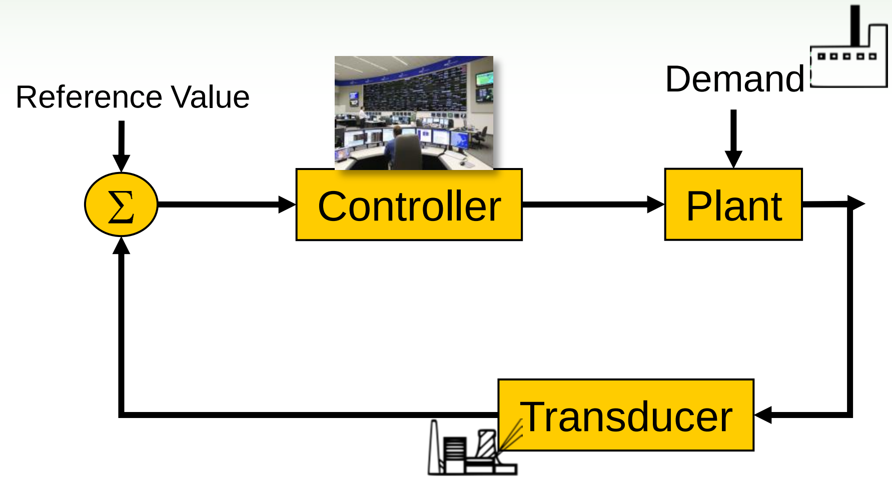
Minimizing the cost of fuel to deliver power is Hard (NP)

Must search through many choices of generator outputs for achieving a desired load

What kind of control?

- Linear vs. Non-linear
- Deterministic vs. Stochastic
- Time-invariant vs. Time-varying
- Continuous-time vs. Discrete-time

Controlling Power Flow



<u>Power Flow Control</u>

- Feed-forward control
- Assume:
  - Linear
  - Deterministic
  - Time Invariant

- Central control

<u>Error (Frequency, Voltage)</u>

- Feedback control
- Account for
  - Non-linearity
  - Dynamics

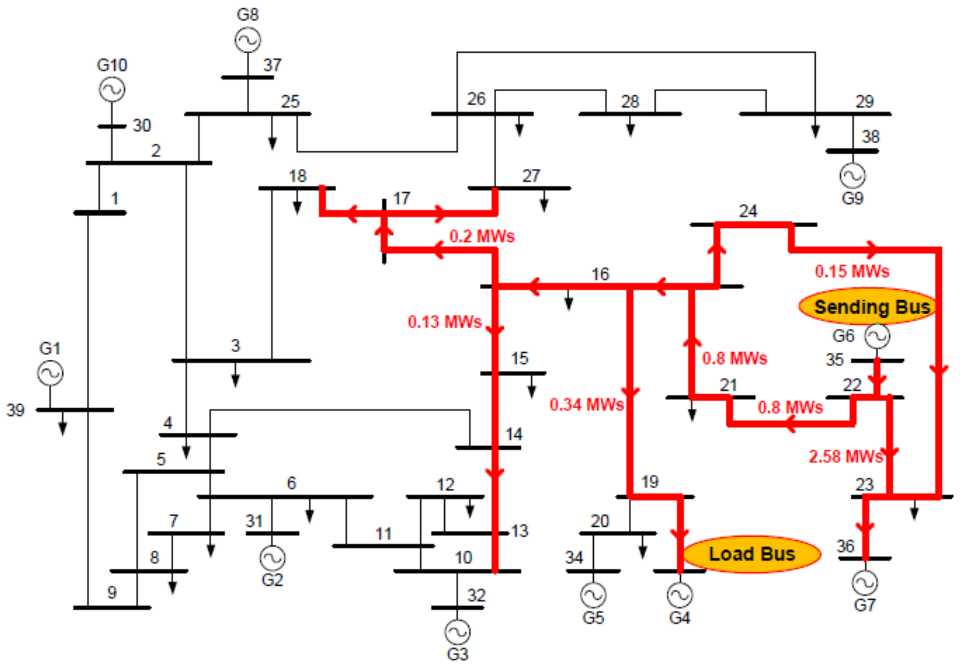
- Distributed or local control

Benefits of Routing Power

GA Tech study of simplified IEEE 39 Bus system with 4 control areas, operation simulated for 20 years, 20% RPS phased in over 20 years, sufficient transmission capacity added each year to eliminate curtailment of renewable generation

Today: Uncontrolled Flows

Power Routing



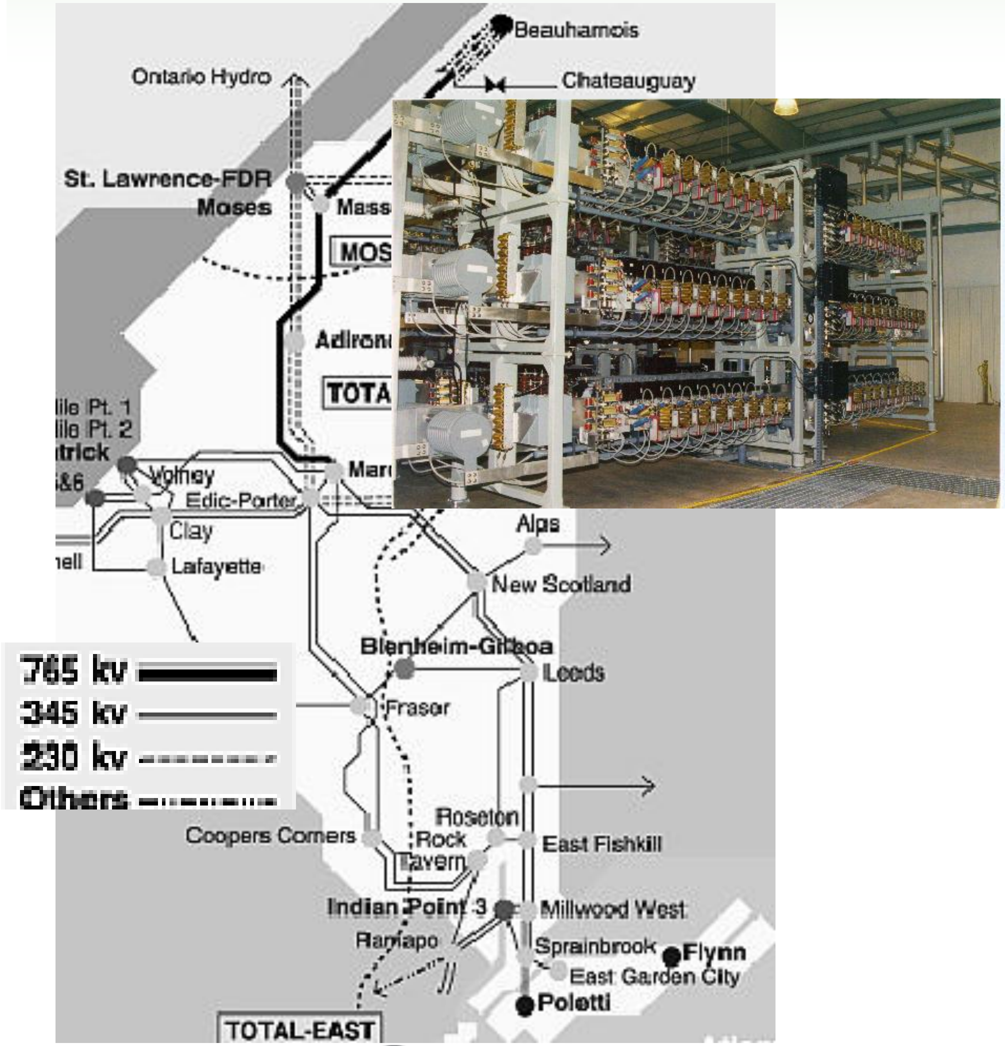
Base Case: 3.4 MW sent; 0.34 MW recd

- BAU case requires upgrade of 3 inter-regional paths, for a total of 186,000 MW-MILES
- Power flow control to route power along underutilized paths, 36,000 MW-miles of new lines needed, only 20% of BAU

ROUTING POWER TODAY

Utility: AC Universal Power Flow Controller

Private: Multiterminal HVDC



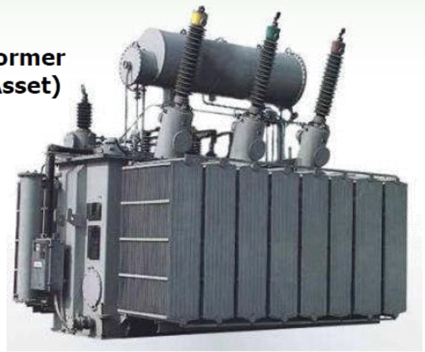
NEXT GENERATION HARDWARE

Power Converter Augmented Transformers

LTC Transformers

Dispatchable P/Q

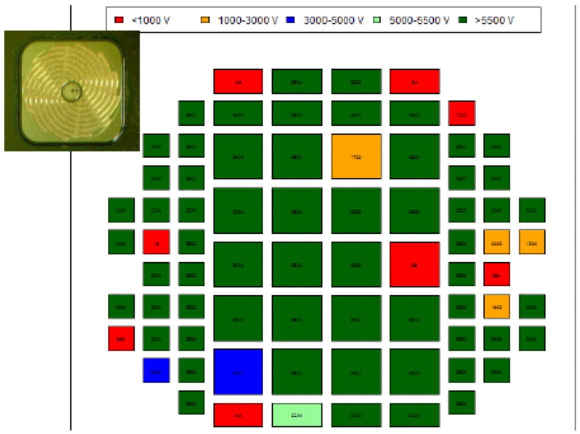
ARPA-E Funded



- A fail-normal mode
- Fractionally rated converters
- High-voltage components

Target < $10/Watt

Resilient HVDC



ADEPT Goal: 13kV SiC GTO

- HVDC fault protection
- High capacity, low cost cable
- High-voltage, uncooled

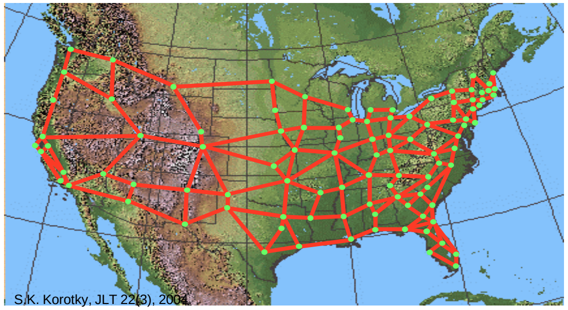
Target < $200/Watt

Control Challenges

- Traditional control theory assumes centralized feedback control.
- Not always feasible for large-scale distributed systems:
  - Inability to communicate with all subsystems
  - Incomplete/imperfect information
  - Complexity of centralized decision-making
  - Asynchrony
  - Heterogonous decision-makers with different objective and uncertain responses

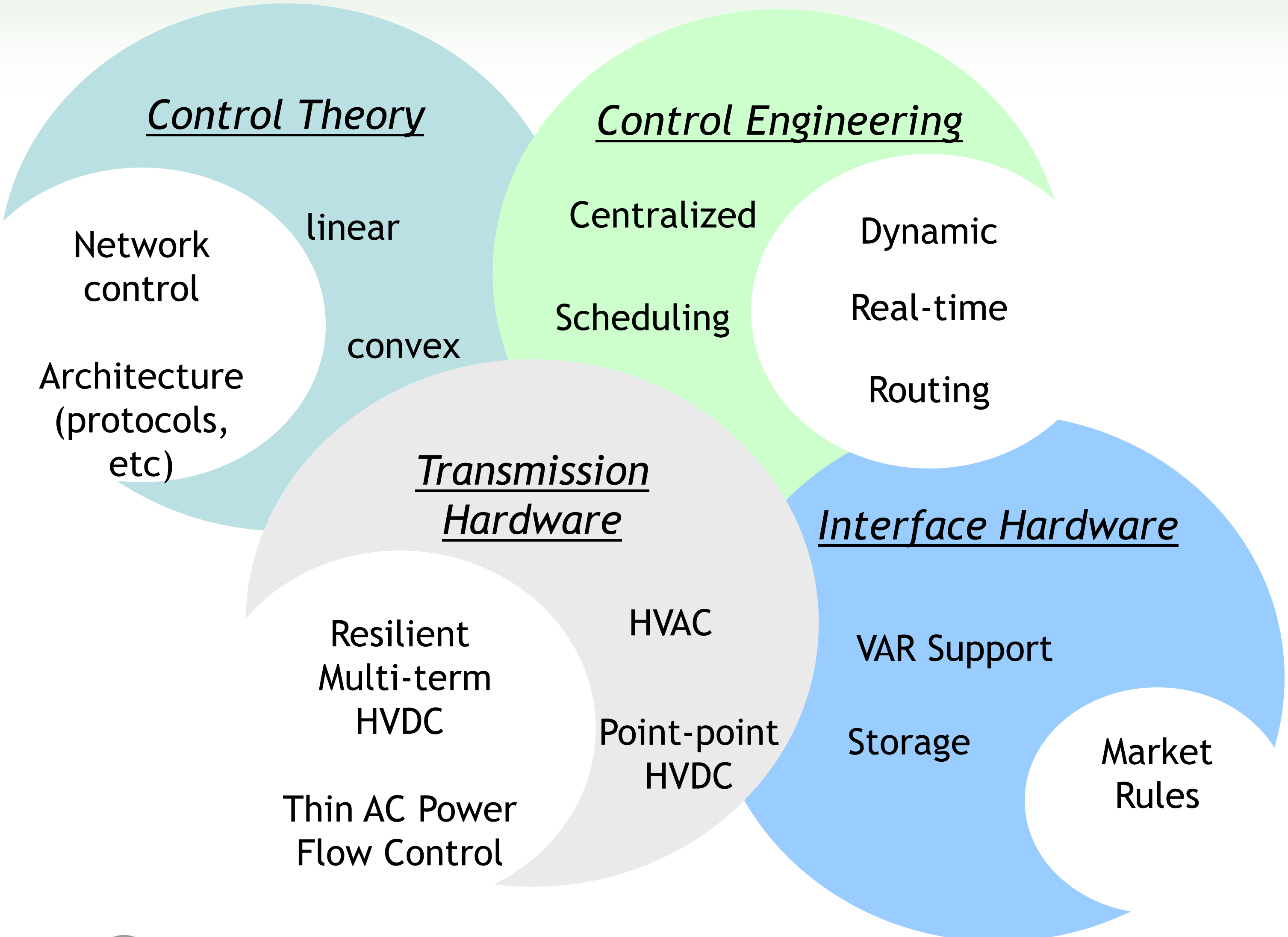
Networked control (Developed since 2005)

- Several layers: Physical, communication, and decision network
  - The physical layer consists of several distributed subsystems, coupled through and/or economics, via static and/or dynamic constraints.



S.K. Korotky, JLT 22(3), 2004

GENI



Control Theory
Network control
Architecture (protocols, etc)
linear
convex
Control Engineering
Centralized
Scheduling
Dynamic
Real-time
Routing
Transmission Hardware
Resilient Multi-term HVDC
Thin AC Power Flow Control
HVAC
Point-point HVDC
Interface Hardware
VAR Support
Storage
Market Rules