# *ARPA-E Past Grid Hardware Projects and Vision for the Future*

Dr. Isik Kizilyalli, Advisor, ARPA-E
Dr. Johan Enslin, Program Director, ARPA-E

2024 DOE Direct Current Circuit Breakers Workshop
Office of Electricity

May 1st, 2024

# ARPA-E Mission

CHANGING WHAT'S POSSIBLE

**REDUCE**
imports

**REDUCE**
emissions

**IMPROVE**
efficiency

**IMPROVE**
radioactive waste management

**IMPROVE**
energy infrastructure resilience

# ARPA-E Impact Indicators 2024

arpa-e CHANGING WHAT'S POSSIBLE

Since 2009
ARPA-E has provided
**$3.76 billion**
in R&D funding to
more than **1,560 projects**
**+ 54 selected projects**

**230 projects**
have attracted more than
**$12.1 billion**
in private-sector follow-on funding

**154 companies**
formed by
**ARPA-E projects**

**29 exits**
market valuations worth
**$21.9 billion**
from mergers, acquisitions, and IPOs

**340 projects**
have **partnered with other government agencies**
for further development

**7,318**
peer-reviewed
**journal articles**
from ARPA-E
projects

**1,120 patents**
issued by
U.S. Patent and
Trademark Office

**405 licenses**
reported from
ARPA-E projects

As of January 2024

## ELECTRICITY GENERATION & DELIVERY

**Active**

- CURIE *(new)*
- ONWARDS
- SHARKS
- BETHE
- GAMOW
- PERFORM
- GEMINA
- ATLANTIS
- DAYS
- MEITNER
- INTEGRATE
- IONICS
- GRID DATA
- NODES
- GENSETS

**Alumni**

- MOSAIC
- ALPHA
- CHARGES
- REBELS
- FOCUS
- SOLAR ADEPT
- HEATS
- GENI
- GRIDS
- IMPACCT

## EFFICIENCY

**Active**

- MINER *(new)*
- HESTIA *(new)*
- REMEDY
- FLECCS
- REPAIR
- DIFFERENTIATE
- BREAKERS
- HITEMMP
- SENSOR
- CIRCUITS
- PNDIODES
- ENLITENED
- ROOTS
- SHIELD

**Alumni**

- ARID
- MONITOR
- DELTA
- SWITCHES
- METALS
- REACT
- BEETIT
- ADEPT

## TRANSPORTATION

**Active**

- EVS4ALL *(new)*
- ECOSYNBIO
- ULTIMATE
- ASCEND
- REEACH
- SMARTFARM
- MARINER
- REFUEL
- NEXTCAR
- RANGE

**Alumni**

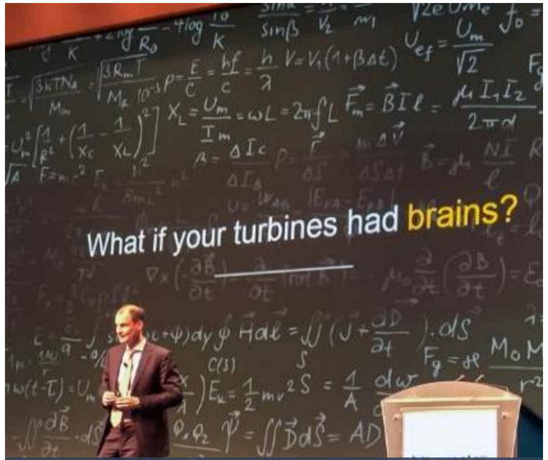
- TERRA
- REMOTE
- TRANSNET
- AMPED
- MOVE
- PETRO
- ELECTROFUELS
- BEEST

**+ OPEN 2009, 2012, 2015, 2018, & 2021 Solicitations**
**+ Seedlings, Competitions, Complementary Exploratory Topics**
**+ SCALEUP 2019 & 2021**

IBLE

# arpa·e energy innovation summit

Highly Selective Technology Showcase




Inspiring Keynotes

Unparalleled Networking


Fast-Paced Technology Pitches

**arpae-summit.com**

## May 22-24, 2024 | Dallas, Texas

# Technology Acceleration Model: Focused Area Program Development

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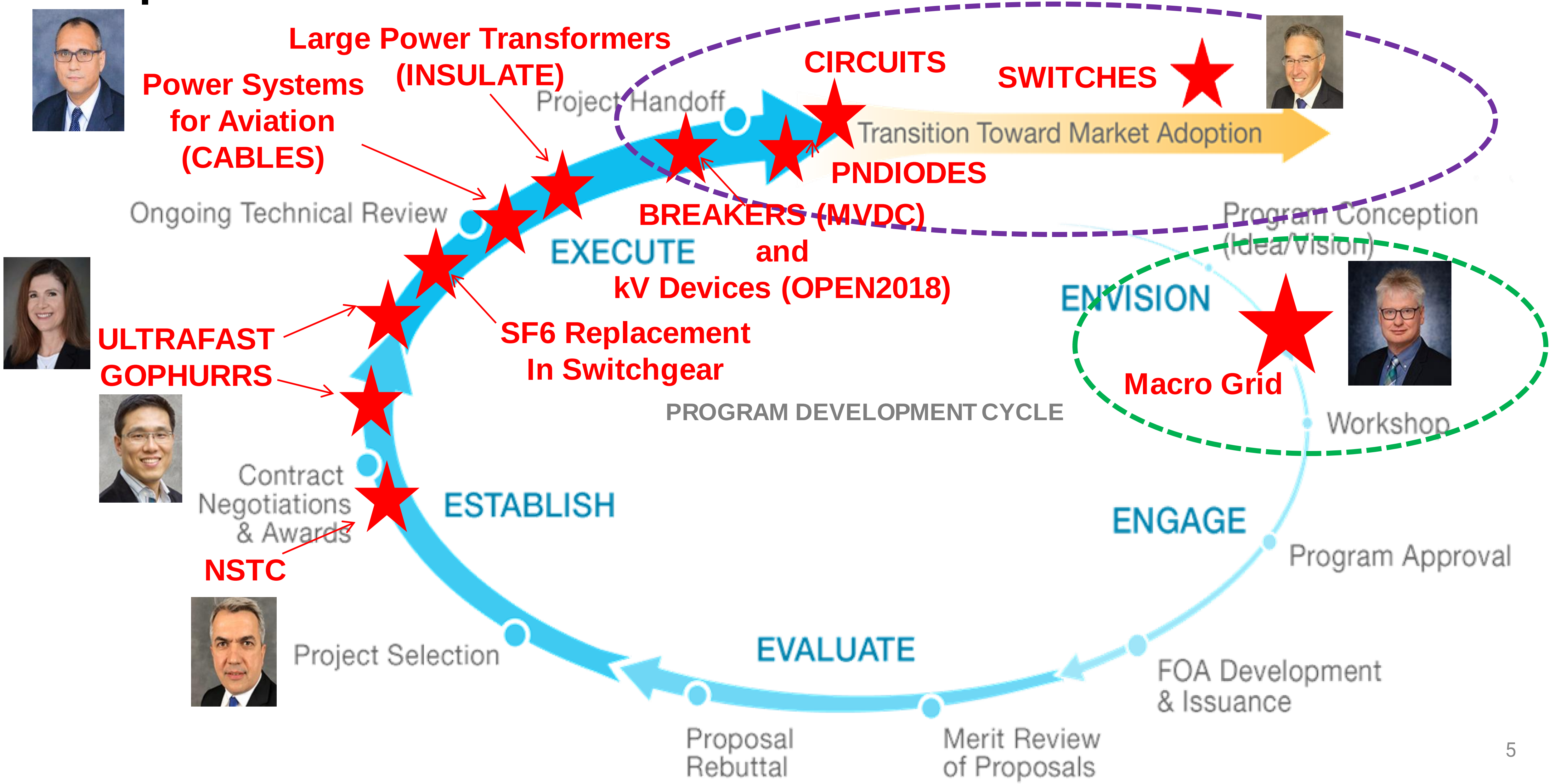
CHANGING WHAT'S POSSIBLE



# Current and Considered Developments in DC Markets

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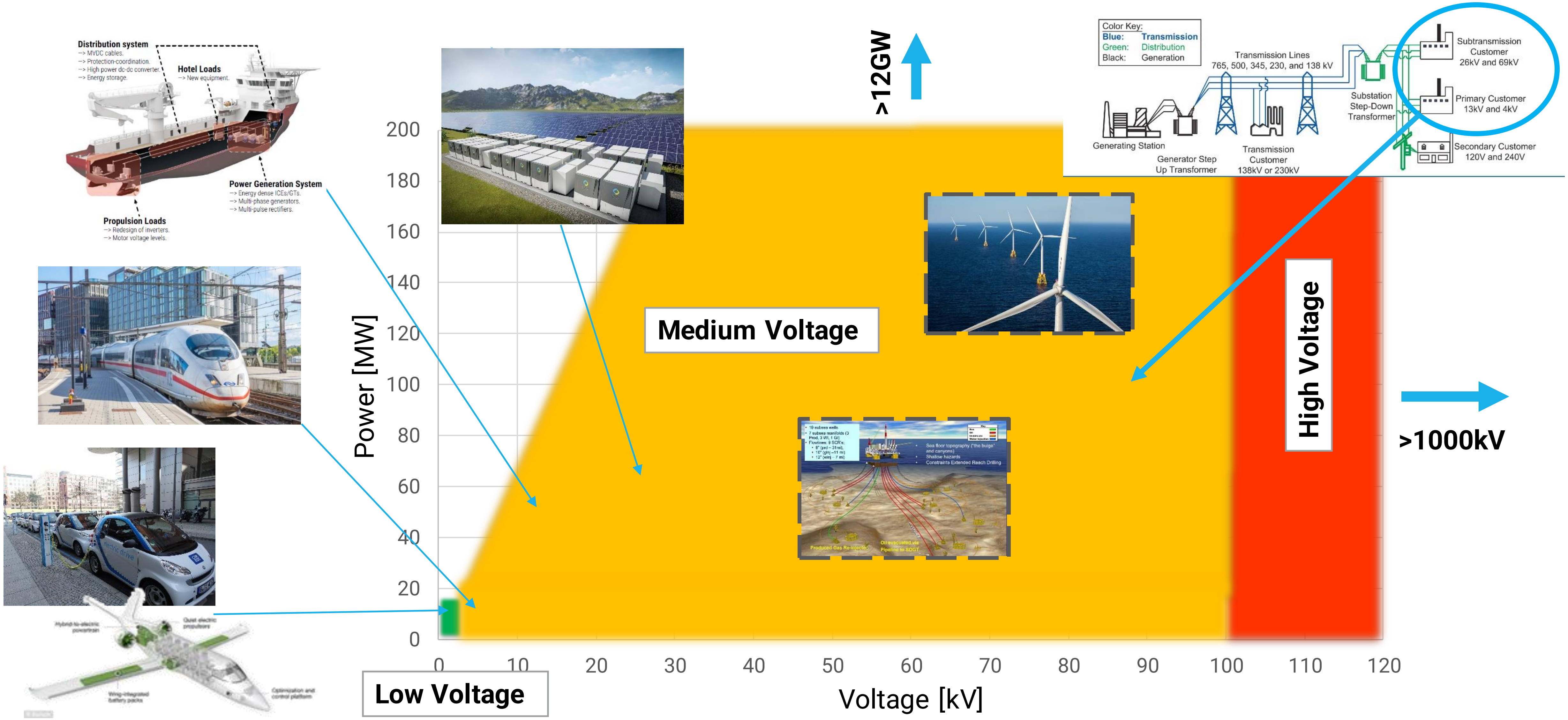


# SWITCHES

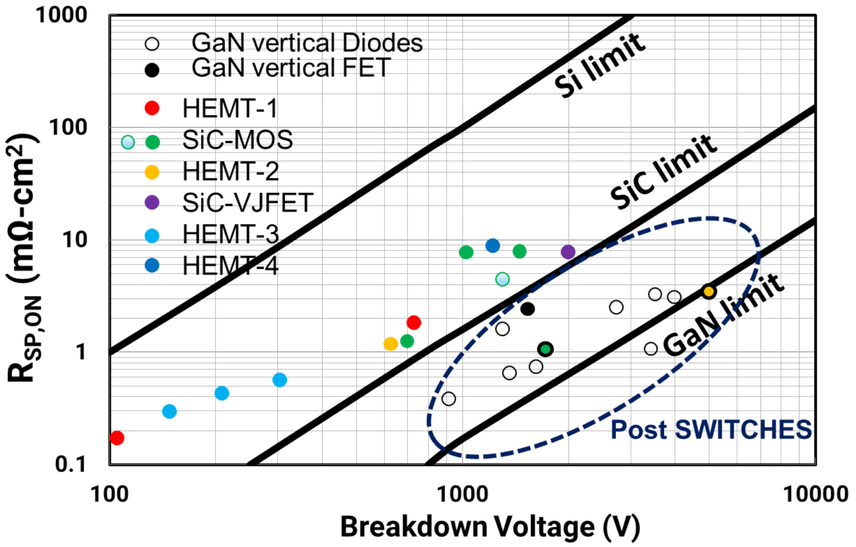
Launched by Timothy Heidel
Program Director: Isik C. Kizilyalli

## Strategies for Wide-bandgap, Inexpensive Transistors for Controlling High Efficiency Systems

**2014**
**$34.3 Million**
**14 projects**

**Enable the development of high voltage (1200+ V), high current (100+ A), wide-bandgap power semiconductor devices that have the potential for functional cost parity ($/A) with Si devices**

**Program demonstrated GaN vertical devices approaching 5 kV and their pathway to 20 kV**




*Monolith Semiconductor, "Advanced Manufacturing for SiC MOSFETS"*

- **6" SiC wafers in CMOS Si foundry: Low Cost**
- **Demonstrated**
  - 150 A, 950V SiC Diodes
  - 100 Amp, 15 mΩ, 1200V MOSFETs
  - Device stability of packaged devices at 175°C (and initial on-wafer results at 225°C)

| | |
|---|---|
| Discrete Device Price | ≤ $0.10 /A |
| Breakdown Voltage | ≥ 1200 V |

| | |
|---|---|
| Continuous Drain Current | ≥ 100 A |
| Specific $R_{DSON}$ | < 3 mΩ*cm² @ $V_{GS}$ = 15 V |



Link: More about the SWITCHES Program

# CIRCUITS

Program Director: Isik C. Kizilyalli

## Creating Innovative and Reliable Circuits Using Inventive Topologies and Semiconductors

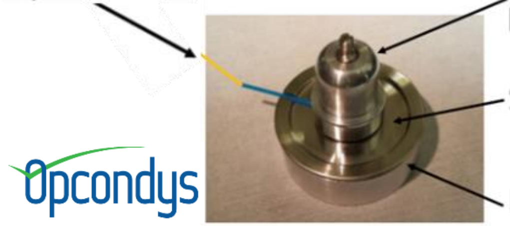

**Use advanced circuit topologies and fundamentally higher performing WBG semiconductor materials to realize efficiency gains both directly and indirectly in electric power conversion**

- **Innovate on circuit topology and controls to increase power density**
- **Innovate on packaging and integration to reduce parasitics**
- **Manage conductive and radiative noise (EMI) of fast switching devices**
- **Manage reliability to reduce risk and cost**

**200 kW SiC Motor Drive**

UNIVERSITY OF ARKANSAS

**20 kV SiC Optical Transconductance Varistor (OTV)**




Opcondys

VIRGINIA TECH

**2 MW, 24 kV Modular Converter**


| | | | |
|---|---|---|---|
| Power and voltage | ≥ 10 kW & ≥ 600 V | Power density | ≥ 9.15 kW/l |
| Efficiency | ≥ 97.5% @ rated power | Specific power | ≥ 5 kW/kg |

Link: More about the CIRCUITS Program

# BREAKERS

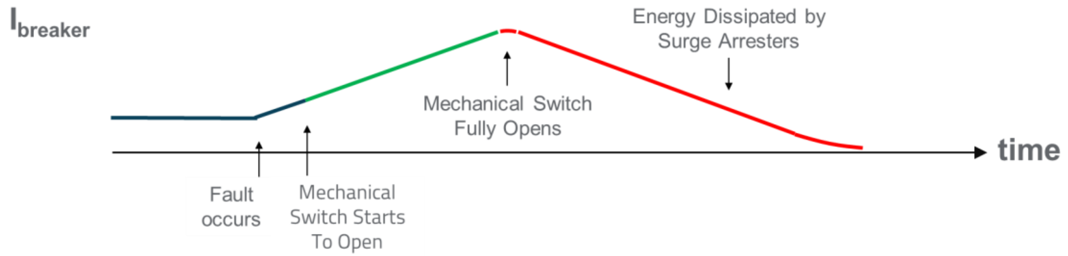
## Building Reliable Electronics to Achieve Kilovolt Effective Ratings Safely

**Program Director: Isik C. Kizilyalli**

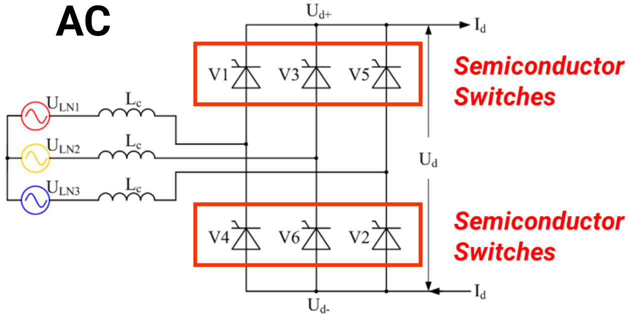
**2018**
**$36.7 Million**
**11 projects**

**Enable and create MVDC markets in the range of 1.5 kV – 100 kV by developing novel DC circuit breaker technologies.**

### DC Has No Zero Crossing Resulting In Persistent Arcs

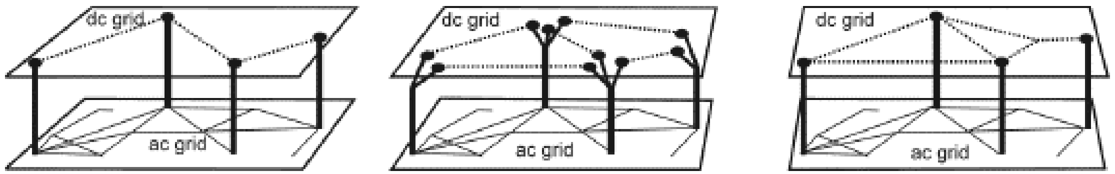



### DC Systems Require Faster Breaking Times Compared to AC




Can only handle **2 – 3 times** the nominal current for **<5ms**

MVDC circuit breakers will enable MVDC distribution which can save 1.1 quads of energy per year, reduce U.S. emissions by 3% via electrification of transportation, and lower offshore oil and gas rig costs by 5%.




Point-to-Point → Collection of Point-to Point → Multi-point DC Network Mesh

***MVDC Distribution: DC network that delivers medium voltage power across interconnected sources and loads.***

# BREAKERS

Program Director: Isik C. Kizilyalli

Building Reliable Electronics to Achieve Kilovolt Effective Ratings Safely

2018
$36.7 Million
11 projects

## Program Technical Requirements

| ID | Category | Target |
|---|---|---|
| 1.1 | Rated Voltage | 1kV DC ≥ V ≥ 100kV DC |
| 1.2 | Power* | ≥ 1MW |
| 1.3 | Efficiency | ≥ 99.97% |
| 1.4 | Response Time | ≤ 500μs |
| 1.5 | Lifetime | ≥ 30,000 cycles, ≥ 30 years |
| 1.6 | Nuisance Trips | ≤ 0.1% |
| 1.7 | Power Density* | ≥ 60 $MW/m^3$ |
| 1.8 | Cooling | Passive or Forced Air |

**Instantaneous Power*

Link: More about the BREAKERS Program

# BREAKERS

## Building Reliable Electronics to Achieve Kilovolt Effective Ratings Safely

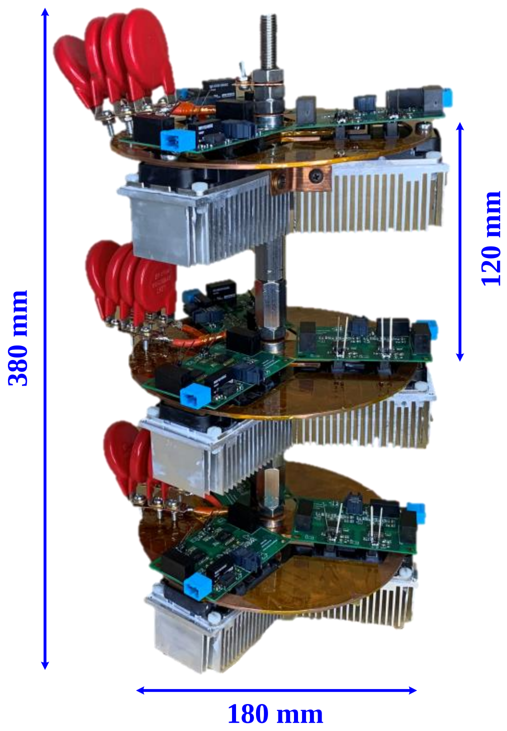
**Program Director: Isik C. Kizilyalli**

BREAKERS Program Outcomes:

- 116 Publications
- 26 Subject Inventions
- 5 Patents Issued

**2018**
**$36.7 Million**
**11 projects**

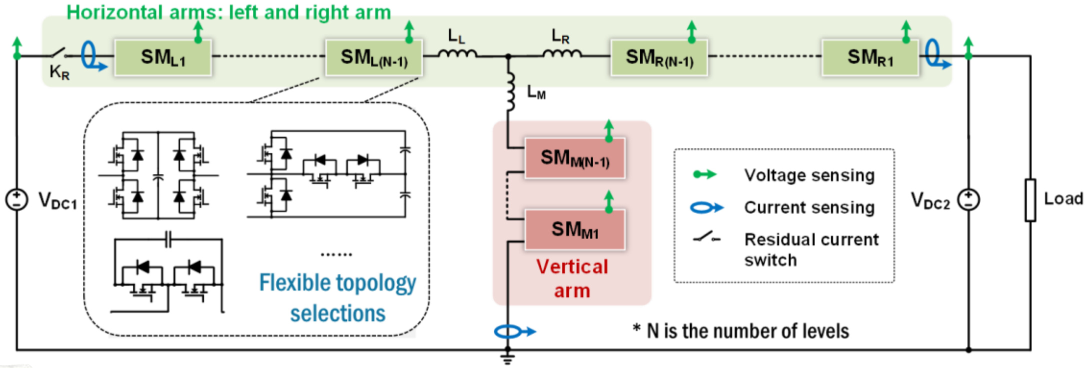
### Solid-State Medium Voltage DC Circuit Breakers

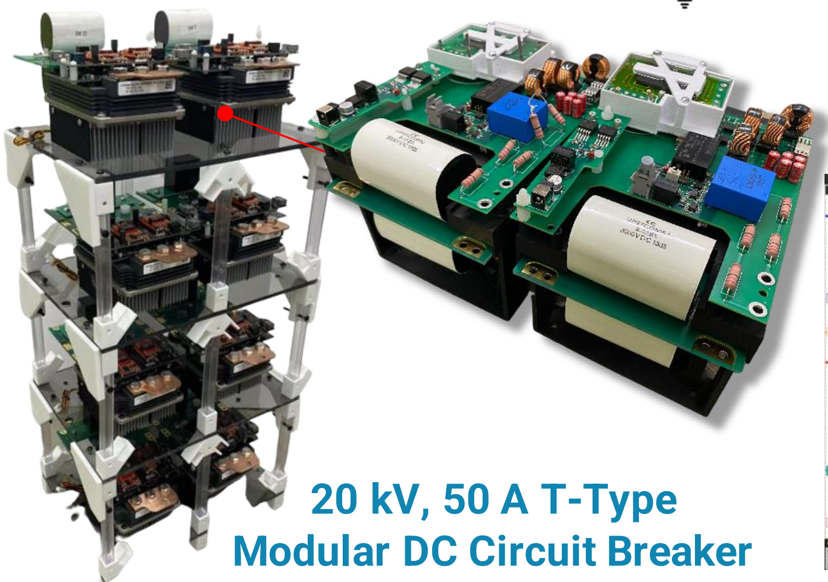



Drexel University

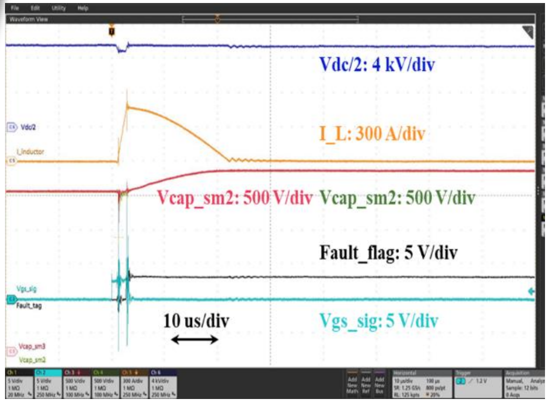
**4 kV, 100 A, <80 μs**

The Ohio State University



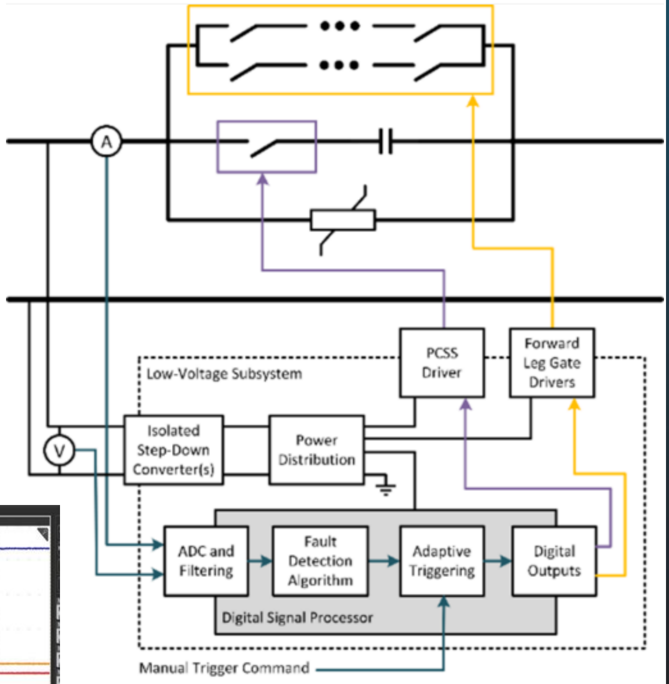



**20 kV, 50 A T-Type Modular DC Circuit Breaker**




Sandia National Laboratories

SiC JFETs



# BREAKERS

## Building Reliable Electronics to Achieve Kilovolt Effective Ratings Safely

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**2018**
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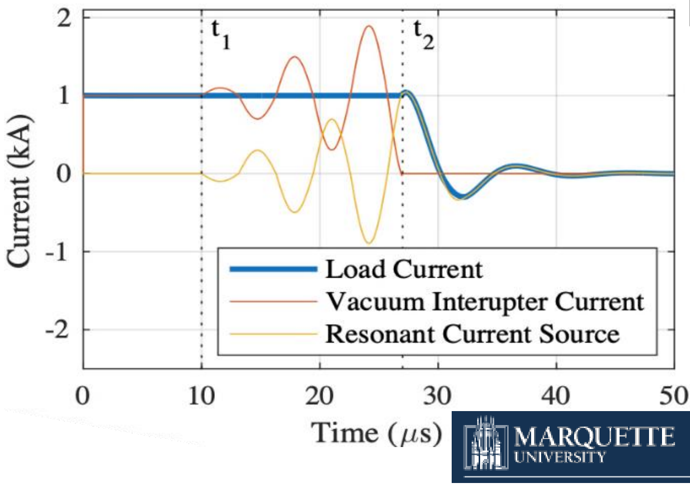
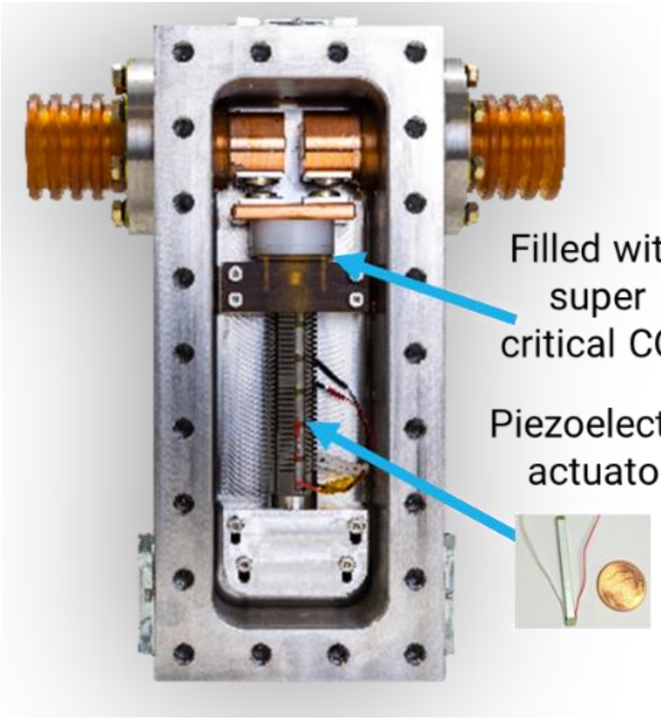
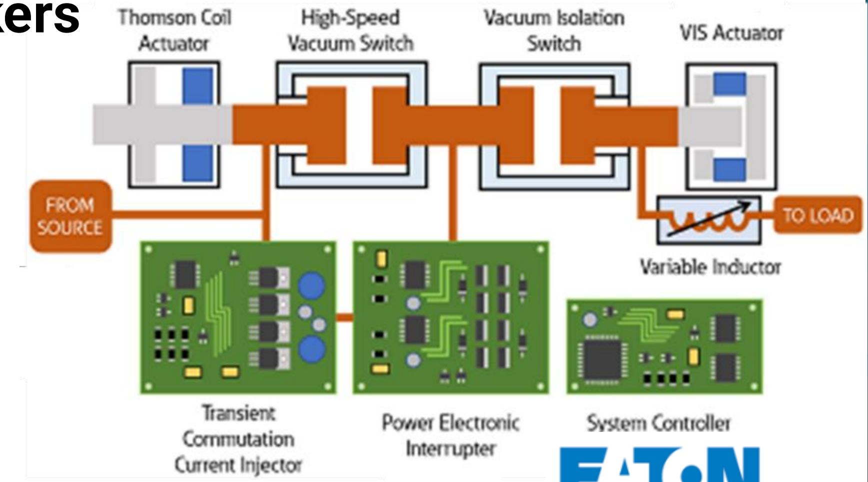



MARQUETTE UNIVERSITY

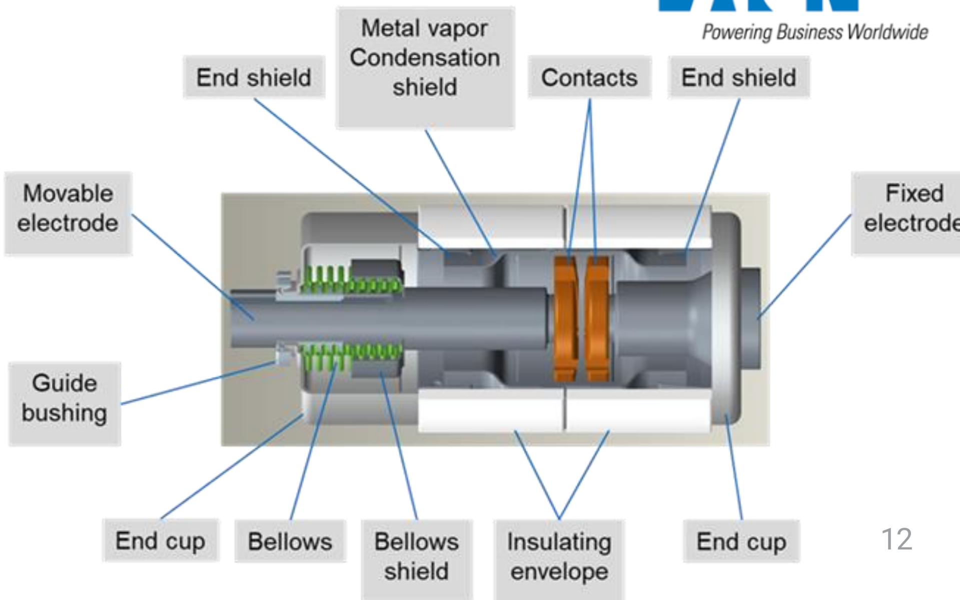
### Hybrid Medium Voltage DC Circuit Breakers




Georgia Institute of Technology

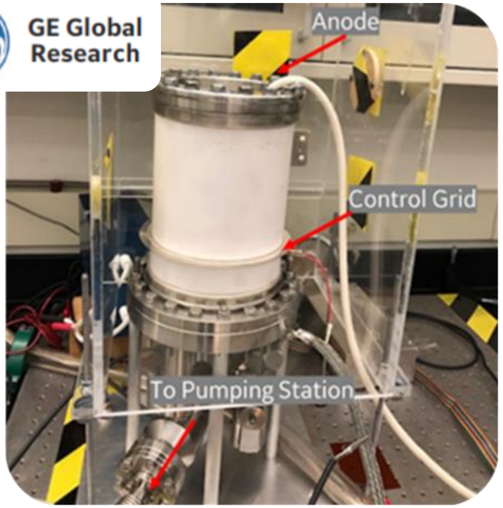



EATON Powering Business Worldwide



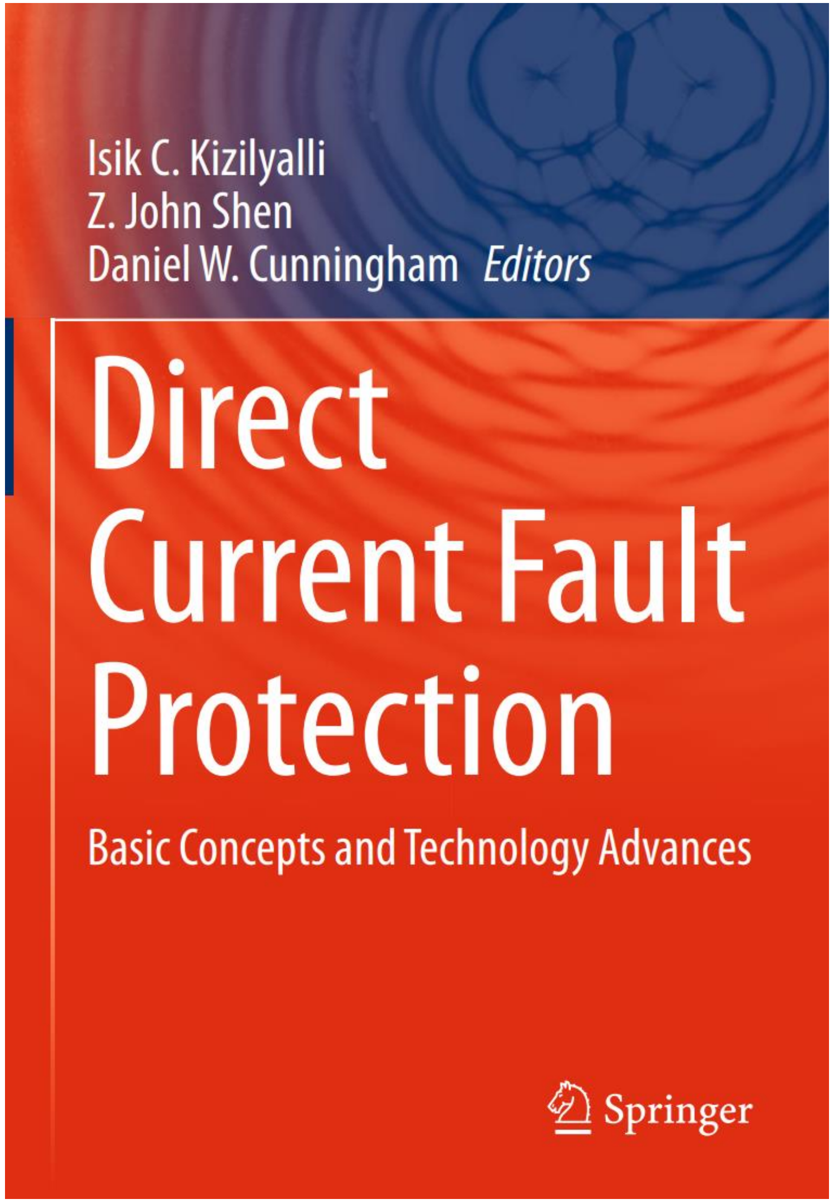

### Inline Gas Discharge Tube

GE Global Research



# April 2023

arpa·e
CHANGING WHAT'S POSSIBLE




## Contents

# SF6-FREE

Program Director: Isik C. Kizilyalli

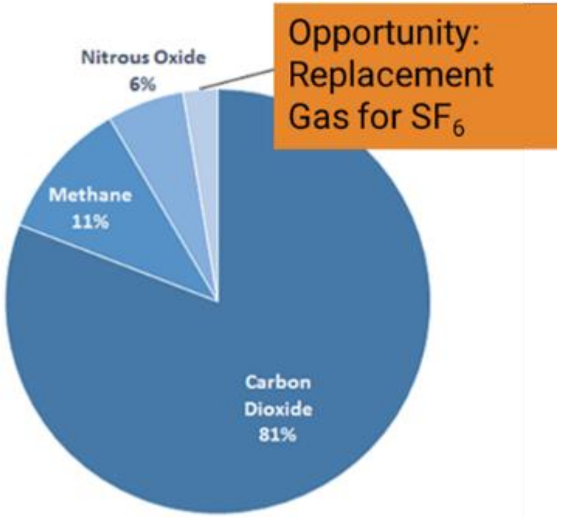
## $SF_6$-Free Routes for Electrical Equipment Exploratory Topic

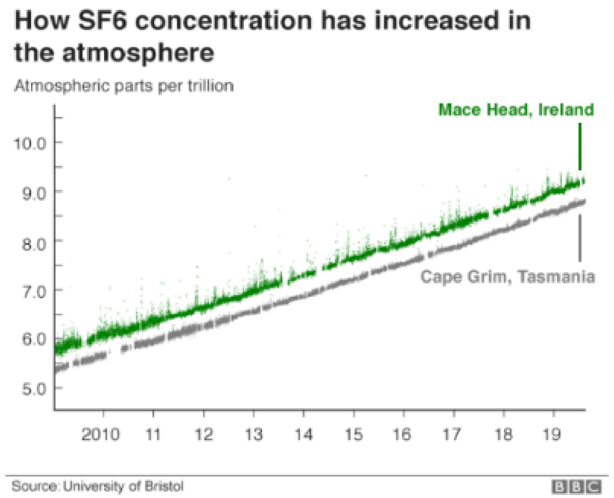
**2021**
**$10 Million**
**3 projects**

**Address innovations in low greenhouse gas (GHG) alternatives for gas-insulated equipment in the electric transmission and distribution sector (see AB 32 California)**

- High-voltage switchgear rely heavily on $SF_6$ for electrical insulation, current interruption, and arc quenching - unique dielectric properties
- **$SF_6$ emissions from the electric T/D sector pose a significant climate risk as a potent and long-lived greenhouse gas (GHG).**

| Greenhouse Gas | Global Warming Potential (100 year time span) |
|---|---|
| $SF_6$ | 22,800 |
| HFC | 12–14,800 |
| PFC | 6,288–17,340 |




Link: More about the SF6-FREE Exploratory Topic

# SF6-FREE

Program Director: Isik C. Kizilyalli

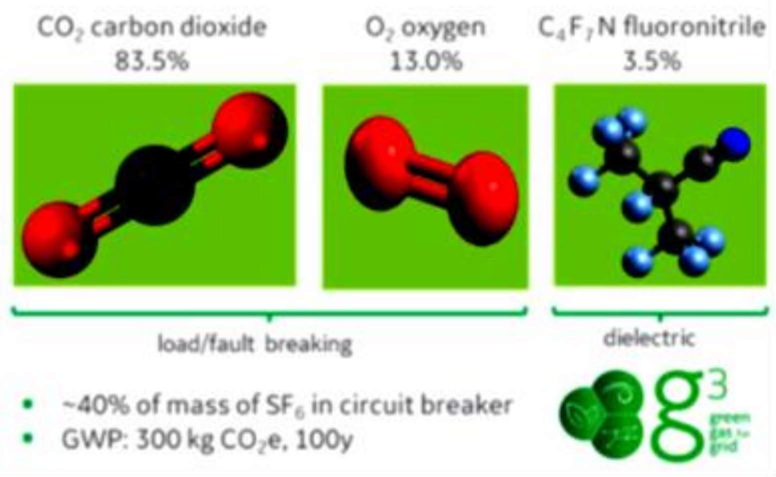
## $SF_6$-Free Routes for Electrical Equipment Exploratory Topic

**2021**
**\$10 Million**
**3 projects**

### 245 kV AC outdoor dead-tank power circuit breaker using $g^{3TM}$ gas mixture as the dielectric

GE VERNOVA

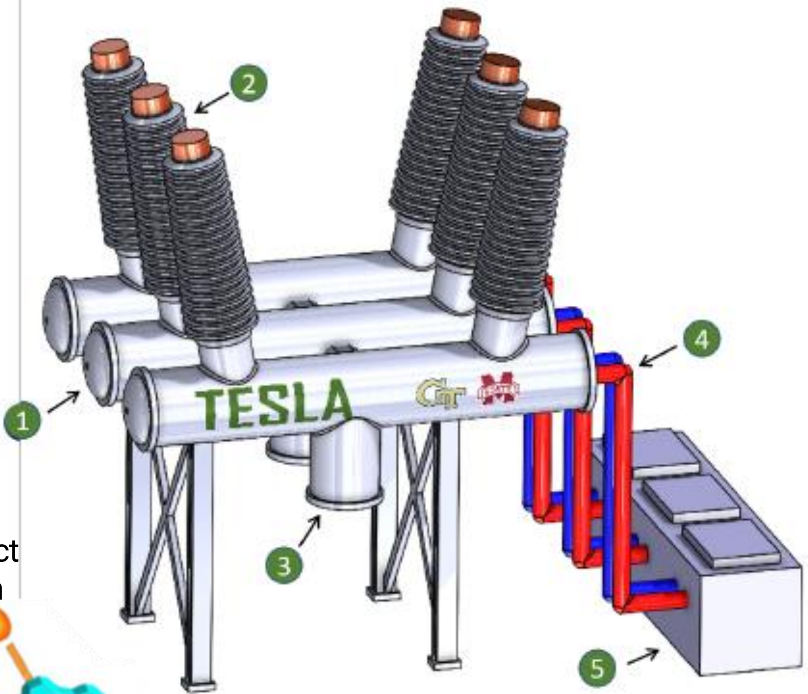

AC outdoor dead-tank CB with $g^{3TM}$ gas undergoing dielectric testing as part of ARPA-E project




Georgia Institute of Technology

UNIVERSITY of WISCONSIN UWMILWAUKEE

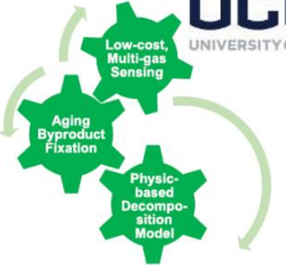
### TESLA 245 kV AC circuit breaker using supercritical fluid as the dielectric and arc-quenching medium




### $SF_6$ alternative life-cycle management framework

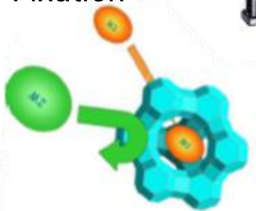
UCONN UNIVERSITY OF CONNECTICUT

GE VERNOVA




Leak Detection Aging Signature Sensing

Byproduct Fixation



Hermosillo, V., I. Garcia T. Irwin, L. Darles, C. Gregoire, "Desarrollo de un Interruptor de Tanque Muerto de 145 kV Aislado con una Mezcla de Gases Compuesta de $CO_2/O_2/C_4FN$", IEEE RVP, August 8th, 2023, Acapulco, MX

# INSULATE

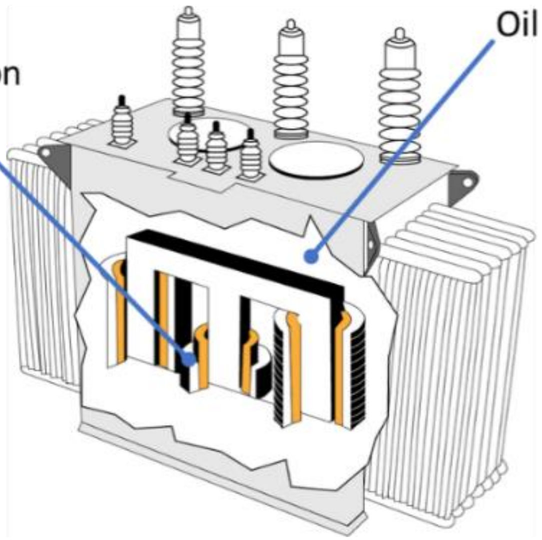
Program Director: Isik C. Kizilyalli

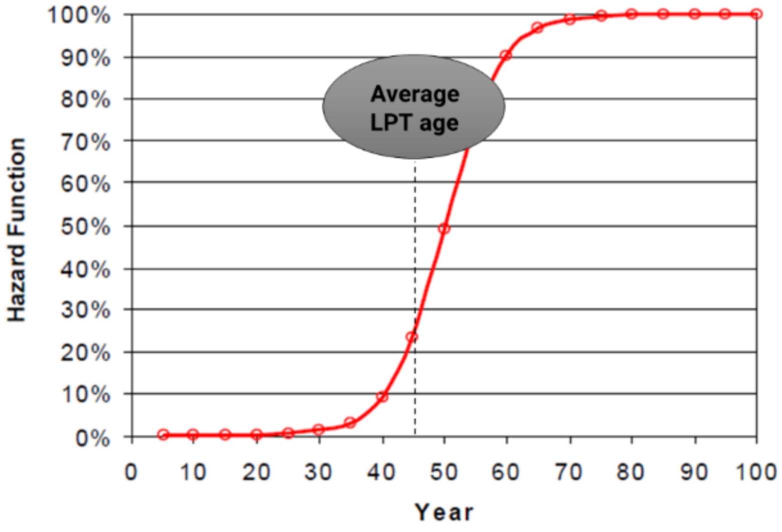
## Insulating Nanofluids and Solids to Upgrade our Large Aging Transformer Equipment Exploratory Topic

2021
$3.5+1.8 Million
3+1 projects

**Increase the durability, reliability, and resilience of large power transformers through improvements in the vital solid and oil insulating elements**

Large Power Transformers (LPTs) carry > 90% of the Nation's power




2015 CIGRE survey of 964 prominent transformer failures found the major reason for transformer collapse was dielectric (i.e., insulation failure).

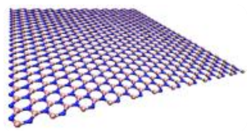
Bartley, William H. "An Analysis of Transformer Failures." *Hartford, CT* (1997).
DOE. Large Power Transformers and the Electric Grid. 2012.

Link: More about the INSULATE Exploratory Topic

# INSULATE program goal is to double transformer lifetime

ARPA-E CHANGING WHAT'S POSSIBLE

Functionalized 2D hexagonal boron nitride nanoparticles



Commercial Transformer Mineral Oil

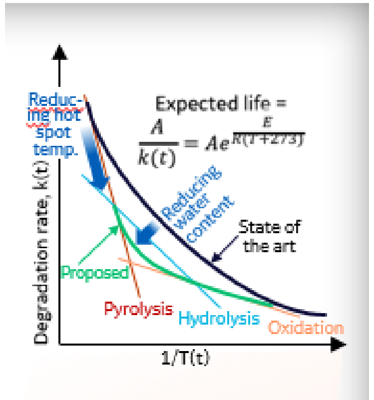
Nanofluid with suspended h-BN

| Thermal Conductivity (W/mK ) | Viscosity (cp) |
|---|---|
| 0.193 | 10.5 |

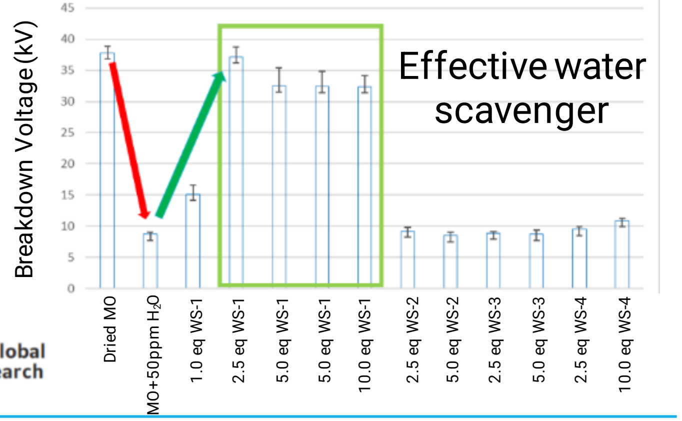
h-BN: excellent electrical insulator, high temperature resistance, high chemical inertness, and superhydrophobicity

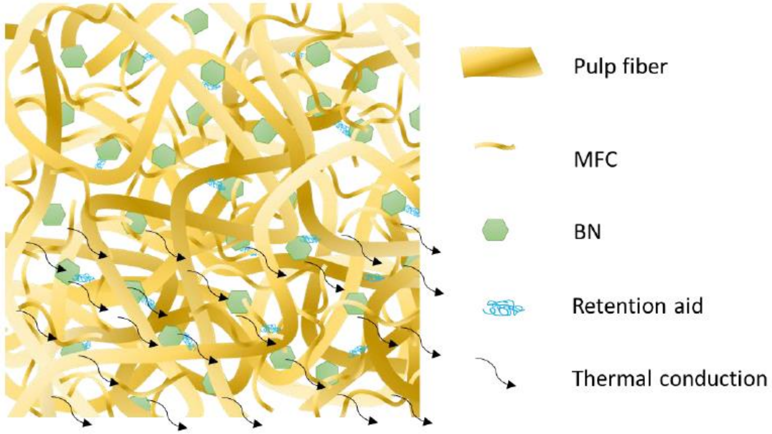
C-Crete TECHNOLOGIES

- $TiO_2$-based nanofluid to improve thermal conductivity and enhance dielectric strength
- Soluble water-scavenger to reduce water content

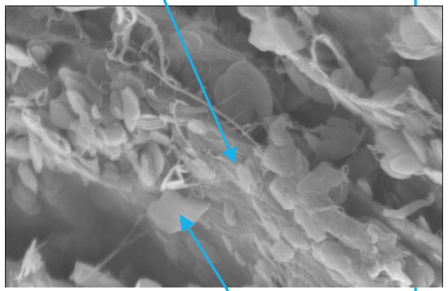



GE Global Research



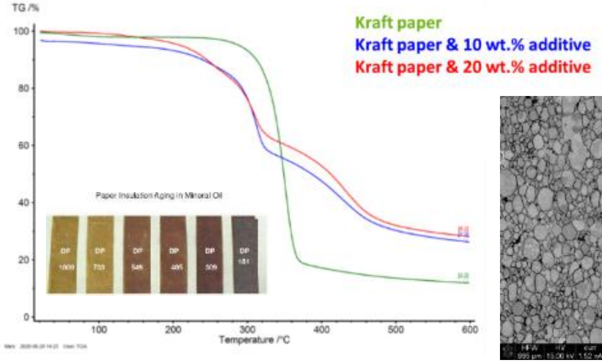

Microfibrillated cellulose (MFC) + pulp fiber

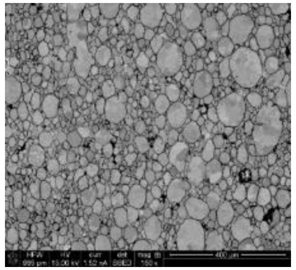


Boron nitride particle nano-additive

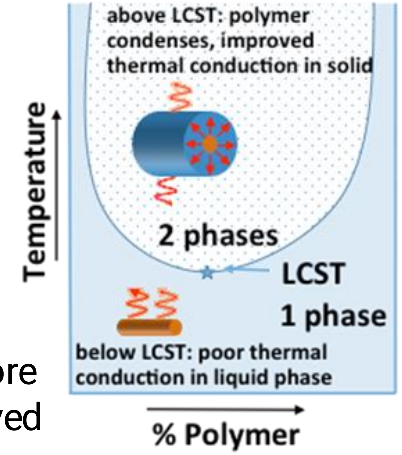
h-BN has high thermal conductivity and high dielectric constant

TEXAS The University of Texas at Austin



- Kraft paper remediation process
- Efficient CoFe/insulating shell transformer core
- Phase changing polymer additives for improved transformer oil heat transfer




Sandia National Laboratories

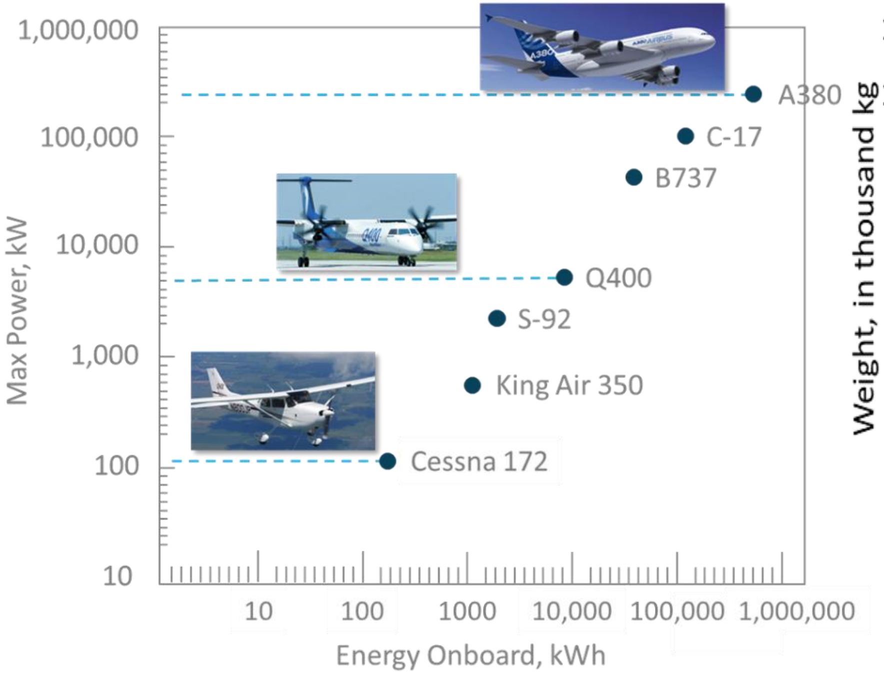
# CABLES

## Connecting Aviation By Lighter Electrical Systems Exploratory Topic

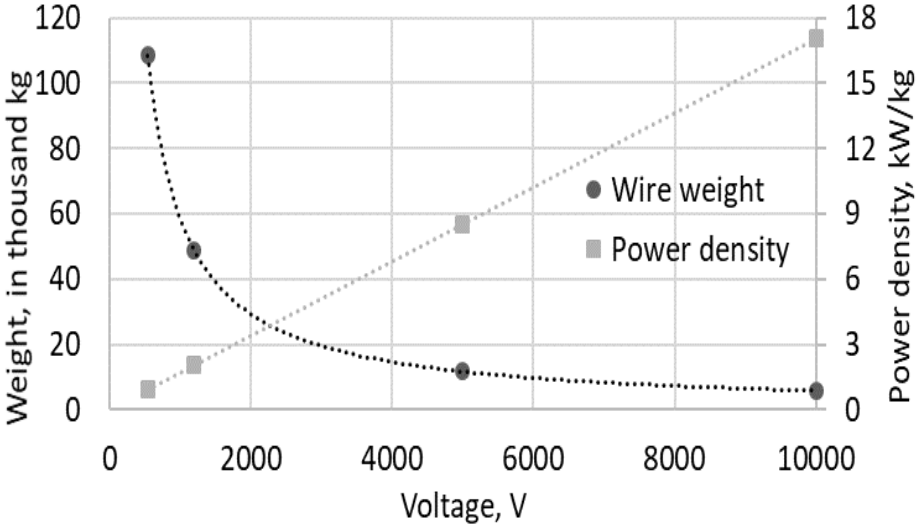
Program Director: Isik C. Kizilyalli

**2021**
**$12 Million**
**7 projects**

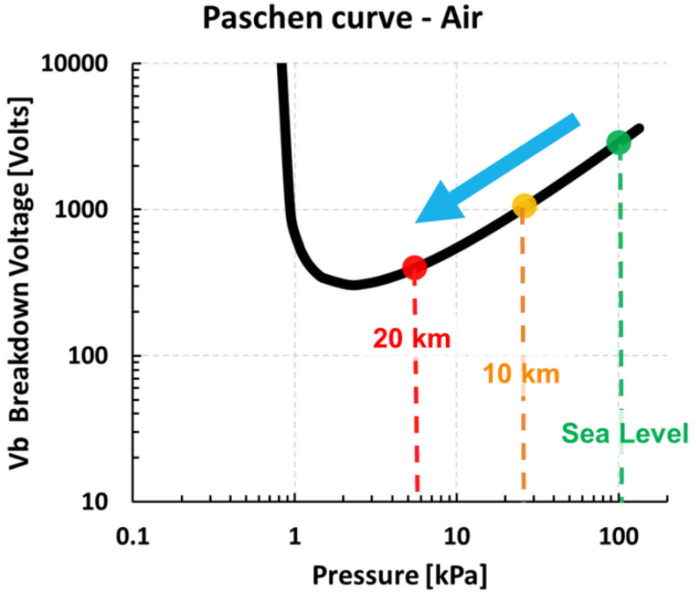
**Develop technologies for medium-voltage (>10 kV) power distribution cables, connectors, and circuit breakers for fully electric aviation applications to enable megawatt scale distribution with minimal impact on weight while maintaining the high reliability and safety requirements of aviation.**



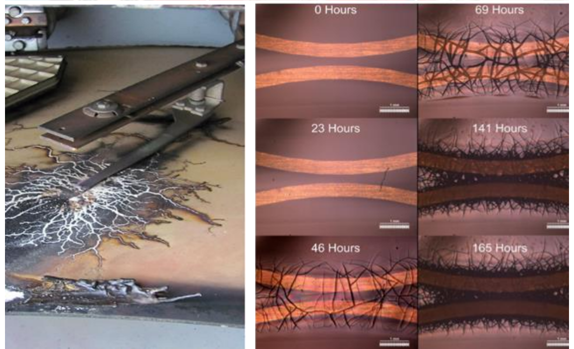

Source: National Academies of Sciences, Engineering, and Medicine. 2016. *Commercial Aircraft Propulsion and Energy Systems Research: Reducing Global Carbon Emissions*. Washington, DC: The National Academies Press.




Voltage *vs.* copper wiring weight (no insulation) and power density




**Partial discharge leads to failure**



Link: More about the CABLES Exploratory Topic

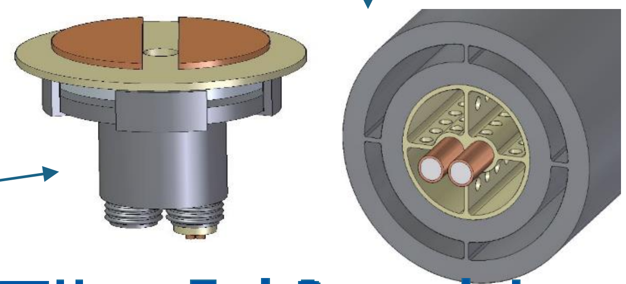
# Connecting Aviation By Lighter Electric Systems (CABLES) Technology Portfolio: 10kV and 10km, Will it Fly?

CHANGING WHAT'S POSSIBLE

GE Global Research

Gas/liquid Electrically Insulated

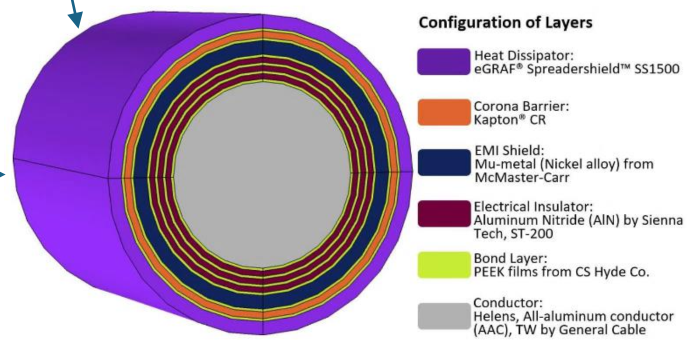
Aluminum Conductors



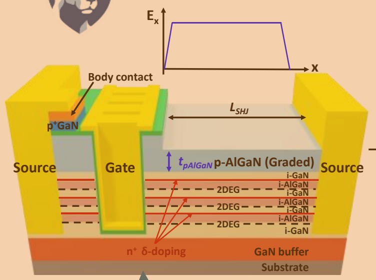
Hyper Tech Research, Inc.

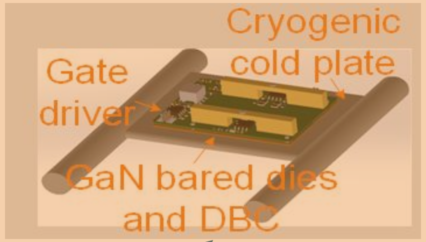
VIRGINIA TECH

Novel Solid Insulation

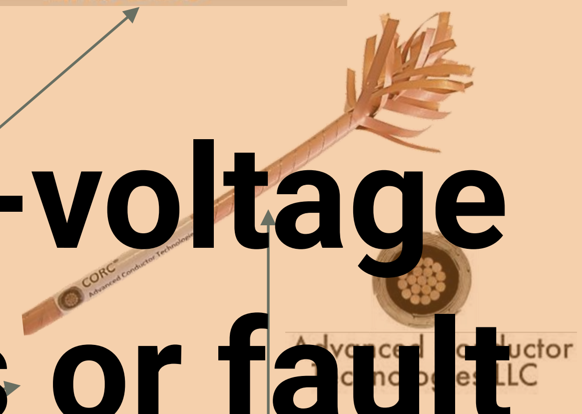



PennState




THE UNIVERSITY OF TENNESSEE KNOXVILLE

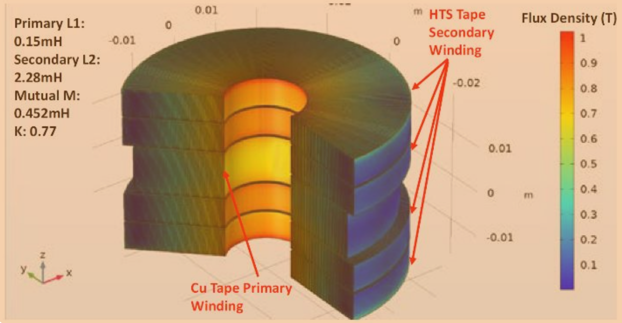



Advanced Conductor Technologies LLC

Medium-voltage breakers or fault current limiters.

Cryocooled

Superconducting

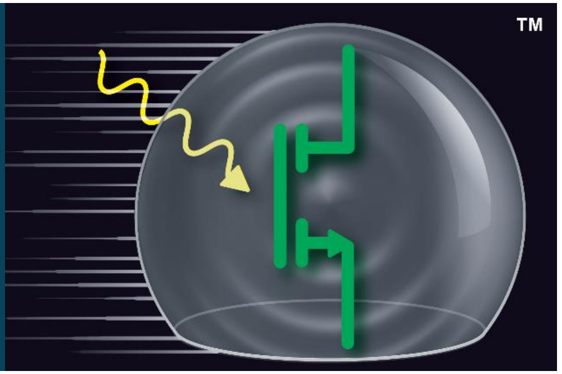



ILLINOIS INSTITUTE OF TECHNOLOGY

# ULTRAFAST

Program Director: Olga Spahn

## Unlocking Lasting Transformative Resiliency Advances by Faster Actuation of power Semiconductor Technologies

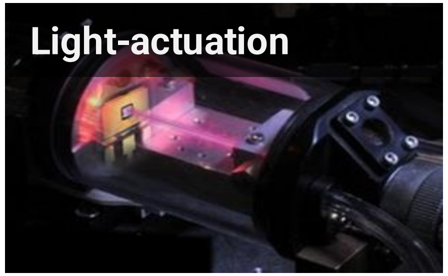


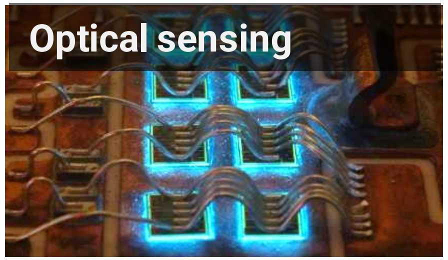

CHANGING WHAT'S POSSIBLE

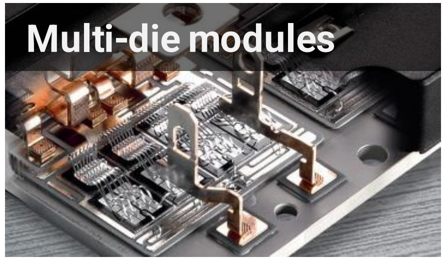
| | |
|---|---|
| **Kickoff Year** | 2024 |
| **Projects** | 15 |
| **Investment** | $42M |
| **Duration** | 36 months |

**Next generation material, device and module technologies for improved power distribution and control in future grid applications**

- **Ultra-wide Bandgap materials for higher power individual devices and modules**
  [protection > 20 kV, > 250 A | continuous switching > 3.3 kV, > 10 A ]
- **EMI mitigation for improved stacking reliability**
  [wireless/optical actuation, control and sensing]
- **Faster actuation – improved protection, better control, lower losses**
  [ 1-100 kHz | > 250 V/ns, > 100 A/ns | > 99% efficiency ]
- **Better Size Weight and Power (SWaP)**
- **Supporting enabling technology – sensing, passives, packaging, gate drive technology**



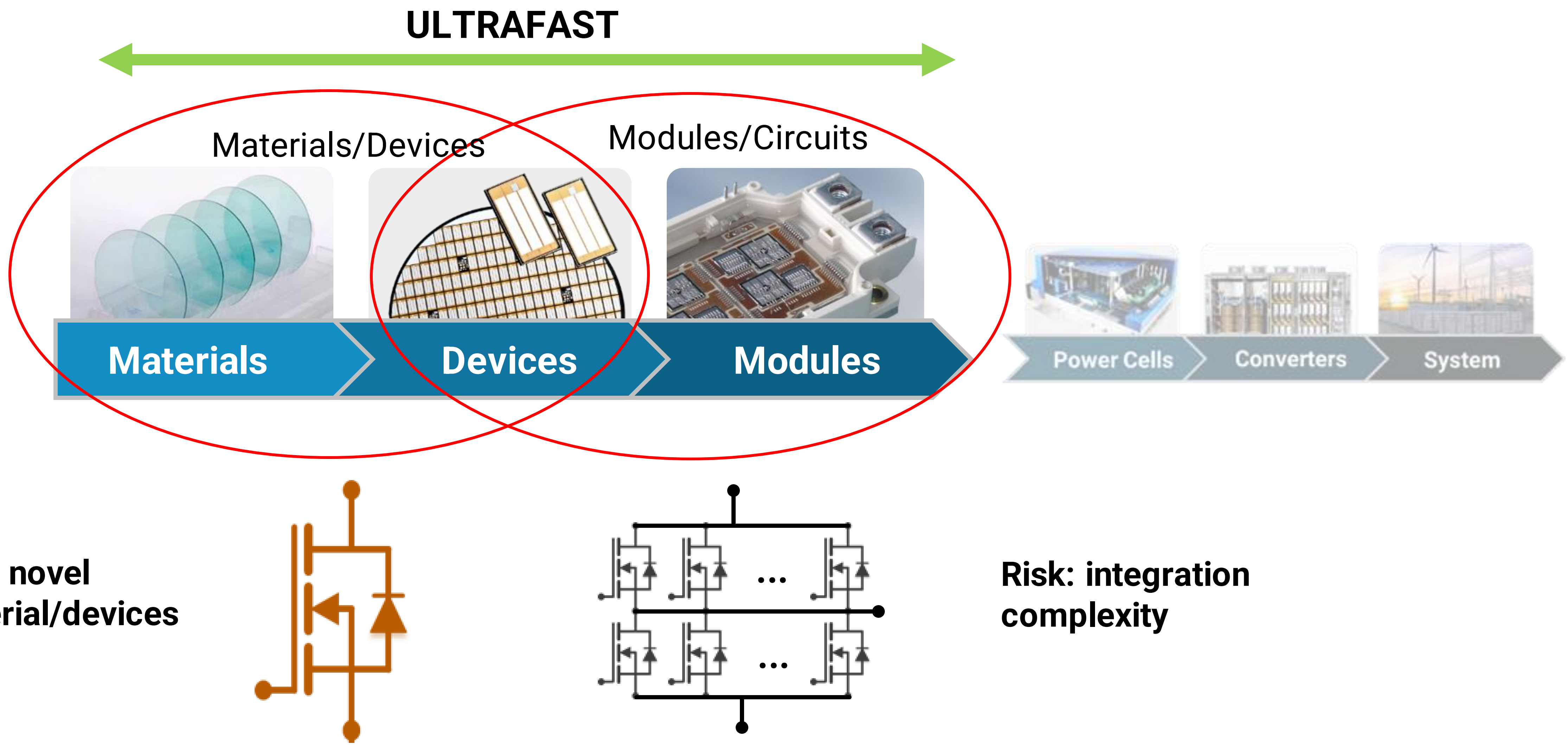




Link: ULTRAFAST Program Announcement Link: Power Magazine News Link: ARPA-E Website Info

# ULTRAFAST Project Types






**Risk: novel material/devices**

**Risk: integration complexity**

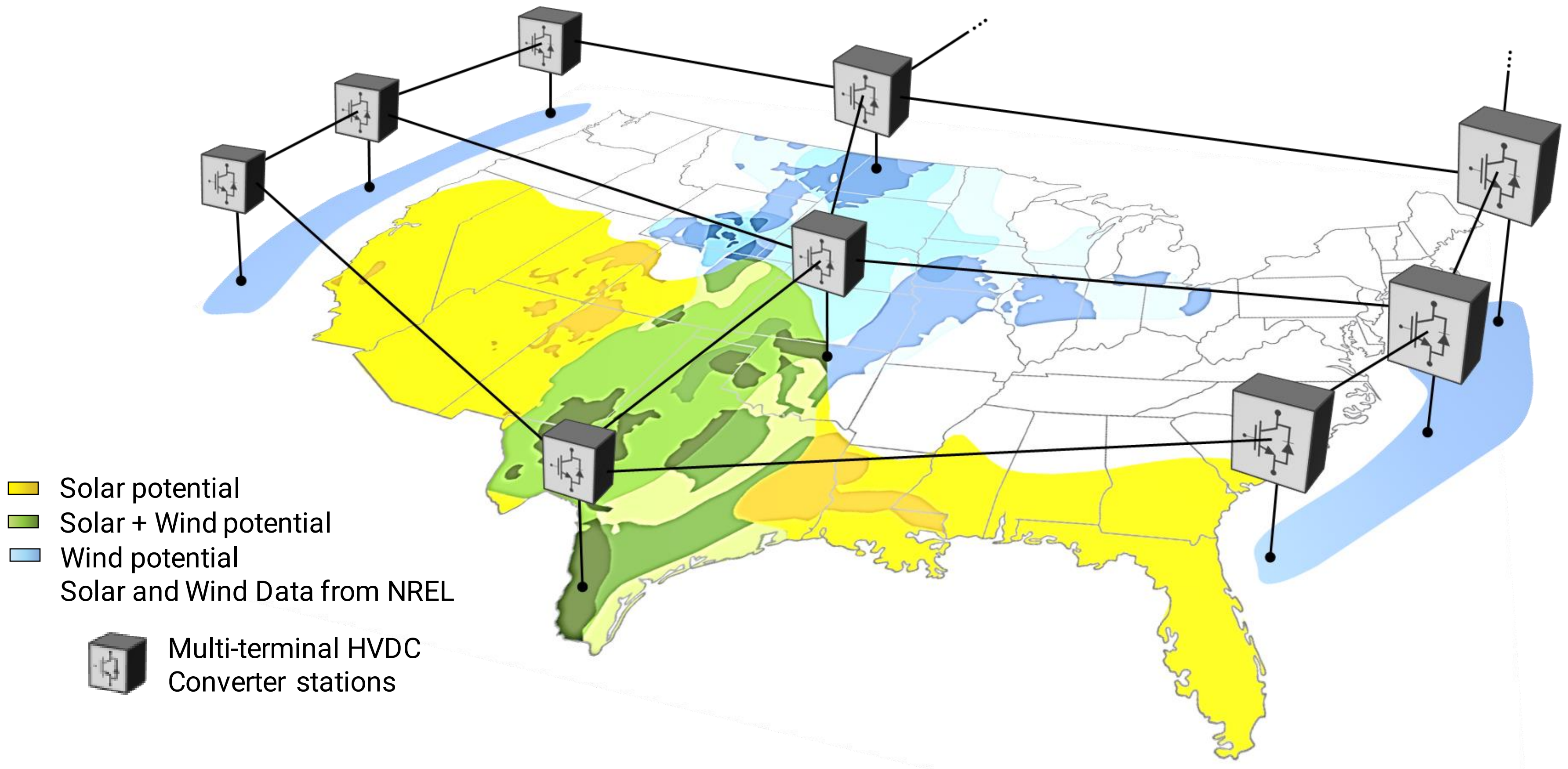
Program Director: Johan Enslin

CHANGING WHAT'S POSSIBLE

# Potential New Program

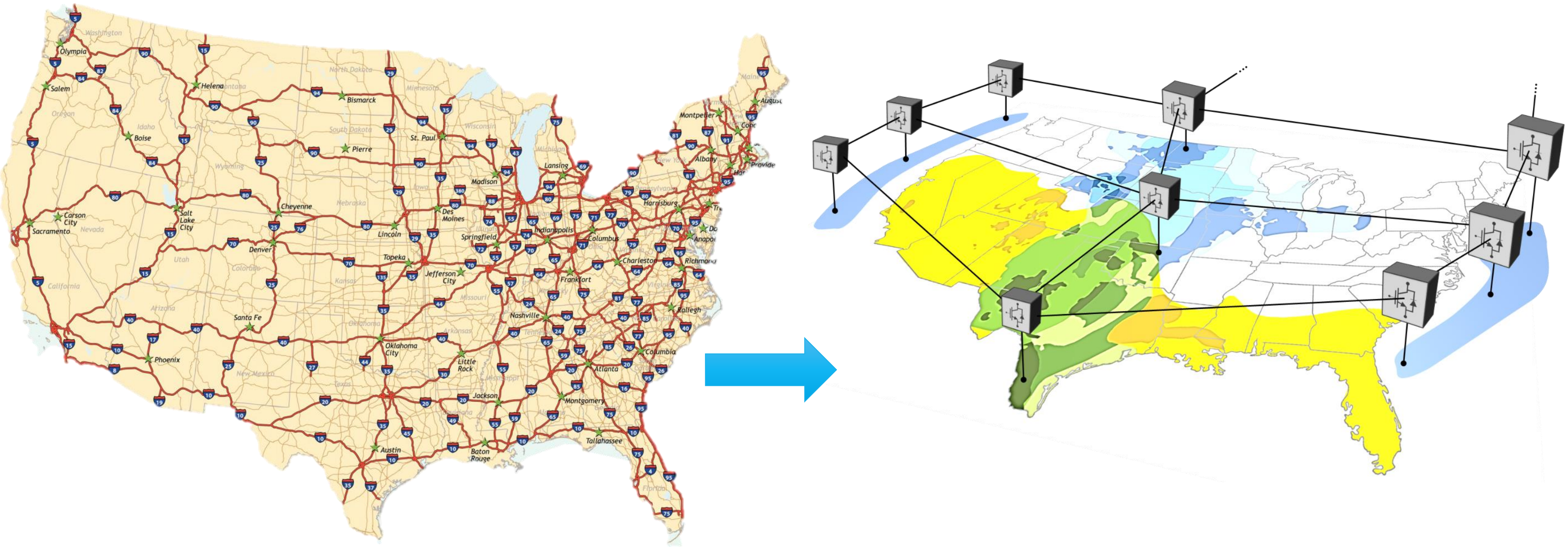
# MTDC Network to Support Grid Capacity for Carbon-free Generation

| | |
|---|---|
| **Kickoff Year** | 2025 |
| **Projects** | TBD |
| **Investment** | TBD |
| **Duration** | TBD |



# Super Electronic Highway Grid is Needed!





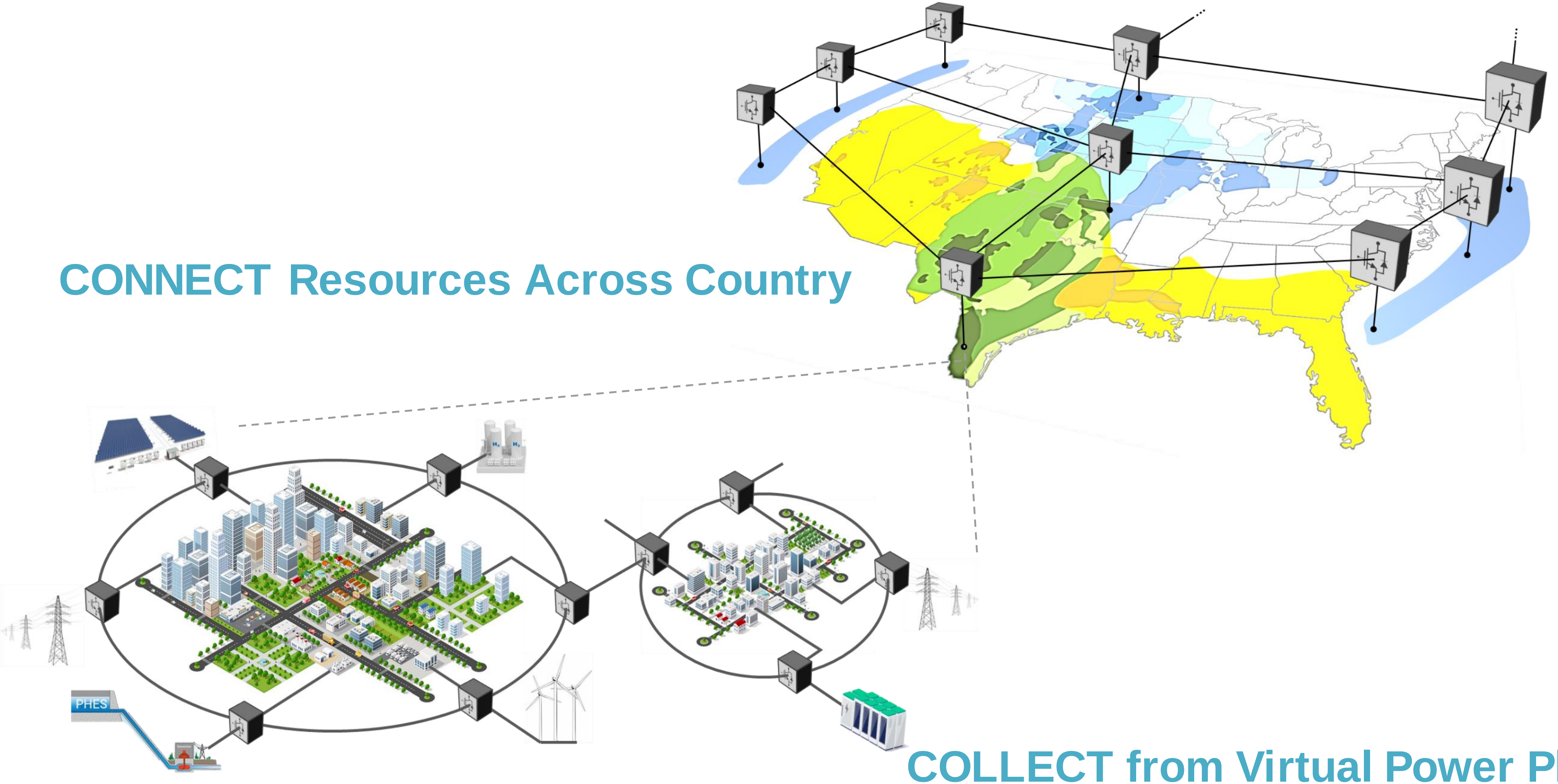

US Transportation Highway System and Transporting to an Electric Super Highway

# Why do we need to Modernize the Power Grid?

- 100 years old centralized T&D infrastructure for centralized plants
- Incompatible with carbon-neutral power generation integration
- Net-zero carbon goals by 2050 – Urgency for new technology


- > 3x Electrical load growth by 2050 (3-4 TW) [EIA]
- Hybrid electrical and hydrogen energy networks
- Large-scale hydro, battery and hydrogen storage

# How are the grid’s *architecture* evolving?




CONNECT Resources Across Country

COLLECT from Virtual Power Plants

# Designing tomorrow's Super Integrated Grid NOW!

CHANGING WHAT'S POSSIBLE

1. **Super Electronic Highway Grid**

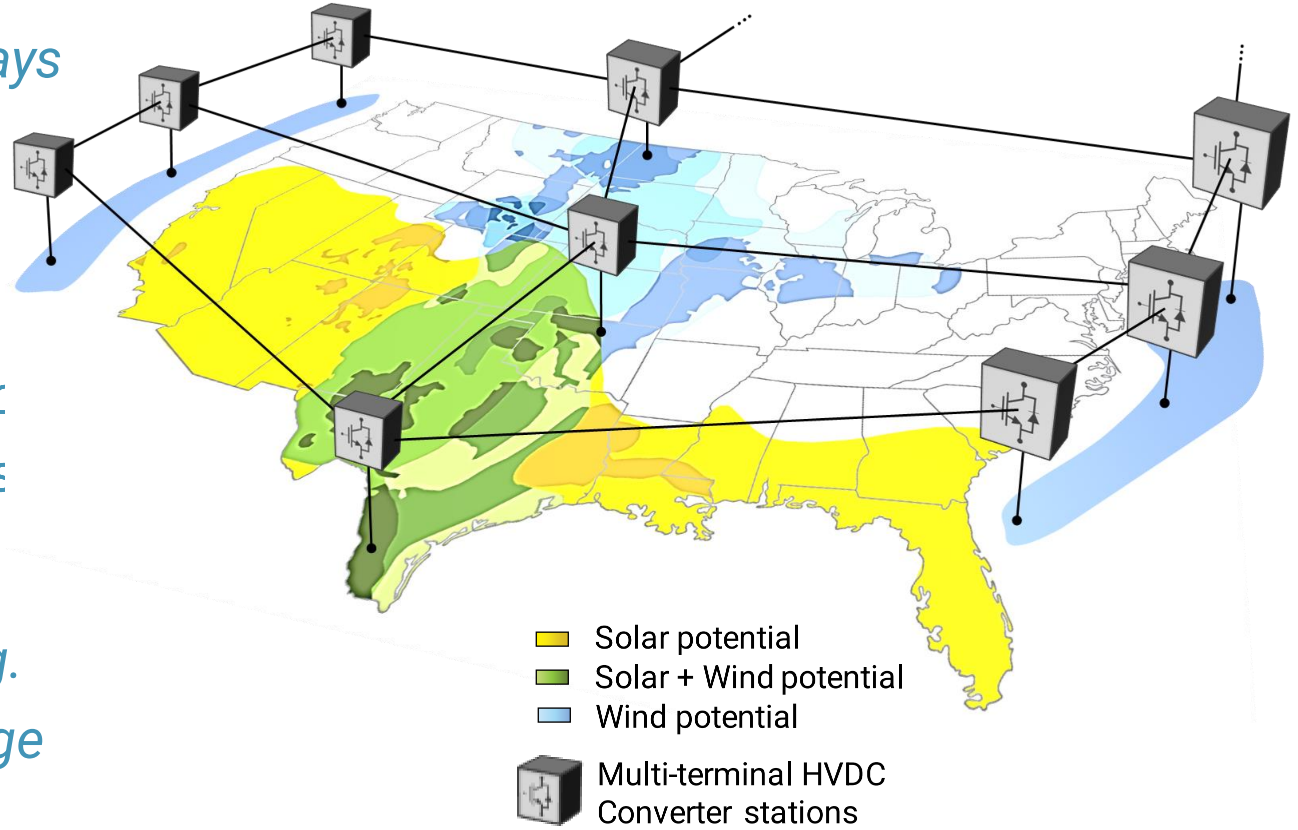
   *Connect with HVDC Electronic Grid-of-Grids*
   *Release Capacity from "Regional AC&DC Grids"*
   *Collect from MicroGrids and Active Loads*
   *Build on Existing Infrastructure & Right of Ways*

2. **Transform Integrated System Operations**

   *Hybrid AC&DC Solid-state Substations*
   *Release existing AC-Grid Capacity -2-3x*
   *Provide Diversity and Equity in Interconnectic*
   *Increase Distributed Resiliency through VPPs*

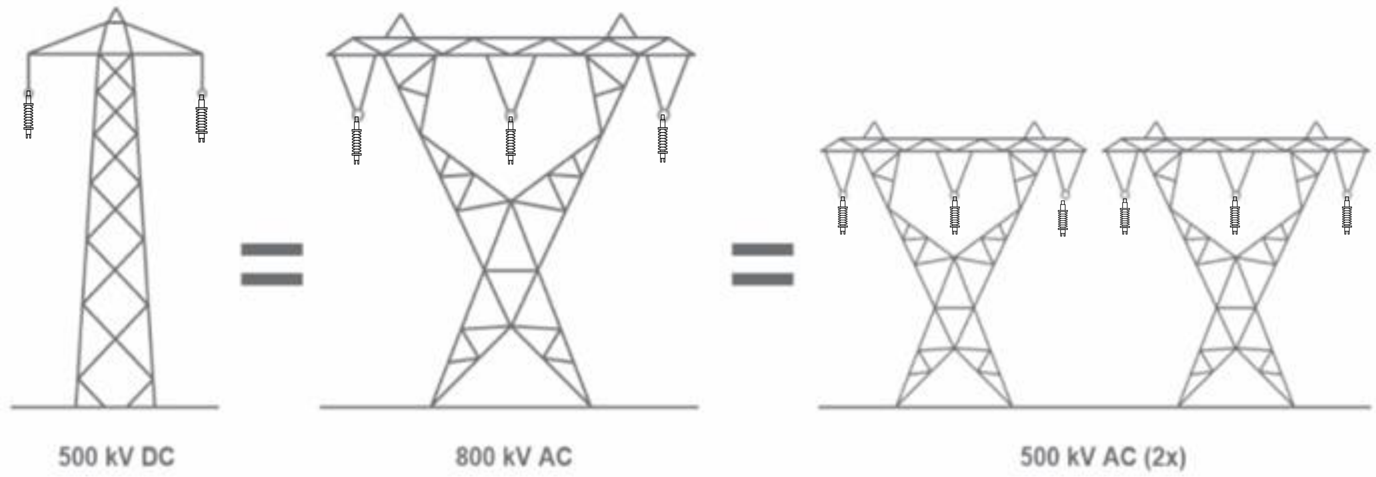
3. **Balance Energy Storage with Time Shift**

   *Seasonable & daily renewable energy shifting.*
   *Interconnecting Dynamic Pump-Hydro Storage*
   *Power-2-X with H2 Storage*
   *Integration of Chemical and Thermal Energy Transfer Networks*



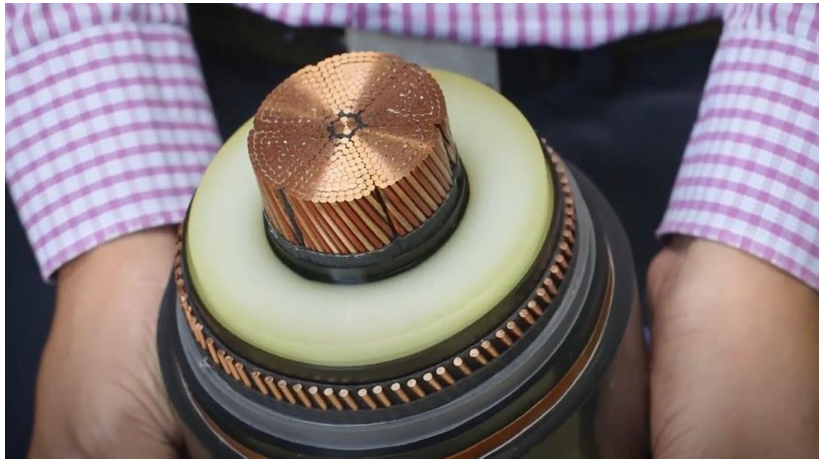
# Utilizing Existing Grid Infrastructure – HVAC v/s HVDC

## 1/3 – DC v/s AC OVL at 500 kV



# DC Enables Fully Imperceptible Infrastructure







525 kV Cable, >2 GW
The whole conductor cross-section utilized

Can either repurpose existing transmission (300 % capacity increase) or go underground:

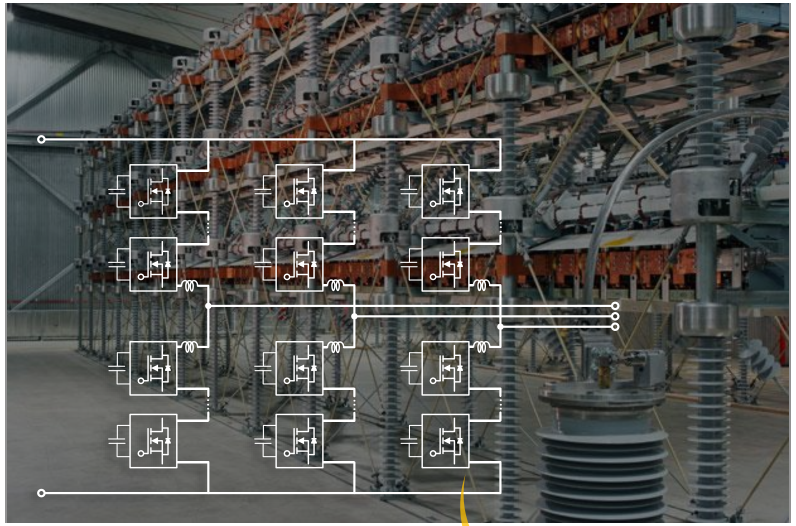
Or utilize highway medians for cable installation

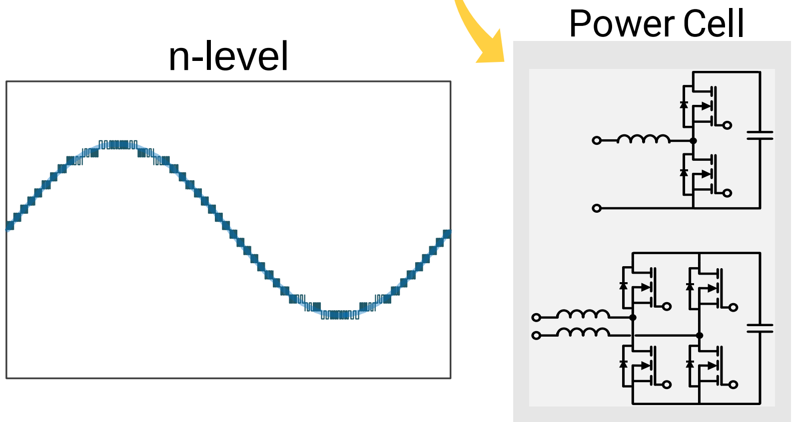


# Technology Gaps

- **New HVDC Converter Topologies**

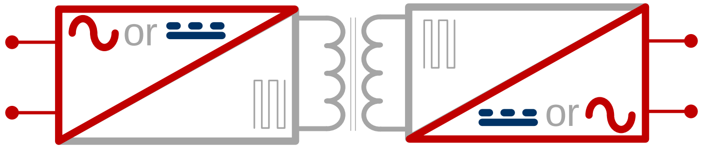
(Beyond state-of-the-art Modular Multi-level Converter)



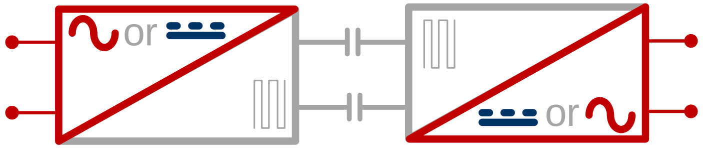



**Now utilizing inductively or capacitively coupled power cells for significantly higher flexibility, modularity, and reliability**

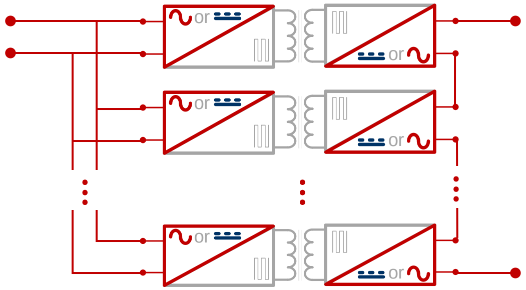
Inductively coupled power cells




Capacitively coupled power cells




Independent series/parallel connection of galvanically isolated power cells for high voltage and high current design



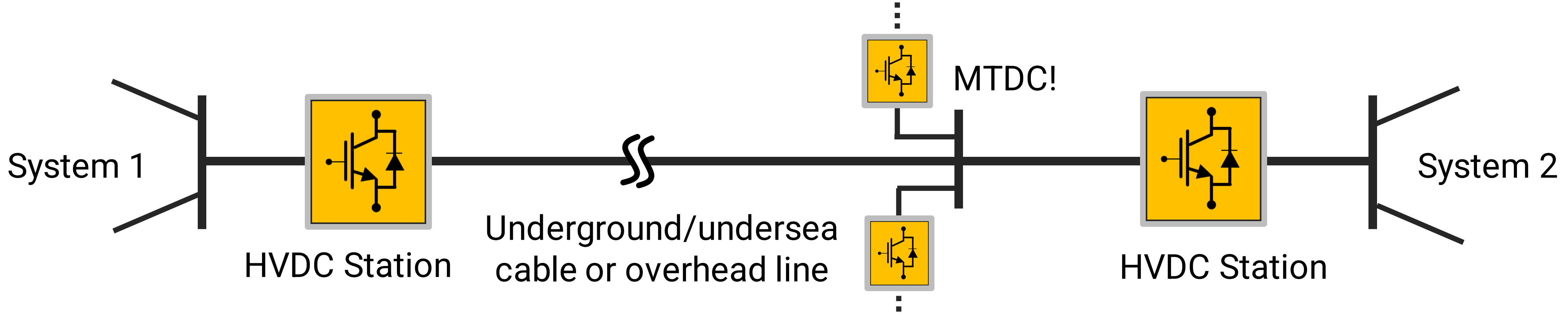
Experimentally validated with scaled-down hardware and P-HIL simulations

# HVDC Stations



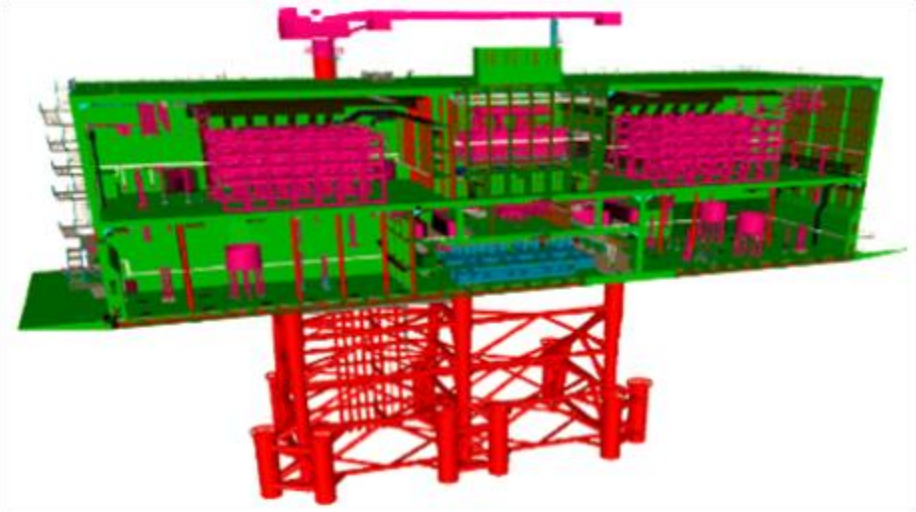
**On-shore HVDC Station**


**Off-shore HVDC Station**

# Example: Dolwin 3 Offshore Platform (SOA)

(HB MMC Topology - < 1 GW / 325 kVdc )

Valve Hall

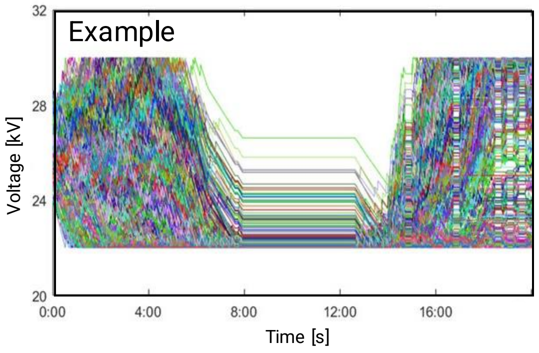
Images by GE Vernova

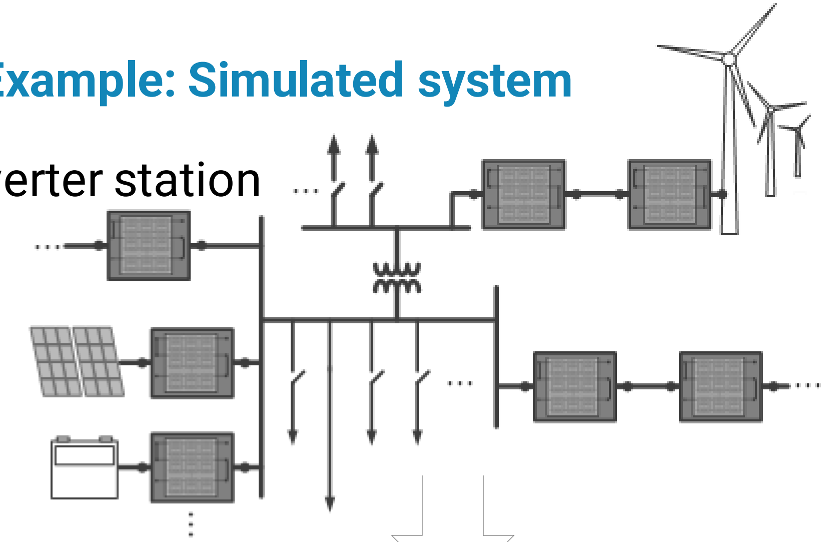
# System-Level EMT Modeling for Planning and Operations

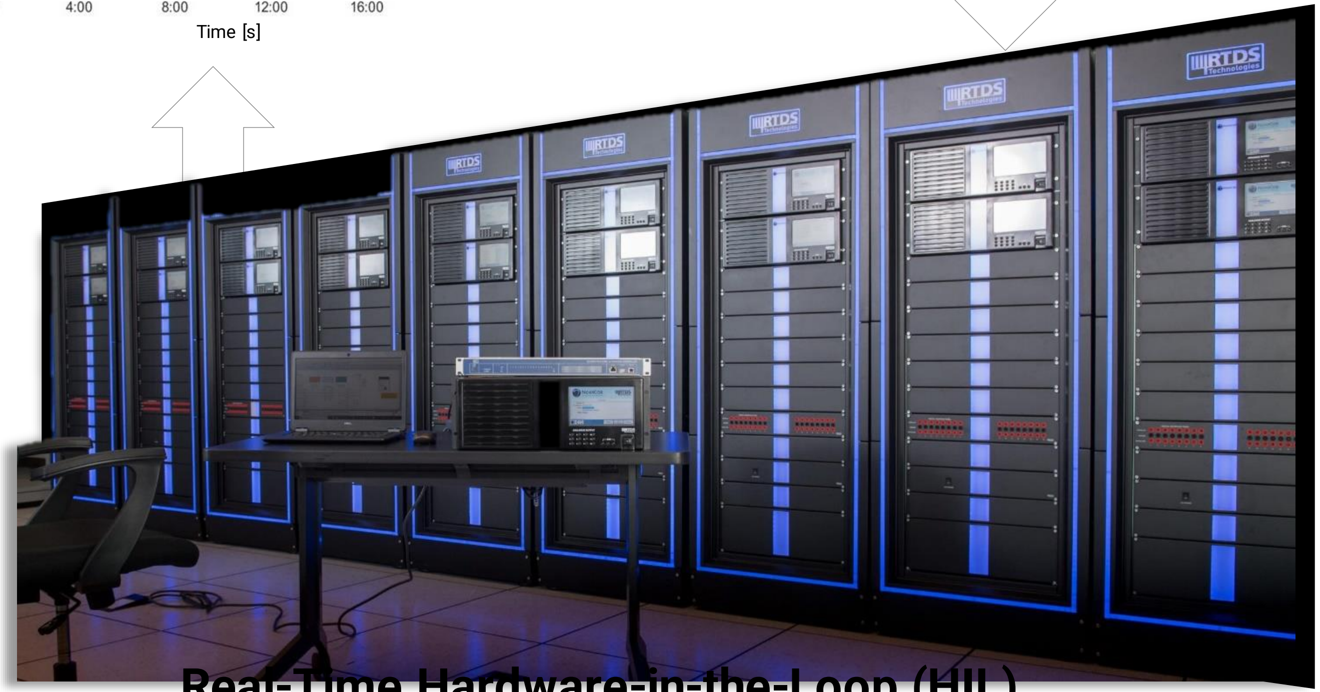
CHANGING WHAT'S POSSIBLE

## Example: Simulated system

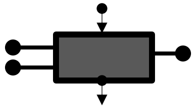
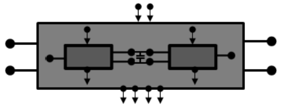
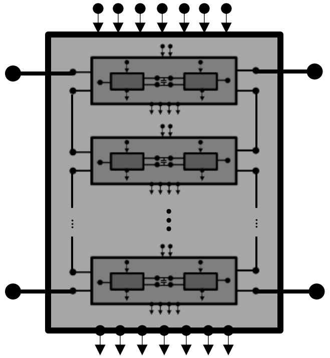
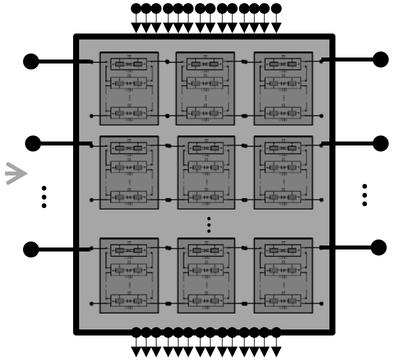
Converter station



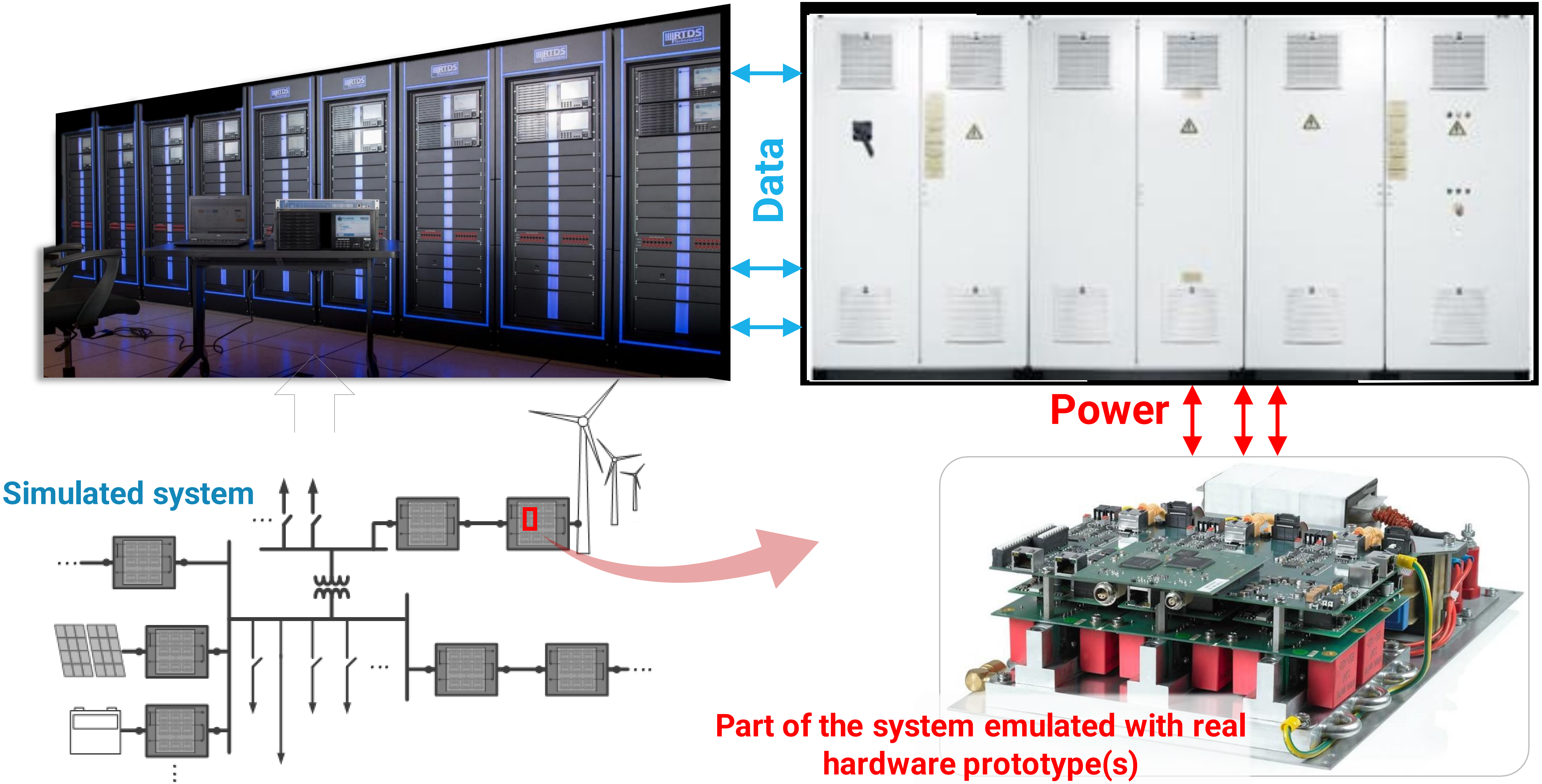



Real-Time Hardware-in-the-Loop (HIL)

| Component | | Model |
|---|---|---|
| Power Module |  |  |
| Power Cell/ Sub-module |  |  |
| Converter "Valve" or DC Breaker |  |  |
| Converter Station |  |  |

# System-Level Emulation in Real-Time Environment, with P-HIL





Program Director: Johan Enslin

## Potential New Program

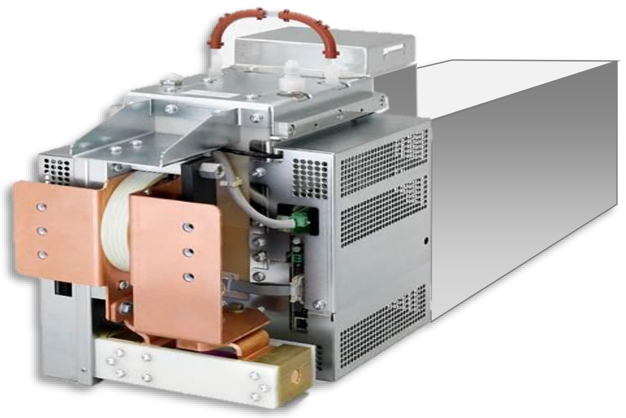
# MTDC Network to Increase Grid Capacity for Carbon-free Generation and Active Loads

CHANGING WHAT'S POSSIBLE

| | |
|---|---|
| **Kickoff Year** | 2025 |
| **Projects** | TBD |
| **Investment** | TBD |
| **Duration** | TBD |

### New Power Electronic Building Blocks for HVDC submodules

**50 kV, 2000 A**, PEBB Sub-Modules featuring **> 50%** higher power density

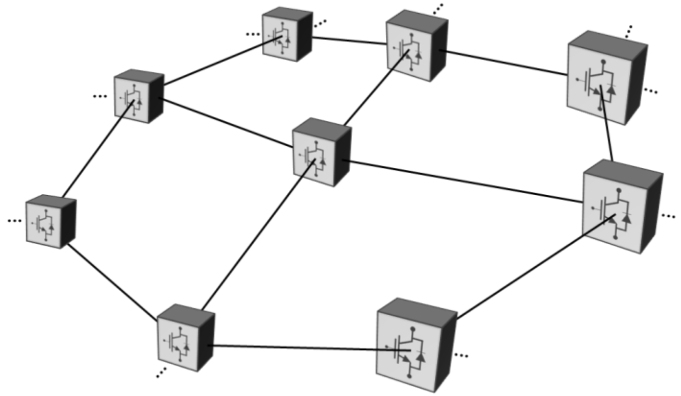


### New Multi-Terminal HVDC Converter Station Design

**5-fold** power density and cost reduction (**from 250 $m^3$/MW and $250 k/MW**)


### System Integration and Operation

Multi-terminal HVDC operation in P-HIL for **> 9 terminals**



# *Thank you*

Questions / Comments / Suggestions ?

Ask us about the Upcoming MTDC Workshop June 6/7 in DC

**Johan Enslin, Program Director, ARPA-E, johan.enslin@hq.doe.gov**

**Isik Kizilyalli, Advisor, ARPA-E, isik.kizilyalli@hq.doe.gov**