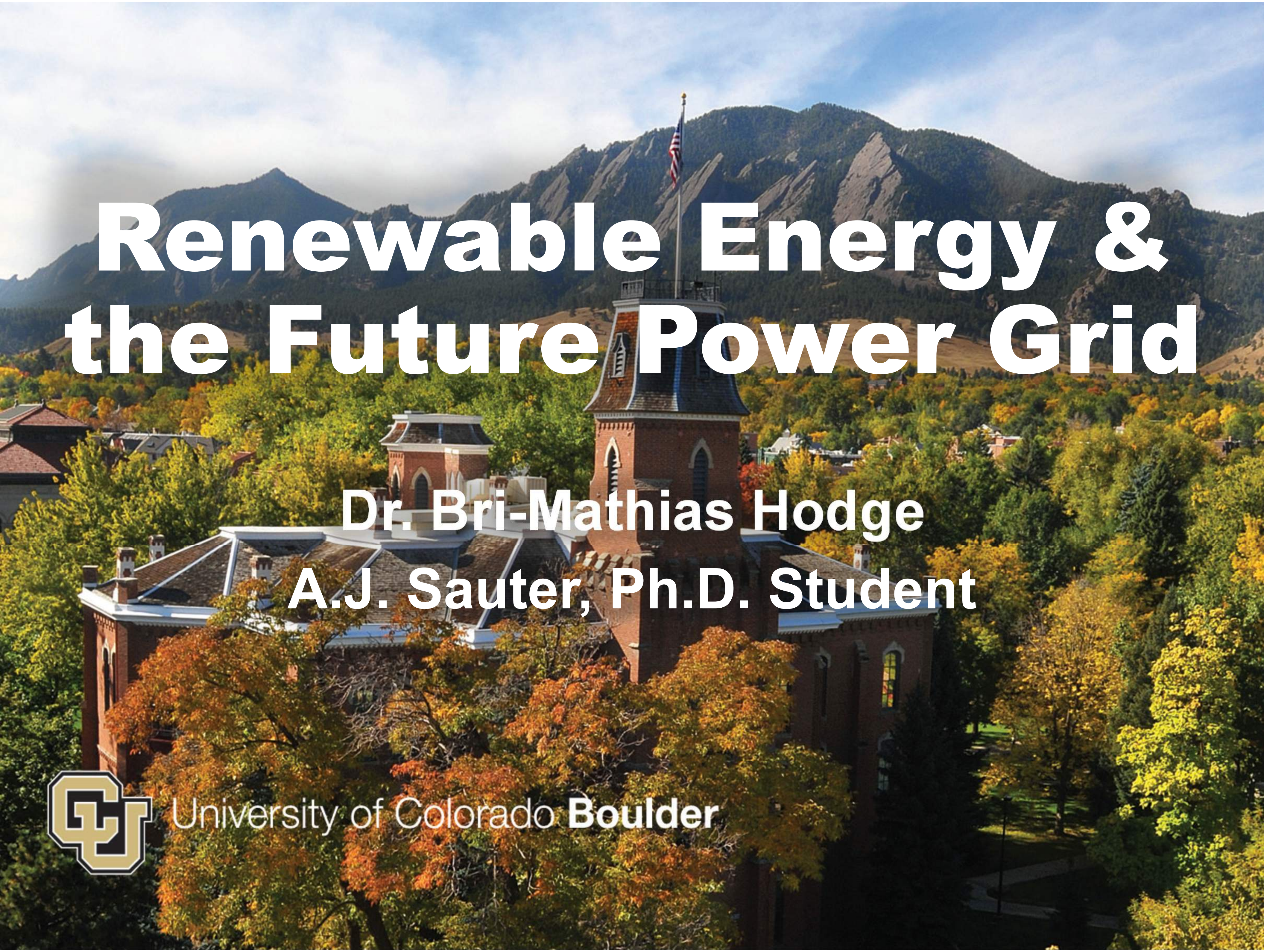


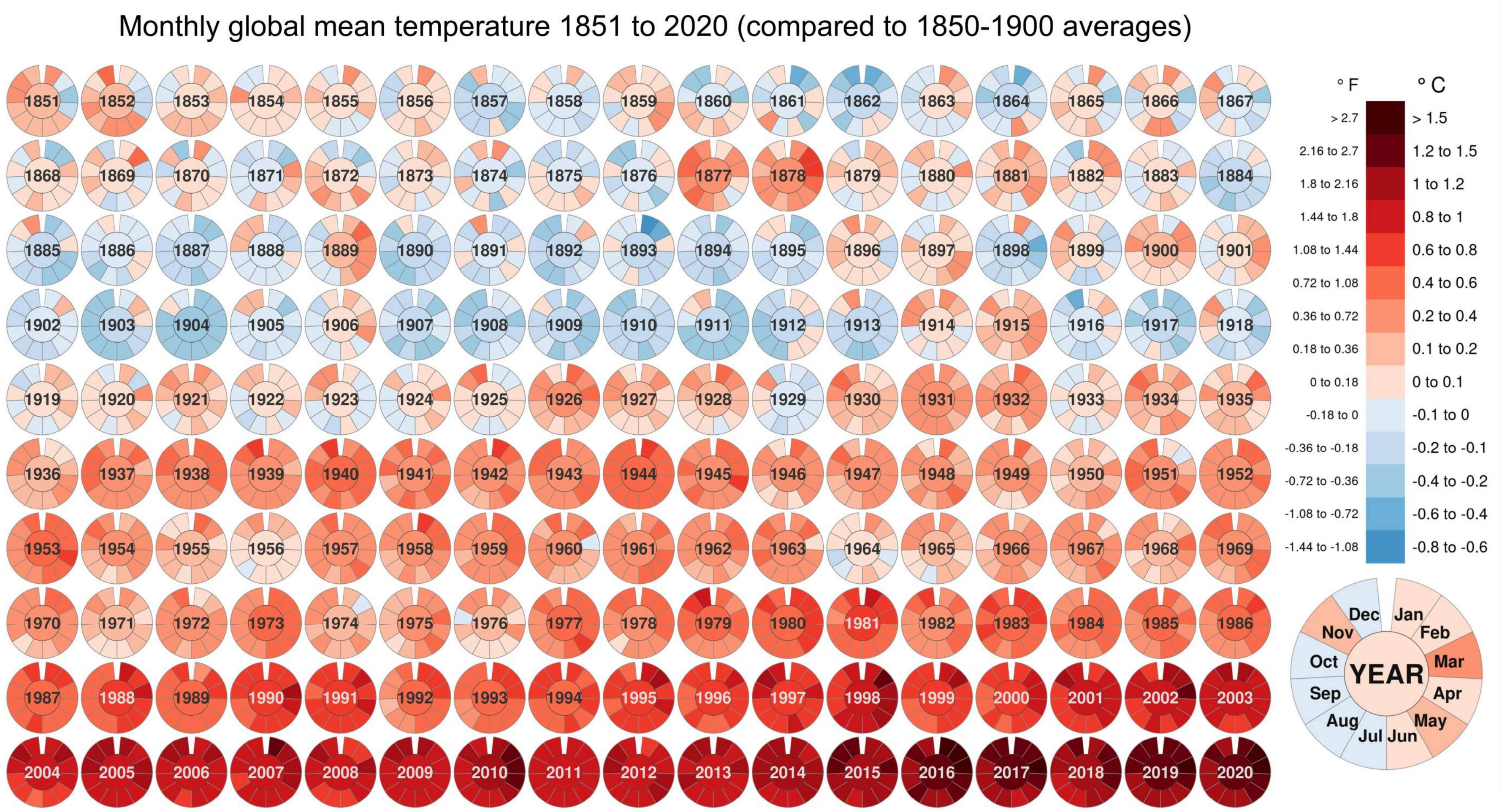
Renewable Energy & the Future Power Grid

Dr. Bri-Mathias Hodge

A.J. Sauter, Ph.D. Student

University of Colorado **Boulder**

The Elephant in the Room



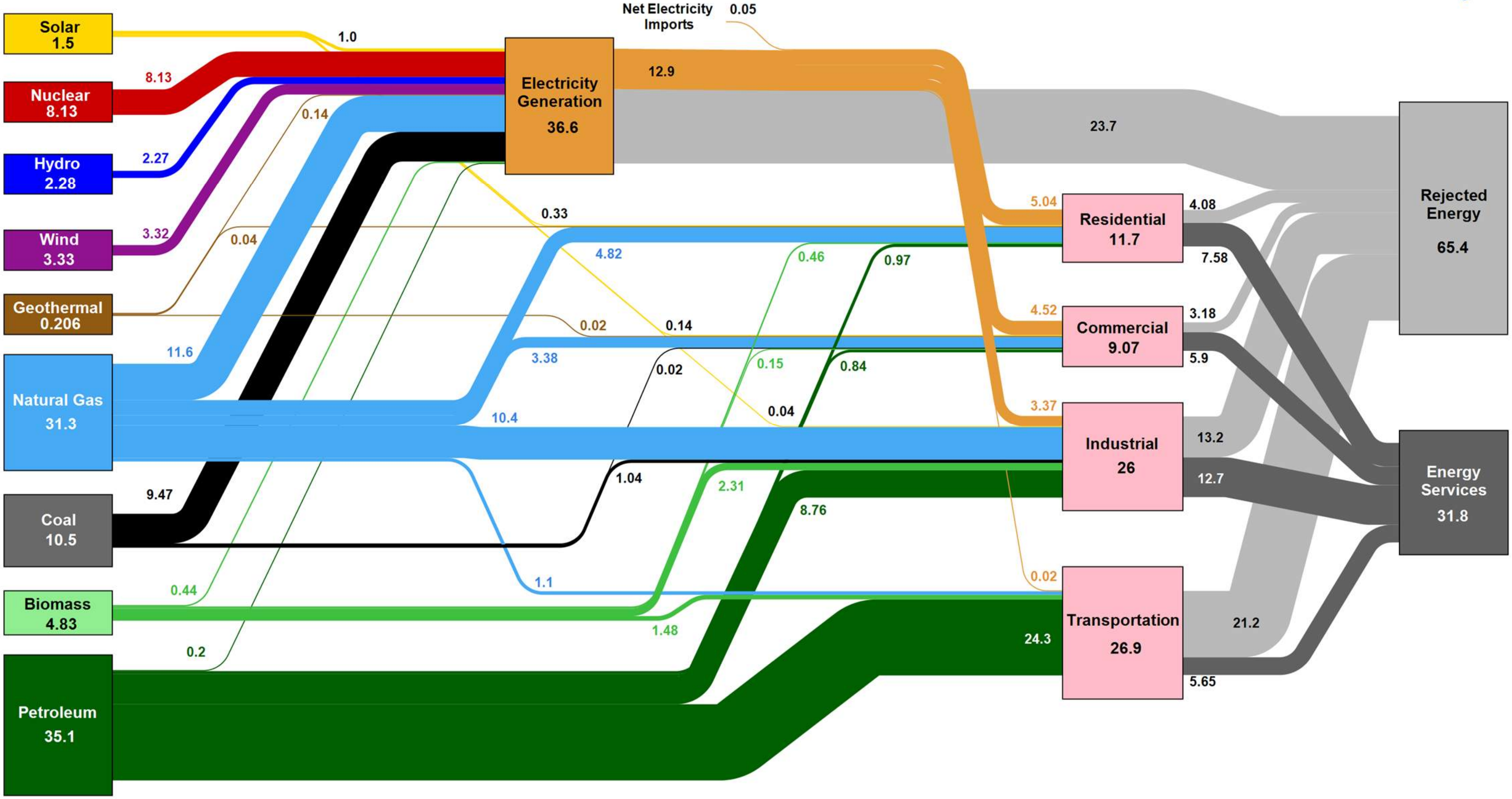
Data: HadCRUT5 - Created by: @neilrkaye

Ref: https://www.visualcapitalist.com/global-temperature-graph-1851-2020/

US Total Energy Consumption

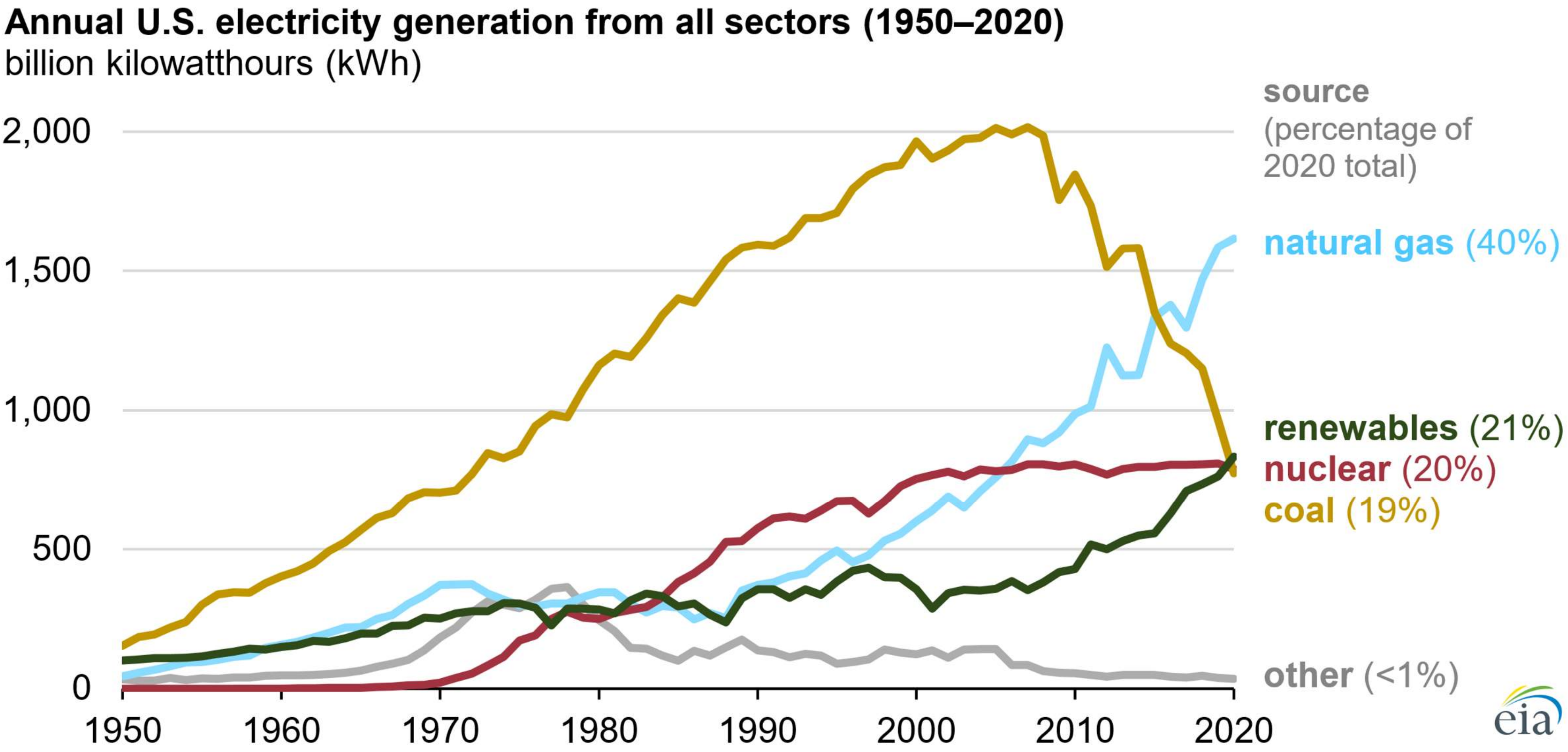
Estimated U.S. Energy Consumption in 2021: 97.3 Quads

Lawrence Livermore National Laboratory

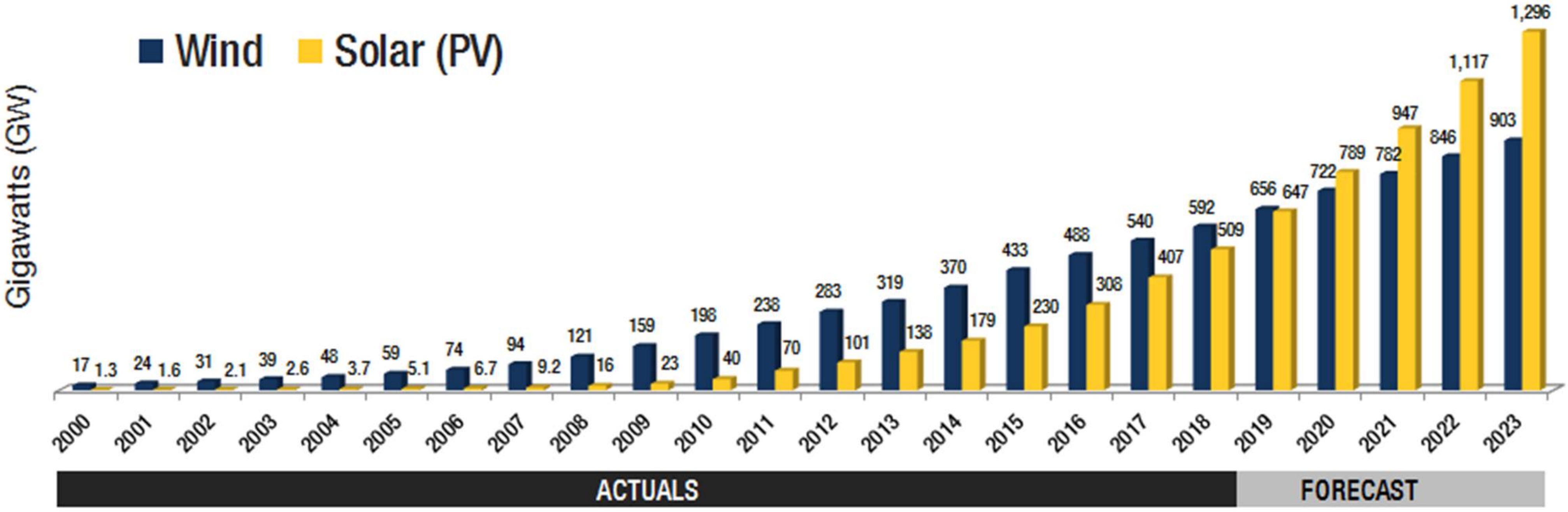


Source: LLNL March, 2022. Data is based on DOE/EIA MER (2021). If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant heat rate. The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 65% for the residential sector, 65% for the commercial sector, 21% for the transportation sector, and 49% for the industrial sector, which was updated in 2017 to reflect DOE's analysis of manufacturing. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

US Electricity Generation Mixture

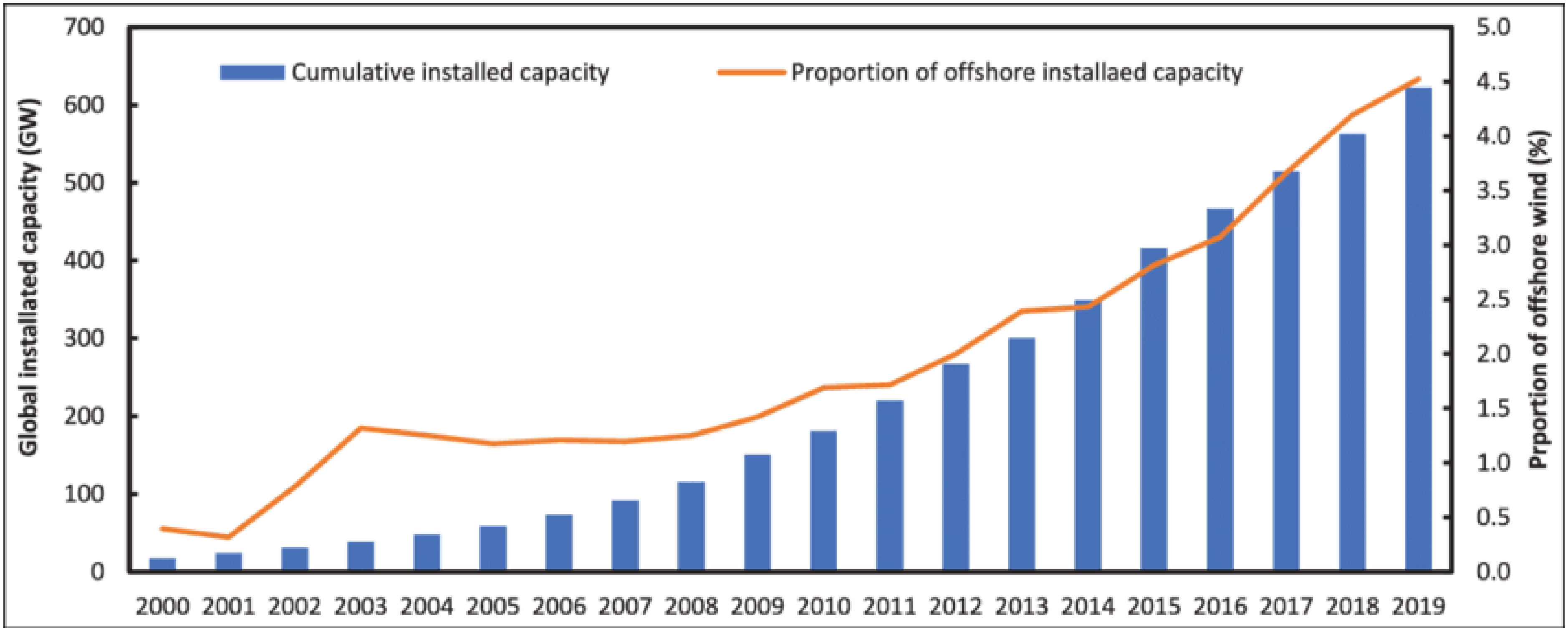


Global Wind and Solar Installation by Capacity



Wind Electricity Generation

United States: ~ 118 GW
Record 14.2 GW installed in 2020
8.4% share in 2020



Global wind capacity end of 2019: ~ **600 GW,** Global electricity generation capacity **~ 6500 GW**

University of Colorado
Boulder

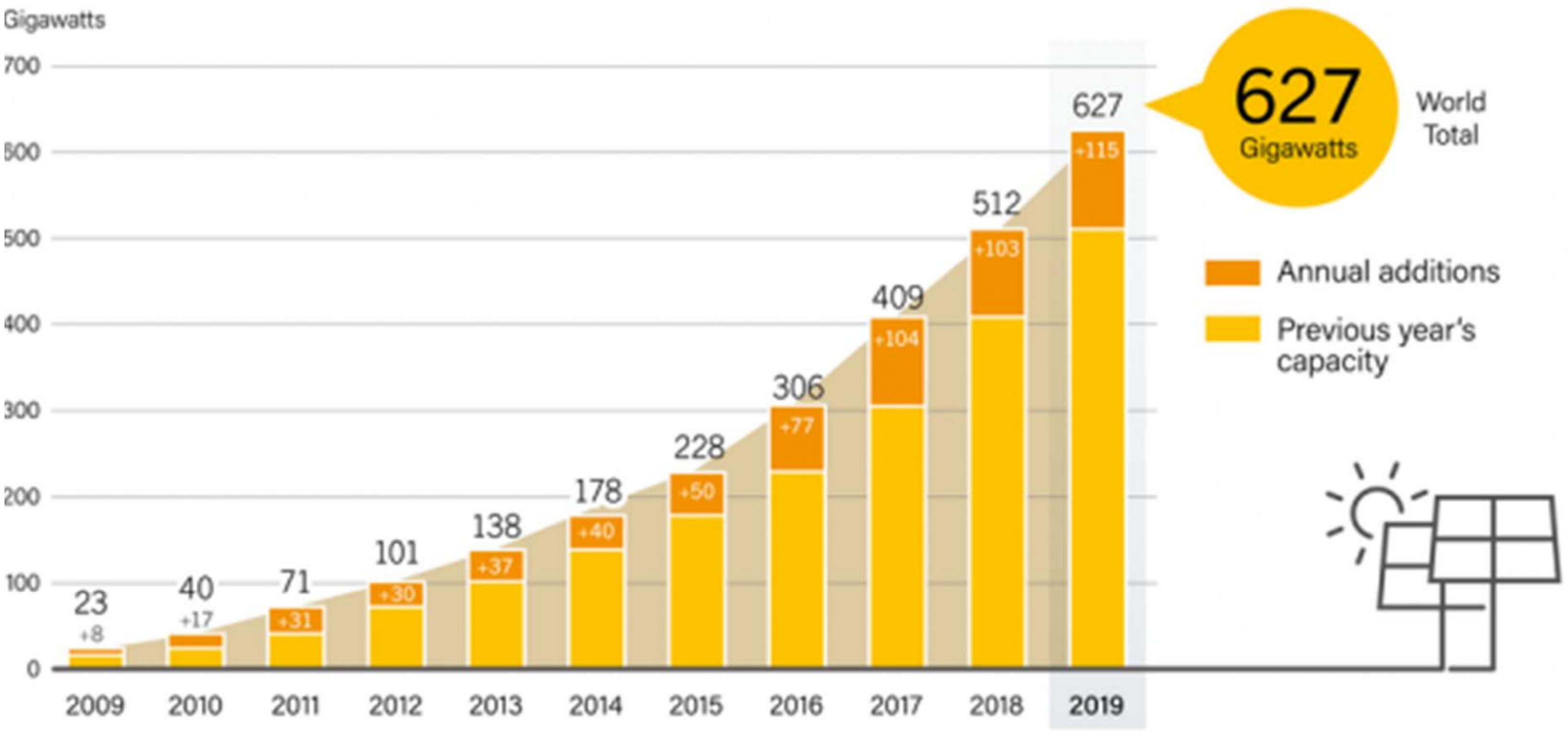
Source: EIA, Monthly Energy Review, Sep. 2017

Be Boulder.

Solar Electricity Generation

United States: ~ 95 GW
2.3% share in 2020

Solar PV Global Capacity and Annual Additions, 2009-2019



Note: Data are provided in direct current (DC).
Totals may not add up due to rounding.

Source: Becquerel Institute and IEA PVPS.

REN21 RENEWABLES 2020 GLOBAL STATUS REPORT

Global solar installations end of 2010: **~ 40 GW,** Global solar capacity end of 2019: **> 600 GW**

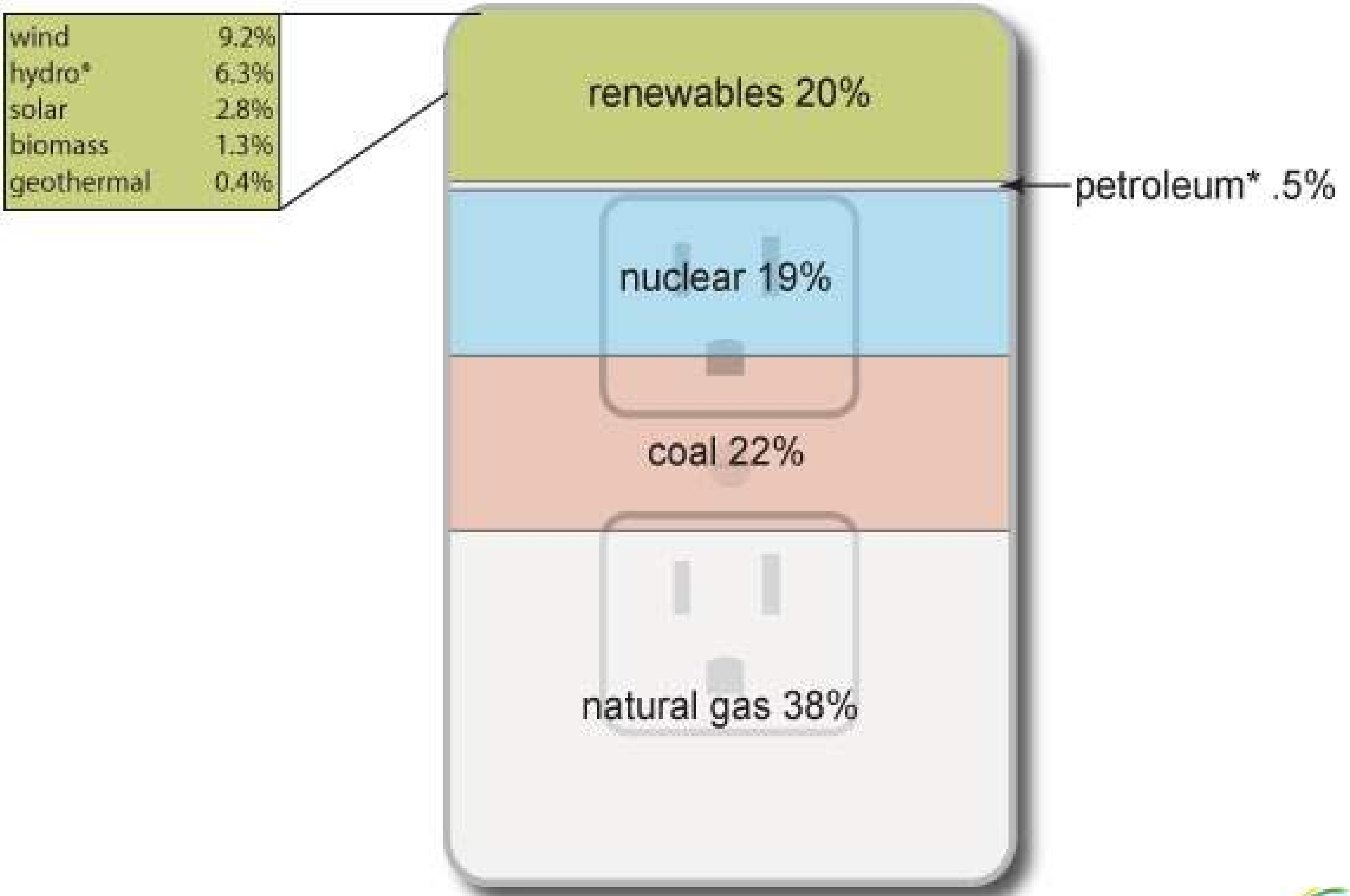
University of Colorado
Boulder

Source: EIA, Monthly Energy Review, Sep. 2017

Be Boulder.

Sources of U.S. electricity generation, 2021

Total = 4.12 trillion kilowatthours



Data source: U.S. Energy Information Administration, *Electric Power Monthly*, February 2022, preliminary data

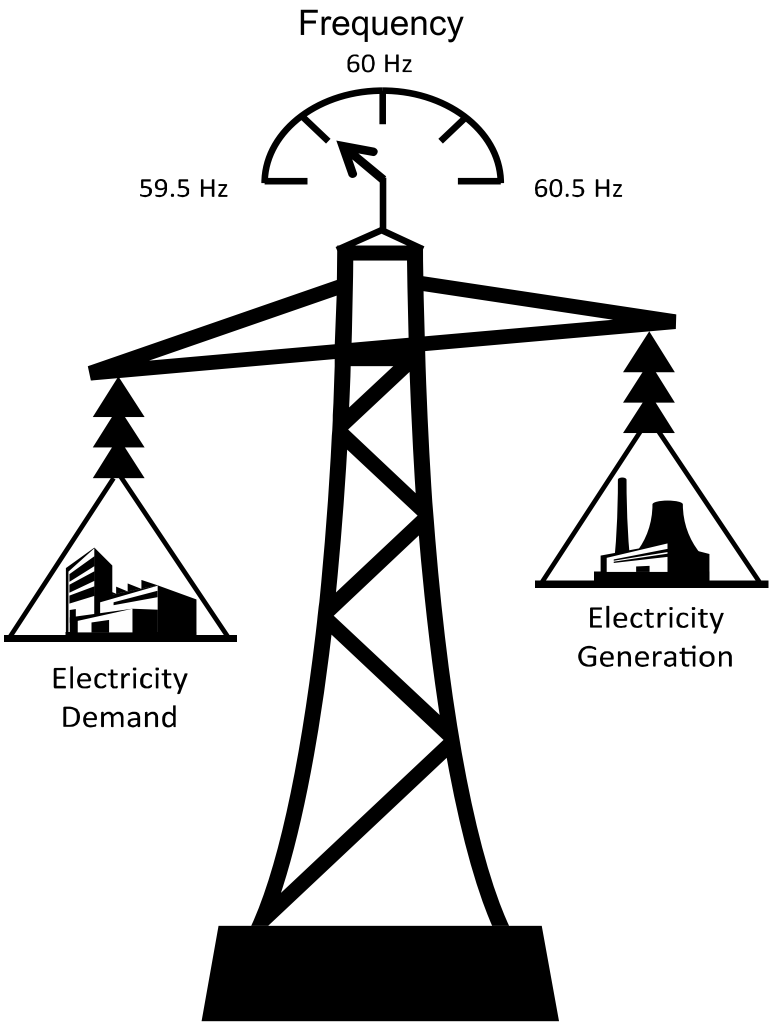
Note: Includes generation from power plants with at least 1,000 kilowatts of electric generation capacity (utility-scale).
*Hydro is conventional hydroelectric. *Petroleum includes petroleum liquids, petroleum coke, other gases, hydroelectric pumped storage, and other sources.

Power System Objective

Supply electric power to customers

- Reliably
- Economically

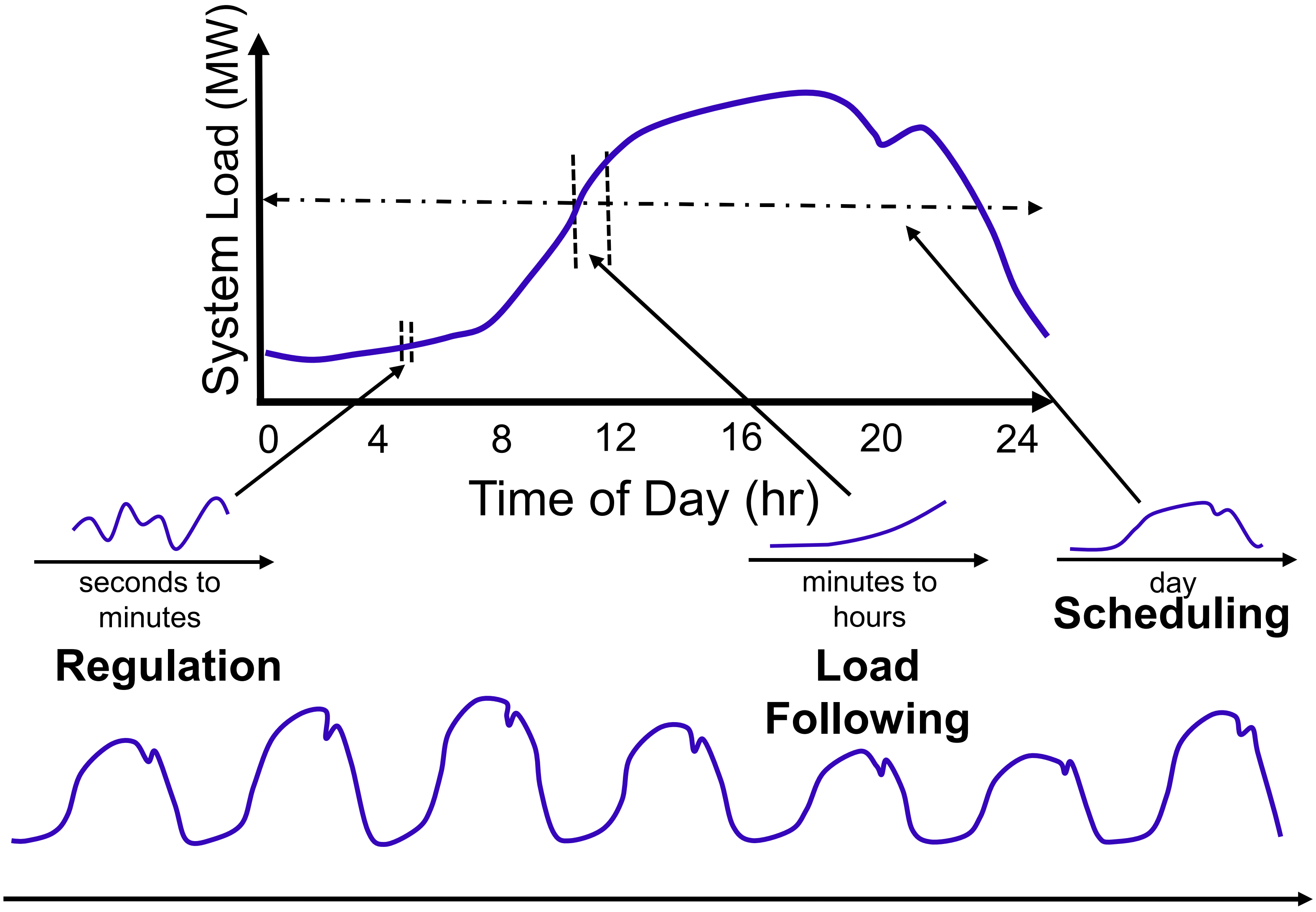
Consumption and production must be ***balanced continuously and instantaneously***



Maintaining system frequency is one of the fundamental drivers of power system reliability

Slide credit: B. Kirby

Power System Timescales



seconds to minutes

Regulation

minutes to hours

Load Following

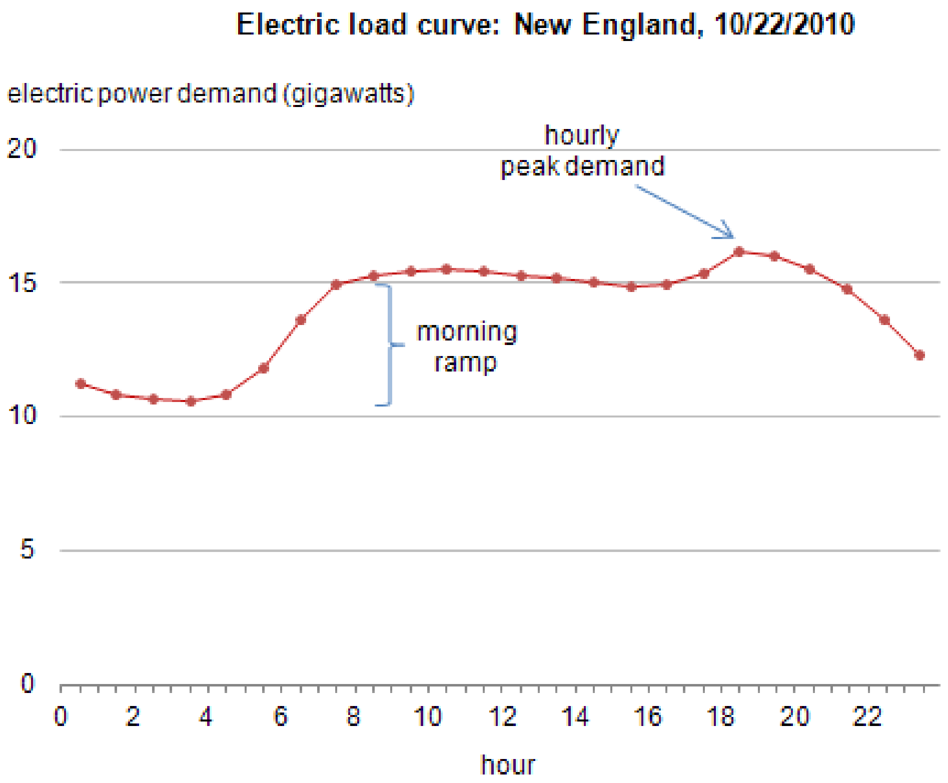
day

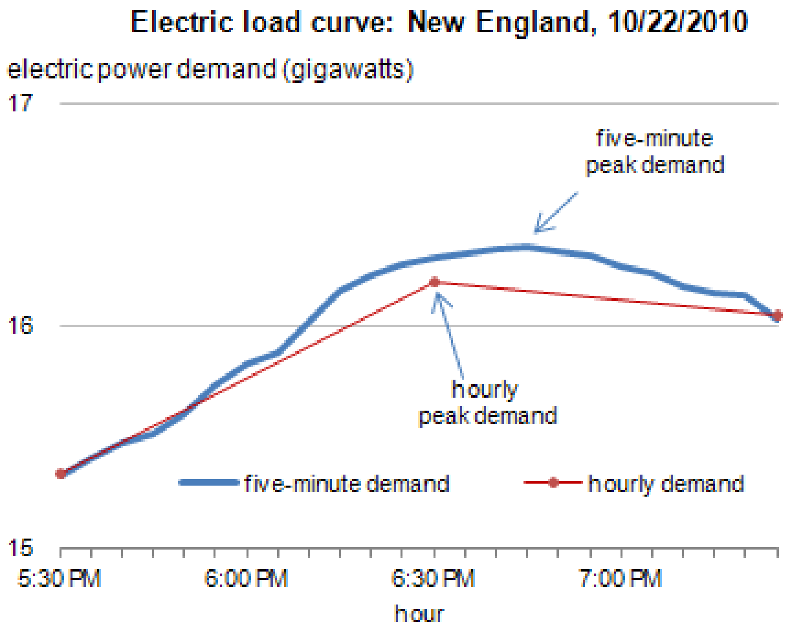
Scheduling

Days

Unit Commitment

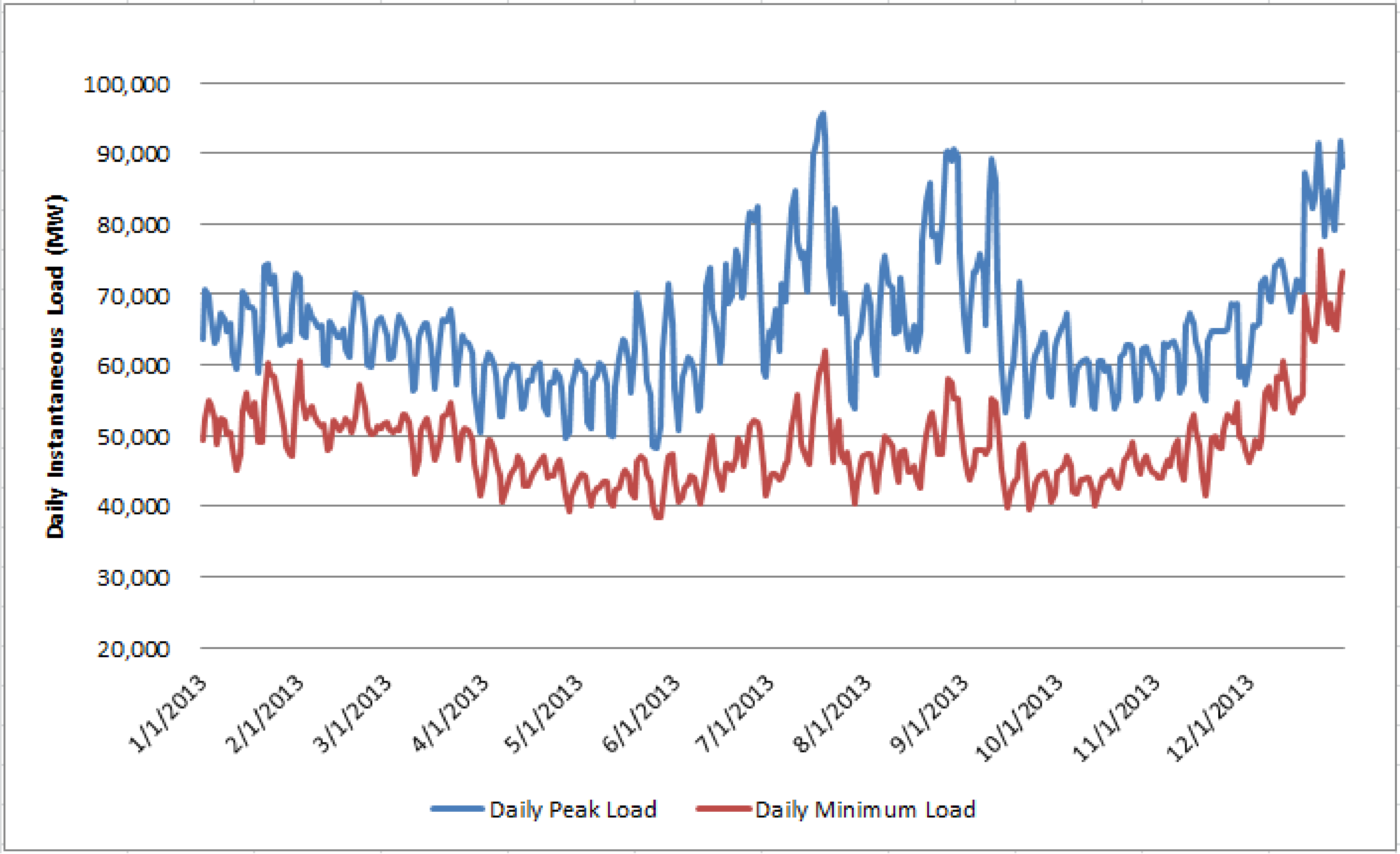
Daily Load Variability





Source: https://www.eia.gov/todayinenergy/detail.php?id=830

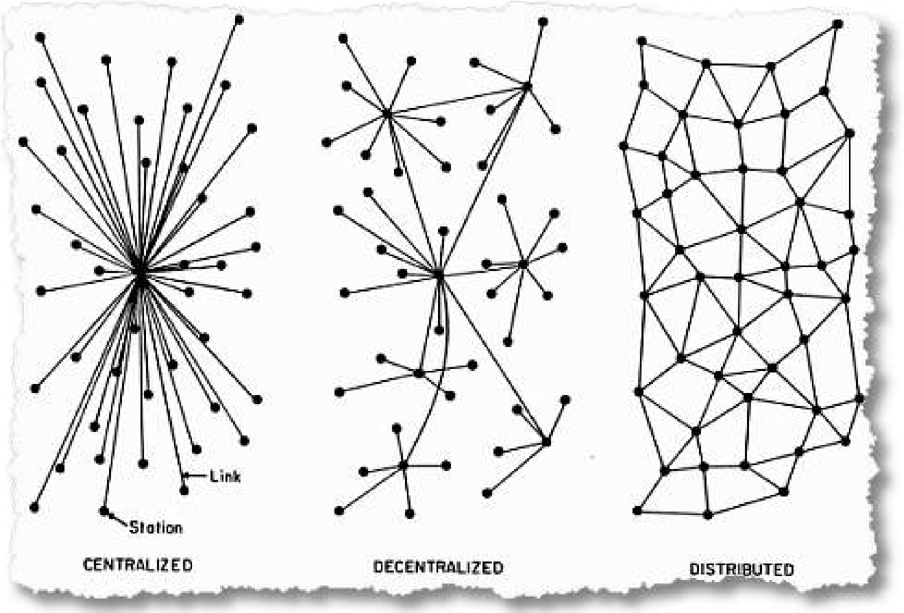
Seasonal Load Variability

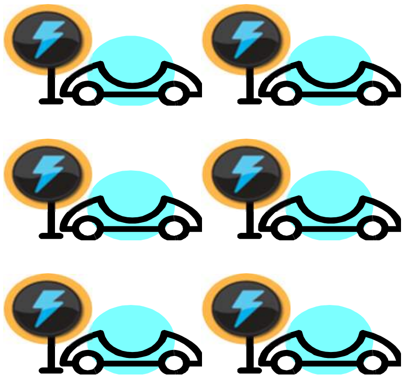


Source: MISO, http://www.misomtep.org/load-statistics/

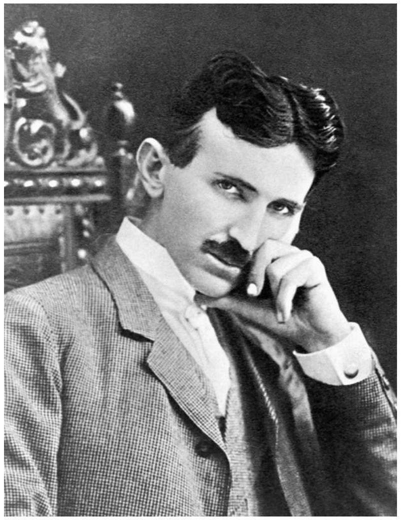
Power System Background

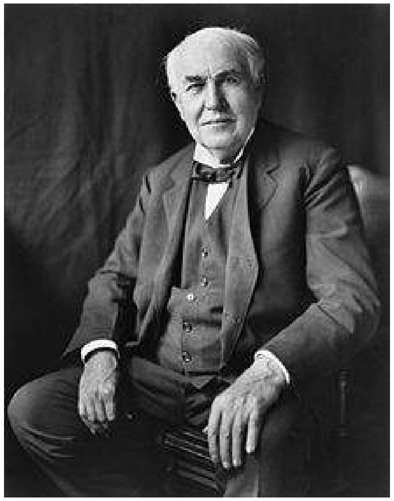
- Transition from centralized to distributed generation
- Variable and uncertain renewable generators
- Advanced communications enable decentralized control of devices





AC vs. DC





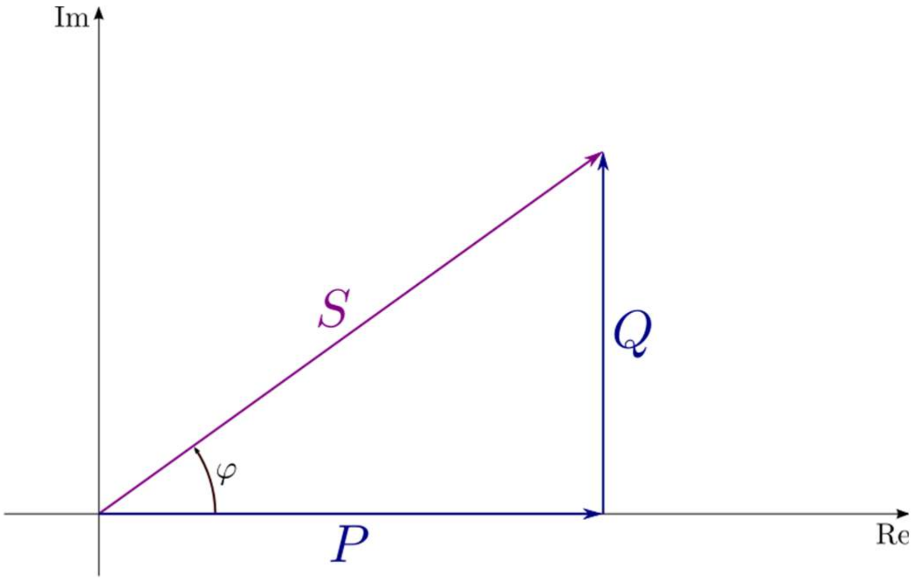
- AC
  - Easy to generate
  - Low losses in long distance transmission
  - Can be changed to DC (bridge rectifier)
  - Central generation

- DC
  - Easy to generate
  - Difficult for long distance transmission
  - Many devices require DC
  - Local generation

Complex Power

- If load is purely **resistive**, current and voltage are in phase, and the product of voltage and current is positive or zero. The **direction of energy flow does not reverse** and **only active power is transferred**.
- If load is purely **reactive**, current and voltage are 90° out of phase, and for 2 quarters of each cycle, the product of voltage and current is positive, and for the other 2 quarters, the product is negative. On average, exactly **as much energy flows into the load as flows back out**.

$S=|V||I|[\cos(\Theta v-\Theta I)+j\ \sin(\Theta v-\Theta I)]$
j = imaginary unit
$S=P+jQ$
P = Real Power (W)
Q = Reactive Power (var)
S = Complex Power (VA)
|S| = Apparent Power
ϕ = $\Theta_v-\Theta_I$
Power factor = cos(ϕ)



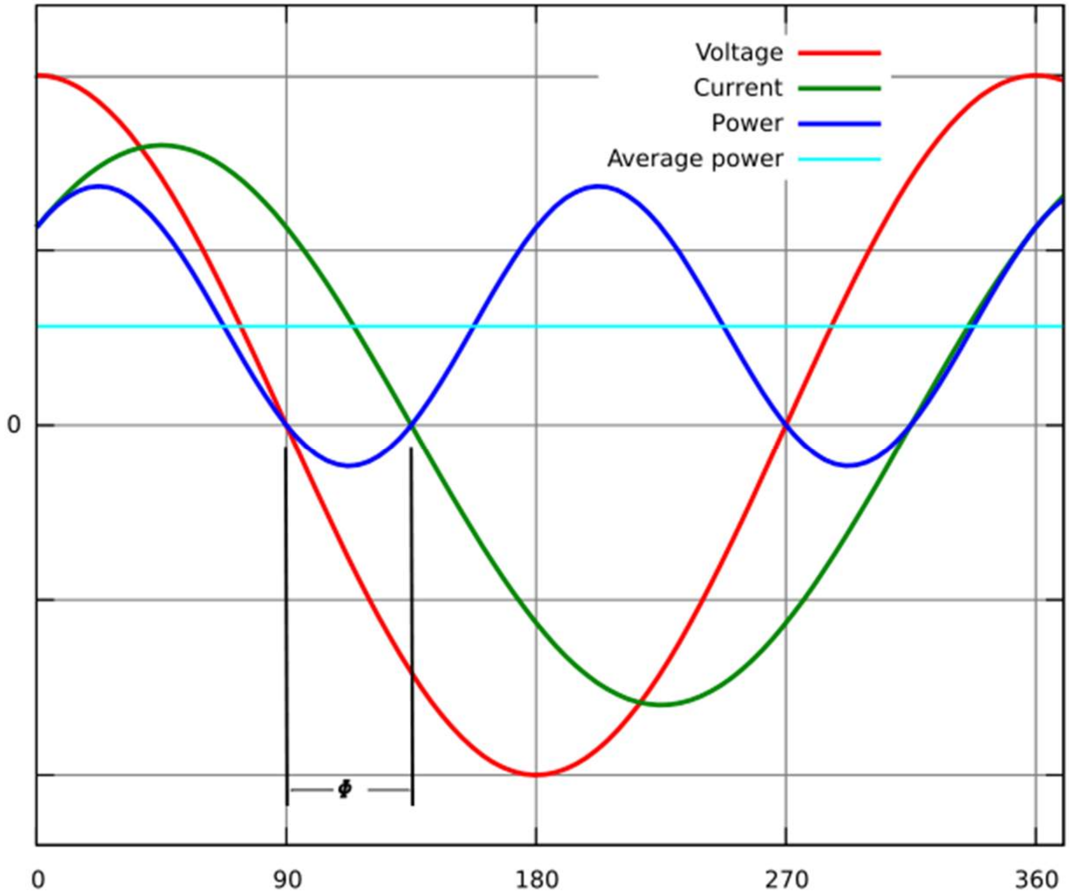
Source: https://en.wikipedia.org/wiki/AC_power

Power Factor

$$\cos\theta = \frac{P}{S}$$

where

$\cos\theta$ = power factor (pf)
P = true power (watts)
S = apparent power (VA)



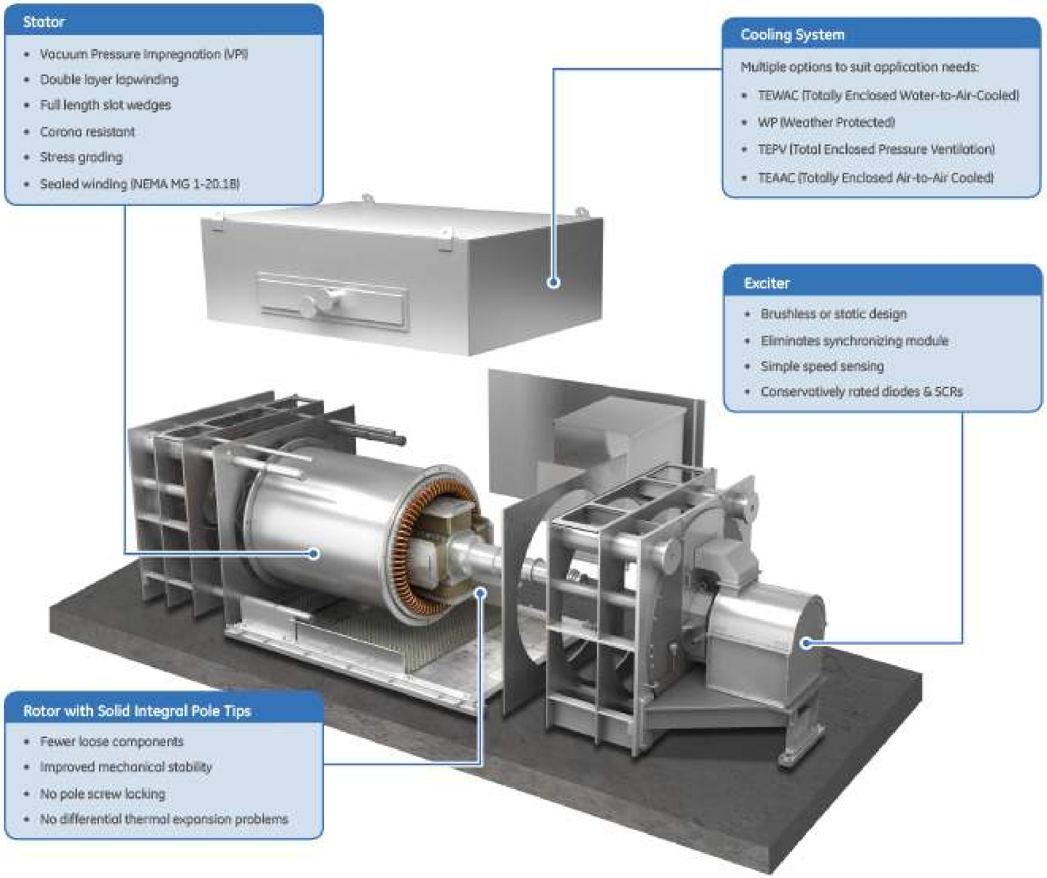
Can change the phase angle between current and voltage to change the power factor.

Source: DOE Fundamentals Handbook: Electrical Science

Beer Analogy

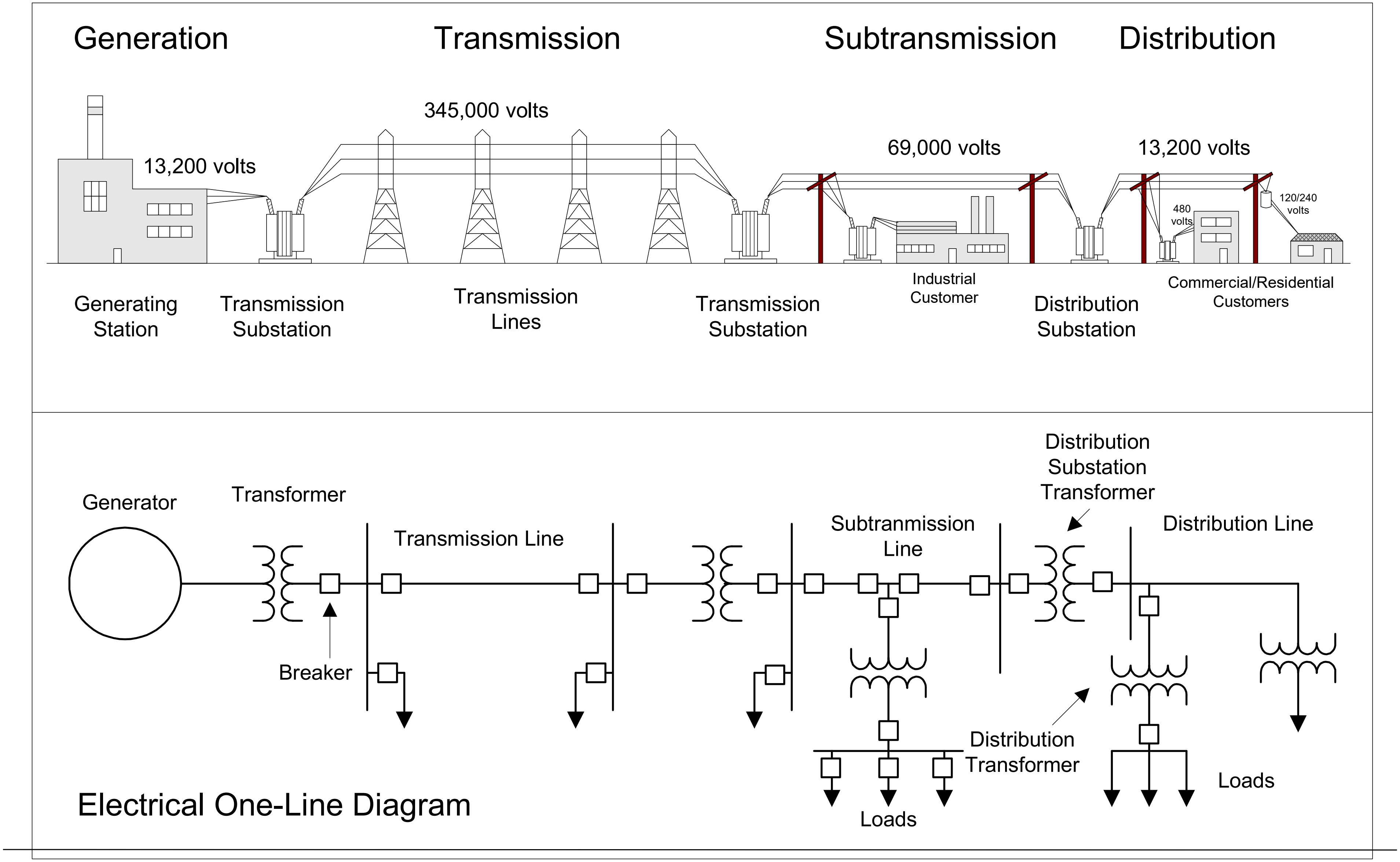
Reactive Power Regulation

- Synchronous generators
- Asynchronous generators (with power electronics)
- Synchronous condensers
- Static VAR compensators
- Capacitor banks

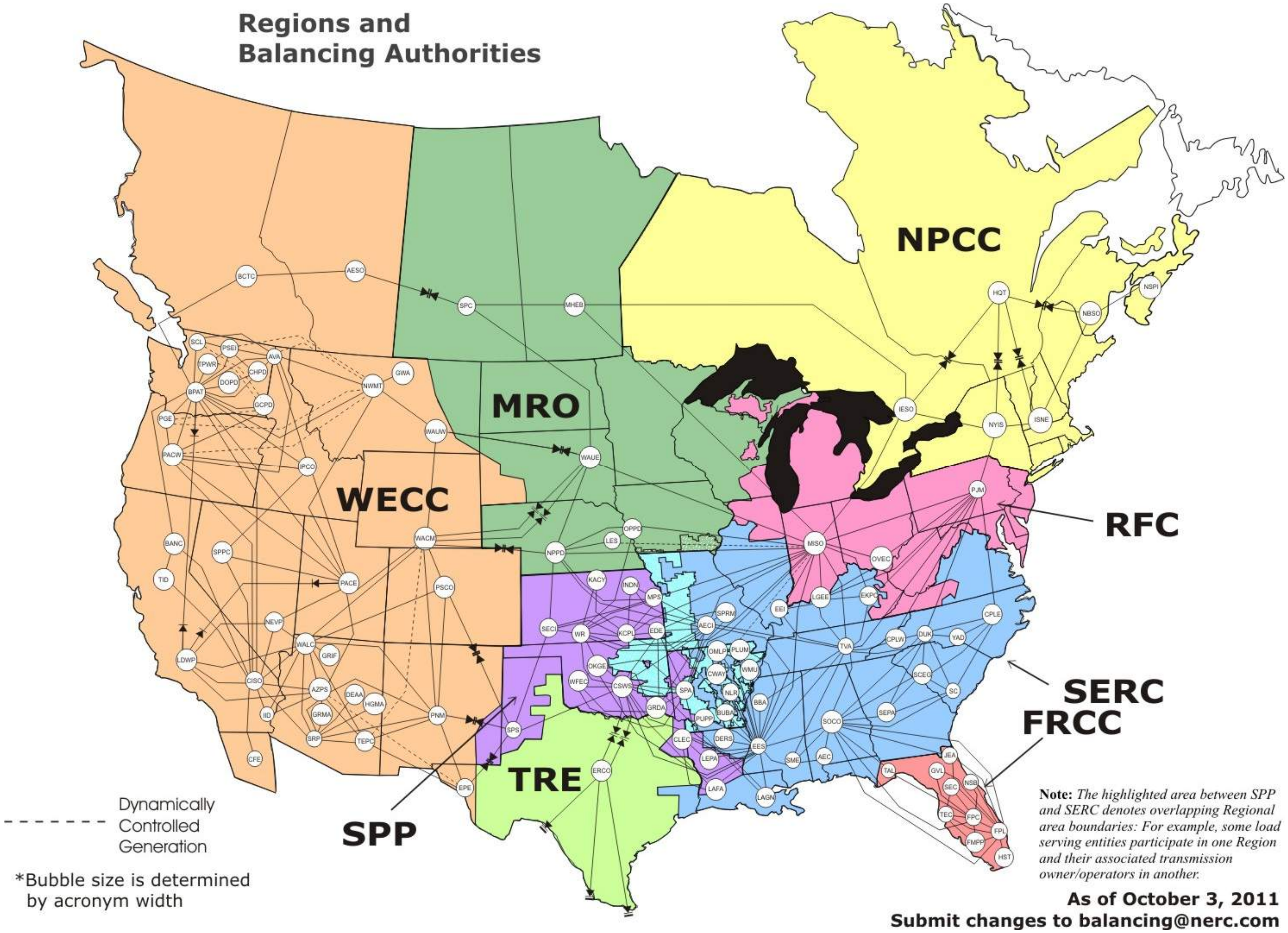


Sources: GE and Scott Engineering

Conventional Power System



US = 3 Synchronous Grids



Regions and Balancing Authorities

Dynamically Controlled Generation

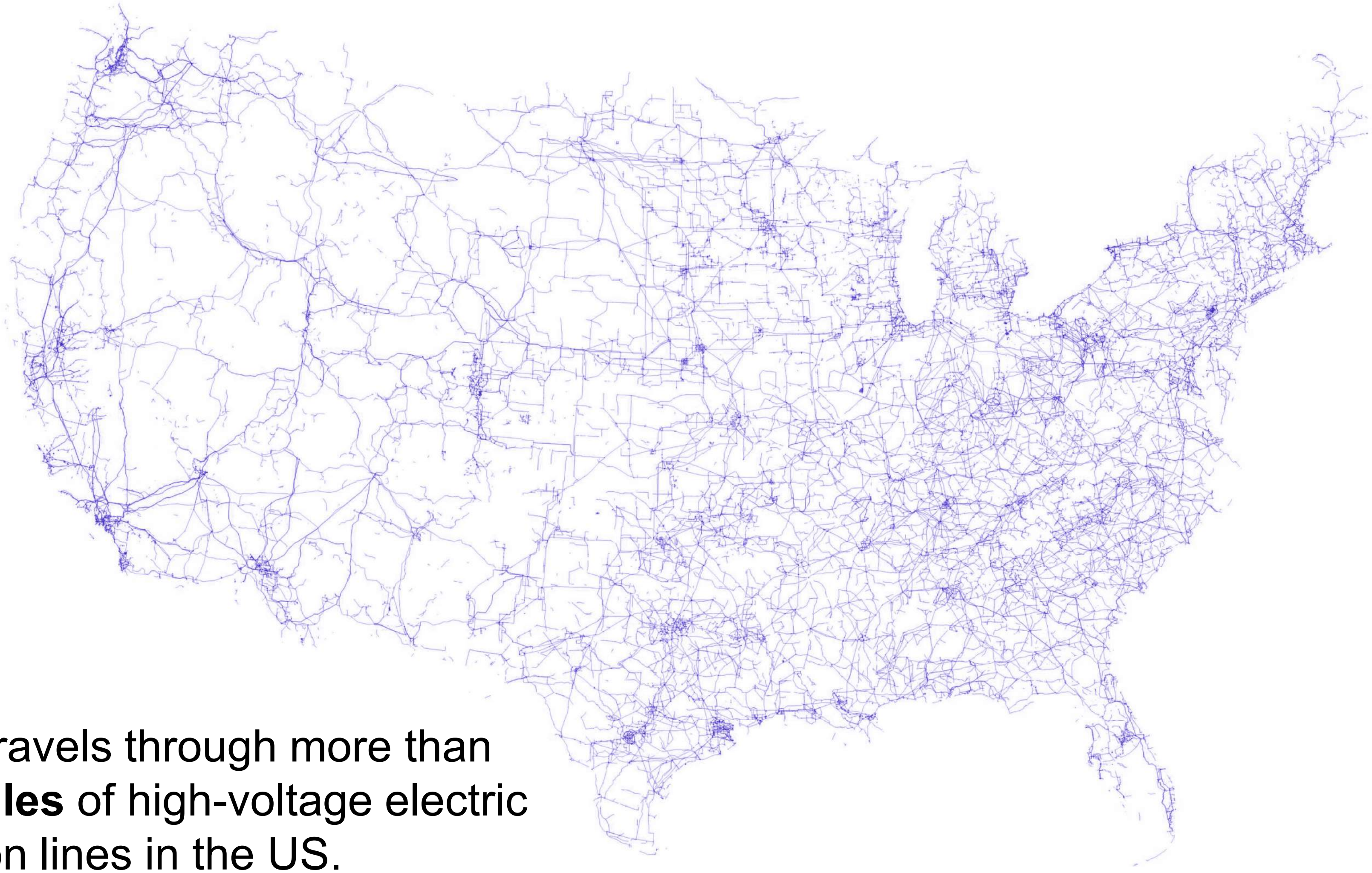
*Bubble size is determined by acronym width

Note: *The highlighted area between SPP and SERC denotes overlapping Regional area boundaries: For example, some load serving entities participate in one Region and their associated transmission owner/operators in another.*

As of October 3, 2011

Submit changes to balancing@nerc.com

US Power System

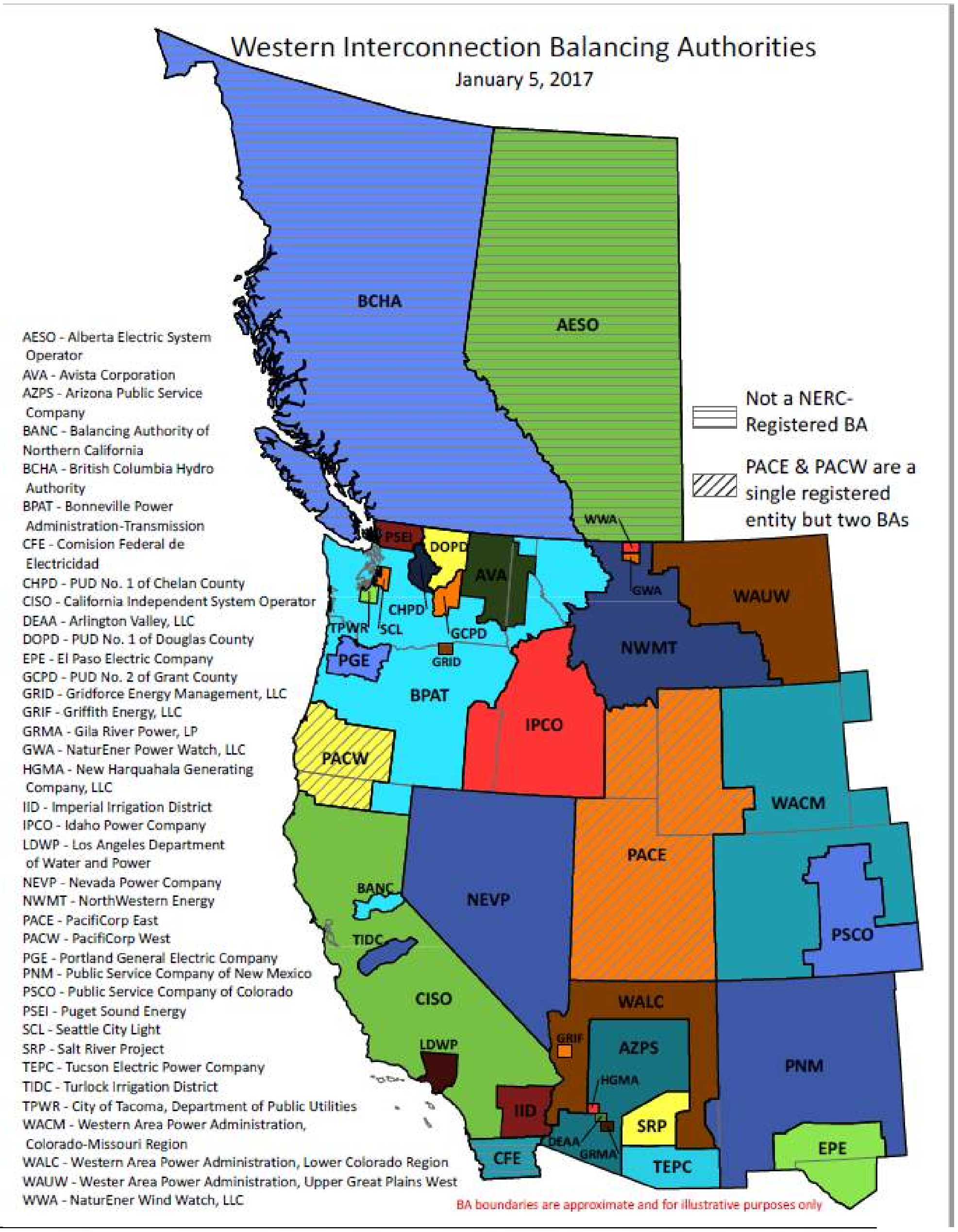


Electricity travels through more than **160,000 miles** of high-voltage electric transmission lines in the US.

Source: Washington Post

Balancing Authorities (BAs)

- **66 BAs** in the United States.
- The actual **operation of the electric system** is managed by BAs.
- Most (not all) balancing authorities are **electric utilities** that have taken on the balancing responsibilities for a portion of the power system.
- All of the **RTOs/ISOs** also function as BAs.
- A BA ensures, in real time, that power system **demand** and **supply** are finely **balanced** to maintain the safe and reliable operation of the power system. This includes managing **transfers** of electricity with other BAs.
- BAs are responsible for maintaining operating conditions under mandatory **reliability standards** issued by NERC and approved by FERC.



Western Interconnection Balancing Authorities

January 5, 2017

AESO - Alberta Electric System Operator
AVA - Avista Corporation
AZPS - Arizona Public Service Company
BANC - Balancing Authority of Northern California
BCHA - British Columbia Hydro Authority
BPAT - Bonneville Power Administration-Transmission
CFE - Comision Federal de Electricidad
CHPD - PUD No. 1 of Chelan County
CISO - California Independent System Operator
DEAA - Arlington Valley, LLC
DOPD - PUD No. 1 of Douglas County
EPE - El Paso Electric Company
GCPD - PUD No. 2 of Grant County
GRID - Gridforce Energy Management, LLC
GRIF - Griffith Energy, LLC
GRMA - Gila River Power, LP
GWA - NaturEner Power Watch, LLC
HGMA - New Harquahala Generating Company, LLC
IID - Imperial Irrigation District
IPCO - Idaho Power Company
LDWP - Los Angeles Department of Water and Power
NEVP - Nevada Power Company
NWMT - NorthWestern Energy
PACE - PacifiCorp East
PACW - PacifiCorp West
PGE - Portland General Electric Company
PNM - Public Service Company of New Mexico
PSCO - Public Service Company of Colorado
PSEI - Puget Sound Energy
SCL - Seattle City Light
SRP - Salt River Project
TEPC - Tucson Electric Power Company
TIDC - Turlock Irrigation District
TPWR - City of Tacoma, Department of Public Utilities
WACM - Western Area Power Administration, Colorado-Missouri Region
WALC - Western Area Power Administration, Lower Colorado Region
WAUW - Wester Area Power Administration, Upper Great Plains West
WWA - NaturEner Wind Watch, LLC

▤ Not a NERC-Registered BA

▨ PACE & PACW are a single registered entity but two BAs

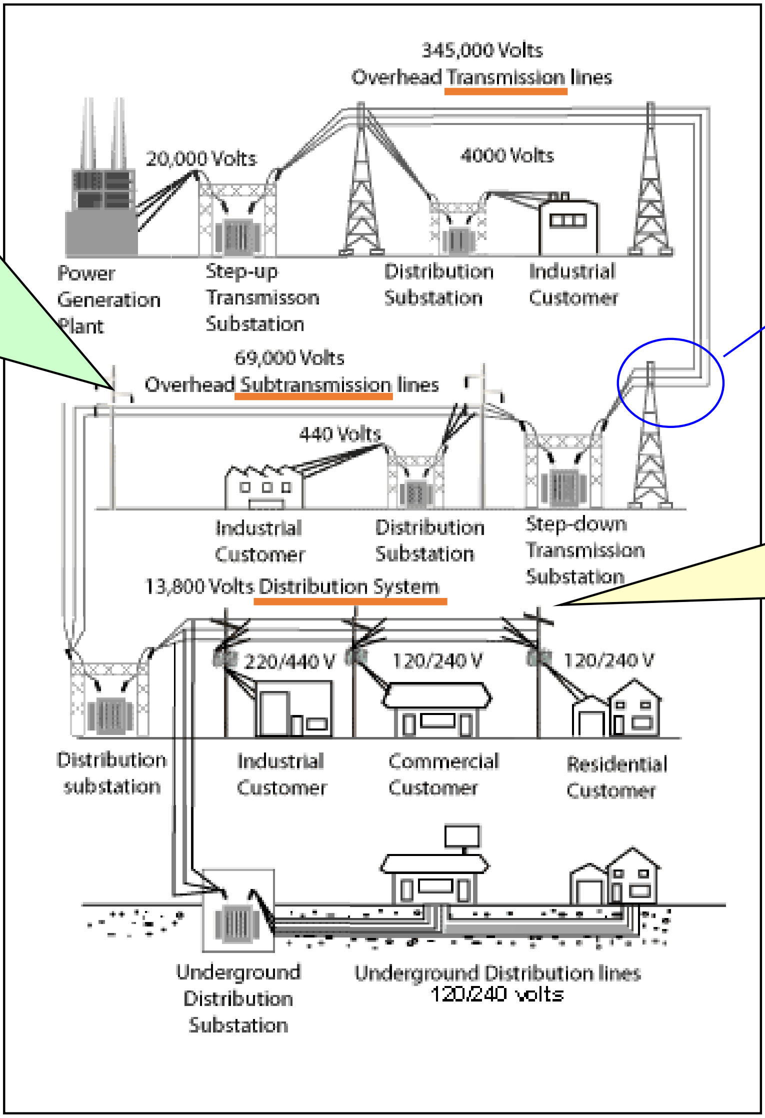
BA boundaries are approximate and for illustrative purposes only

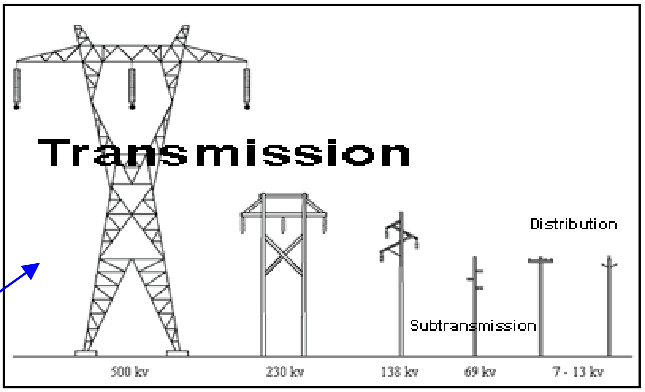
Renewable Energy Interconnection

Central Station

Large
wind farms, CSP,
large PV, biopower,
hydro, geothermal,
hydrokinetic,
interconnect at
transmission and
sub-transmission
levels

Electric Power System

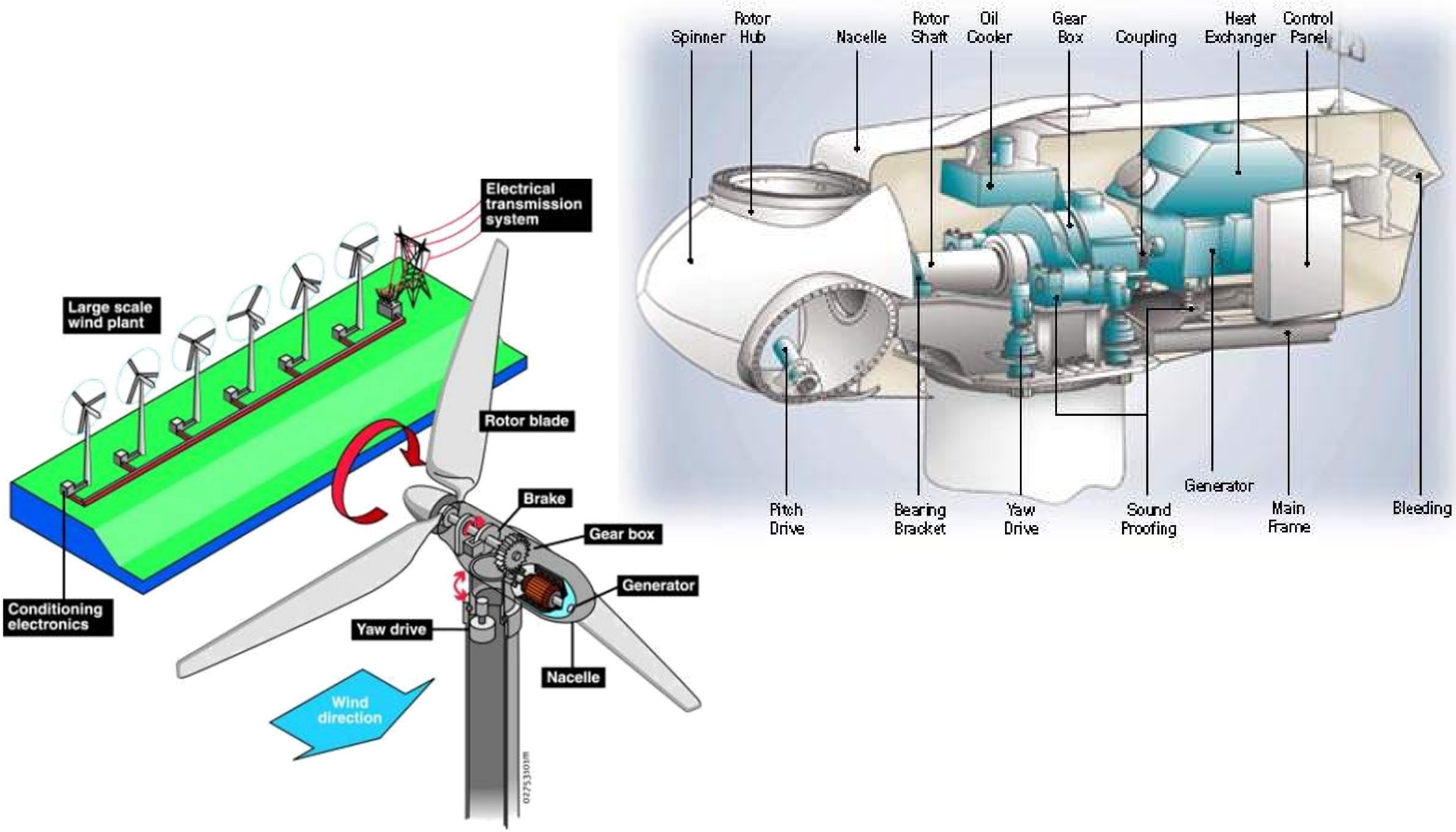




Distributed

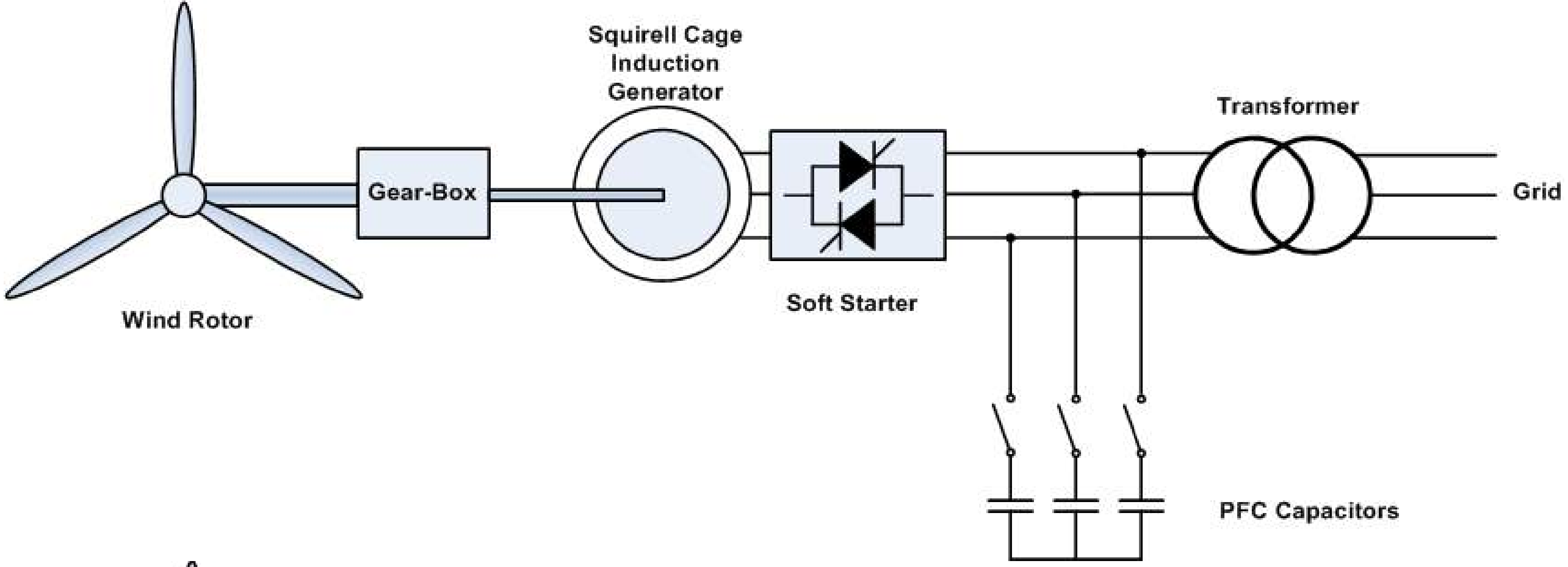
PV, small
wind, and fuel cells
interconnect at the
distribution level

Parts of Modern Commercial Turbines

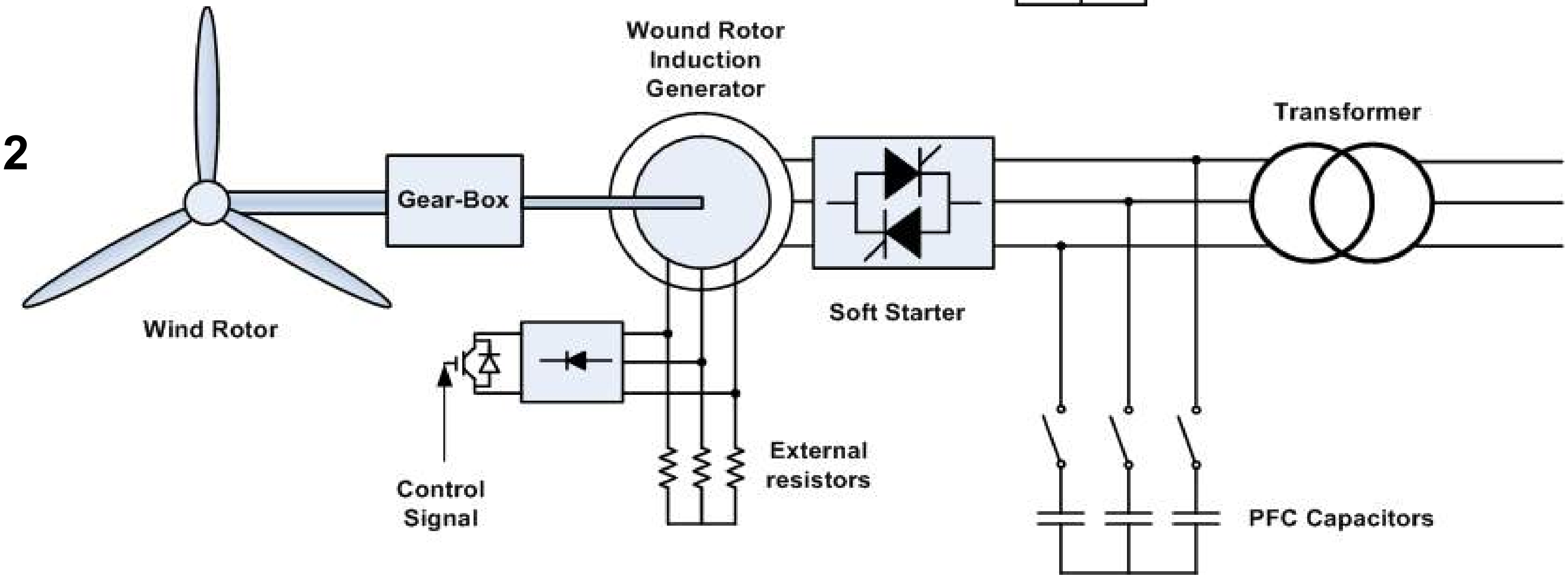


Wind Turbine Generator Types

Type 1



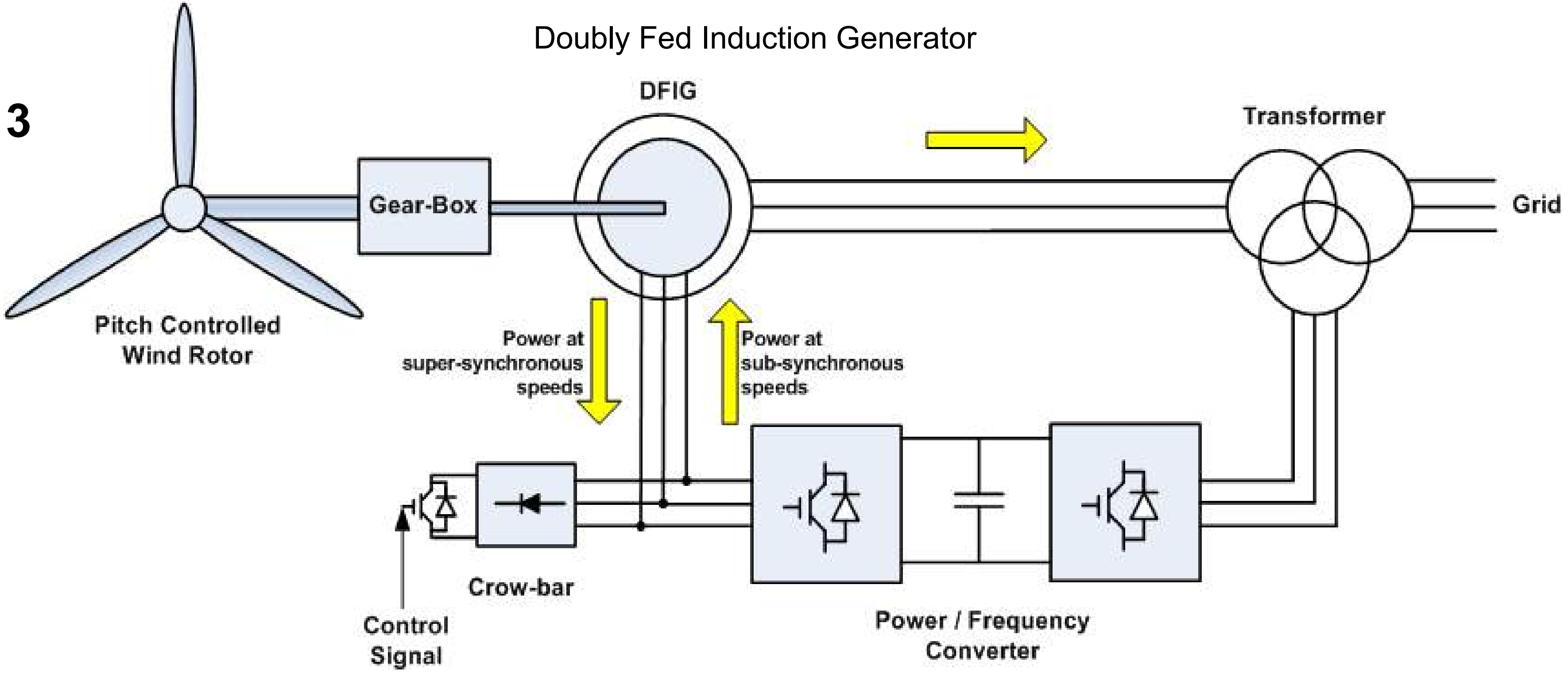
Type 2



Wind Turbine Generator Types Continued

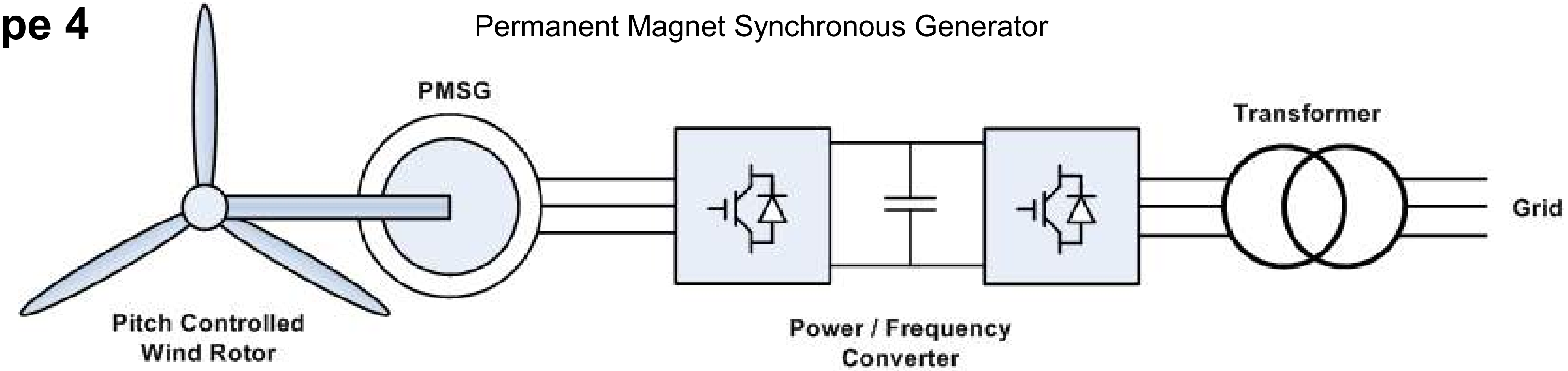
Type 3

Doubly Fed Induction Generator

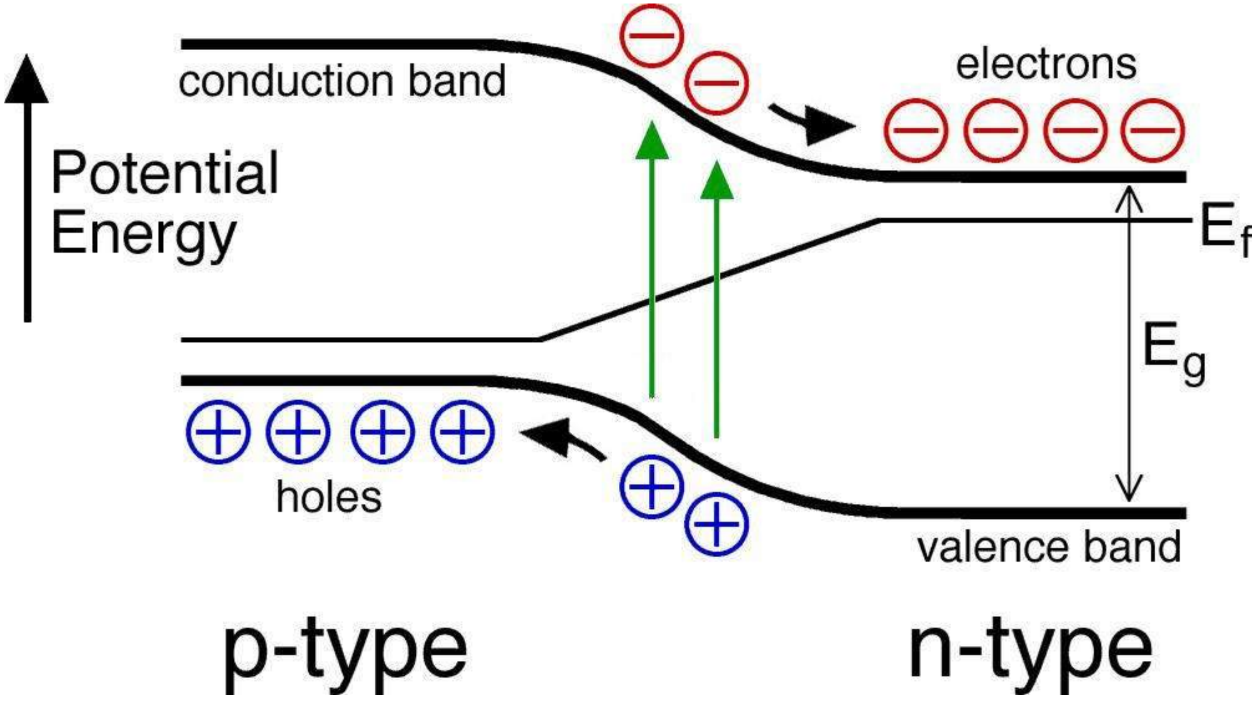


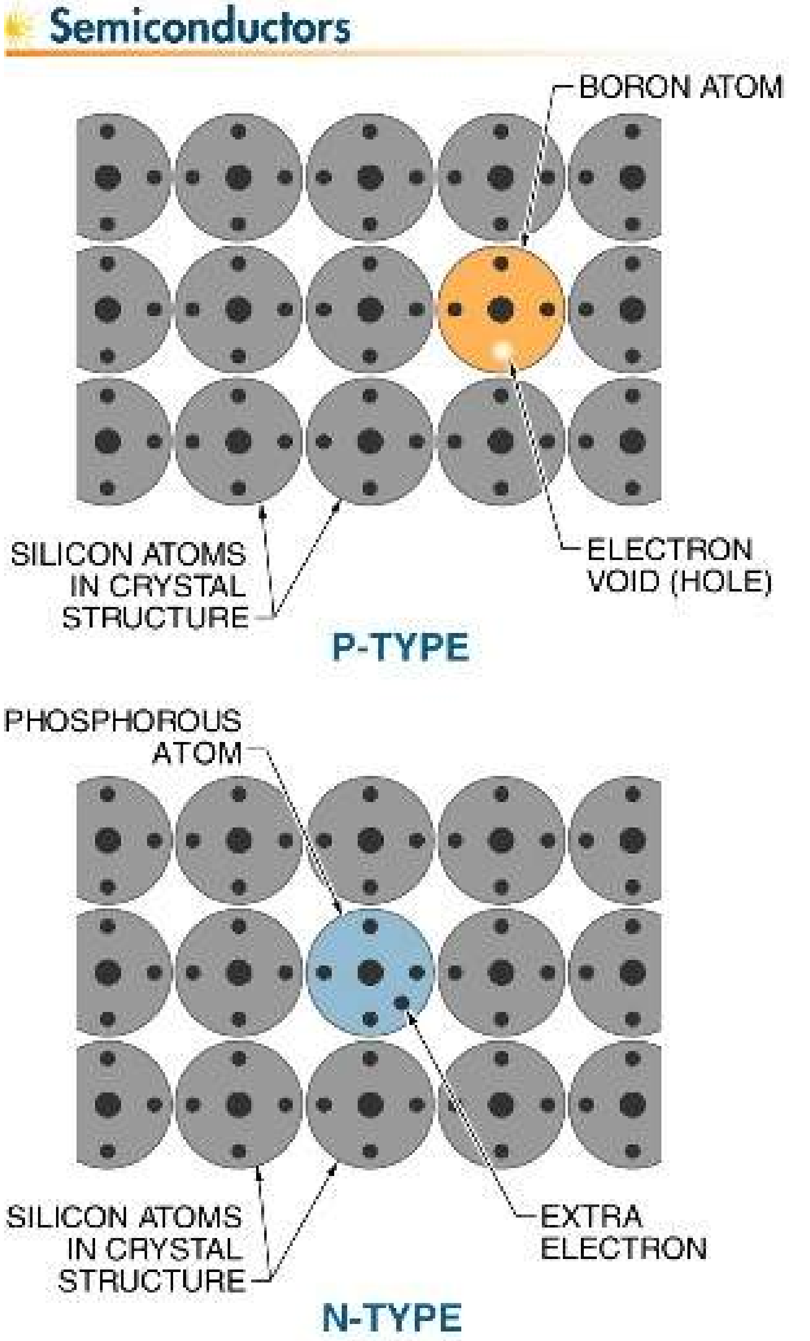
Type 4

Permanent Magnet Synchronous Generator

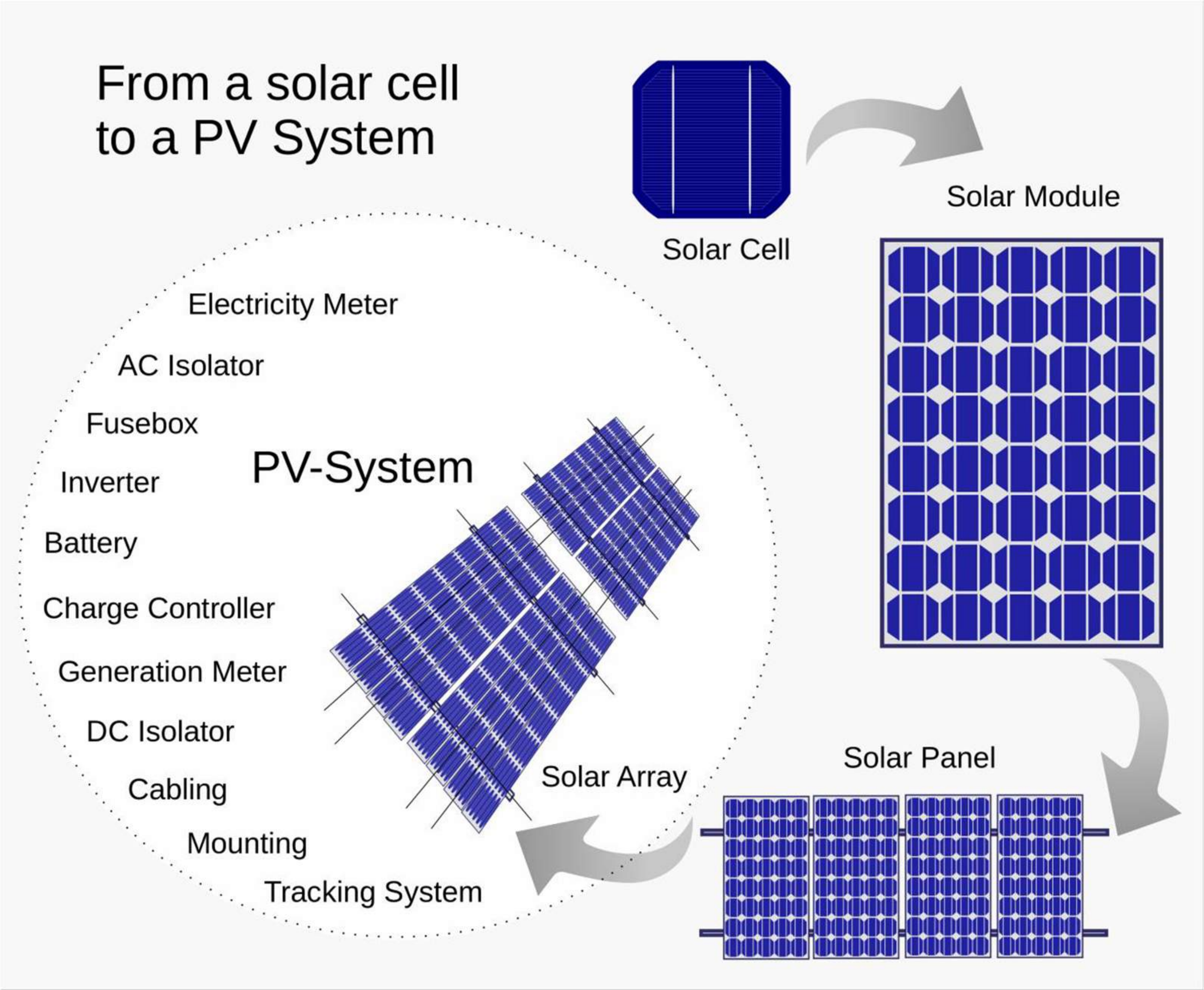


PV Device Physics

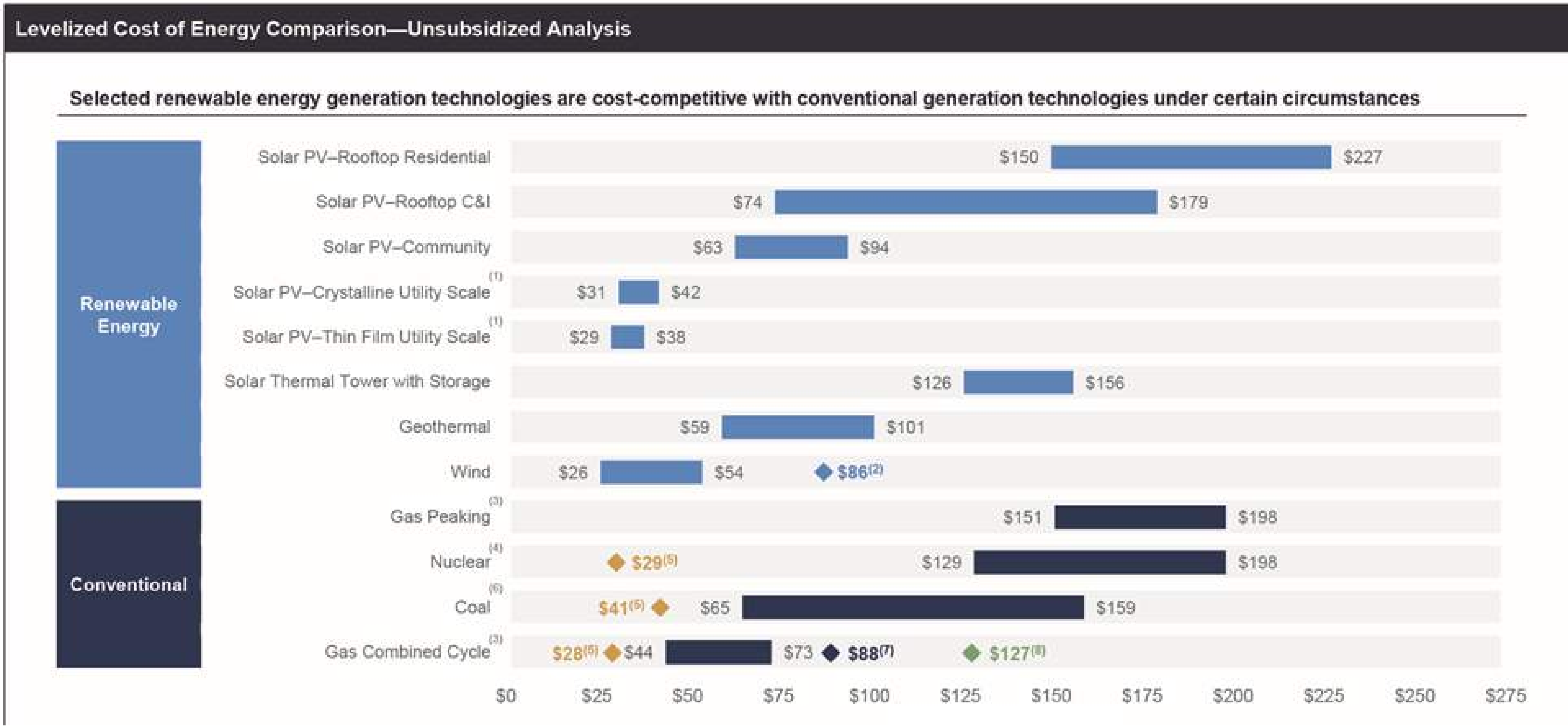




PV System


From a solar cell to a PV System
Solar Cell
Solar Module
Solar Panel
Solar Array
PV-System
Electricity Meter
AC Isolator
Fusebox
Inverter
Battery
Charge Controller
Generation Meter
DC Isolator
Cabling
Mounting
Tracking System

Levelized Cost of Energy

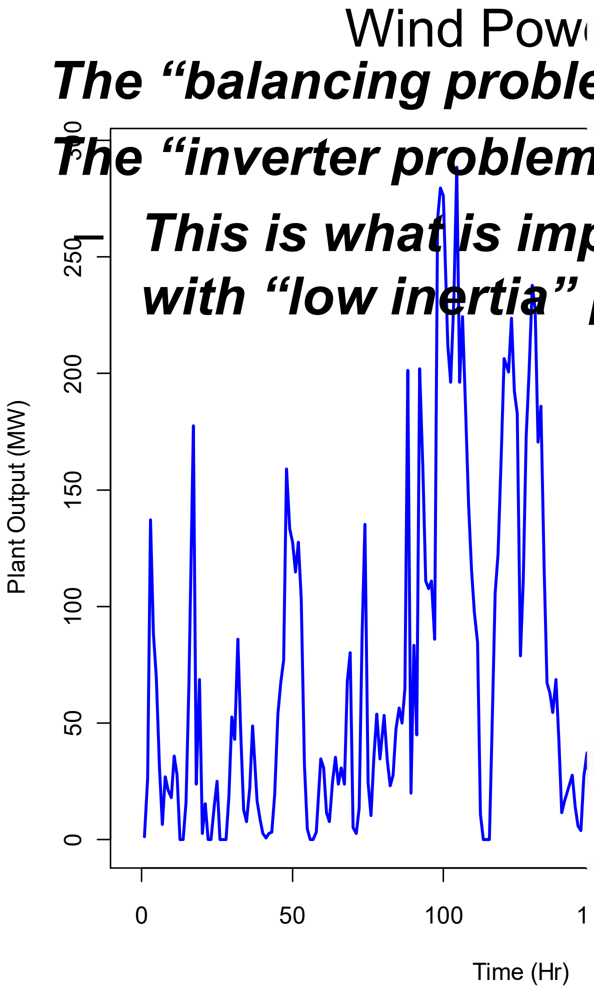


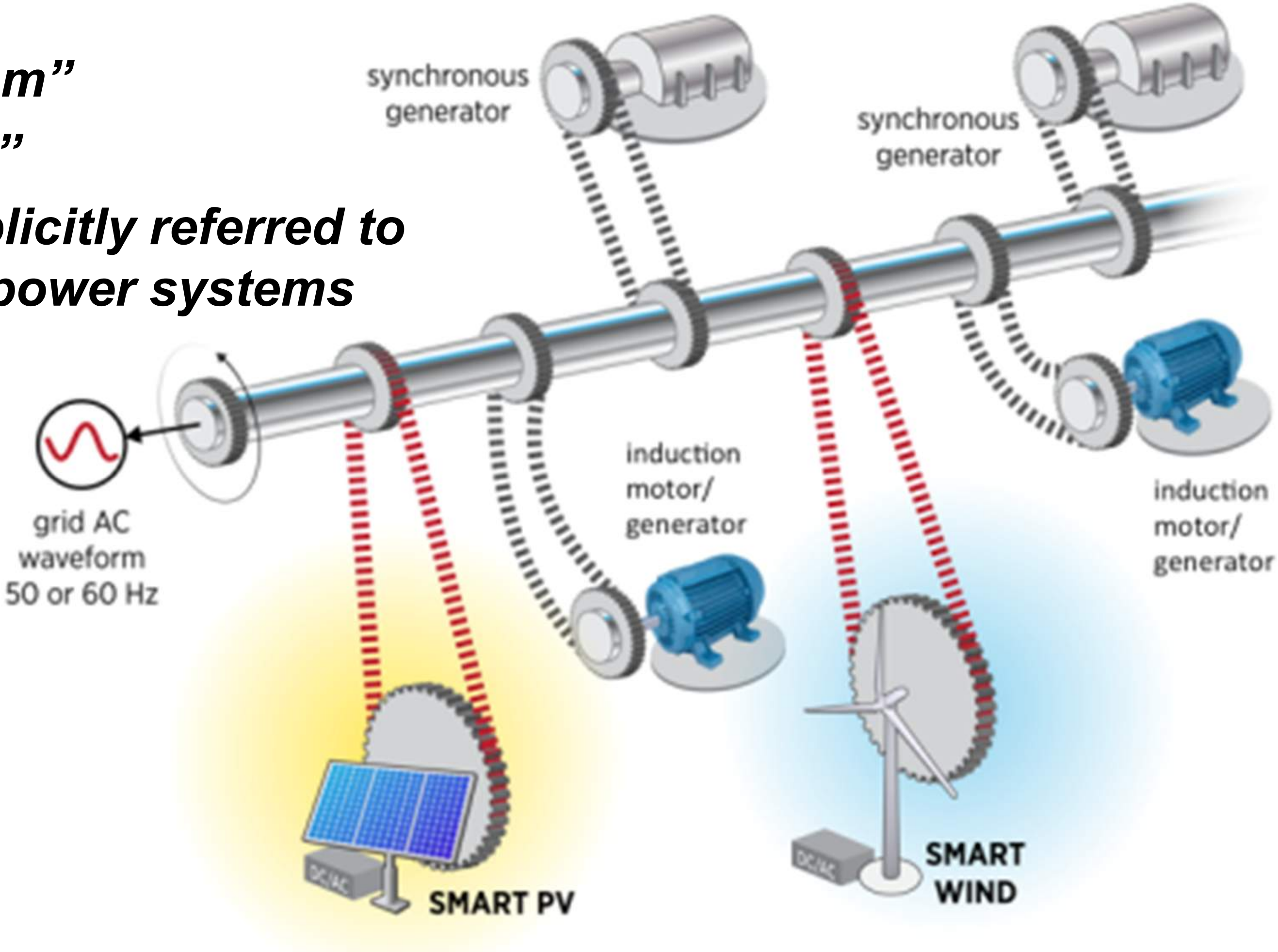
Source: Lazard LCOE V14, 2020

Wind and Solar Power are Variable, Uncertain, and Asynchronous

- ***The "balancing problem"***
- ***The "inverter problem"***

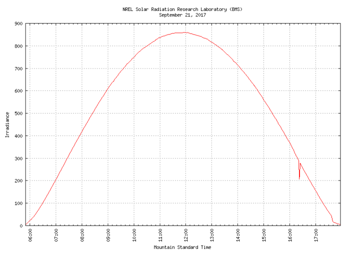
This is what is implicitly referred to with "low inertia" power systems

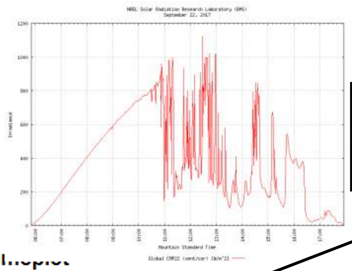




Real World Interlude: Voltage @ My House

ANSI voltage limit: 1.05 p.u.

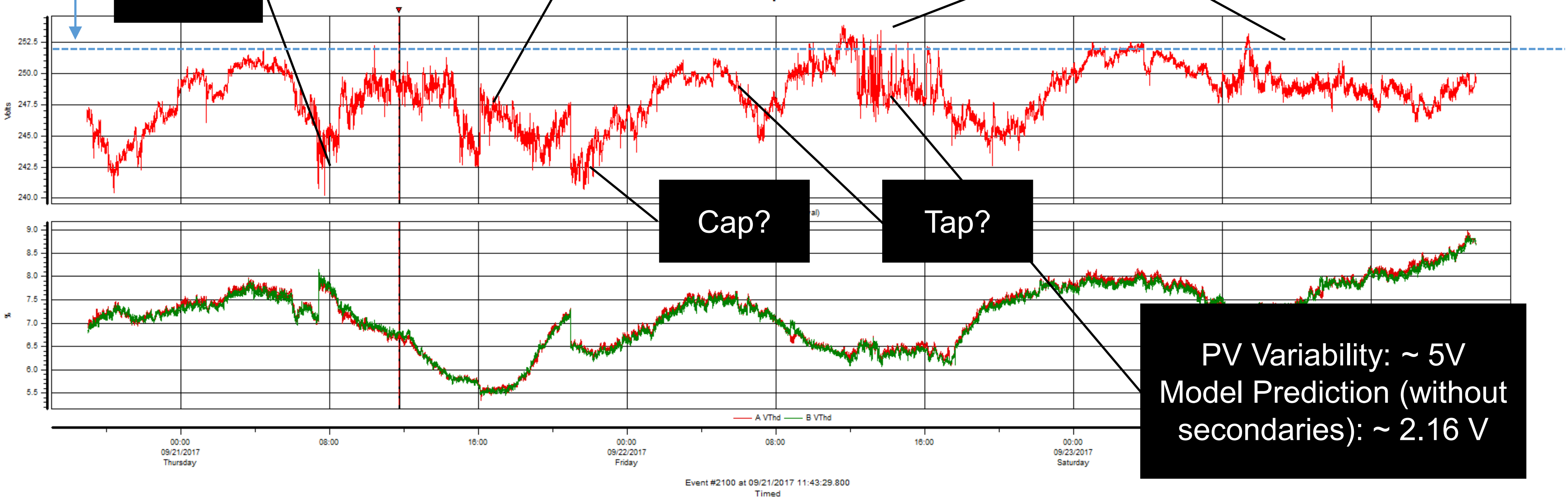




Cap?

Tap/Cap?

Overvoltage



Cap?

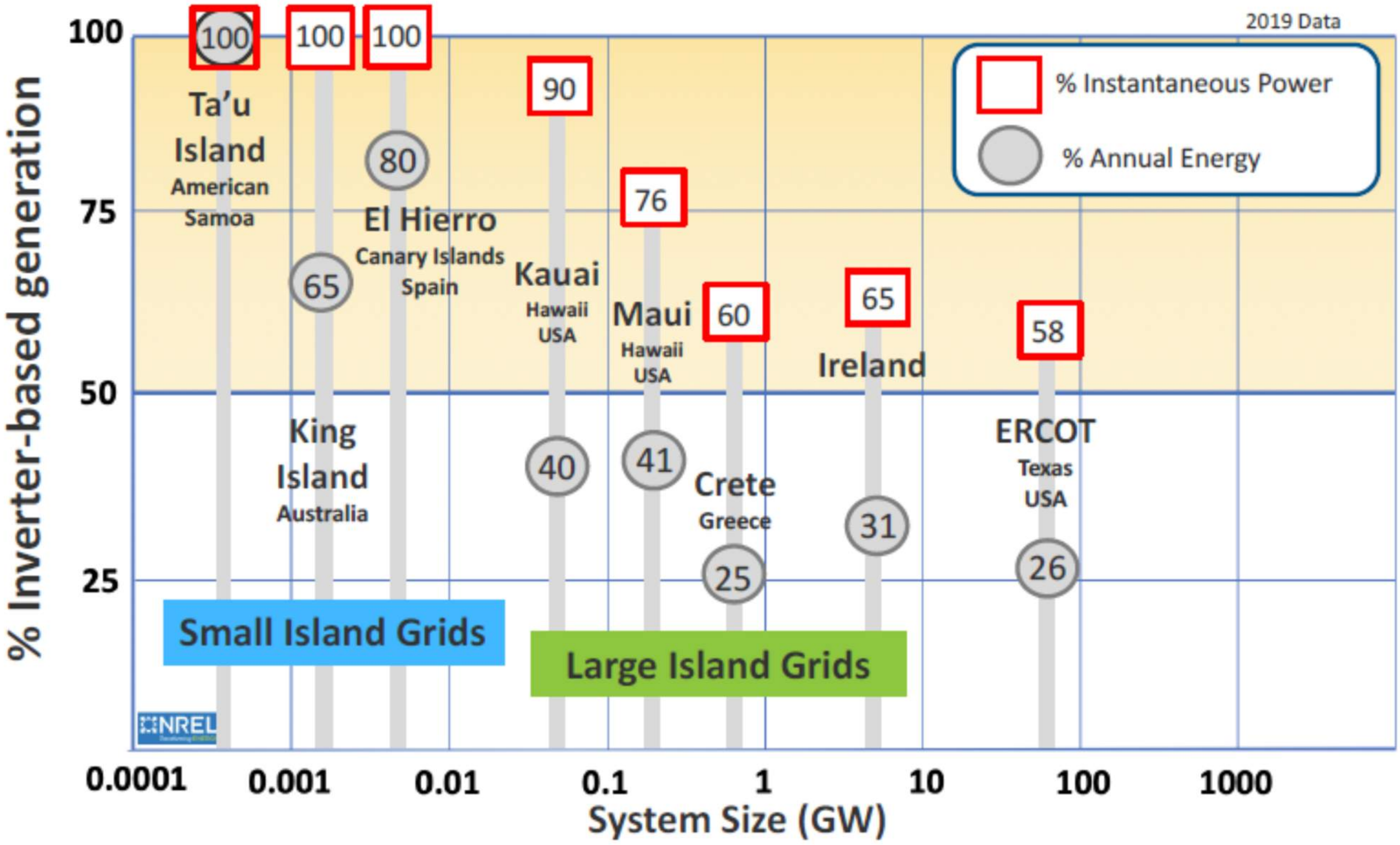
Tap?

PV Variability: ~ 5V
Model Prediction (without secondaries): ~ 2.16 V

University of Colorado Boulder

Be Boulder.

Power Systems with High Instantaneous Shares of VIBRES

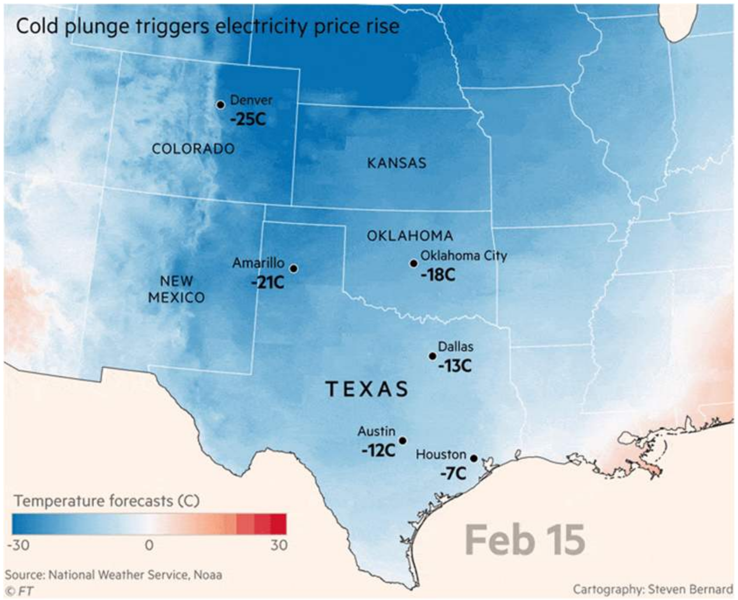


The Need for Power and Energy Systems Simulation

- The power system is becoming even more:
  - Complex with variable and distributed generators
  - Integrated with other energy systems

- The system has stringent reliability standards

- Changes to the system require massive investments with long timescales


Cold plunge triggers electricity price rise

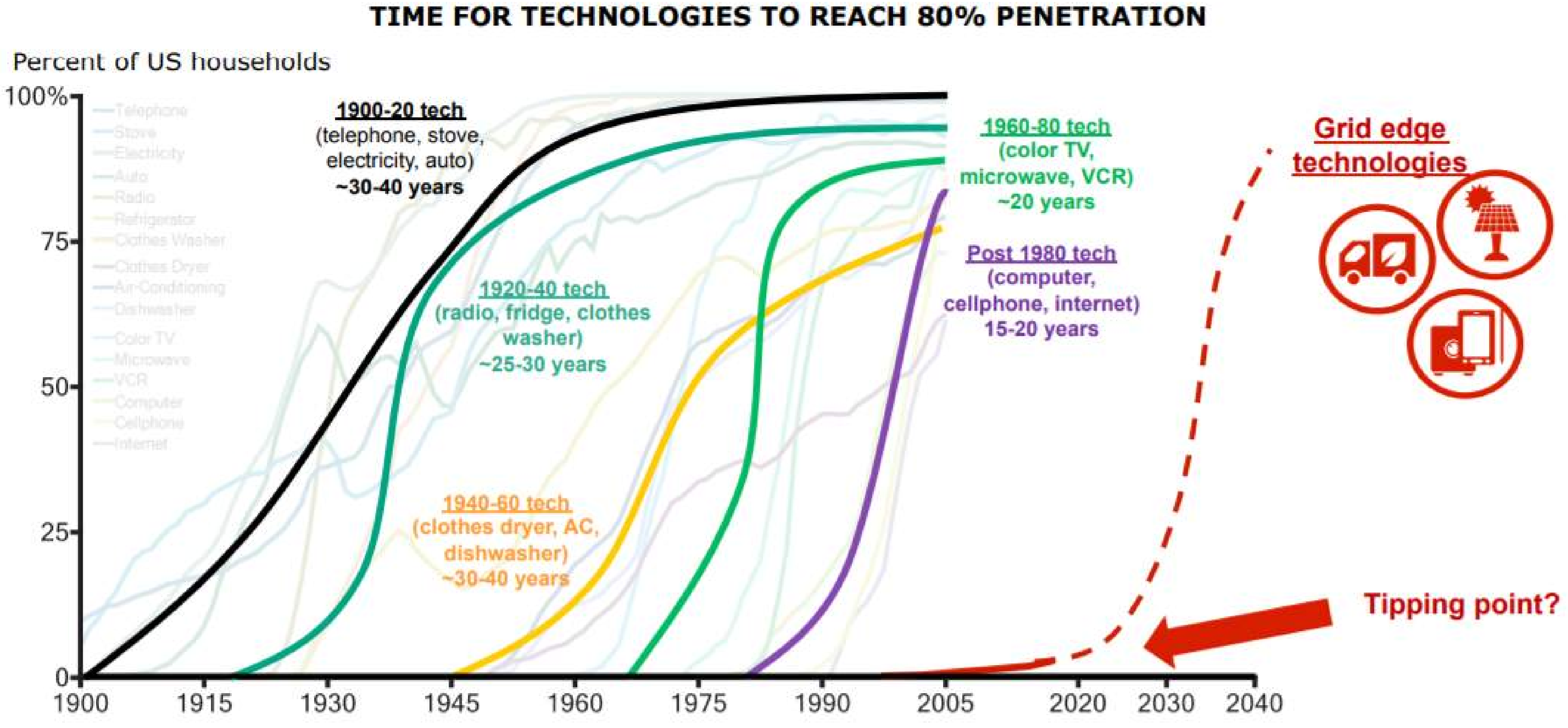
Source: National Weather Service, Noaa
© FT

Cartography: Steven Bernard

Therefore, we need computational models and high-quality data that can predict the impacts of new technologies before they are implemented in practice.

Grid Edge Technologies

- Renewable Sources
- Storage
- Electrification of Transportation
- Electrification of Comfort
- Smart Devices



Source: World Economic Forum and New York Times

Prosumer Friendly Grid Edge Technologies


Distributed PV


Electric Vehicle


Home Battery
Energy Storage


HVAC Load


Electric Water
Heater Load

Understanding EV Impacts

- Vehicle type (battery size)
- Charging type and location
  - Level I, II, III?
  - Home charging only?
  - Public charging infrastructure?
  - *Dynamic wireless charging*?
- Driving patterns and timing
  - Urban or rural
  - Weather conditions
  - Weekend or weekday?
  - Multiple drivers?
- Charging timing
  - Unconstrained?
  - Utility controlled?
  - Incentivized? (Time of use or off-peak pricing?)

Vehicle Usage

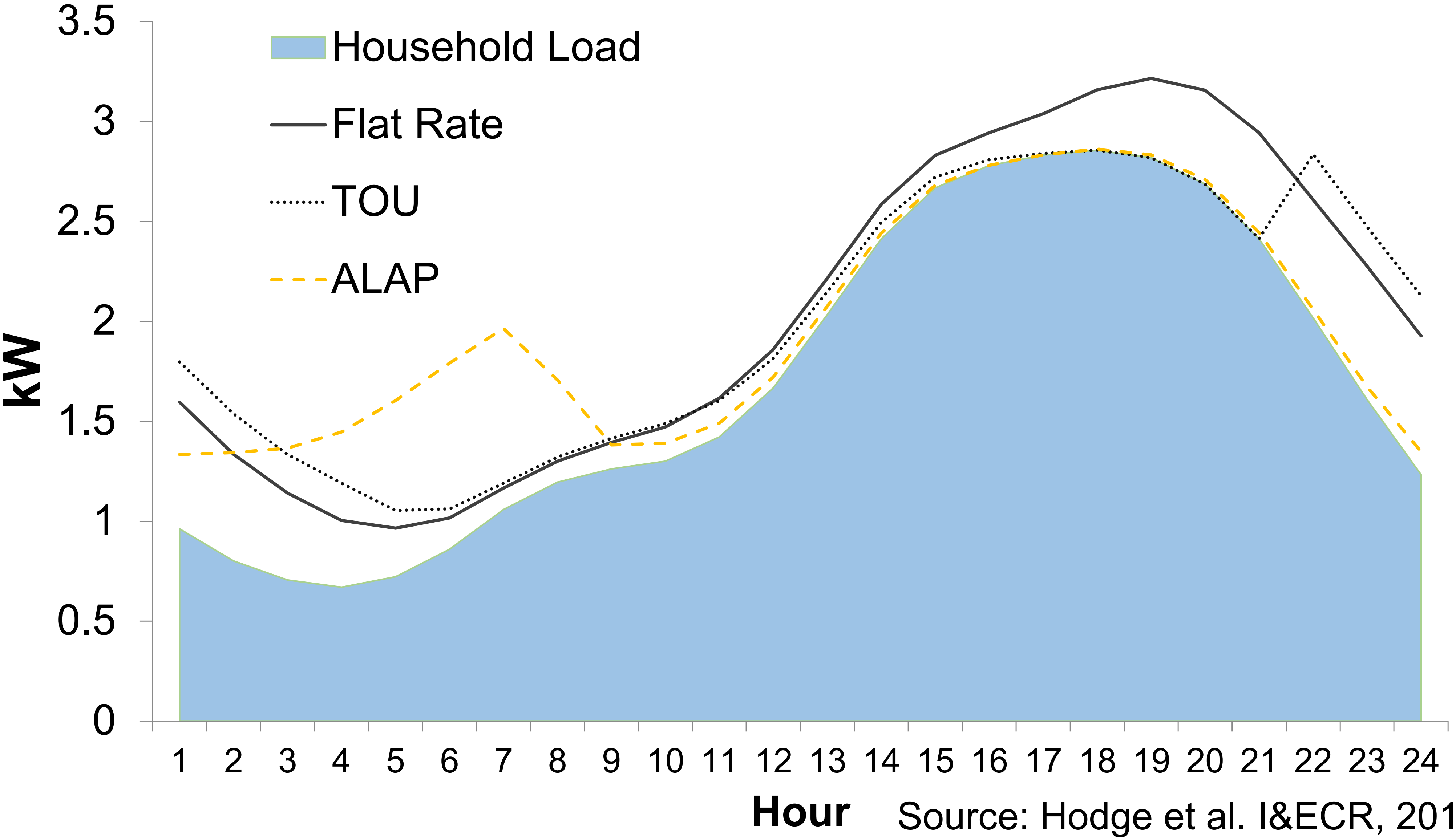
- Trip distances
  - Weekend vs. weekday
  - Daily trips vs. special trips
- Number of trips
  - Weekend vs. weekday
- Chained trips?

EV Charging Levels

- Level 1 (120 V):
  - 3-5 mph charge speed
  - 8-12 hours for a full charge
- Level 2 (240 V):
  - 12-80 mph charge speed
  - 4-6 hours for a full charge
- Level 3 (480V DC):
  - 3-20 miles per *minute*
  - 80% charge in 30 minutes;
  - not standardized with all vehicles

Source: Forbes Wheels

Vehicle Charging Patterns



Source: Hodge et al. I&ECR, 2011

Vehicle Impacts of Charging

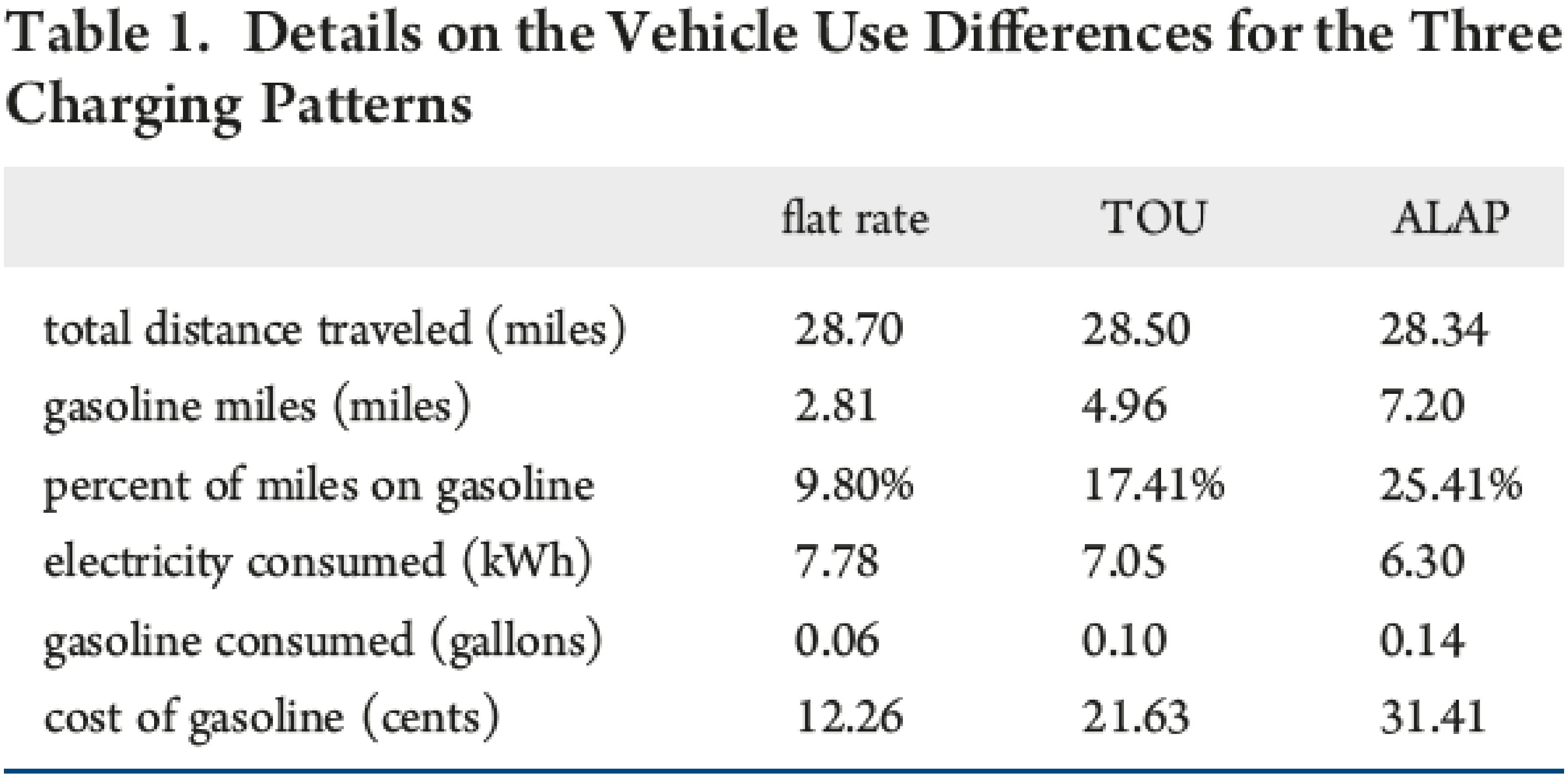


Table 1. Details on the Vehicle Use Differences for the Three Charging Patterns

	flat rate	TOU	ALAP
total distance traveled (miles)	28.70	28.50	28.34
gasoline miles (miles)	2.81	4.96	7.20
percent of miles on gasoline	9.80%	17.41%	25.41%
electricity consumed (kWh)	7.78	7.05	6.30
gasoline consumed (gallons)	0.06	0.10	0.14
cost of gasoline (cents)	12.26	21.63	31.41

Source: Hodge et al. I&ECR, 2011

Household Impacts

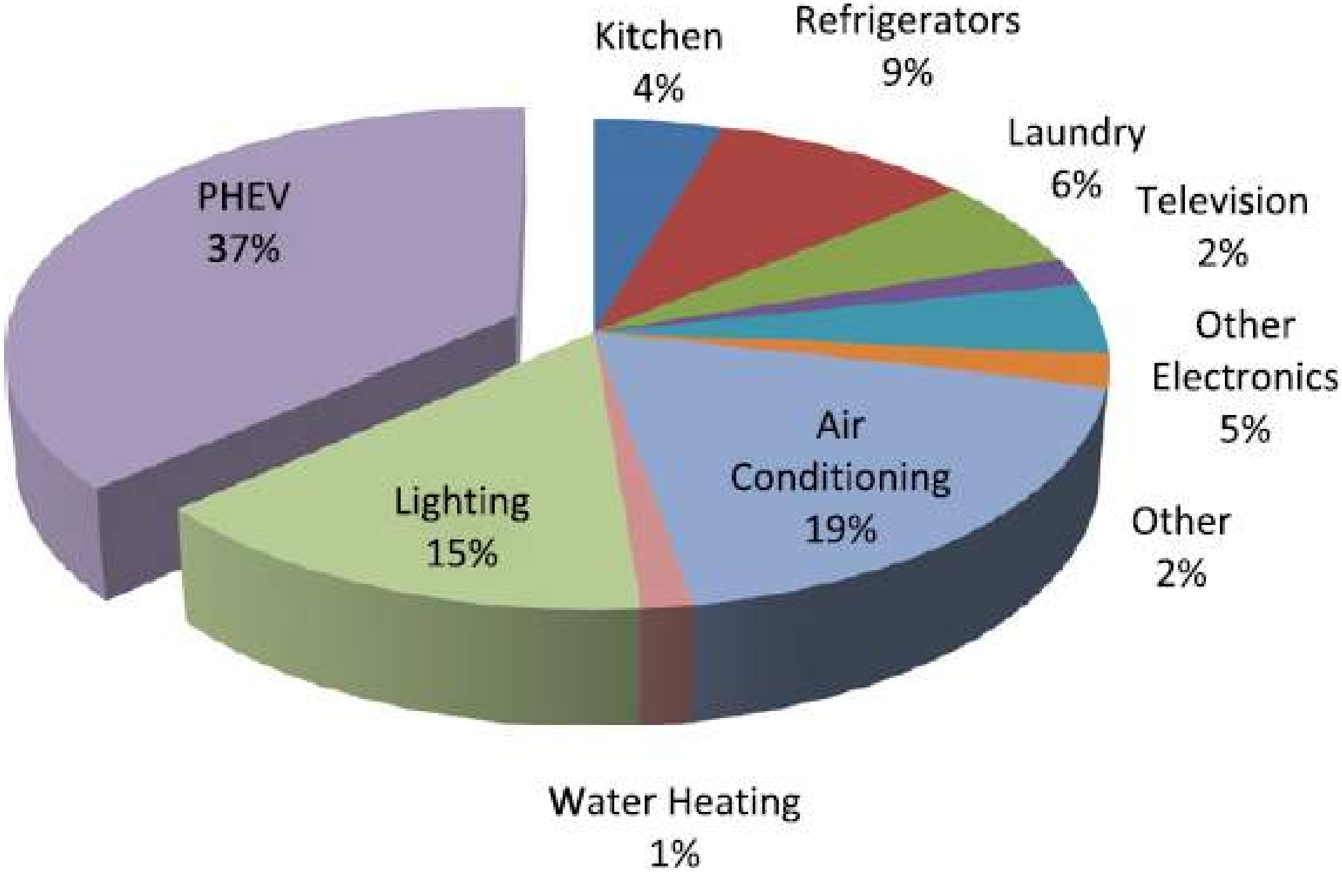
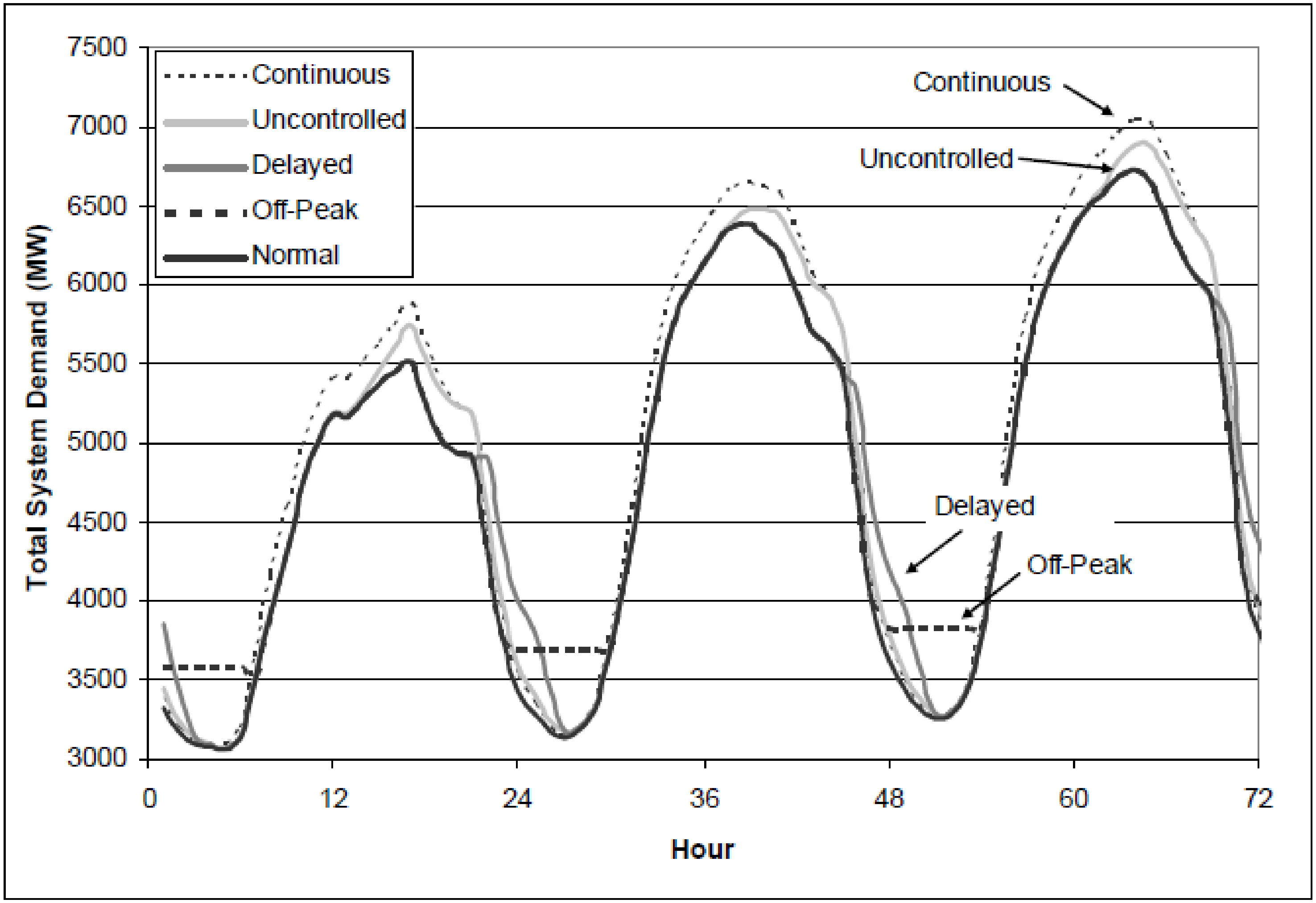


Fig. 4. Breakdown of electricity consumption of an average Californian household in summer with the addition of PHEVs.

Source: Huang et al. Energy Policy, 2011

Bulk Impacts – Xcel Case

- 500,000 EVs in Xcel Colorado territory (1/3 vehicle fleet)
- Summer conditions shown at right



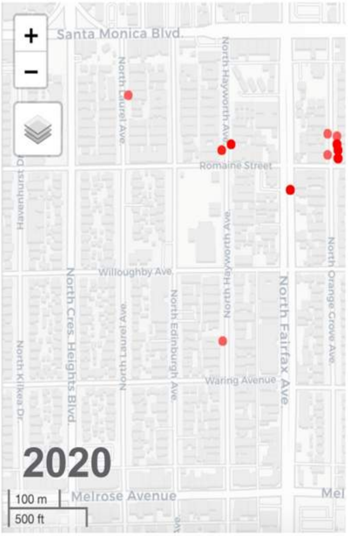
Source: Parks et al., NREL 2007

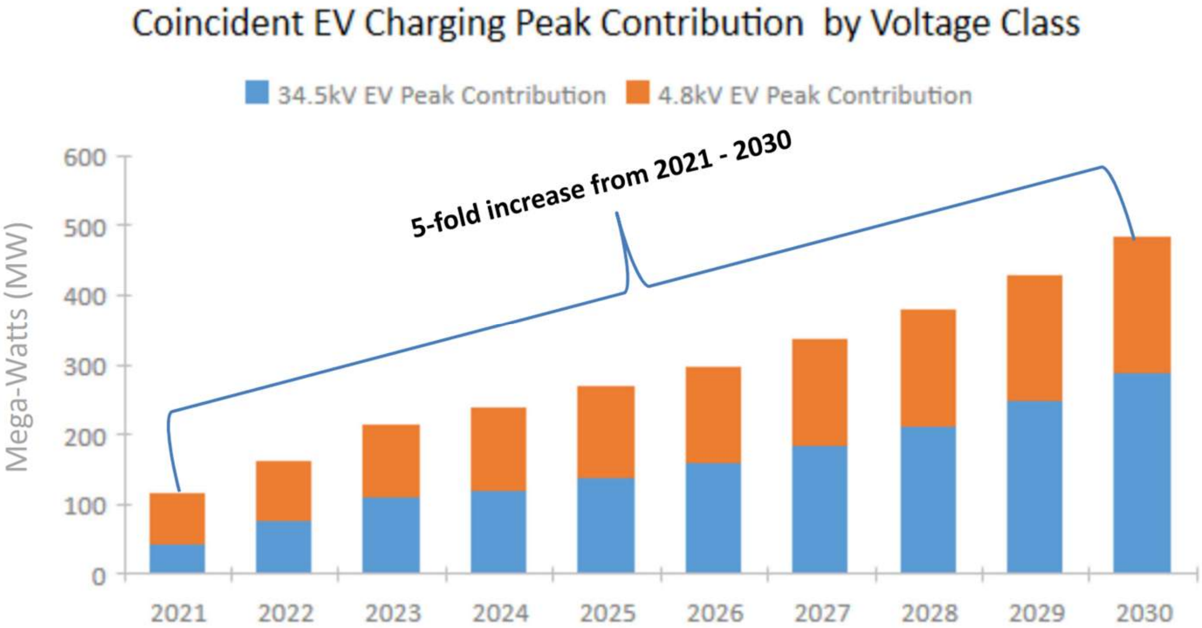
Consumer Issues

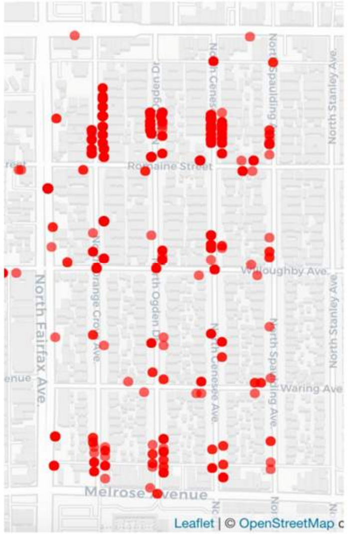
- Public charging station availability
- “Range anxiety”
- Additional capital costs
- Battery degradation from increased cycling
- “Full charge whenever I need it”
- Financial incentives

Power Distribution System Impacts

- Distribution challenges:
  - Headroom disappears
  - Lack of equitable adoption creates imbalance





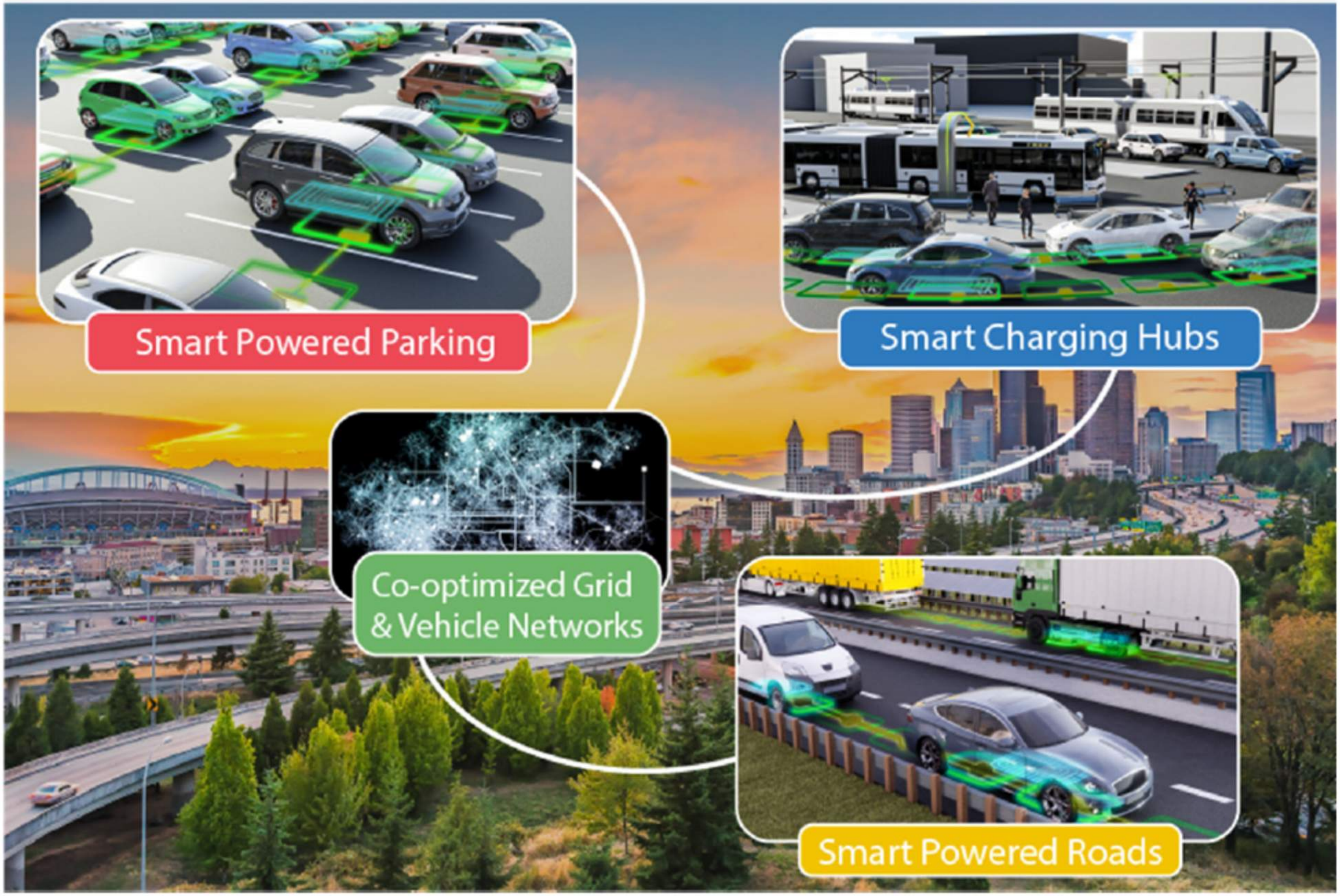


Source: LADWP EV Charging Peak – NASEM EV Workshop 2021

Source: PNNL LDV EV Adoption Model – Michael Kinter – NASEM EV Workshop 2021

ASPIRE Engineering Research Center

Future Transportation-Grid Interactions



Wireless Power Transfer (WPT)

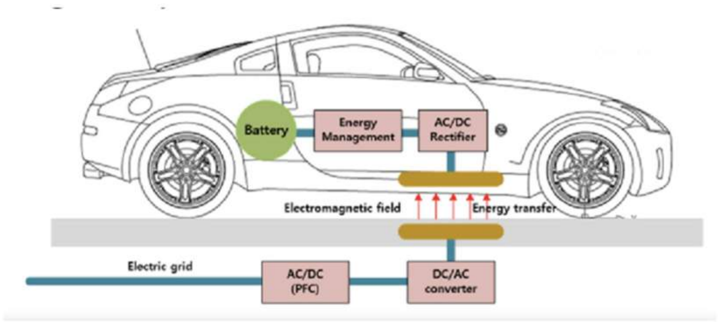


Figure 2.2: A Diagram of a 4kW Magnetic Resonance Wireless Power Transfer System taken from Choi et al. [5]

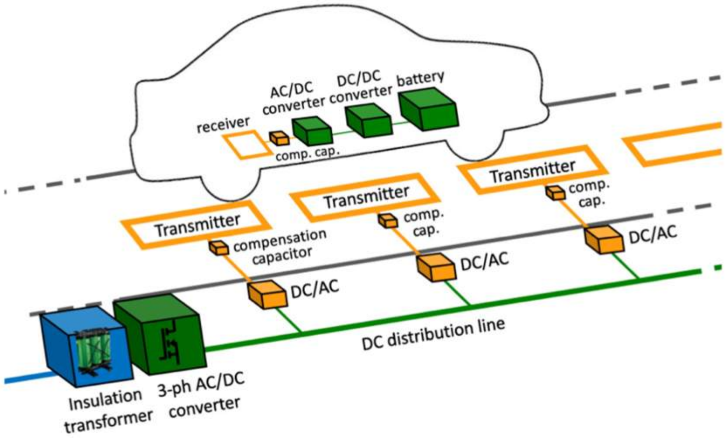
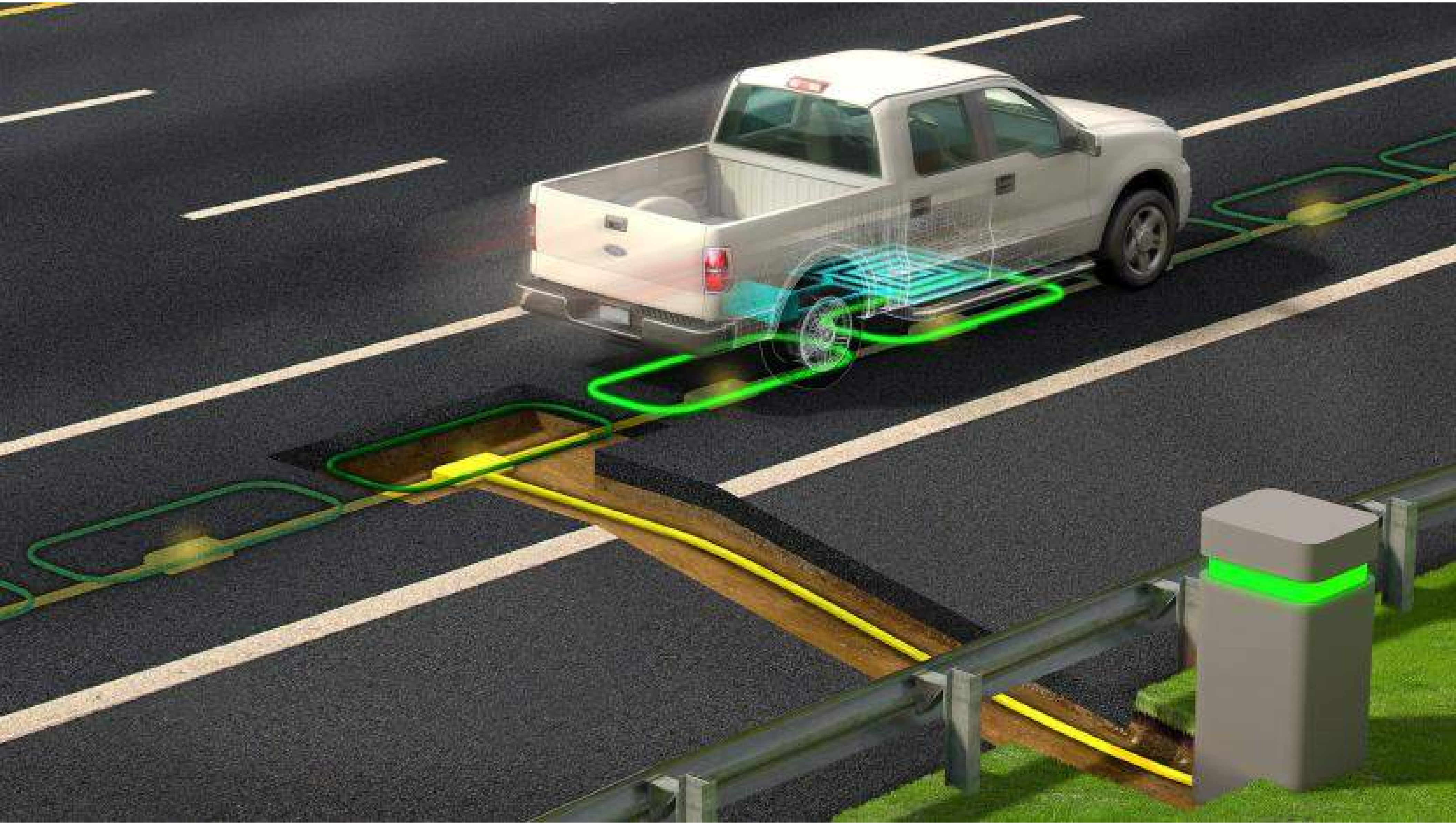
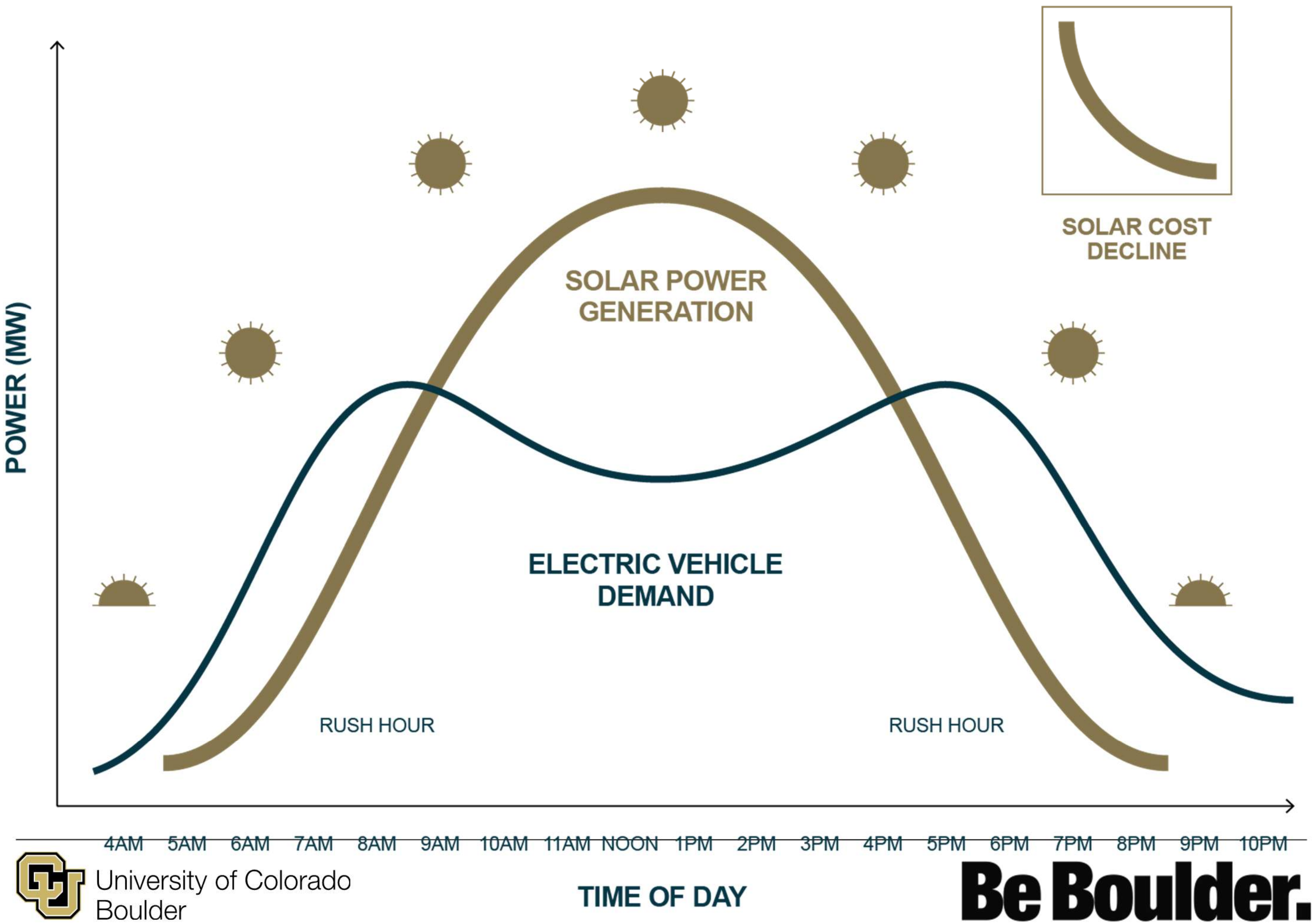


Figure 2.8: Electrical infrastructure of PoliTo DWPT charging lane [1]

Dynamic Wireless Vehicle Charging



Wireless/Solar Timing



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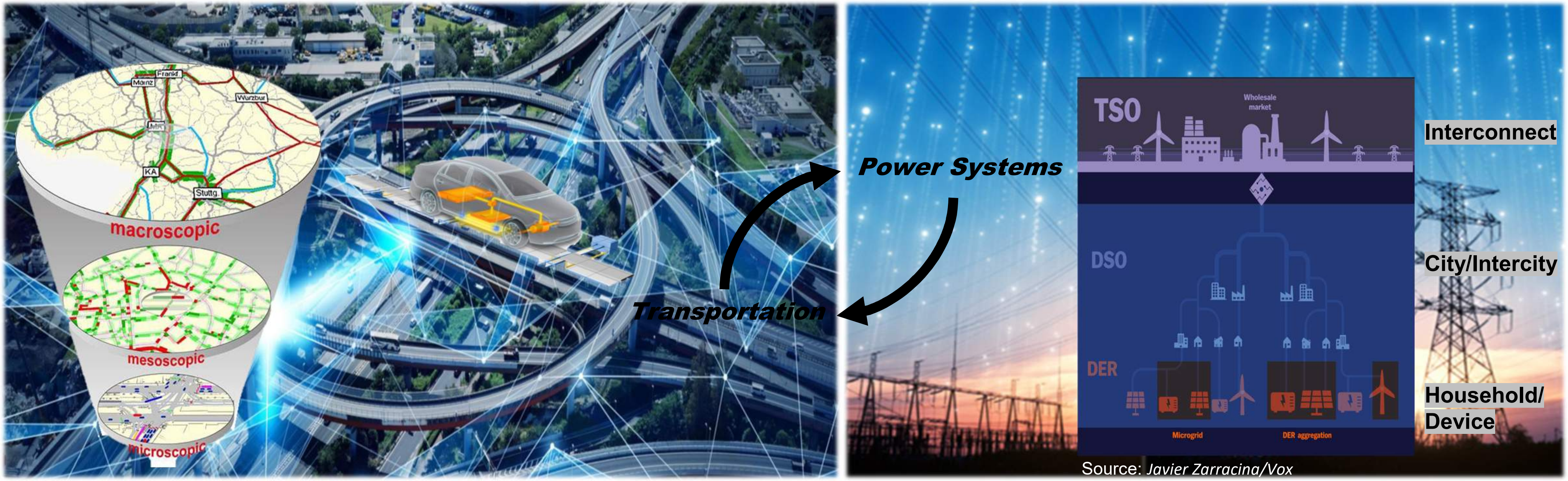
ASPIRE's Co-Simulator

The Impact of Dynamic Wireless Charging



Source: *Javier Zarracina/Vox*

Driving Conditions

Electricity Prices

Open-Source

Energy Justice

Health & Air Quality

Regional Case Study

- PCM to evaluate regional impacts of DWPT
  - Establish relationship between in-transit EV charging and solar curtailment

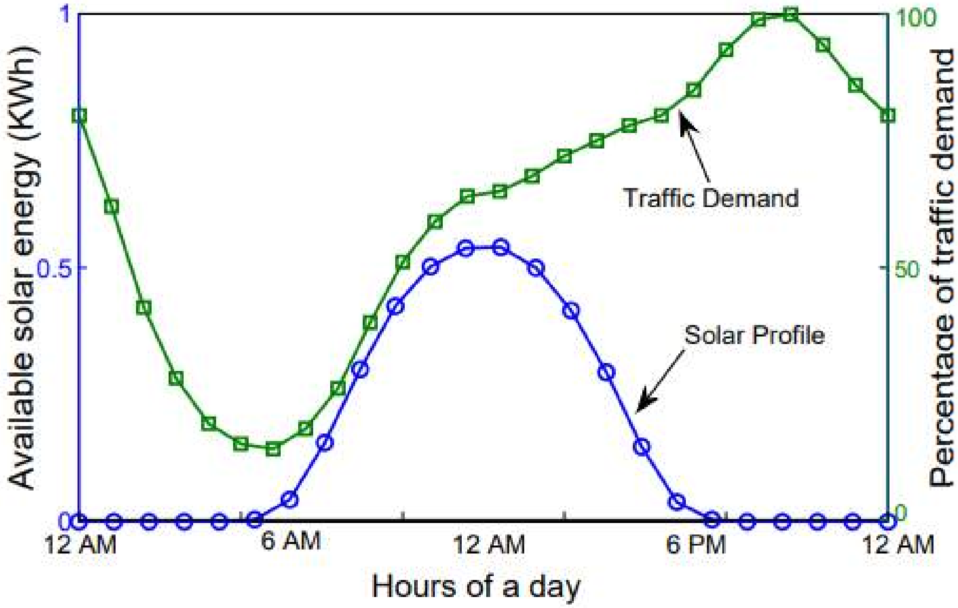
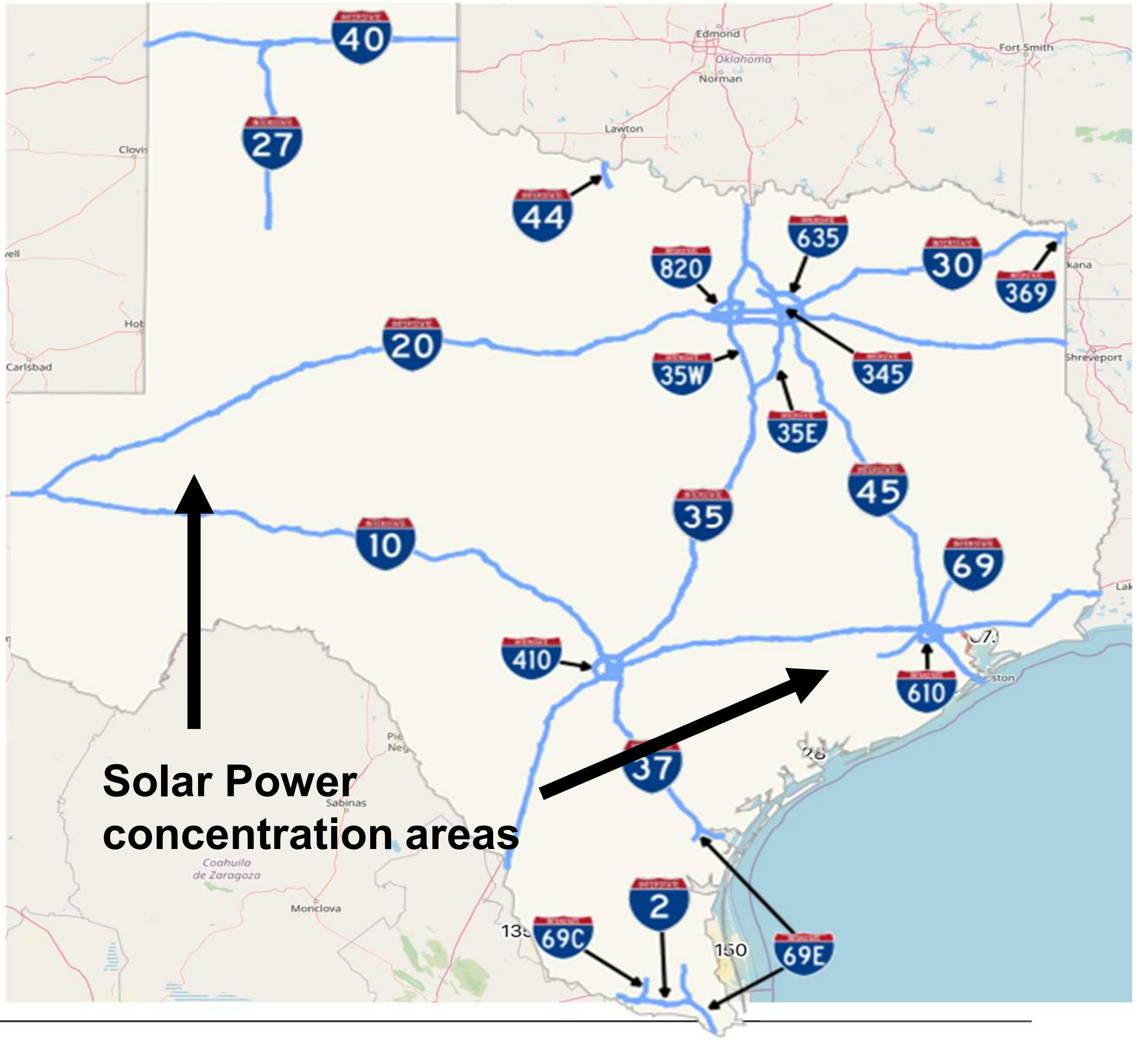
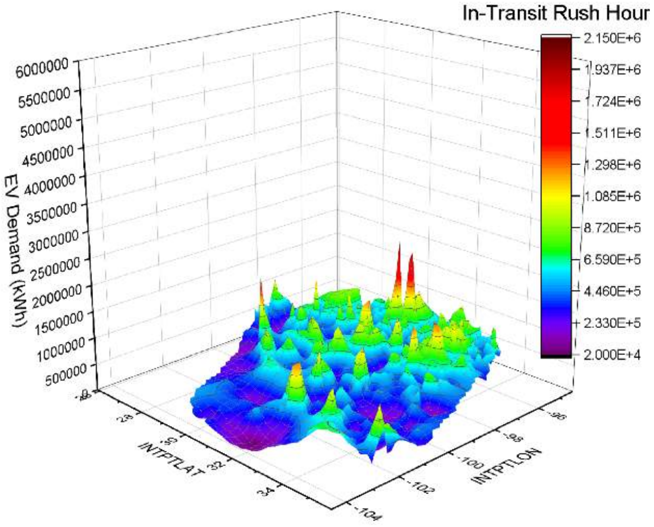


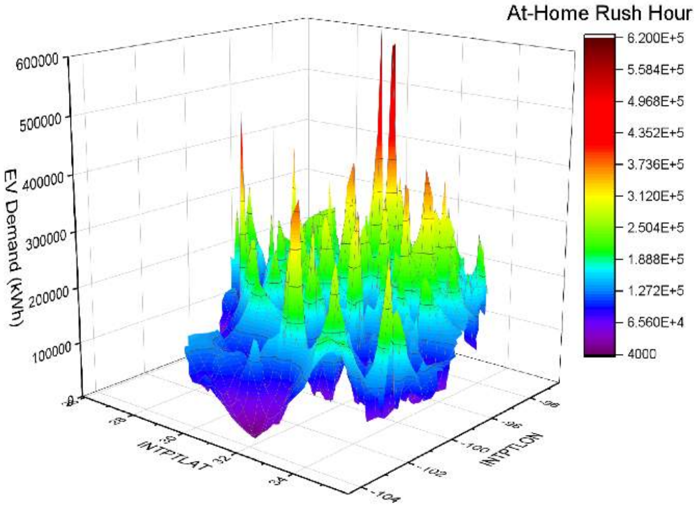
Fig. 2. Average hourly solar energy generation and daily traffic profile of a residential area.

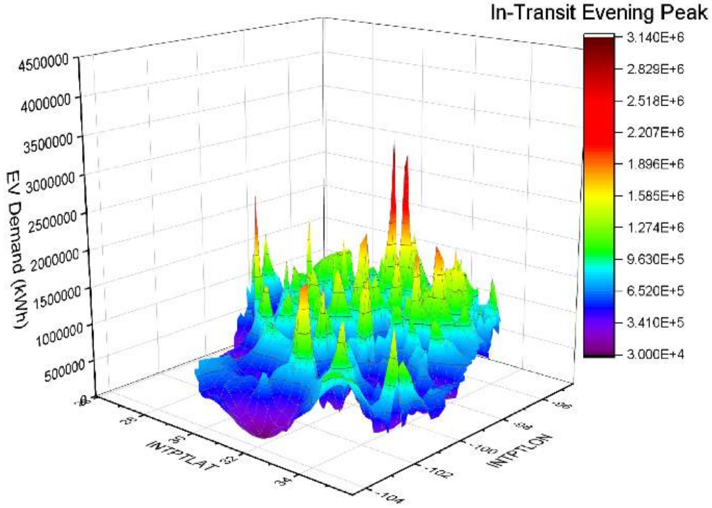


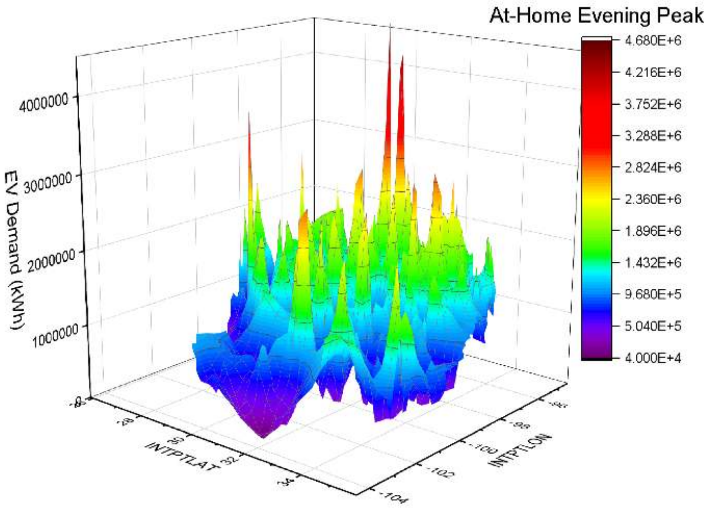
Solar Power concentration areas

In-Transit Charging

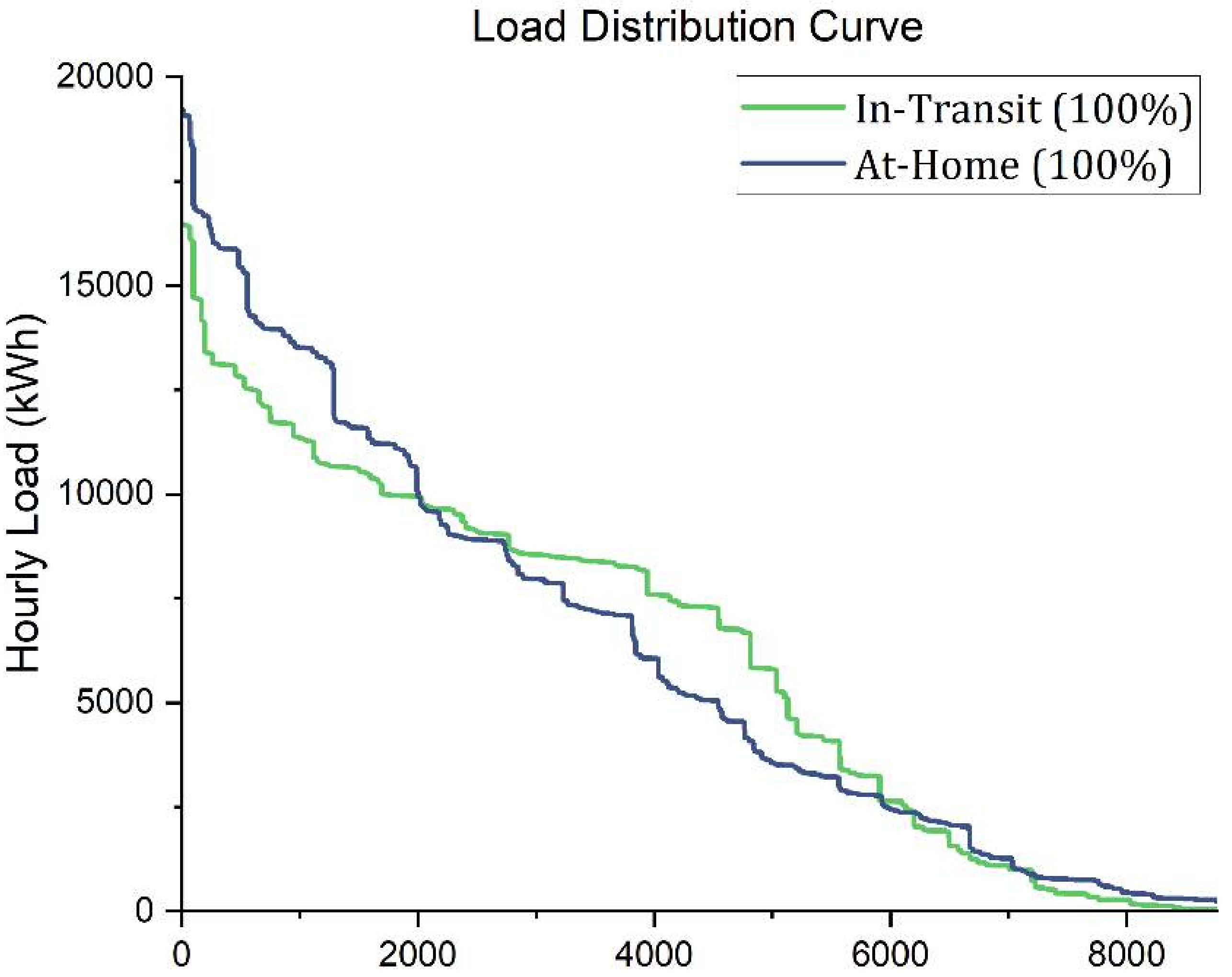






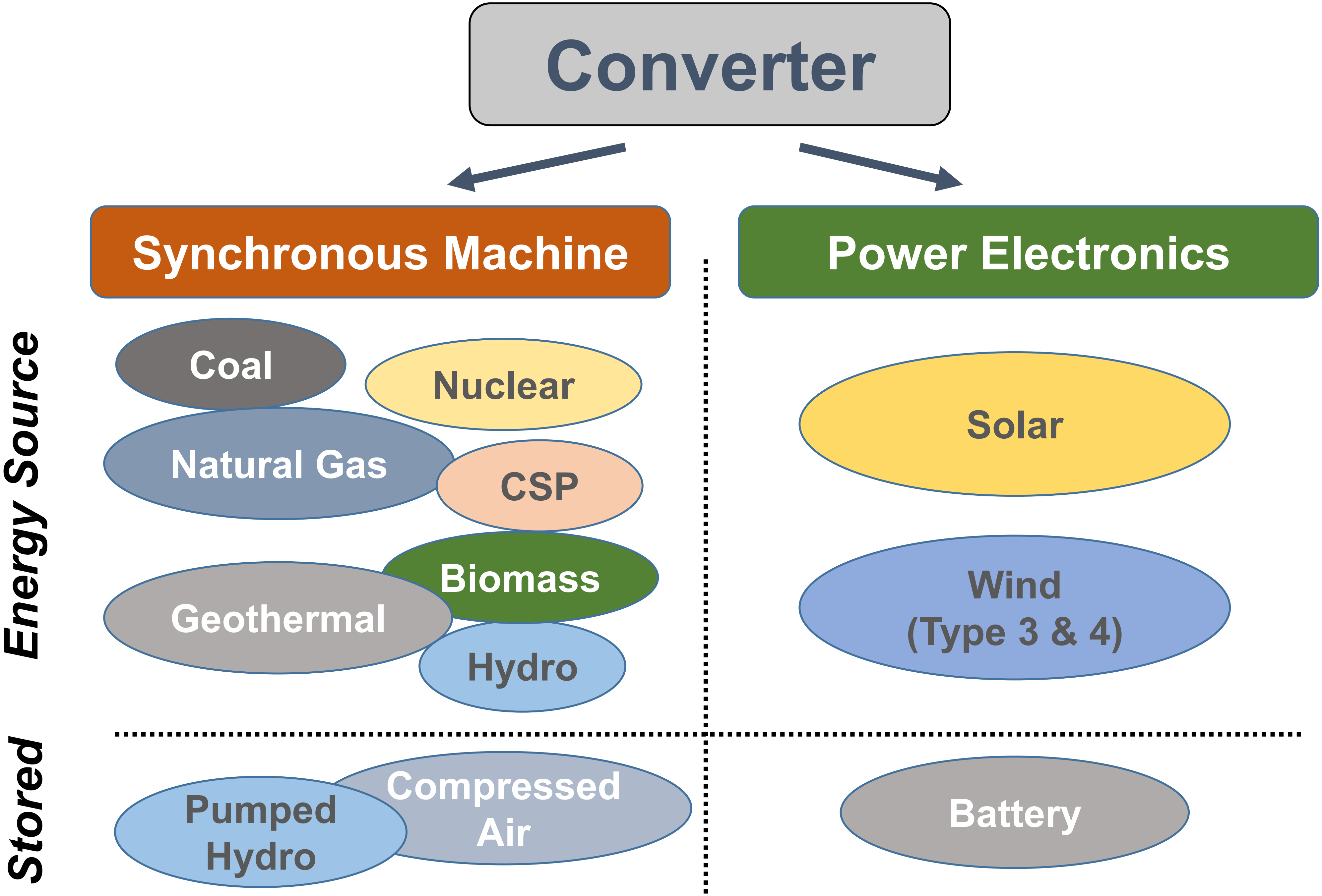


Additional ERCOT EV Load



EV Impacts Summary

- Rapid adoption of EV’s will strain the bulk-electric and distribution grid systems
- Innovative charging technology such as DWPT can alleviate peak loads
- Co-simulation models highlight system-level impacts to both transportation and power



Converter

Synchronous Machine

Power Electronics

Energy Source

Coal

Nuclear

Natural Gas

CSP

Biomass

Geothermal

Hydro

Solar

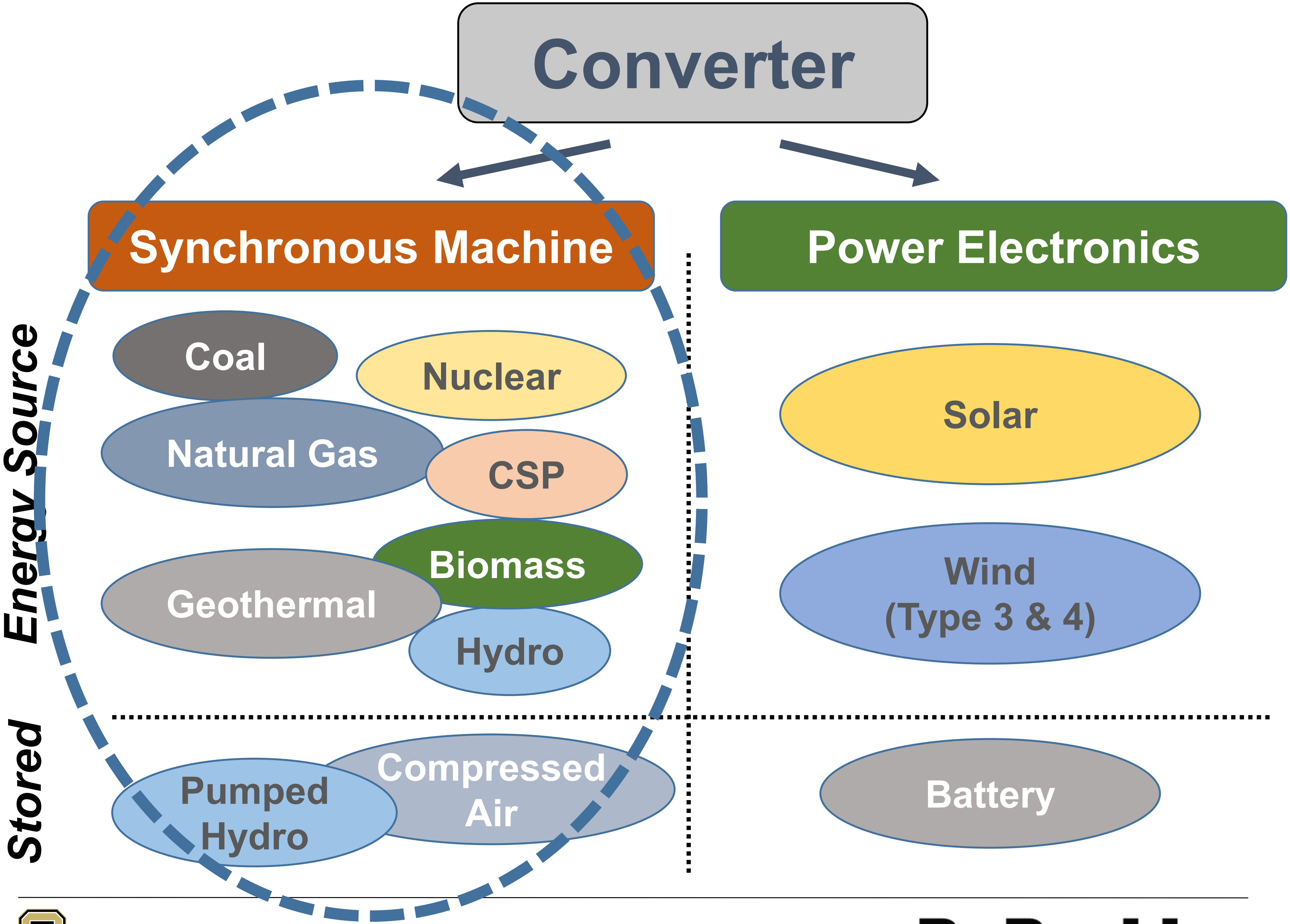
Wind
(Type 3 & 4)

Stored

Pumped
Hydro

Compressed
Air

Battery



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Synchronous Machine

Power Electronics

Energy Source

Coal

Nuclear

Natural Gas

CSP

Biomass

Geothermal

Hydro

Solar

Wind
(Type 3 & 4)

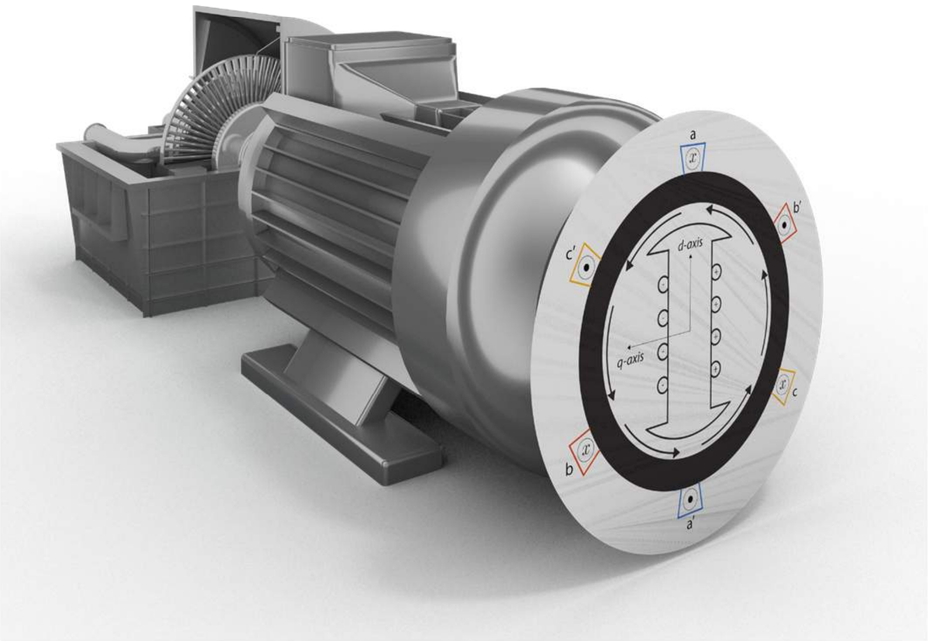
Stored

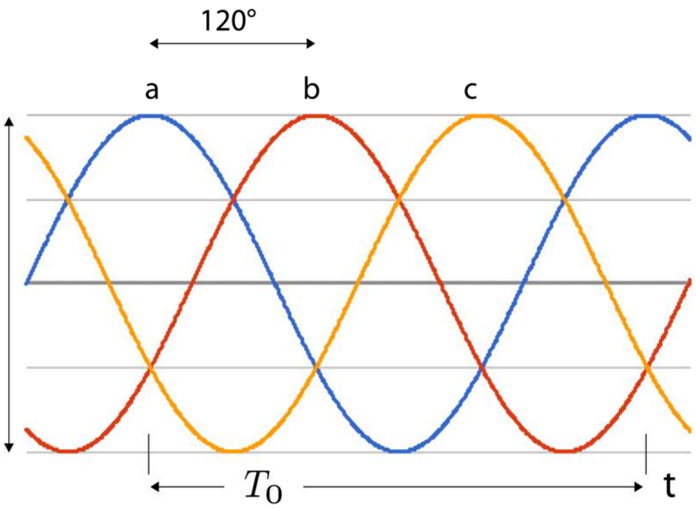
Pumped
Hydro

Compressed
Air

Battery

Synchronous Machine Converters (Generators)





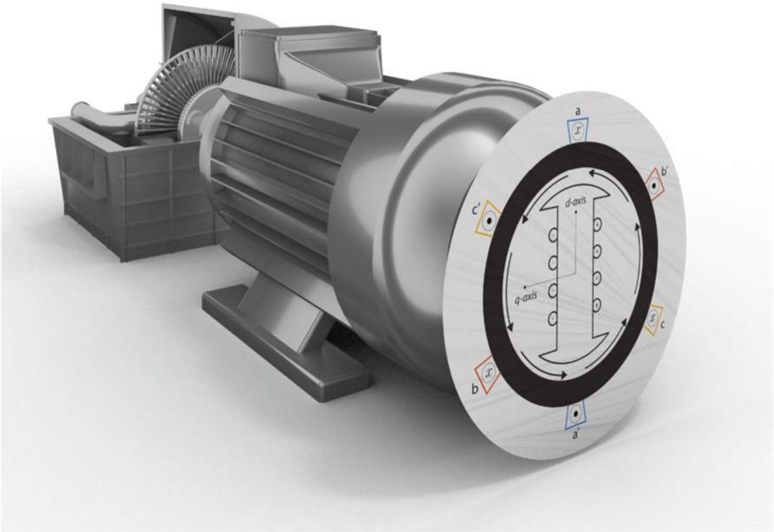
T_0 = one rotor revolution if single pole pair

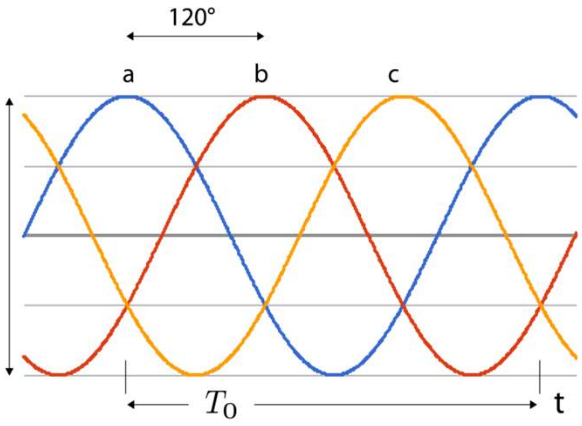
Create steam or hot air by burning or fissioning fuel, use this fluid to rotate a generator

$$\omega_0 = \frac{2\pi}{T_0} = \frac{P}{2}\omega_{Shaft}$$

… hence, synchronous

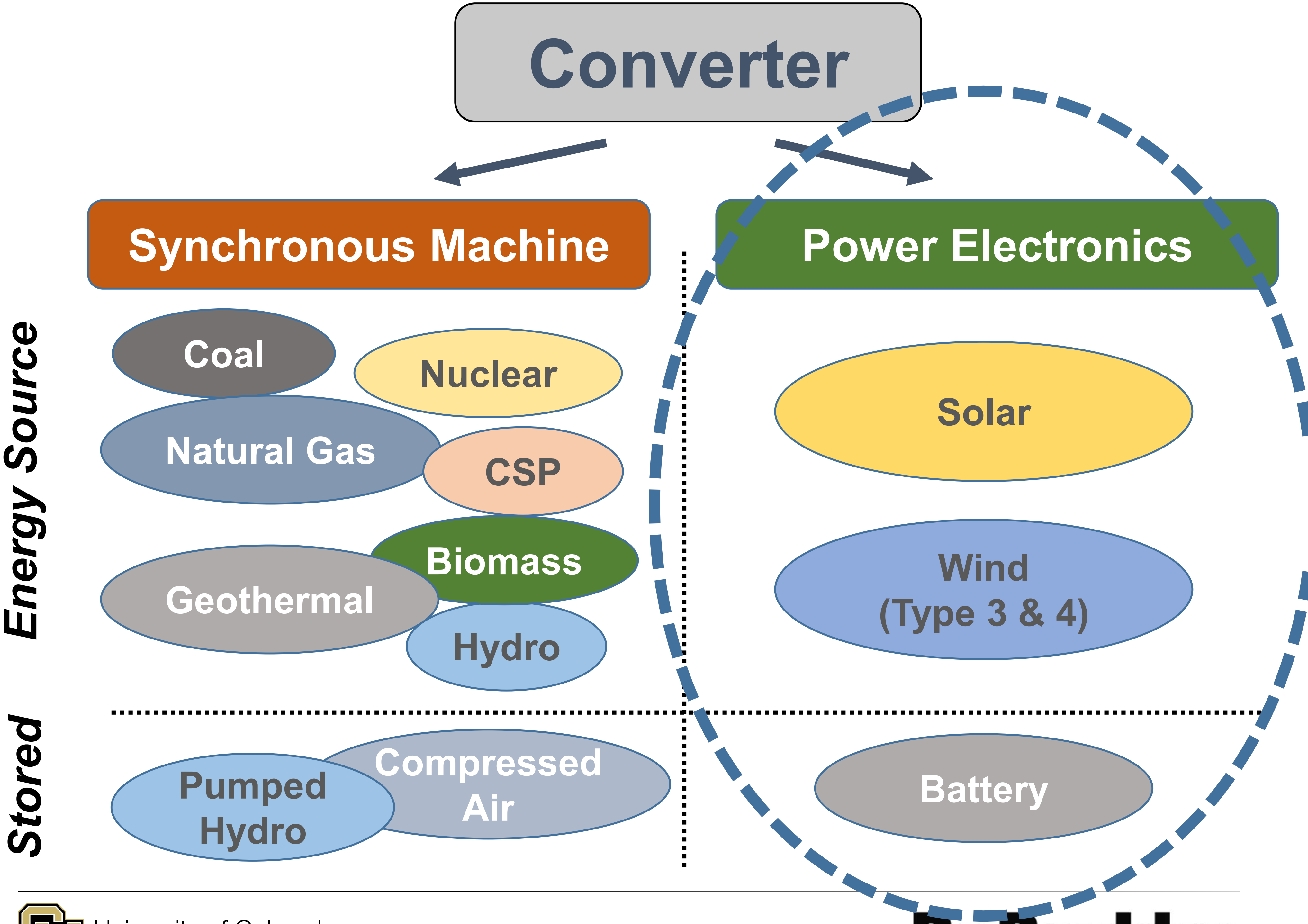
Synchronous Machine Converters (Generators)





T_0 = one rotor revolution if single pole pair

- Large mass is electromagnetically coupled to AC power system
  - Embeds inertial characteristics in power system
  - ***Naturally forms a sinusoidal output***
- Governors are relatively slow (> 0.5 second response time)
  - Means a load disturbance is initially met by inertial energy
- Large, transient overcurrents in faulted conditions (4 – 7 times rated)
  - Basis for many protection systems


Converter
Synchronous Machine
Power Electronics
Energy Source
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Coal
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Hydro
Pumped Hydro
Compressed Air
Solar
Wind (Type 3 & 4)
Battery

Two Terminal:
diodes

indiamart.com

Three Terminal:
MOSFETs, BJTs, IGBTs

digikey.com

Four Terminal:
thyristors

electricsoftstarter.com

extreme-ltd.com

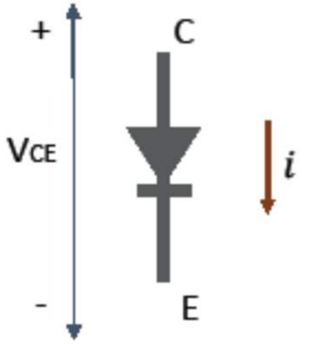
Renewable Interfacing Devices

ABB.com

Historically:
HVDC Applications

Diode Operation:

2 Terminal



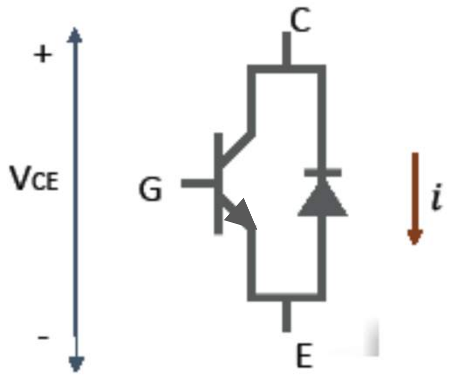
In General

$i > 0;\ \ if\ V_{CE} > 0$

$i = 0;\ \ if\ V_{CE} < 0$

Transistor Operation:

3 Terminal



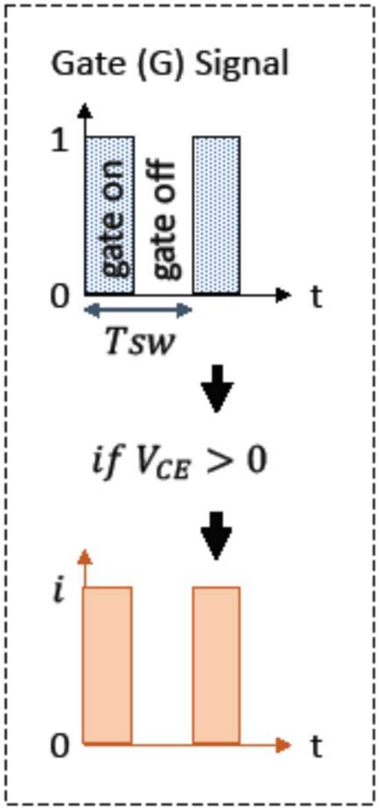
In General

$i > 0;\ \ if\ V_{CE} > 0, \&\ G > 0\ (i.e.\ on)$

$i = 0;\ \ if\ V_{CE} > 0, \&\ G = 0\ (i.e.\ off)$

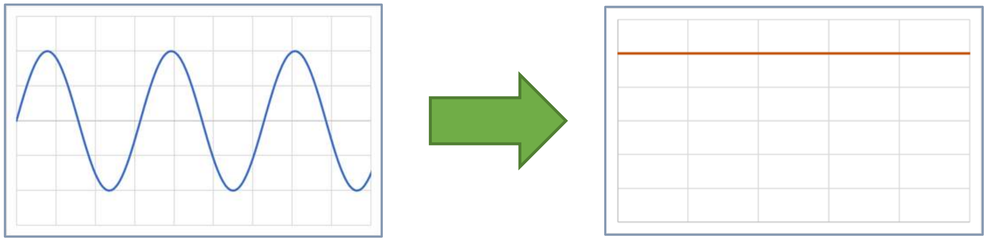
$i < 0;\ \ if\ V_{CE} < 0\ (due\ to\ body\ diode)$

Digital Control

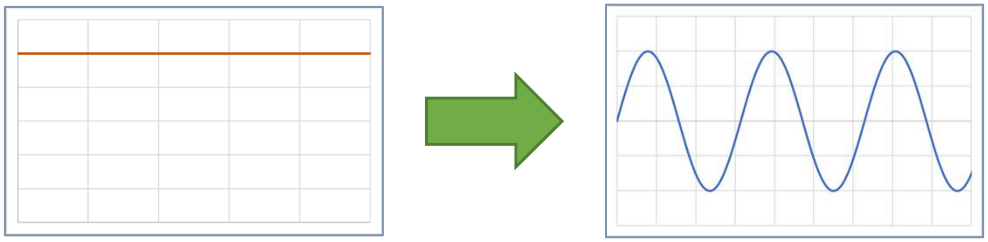


Four Basic Topologies

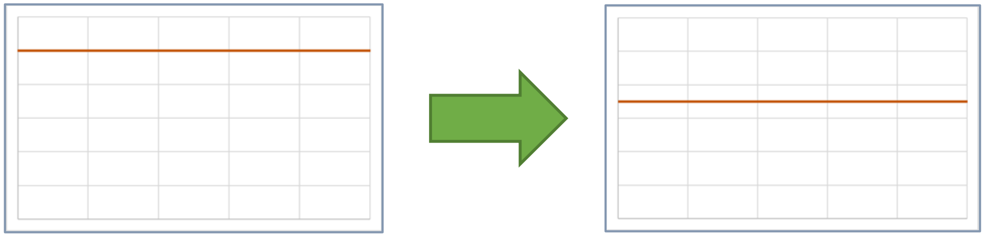
- **Rectifier (AC to DC):**



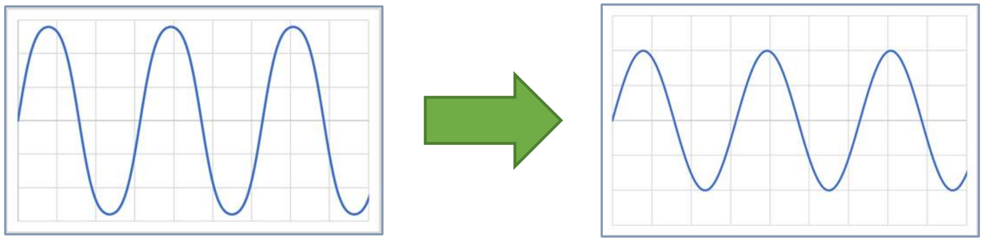
- **Inverter (DC to AC):**



- **Converter (DC to DC):**



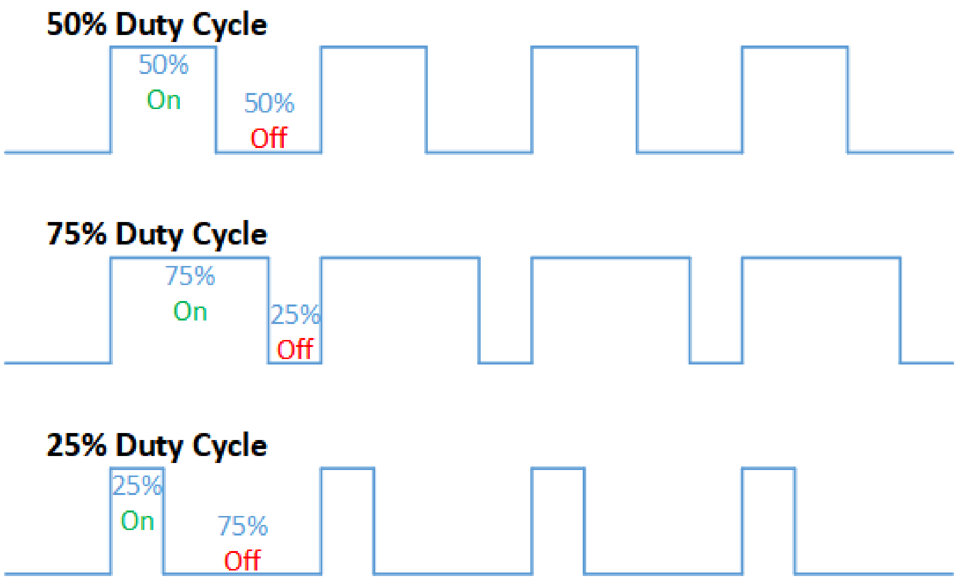
- **Cycloconverter (AC to AC):**



Rapid Switching:

Duty Cycle: time ‘on’ per cycle

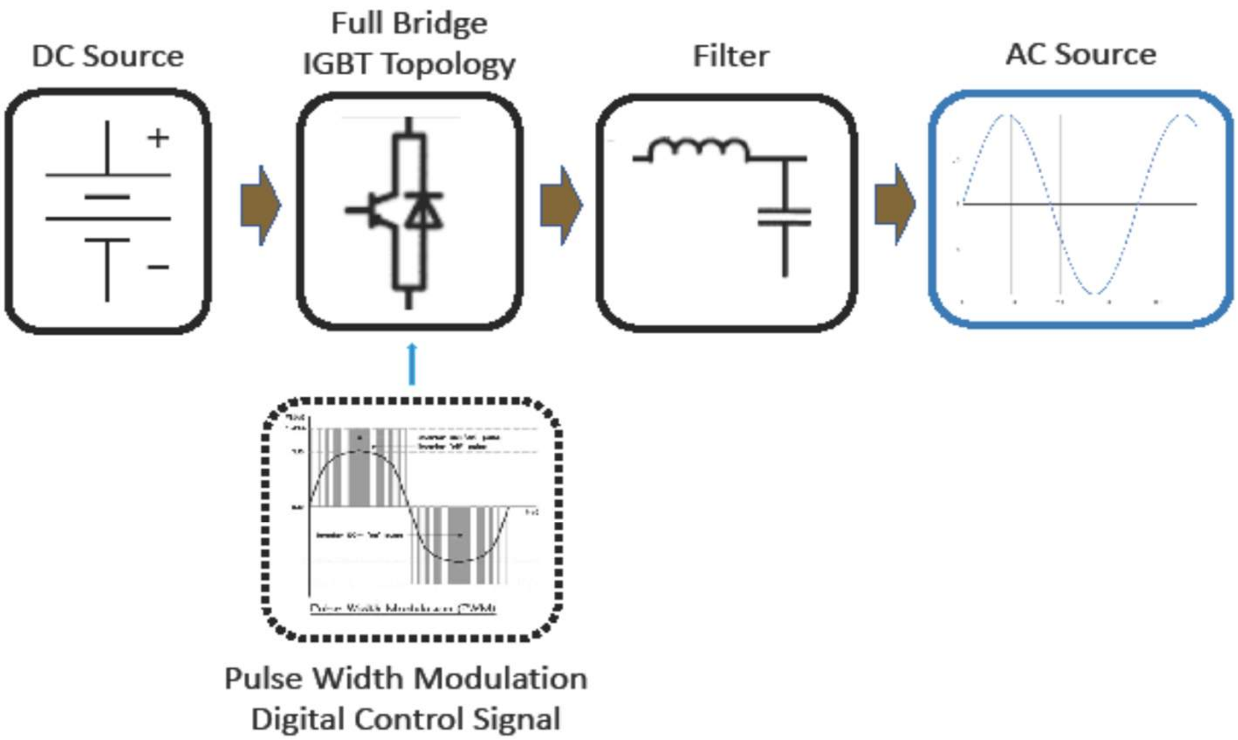
$$D = \frac{T_{on}}{T_{switch}}$$



wikipedia.com

- *Very* rapid switching;
  - $f_s = 1 - 1{,}000\ kHz$
- In general, larger f_s yields a larger bandwidth; i.e. greater control
- But some non-ideal switching losses occur per cycle
  - proportional to switching frequency, f_s
- A trade off; higher power devices with smaller switching frequencies ($f_s = 1 - 5\ kHz$) -> less control, smaller losses

The Ubiquitous Inverter:



DC Source

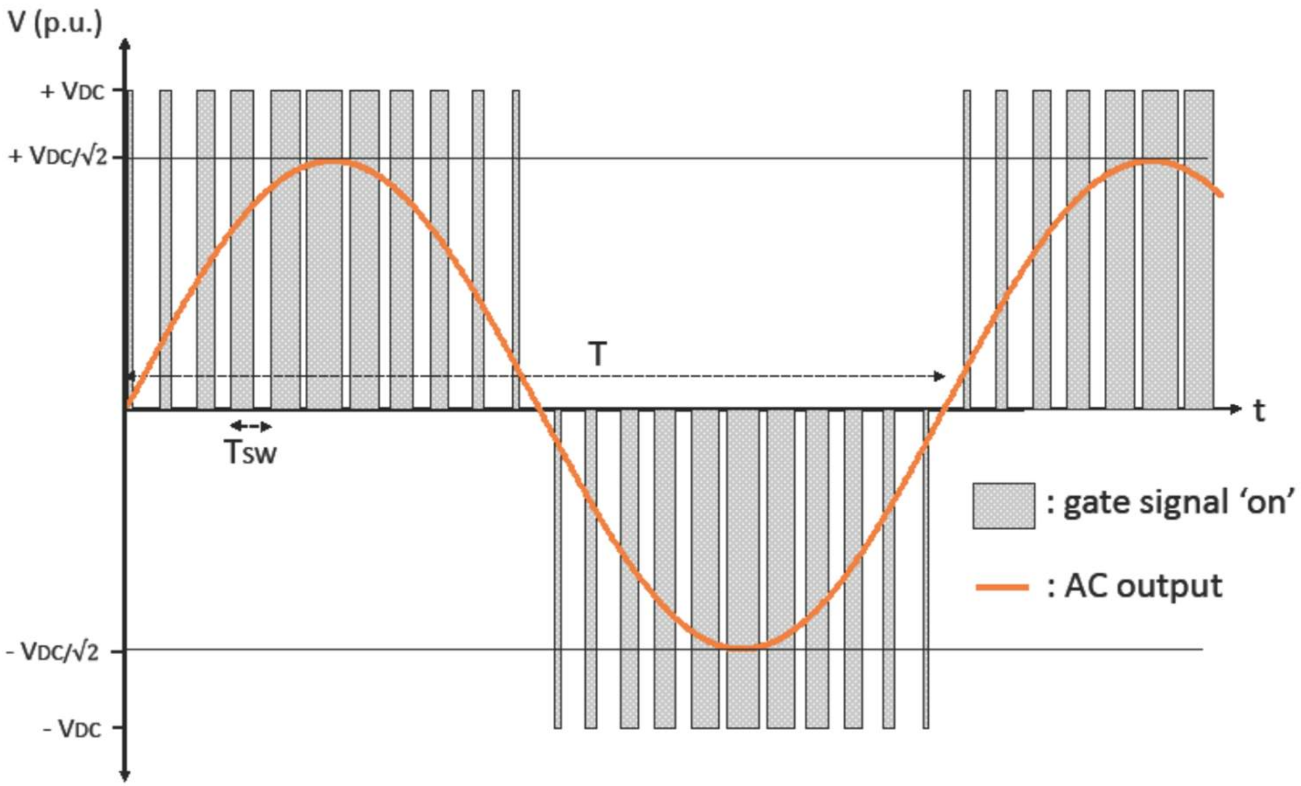
Full Bridge
IGBT Topology

Filter

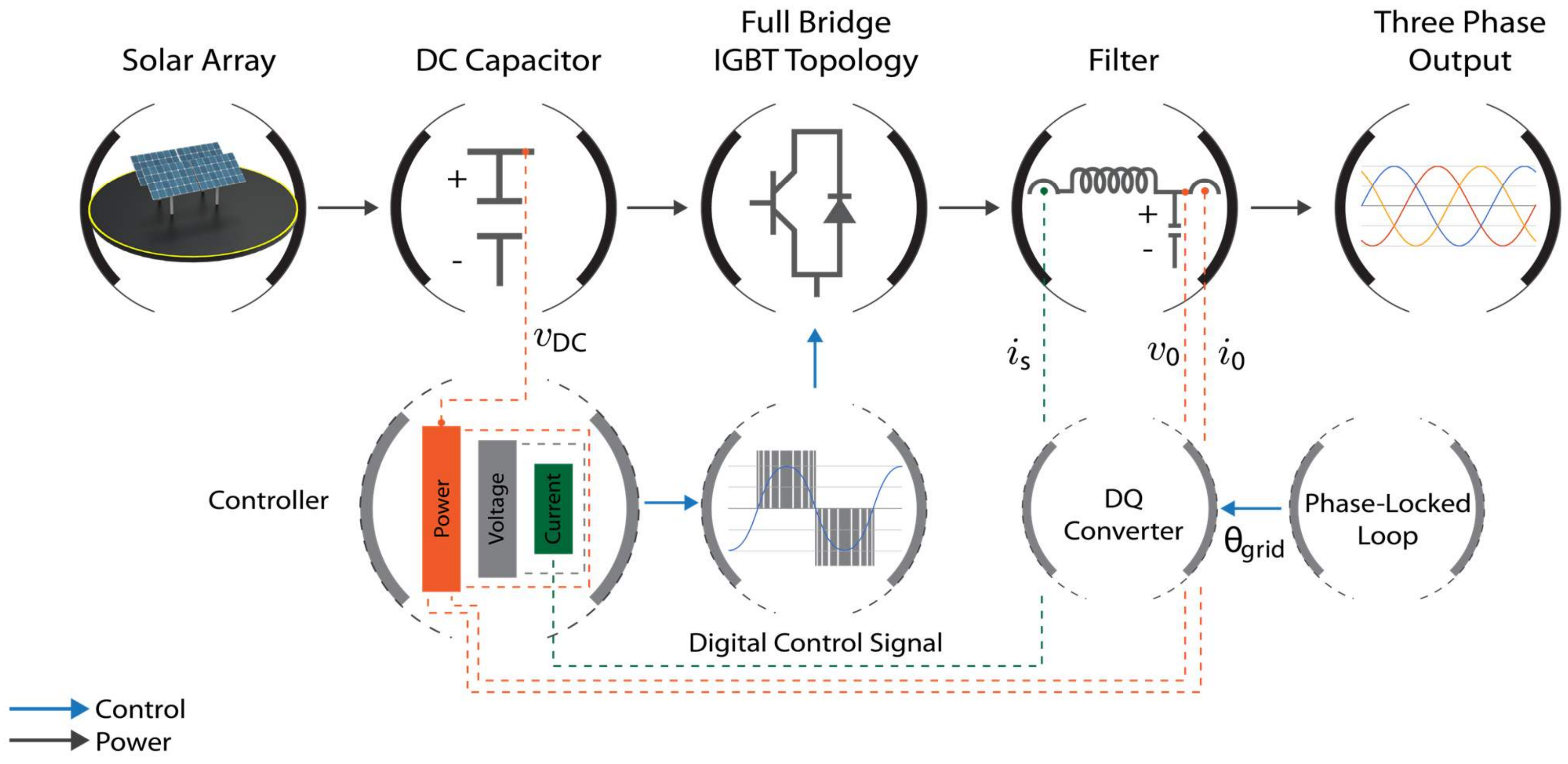
AC Source

Pulse Width Modulation
Digital Control Signal

Pulse Width Modulation:



3-Phase Grid Following
Power Electronic Converter



Solar Array

DC Capacitor

Full Bridge
IGBT Topology

Filter

Three Phase
Output

v_{DC}

i_s

v_0

i_0

Controller

Power

Voltage

Current

Digital Control Signal

DQ
Converter

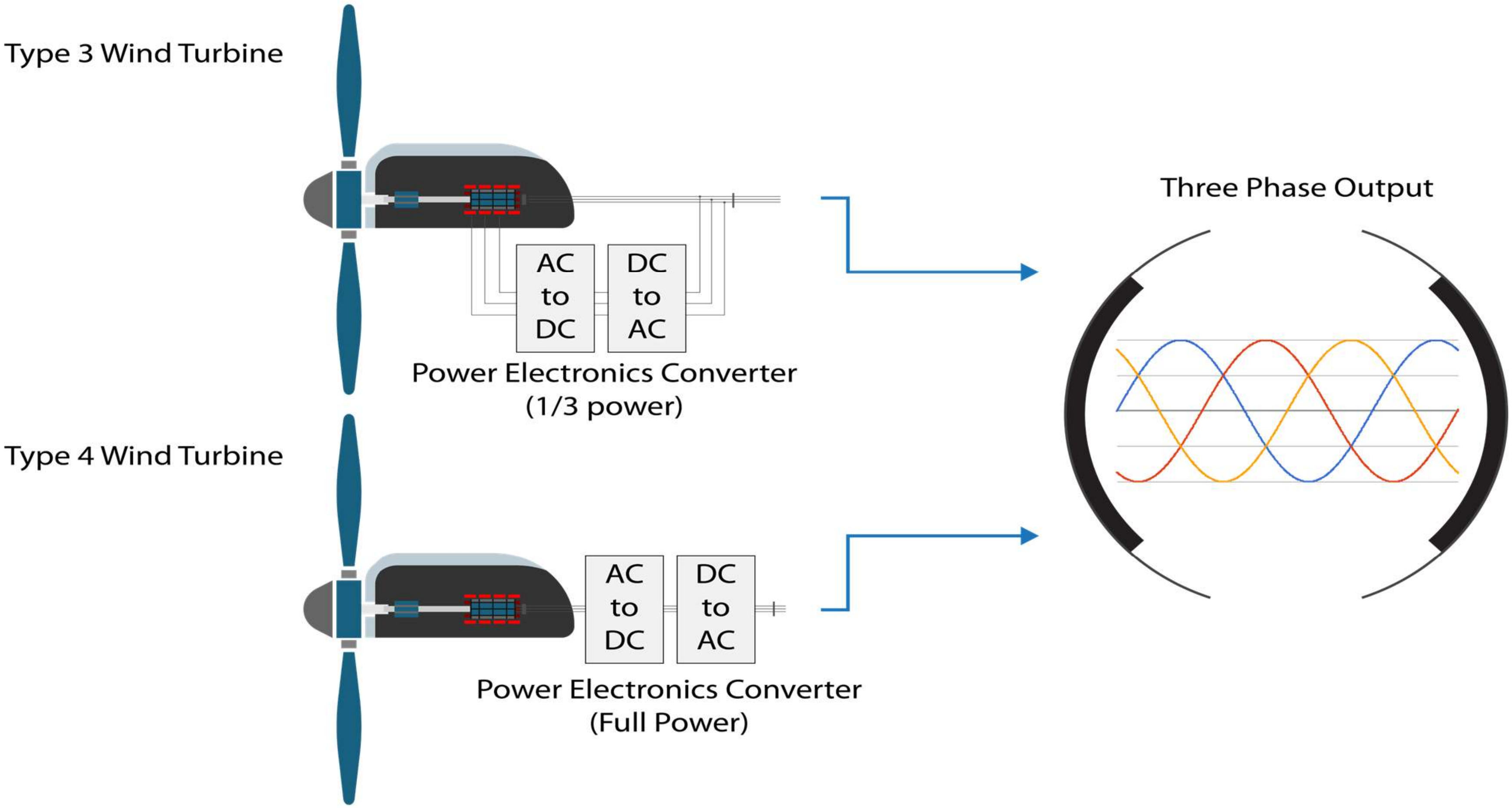
θ_{grid}

Phase-Locked
Loop

Control

Power

Wind Turbines Use PECs Also



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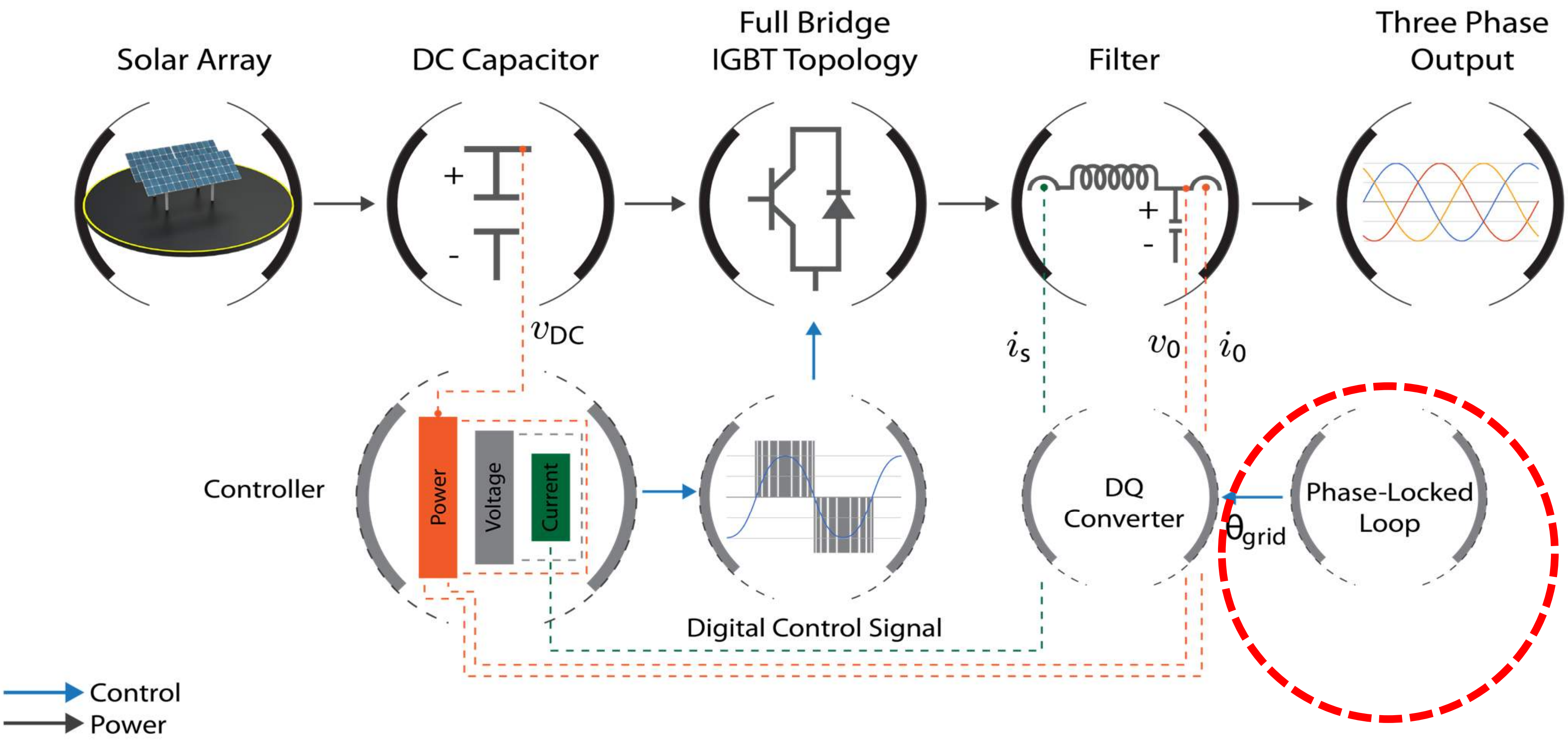
3-Phase Grid Following
Power Electronic Converter



- Operation anticipates an existing power system (i.e. a sinusoidal voltage at the connection point), historically created by synchronous converters

An Emerging Problem

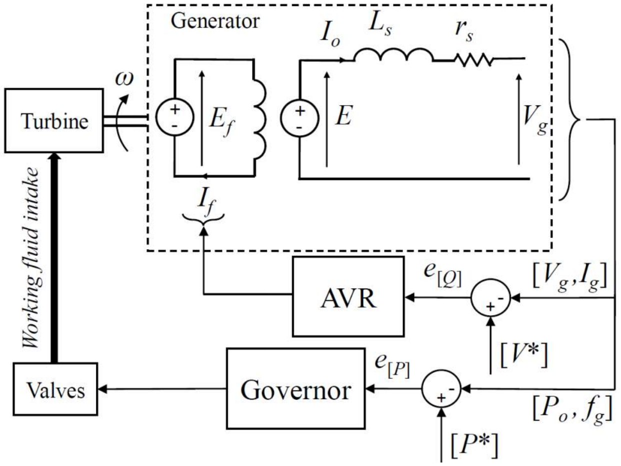
- Except for very small, electrically isolated systems (i.e. nano/micro grids), all contemporary PECs operate as **grid following**.

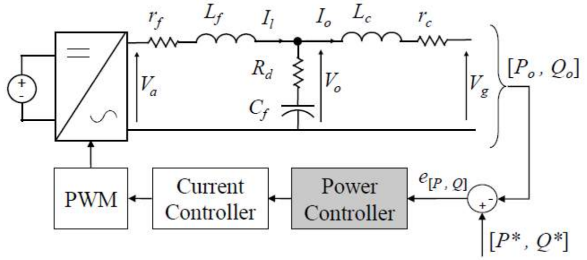
- But, if these grid following resources displace the grid forming SMCs, what is forming the sinusoidal waveforms of the power system?

What’s Changing?

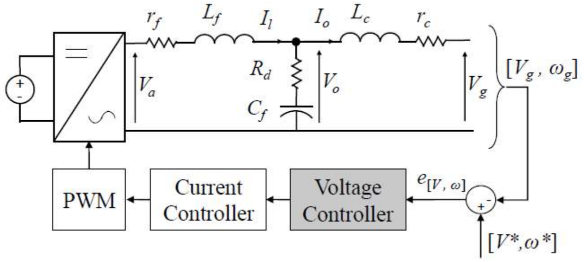
Synchronous-machine

Inverter-based (IBR)





(a) GFL



(b) GFM

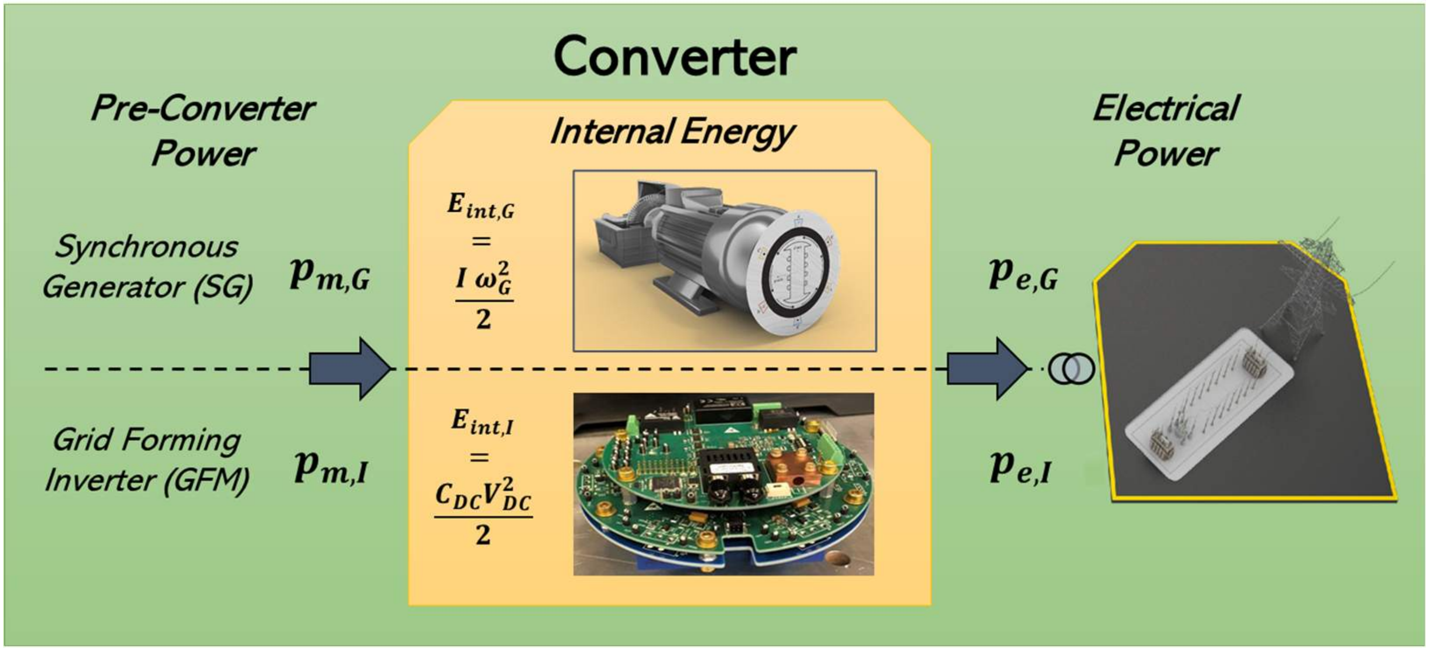
Mechanical

Deterministic

Digital

Stochastic

Device Level Power Mismatch



Converter

Pre-Converter Power

Internal Energy

Electrical Power

Synchronous Generator (SG) $p_{m,G}$

$E_{int,G} = \frac{I\,\omega_G^2}{2}$

$p_{e,G}$

Grid Forming Inverter (GFM) $p_{m,I}$

$E_{int,I} = \frac{C_{DC} V_{DC}^2}{2}$

$p_{e,I}$

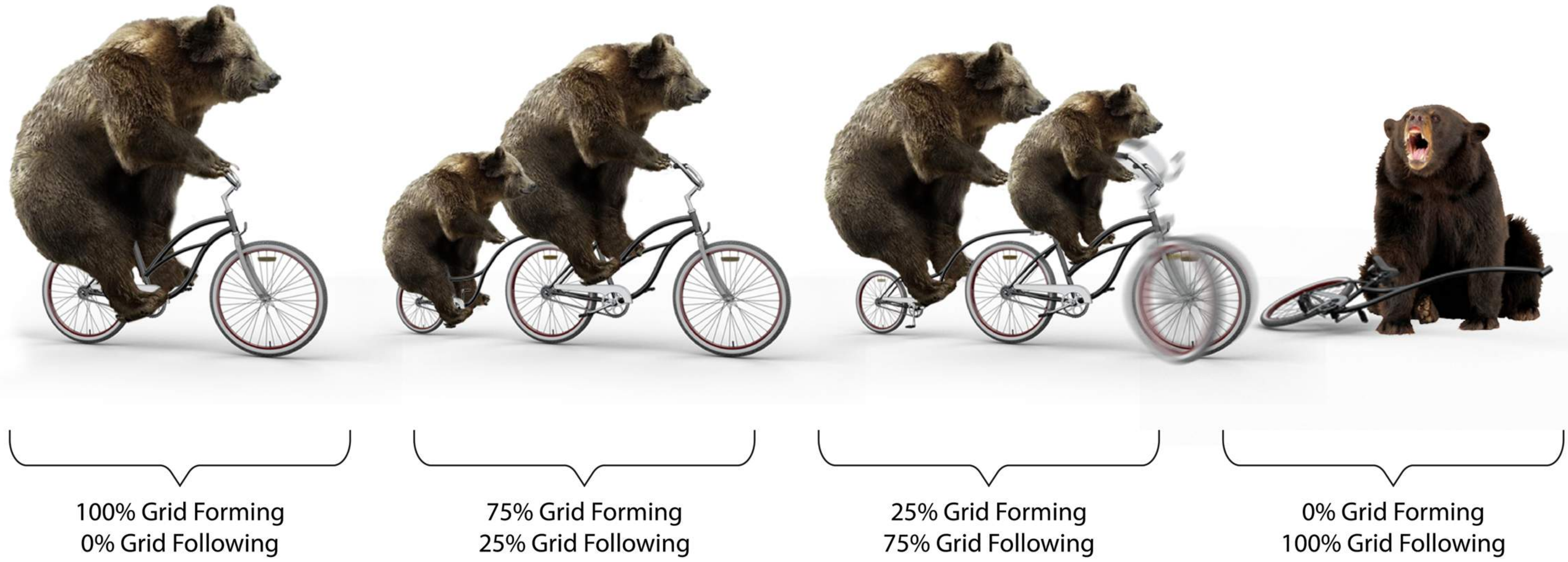
$$\ddot{p}_{m,G} \propto p_{e,G}$$

$$\dot{p}_{m,I} \propto p_{e,I}$$

- A multi-loop droop GFM inverter has a lower order relation between pre-converter power and electrical power, as compared to an SG. A GFM device makes a first order exchange of energy with the system; there is no second order transfer of energy as in a SG, which is the source of substantial overshoot and oscillations.

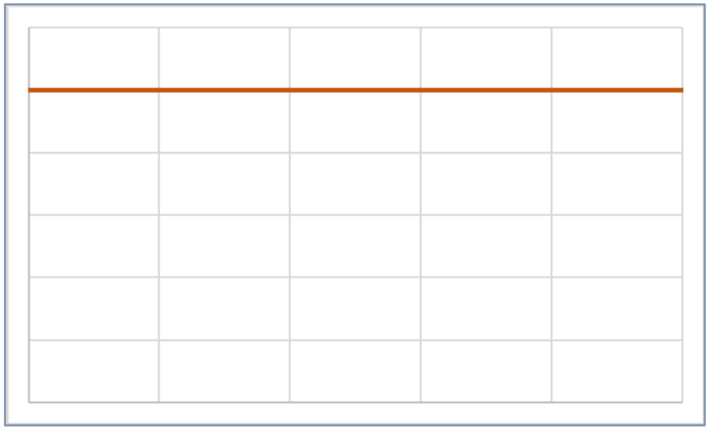
- An SG only modifies pre-converter power after a change in frequency is registered; a GFM modifies frequency after changing pre-converter power. They are inverses of each other.

Why is this distinction important?

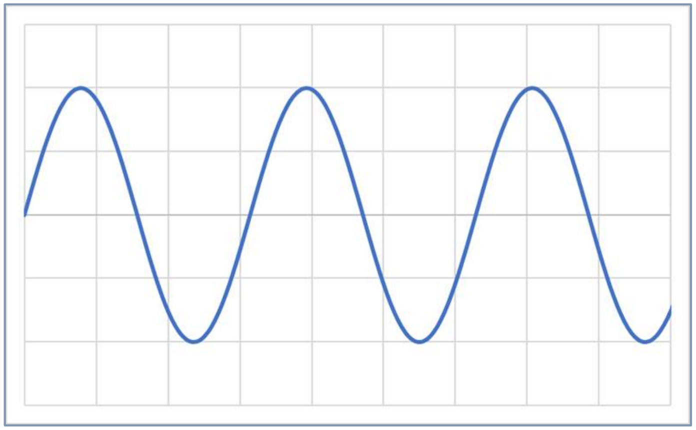


Need to use Different Simulation Tools

Positive Sequence:
Voltage as RMS (Phasor Domain)



Electromagnetic Transient:
Voltage as Sinusoid (Full Time)



- Most dynamic simulation software is positive sequence (PSLF, PSSE)
  - Treats the network algebraically (as opposed to differentially)
  - But allows larger simulations with low computational cost…

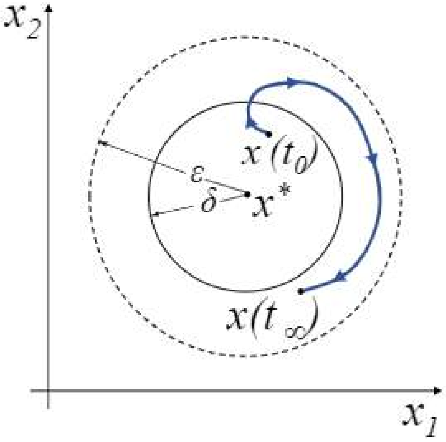
- This is fine for synchronous generator dominated systems
  - They don't react within network transient settling times
  - Inverters do!

- Modeling in electromagnetic transient (EMT) domain?

Small Signal Stability

For small-perturbations:

Consider an equilibrium point x^* of a system $\dot{x}(t) = \varphi(x(t))$ is said to be locally stable for each $\varepsilon > 0$ if there exists a $\delta > 0$ such that $\|x(0)-x^*\| < \varepsilon$ for $t > t_0$ and every solution of $x=\varphi(t)$ of the system which at $t = t_0$ satisfies $\|\varphi(t_0)-x^*\| < \delta$.



Phase portrait of a locally stable system: A locally stable system refers to a condition under which any trajectory that starts within a distance δ of x^* remains within the circle of ε of x^* for all positive time.

- The formal expression of the solution for the characteristic equation $p(\lambda)$ can be written in the form of

$$p(\lambda) = \prod_{i=1}^{(n-1)} \underbrace{(\lambda^2 + 2\zeta_i\omega_{n_i}\lambda + \omega_{n_i}^2)}_{internal\ \ modes} \cdot \underbrace{(\lambda + k_d)}_{coupling\ \ mode} = 0$$

- The first part is the generators' internal modes involving the electric angle and speed of the generators, which presents a pair of complex conjugate eigenvalues.
- The second part is the system's coupling mode and presents as a real eigenvalue whose value is a function of the generators damping coefficient.

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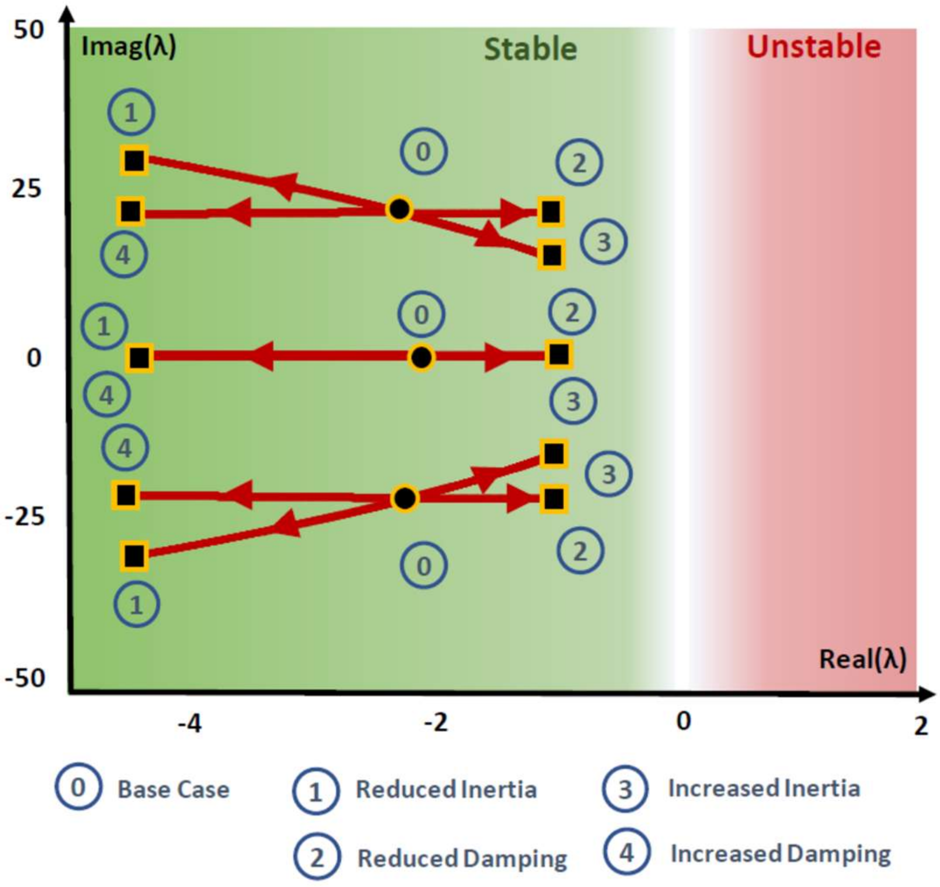
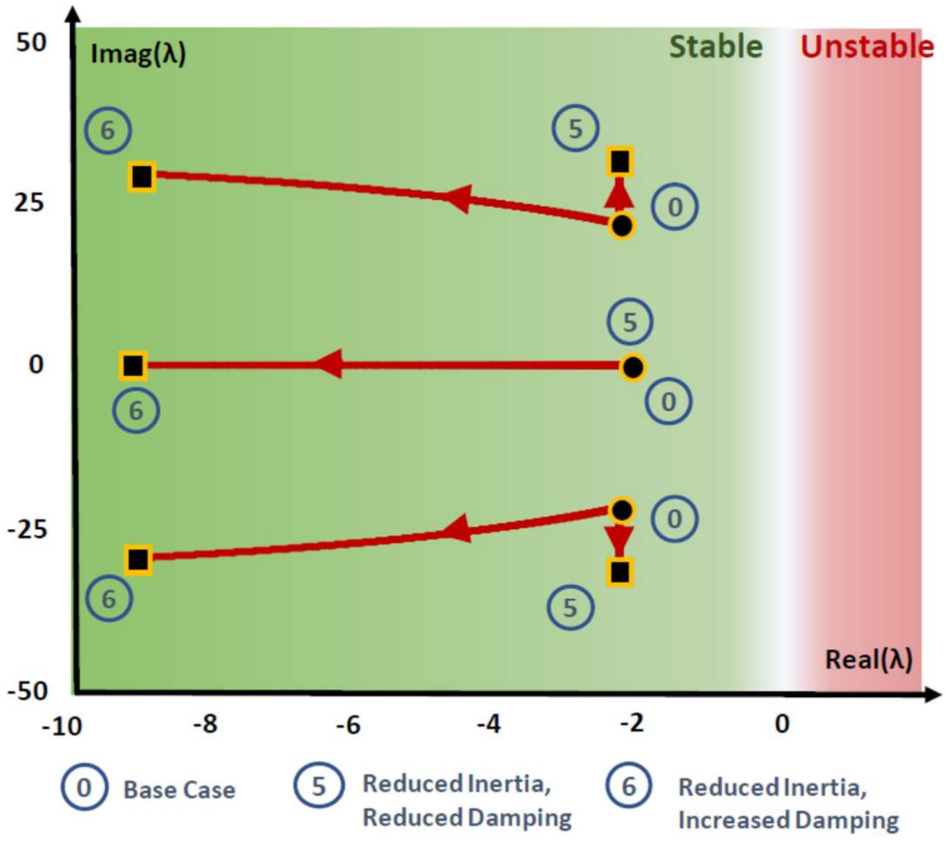
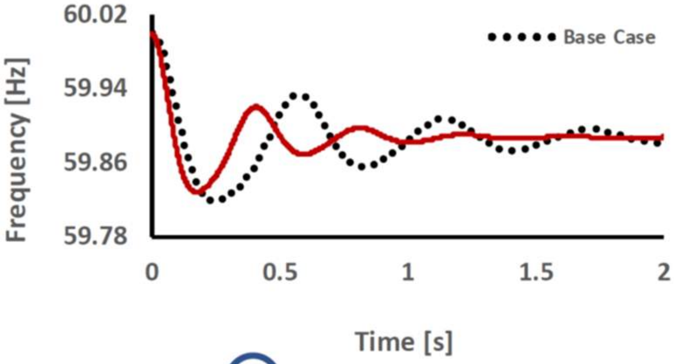
Eigenvalue Analysis

For a 3-generator, 9-bus system (commonly known as the WSCC system)

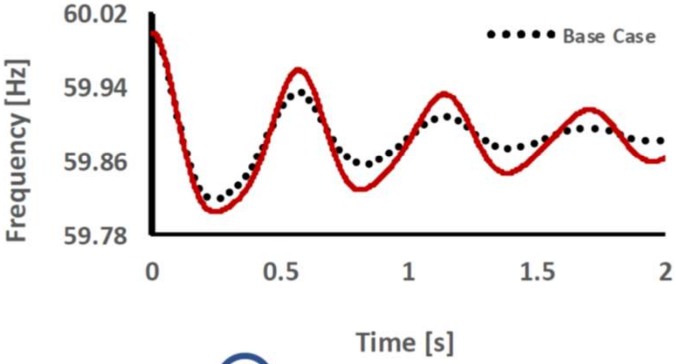




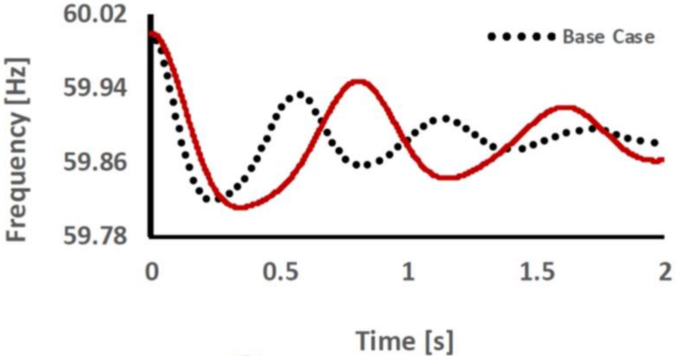
Frequency Impact in the Time Domain



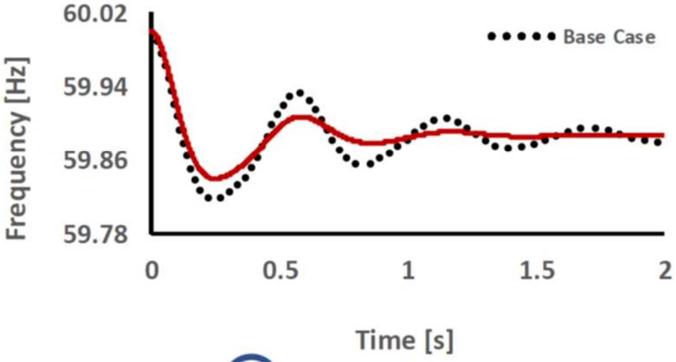
① Reduced Inertia



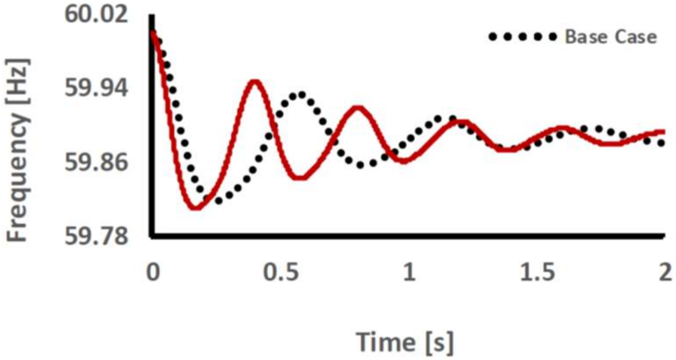
② Reduced Damping



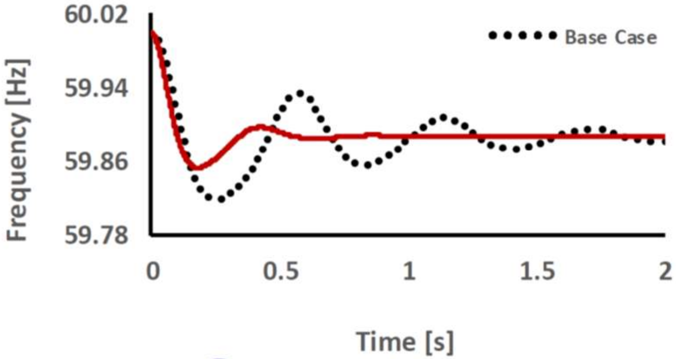
③ Increased Inertia



④ Increased Damping

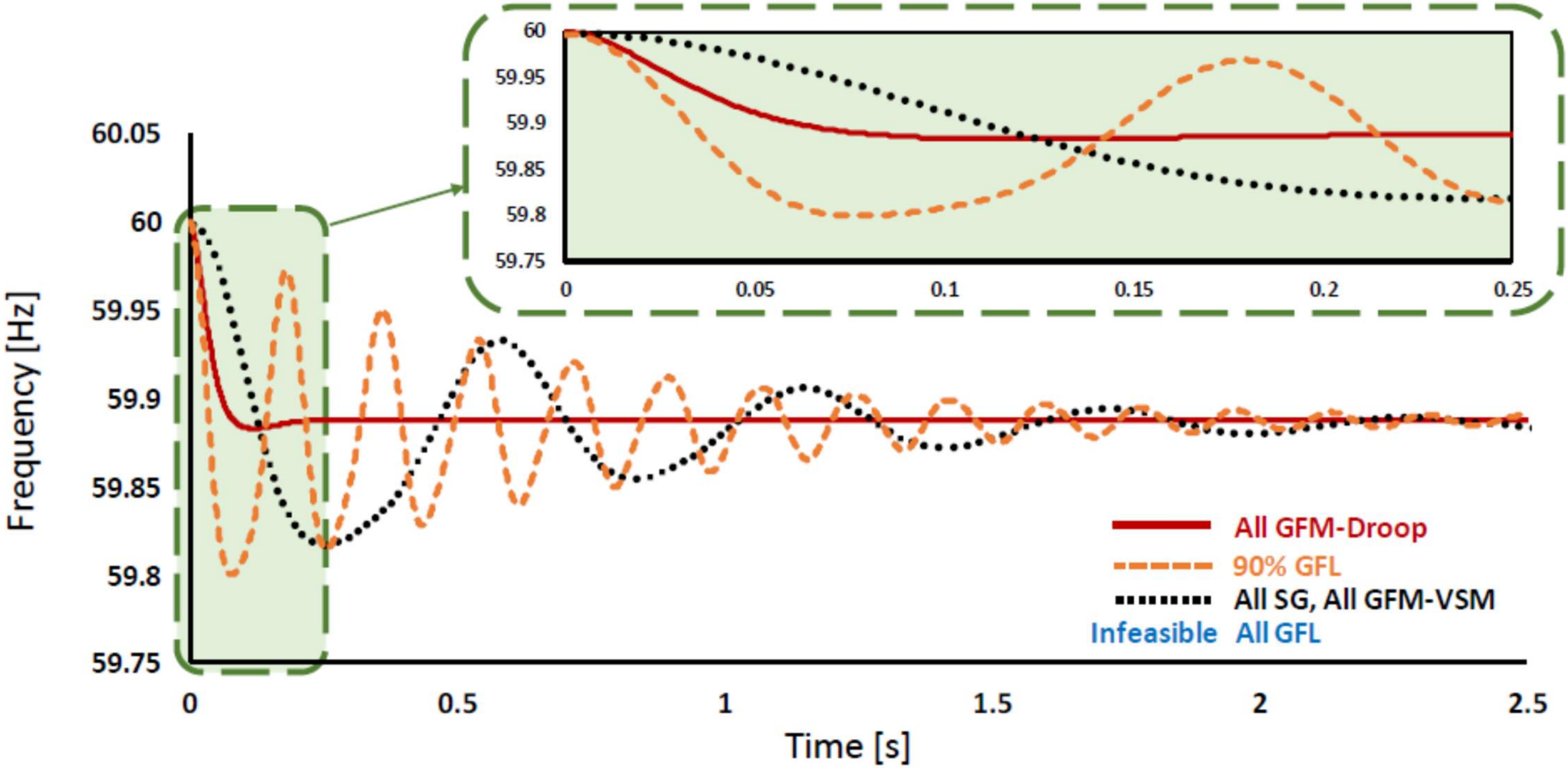


⑤ Reduced Inertia,
Reduced Damping



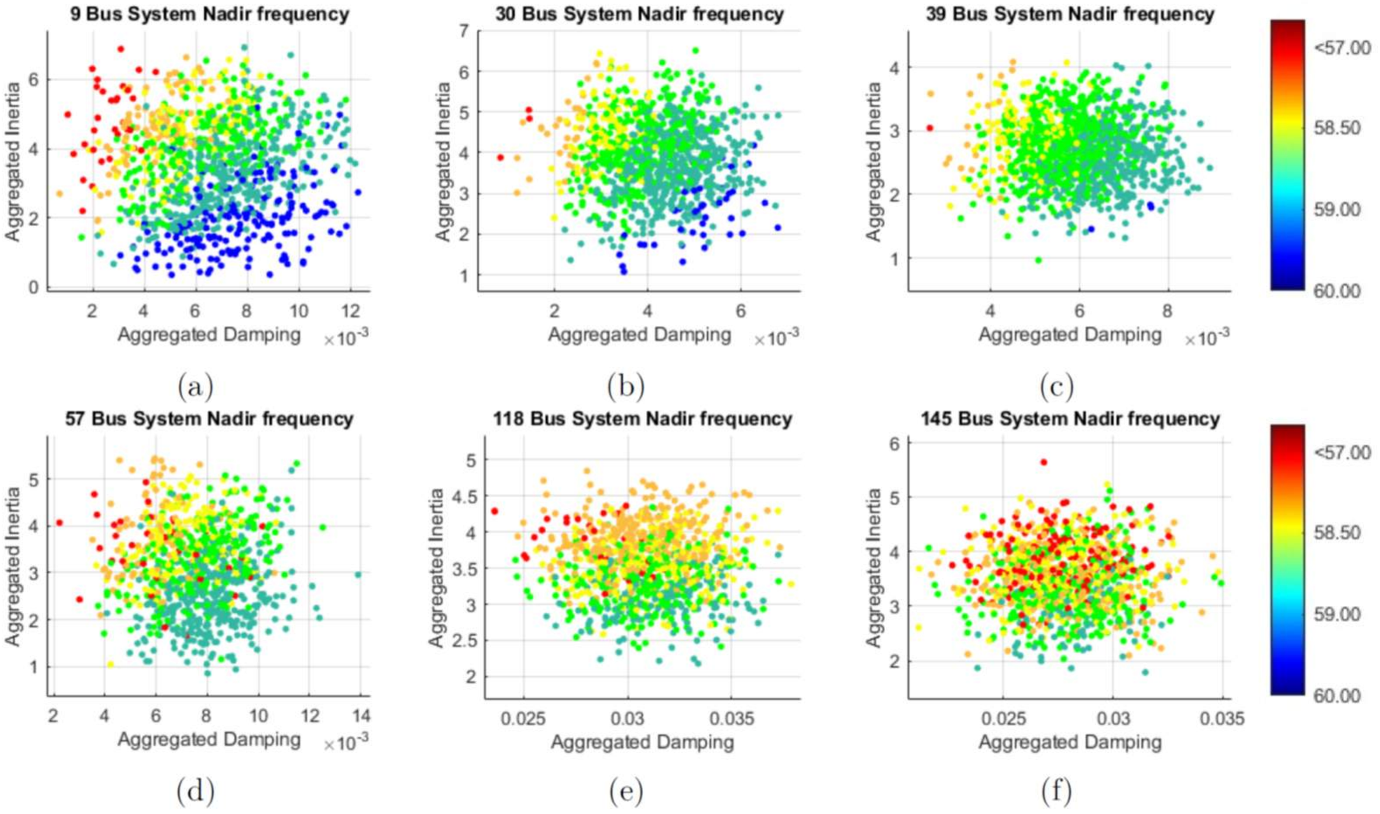
⑥ Reduced Inertia,
Increased Damping

New Frequency Dynamics



Stochastic Analysis

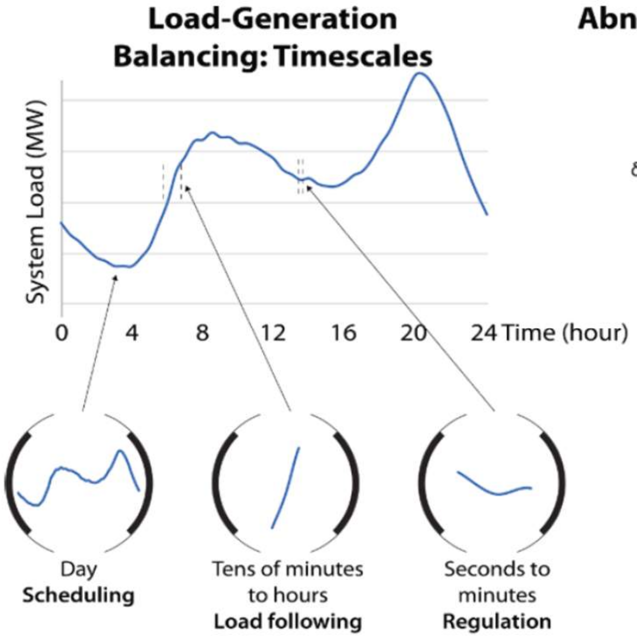
- 1,000 random parameters and system conditions
- 6 different power systems
- The randomness of generator inertia and damping coefficients represents technological variations to include both conventional and renewable generation
- The randomness of loading condition resembles the loading variations which determines node voltages and flow of power across the power lines in a power system and, therefore, represents the varying system dynamic states



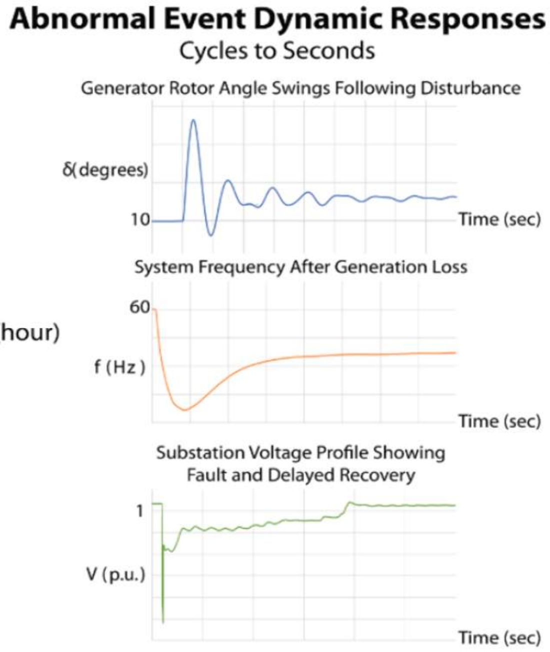
(a) (b) (c)

(d) (e) (f)

Power System Transient Stability

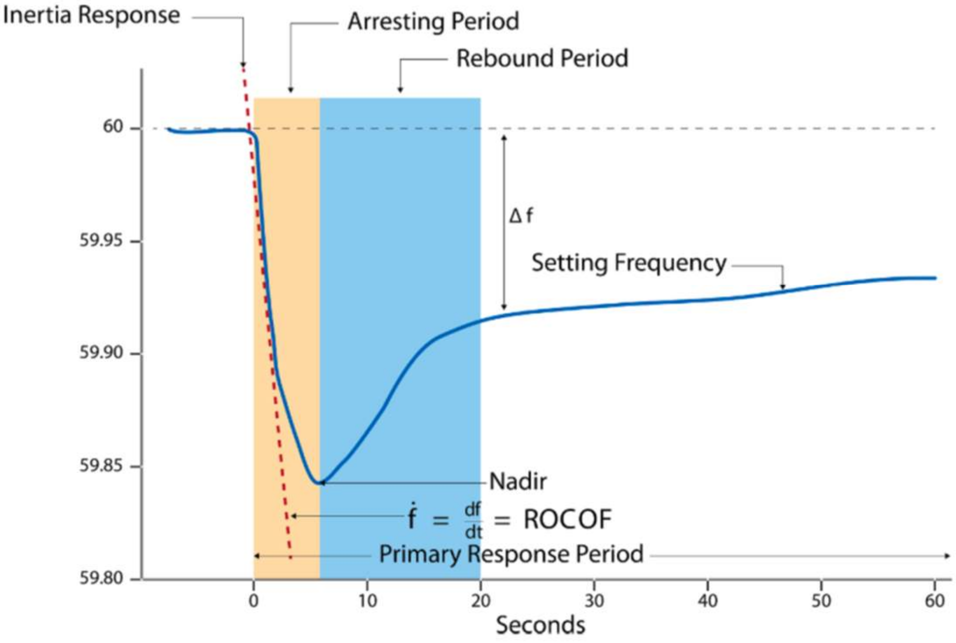


Load-Generation Balancing: Timescales



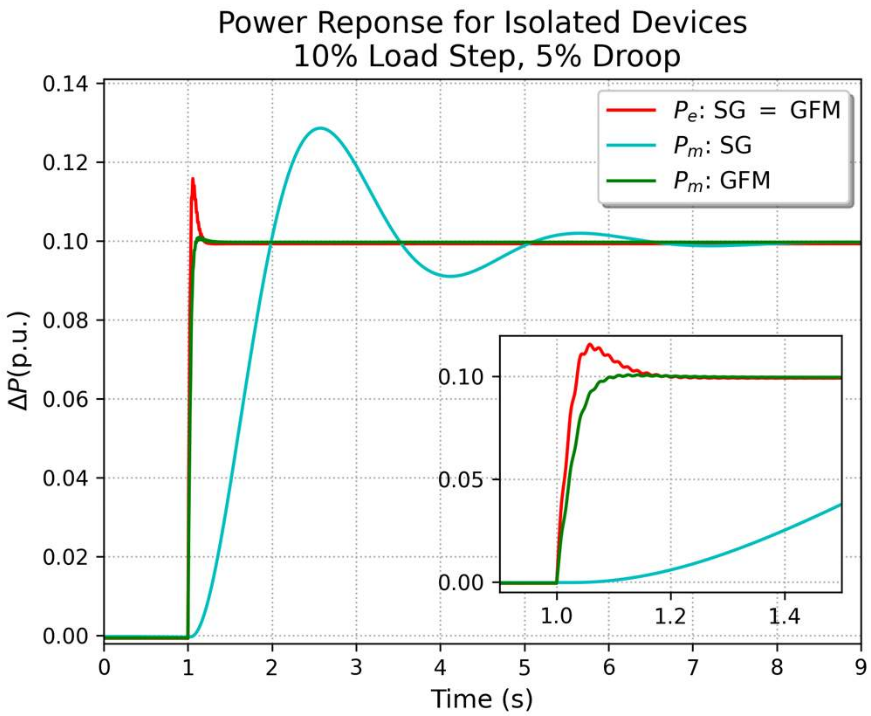
Abnormal Event Dynamic Responses

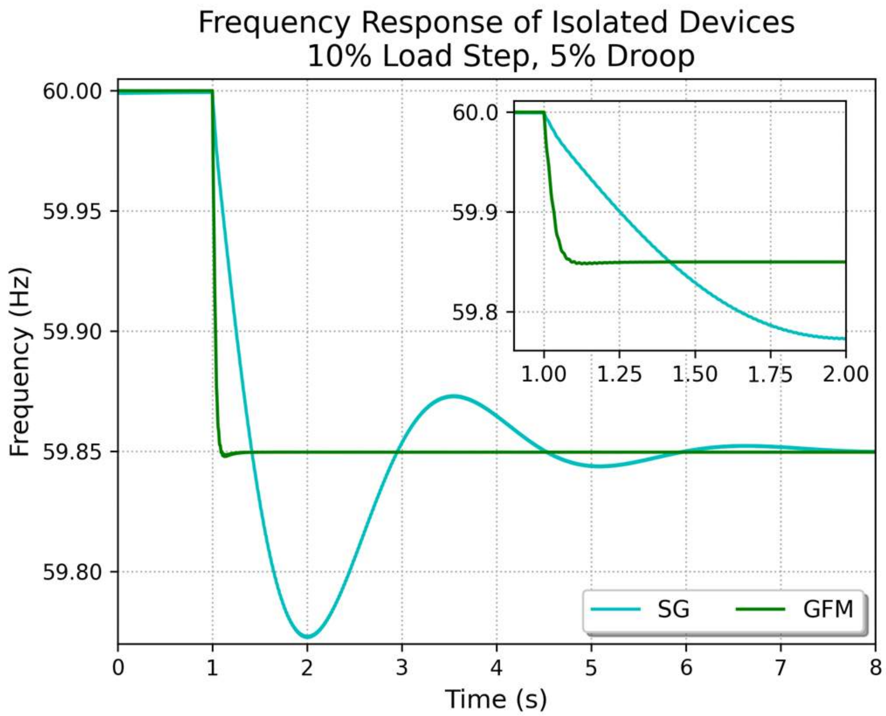
Cycles to Seconds



Individual Step Response

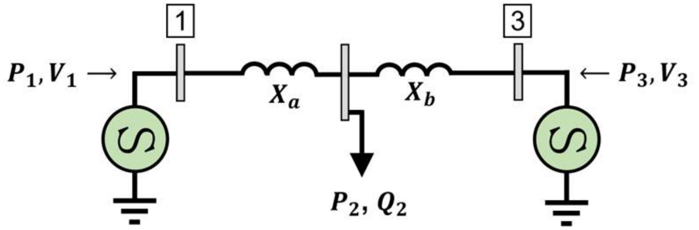
- Isolated device; 50% steady state dispatch

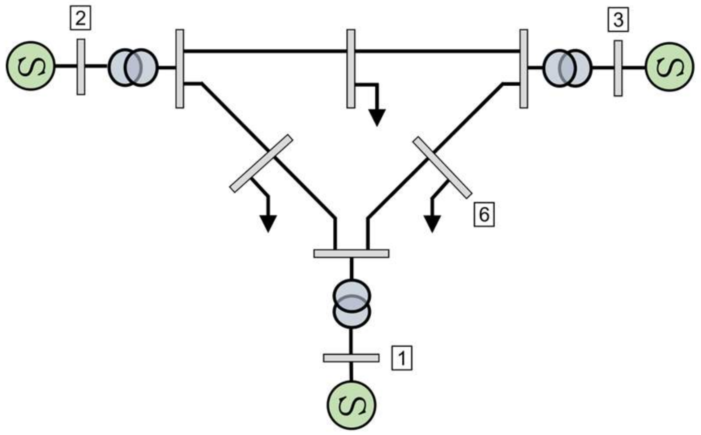


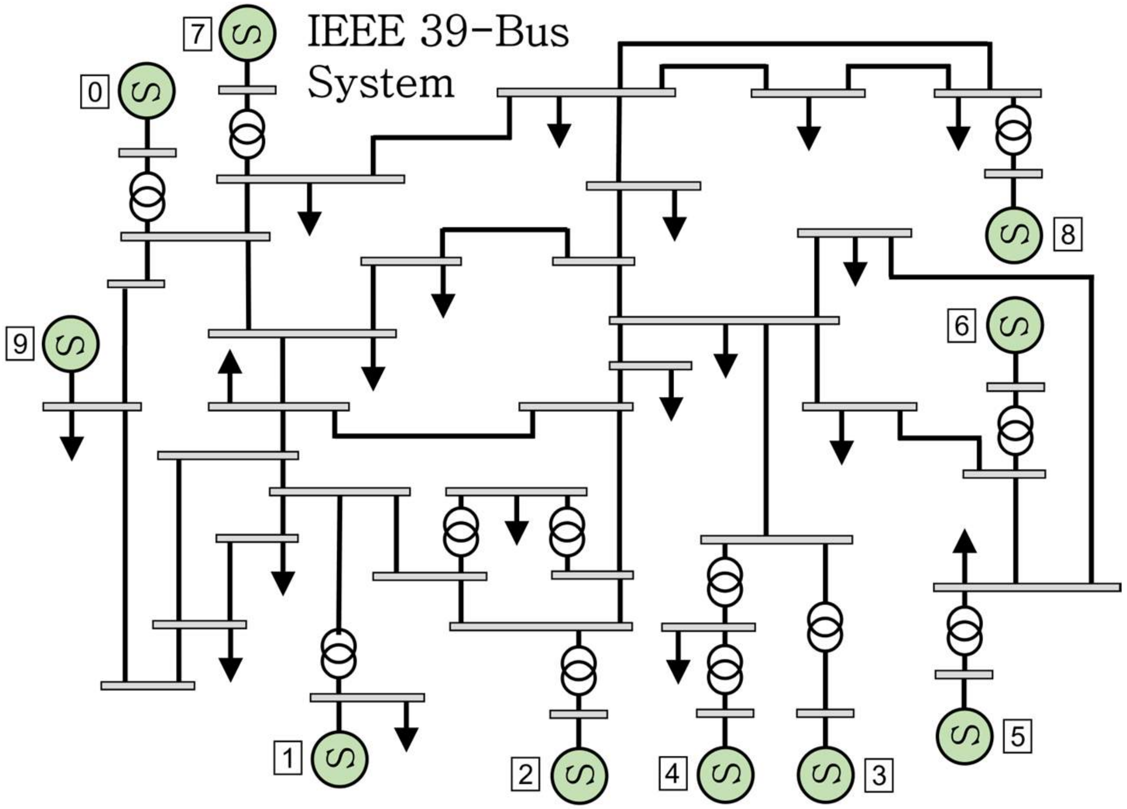


Grid-Forming Inverters vs. Synchronous Generators: Disparate Power Conversion Processes

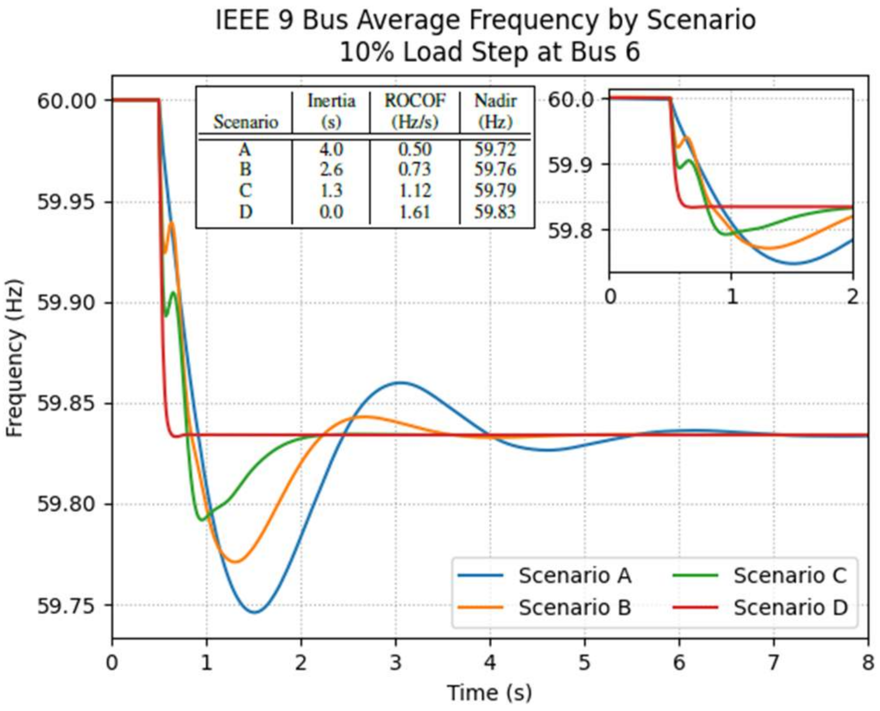
3, 9, and 39 Bus Systems





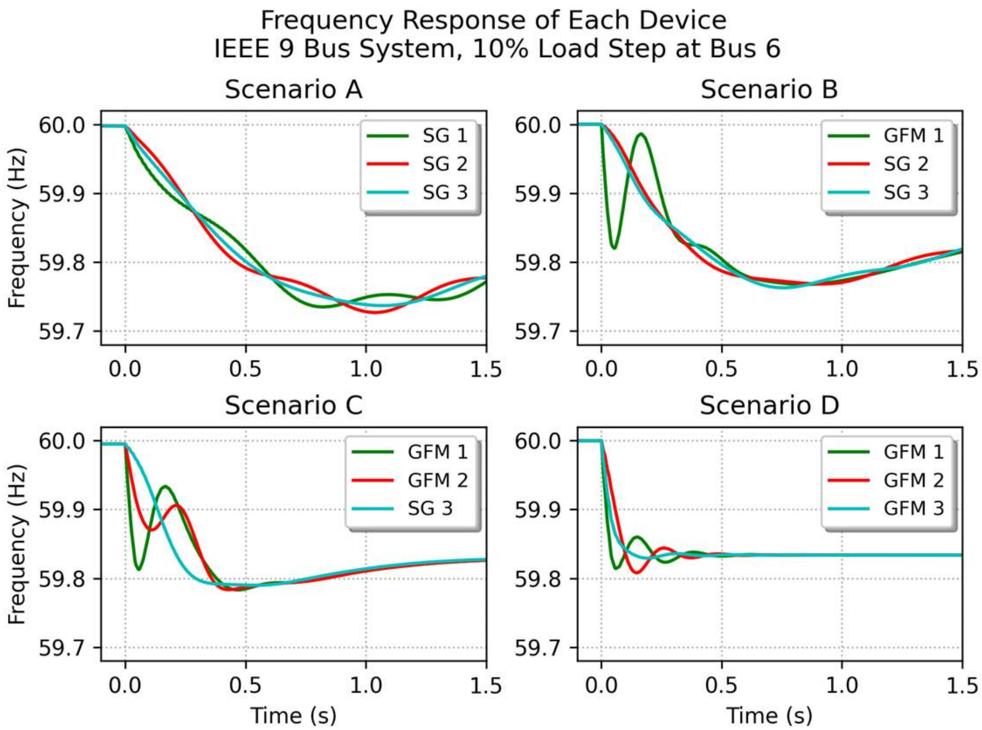


10% Load Step on IEEE 9 Bus System



IEEE 9 Bus Average Frequency by Scenario
10% Load Step at Bus 6

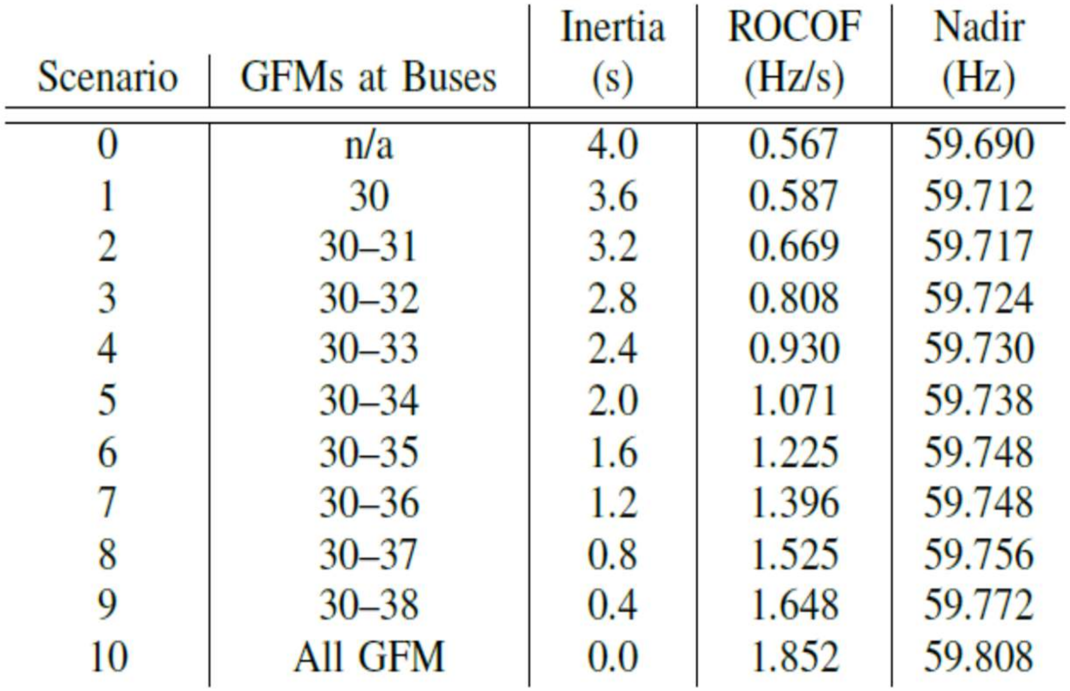
Scenario	Inertia (s)	ROCOF (Hz/s)	Nadir (Hz)
A	4.0	0.50	59.72
B	2.6	0.73	59.76
C	1.3	1.12	59.79
D	0.0	1.61	59.83



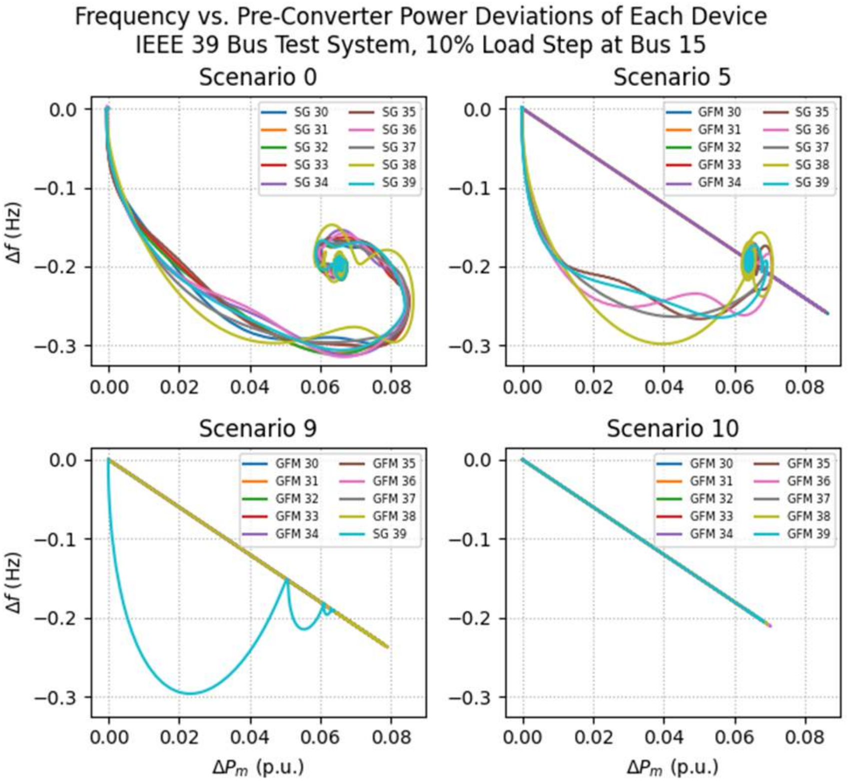
Frequency Response of Each Device
IEEE 9 Bus System, 10% Load Step at Bus 6

- All simulations in PSCAD with full order GFM inverter models (12+ states), and full order SG models.
- Scenarios A to D are a consecutive changeover of SGs to GFMs at the three generation buses.
- Inertia is aggregate, and only contributed by SGs. Larger ROCOFs with GFMs, but lower nadirs.
- Lower order frequency response with all GFM is evident

10% Load Step on IEEE 39 Bus System



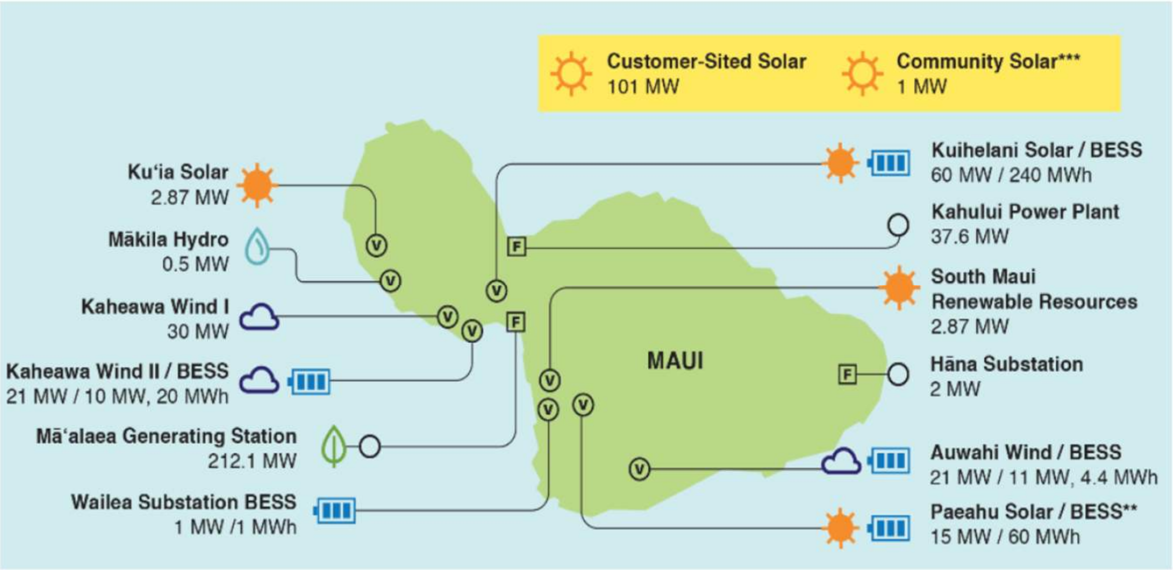
Scenario	GFMs at Buses	Inertia (s)	ROCOF (Hz/s)	Nadir (Hz)
0	n/a	4.0	0.567	59.690
1	30	3.6	0.587	59.712
2	30–31	3.2	0.669	59.717
3	30–32	2.8	0.808	59.724
4	30–33	2.4	0.930	59.730
5	30–34	2.0	1.071	59.738
6	30–35	1.6	1.225	59.748
7	30–36	1.2	1.396	59.748
8	30–37	0.8	1.525	59.756
9	30–38	0.4	1.648	59.772
10	All GFM	0.0	1.852	59.808

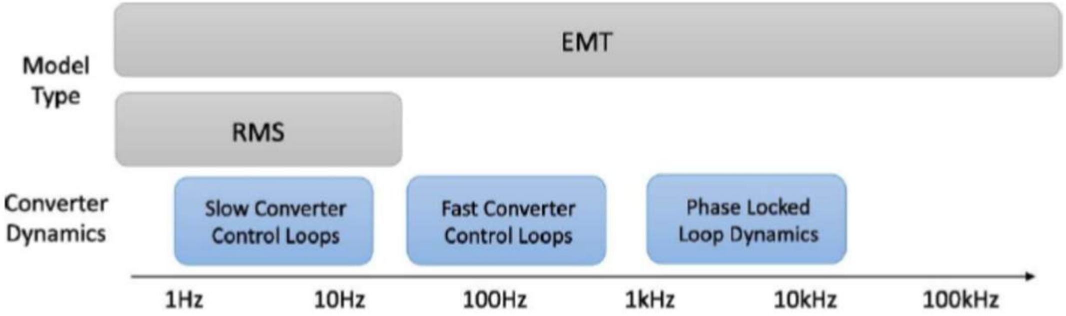


- All simulations in PSCAD with full order GFM inverter models (12+ states), and full order SG models.
- Very similar story to 9 bus system. Reduced nadir, larger ROCOF.
  - **Note: in a SG dominated system a larger ROCOF generally yields a lower nadir due to the reactive nature of SG governors to a change in frequency.**

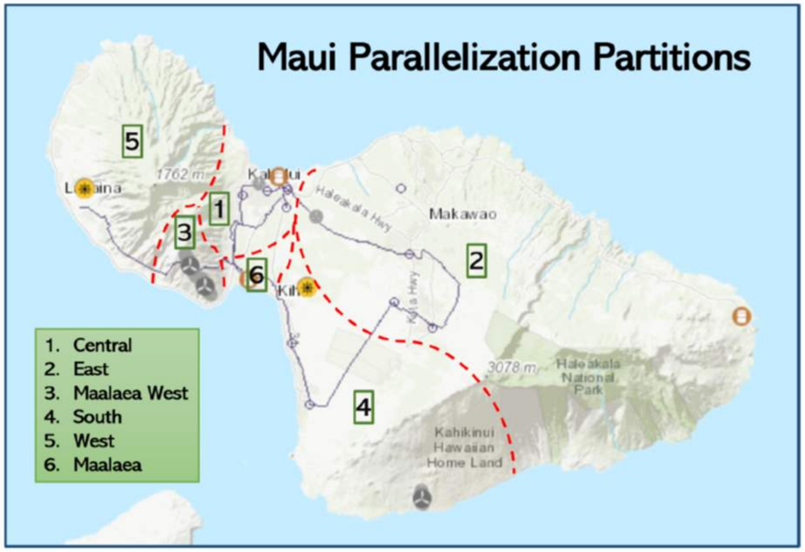
Maui Background

- Hawaiian Electric expects Maui to be the first large island capable of operating with 100% inverter-based power resources, possibly by 2023
  - 2020 peak: ~89.5% IBR (DER and wind)
  - interconnected power system (~200 MW peak)
  - highly distributed utility-scale generation
  - 69 kV voltage levels



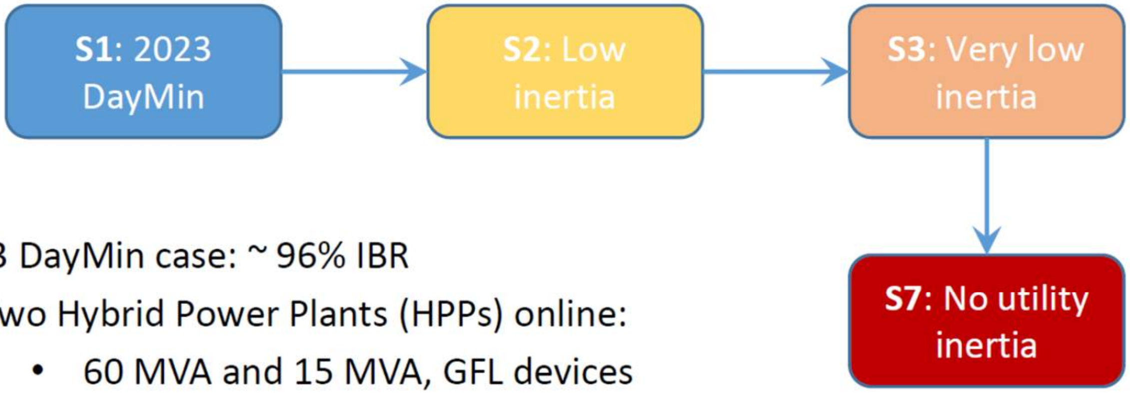


Maui Parallelization Partitions



1. Central
2. East
3. Maalaea West
4. South
5. West
6. Maalaea

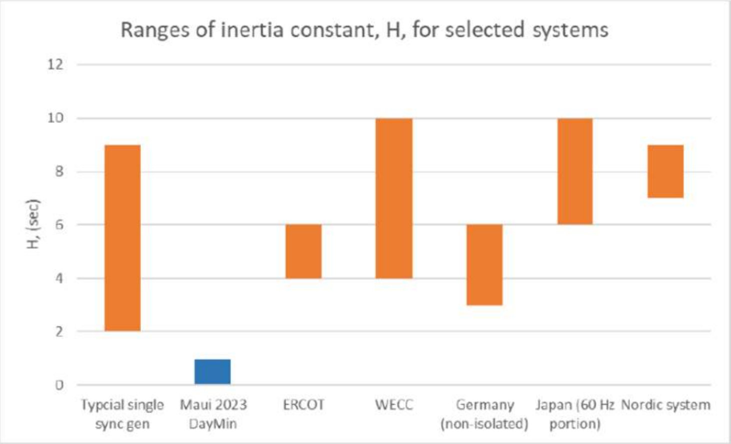
Simulation Base Case


S1: 2023 DayMin

S2: Low inertia

S3: Very low inertia

S7: No utility inertia



2023 DayMin case: ~ 96% IBR

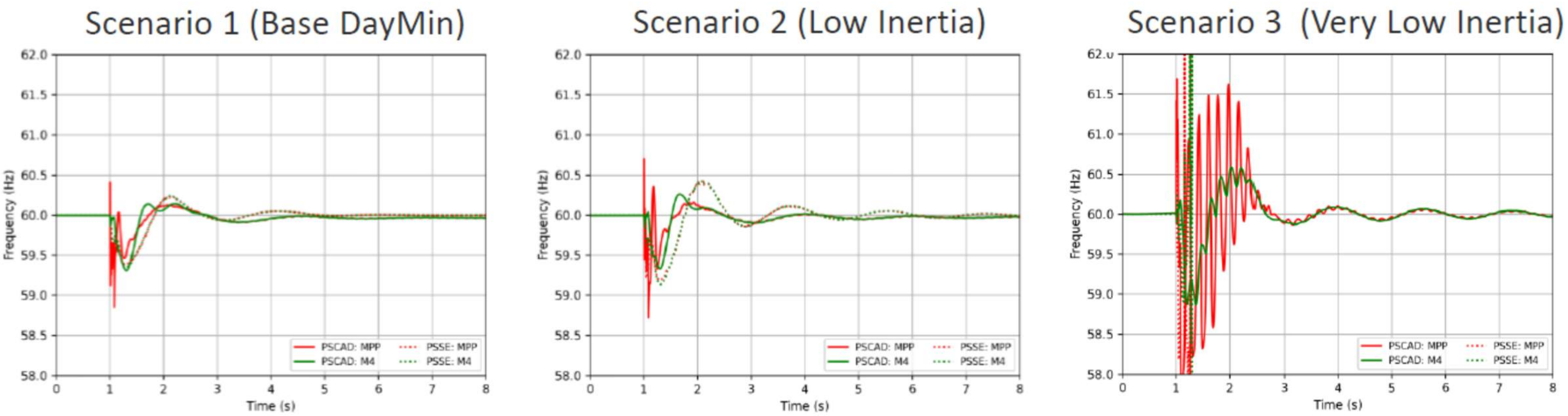
- Two Hybrid Power Plants (HPPs) online:
    - 60 MVA and 15 MVA, GFL devices
- Inertia: 370 MVA·s; Inertia constant H = 0.97 s (~1 order of magnitude below typical systems)
    - ~ 75% is sourced via 6 synchronous condensers
- Will compare results of PSSE and PSCAD

Note: We use “inertia” as a proxy metric for online synchronous machines

Dispatch, MW

Total Load	Total Gen	Dist. PV “rooftop”	Existing large PV 2 plants	Wind 4 plants	Paeahu PV-BESS HPP	Kuihelani PV-BESS HPP	Sync Gens 3 generators
144.6	146.0	104.3	5.3	24.9	0	5.7	5.7

Event: Fault at low Short Circuit Ratio (Weak) Bus

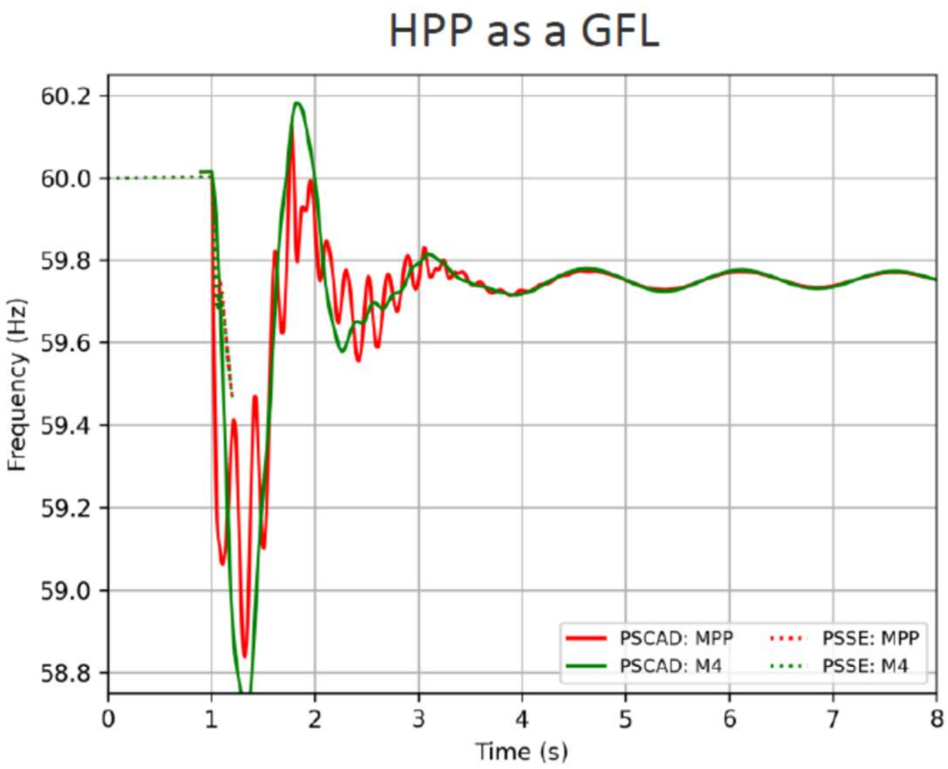

Scenario 1 (Base DayMin)
Scenario 2 (Low Inertia)
Scenario 3 (Very Low Inertia)

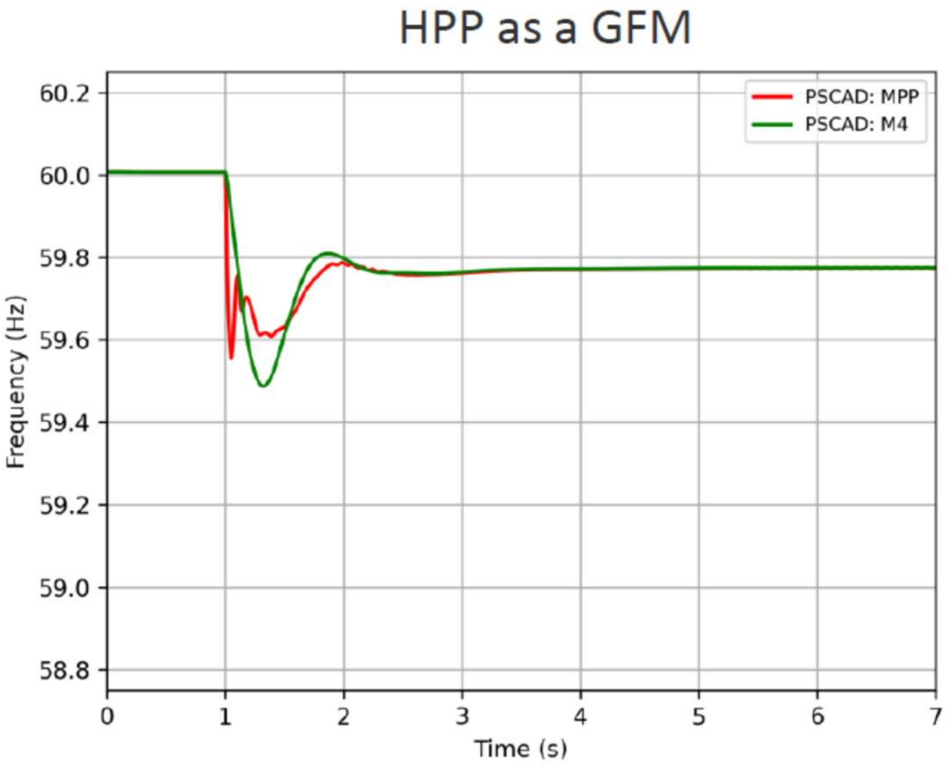
PSCAD: MPP is a PLL-measured frequency. PSCAD: M4 is a generator shaft rotation speed-derived frequency

- Scenario 1 --> Scenario 3: reduced inertia and fewer voltage sources
    - Exacerbated oscillatory modes in S3, both in damping and quantity of modes

- PSSE simulation for Scenario 3 is numerically unstable shortly after the fault

Scenario 3: Largest Generator Trip (GFL vs. GFM)


HPP as a GFL


HPP as a GFM

- Substantial increase in primary damping; major reduction in faster modes
- Nadir is raised significantly (58.7 to 59.5 Hz), and ROCOF improved (despite no increase in inertia)

Conclusions and Implications

- Is damping just as important as inertia in “low-inertia power systems”?
- First order relation of GFM between electrical and pre-converter power permits substantial ‘damping’ for SGs (which have a second order relation).
  - Relation between pre-converter power and frequency is also inverted for these devices
    - SGs change pre-converter power due to frequency changes…
    - GFMs change frequency due to pre-converter power changes…
- The network frequency is no longer easily approximated by an aggregate swing equation
- A larger ROCOF no longer means a lower nadir
- *Do we need GFMs already?*
  - *How many? Where? Which types of devices?*
  - *Should this be an interconnection requirement, or should there be a market?*

Acknowledgements

- Dr. Amir Sajadi – CU Boulder (now Span)
- Dr. Wallace Kenyon – CU Boulder
- Matt Bossart – CU Boulder
- Dr. Andy Hoke – NREL

Thank you!

Extra Slides

Importance of Reactive Power

- Provides voltage control to ensure proper operations
- Voltage control important for:
  - Preventing damage to generators and motors
  - Reducing line losses
  - Preventing voltage collapse
    - Occurs when the system is trying to serve more load than the voltage can support

Reactive Power Sinks and Sources

- Sources:
  - Shunt capacitors
  - Underground AC lines (high capacitance)
  - Overhead AC lines (light loading)
    - Capacitance exceeds reactive lines due to impedance

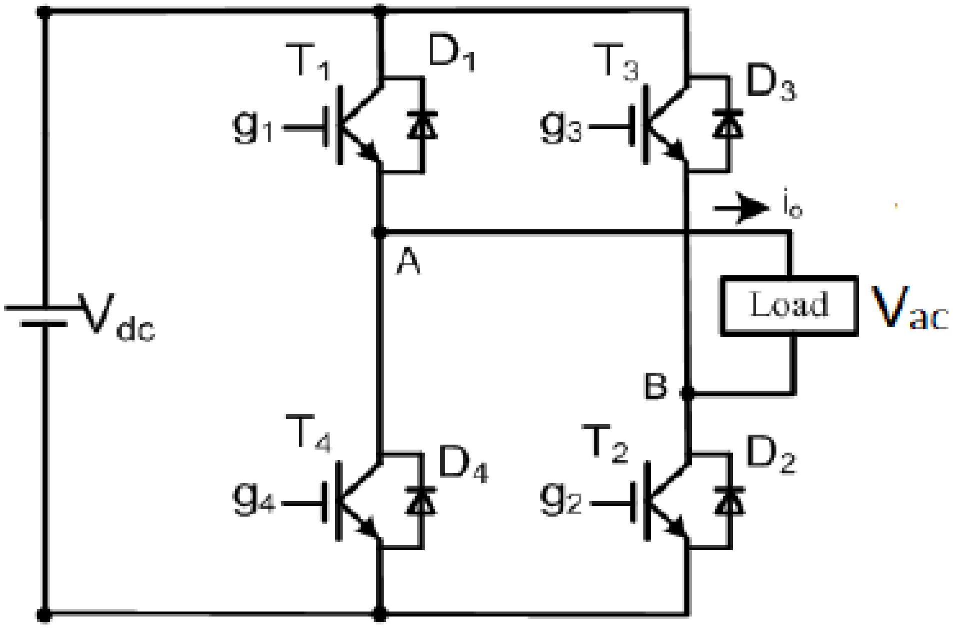
- Sinks:
  - Transformers – reactive losses
  - Shunt reactors
  - Overhead AC lines (heavy loading)
  - Load (aggregated at transmission level)

AC Power System

- Electricity loads can be **resistive** (e.g. heaters), **inductive** (e.g. motors), and **capacitative** (e.g. capacitors).
- **Active power** is the power that is dissipated in the resistance of the load.
- **Reactive power** is the power that is exchanged between reactive components. Capacitors generate reactive power and inductors consume it.
- **Apparent power** is taken into account when designing and operating power systems, because although the current associated with reactive power does no work at the load, it still must be supplied by the power source.
- **Frequency control**: active power balance (system wide)
- **Voltage control**: reactive power balance (local)
- **Electricity is traded in terms of active power over a period of time.**

Single Phase Inverter

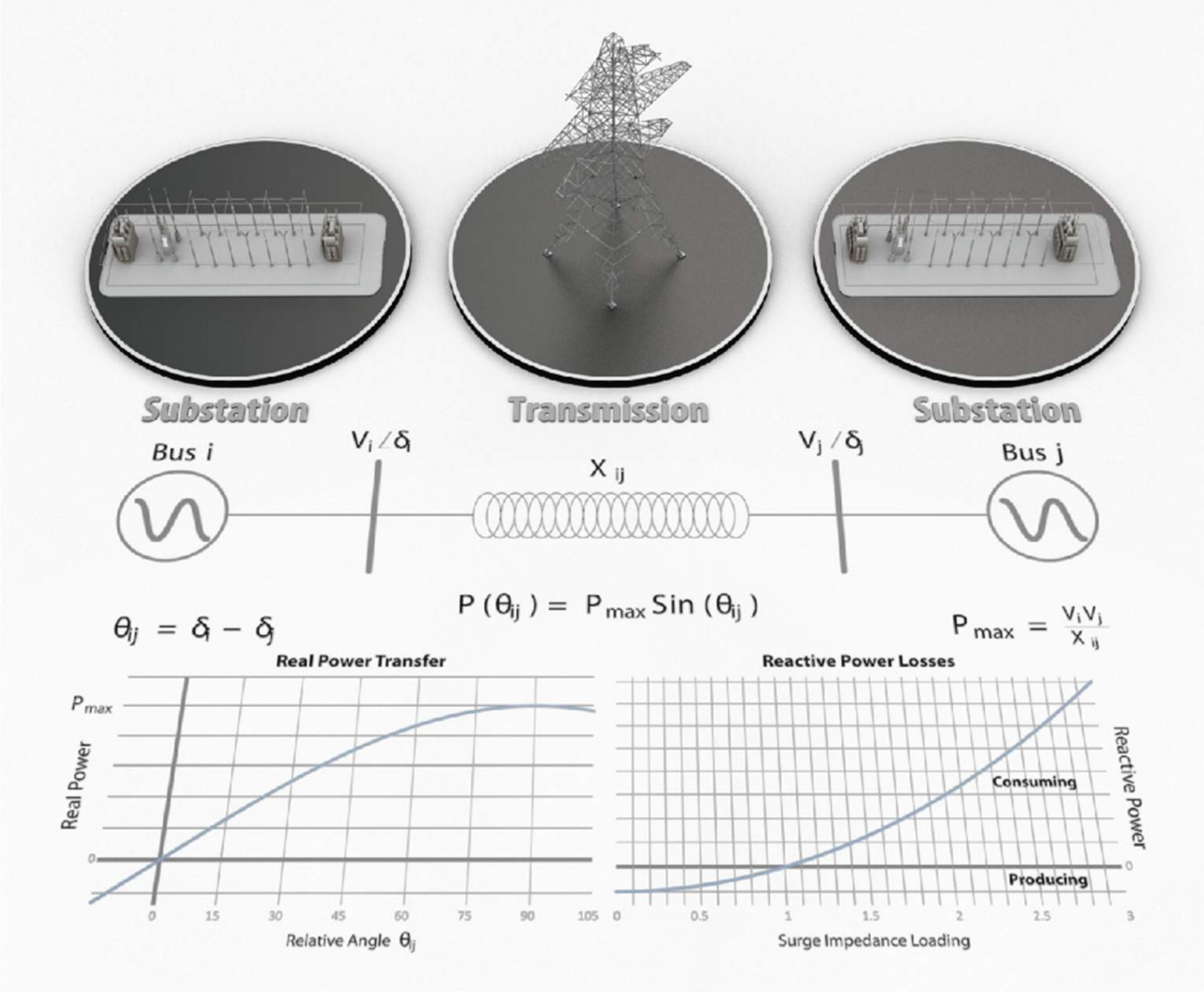
Full-bridge Switch Topology:



Hassan M. Abdar, researchgate.net

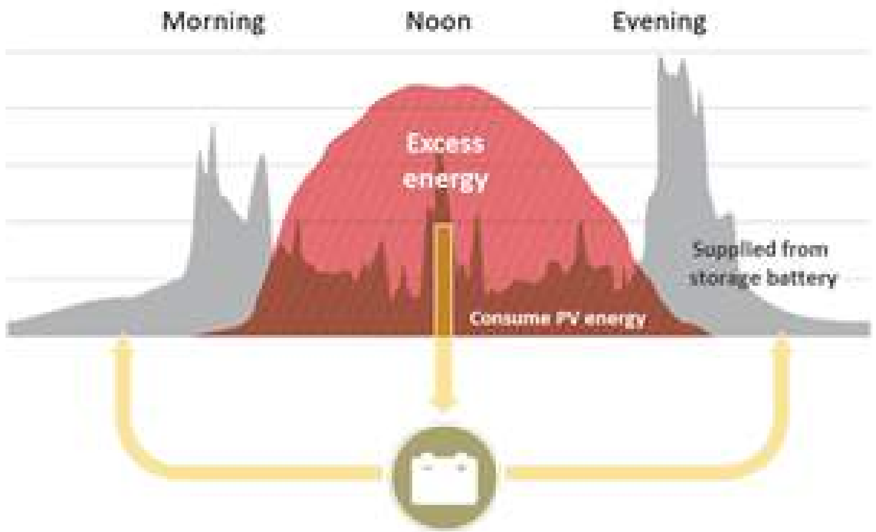
- T_1/T_2 & T_3/T_4 operate as pairs
- When T_1/T_2 are conducting, T_3/T_4 are not and i_0 is positive
- When T_3/T_4 are conducting, T_1/T_2 are not and i_0 is negative

Power Flow Primer

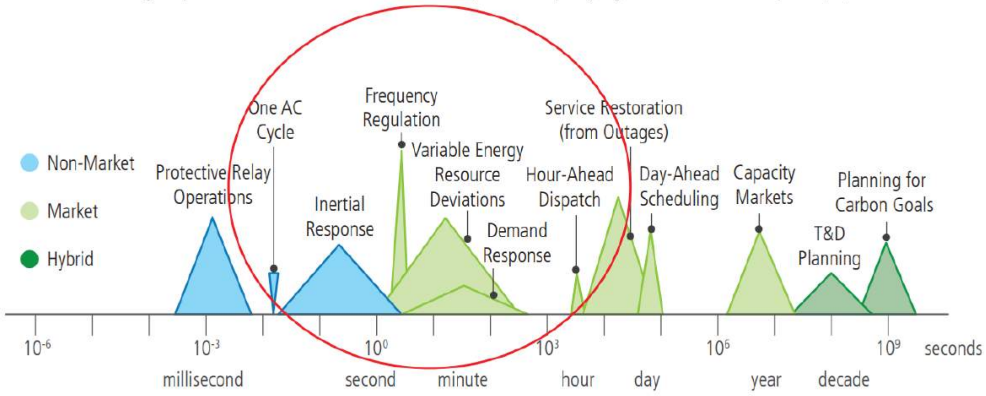


Energy Storage

- Backup power in case of grid disconnection
- Rate management
- Self-consumption
- Renewable shifting/ smoothing
- Increased PV accommodation
- Demand response, Congestion management, Deferrals
- Ancillary services/Frequency regulation



Markets are used for grid operations in the order of seconds to minutes, such as frequency regulation and demand response (DR). Some essential

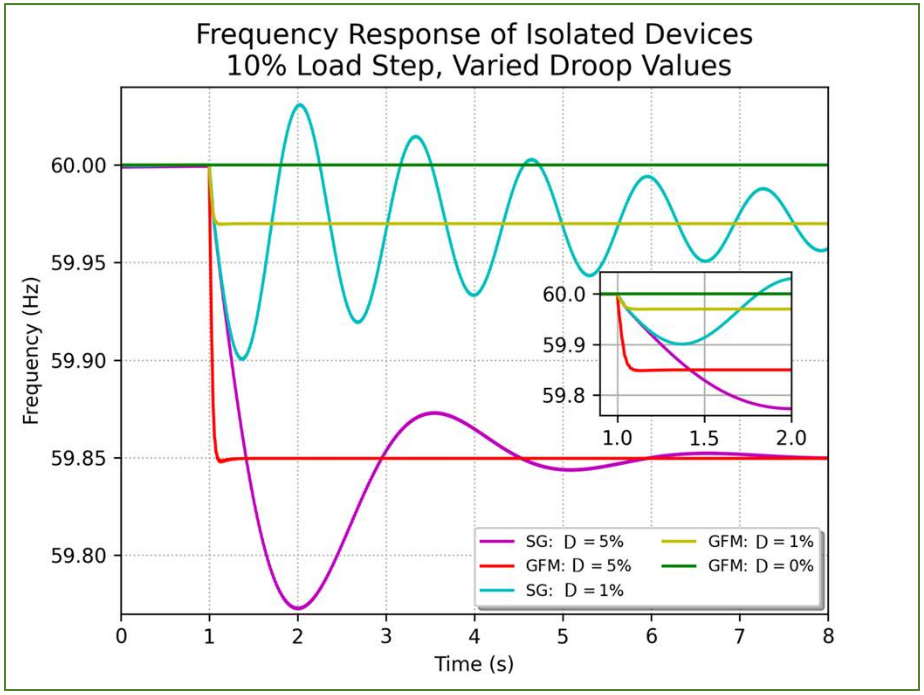


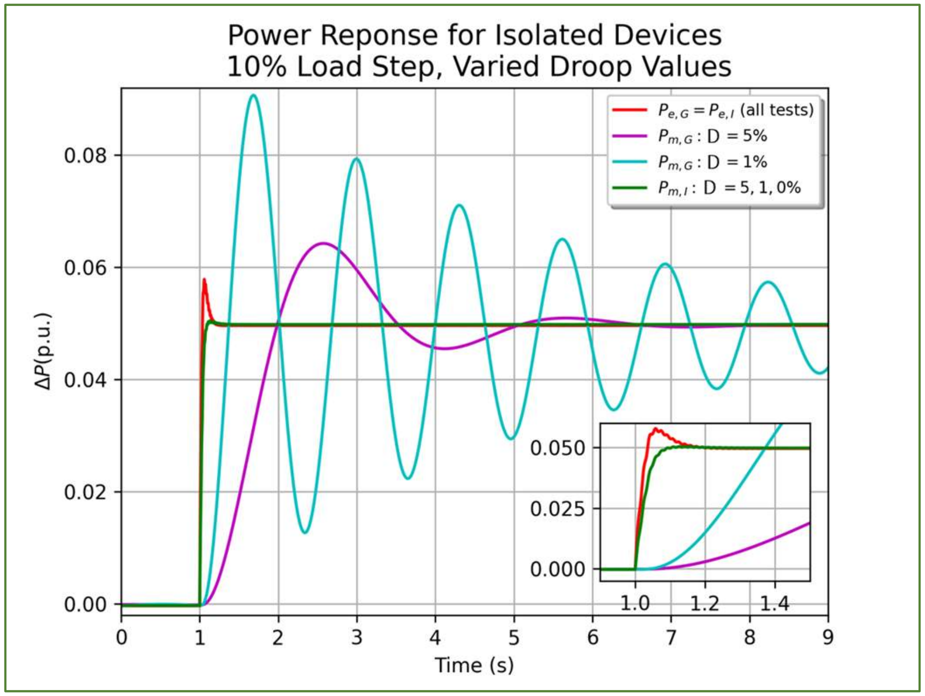
reliability capabilities, such as inertial response, occur faster than typical market signals. Acronyms: transmission and distribution (T&D), alternating current (AC).

Source: US DOE Quadrennial Energy Review, Second Installment, January 2017

Droop-e: Exponential Droop as a Function of Power Output for Grid Forming Inverters with Autonomous Power Sharing

Inspiration for Treating D Dynamically

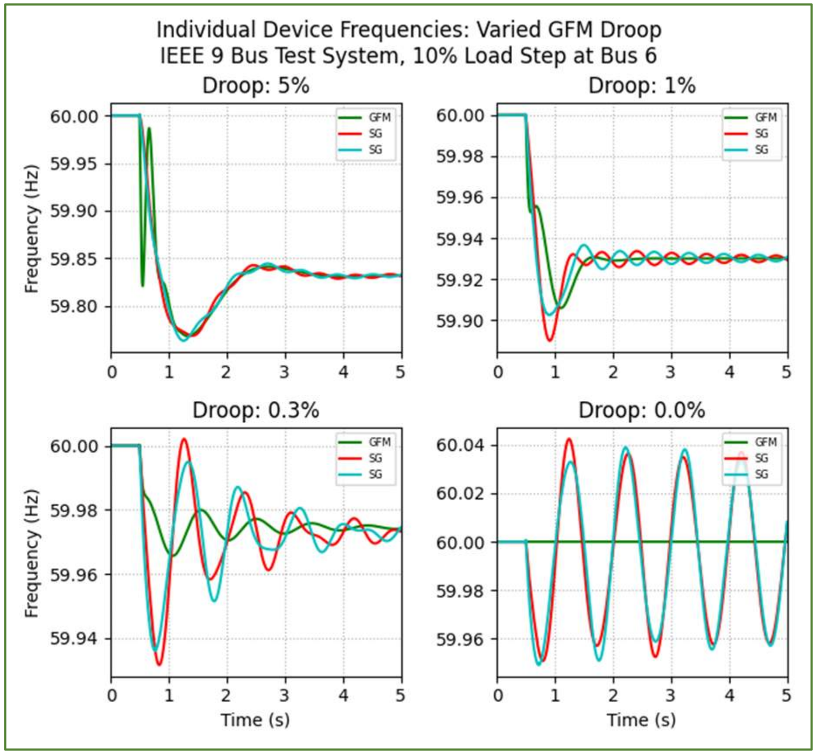


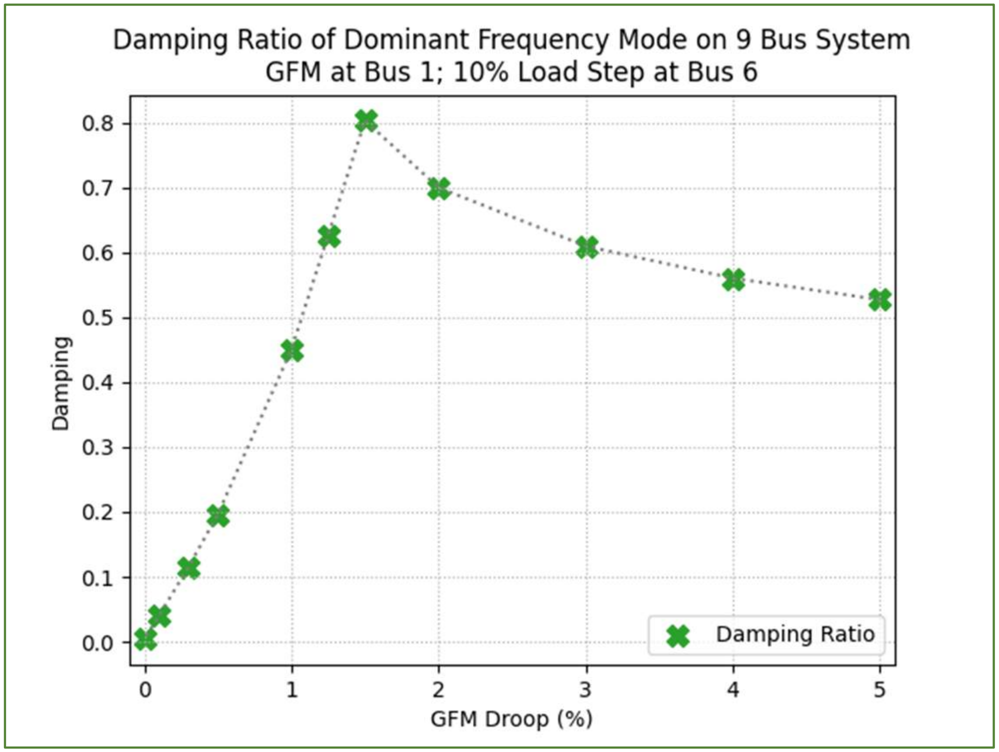


- Adjusting the droop gain of synchronous generators yields instability for smaller values
- Response of grid-forming inverter to these droop gain changes is stable regardless of value

Droop-e: Exponential Droop as a Function of Power Output for Grid Forming Inverters with Autonomous Power Sharing

Initial limit investigation yields a curious loss in damping for static droop gains below 1.5%



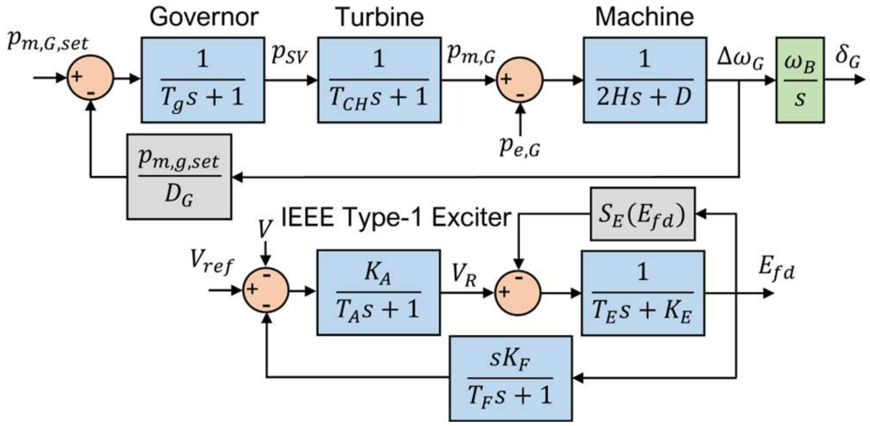


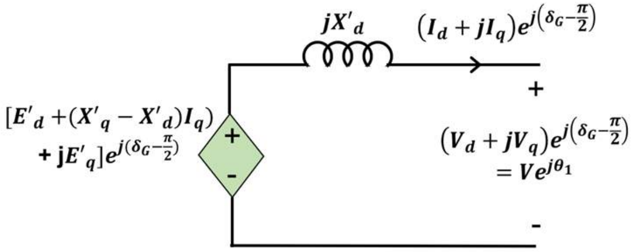
- For droop gains below 1.5%, there's an inversion in the damping ratio trend (based on average frequency)
- Time domain indicates the neighborhood below 0.5% creates large, persistent oscillations
- Looks like the GFM is just exchanging power with the SGs, which oscillate in phase

Droop-e: Exponential Droop as a Function of Power Output for Grid Forming Inverters with Autonomous Power Sharing

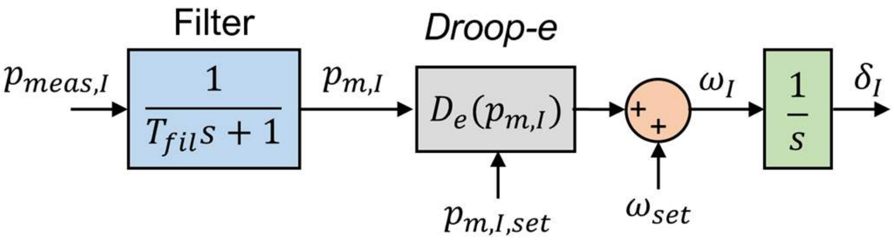
Models Used for Small Signal Stability Analysis

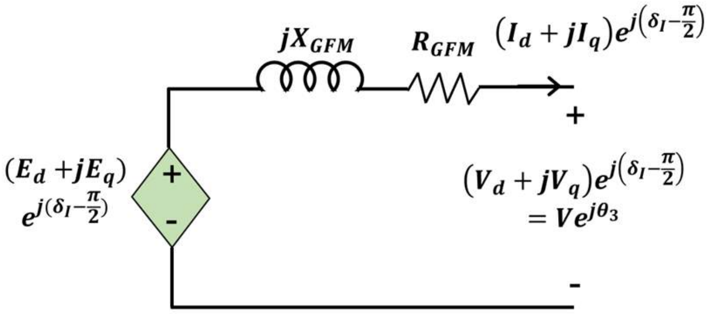
Synchronous
Generator





Grid-Forming Inverter





- Assumed constant voltage for grid-forming inverter, greatly reduces model complexity