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Title:	Microgrids, Distributed Energy Resources, Standards, and the ‘Smart’ Power Grid
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Los Alamos
NATIONAL LABORATORY

Microgrids, Distributed Energy Resources, Standards, and the 'Smart' Power Grid

Guest Lecture
MSU EELE 455/555

Juan Ospina, Scientist
A-1 Information Systems & Modeling Group

10/08/2024

LA-UR-XXXXX

Outline

- Emerging Energy Challenges
- Review of Microgrids & the Smart Grid Concept
- Review of Distributed Energy Resources (DERs)
- Review of IEEE 1547 Standard
- Tools and Work Conducted at LANL

Emerging Energy Challenges

Emerging Energy Challenges

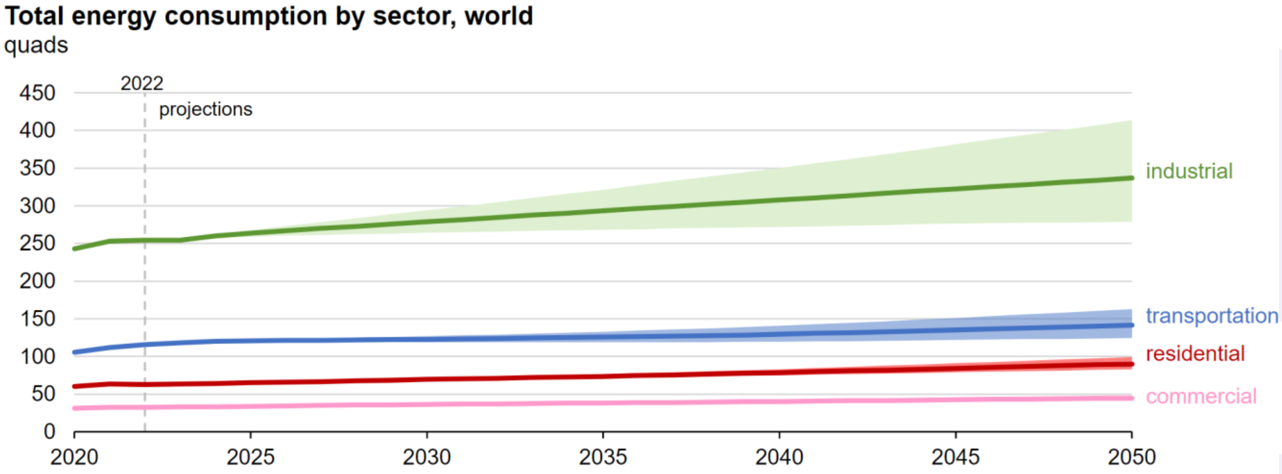
- According to EIA - the total world energy consumption (not including losses) is expected to grow through 2050 across all sectors. Main sector is industrial, which in the High-case is expected to grow up to **159 Quadrillion Btu**

Main Sectors:

- Industrial
- Residential
- Commercial
- Transportation

Other concerns:

- Environmental:
  - Pollution
  - Climate change



[1] "International Energy Outlook 2023," U.S. Energy Information Administration, 2023.

Emerging Energy Challenges

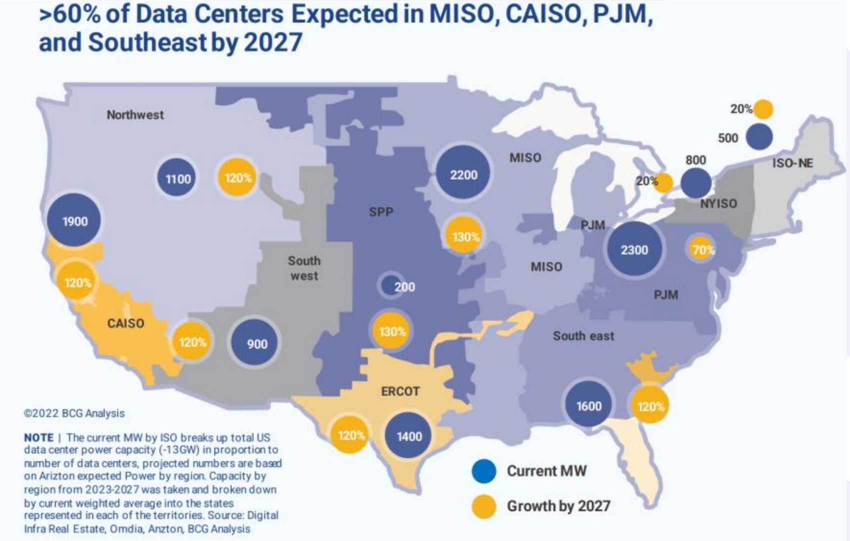
Over the next **5 years US load demand** is expected to grow **4.7%** (amended from 2.6% estimation made in 2022) [2]

Energy demands risen, driven by [3]:

- population growth
- increased data centers (e.g., AI)
- electric vehicle (EV) adoption

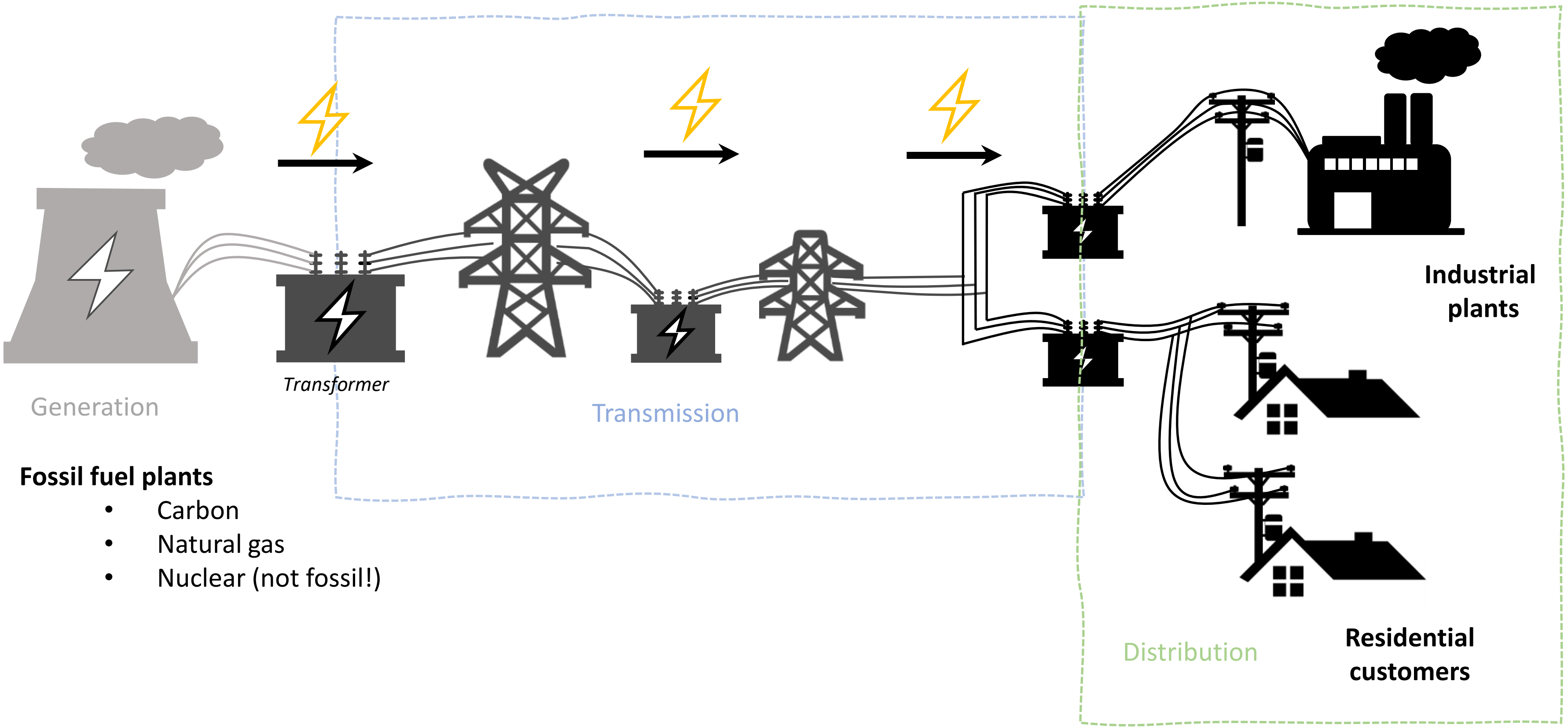
Experts' advice [1]:

- "the electric grid is 'not prepared' for this significant load growth"
- 'low transfer capabilities between regions' are a key risk for reliability
    - *if new generation resources are not integrated into the grid*



[2] https://www.utilitydive.com/news/electricity-load-growing-twice-as-fast-as-expected-Grid-Strategies-report/702366/
[3] https://gridstrategiesllc.com/wp-content/uploads/2023/12/National-Load-Growth-Report-2023.pdf

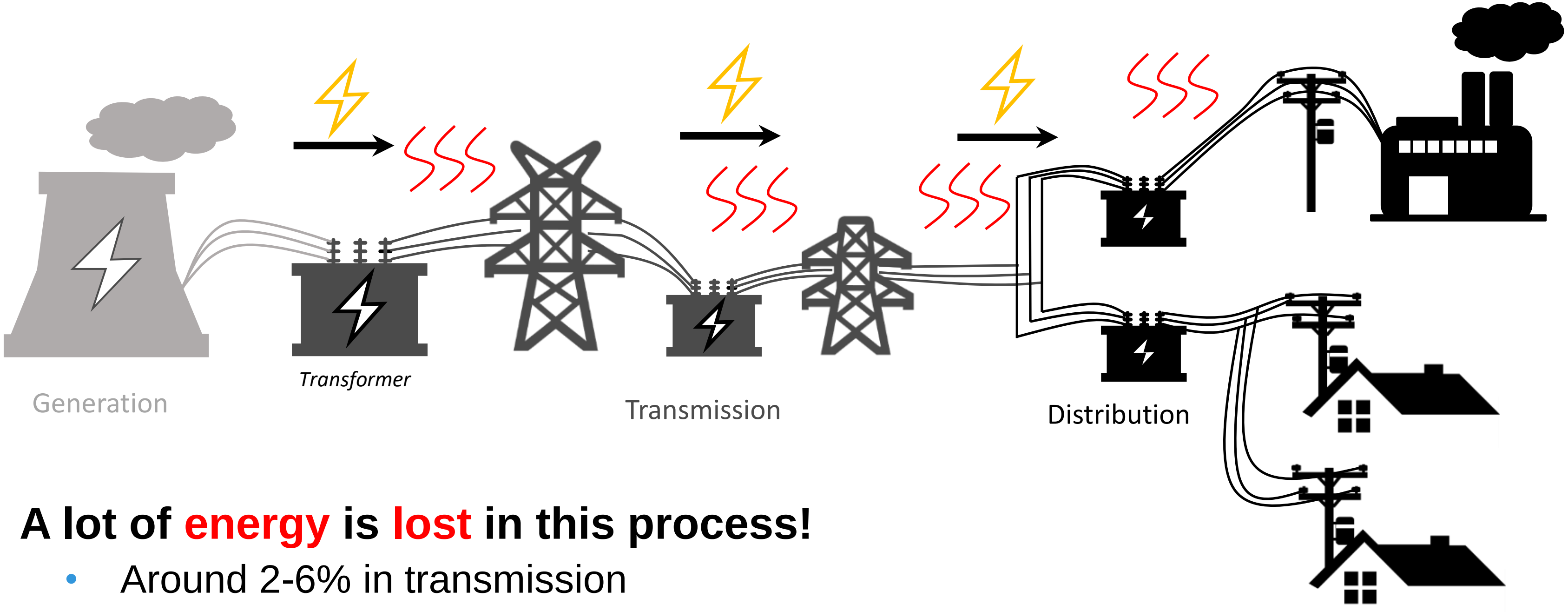
Traditional Power Generation/Consumption



Fossil fuel plants

- Carbon
- Natural gas
- Nuclear (not fossil!)

Transmission & Distribution - Energy Loss



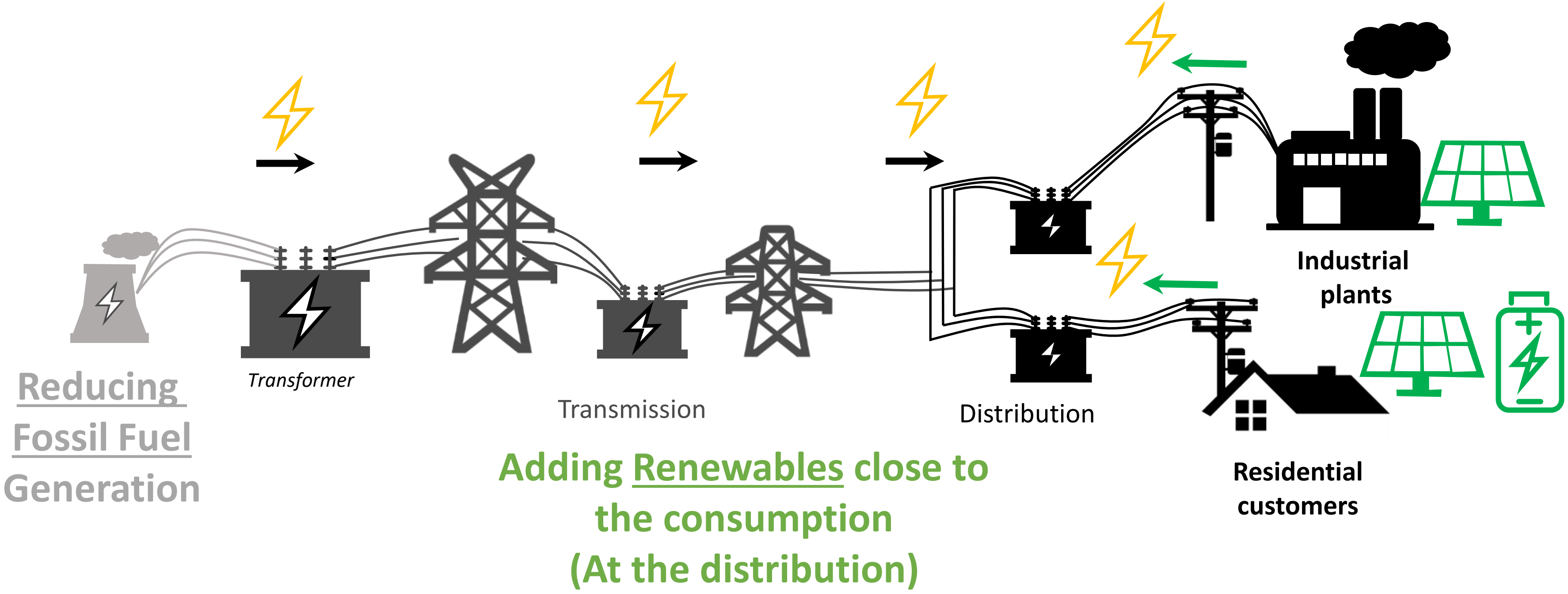
A lot of energy is lost in this process!

- Around 2-6% in transmission
- Around 4% in distribution

[4] http://insideenergy.org/2015/11/06/lost-in-transmission-how-much-electricity-disappears-between-a-power-plant-and-your-plug/
[5] https://www.eia.gov/energyexplained/us-energy-facts/

Efforts to Reduce Losses and Satisfy Load Growth

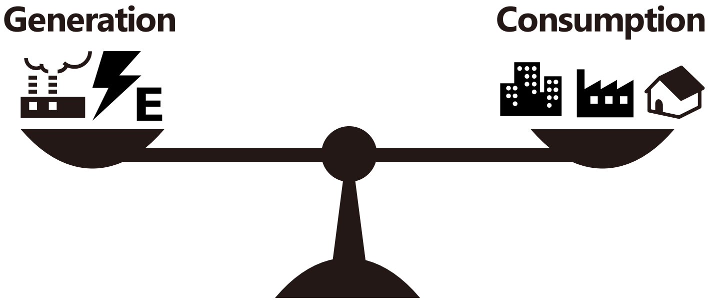
1. Renewable energy sources (Microgrids & DERs)
2. Energy storage devices (e.g., Batteries)



Adding DERs

- Just adding **Renewables (e.g., DERs) everywhere** is not a **realistic** solution
  - A balance between **Generation** & **Consumption** needs to be **always maintained**

  - **Optimization & Control is needed! (Smart Grids, Microgrids, etc.)**



Review of Microgrids & the 'Smart Grid'

Microgrids

What is a Microgrid?

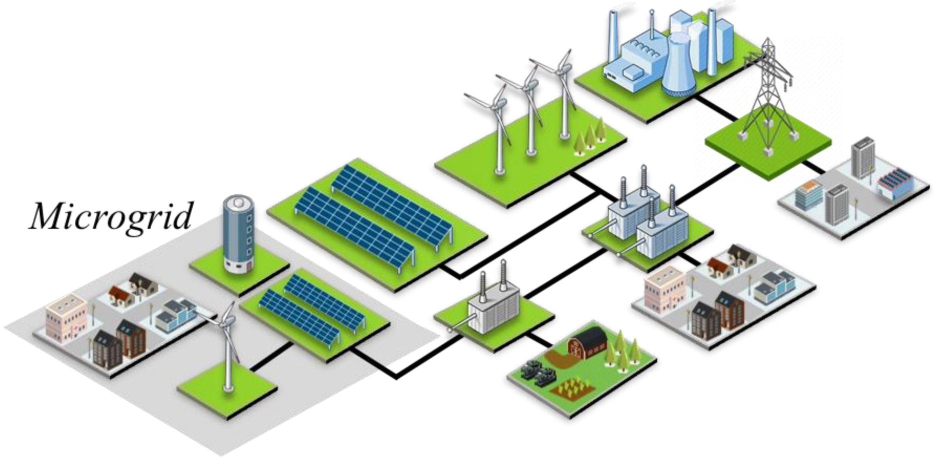
US DOE: "*a group of interconnected loads and distributed energy resources (DER) with clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid and can connect and disconnect from the grid to enable it to operate in both grid-connected or island modes" [6]*

Benefits:

1. Reliability (e.g., satisfy load growth)
2. Resilience (support grid during power outages)
3. Lower energy costs and losses
4. Strengthen central grid and ancillary services

Challenges:

1. Intermittent generation
2. High generation doesn't match high peak demands
3. Island mode (disconnection)
4. Protection



[6] D. Wangman, "First Utility-Scale Microgrid in U.S. Enters Service," IEEE Spectrum, 26 May 2017. [Online].

Types of Microgrids

1. ***Customer microgrids**:* self-governed system of distributed energy resources (DER) connected to single a point of common coupling (PCC)

2. ***Utility or community microgrids:*** a segment or portion of the grid containing multiple DER

3. ***Virtual microgrids**:* multiples sites with DER controlled in such a coordinated way that they can be seen as a single controlled entity from the main grid.

4. ***Remote microgrids:*** These systems are designed to be deployed in remote locations

Brooklyn Microgrid
Brooklyn, NY

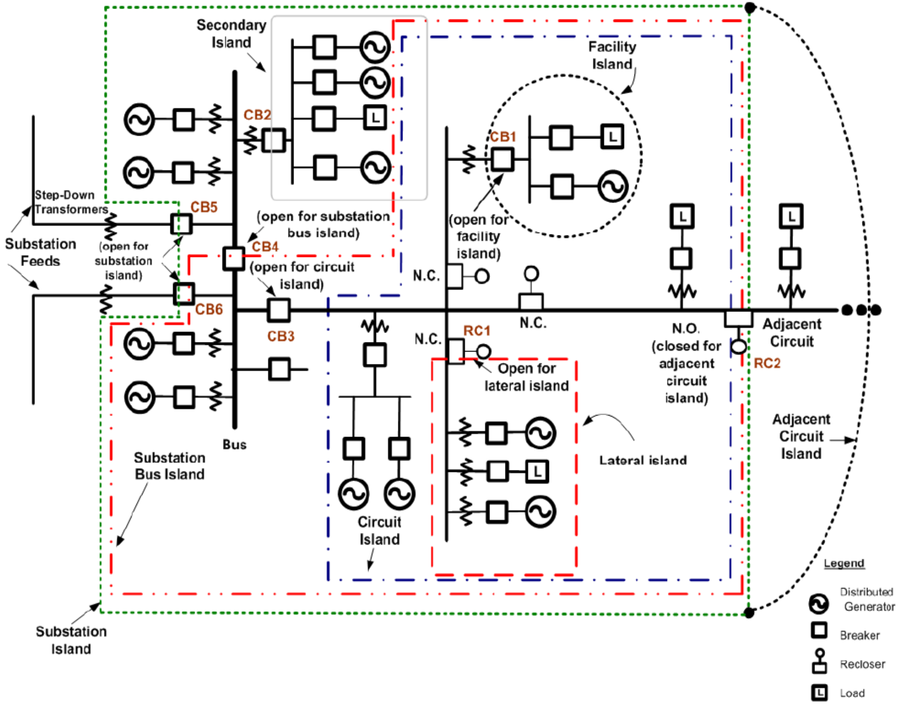
[7] https://clean-coalition.org/community-microgrids/microgrids-across-the-united-states/

Types of Microgrids (IEEE 1547.4)

IEEE Std 1547.4 document categorizes “island” systems, or microgrids, according to their interconnection with the substation feeders connected to the main grid [8].

Types of islands:

1. Local island (facility island)
2. Secondary island
3. Lateral island
4. Circuit island
5. Substation island
6. Adjacent circuit island



[8] https://sagroups.ieee.org/scc21/ieee-1547-series/

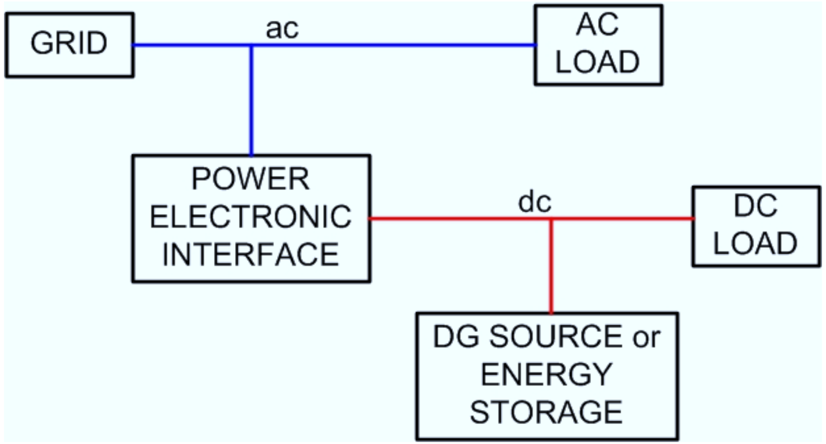
Microgrids & Grid Interaction

DC microgrids (Microgrids with DC sources) integration with the grid

The interface **may** or **may not** allow for **bidirectional** power flow.

Bidirectional power flow can be needed for:

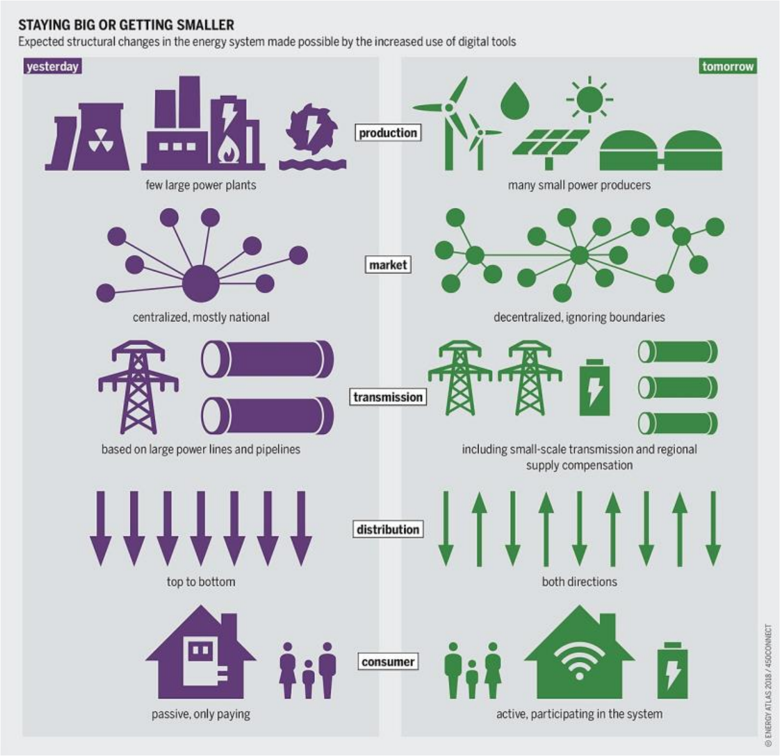
- Energy storage
- DC loads



The ‘Smart Grid’

The ‘power grid’ but with:

- Two-way communication & electricity
- Controls, automation, internet devices
- Smart meters
- DERs (Solar PV, Batteries, Wind)
- Microgrids
- Prosumers (Producers-Consumers)
- Smart appliances
- Electric vehicles & smart charging stations
- Cyber-physical systems (CPS)



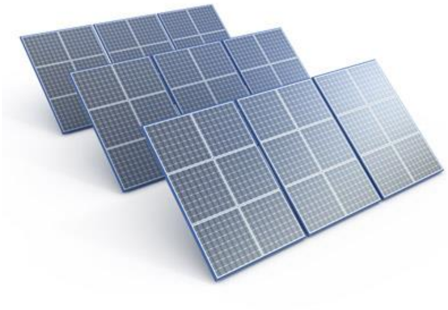
https://en.wikipedia.org/wiki/Smart_grid

Review of DERs

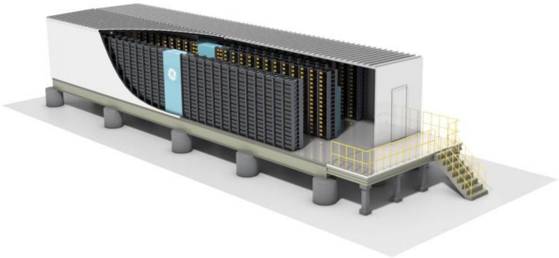
Distributed Energy Resources (DERs)

Microgrids (or distribution systems) can contain any combination of Distributed Energy Resources (DERs). These can be divided in:

1) Distributed Generation (DG)
    a) Combined heat and power (CHP) systems
    b) Solar PV systems
    c) Wind energy conversion systems (WECS)
    d) Conventional generators (Diesel or gas)
    e) Small-scale hydroelectric generators



2) Distributed Storage (DS)
    a) Battery ESS (BESS)
    b) Flywheel ESS (FESS)
    c) Thermal ESS (TESS)



Combined Heat and Power (CHP)

- CHP systems are characterized by being **high energy efficient** due to its property of capturing **otherwise wasted heat** for residential and industrial heating applications.

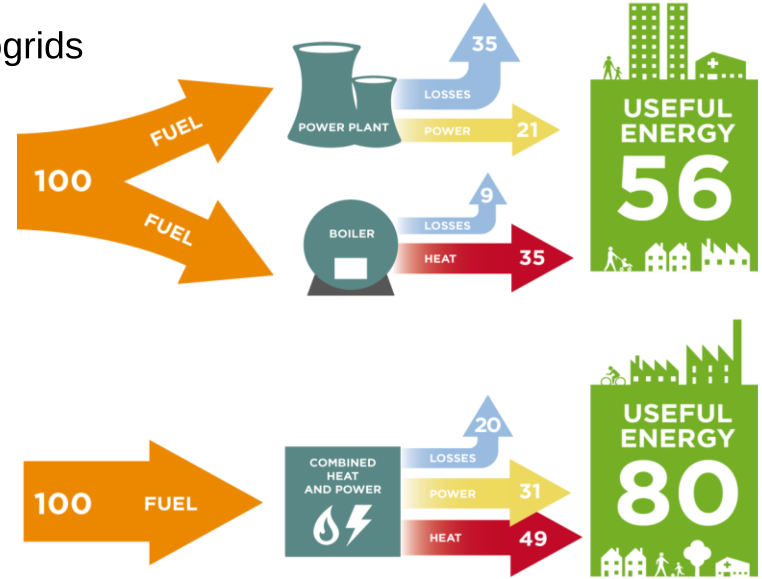
- CHP can reach more than **80%** energy efficiency

- Typically, CHP systems are called **Micro-CHP** in Microgrids

  - ***Large CHP*** – Electricity main product. Heat as byproduct
  - ***Micro-CHP*** – Heat as main product. Electricity as byproduct

Common micro-CHP:

1. Microturbines
2. Fuel cells

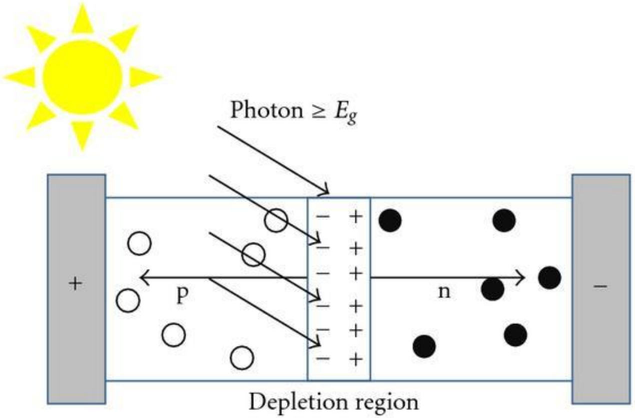


[9] http://northernutilities.co.uk/combined-heat-and-power/

Solar PV Systems

Solar cells or **Photovoltaic (PV) cells** convert sunlight to electricity through the photovoltaic effect:

P-N junction diodes are exposed to small packets of incoming light

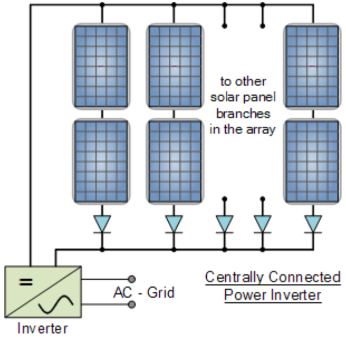


Types of solar cells:

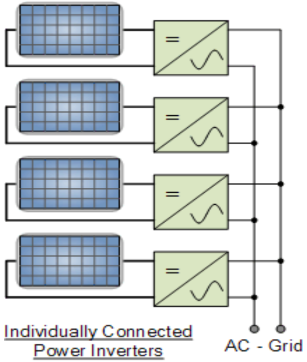
1. Monocrystalline silicon
2. Polycrystalline silicon
3. Thin-film
4. Hybrid

Solar PV Systems

Central inverter topology



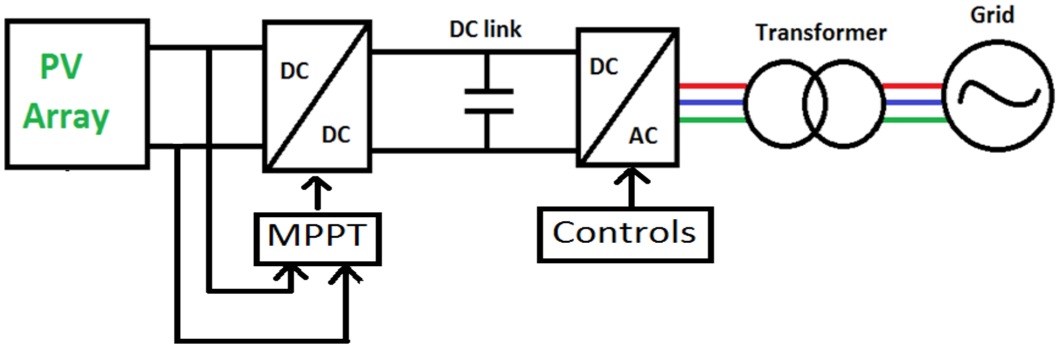
Micro inverter topology



- Multiple solar cells are connected in series and arranged into modules

Common components found in grid-connected PV Systems [10]:

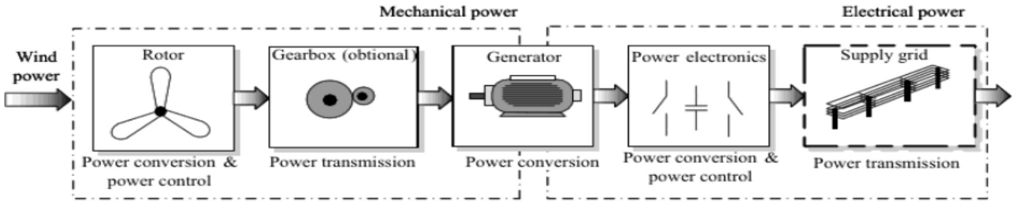
1. DC/DC Converters
2. DC/AC Converters
3. Filters
4. MPPT System
5. Controls



[10] Solar Electric System Design, Operation and Installation," Washington State University , Washington, 2009.

Wind Energy Conversion Systems (WECS)

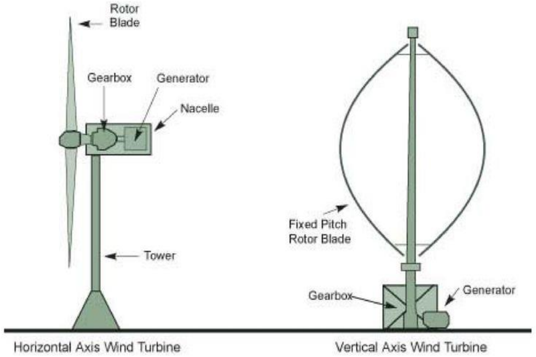
WECS convert wind energy into electrical energy by using turbines connected to the main shaft of a generator



Basic components of a wind energy conversion system (WECS)

Types of wind energy systems can be classified [11]:

1. Horizontal-axis wind turbines (HAWT)
2. Vertical-axis wind turbines (VAWT)



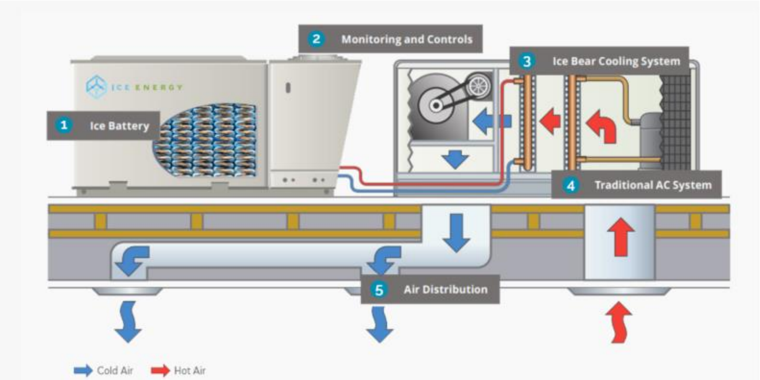
[11] T. Gonen, Electric Power Distribution Engineering 3rd edition, Boca Raton: CRC Press, 2014.

Distributed Storage (DS) – or simply Energy Storage

Distributed storage (DS) systems have become a critical part of the deployment of DER in modern distribution systems due to economic viability

Widespread DS technologies:

1. **Battery ESS (BESS) [12]:** 32 MW Li-ion California, US
2. **Flywheel ESS (FESS) [13]:** Amber Kinetics M32 8 kW, 32 kWh
3. **Thermal ESS (TESS) [14]:** IceBear20, Max. cooling load 10 tons, up to 14 kW on-peak reduction



[12] X. Hu, C. Zou, C. Zhang and Y. Li, "Technological Developments in Batteries: A Survey of Principal Roles, Types, and Management Needs," in IEEE Power and Energy Magazine, vol. 15, no. 5, pp. 20-31, Sept.-Oct. 2017
[13] http://amberkinetics.com/products-2/
[14] https://www.ice-energy.com/technology/

How to Size Solar PV & Energy Storage

System Advisory Model (SAM)

Free desktop application for techno-economic analysis of energy technologies.

Used by:

- project managers and engineers
- policy analysts
- technology developers
- researchers

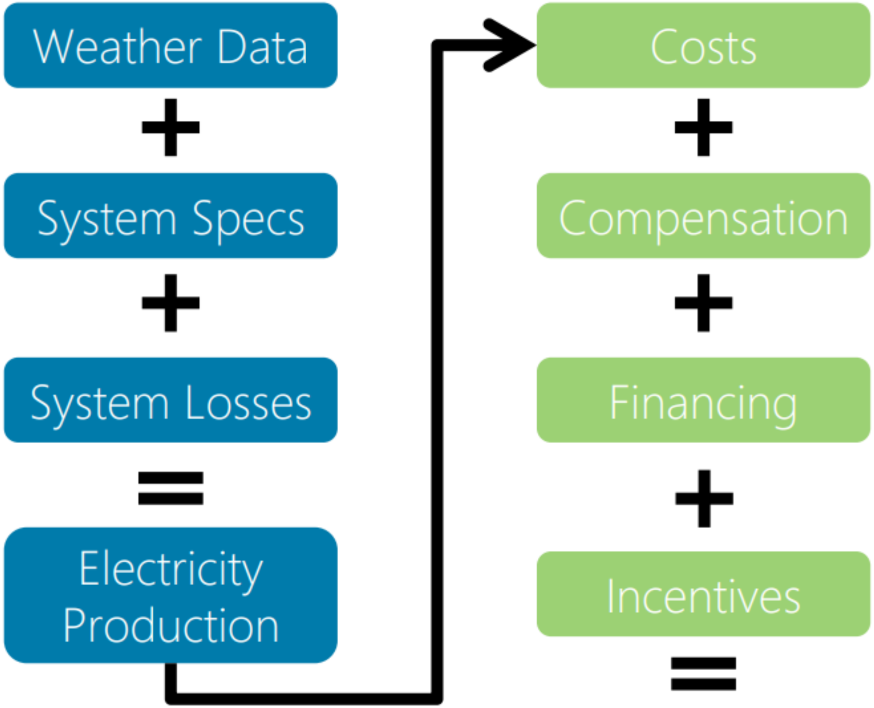
Investigate questions about:

- technical, economic, and financial feasibility of renewable energy projects.

https://sam.nrel.gov/

https://sam.nrel.gov/images/webinar_files/sam-webinars-2020-intro-to-sam.pdf

System Advisory Model (SAM)



Results

Annual, Monthly, and Hourly Power/Energy Output, Capacity Factor, LCOE, NPV, Payback, Revenue

https://sam.nrel.gov/images/webinar_files/sam-webinars-2020-intro-to-sam.pdf

How to Size Solar PV & Energy Storage

Renewable Energy Integration & Optimization (REOpt)

- Evaluate the economic viability of distributed:
  - PV
  - Wind
  - Battery storage,
  - Combined heat and power (CHP)
  - Thermal energy storage
- Identify system sizes and dispatch strategies to minimize energy costs.
- Estimate how long a system can sustain critical load during a grid outage.

REOpt

	Resilience	Financial
System	1,271 kW PV 396 kW Battery 3,911 kWh Battery	249 kW PV 34 kW Battery 60 kWh Battery
NPV	-$2,301,077	$112,501
Survives Specified Outage	Yes	No
Average	410 hrs	3 hrs
Minimum	0 hrs	0 hrs
Maximum	2,155 hrs	19 hrs

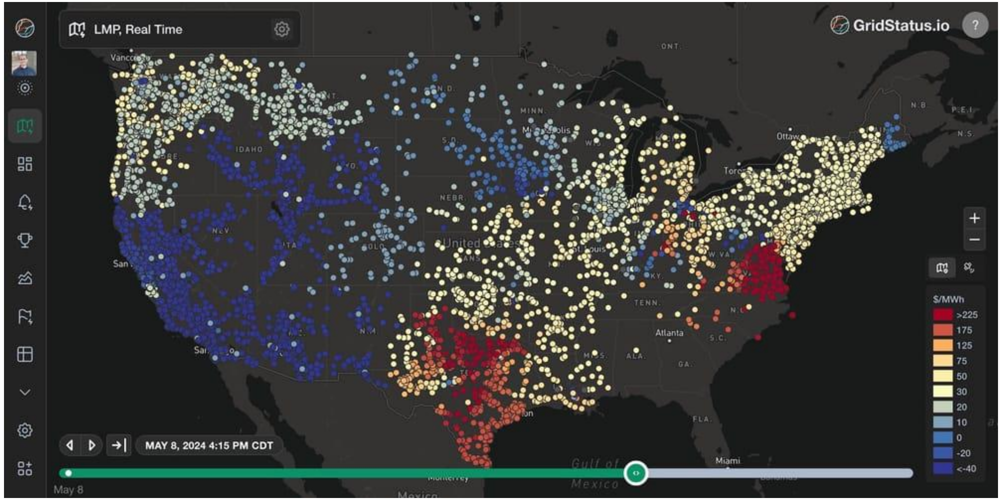
https://reopt.nrel.gov/tool

Brief Review of Electricity Pricing Programs

Locational Marginal Prices (LMPs)

Locational marginal prices are a way for wholesale electric energy prices to reflect the value of electric energy at different locations, accounting for the patterns of load, generation, and the physical limits of the transmission system.

- Dual-variable solutions for nodal power-balance constraints in OPF results ($/MW)



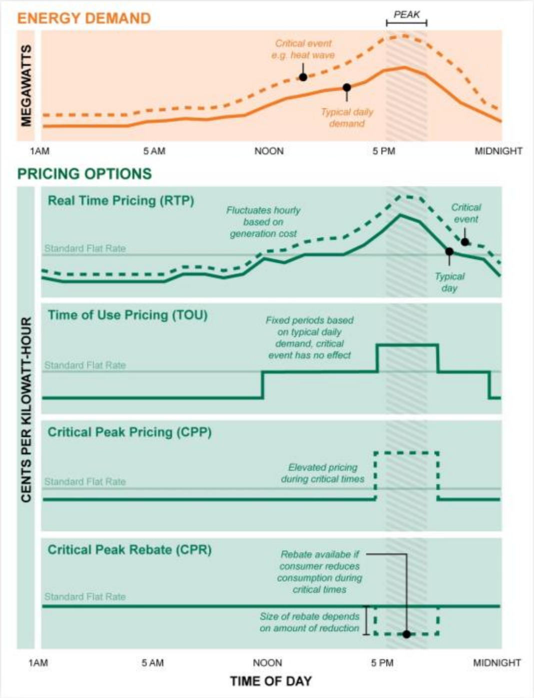
https://www.gridstatus.io/map?ref=blog.gridstatus.io

Electricity Pricing Programs

Objective: active consumer participation in the demand and supply of energy through a more active ‘energy market’

Major pricing models:

- Feed-in tariff
- Net-metering
- Time-of-use (ToU)
- Critical peak pricing (CPP)
- Critical peak rebate (CPR)
- Real-time pricing (RTP)



[15] https://blogs.edf.org/energyexchange/2015/01/27/all-electricity-is-not-priced-equally-time-variant-pricing-101/

Review of IEEE 1547 Standard

Background

IEEE Standards Coordinating Committee 21 (SCC21)

- Oversee the development of standards in the areas of
  - fuel cells,
  - Photovoltaics
  - dispersed generation
  - energy storage
- Coordinates efforts among the various IEEE societies
- Reviews all proposed IEEE standards for approval

IEEE 1547 Series of Distributed Energy Resources Interconnection and Interoperability Standards, Guides, and Recommended Practices

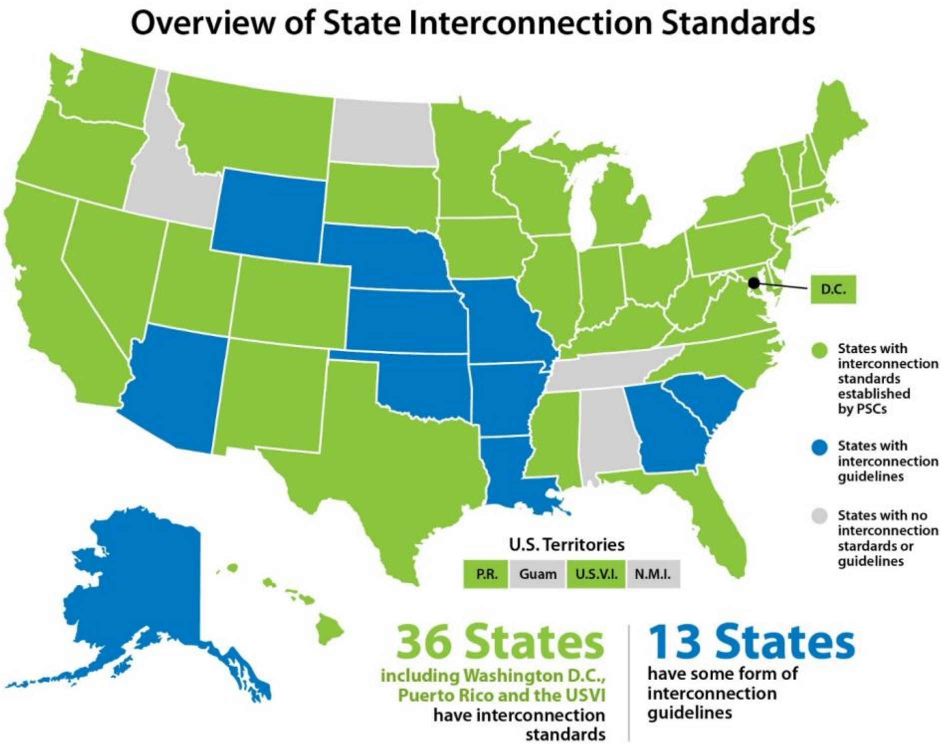
EEE 1547 focuses on:

- Specifications for, and testing of, the interconnection, and **not** on the types of DER technologies
- Technology neutral
- Provides requirements relevant to
  - Performance
  - Operation
  - Testing
  - Safety considerations
  - Maintenance of the interconnection.

IEEE 1547 SERIES

[8] https://sagroups.ieee.org/scc21/ieee-1547-series/

Interconnection Standards in the US



Source: Based on information from the Database of State Incentives for Renewables & Efficiency, North Carolina Clean Energy Technology Center

https://www.nrel.gov/docs/fy22osti/75290.pdf

IEEE 1547 Series Standards

- **1547-2018** IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces
- **1547.1-2020** IEEE Standard Conformance Test Procedures for Equipment Interconnecting Distributed Resources with Electric Power Systems and Associated Interfaces
- **1547.2-2023** IEEE Application Guide for IEEE Std 1547(TM), IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems
- **1547.3- 2023** IEEE Guide for Cybersecurity of Distributed Energy Resources Interconnected with Electric Power Systems
- **1547.4-2011** IEEE Guide for Design, Operation, and Integration of Distributed Resource Island Systems with Electric Power Systems

IEEE 1547-2018

IEEE STANDARDS ASSOCIATION | IEEE

IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces

IEEE Standards Coordinating Committee 21

Sponsored by the
IEEE Standards Coordinating Committee 21 on Fuel Cells, Photovoltaics, Dispersed Generation, and Energy Storage

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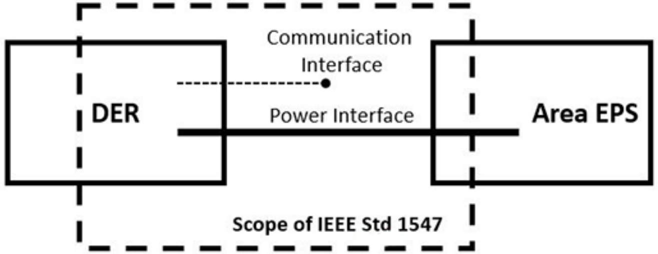
IEEE
3 Park Avenue
New York, NY 10016-5997
USA

IEEE Std 1547™-2018
(Revision of IEEE Std 1547-2003)

IEEE 1547-2018

Scope:
This standard establishes criteria and requirements for interconnection of distributed energy resources (DER) with electric power systems (EPS) and associated interfaces.

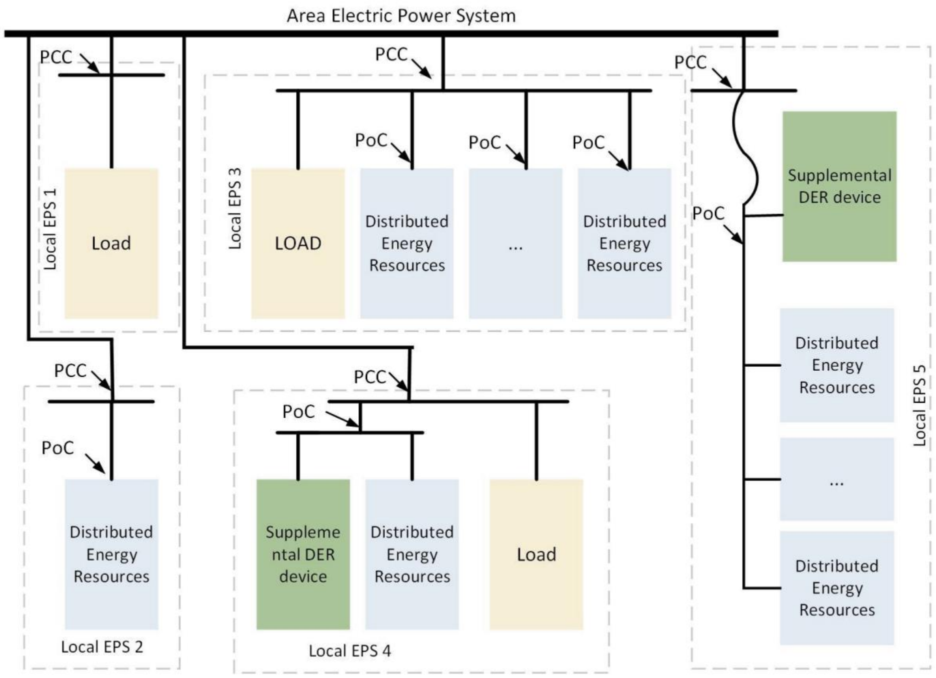
Purpose:
This document provides a uniform standard for the interconnection and interoperability of distributed energy resources with electric power systems. It provides requirements relevant to the interconnection and interoperability performance, operation and testing, and, to safety, maintenance and security considerations.



[9] https://sagroups.ieee.org/scc21/standards/1547rev/

Point of Common Coupling (PCC)

- Point of Common Coupling (PCC)
- Point of Connection (PoC)
- Electric power system (EPS)



[9] https://sagroups.ieee.org/scc21/standards/1547rev/

DER Requirements

1. **Voltage** ride-through requirements
2. **Frequency** ride-through requirements
3. **Islanding requirements** (intentional and unintentional)
4. **Active** and **reactive** power control capability and voltage/power control requirements

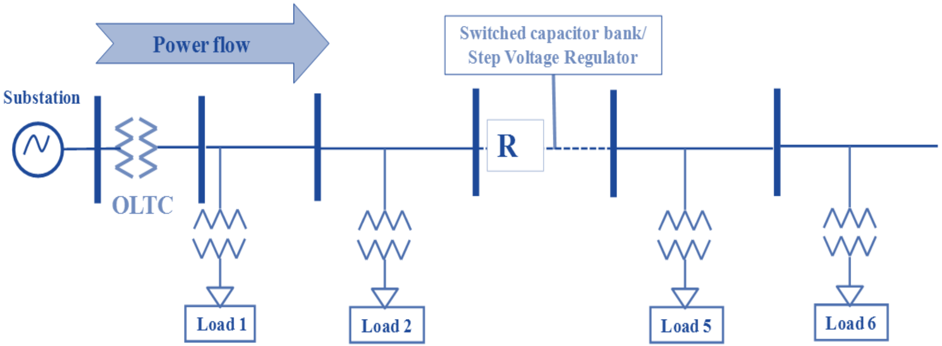
Table 6—Voltage and reactive/active power control function requirements for DER normal operating performance categories

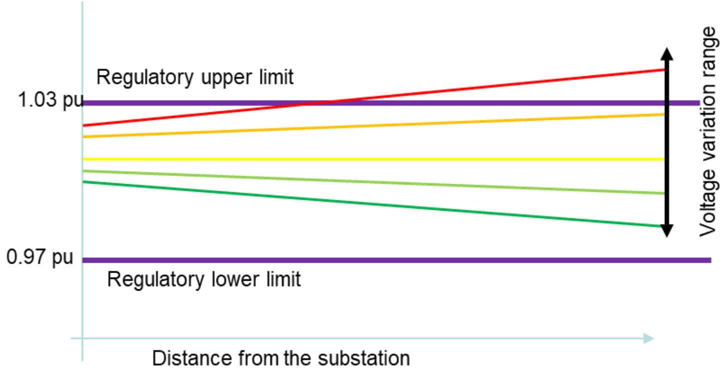
DER category	Category A	Category B
Voltage regulation by reactive power control		
Constant power factor mode	Mandatory	Mandatory
Voltage—reactive power mode[a]	Mandatory	Mandatory
Active power—reactive power mode[b]	Not required	Mandatory
Constant reactive power mode	Mandatory	Mandatory
Voltage and active power control		
Voltage—active power (volt-watt) mode	Not required	Mandatory

[a]Voltage-reactive power mode may also be commonly referred to as "volt-var" mode.
[b]Active power-reactive power mode may be commonly referred to as "watt-var" mode.

Impacts of DERs in Voltage Regulation

- DERs may impact voltage level when starts injecting **power** to the grid
- Abnormal voltages could arise, and client service voltage may **exceed the limit**
- DERs may cause higher terminal voltage

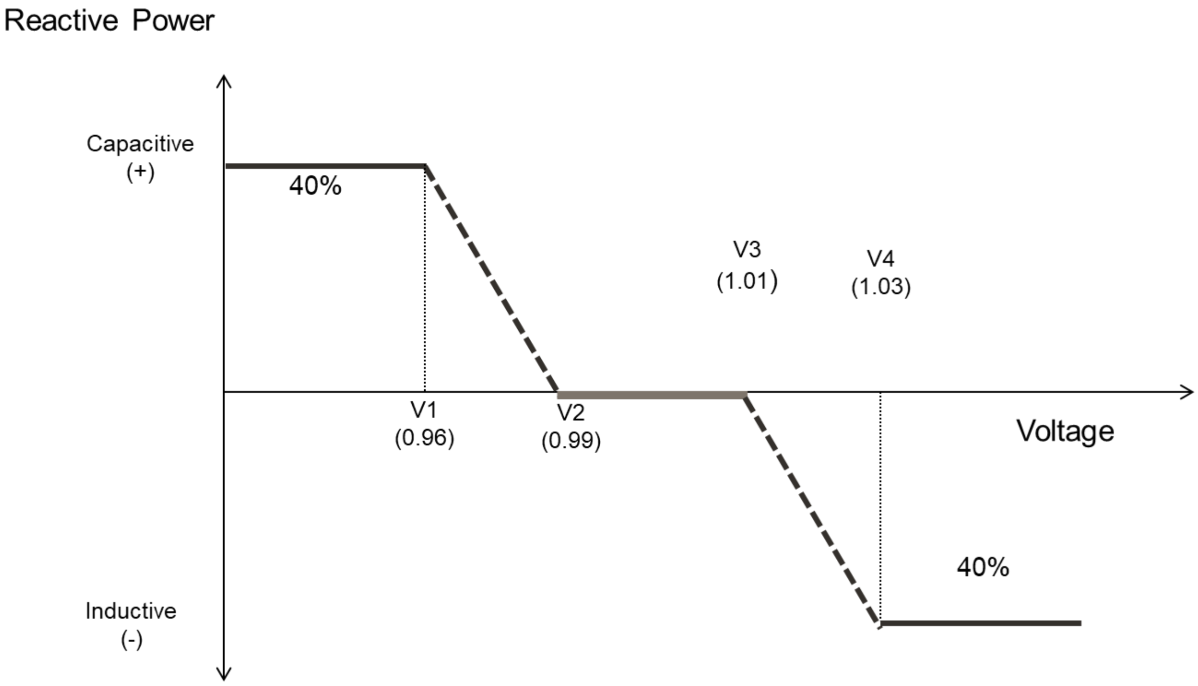




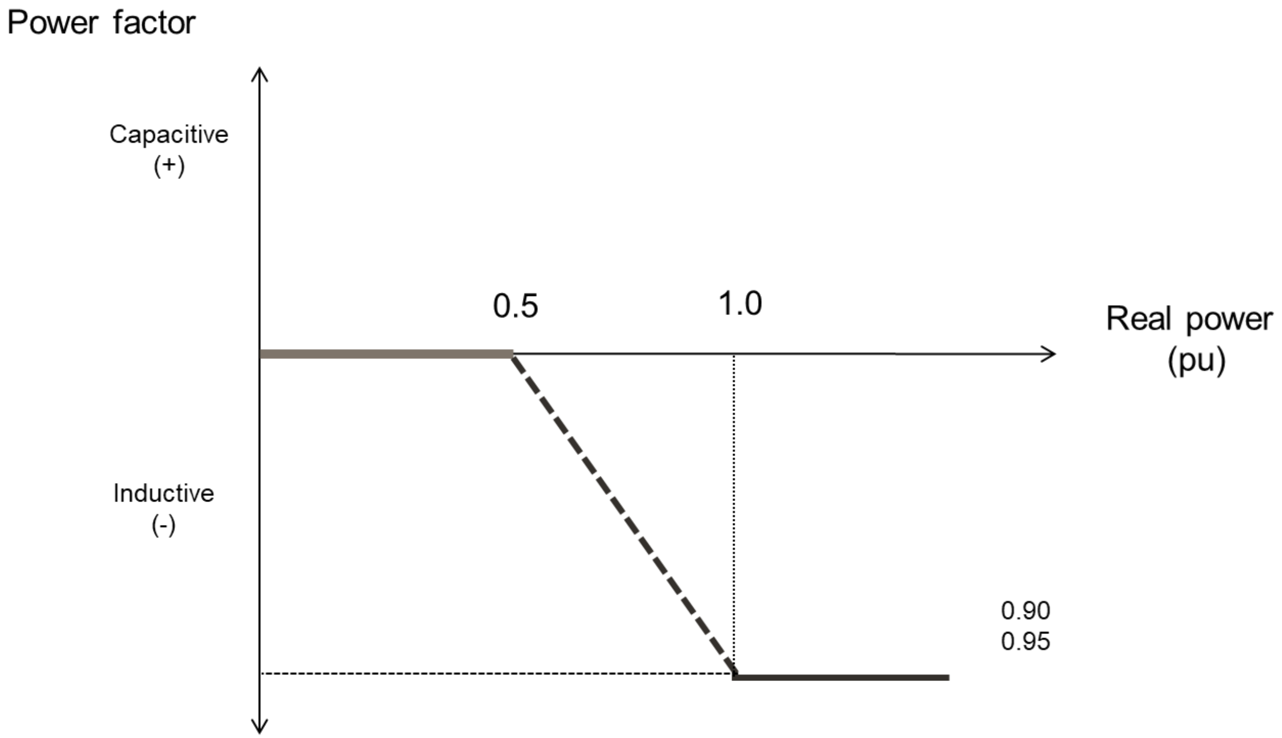
Voltage Control Schemes

- Constant Power Factor (PF) mode
  - Real and reactive power could vary keeping PF constant
  - Can be used for both leading and lagging mode
- Constant reactive power (Q) mode
- Reference voltage control mode (e.g., Volt-Var)
  - Active (P) and reactive (Q) power varies to keep the voltage within bounds

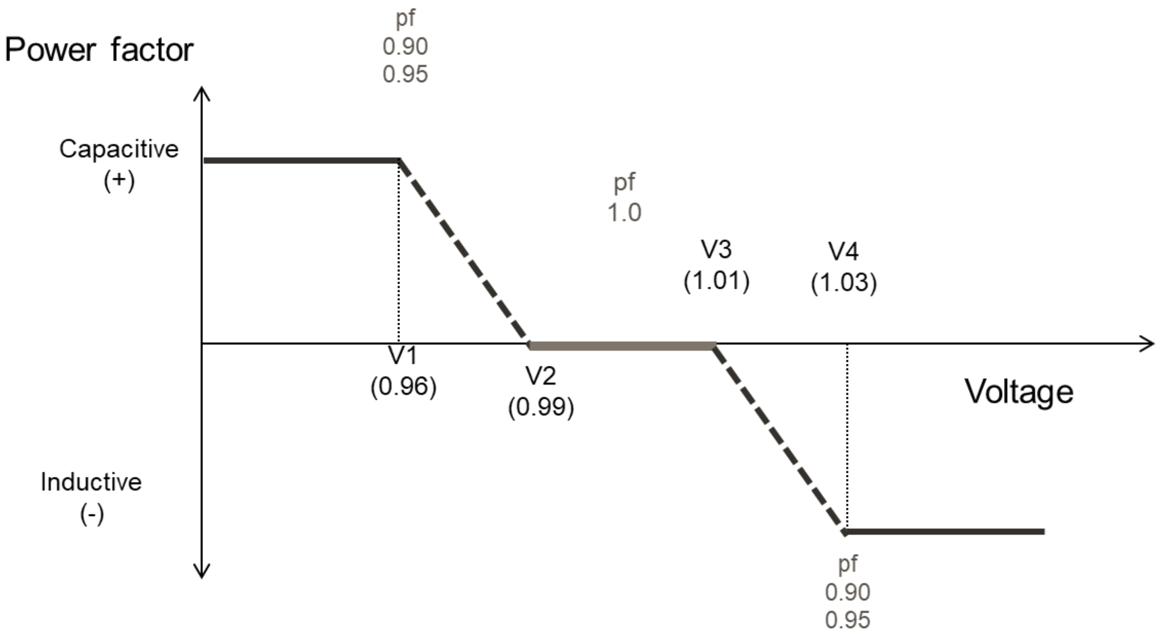
Volt-Var Curve



German LV Curve



Volt – PF curve



Frequency Ride-Through

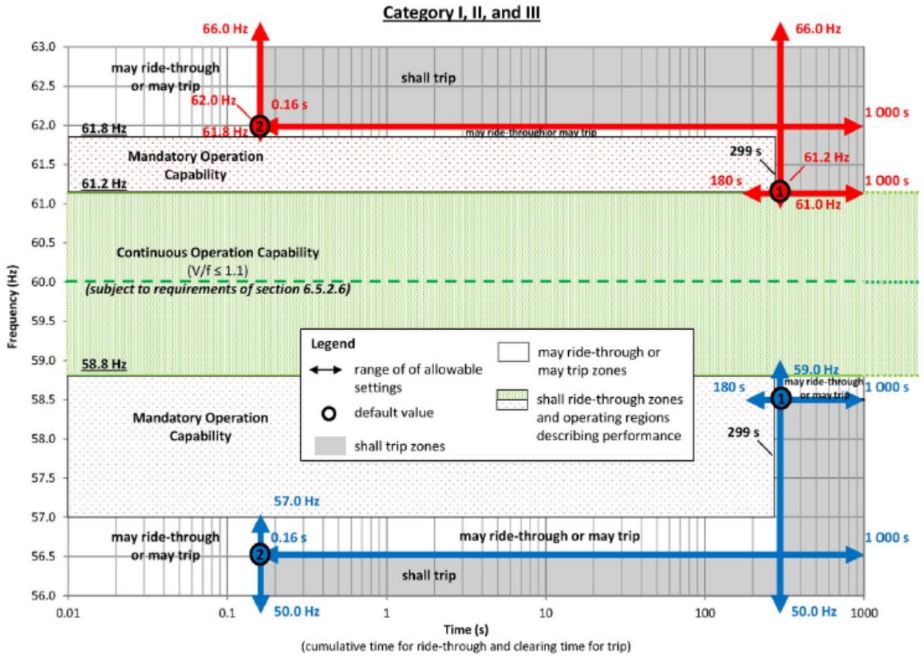


Figure H.10—DER default response to abnormal frequencies and frequency ride-through requirements for DER of abnormal operating performance Category I, Category II, and Category III

Tools and Work Conducted at LANL

LANL: A-1 Critical Infrastructure Team

1. **Electric Power Systems**
   - Transmission (PowerModels.jl)
   - Distribution (PowerModelsDistribution.jl
   - T&D (PowerModelsITD.jl)
   - Protection (PowerModelsProtection.jl)
   - Networked Microgrids (PowerModelsONM.jl)

   https://www.youtube.com/watch?v=D5k-lMicMPM

2. **Other Projects**
   - Cyber-Physical Energy Systems
   - MG-RAVENS (Application Programming Interfaces for Grid Modeling)

https://github.com/lanl-ansi

Modeling & Optimization Ecosystem

Optimization

AC Polar

Variables:

$S_{g,k}, \forall k \in G$

$V_i, \forall i \in N$

$\theta_i, \forall i \in N$

$S_{ij}, \forall (i,j) \in E \cup E_R$

Minimize:

$$\sum_{k \in G_i} c_{2k} \left(\Re(S_{g,k})\right)^2 + c_{1k} \left(\Re(S_{g,k})\right) + c_{0k}$$

Subject to:

$\theta_r = 0, \forall r \in R$

$S^l_{g,k} \le S_{g,k} \le S^u_{g,k}, \forall k \in G$

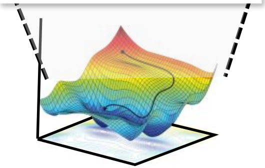
$v^l_i \le |V_i| \le v^u_i, \forall i \in N$

$\sum_{k \in G_i} S_{g,k} - S_{d,i} - \sum_{(i,j) \in E \cup E_R} S_{ij} = 0, \forall i \in N$

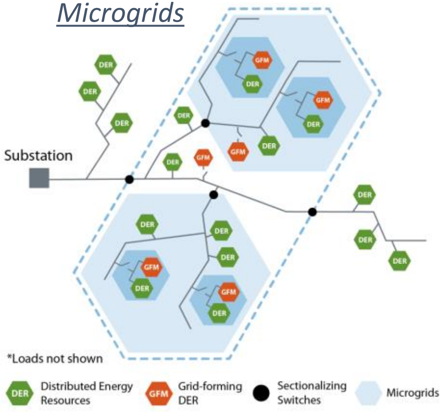
$\theta^{\Delta l}_{ij} \le \theta_i - \theta_j \le \theta^{\Delta u}_{ij}, \forall (i,j) \in E$

$|S_{ij}| \le s^u_{ij}, \forall (i,j) \in E \cup E_R$

...



Microgrids



PowerModelsITD.jl

- Open-source tool (Written in **Julia**)
- Based on **LANL multi-infrastructure ecosystem**
- Used for **modeling** and **optimizing T&D systems**
- Solve steady-state **ITD Optimal Power Flow (OPF)**
- Evaluate diverse **network formulations**
- Common research platform for **emerging formulations**

GitHub [16] https://github.com/lanl-ansi/PowerModelsITD.jl

[17] Ospina, J., et al. (2023). Modeling and Rapid Prototyping of Integrated Transmission-Distribution OPF Formulations with PowerModelsITD.jl. IEEE Transactions on Power Systems.

Using PowerModelsITD.jl

Simple User Interface

```julia
using PowerModelsITD
import Ipopt
ipopt = Ipopt.Optimizer

# Path for the files
pmitd_path = joinpath(dirname(pathof(PowerModelsITD)), "..")

# Files
pm_file = joinpath(pmitd_path, "test/data/transmission/case5_with2loads.m")
pmd_file1 = joinpath(pmitd_path, "test/data/distribution/case3_unbalanced.dss")
pmd_file2 = joinpath(pmitd_path, "test/data/distribution/case3_balanced.dss")
boundary_file = joinpath(pmitd_path, "test/data/json/case5_case3x2_unbal_bal.json")

pmd_files = [pmd_file1, pmd_file2] # vector of files
pmitd_type = NLPowerModelITD{ACPPowerModel, ACPUPowerModel}

result = solve_opfitd(pm_file, pmd_files, boundary_file, pmitd_type, ipopt)
```

Case w/ 2 distro. systems

Beginners Guide (Other examples)

https://lanl-ansi.github.io/PowerModelsITD.jl/stable/tutorials/BeginnersGuide.html

Results

```
julia> result
Dict{String, Any} with 8 entries:
  "solve_time"         => 0.12712
  "optimizer"          => "Ipopt"
  "termination_status" => LOCALLY_SOLVED
  "dual_status"        => FEASIBLE_POINT
  "primal_status"      => FEASIBLE_POINT
  "objective"          => 18146.3
  "solution"           => Dict{String, Any}("multiinfrastructure"=>true, "it"=>Dict{String, Any}("pmd…
  "objective_lb"       => -Inf
```

Transmission

```
julia> result["solution"]["it"]["pm"]
Dict{String, Any} with 6 entries:
  "baseMVA"      => 100.0
  "branch"       => Dict{String, Any}("3"=>Dict{String, Any}("qf"=>206.656, "qt"=>-202.276, "pt"=>221.006, "pf"=>-220.308), "4"=>Dict{String, Any}("qf"=>-217.108, "qt"=>221.882, "pt"=>79.0383, "pf"=>-78.3924), "1"=…
  "gen"          => Dict{String, Any}("4"=>Dict{String, Any}("qg"=>56.3262, "pg"=>18.0328), "1"=>Dict{String, Any}("qg"=>30.0, "pg"=>40.0), "5"=>Dict{String, Any}("qg"=>-201.205, "pg"=>461.003), "2"=>Dict{String, A…
  "multinetwork" => false
  "bus"          => Dict{String, Any}("4"=>Dict{String, Any}("va"=>-1.06955e-34, "vm"=>0.9), "1"=>Dict{String, Any}("va"=>3.95367, "vm"=>0.917681), "5"=>Dict{String, Any}("va"=>-0.949629, "vm"=>0.937736), "2"=>Dict…
  "per_unit"     => false
```

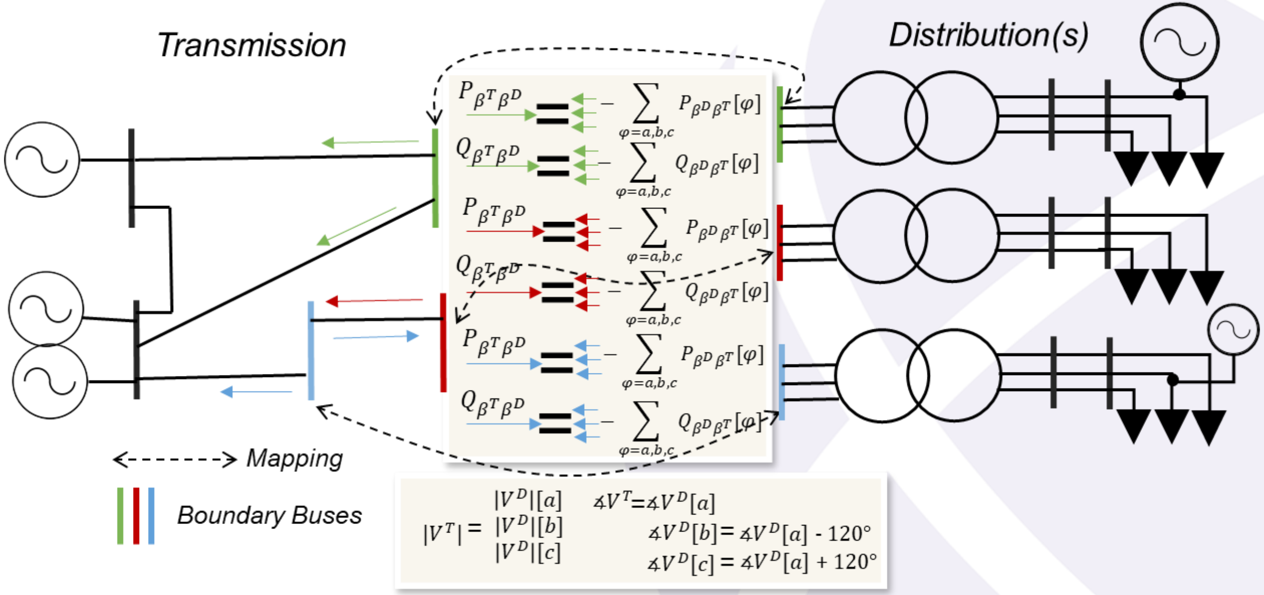
Distribution

```
julia> result["solution"]["it"]["pmd"]
Dict{String, Any} with 7 entries:
  "line"        => Dict{String, Any}("3bus_unbal.quad"=>Dict{String, Any}("qf"=>[1344.85, 1503.97, 1502.46], "qt"=>[-1333.33, -1500.0, -1500.0], "pt"=>[-3333.33, -2333.33, -2333.33], "pf"=>[3351.62, 2340.39, 2344.9…
  "settings"    => Dict{String, Any}("sbase"=>100000.0)
  "transformer" => Dict{String, Any}("3bus_bal.subxf"=>Dict{String, Any}("q"=>[[1508.51, 1508.51, 1508.51], [-1508.41, -1508.41, -1508.41]], "p"=>[[2351.59, 2351.59, 2351.59], [-2351.58, -2351.58, -2351.58]]), "3bu…
  "generator"   => Dict{String, Any}("3bus_unbal.gen1"=>Dict{String, Any}("qg_bus"=>[-0.0, -0.0, -0.0], "qg"=>[-0.0, -0.0, -0.0], "pg"=>[666.668, 666.668, 666.668], "pg_bus"=>[666.668, 666.668, 666.668]), "3bus_bal…
  "load"        => Dict{String, Any}("3bus_unbal.l2"=>Dict{String, Any}("qd_bus"=>[1500.0], "pd_bus"=>[3000.0], "qd"=>[1500.0], "pd"=>[3000.0]), "3bus_bal.l3"=>Dict{String, Any}("qd_bus"=>[1500.0], "pd_bus"=>[3000.…
  "bus"         => Dict{String, Any}("3bus_unbal.loadbus"=>Dict{String, Any}("va"=>[-1.10106, -120.971, 119.172], "vm"=>[7.38801, 7.42776, 7.41273]), "3bus_bal.substation"=>Dict{String, Any}("va"=>[-1.08179, -121.0…
  "per_unit"    => false
```

Boundary

```
julia> result["solution"]["it"]["pmitd"]["boundary"]
Dict{String, Any} with 4 entries:
  "(100001, 5, voltage_source.3bus_unbal.source)" => Dict{String, Any}("pbound_fr"=>[8068.8], "qbound_fr"=>[4367.42])
  "(100001, voltage_source.3bus_unbal.source, 5)" => Dict{String, Any}("pbound_to"=>[-3367.36, -2346.47, -2354.97], "qbound_to"=>[-1355.14, -1507.53, -1504.75])
  "(100002, voltage_source.3bus_bal.source, 6)"   => Dict{String, Any}("pbound_to"=>[-2351.62, -2351.62, -2351.62], "qbound_to"=>[-1508.64, -1508.64, -1508.64])
  "(100002, 6, voltage_source.3bus_bal.source)"   => Dict{String, Any}("pbound_fr"=>[7054.87], "qbound_fr"=>[4525.93])
```

Mathematics at the T&D Boundaries



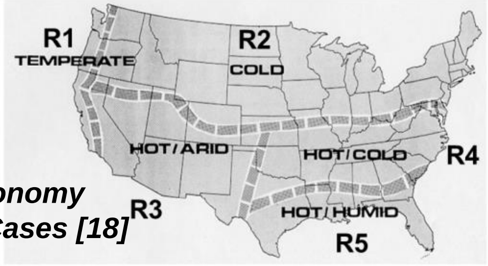
Experimental Test Cases: OPF ITD

PGLib 500 bus

224 Gens

Boundary Bus

2	R1-25-1
3	R1-1247-1
4	R1-1247-2
5	R1-1247-3
6	R1-1247-4
12	R2-25-1
13	GC-1247-1
14	R2-1247-1
15	R2-1247-2
29	R4-1247-2
55	R5-25-1
56	R5-35-1
57	R5-1247-4



Taxonomy PNNL Cases [18]

PVs: 55

DGs: 17

13 distribution systems w/ **759** - **3,403** nodes (range)

Test Cases	N	E
case_r1_25_1	759	762
case_r1_1247_1	3403	3583
case_r1_1247_2	1450	1527
case_r1_1247_3	168	165
case_r1_1247_4	970	981
case_r2_25_1	1617	1681
case_gc_1247_1	96	93
case_r2_1247_1	1731	1750
case_r2_1247_2	1207	1275
case_r4_1247_2	1155	1202
case_r5_25_1	3116	3250
case_r5_35_1	1435	1505
case_r5_1247_4	2030	2088

Totals:

Buses/Nodes: 19,637 (w/ +500 from transmission)

Edges: 20,595 (w/ +733 from transmission)

[18] Schneider, Kevin P., et al. *Modern grid initiative distribution taxonomy final report*. No. PNNL-18035. Pacific Northwest National Lab.(PNNL), Richland, WA (United States), 2008.

Experimental Test Cases: T&D OPF Results

CPU: 2.80 Ghz
RAM: 128 GB

Solver:
Ipopt vers.: 3.14.4
MUMPS vers.: 5.4.1

Formulation	$/hr	Time (s)	Iterations
ACP-ACPU	422,095.2350	525.154	94
IVR-IVRU	422,095.2348	360.954	99
NFA-NFAU	412,286.7567	10.860	24
ACR-FBSUBF	422,074.7218	226.852	97
BFA-LinDist3	412,286.7567	146.084	45
SOCBF-LinDist3	421,529.7893	241.203	75

LANL: A-1 Critical Infrastructure - Example Projects

1. A Framework for Exploring Power Flow Formulations
    - *Coffrin, C., Bent, R., Sundar, K., Ng, Y., & Lubin, M. (2018, June). Powermodels. jl: An open-source framework for exploring power flow formulations. In 2018 Power Systems Computation Conference (PSCC) (pp. 1-8). IEEE.*
    - PowerModels.jl: A Framework for Exploring Power Flow Formulations
2. Phase-Unbalanced Power Distribution Network Optimization with PowerModelsDistribution.jl
    - *Fobes, D. M., Claeys, S., Geth, F., & Coffrin, C. (2020). PowerModelsDistribution. jl: An open-source framework for exploring distribution power flow formulations. Electric Power Systems Research, 189, 106664.*
    - PowerModelsDistribution.jl: A Framework for Exploring Distribution Network Power Flow Formulations
3. Microgrids for Resilience and Reliability
    - *Fobes, D. M., Bent, R., Jain, R., Flores-Espino, F., Pratt, A., Mahoney, R., ... & Reno, M. J. (2023). Quantifying resiliency benefits of networked microgrids using PowerModelsONM. jl.*
    - *Fobes, D. M., Nagarajan, H., & Bent, R. (2022). Optimal Microgrid Networking for Maximal Load Delivery in Phase Unbalanced Distribution Grids: A Declarative Modeling Approach. IEEE Transactions on Smart Grid, 14(3), 1682-1691.*
    - R&D 100 - PowerModels ONM
4. Towards the Secure Operation of Cyber-Physical Energy Systems
    - *Ospina Casas, J. J. (2022). Towards the Secure Operation of Cyber-Physical Energy Systems (CPES) (No. LA-UR-22-31034). Los Alamos National Lab.(LANL), Los Alamos, NM (United States).*
    - *Ospina, J., Venkataramanan, V., & Konstantinou, C. (2022). CPES-QSM: A Quantitative Method Toward the Secure Operation of Cyber–Physical Energy Systems. IEEE Internet of Things Journal, 10(9), 7577-7590.*

Thanks for your time

Questions?