Manufacturing Low-Cost High-Voltage SiC Power Modules

APEI

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HV “SiC-Optimized” Power Modules

- A power module is a complex electro-, thermo-, mechanical-, chemical-system
- APEI works on the following premise: To fully harness the breakthrough potential of SiC power semiconductor devices, one maximizes their probability of succeeding by “working inside out.”
- “SiC Optimized” ≠ Si power modules + additional creepage and clearance
- Low inductance power module, < 10 nH for our 1200/1700 V modules; < 30 nH for our 15 kV module
- Thermal impedance j-c vs. voltage isolation trade-offs

APEI WBG Module to Application Roadmap

> 20 kV

> 10 years:
- DoD Applications
- Direct Drive wind turbines
- Off-shore wind turbines
- HVDC Grid (Transmission)
- Variable Speed Drives
- Transmission-level FACTS

10-15 kV

5-10 Years:
- Distribution-level FACTS
- Mid. size turbines
- Med. voltage drives
- Grid Tied Energy Storage

> 10 years:
- Direct Drive wind turbines
- Off-shore wind turbines
- MVDC Grid (Distribution)
- Variable Speed Drives

3.3 kV – 6.5 kV

5-10 Years:
- MVDC power distribution
- DoD protection
- Medium voltage drives
- Locomotive traction

≤ 1700 V

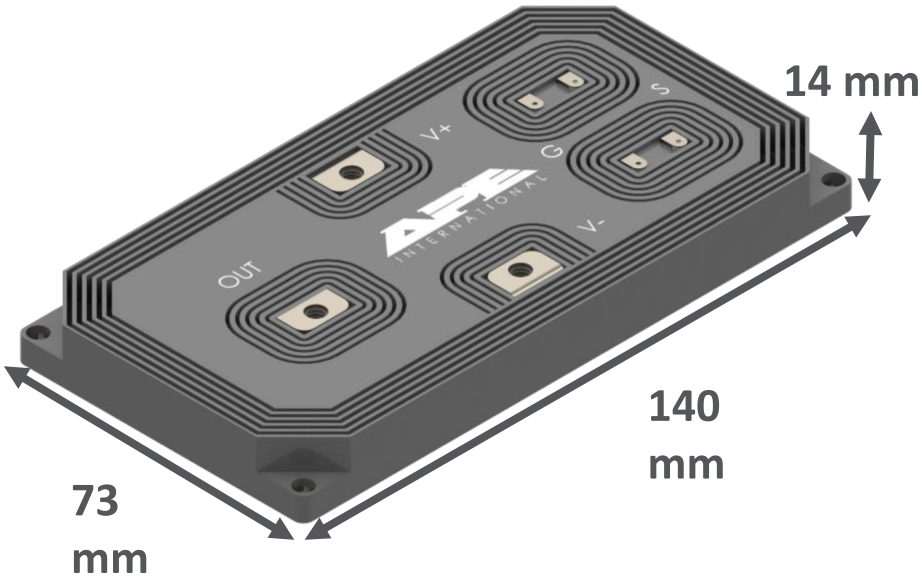
Near Term:
- Data centers (PFC, DC/DC)
- DC power supplies / radar
- Traction inverters
- Solar systems, grid-tie
- Energy storage systems, grid-tie

2-5 Years:
- Mid-size turbine interface
- Solar inverter, MPPT
- Industrial motor drives
- Automotive traction motor drives
- Level 2/3 battery chargers

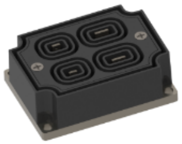
Near Term | 2-5 Years | 5-10 Years | > 10 years

HV SiC MCPM Design

- Device neutral
- Standard footprint
- Wire bondless
- Low profile
- Reduce volume/weight
- Low parasitic design
- Low R_{jc}
- **Reworkable**
- High temperature capable (> 200 °C)
- Low cost manufacturing



APEI HV Module Roadmap

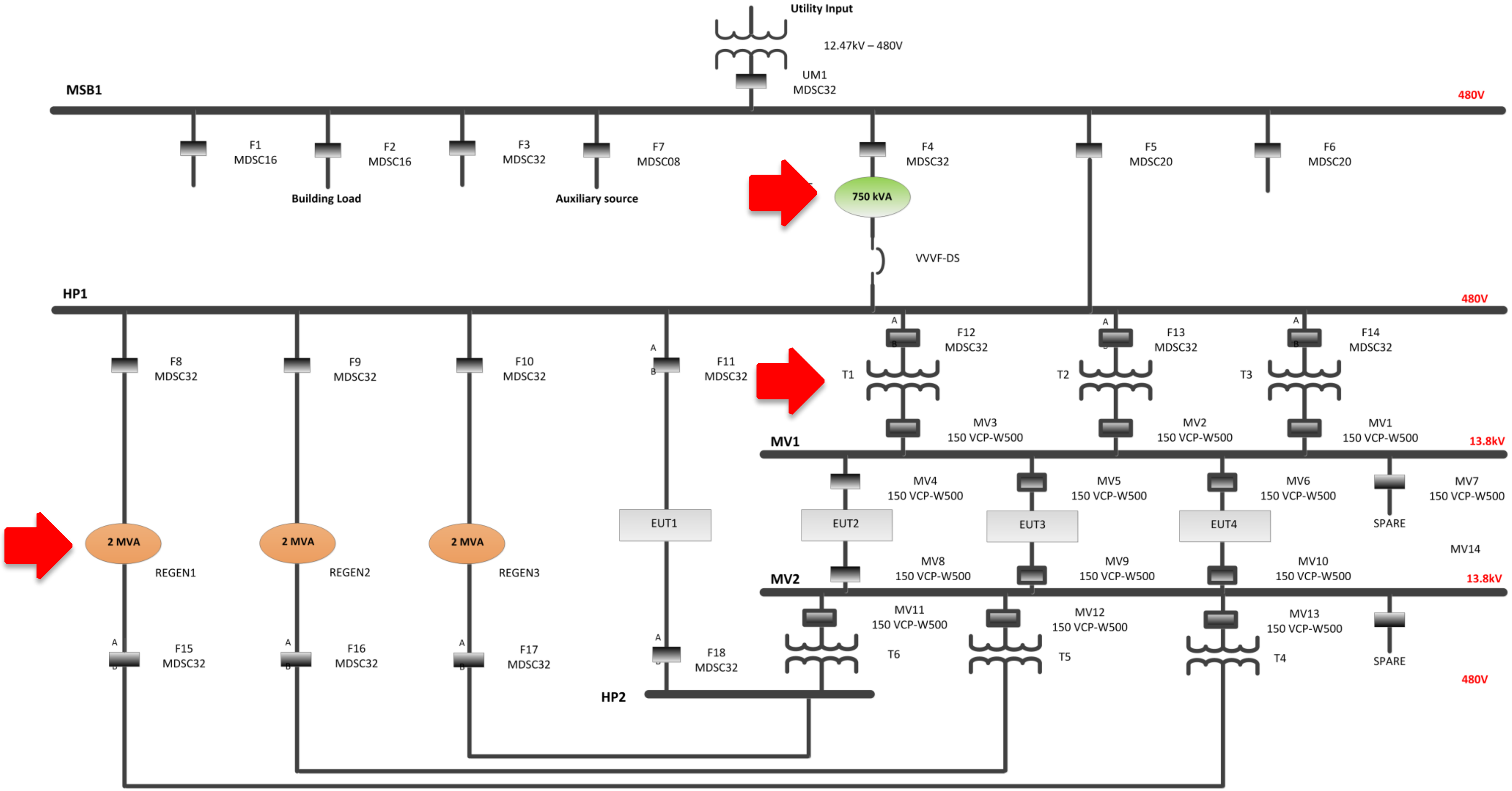
Name	Image	Project	Voltage Rating	Current Rating	Target Applications	Package Advantages
XHV-2		DOE HV Phase I	15 kV	50 A	Energy Storage; Smart Grid; Naval Power Dist.; HV Circuit Breakers; Pulsed Power; Rail	Wire bonded/bondless; PCB/Busbar connections; Multiple base plates; High temp. capable; Relatively low profile
XHV-3		DOE HV Phase II	15 kV	40 A 80 A 120 A	Energy storage; Smart Grid; Naval power dist.; HV circuit breakers; Pulsed power; Rail	Wire bonded/bondless; Higher voltage than anything on the market; PCB/Busbar connections; Multiple base plates; High temp. capable; Low profile
XHV-4	Boost Chopper & Discrete	ARL HVPT	25 kV	30 A	Charge/Discharge 20 kV capacitors	Very high voltage; Simple build
XHV-5	Half-Bridge	ARL HVPT	25 kV	30 A	Charge/Discharge 20 kV capacitors	Very high voltage; Simple build

UA National Center for Reliable Electric Power Transmission

1.6 MW converter on a semi-tractor trailer in the NCREPT test bay

IEEE 1547 and UL 1741 standards testing

UA National Center for Reliable Electric Power Transmission System One-Line Diagram



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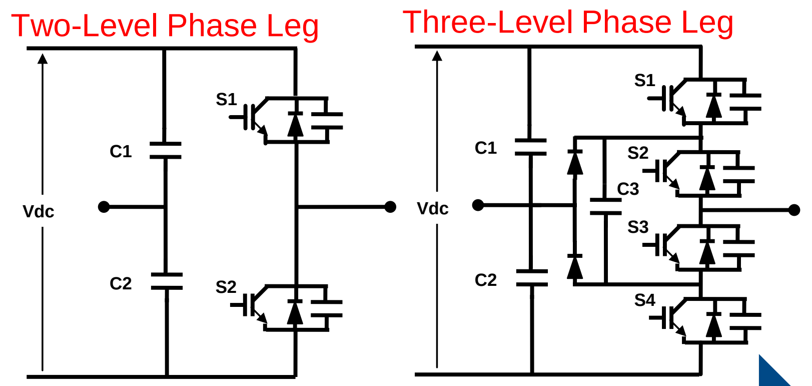
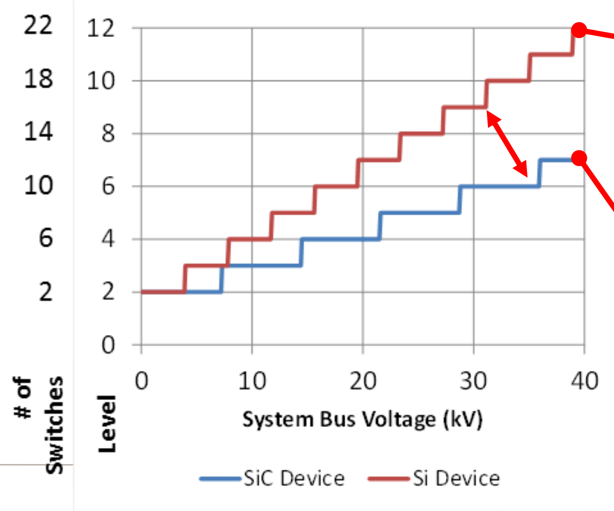
System Advantages of SiC over Si

Reduction of System Size, Complexity, Cost

- Multi-level converter schemes are necessary to increase system bus voltage
- Multi-level converters reduce stress on power die
- Since SiC inherently has a higher blocking voltage than Si, the number of switches are reduced



Size/Complexity of System Increases



40 kV Si-based system
12 levels, 22 switches

40 kV SiC-based system
7 levels, 12 switches

Projected Size Reduction using a SiC-Based System

[2]. N. Wade, et.al., "Energy Storage for Power Flow Management and Voltage Control on an 11kV UK Distribution Network," 20th International Conference on Electricity Distribution, June 2009.
[3]. S. Bhattacharya, "15kV SiC IGBT Modules for Grid Scale Power Conversion," ARPA-ADEPT Program, 2010.

Application 1: Energy Storage System

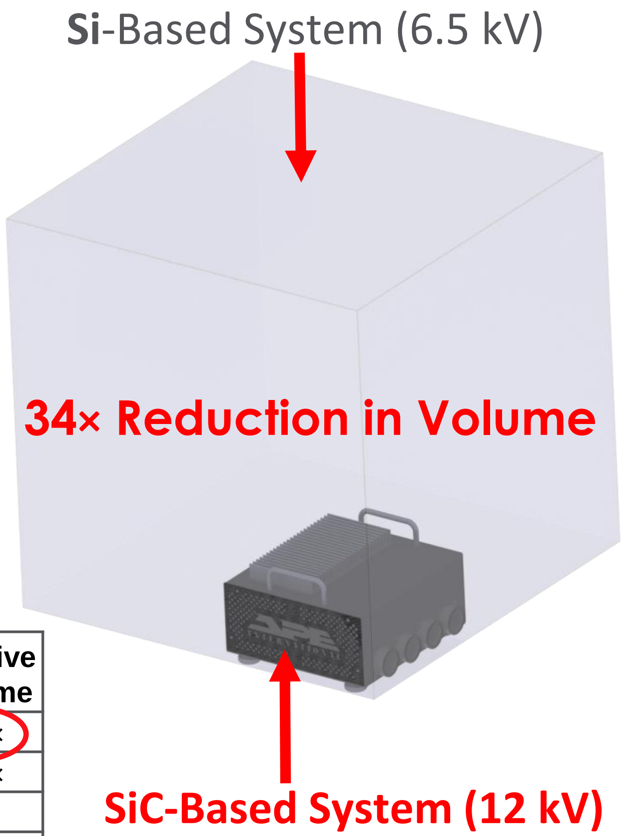
- ABB's SVC Light energy storage system [2]
- Comparison of solutions for an 11 kV 600 kW ESS

Technology	Power Electronics					Relative Size/Mass
	V_{BD}	T_j (°C)	Level	No. Switches	Freq. (Hz)	
Si Device	6.5 kV	125	10	54	900	28×
SiC Device	12 kV	175	6	30	18,000	1.4×
SiC Device	12 kV	225	6	30	25,000	1×

Application 2: Solid-State Transformer

- Replace passive transformers with power electronic converters to reduce size
- Comparison of solutions for a 13.8 kV / 480 V 100 kVA transformer [3]

Technology	Power Electronics				Isolation Transformer			Relative Volume
	V_{BD}	T_j (°C)	Level	No. Switches	Freq. (Hz)	Mass (kg)	Volume (m³)	
Passive	N/A	N/A	N/A	N/A	60	370	0.480	34×
Si Device	6.5 kV	125	7	70	1,000	35.8	0.286	20×
SiC Device	12 kV	175	4	40	17,000	10.2	0.057	4×
SiC Device	12 kV	225	4	40	24,000	5.32	0.014	1×



Design Considerations…Application Matters

Size

- Would it be advantageous to design the module with a standard footprint?
- If the size of the module is reduced, how much would that impact your power inverter?

Electrical Specifications

- What voltage and current ratings would work well with existing grid-tie systems?

Power and Signal Connectors

- What is the present connection scheme that you use on your modules?

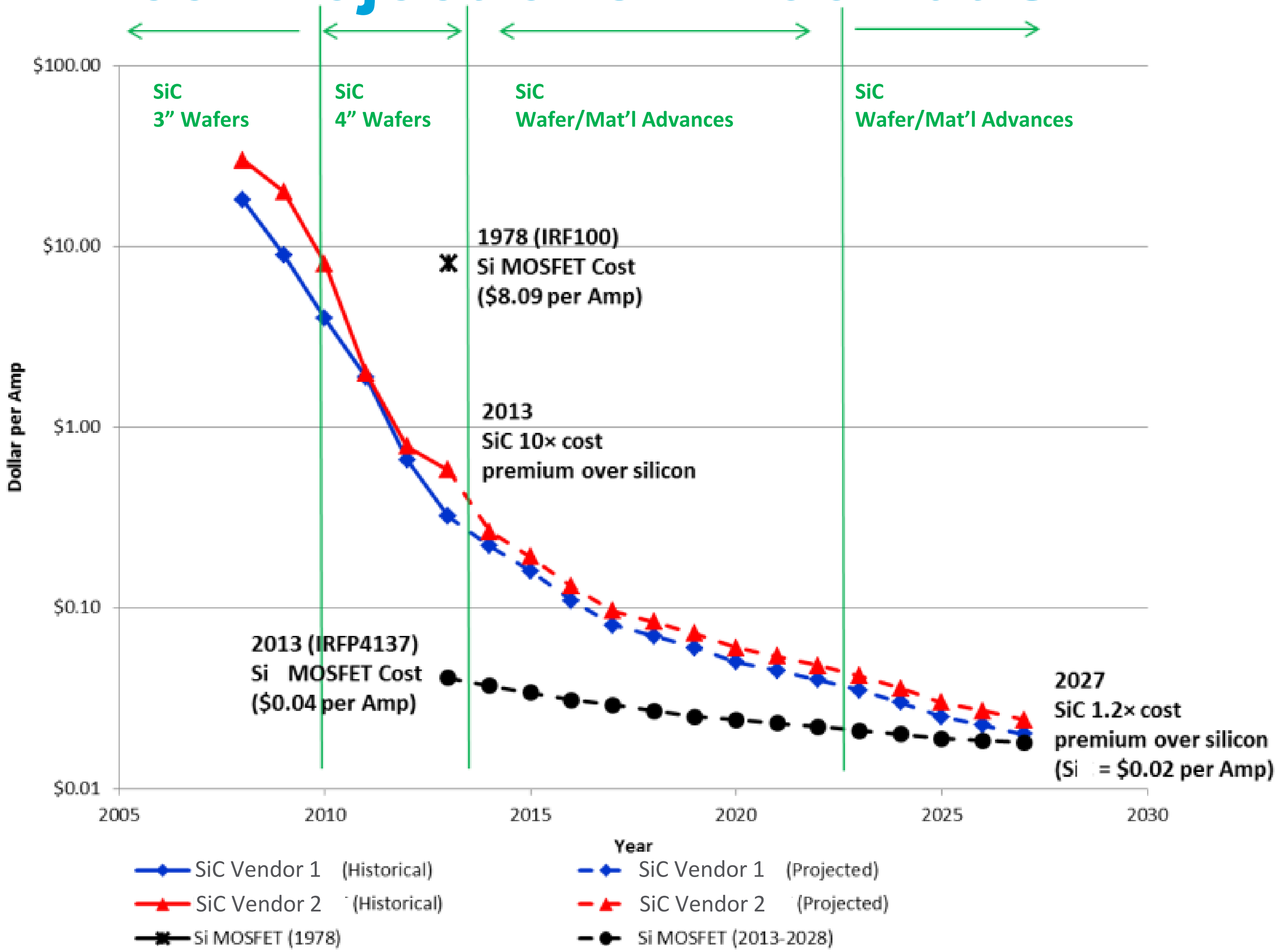
Production Example of Lowering Cost in SiC HV Power Modules

- To minimize the cost of SiC HV power modules, optimization must take place throughout the whole value chain
- Categorize as:
  - Supply chain (e.g., volume purchase break points, inbound shipping costs, inbound duties/tariffs, etc.)
  - Manufacturing (e.g., re-workable processes, increase automation; reduce: parts, product size, material volume, manufacturing steps)
  - Sales/distribution (e.g., outbound shipping costs, overhead associated with export control management)

Availability and Reliability of > 10 kV SiC Power Die

- A limited number of HV parts are presently being fabricated; no catalog parts
- Parts are R&D samples, unknown market price
- Screening prior to packaging is often required, additional cost
- Failure mechanisms and activation energies unknown
- No HT qualification standards beyond automotive (Si)

WBG Price Projections – Look at Si

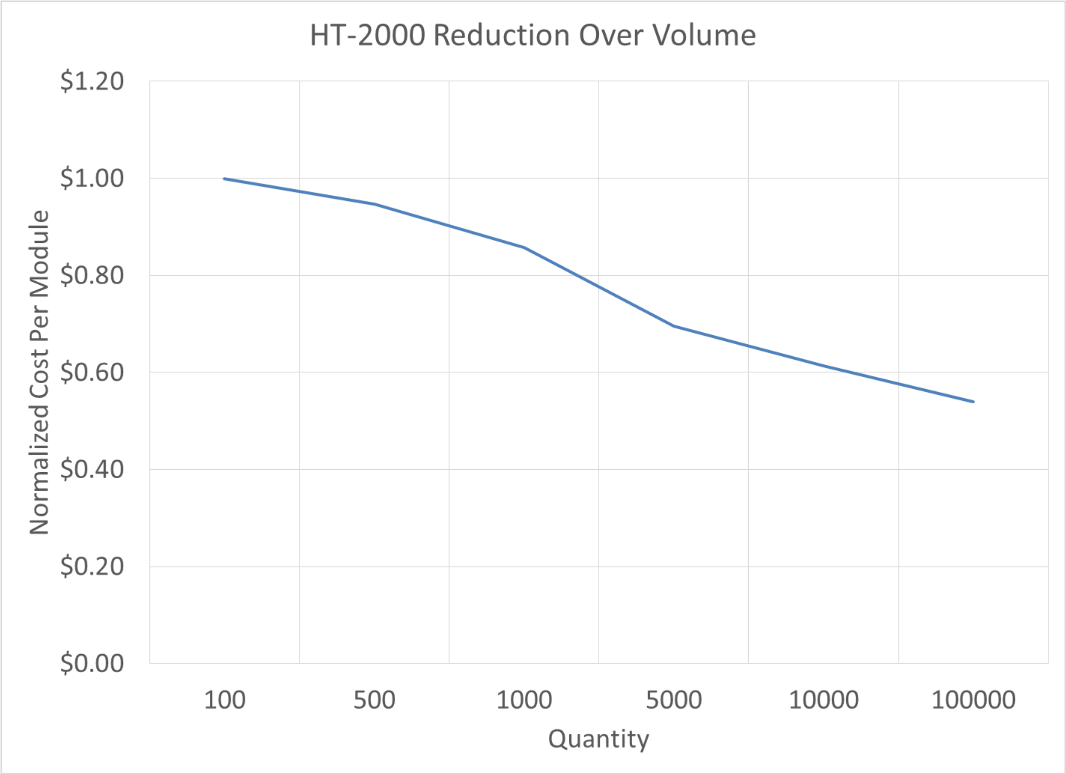


Module Cost Reduction With Volume

- Economies of scale impacts labor, shipping, M&S costs, stocking, etc.

Other reduction areas:

- Labor will drastically reduce with automation
- Automated die screening & inspection to increase yield
- In-line testing & inspection to keep production costs low, increase yield
- Design in re-workability

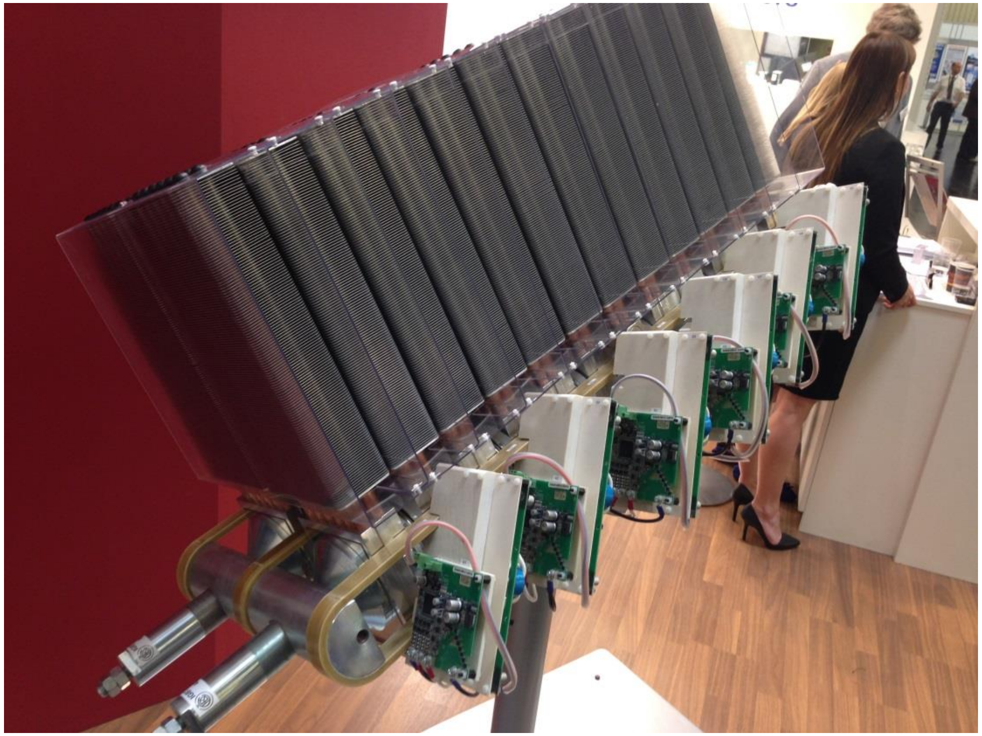


HV Module Development & Insertion Challenges/Gaps

- High temperature, high dielectric strength materials
- Small form factor, high current/power sealable connectors
- Small form factor, signal sealable connectors
- Low cost, high voltage isolation power substrates
- High voltage measurement systems (curve tracers, partial discharge, etc.)
- Identifying significant applications/target customers outside energy storage and electric locomotives
- HV isolated gate drivers and gate driver power supplies
- HV bussing solutions may be needed

System Challenges and Payoffs

- Thermal Management System
  - Limited applications, increases costs due to:
    - Large form factor
    - Heavy
- System-Level Packaging
  - Size affects bussing strategy
  - Small form factor connectors, signal & high current



Thank You