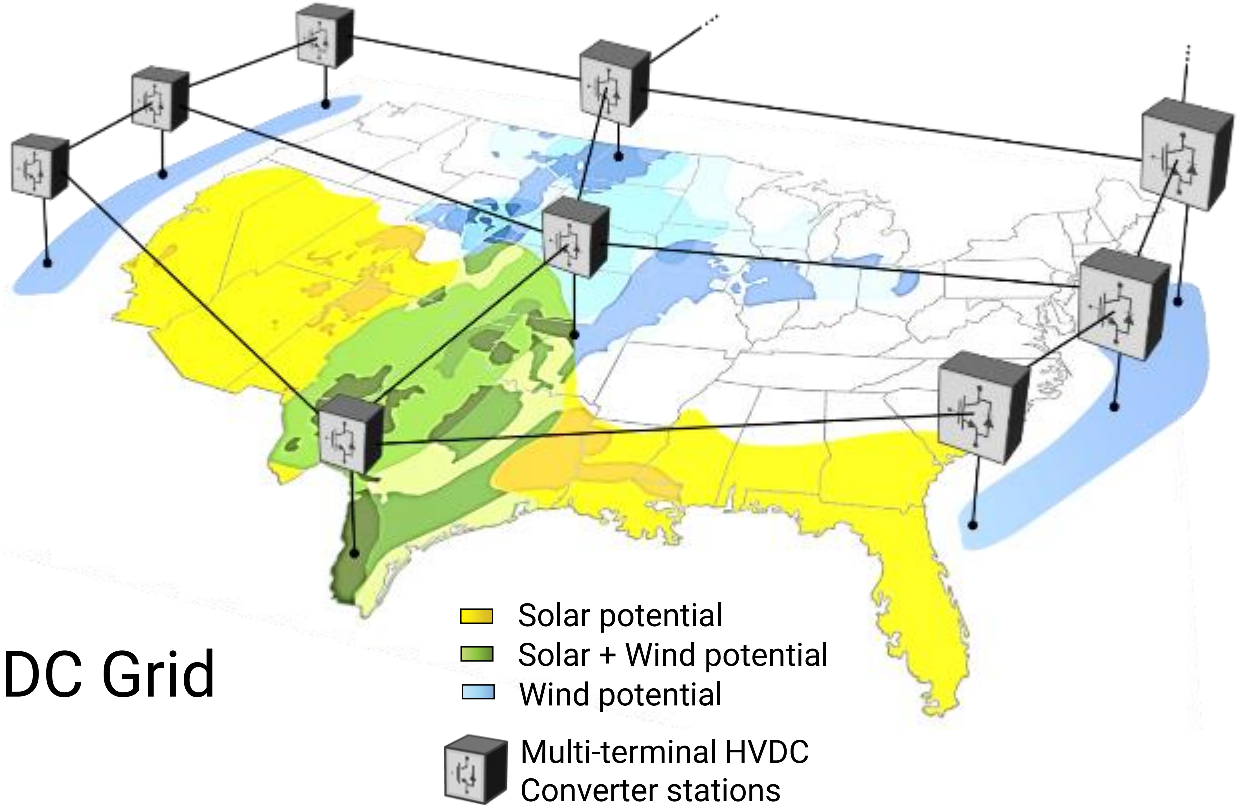
Transmission Grid Technical Requirements, Skills, Career Opportunities by 2050

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

August 29, 2024

Outline

- Introduction
- Status of Grid in USA
- Motivation and problem statement
- Need for a Macro DC Grid in USA
- Technology Gaps
- System Operation Challenges
- Skills Needs for the Integrated AC & DC Grid
- Conclusions



[ARPA-e MeGRID Workshop 6-7 June 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

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

There are three distinct (AC) grids in the U.S.

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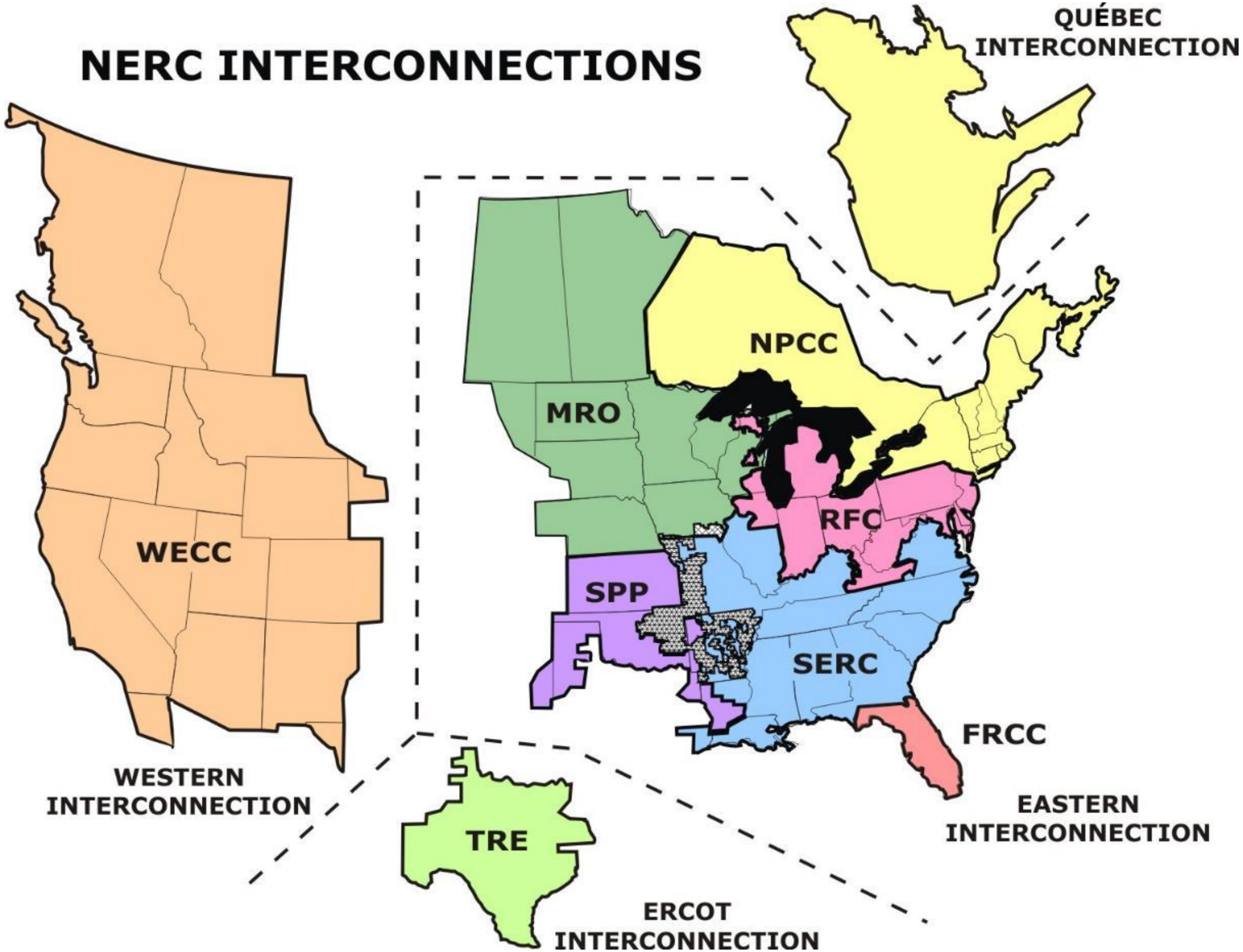

https://www.vox.com/energy-and-environment/2018/8/3/17638246/national-energy-grid-renewables-transmission

Climate crisis is exacerbating reliability concerns

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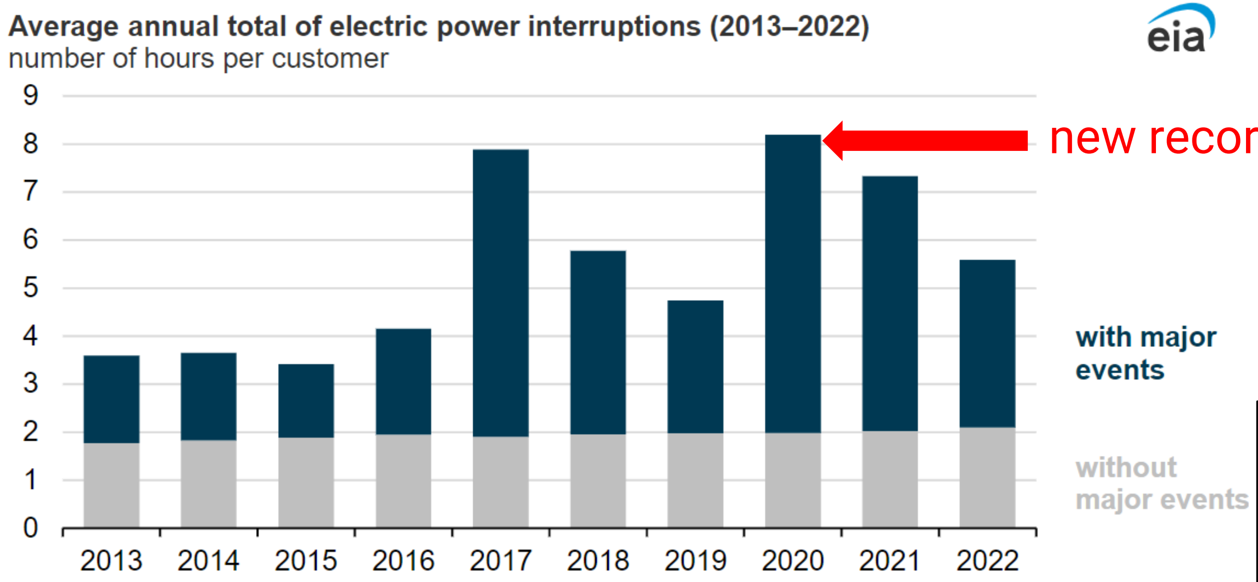
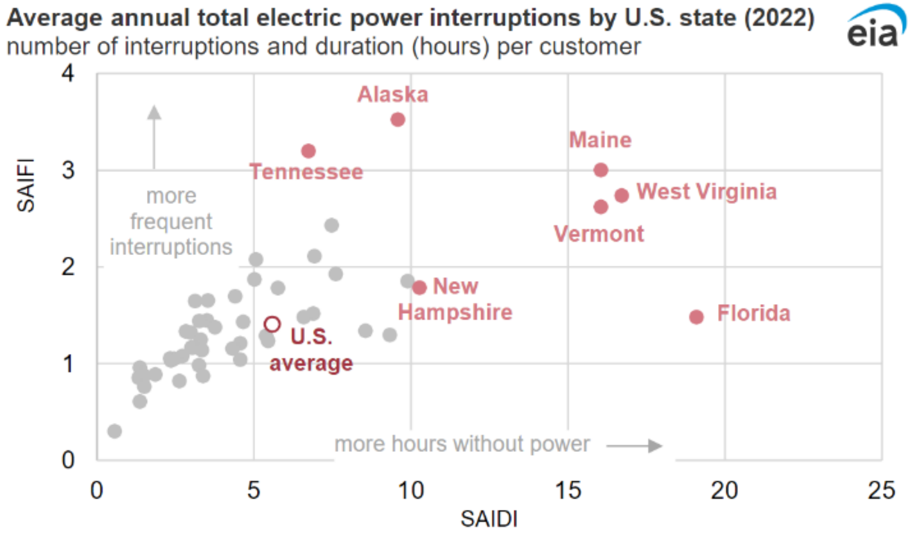
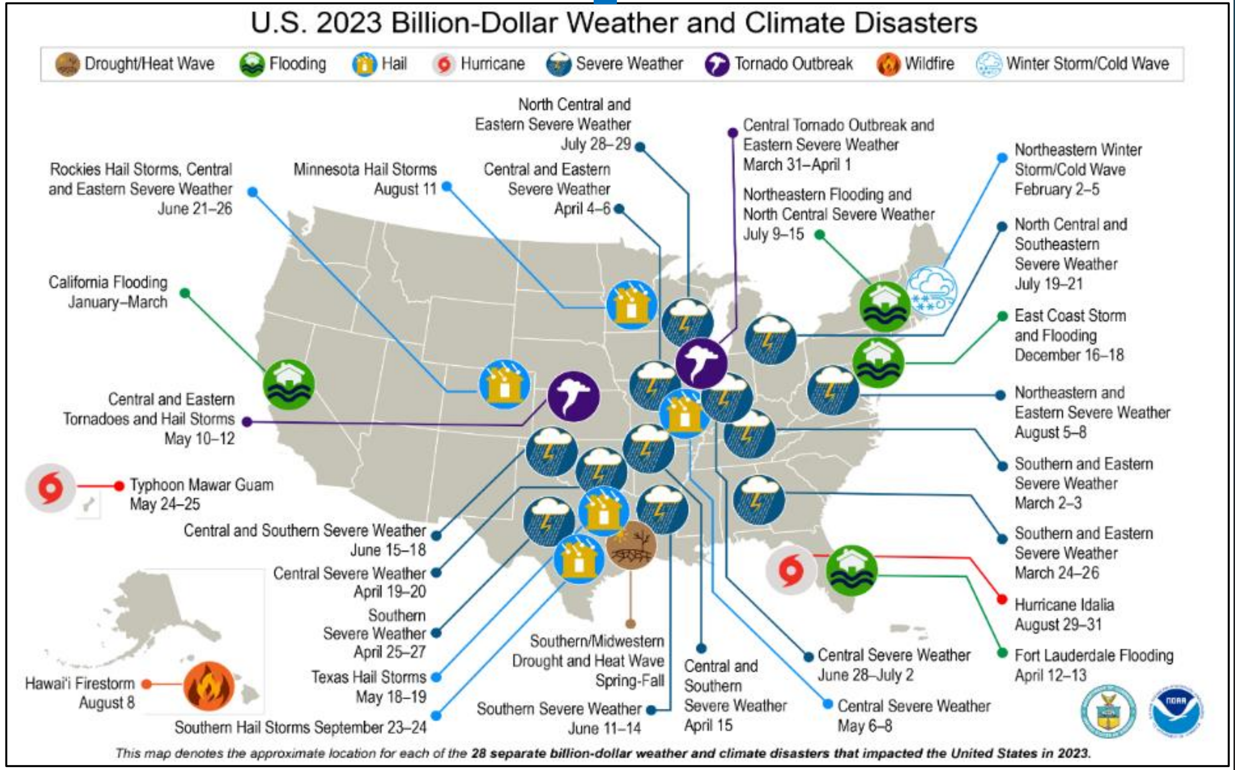


Data source: U.S. Energy Information Administration, *Annual Electric Power Industry Report*



Data source: U.S. Energy Information Administration, *Annual Electric Power Industry Report*

*SAIDI (System Average Interruption Duration Index)



https://www.climate.gov/news-features/blogs/beyond-data/2023-historic-year-us-billion-dollar-weather-and-climate-disasters

Impact: Reliable, Resilient Grid Avoids Outage Costs

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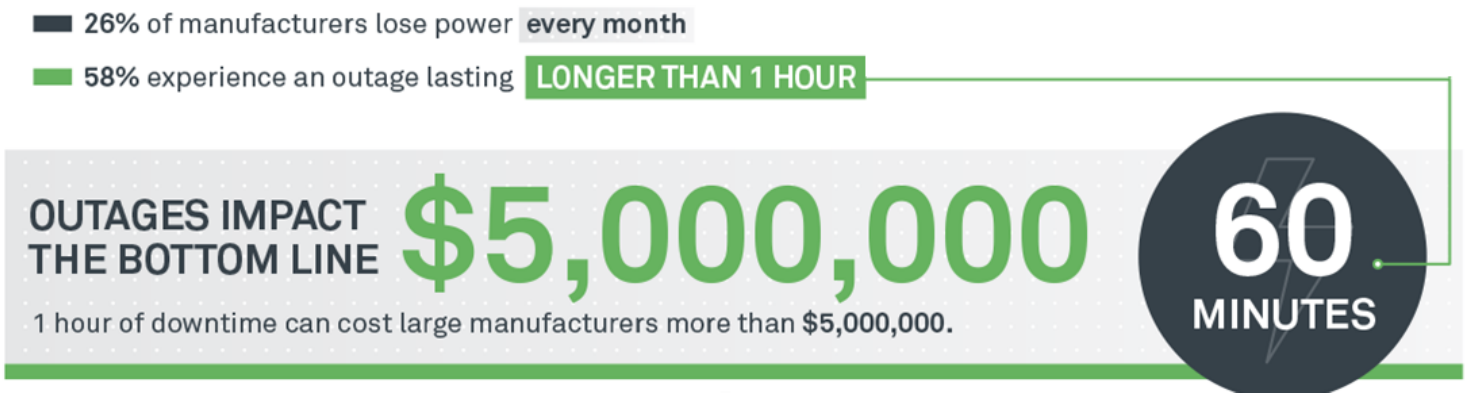
Credit: Joe Raedle - Getty Images

Credit: Monty Rakusen - Getty Images

Credit: KCBD Digital

Credit: The University of Texas at Austin

DOE estimates that outages cost the U.S. economy $150 billion annually!



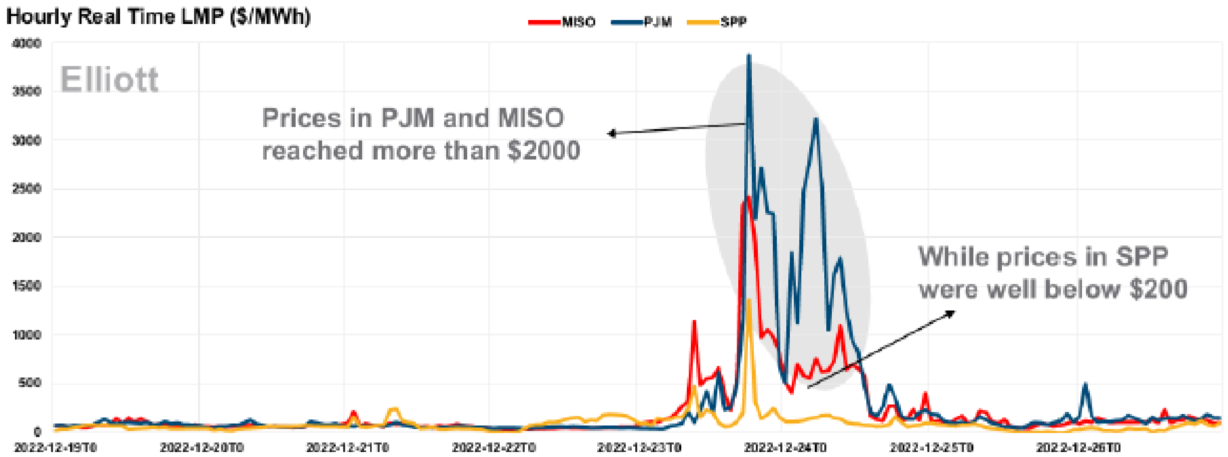
- 8+ hours/customer/year without power
- 500K people affected daily
- Weather-related outages cost up to $70 billion per year

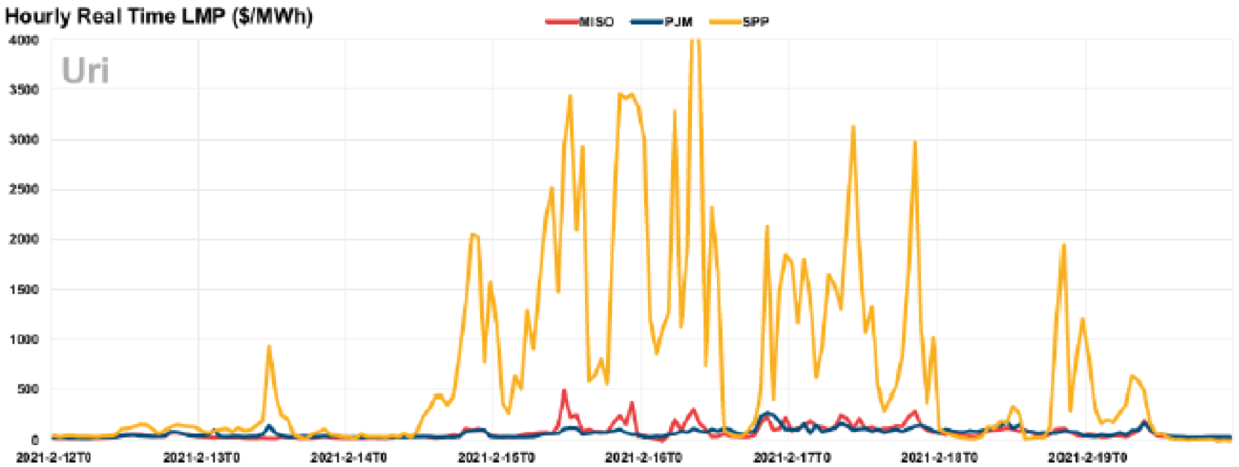
- Department of Energy Report Explores U.S. Advanced Small Modular Reactors to Boost Grid Resiliency | Department of Energy
- https://www.bloomenergy.com/blog/a-day-without-power-outage-costs-for-businesses
- https://www.economist.com/graphic-detail/2021/03/01/power-outages-like-the-one-in-texas-are-becoming-more-common-in-america

Energy Pricing Driven Motivation

Extreme Weather Events

Ref: Platts Market Data 3.0. Real-Time Locational Marginal Pricing [Data set]. S&P Global Market Intelligence. Accessed April 23, 2023

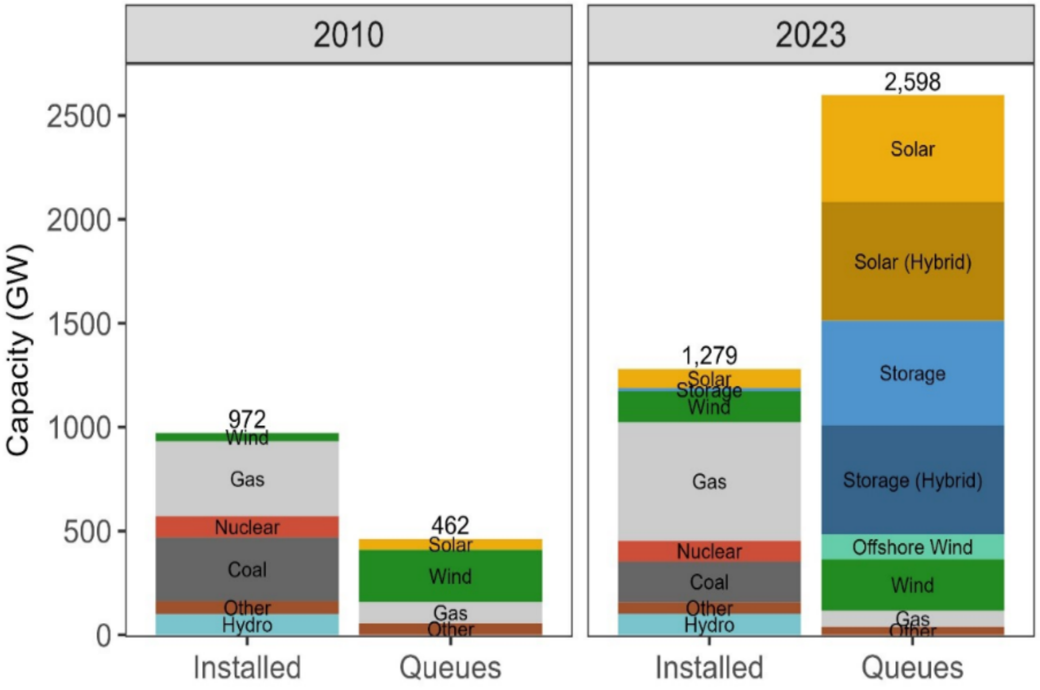




- The extent of the energy shortage in SPP with LMPs in excess of $1,000/MWh for 3 days and at one point exceeding $4,000/MWh
- During that time, PJM and MISO markets were not generally impacted by Uri, and the LMPs reflect that during that time period
- *“Grid Strategies LLC. “Transmission Makes the Power System More Resilient to Extreme Weather.” American Council on Renewable Energy. July 2021”* found that an increase in **1GW of transfer capacity between ERCOT and the southeast during Winter Storm Uri would have saved $1 billion**

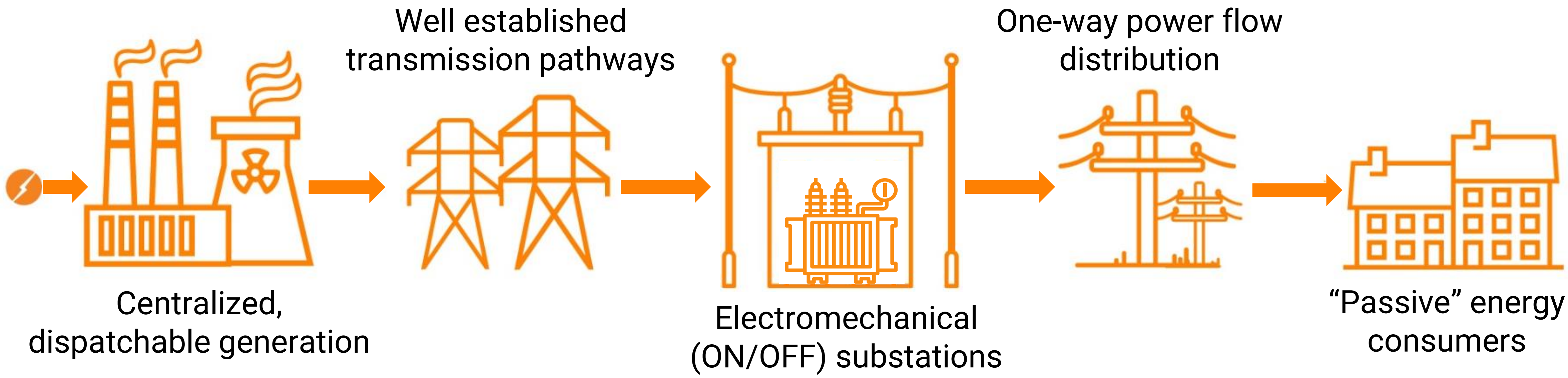
Substantial Load Growth in the Coming Decades

- > 3x Electrical load growth by 2050 (3-4 TW)
  - Data centers expansion & electrification of transportation
- $25+ billion in annual U.S. transmission investments
  - Interconnecting Queues drastically increased
- Weather causes 40% to 65% of all outages – $ 150 B p.a.
  - Each 1h downtime costs large manufacturers $ 5 M
- Net-zero carbon goals by 2050 – **2.6 TW New Generation waits in the queue to interconnect**

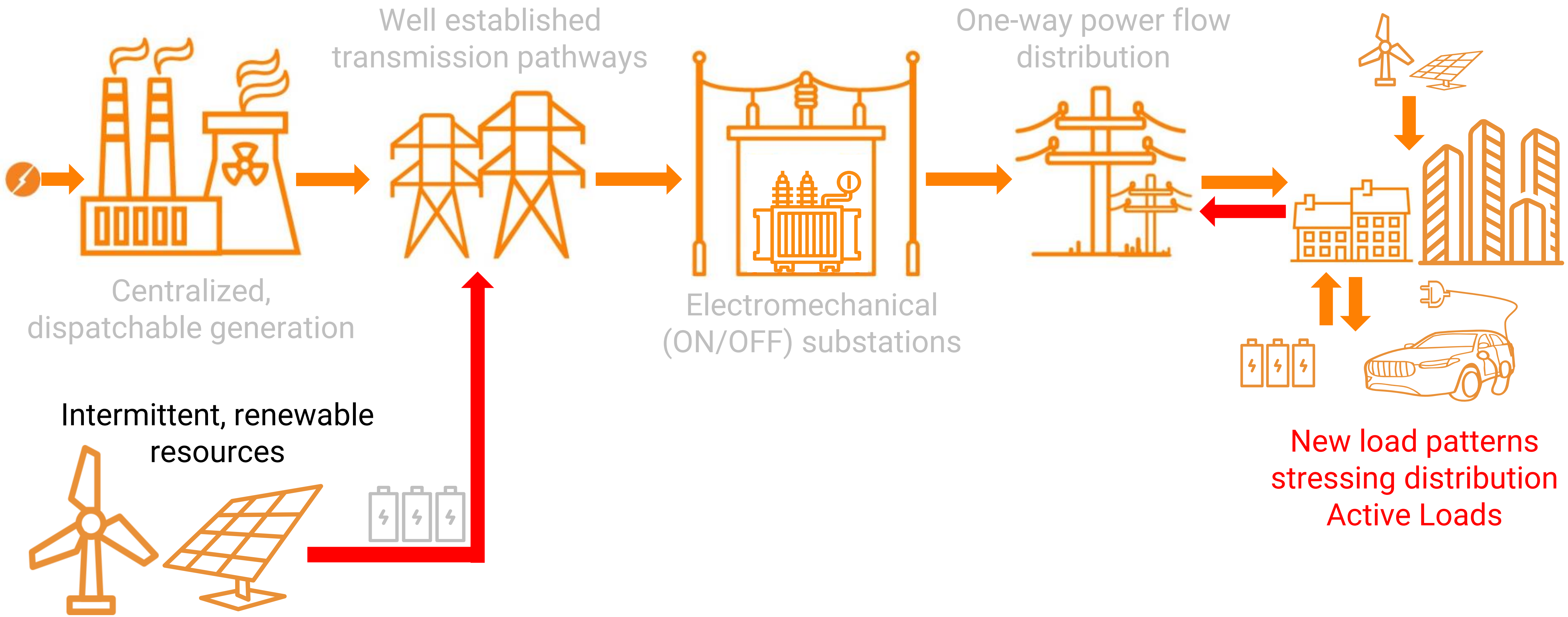


Demand-Side Impacts of a Highly Electrified Future, 2023 Goldman Sachs Global Investment Research, 2024 Annual US Transmission Investments 1996-2023 (brattle.com) LBNL Data

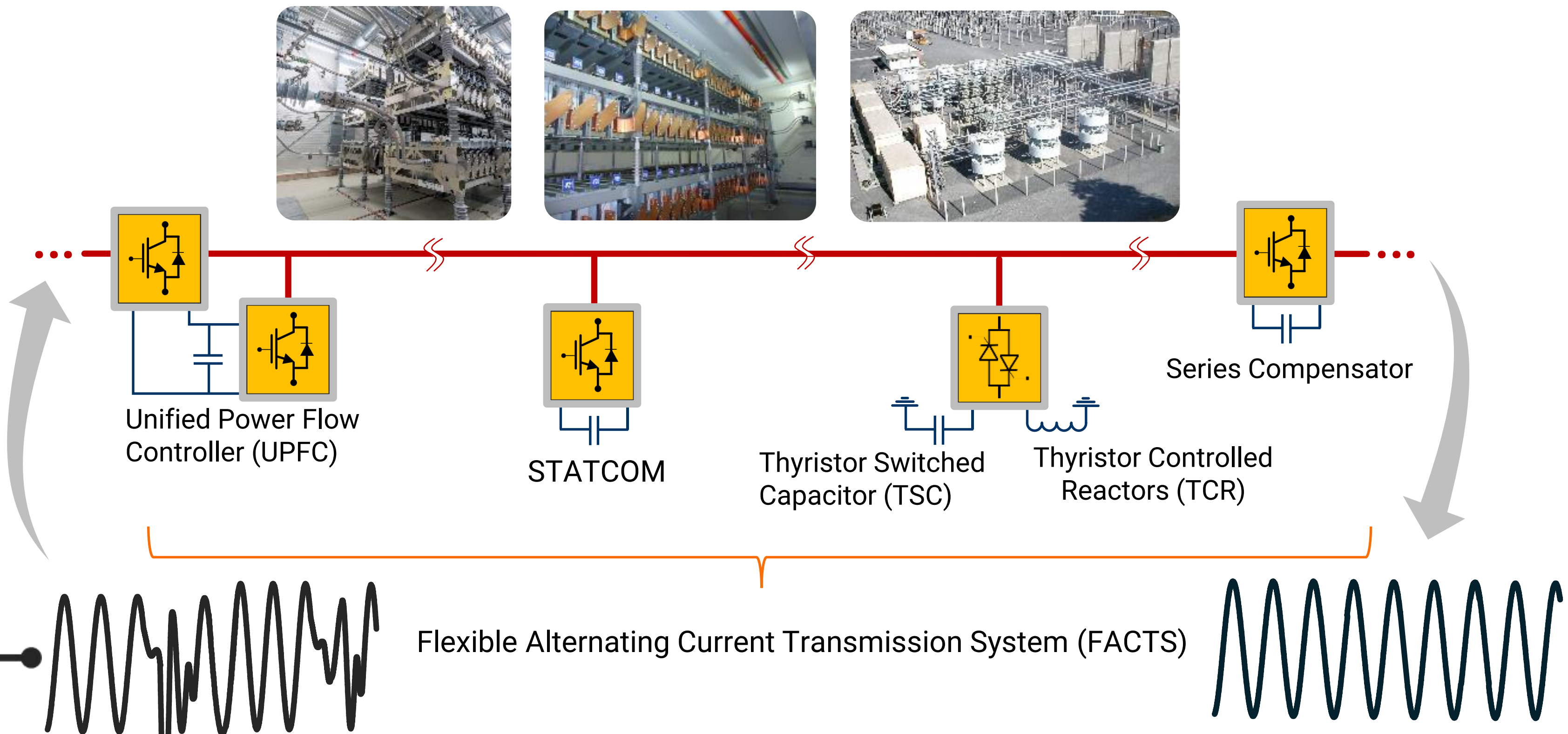
Our Grandparents’ Grid



Our Grid (patching up our Grandparents')

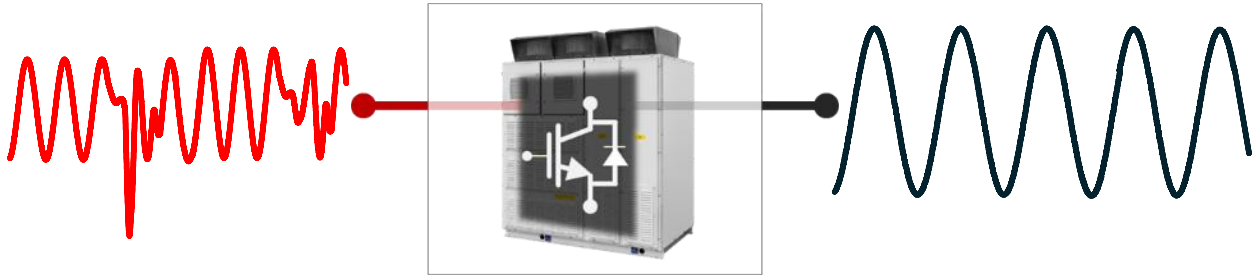


We Have Been "Patching" the Existing Grid



Conventional Transformer

Solid-state Transformer



- Transformer only features voltage step-up/down functionality, no active filtering, control and protection
- FACTS devices / active filtering needed to improve power quality (harmonic distortion)
- These devices cannot increase the line capacity in the way HVDC can
- HVDC inherently includes most of the FACTS functionality

Renewables and IBR Impacts on the Grid

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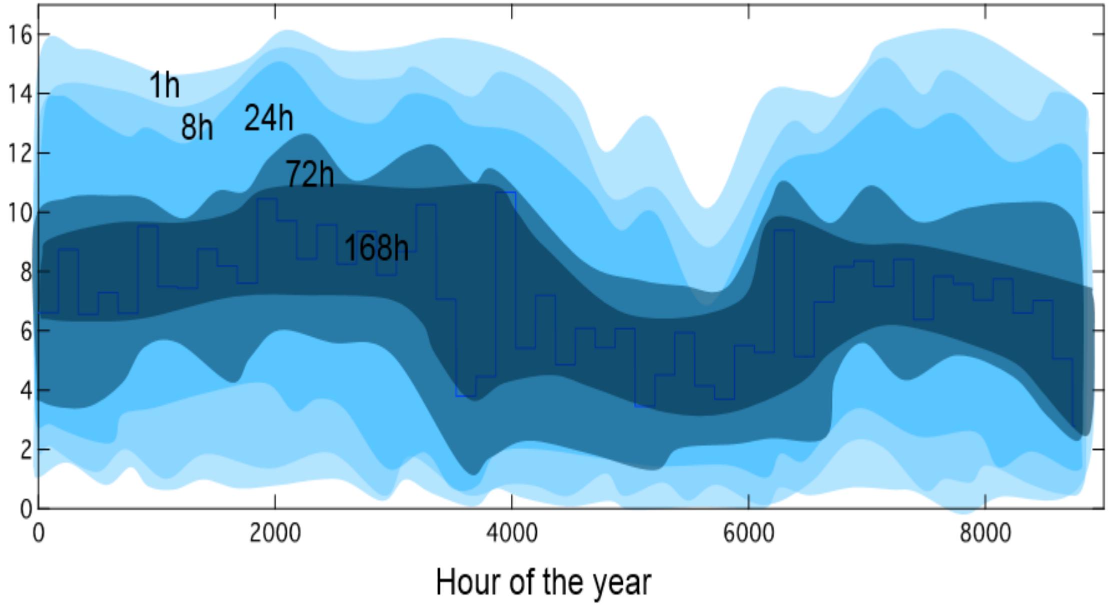
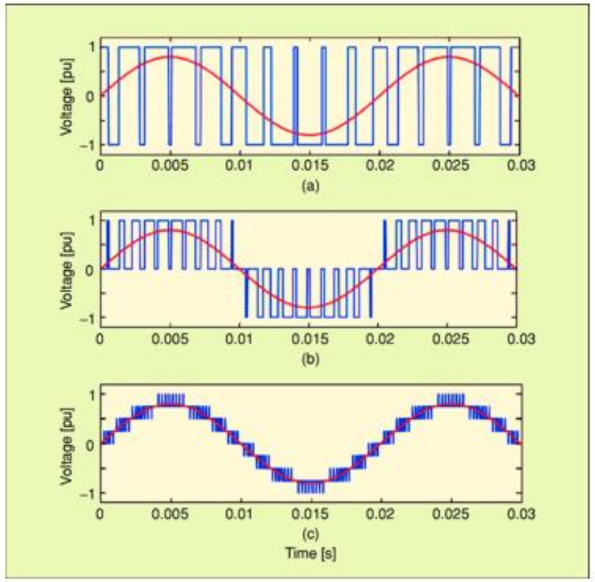
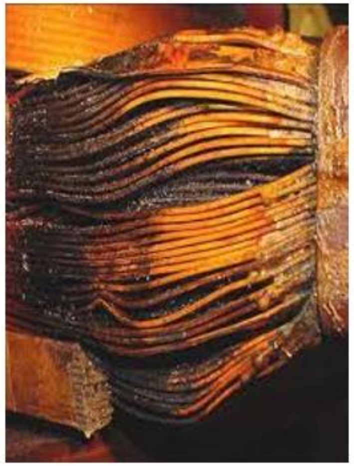
- **Intermittency**
  - Address with storage
  - Develop baseload renewables



- **Resiliency Impact** vs
  - Interface inertia mismatch
  - Grid stability issues
  - Degrades traditional transformer reliability



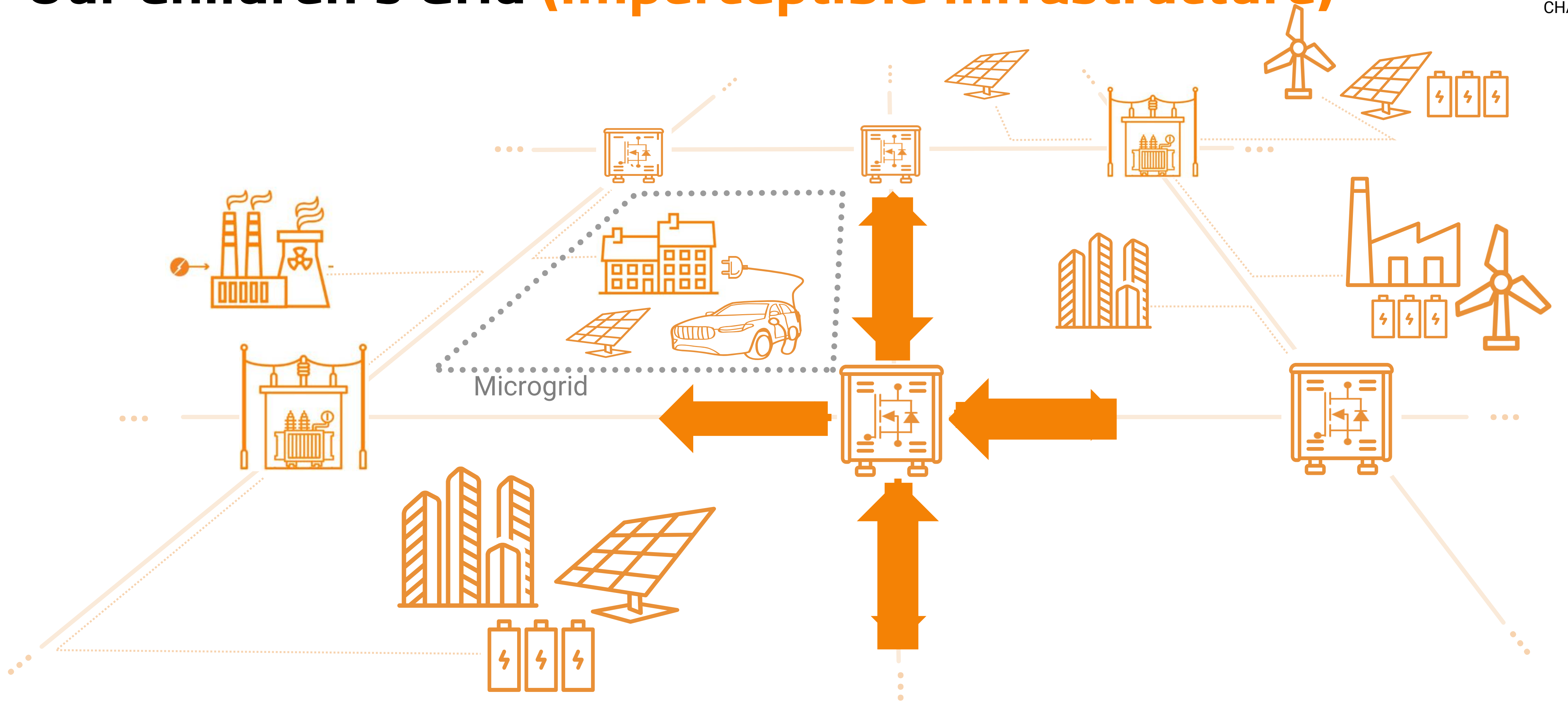
High dV/dt



Transformer Winding Insulation Failure

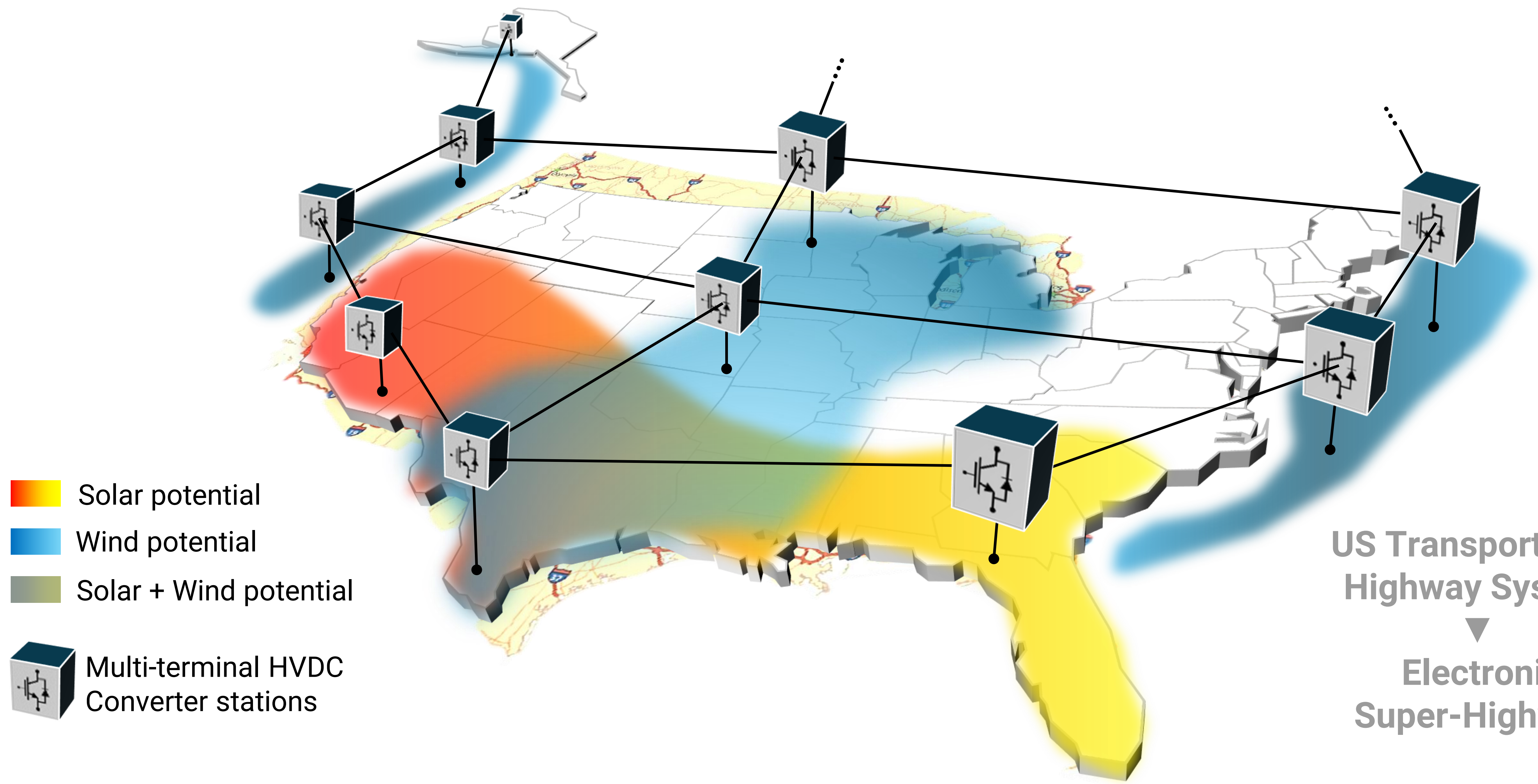
- **Inverter-based Resources (IBRs)**
  - Interconnection Standards
  - Protection Coordination
  - Replacing inertia
  - Grid-forming v/s Grid-following
  - EMI and Reliability

Our Children's Grid (Imperceptible Infrastructure)



- Hybrid AC/DC mix for HV and MV Networks
- Solid-state and traditional substations
- Distributed mixed generation (and storage)
- Dynamic, two-way power flow... Everywhere
- Prosumers and Active Loads
- Microgrids

A Macro Super-Highway Grid is Needed!



US Transportation Highway System

▼

Electronic Super-Highway

How may the MacroGrid architecture evolve?

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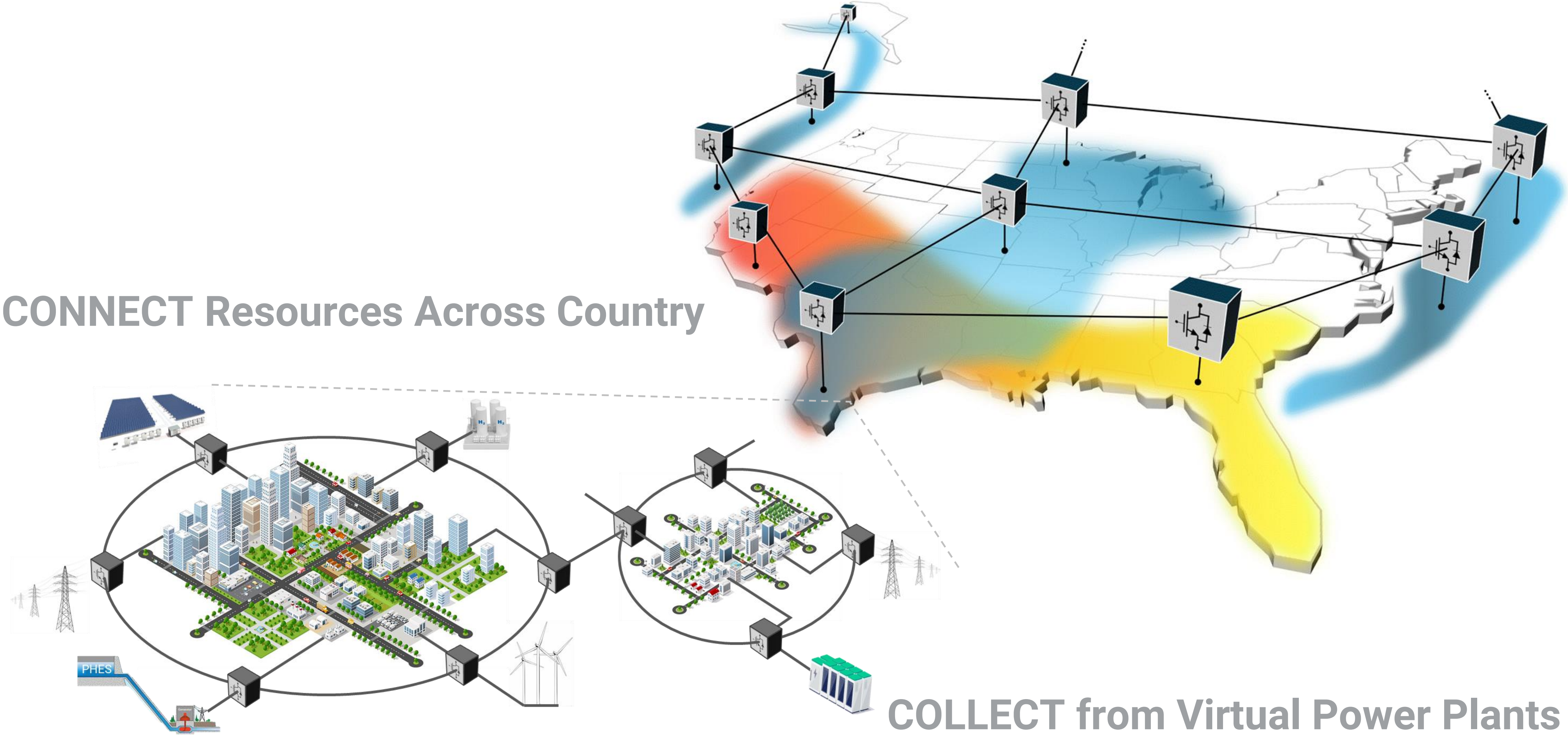
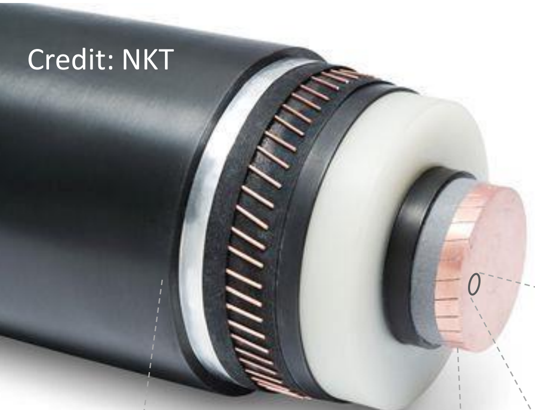
CONNECT Resources Across Country



COLLECT from Virtual Power Plants

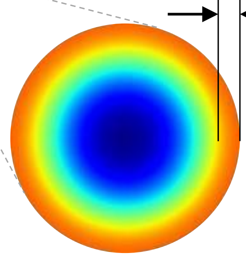
Why HVDC vs HVAC in Cables and Lines?



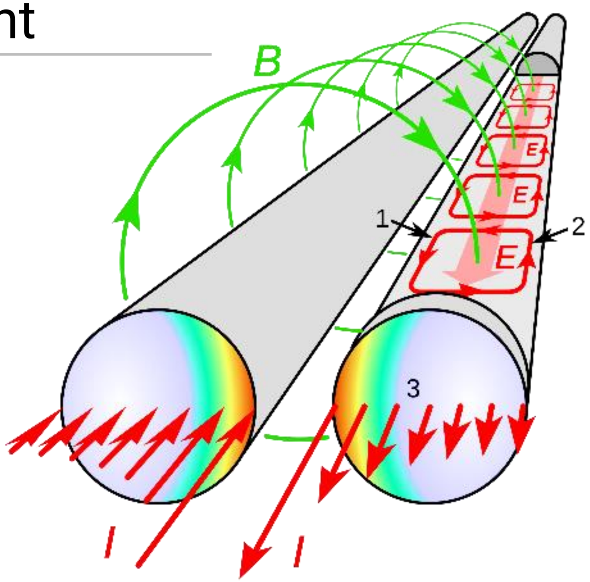
AC current

Resistance ↑

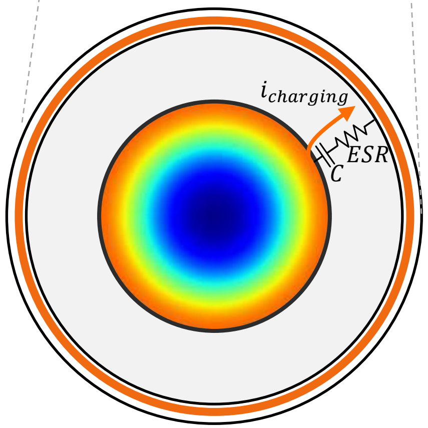
$$\delta = \sqrt{\frac{\rho}{\mu \pi f}}$$



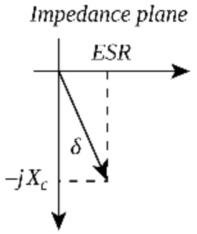
Skin Effect



Proximity effect



$$i_{charging} = C\frac{dv}{dt}$$



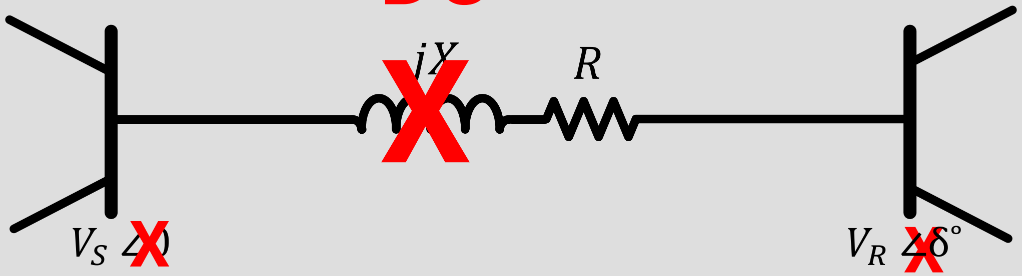
Dielectric loss $\tan\delta = \frac{ESR}{|X_c|}$

DC current

- No skin effect
- No proximity effect
- No dielectric loss
- No harmonics
- No Stability
- Control Power Flow

- Whole conductor cross-section area
- Less Cu/Al for DC

Power Transfer: **DC**



with X >> R in Transmission Networks

What is HVDC and Why is it an Important Solution

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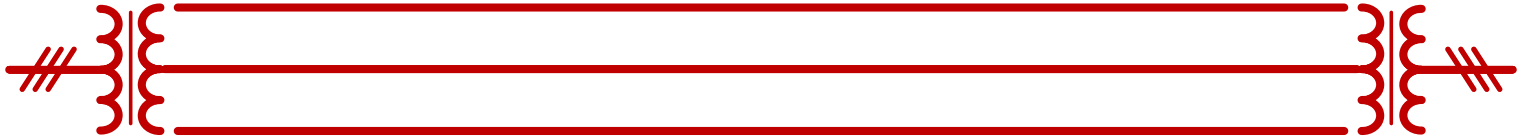
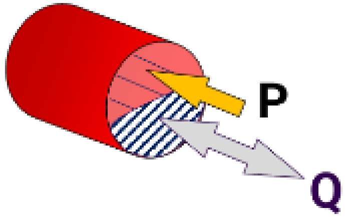
HVAC

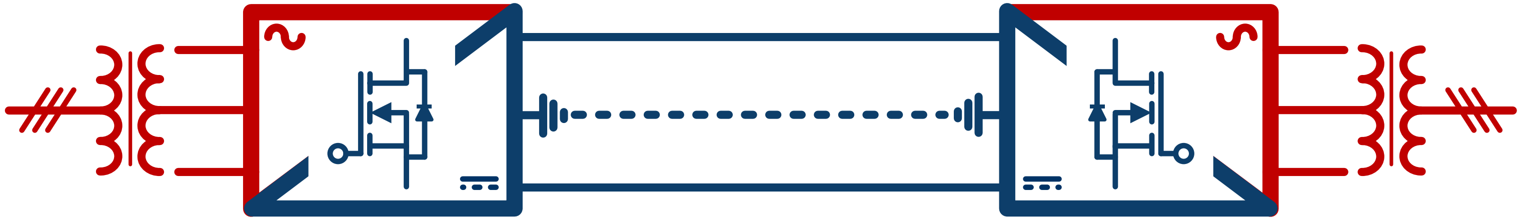


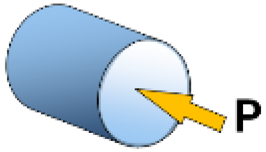


Advantages of HVDC:

- Controlled bidirectional power flow
- Release capacity on AC networks
- Reduce cost of bulk renewable integration
- Remote renewable energy integration
- Underground (cable) friendly
- Connect asynchronous grids

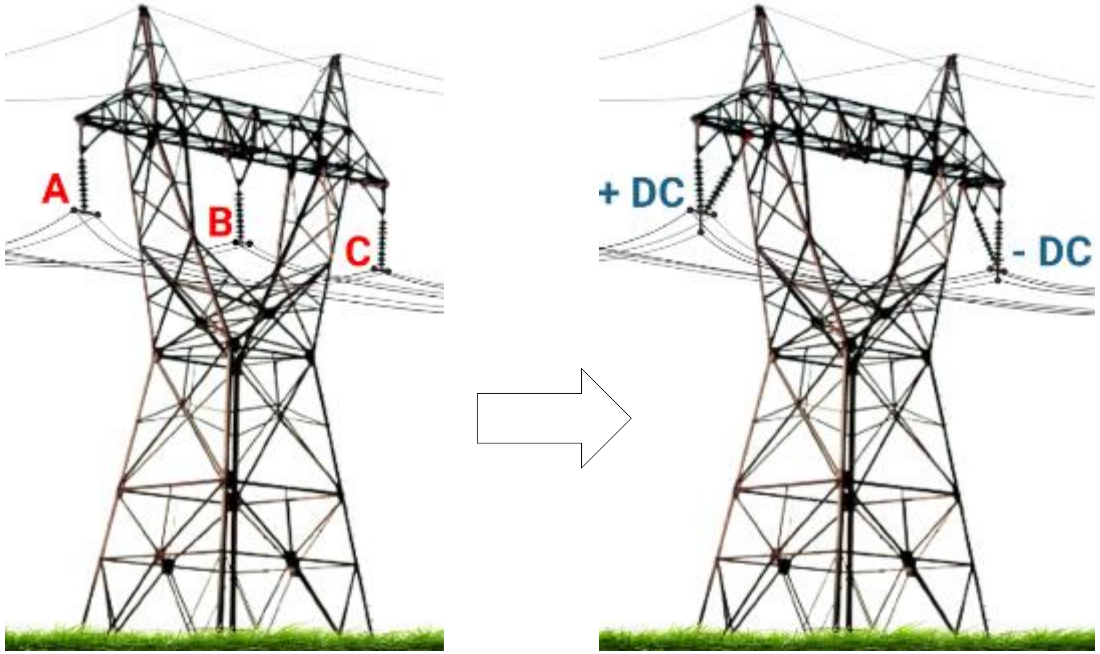
HVDC





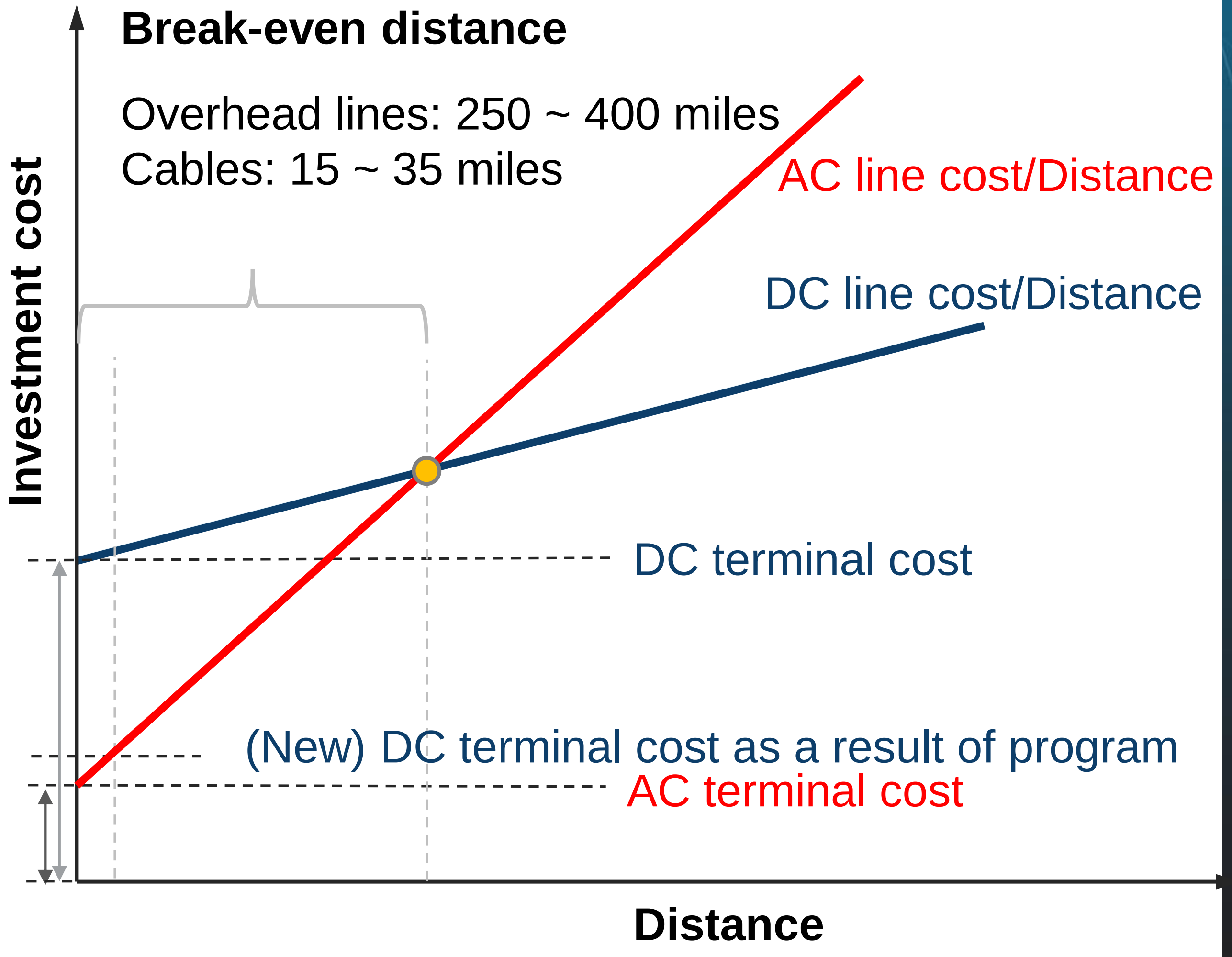
Why HVDC vs HVAC in Cables and Lines?

- 3x power transfer on same infrastructure
- 3x power transfer on same *Right of Way*



430 MW @ 220 kV AC (for PF=0.9)

1440 MW @ ±380 kV DC



https://www.eia.gov/analysis/studies/electricity/hvdctransmission/pdf/transmission.pdf, https://www.pnas.org/doi/epdf/10.1073/pnas.1905656116
Juan, P., Novoa., Mario, A., Rios. (2017). Conversion of HVAC Lines into HVDC in Transmission Expansion Planning. International Journal of Energy and Power Engineering

Materials/Cost Saving for Underground Cables

Example for **345 kV, 2000 A** cable transmission (**1GW**) per mile
Density - Cu: 8,960 kg/m^3, Al: density 2,700 kg/m^3; Current density – Cu: 1 A/mm^2, Al: 0.7 A/mm^2

HVAC	HVDC
Cu conductor 9.6 m^3 86 metric tons	**Cu** conductor 1.4 m^3 12.2 metric tons
or	or
Al conductor 13.7 m^3 37 metric tons	**Al** conductor 2.4 m^3 6.4 metric tons

Savings:

Cu: 74 metric tons ($740k)/mile

Al: 31 metric tons ($76k)/mile

Credit: NKT

North American view of all HVDC projects

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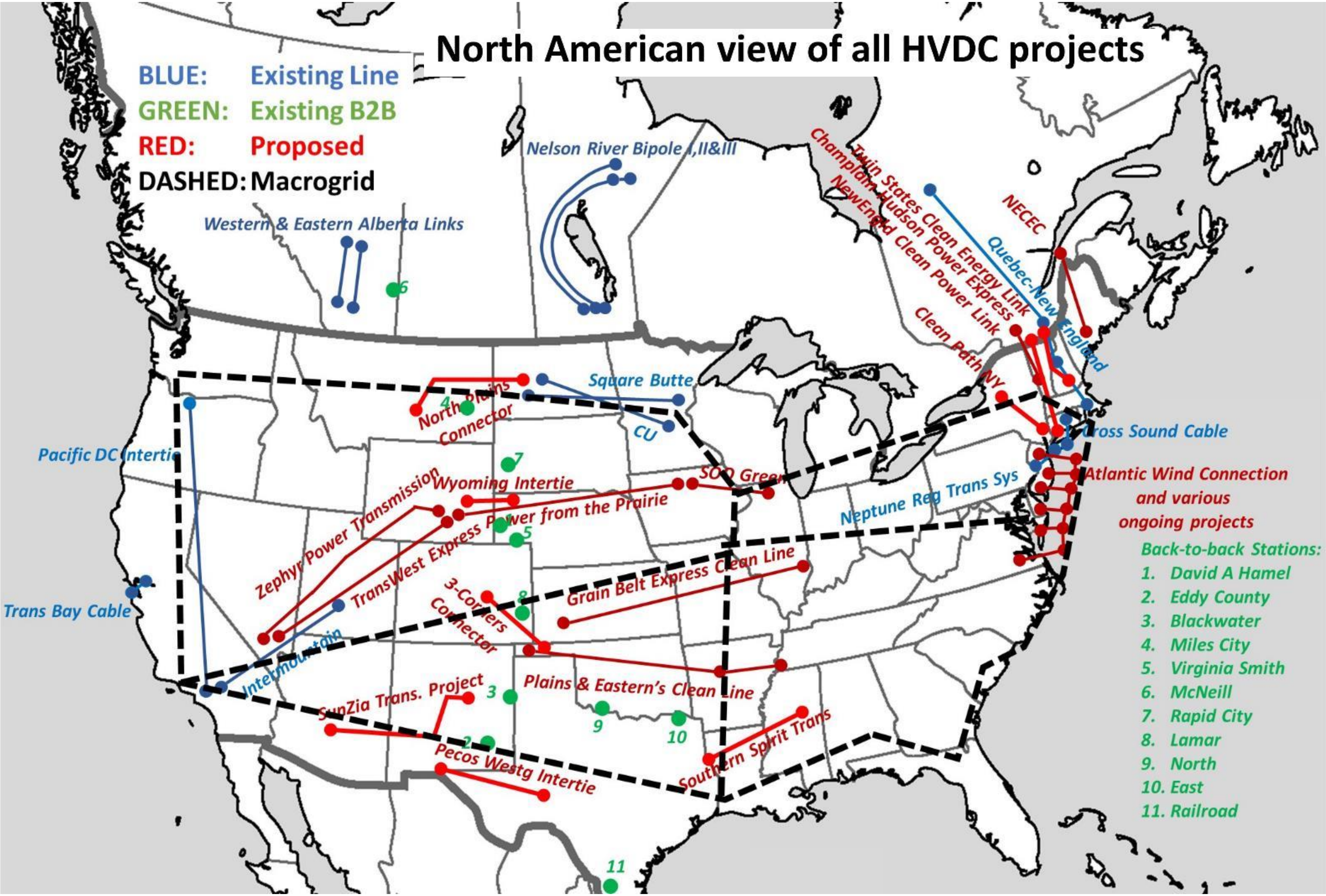

U.S. Tx Lines ≥345 kV AC may be Converted to HVDC

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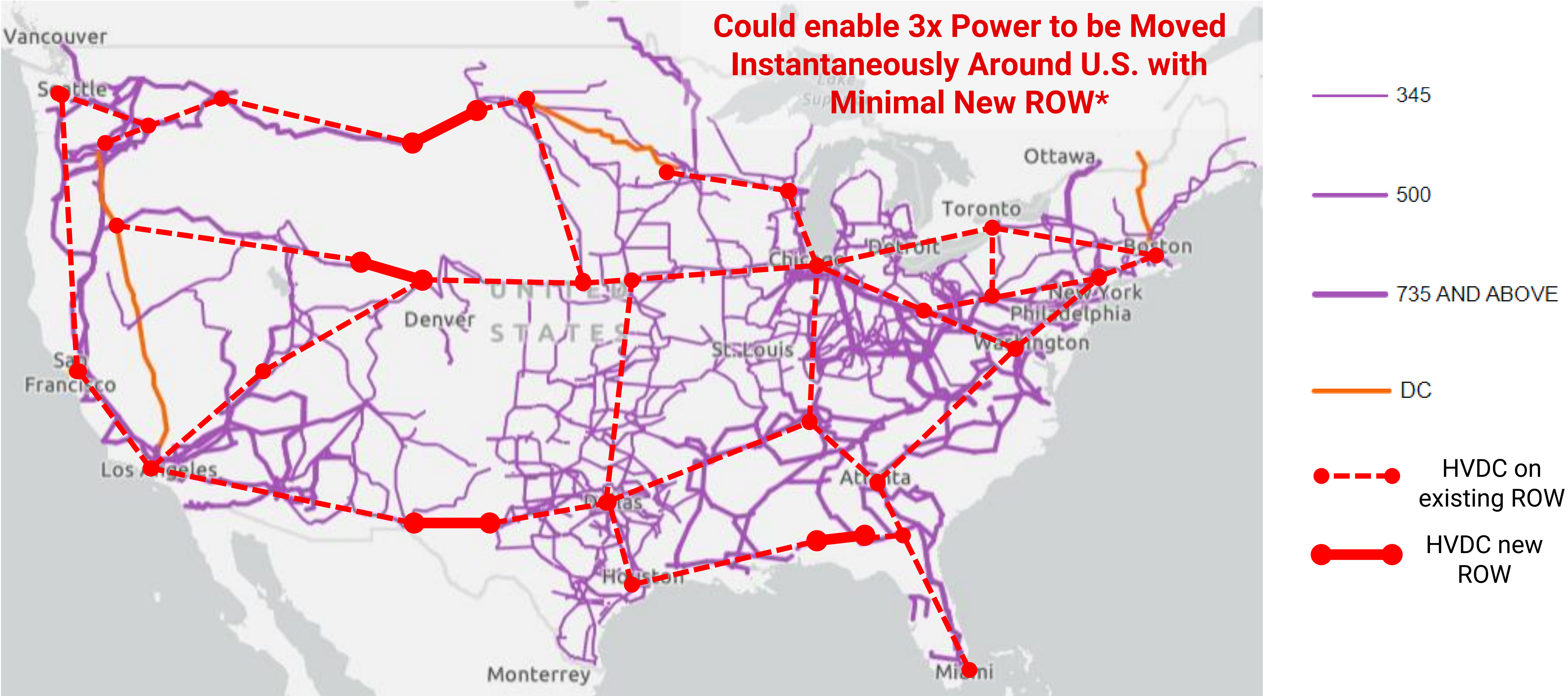

For 160 GW Offshore Wind, a $45B reduction in upgrades if HVDC MacroGrid is used!
Jim McCalley, Iowa-State, IEEE PES-24

https://atlas.eia.gov/apps/electricity/explore
*Red HVDC lines are illustrative only as an example

From HVDC Links to a Macro DC Grid

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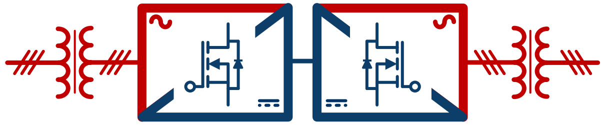
HVDC Converter Stations Configurations

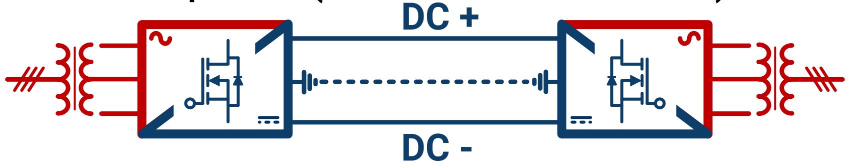
Back-to-Back (in the same station)



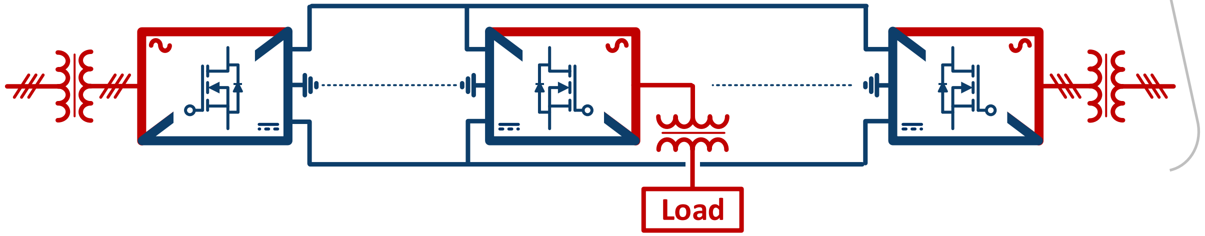
Point-to-Point

Monopolar

Bipolar (the most common)

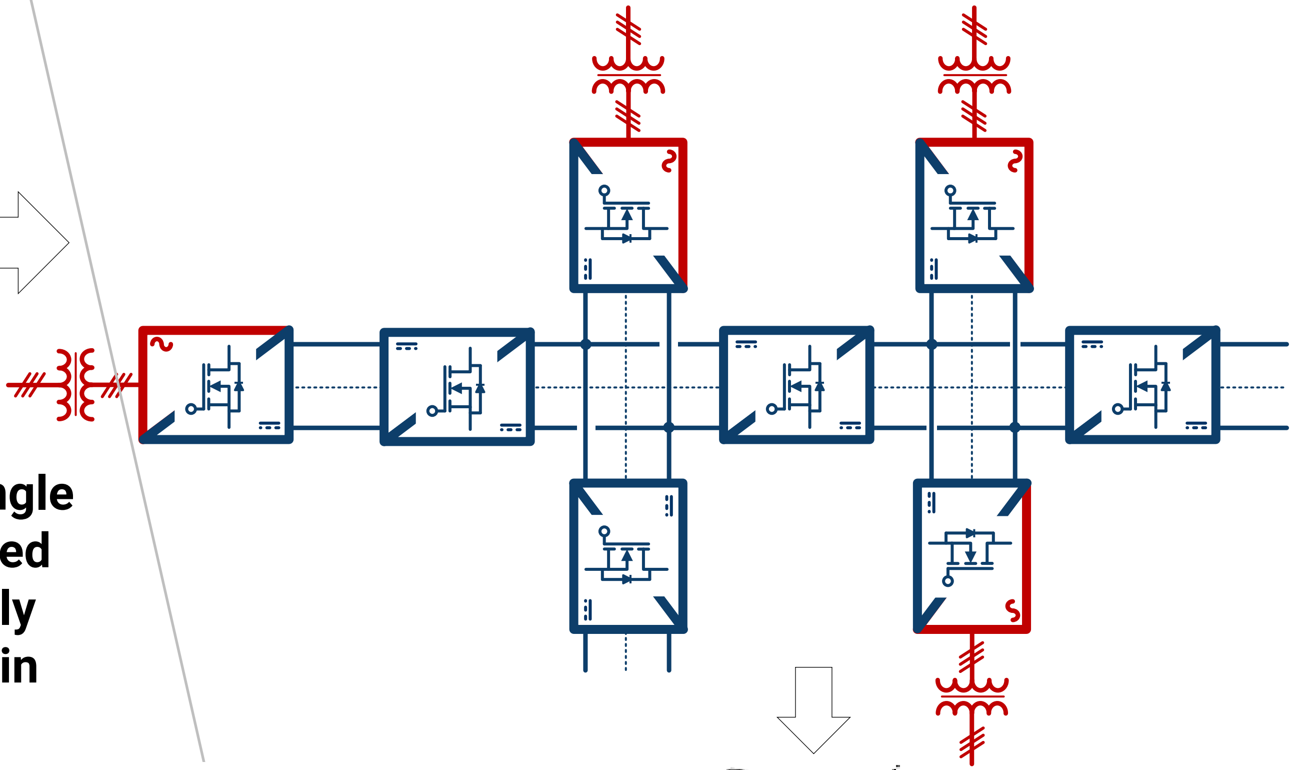


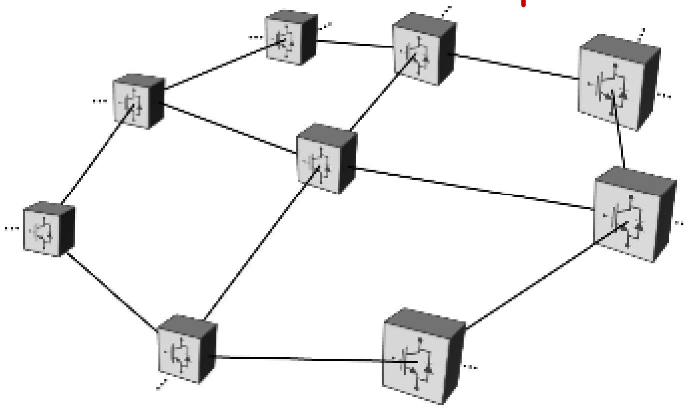
Multi-terminal (3 or more terminals)



However, single vendor-based and not fully integrated in grid!

Macro Electronic Grid





Vendor-agnostic and truly a MacroGrid!

What is Missing (Technology and Skills Gaps)?

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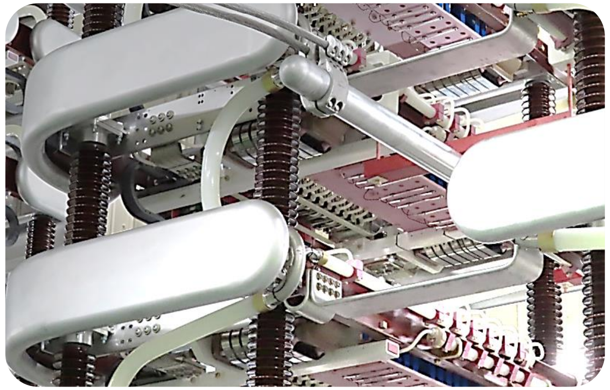
- **Fast Track Transmission Buildout by 2050**
- **Europe and Asia surpassed the U.S. with HVDC over a decade:**
  - Limited innovations in the HVDC technology – New topologies; HF
  - MTDC converter cost ($0.2 - 1 billion/GW) – Plan reduction
  - Air is electric isolation – New HV dielectrics > size reduction
  - No Operations of DC Grid – Integrated AC & DC operations
  - Transmission permitting takes decades – Use existing infrastructure

Credits: Wolfspeed


SIEMENS Energy


GE VERNOVA


Hitachi Energy

DC Enables Fully Imperceptible Infrastructure

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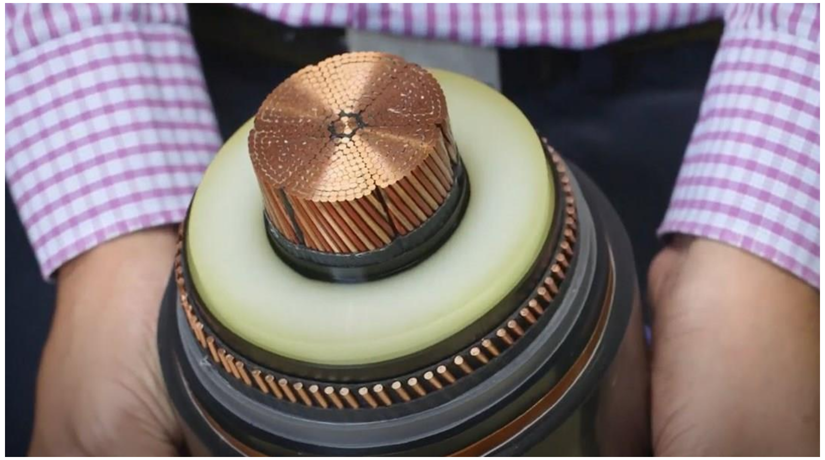


525 kV Cable, >2 GW
The whole conductor cross-section utilized

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

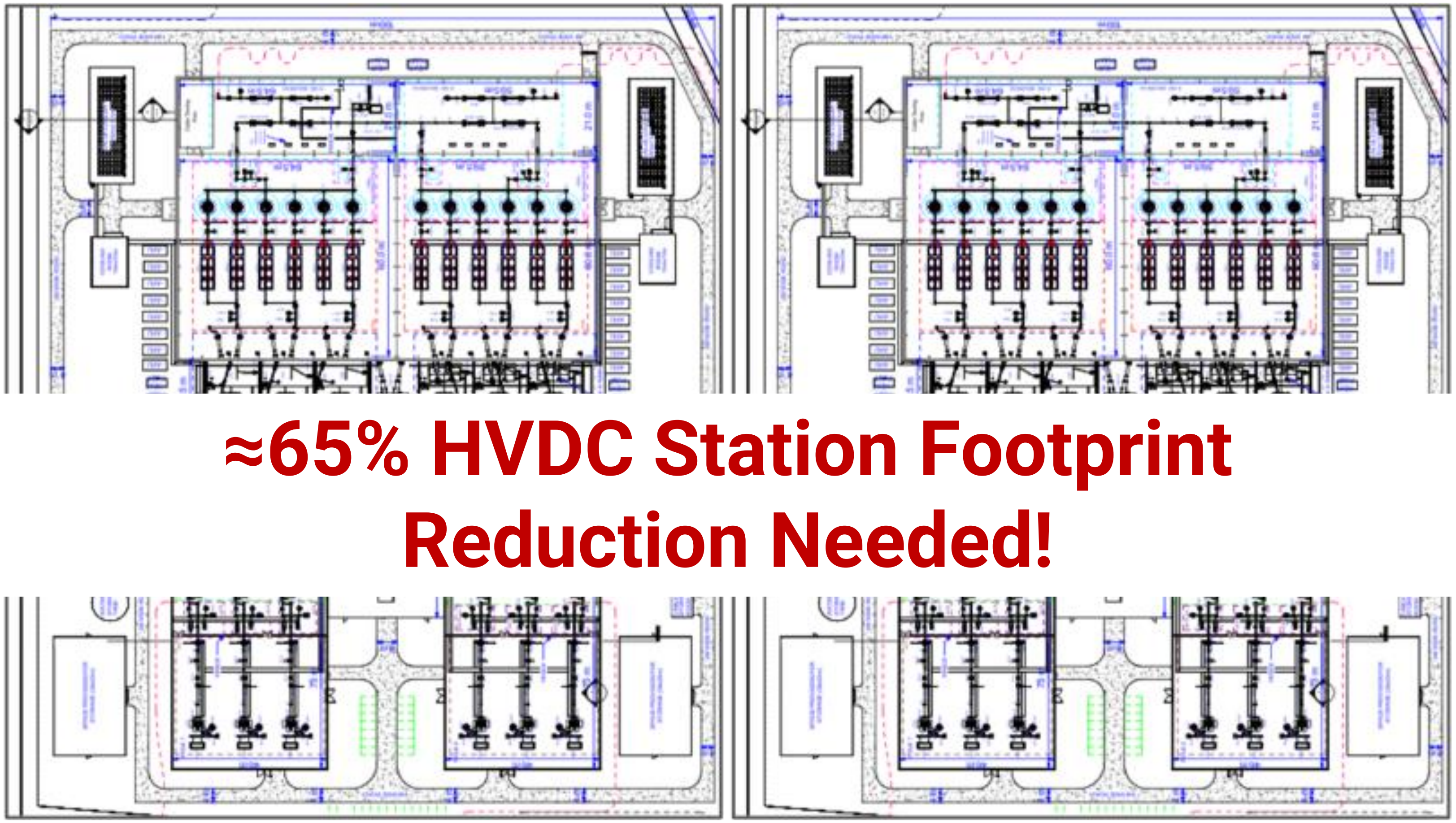
Or utilize highway medians for cable installation

New Multi-Terminal HVDC Converter Station Design

Example:

Dysinger switchyard, Royalton, NY
345 kV, 3,700 MW

GE VSC HVDC Station design blueprint (N/A location)
± 525 kV, 2 x 2,000 MW



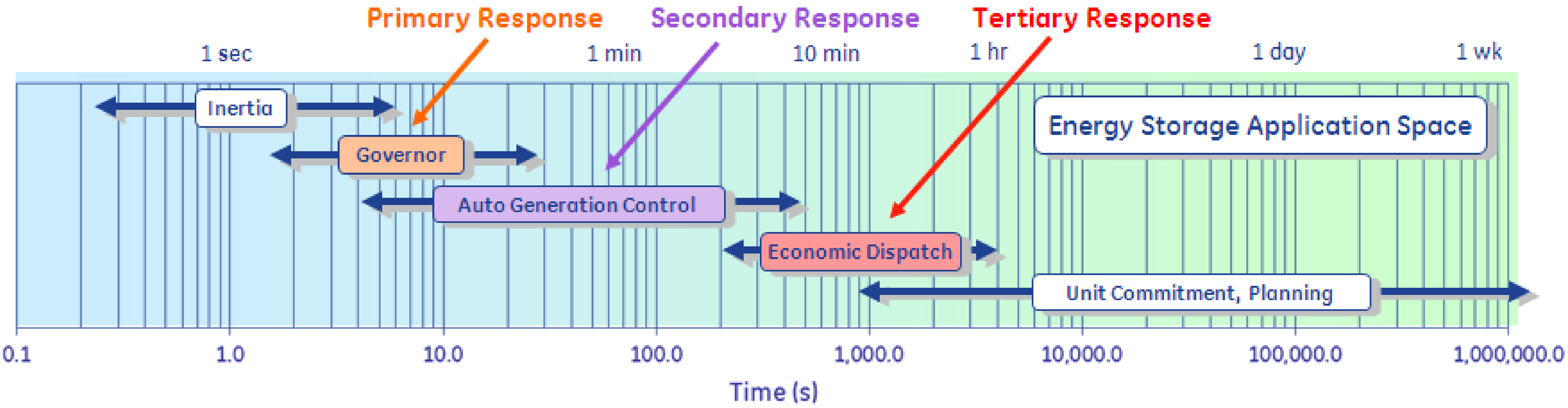
≈65% HVDC Station Footprint Reduction Needed!

Substation area: ≈**110,000 m³**

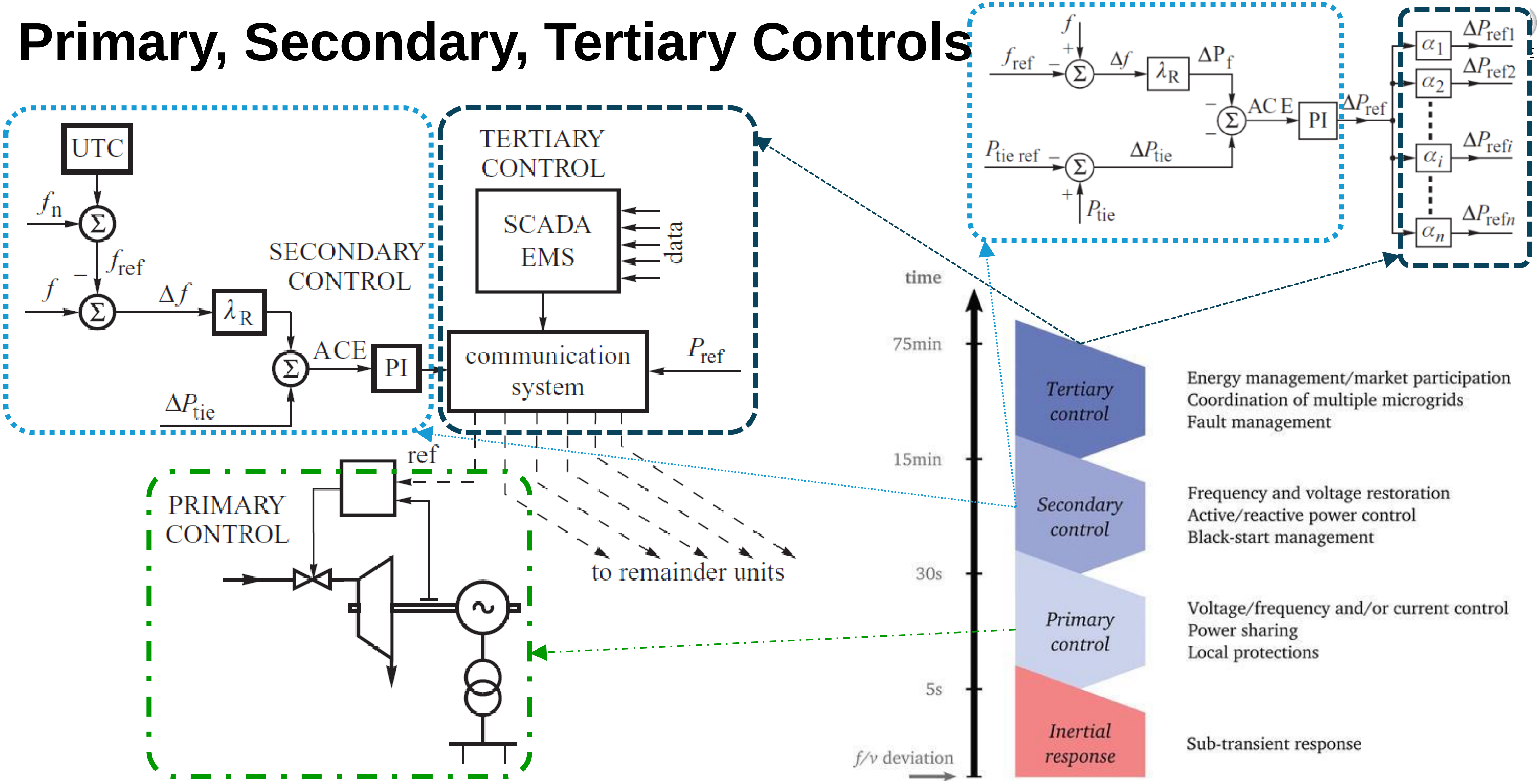
The 345-kV Empire State Transmission Line is now complete (power-grid.com)

arpa-e.energy.gov/sites/default/files/Marek Furyk.pdf

Hybrid AC & DC Grid Operation ... timescales

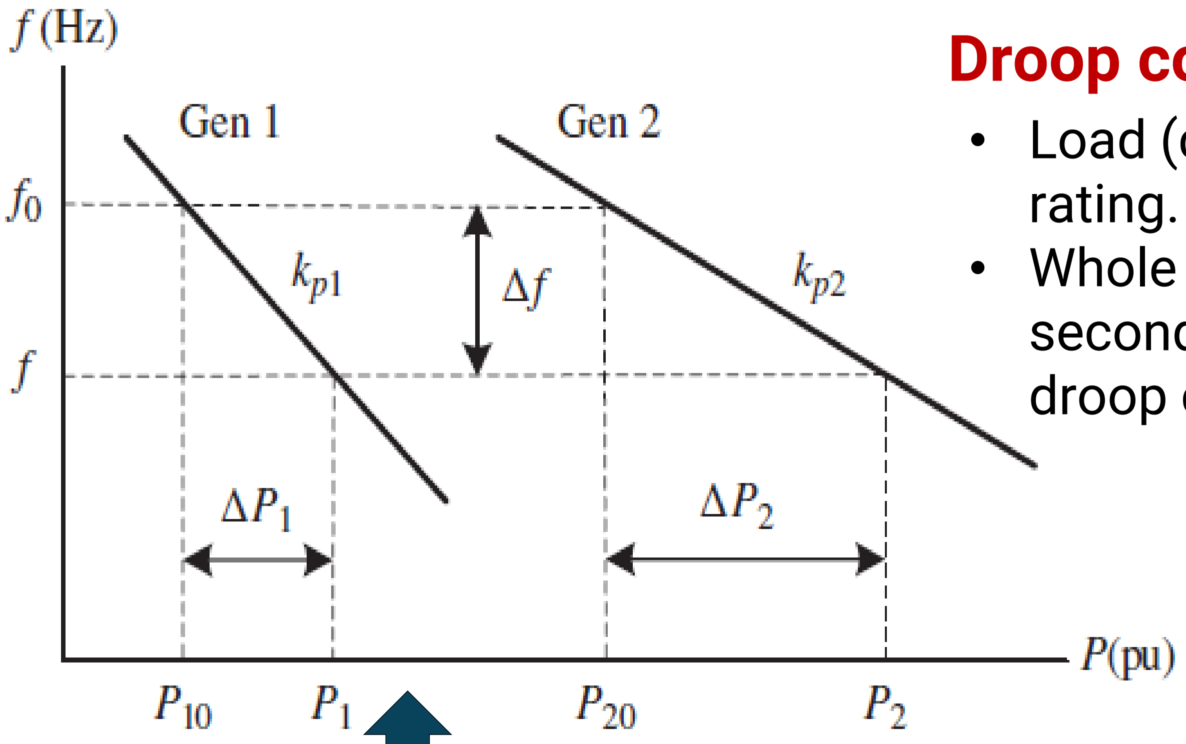


Primary, Secondary, Tertiary Controls



ACE: Area Control Error; AGC: Automatic Generation Control. *Frequency/Active power control*

Conventional Synchronous Generator Structure



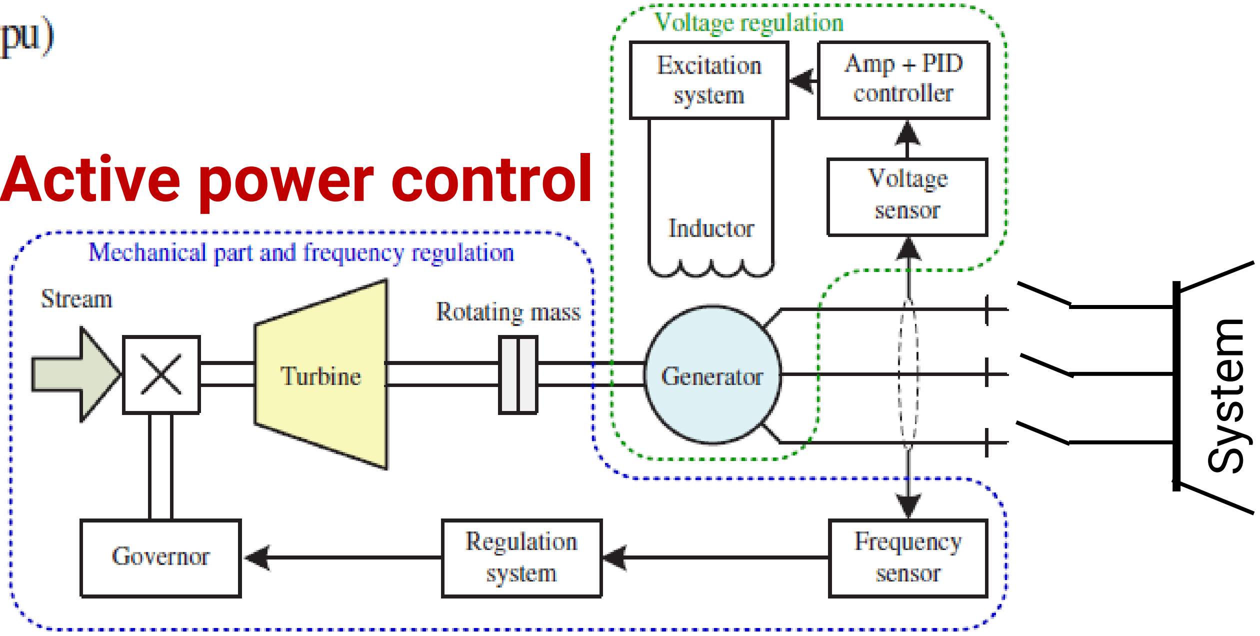
Droop control

- Load (current) sharing in proportion to generator's power rating.
- Whole grid "communicates" on timescales of a few seconds or even milliseconds to support transients with droop control

Similar droop control can be implemented in "grid-forming" power converters interfacing PV, Wind, ES, HVDC, etc… to the AC grid.

Reactive power control

Active power control



Grid - Frequency Stability

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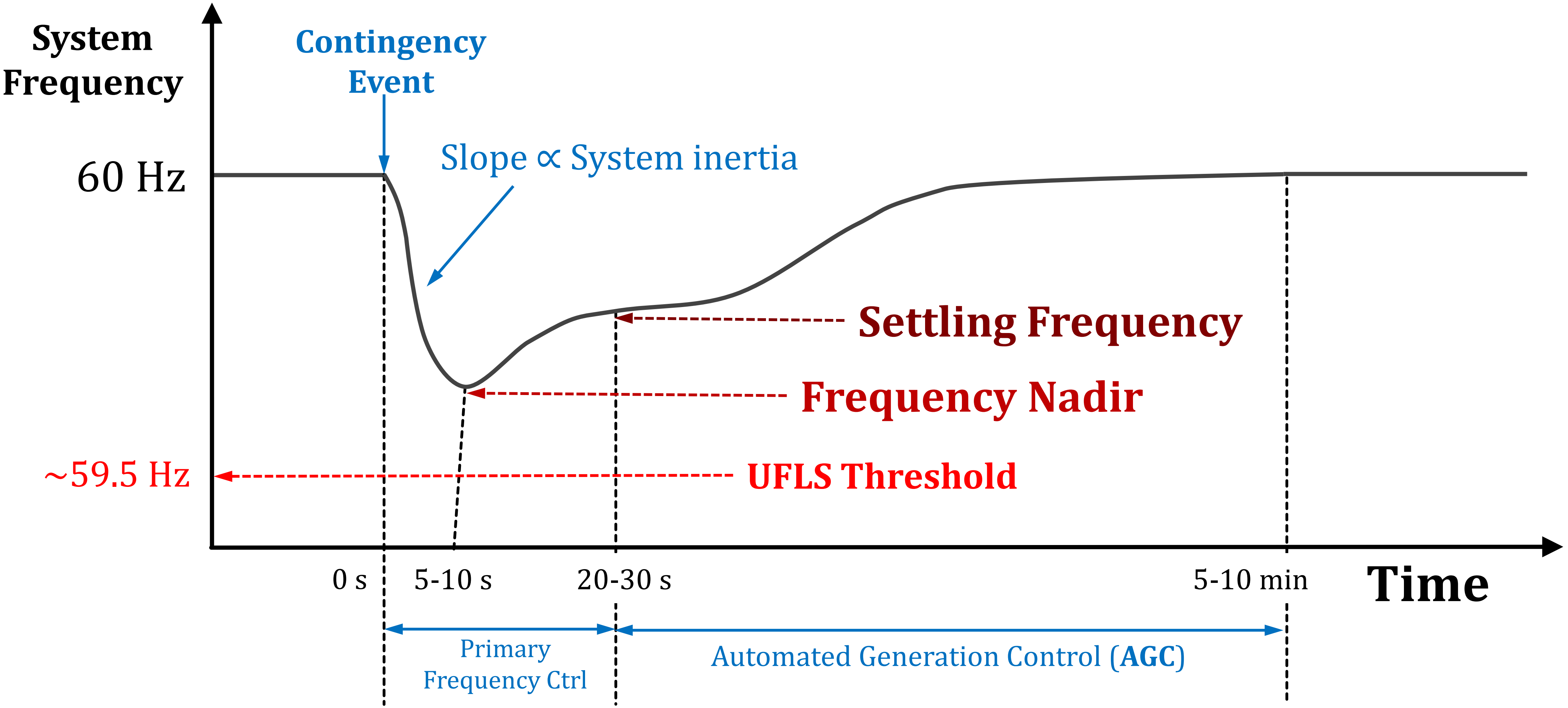
Directly affected by generation-demand balance



New Power Electronic Building Blocks for HVDC submodules

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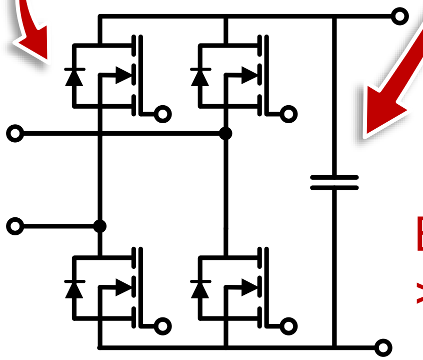
State of the art PEBB

MMC PEBB with 4.5 kV IGBT Modules



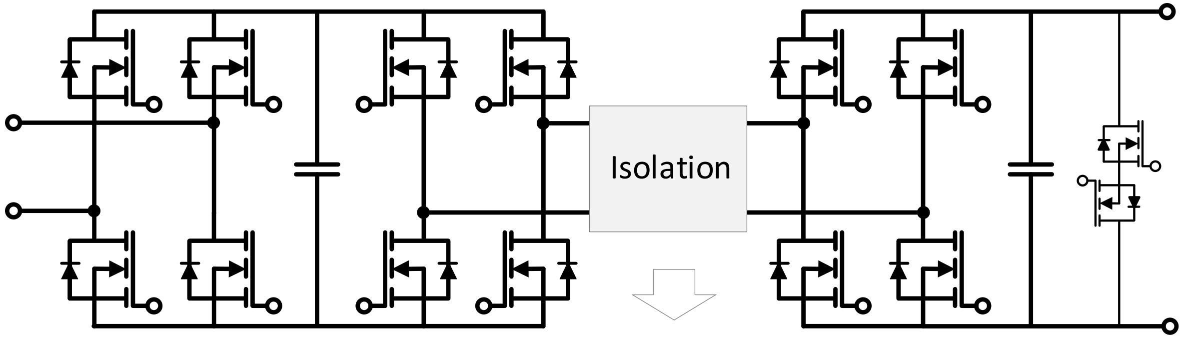
Capacitor occupies 75-80% PEBB volume

Bypass protection **>100+ µs**

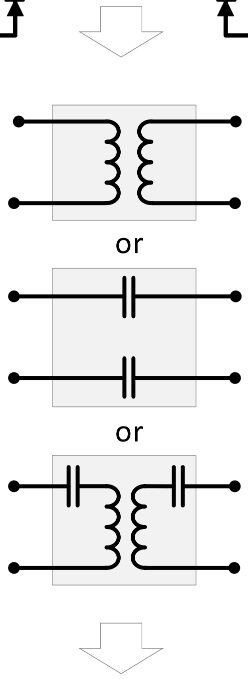
Example Technology Takes hundreds of 4.5 kV PEBBs to get to 500 kV!

Featuring **> 100%** higher power density

100 times smaller capacitor



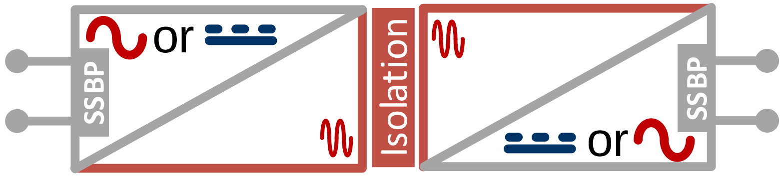
Galvanic isolation



Bypass protection **< 10 µs** reaction time

30 – 50 kV PEBBs

Inductive, capacitive, resonant, etc... Interface



New Multi-Terminal HVDC Converter Station Design

CHANGING WHAT'S POSSIBLE

Trans Bay On-shore HVDC Station (2010)

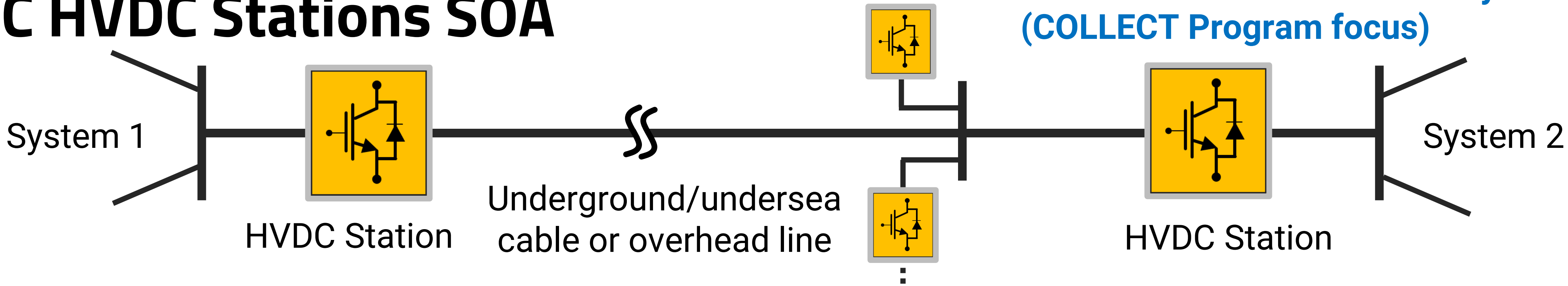
Credit: T&D World

Dolwin-3 Off-shore HVDC Station (2017)

Credit: GE VERNOVA

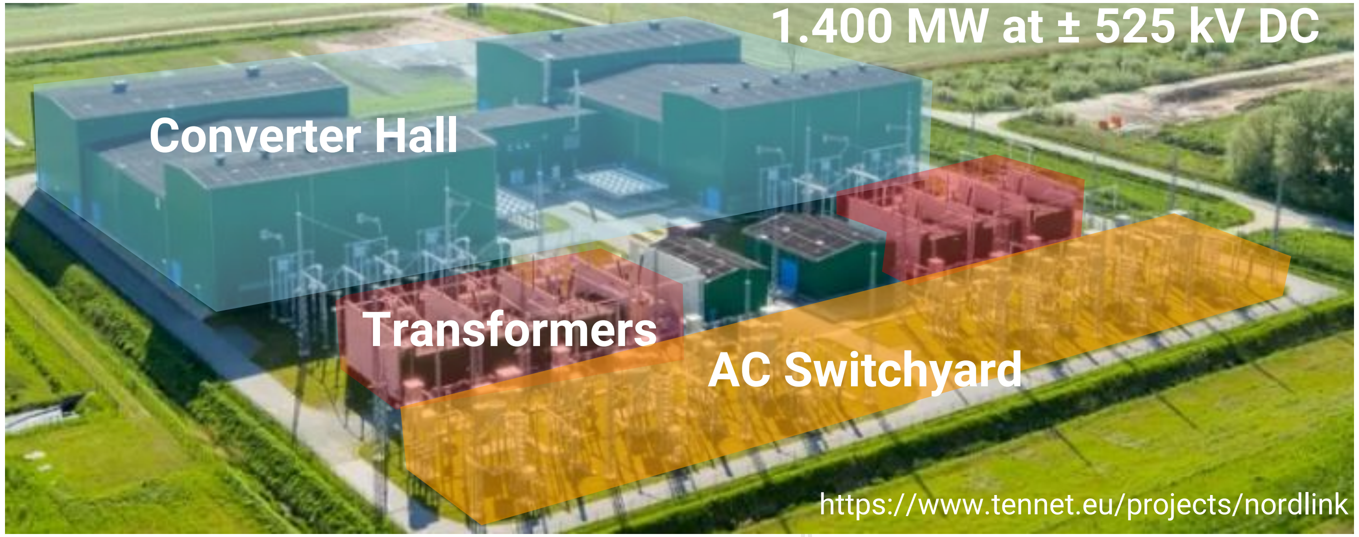
VSC HVDC Stations SOA

Macro DC Grid – This does not exist yet!
(COLLECT Program focus)



Multi-Terminal HVDC Converter Station Design

CHANGING WHAT'S POSSIBLE



Converter Stations Deliverables:

Critical Station Equipment Design

- 3X smaller, modular substation design
  - Insulation, capacitors, transformers, filters, switchgear, converter design
- 500 – 625 kV / 4 GW Multi-Vendor standard
- Availability > 99%

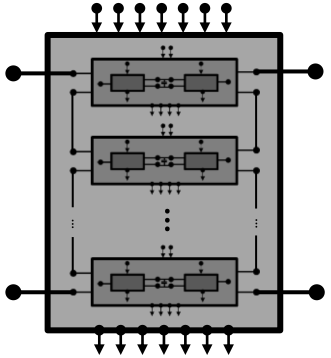
Station Integration and Control

- Substation interaction with AC system:
  - Local active/reactive power control
  - Blackstart and Grid-forming
- MacroGrid Integration:
  - Bypass and bi/mono-pole operation
  - Local DC protection coordination
  - DC power flow control integration
  - Multi-vendor operations

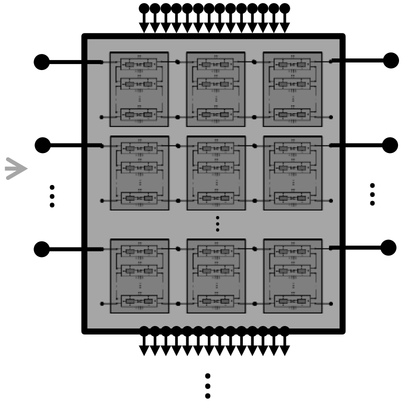
Control Hardware in the Loop (C-HIL)

Signal-level emulation

Converter “Valve” or DC Breaker



Converter Station

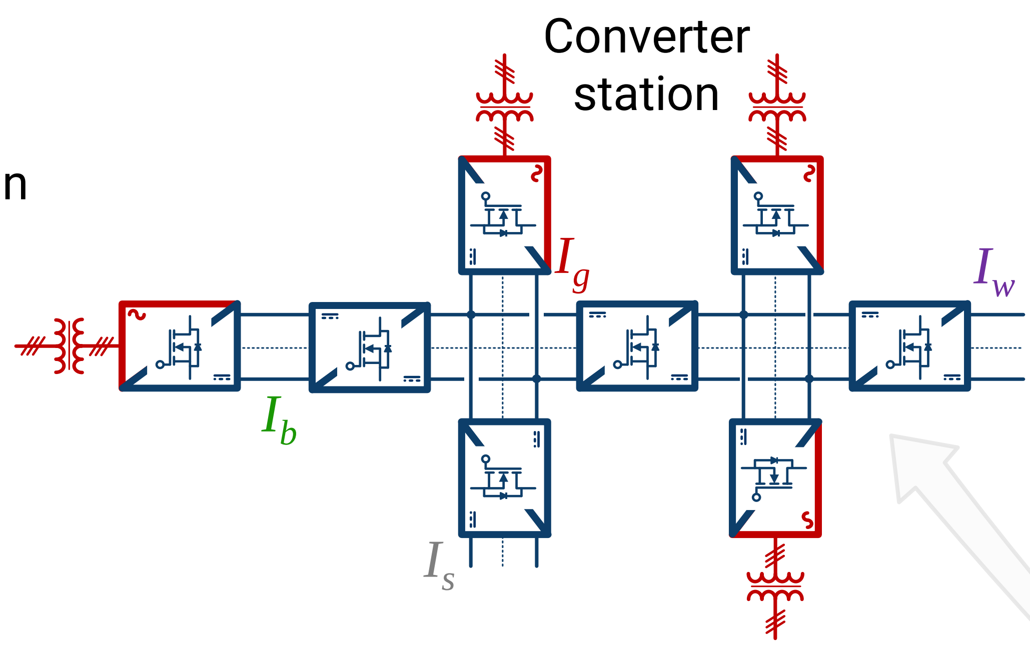


System-Level Operations of DC MacroGrid with AC Grid

CHANGING WHAT'S POSSIBLE

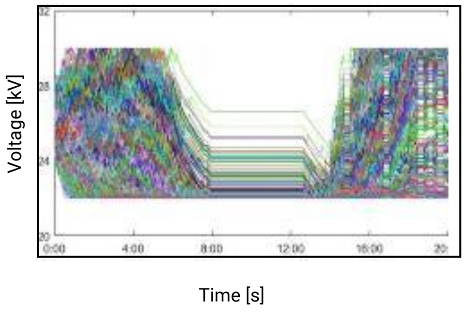
MacroGrid Studies

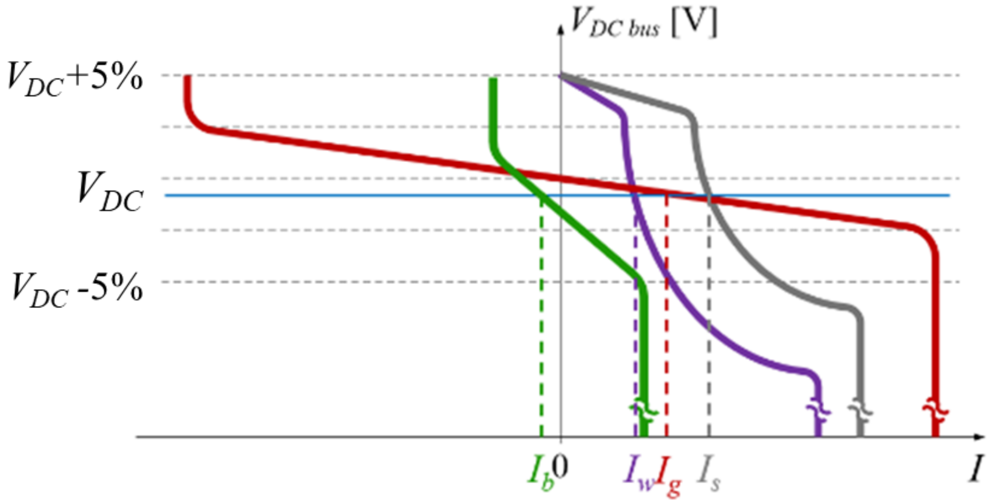
- System protection
- Power sharing
- Novel optimization or reconfiguration
- Multi-vendor coordination

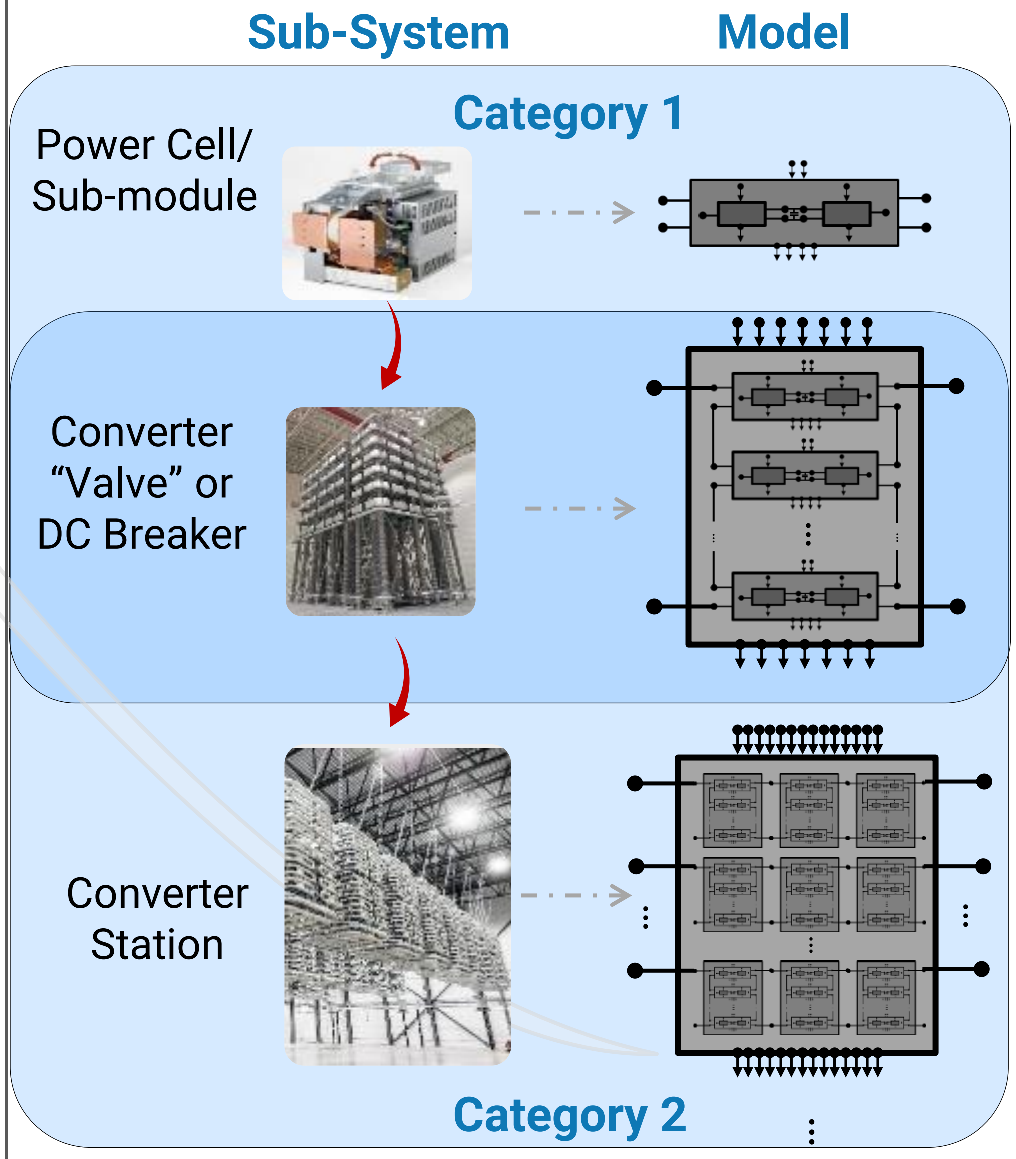


… with advanced system-level algorithms:

Example



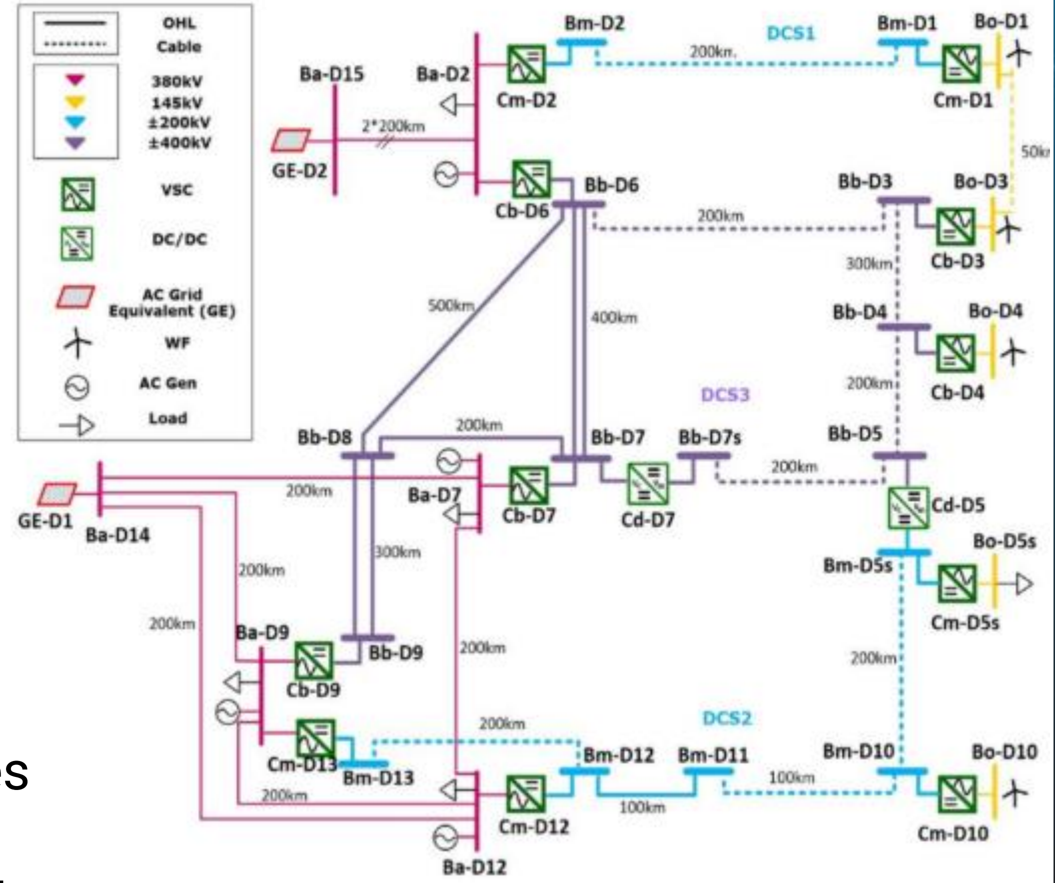




MTDC Studies for HVDC

CHANGING WHAT'S POSSIBLE

- CIGRE released 7 DC Grid Benchmark Models (BM):
  1. HVDC grid model for the integration of large scale onshore renewable generation
  2. ±800 kV Line Commutated Converter (LCC) HVDC grid model
  3. MTDC system model for integration of small onshore renewables
  4. HVDC grid model for offshore wind platform connection
  5. LCC/VSC hybrid HVDC grid model
  6. HVDC grid model for parallel interconnection of two AC power systems
  7. Large comprehensive HVDC grid model
- BMs will enable comparative studies on stability, node interactions, and system benefits of various technologies and control and protection strategies.
- Models published in: PSCAD, EMTP, DigSilent, RTDS and Opal-RT.
- New Tools are needed for EMT modeling and operations.



BM4: HVDC grid for offshore system integration wind generation and offshore platform loads

https://electra.cigre.org/311-august-2020/technical-brochures/dc-grid-benchmark-models-for-system-studies.html

Can AI open the door?

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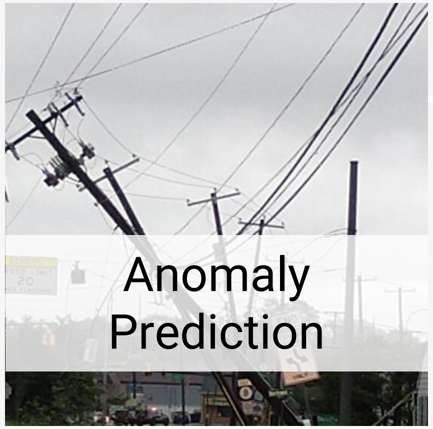
Today

Interconnect studies

Load forecasting

System Operations



Clean electricity for all

New Sources

10X solar, 10X wind

New Uses

2-3X demand

Reliability

Outages > 64%

We have to transform the grid in 25 years!

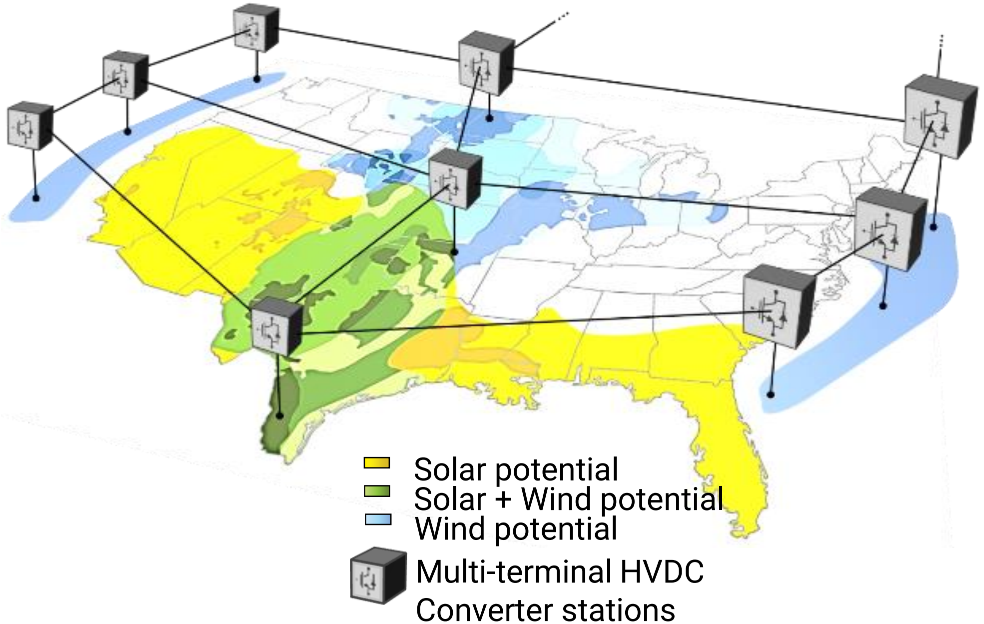
Credits: Window Spotlight Images

TESLA

512th Airlift Wing

Summary of Skills Required

- High power electronics and converter technology
- Integrated heat transfer and high voltage dielectric technology
- System modeling algorithms and tools
- High voltage, high power labs and testing expertise
- P-HIL and HPC software and hardware development
- ML hardware and algorithm development
- Role and challenges using AI?
- Integrated systems operations
- Business models for the utility of the future
- Regulatory and energy policy development



ARPA-E
CHANGING WHAT'S POSSIBLE