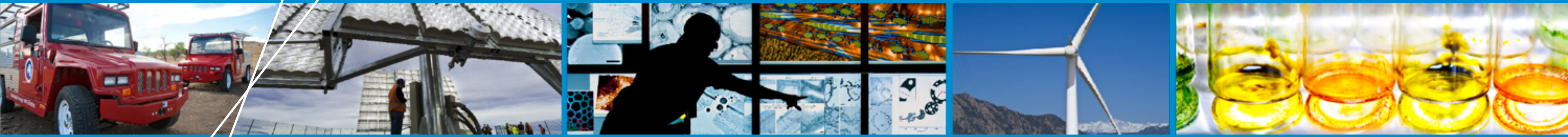
Integrated electricity & market models

with distribution on high performance computing



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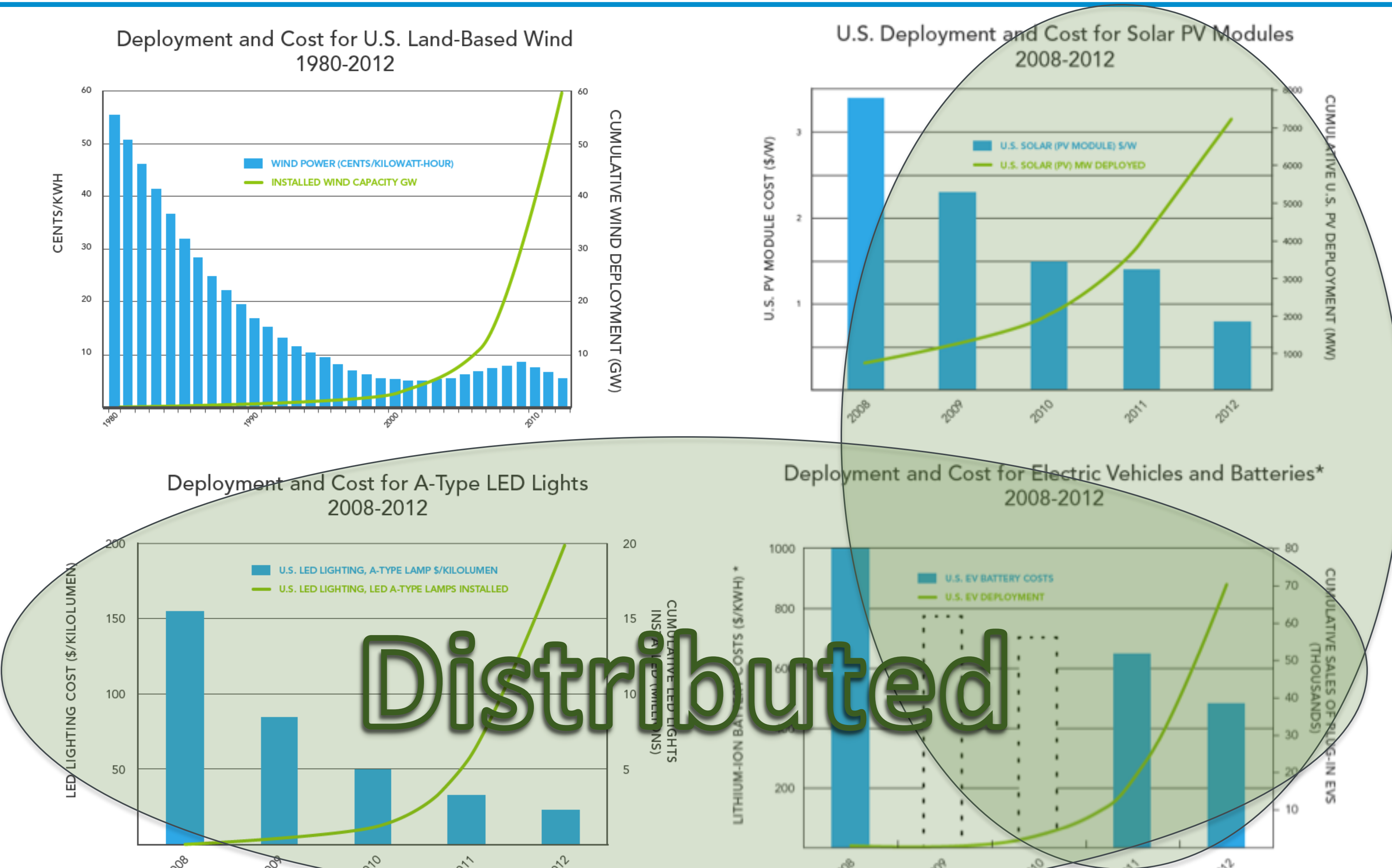
Energy Systems Integration 102
iiESI/NREL
August 6, 2015

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Outline

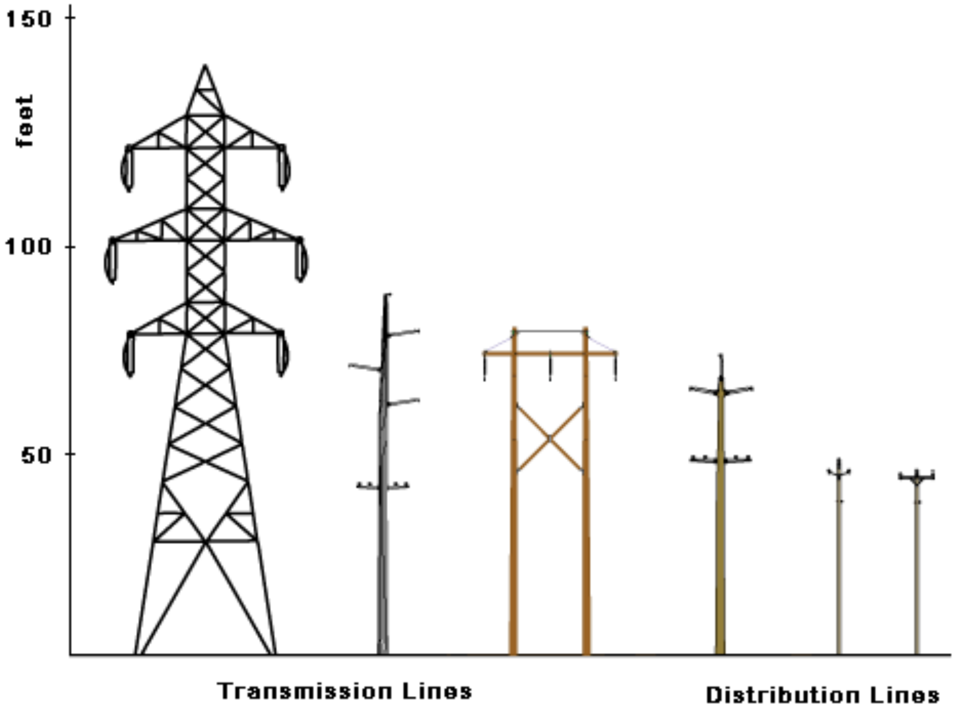
- **Background**
    - Distribution Considerations
    - Hosting Capacity
- **Pricing and Controls**
- **Modeling Tariffs and Smart Homes**
- **Transmission + Distribution**

The Revolution is … ~~Coming~~ Now



Source: "Revolution Now (2013)" – US Department of Energy

Transmission and Distribution Systems



Utility Concerns for Distributed Generation

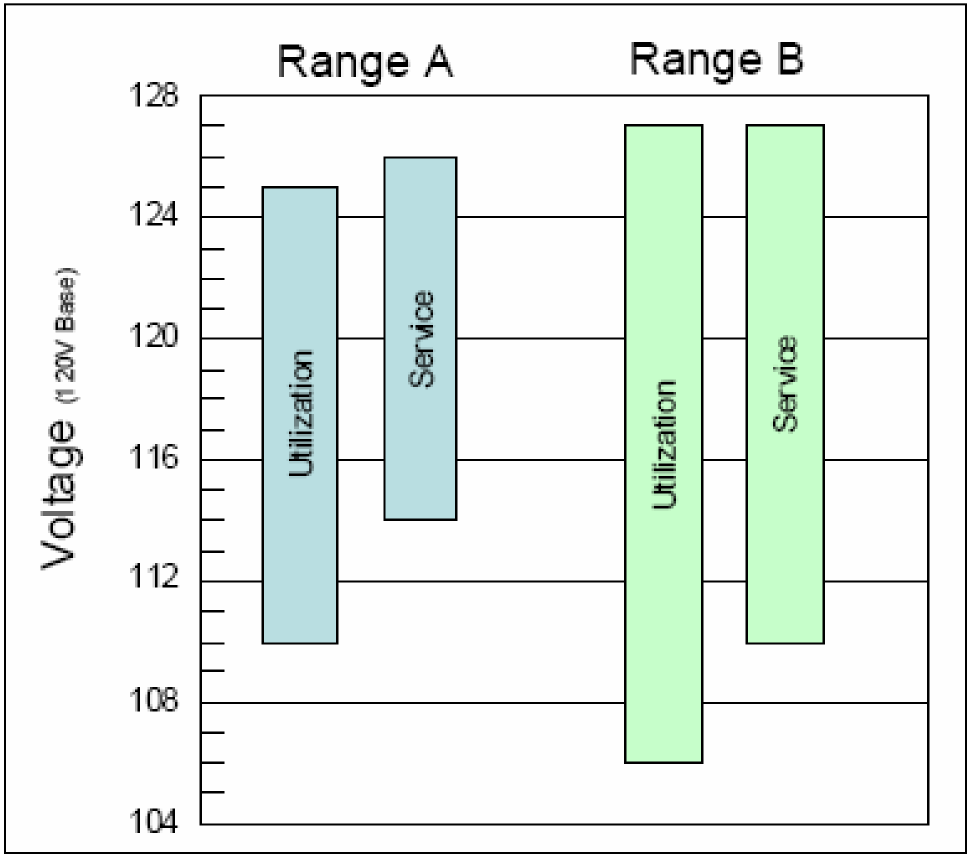
Identified Issues	Relative Priority	Identified Issues	Relative Priority
Voltage Control	High	Equipment Specs	High
Protection	High	Interconnection Handbook	Medium
System Operations	High	Rule 21 and WDAT	Medium
Power Quality	High	IEEE 1547/ UL 1741	Medium
Monitoring and Control	Medium	Application Review	High
Feeder Loading Criteria	High	Clarification of Responsibilities	High
Transmission Impact	Medium	Integration with Tariffs	Medium
Feeder Design	Medium	Coordination with Other Initiatives	Medium
Planning Models	Medium		

Source: Southern California Edison

ANSI C84.1 Voltage Limits

ANSI C84.1
Standard for Electrical Power Systems and Equipment-Voltage Ratings (60 Hz)

- Service Voltage – Voltage at the point of delivery.
- Range A (114-126V) is favorable, Range B (110-127V) is tolerable.

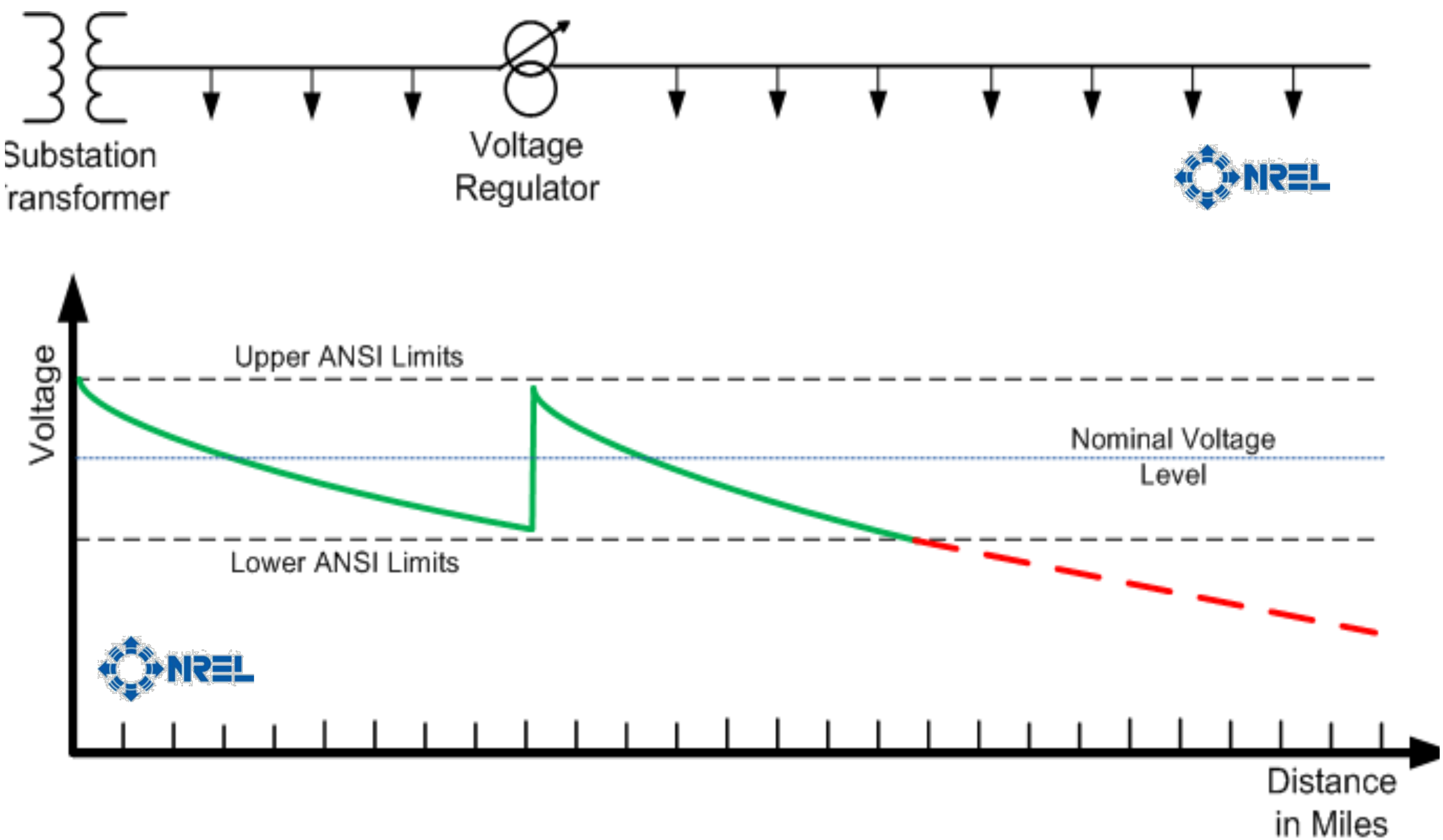


Voltage Regulation Devices

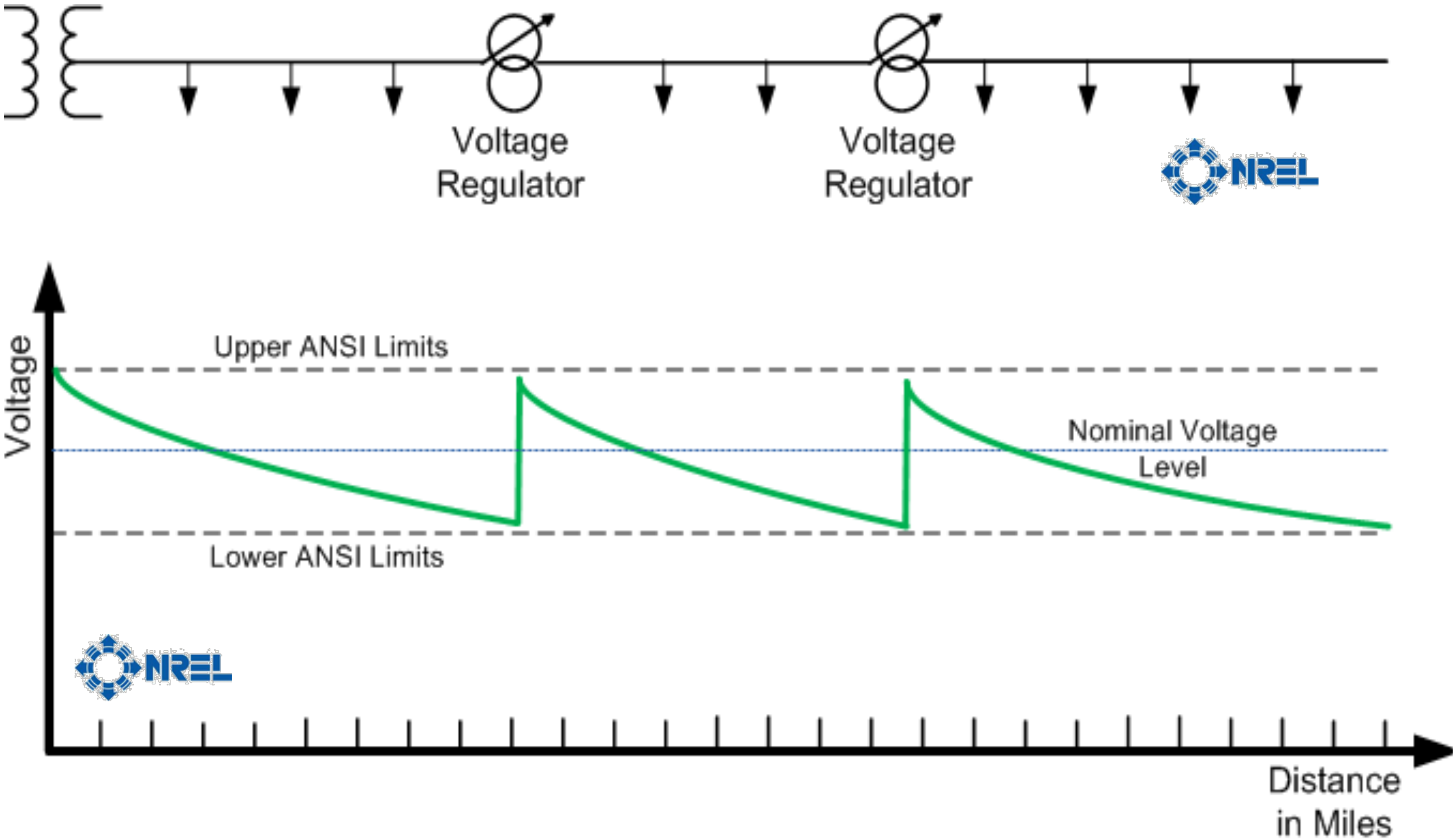
Load Tap Changers (LTCs)

Voltage Regulators

Distribution System Voltage Profile

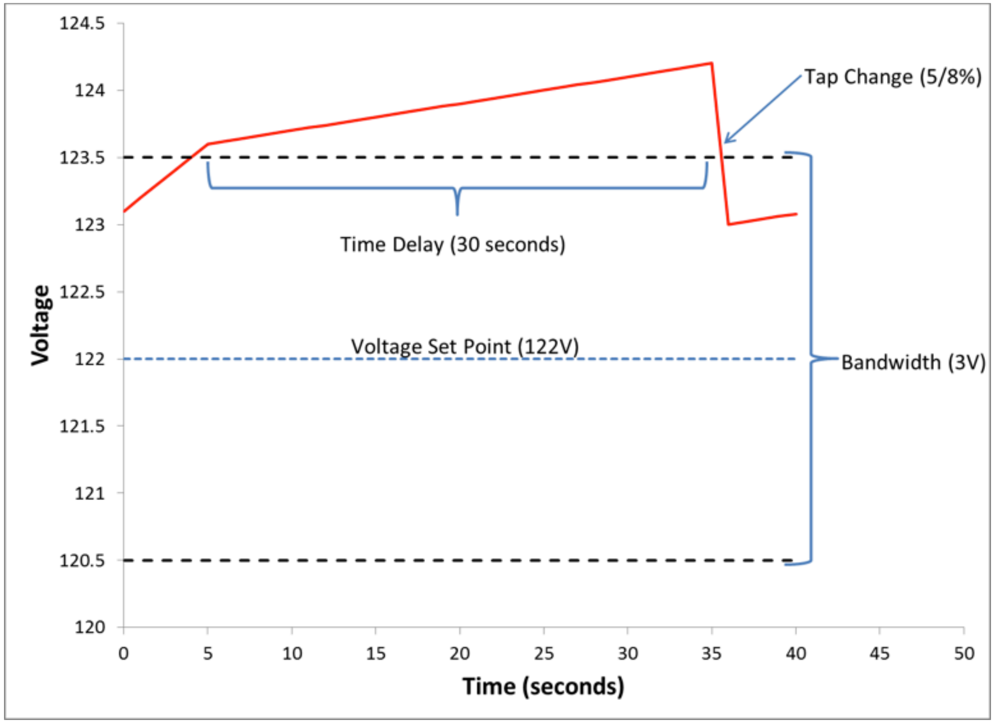


Distribution System Voltage Profile



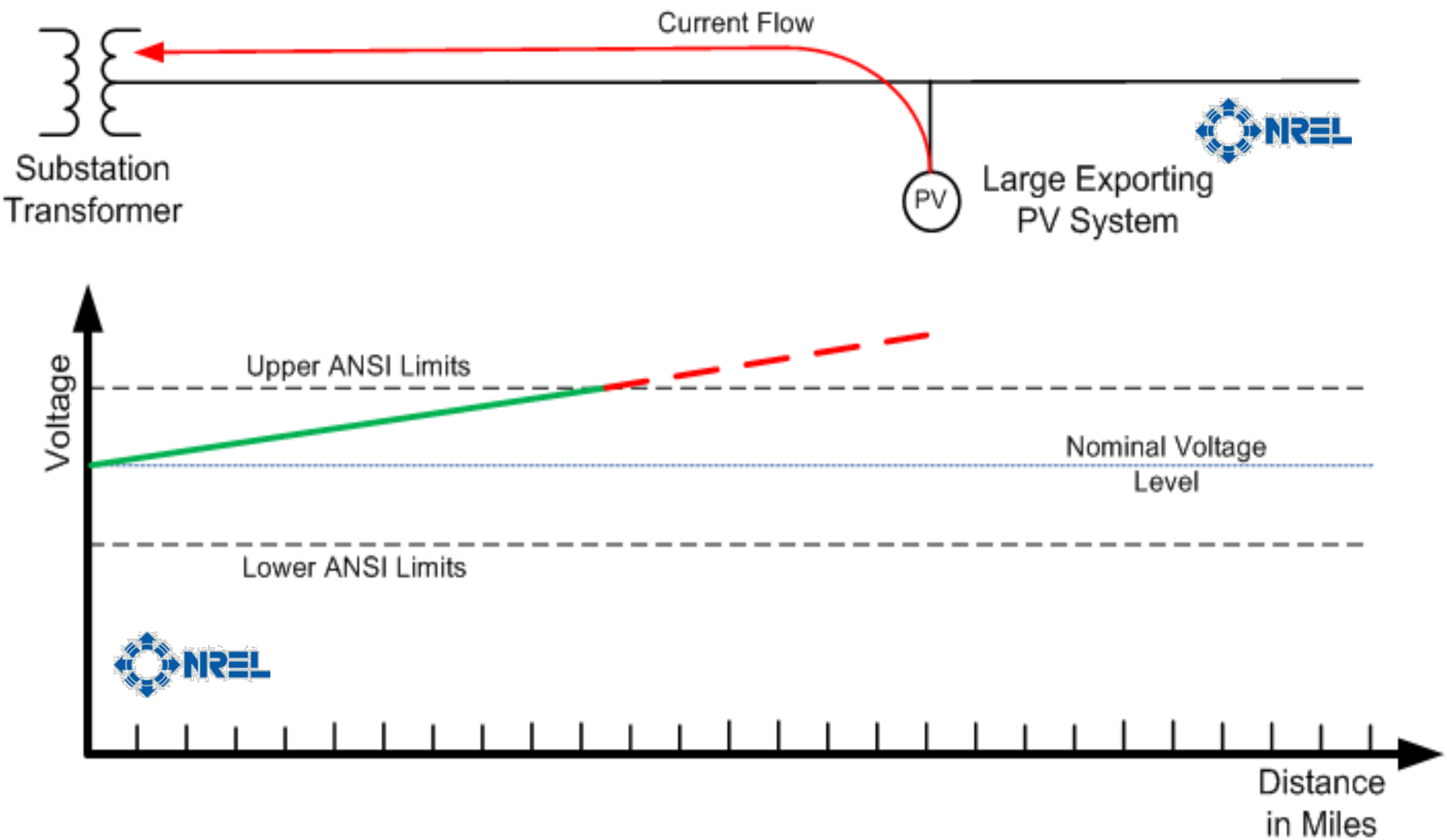
LTCs and VREGs Basic Settings

- **Voltage set point**
- **Bandwidth**
- **Time Delay**

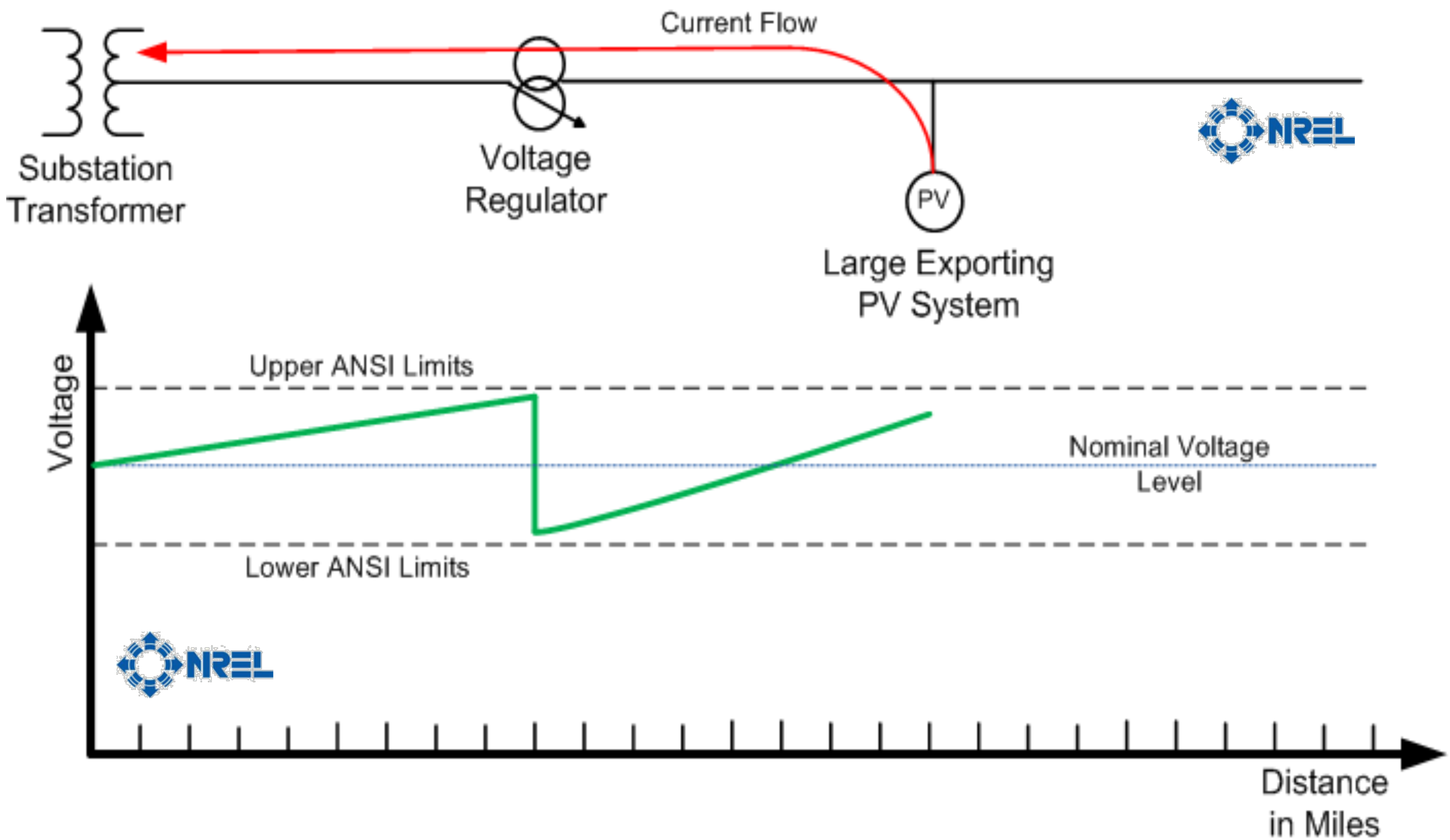


Courtesy: Jimmy Quiroz, SNL

Distribution System Voltage Profile – Large PV



Distribution System Voltage Profile – Large PV

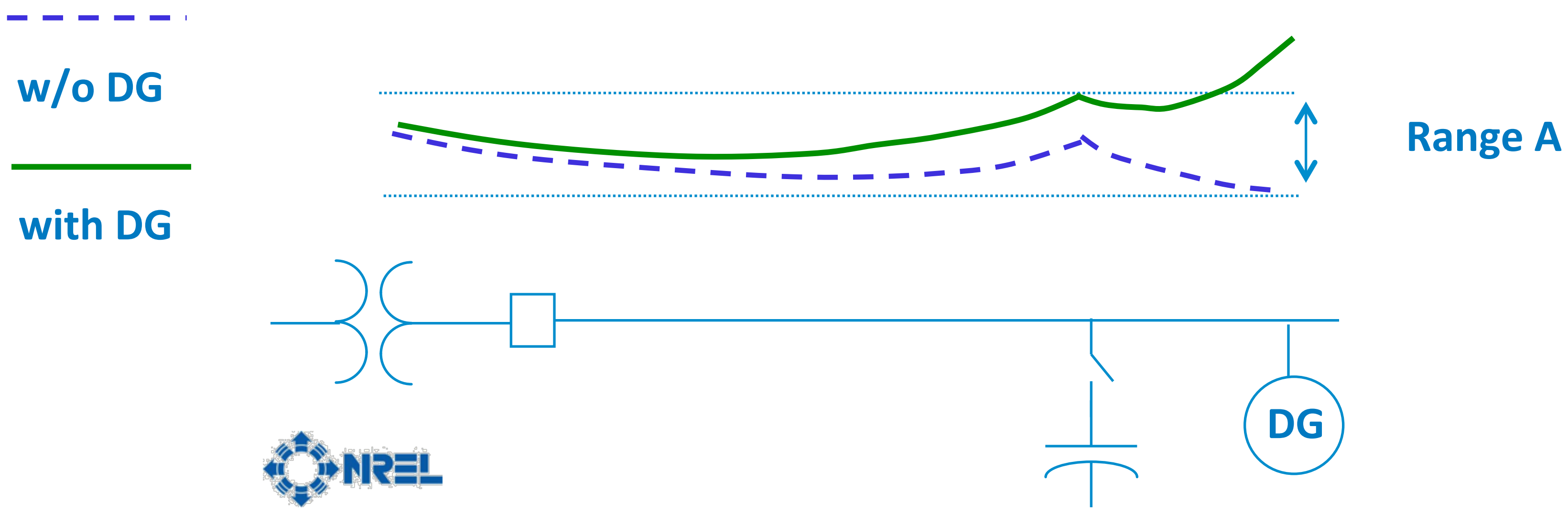


Voltage Regulation Devices

- **Switched Capacitor Banks**
  - Defined by kVAr rating of bank.
  - Voltage rise proportional to rating.

http://www.energyinnovationcorridor.com/page/wp-content/uploads/2011/01/IMG_0574.jpg

Voltage Profile, with Caps

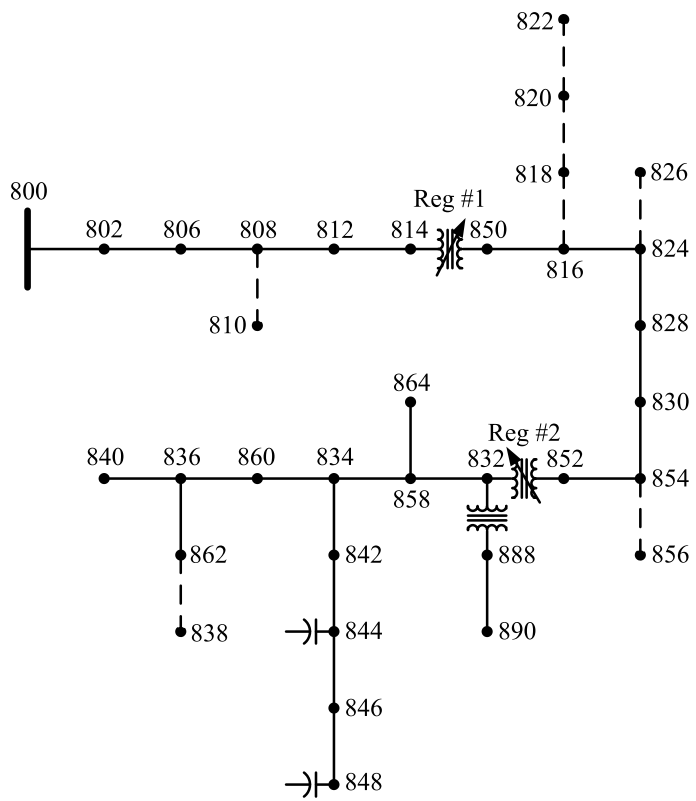


Distribution System Modeling Overview

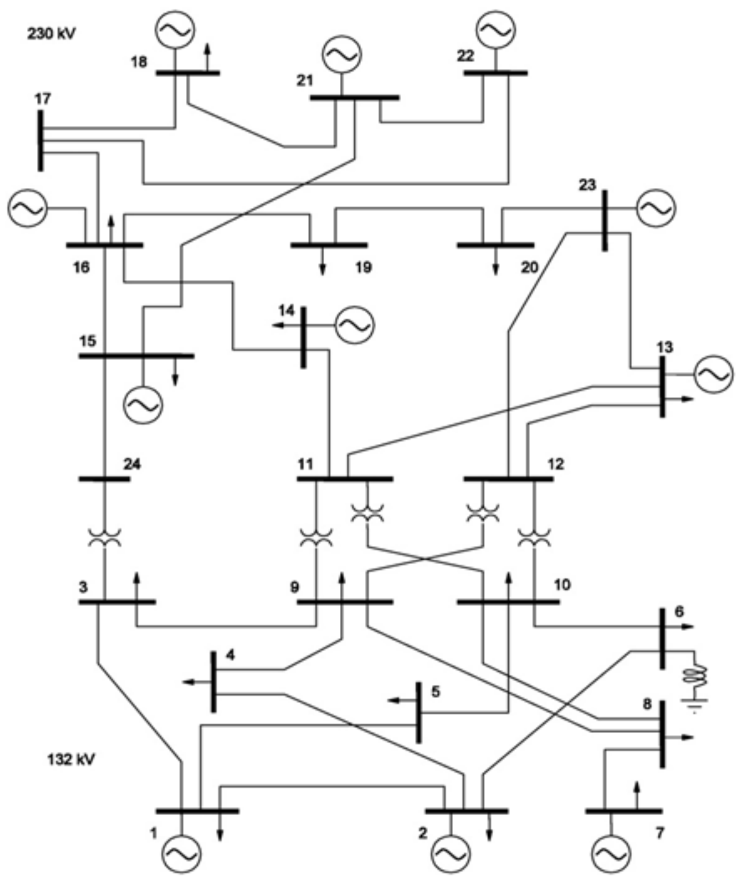
- **Steady-State Distribution system modeling is similar to classical transmission system modeling with a few caveats:**
  - System is typically non-meshed/radial instead of heavily meshed (outcome – alternate solution techniques)
  - System is modeled as an unbalanced three-phase system instead of a balanced three-phase system (outcome – three or four times more variables to solve for!)
  - System X/R values are much lower and system is much smaller (outcome – computational precision requirements are higher)
  - System equipment models is more detailed (outcome – more difficult to define useful models)

Radial vs. Meshed

Distribution: 34 Node Test Feeder

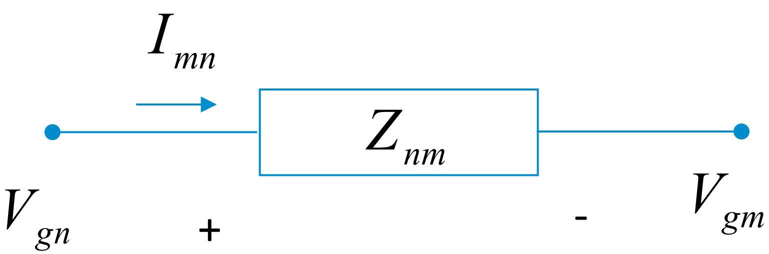


Transmission: 24 Bus Test System



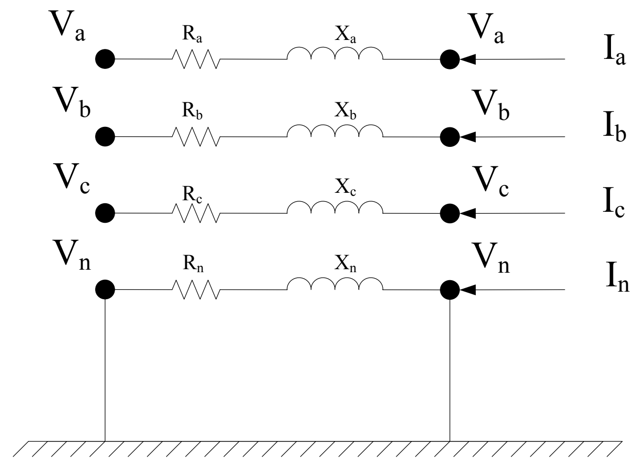
Modeling comparisons

Positive Sequence



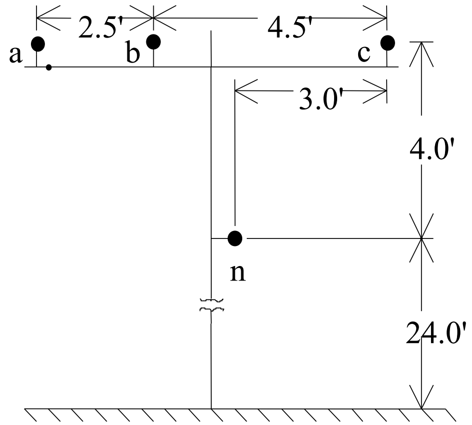
$$V_{gn} = V_{gm} + Z_{nm} I_{nm}$$

Unbalanced



$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}_{to} = \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}_{from} + \begin{bmatrix} Z_{aa} & Z_{ab} & Z_{ac} \\ Z_{ba} & Z_{bb} & Z_{bc} \\ Z_{ca} & Z_{cb} & Z_{cc} \end{bmatrix} * \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}$$

Three-phase Unbalanced



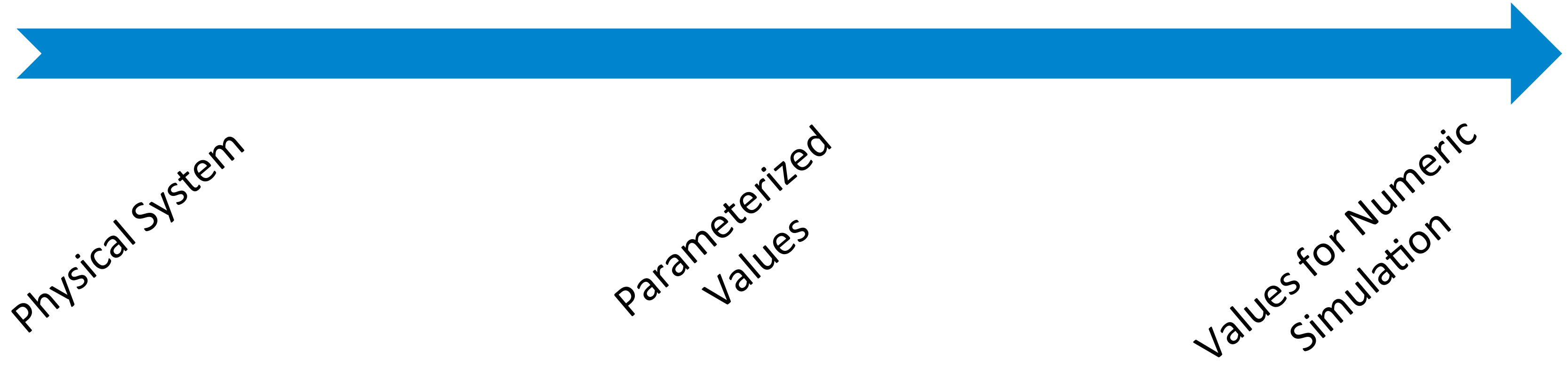
Phase Conductor: 336,400 26/7

GMR = 0.0244 ft., Resistance = 0.306 Ω/mile, Diameter = 0.721 inch

Neutral Conductor: 4/0 6/1 ACSR

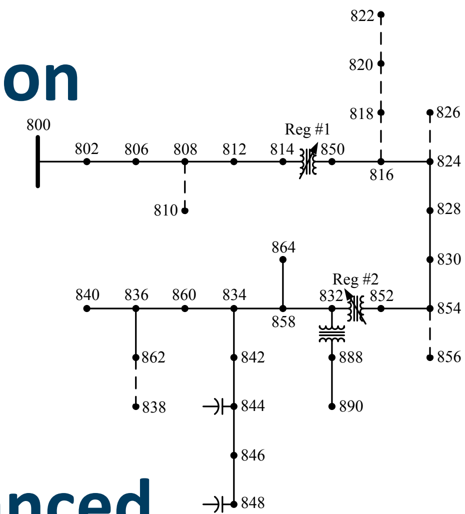
GMR = 0.00814 ft., Resistance = 0.592 Ω/mile, Diameter = 0.563 inch

$$\begin{bmatrix} Z_{aa} & Z_{ab} & Z_{ac} \\ Z_{ba} & Z_{bb} & Z_{bc} \\ Z_{ca} & Z_{cb} & Z_{cc} \end{bmatrix}$$



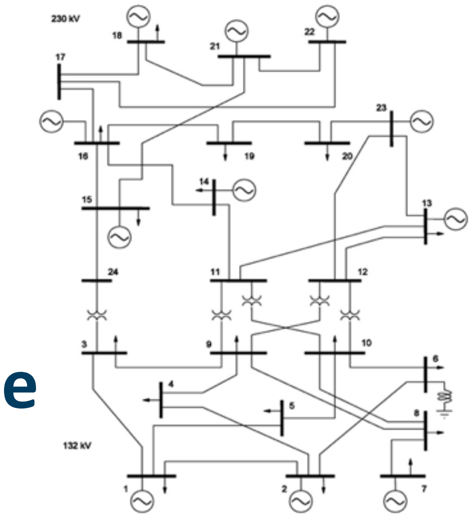
Distribution System Modeling

Distribution



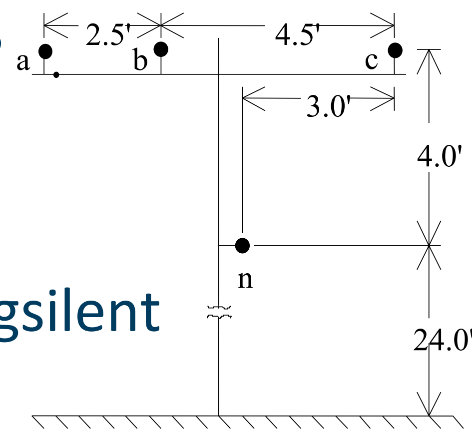
- Radial
- 3-ph
- Unbalanced
- High X/R

Transmission



- Meshed
- Pos sequence
- Balanced

- Distribution Tools
  - OpenDSS
  - GridLAB-D
  - CyME, Synergi, Digsilent



$$\begin{bmatrix} Z_{aa} & Z_{ab} & Z_{ac} \\ Z_{ba} & Z_{bb} & Z_{bc} \\ Z_{ca} & Z_{cb} & Z_{cc} \end{bmatrix}$$

Important: US and Europe have very different distribution system designs

“Alternatives to the 15% rule (of-thumb)”

PV HOSTING CAPACITY IN DISTRIBUTION SYSTEMS

DEVELOPMENT OF ALTERNATIVE SCREENING METHODS

High Penetration Solar Forum 2013

Feb 13-14, San Diego, CA

Why Consider Alternatives to Existing Screening?

- Feeder's ability for hosting PV w/o adverse impact on performance depends upon many feeder-specific factors
- "Rule-of-thumb" penetration limits such as 15% rule are not very accurate
- Typical characteristics used to classify/screen feeders (i.e. voltage class and load level) may not be sufficient
- Example illustrates different hosting capacity for "similar" circuits

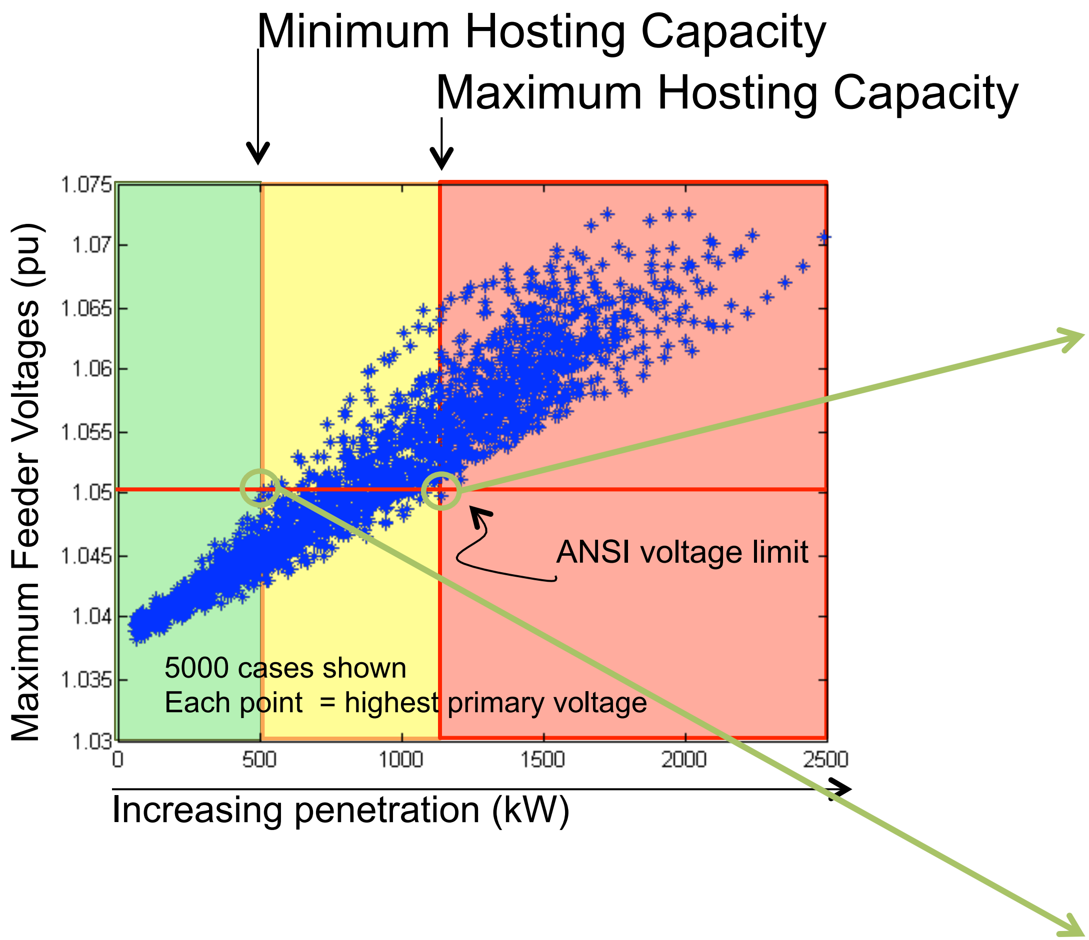
Sample analysis results from DOE-funded VT/EPRI Hi-Pen Project

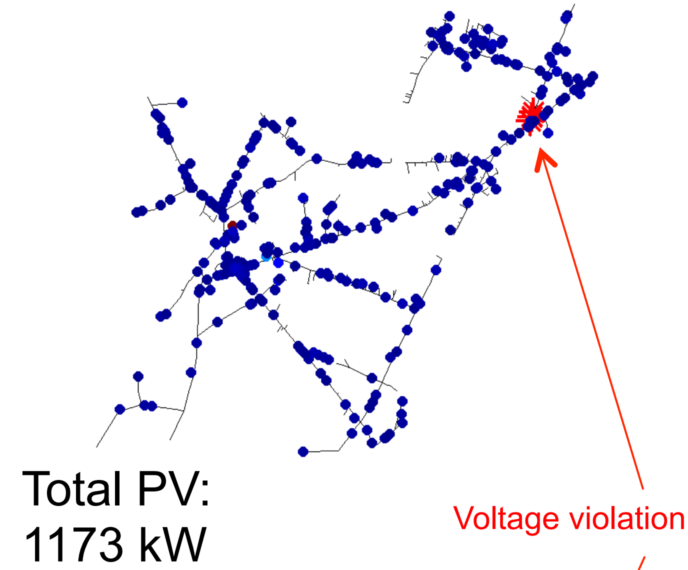
Feeder Characteristics	Feeder A	Feeder B
Voltage (kV)	13.2	12.47
Peak Load	5 MW	6 MW
Minimum Load	0.8 MW	0.7 MW
Minimum Daytime Load	1.1 MW	0.7 MW
Existing PV (MW)	1.0	1.7
Feeder Regulation	Only @ Substation	Yes, highly regulated
Total Circuit Miles	28	58
Feeder "Footprint"	7 mi²	35 mi²
Minimum Hosting Capacity		
Due to Voltage Impacts	**>3500 kW**	**250 kW**
Due to Protection Limit	**777 kW**	**390kW**

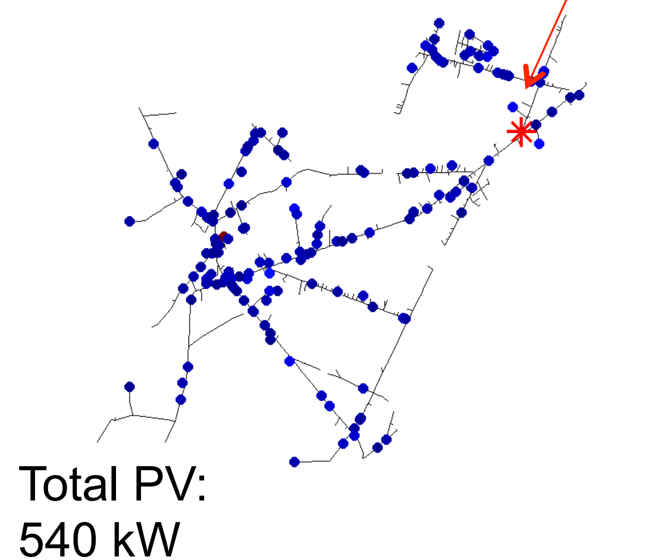
70% of Peak Load

4% of Peak Load

Hosting Capacity Explanation



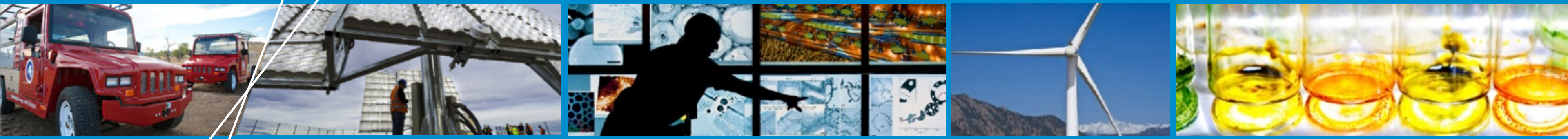




No observable violations regardless of size/location

Possible violations based upon size/location

Observable violations occur regardless of size/location

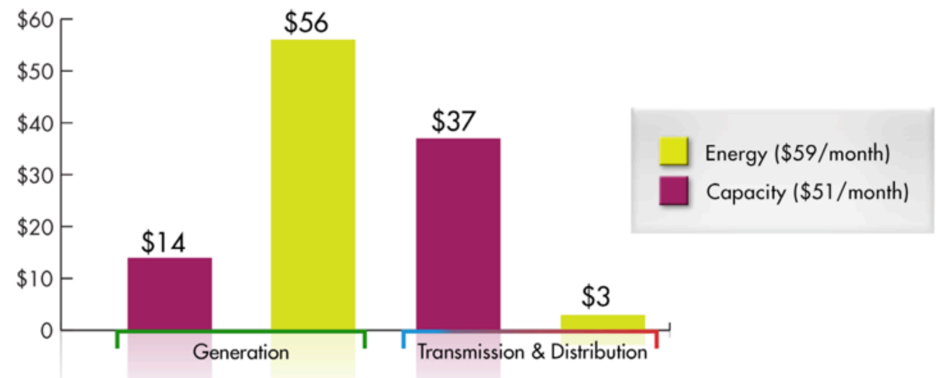


Pricing and Controls

Issues with Retail Market Structures

Utility

- Net metering is unsustainable



Credit: EPRI "The Integrated Grid: Realizing the Full Value of Central and Distributed Energy Resources" (October 2007)

Grid Value = $51/month of $110/month average electric bill to provide (982kWh / month)

- Reliability
- Startup power
- Voltage quality
- Efficiency
- Energy transaction

Replacement estimate = $275-$430/month now
$165-$262/month potential

Issues with Retail Market Structures

Utility

- Net metering is unsustainable
- Shape of net-loads

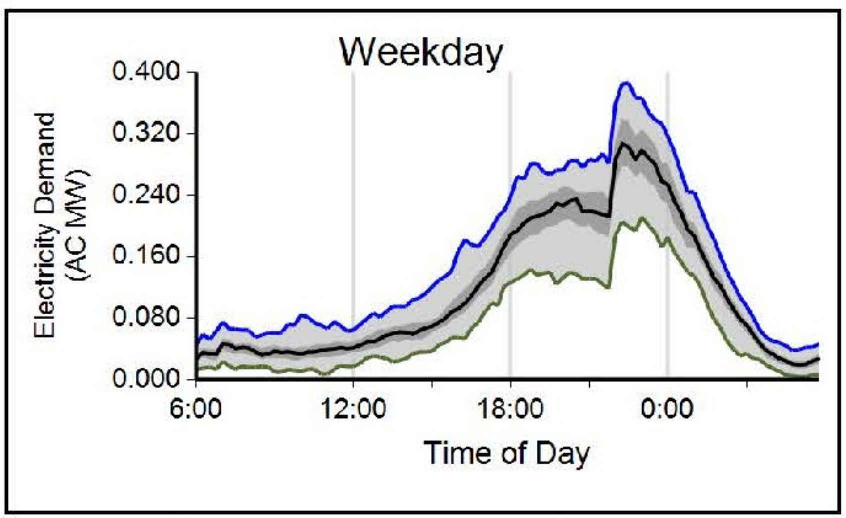
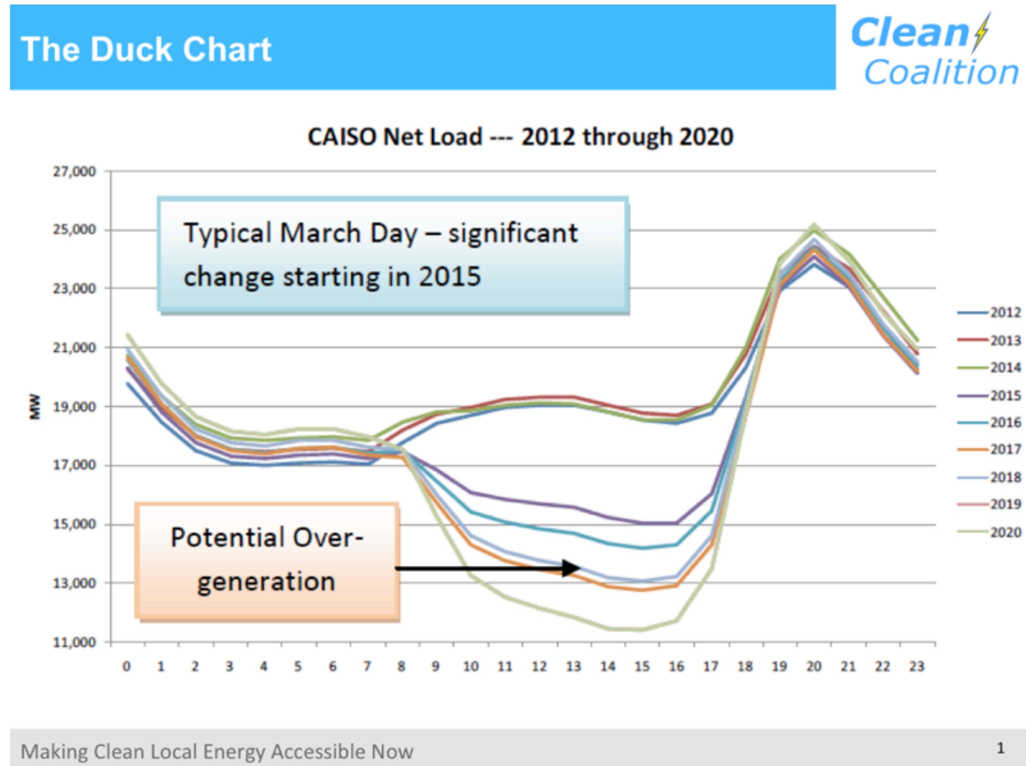


Figure 8 Weekday Residential Charging Demand in PGE Territory, Q1 2013



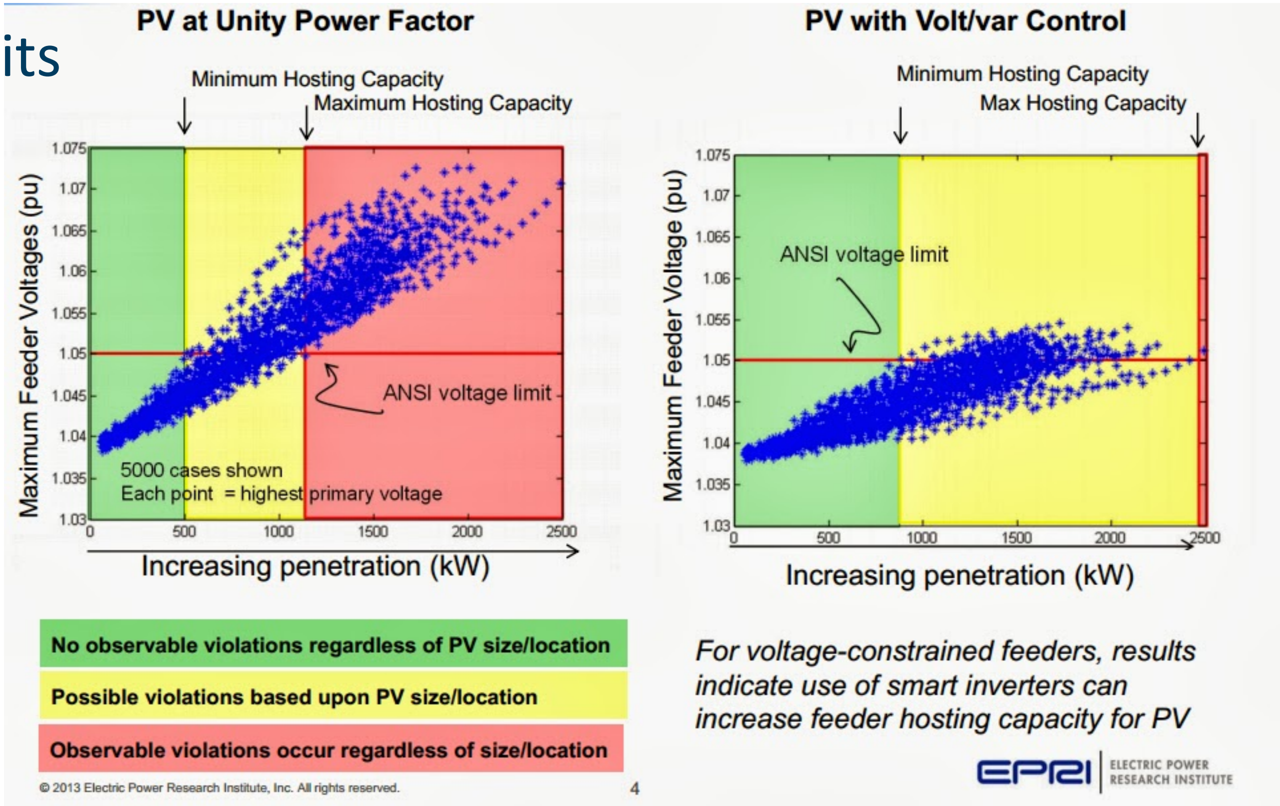
Credit: CA-ISO

Issues with Retail Market Structures

Utility

- Net metering is unsustainable
- Shape of net-loads
- DG penetration limits

Credit: EPRI Analysis of Distributed Solar



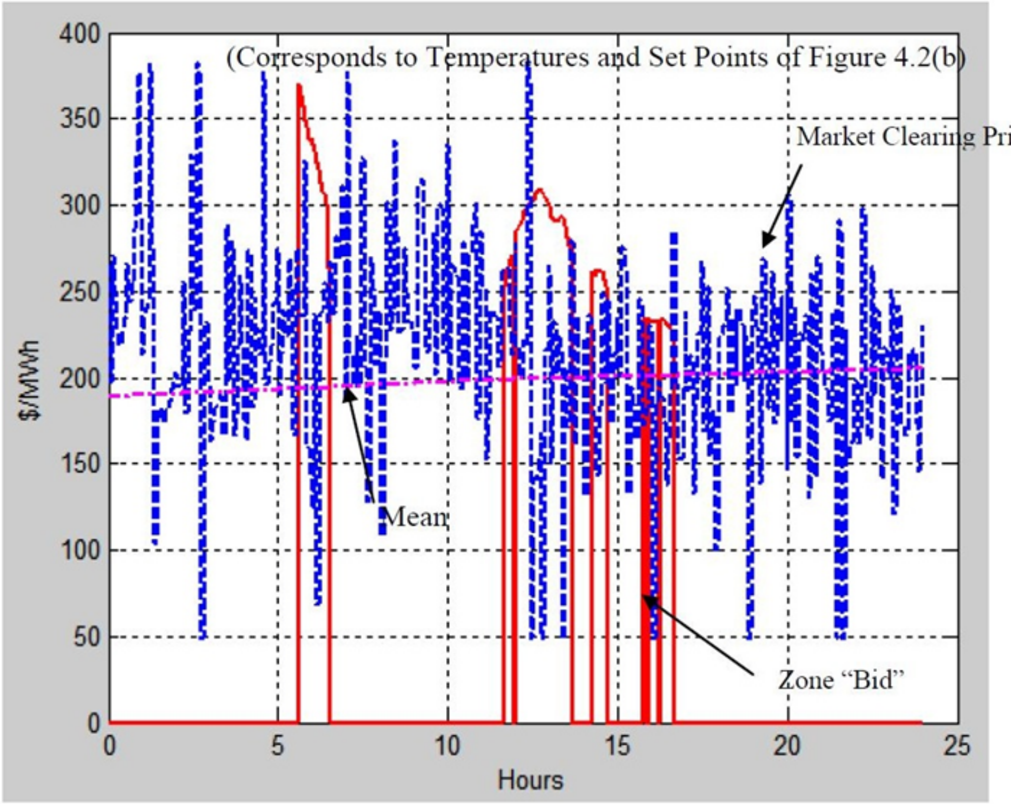
Issues with Retail Market Structures

Utility

- Net metering is unsustainable
- Shape of net-loads
- DG penetration limits
- Volatility with real-time pricing

Prosumer

- Volatility affects comfort
- No motivation to schedule

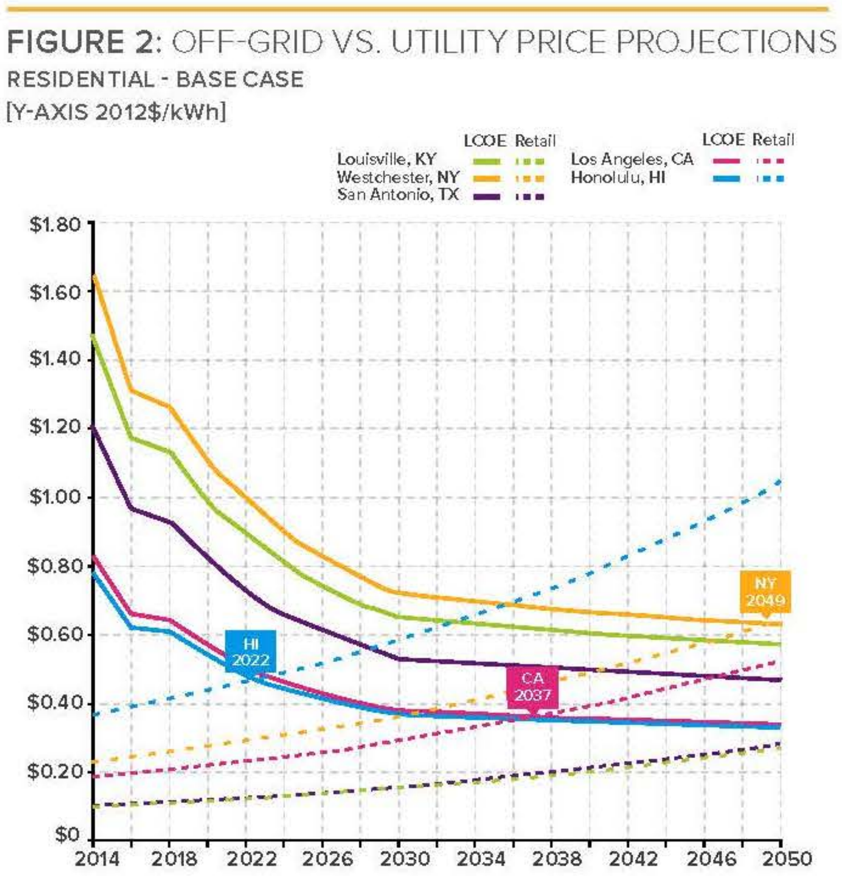


Credit: D. Hammerstrom, et al "Pacific Northwest GridWise Testbed Demonstration Projects Part I. Olympic Peninsula Project" (October 2007)

Market evolution essential to realize the promise of ESI

Potential for Grid Defection & Load Defection

The "utility death spiral" is becoming a concern to both utilities and regulators.

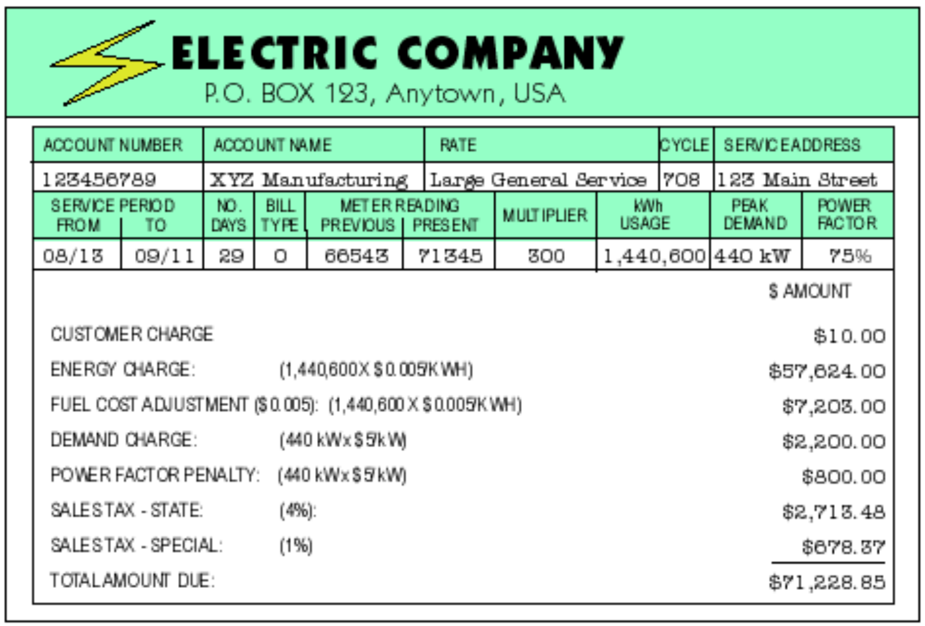


Credit: Rocky Mountain Institute "The Economics of Grid Defection"

Tariffs are Evolving

Tariffs are evolving to balance revenue adequacy, costs, and fairness

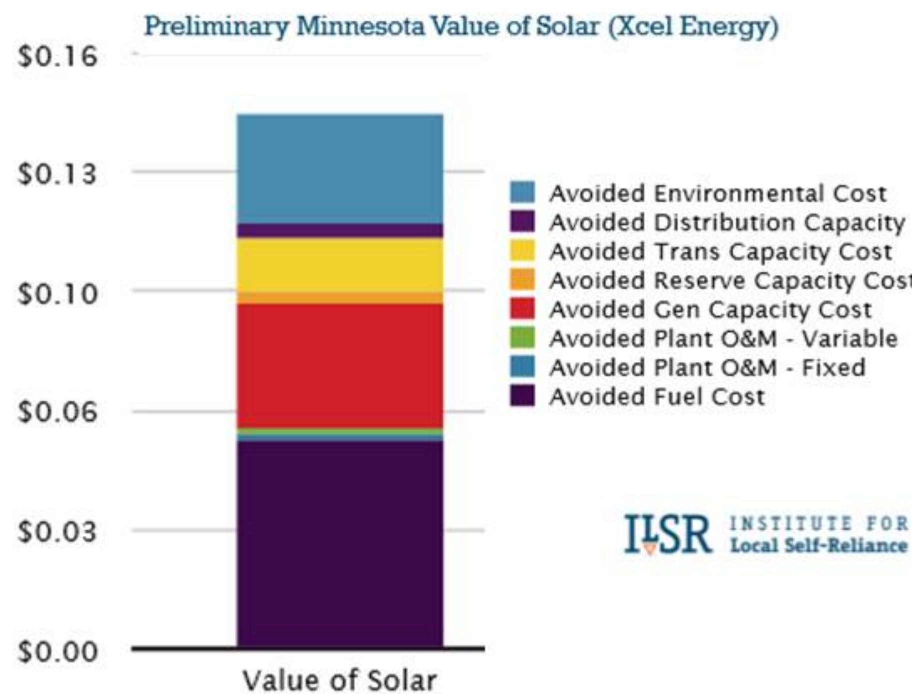
In addition to energy charges, rates are starting to include demand charges, grid support costs, and environmental costs.


ELECTRIC COMPANY
P.O. BOX 123, Anytown, USA

ACCOUNT NUMBER	ACCOUNT NAME	RATE	CYCLE	SERVICE ADDRESS
123456789	XYZ Manufacturing	Large General Service	708	123 Main Street

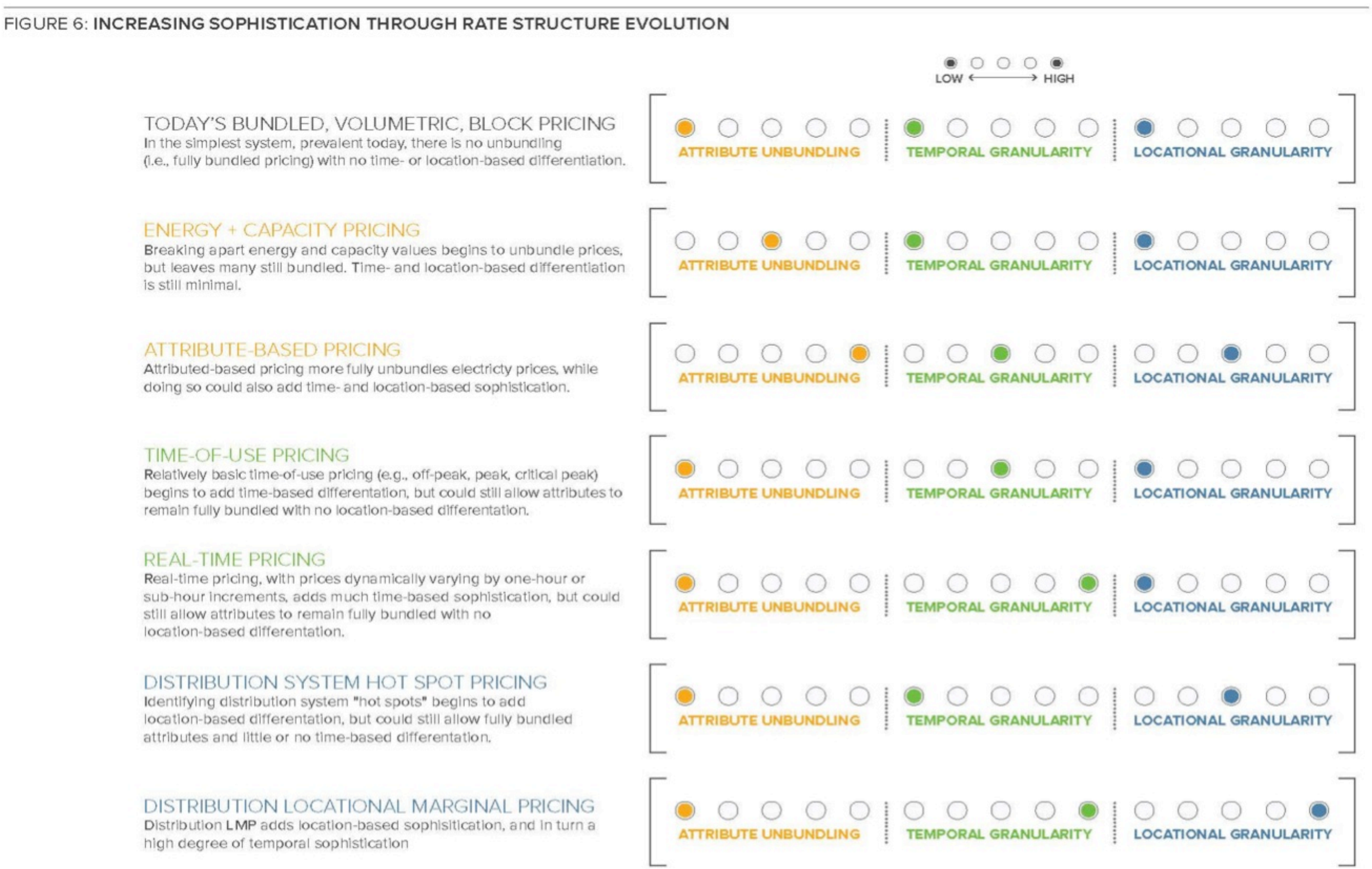
SERVICE PERIOD FROM	SERVICE PERIOD TO	NO. DAYS	BILL TYPE	METER READING PREVIOUS	METER READING PRESENT	MULTIPLIER	KWh USAGE	PEAK DEMAND	POWER FACTOR
08/13	09/11	29	0	66543	71345	300	1,440,600	440 kW	75%

		$ AMOUNT
CUSTOMER CHARGE		$10.00
ENERGY CHARGE:	(1,440,600 X $0.005/KWH)	$57,624.00
FUEL COST ADJUSTMENT ($0.005):	(1,440,600 X $0.005/KWH)	$7,203.00
DEMAND CHARGE:	(440 kW x $5/kW)	$2,200.00
POWER FACTOR PENALTY:	(440 kW x $5/kW)	$800.00
SALES TAX - STATE:	(4%):	$2,713.48
SALES TAX - SPECIAL:	(1%)	$678.37
TOTAL AMOUNT DUE:		$71,228.85



Credit: http://c03.apogee.net/contentplayer/?coursetype=foe&utilityid=wppi&id=4603

Potential Rate Structure Evolution



Bonbright's Principles

TABLE 4: A 21ST CENTURY INTERPRETATION OF THE BONBRIGHT PRINCIPLES OF PUBLIC UTILITY RATEMAKING

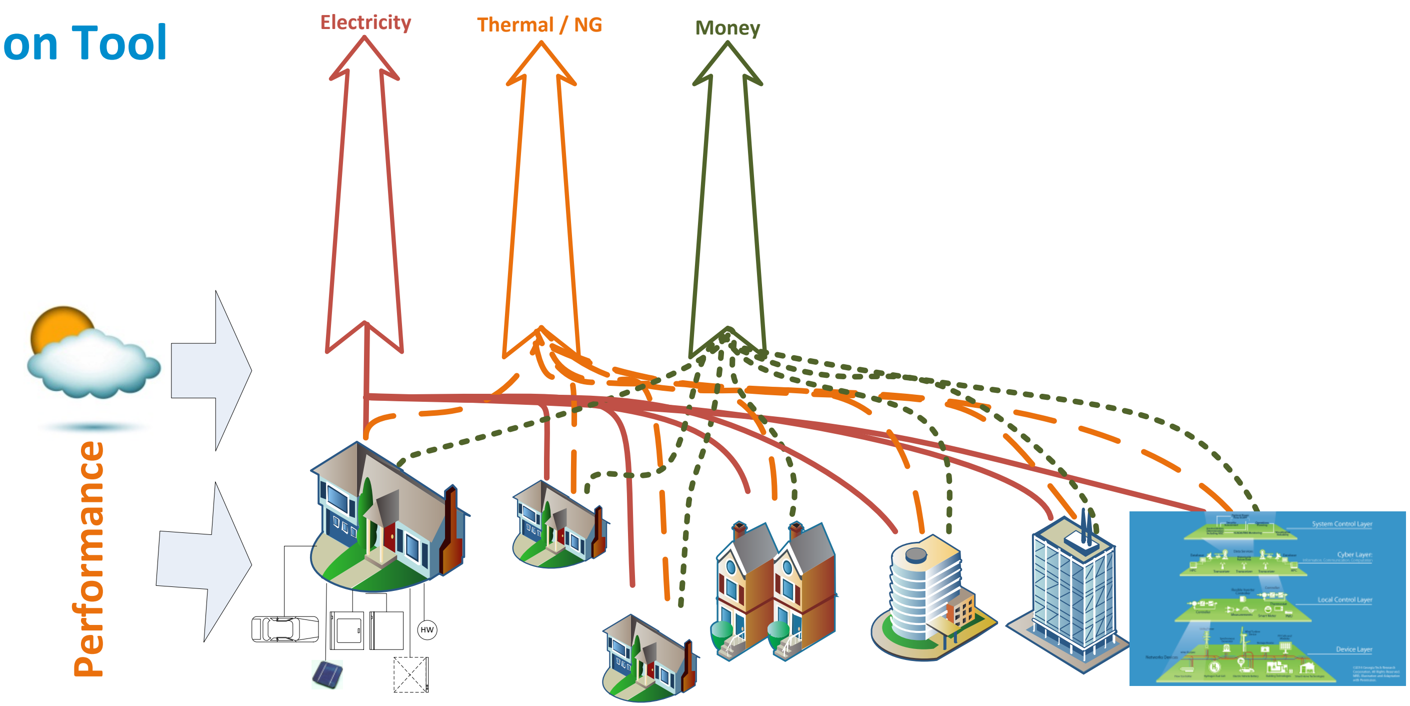
BONBRIGHT PRINCIPLES	21ST CENTURY INTERPRETATION
Rates should be practical: simple, understandable, acceptable to the public, feasible to apply… and free from controversy in their interpretation.	*The customer experience* should be practical, simple, and understandable. New technologies and service offerings that were not available previously can enable a simple customer experience even if underlying rate structures become significantly more sophisticated.
Rates should keep the utility viable, effectively yielding the total revenue requirement and resulting in relatively stable cash flow and revenues from year to year.	*Rates* should keep the utility viable by encouraging economically efficient investment in both centralized and distributed energy resources.
Rates should be relatively stable such that customers experience only minimal unexpected changes that are seriously adverse.	*Customer bills* should be relatively stable even if the underlying rates include dynamic and sophisticated price signals. New technologies and service offerings can manage the risk of high customer bills by enabling loads to respond dynamically to price signals.
Rates should fairly apportion the utility's cost of service among consumers and should not unduly discriminate against any customer or group of customers	*Rate design* should be informed by a more complete understanding of the impacts (both positive and negative) of DERs on the cost of service. This will allow rates to become more sophisticated while avoiding undue discrimination.
Rates should promote economic efficiency in the use of energy as well as competing products and services while ensuring the level of reliability desired by customers.	*Price signals* should be differentiated enough to encourage investment in assets that optimize economic efficiency, improve grid resilience and flexibility and reduce environmental impacts in a technology neutral manner.

http://blog.rmi.org/
blog_2015_02_25_why_new_electricity_pricing_approaches_are_a_sheep_in_wolfs_clothing

Modeling Loads, Tariffs, & Distribution Feeders

Integrated Energy System Model (IESM)

- **Distribution system and load**
- **Minute-scale resolution**
- **Evaluate impact of markets and technologies**
  - Physics-based performance of technologies and buildings
  - Multiple retail markets and tariff structures
- **Provide market layer input to market-to-device HIL testing**
- **Co-Simulation Tool**

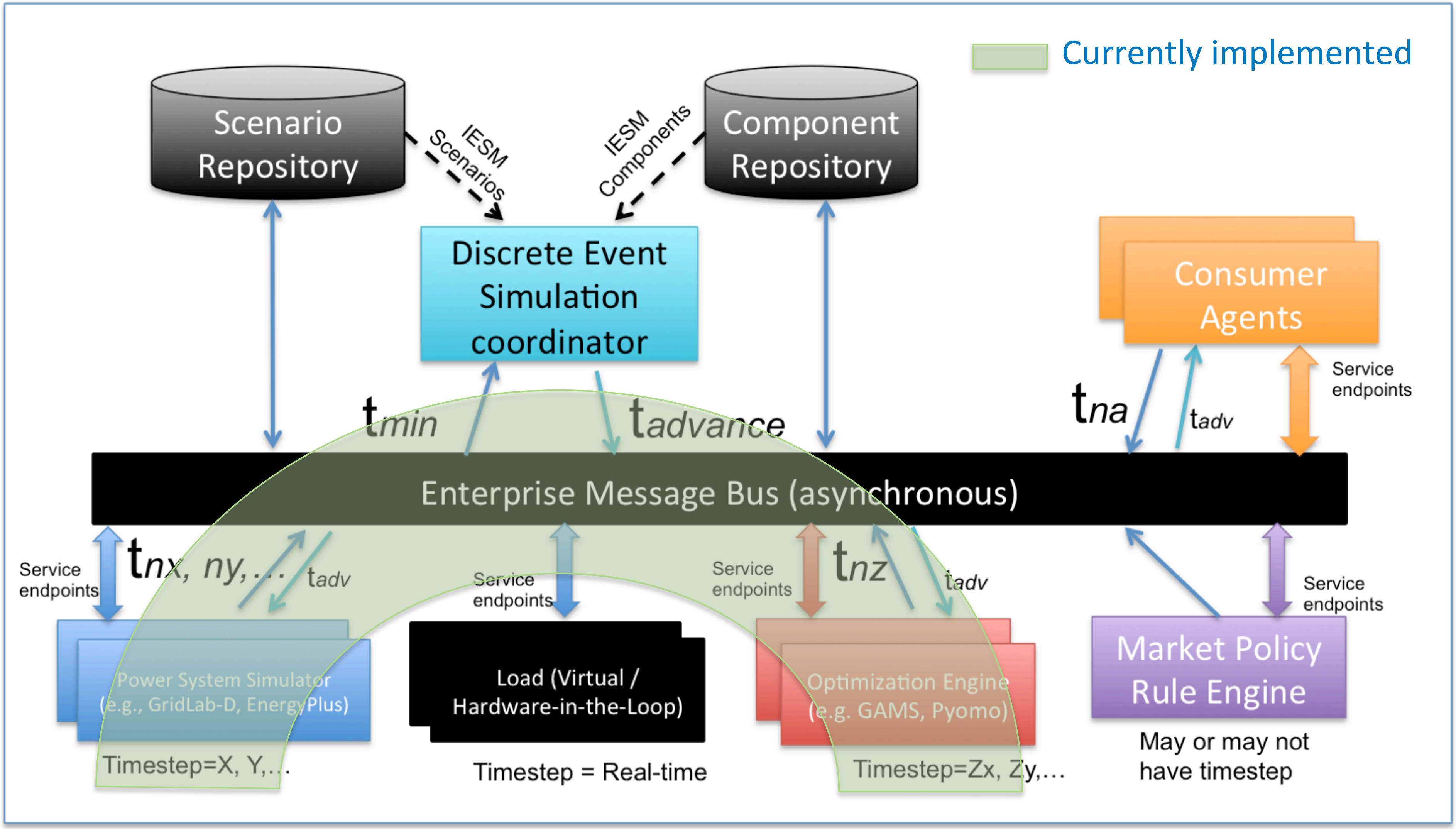


Current IESM Analysis Efforts

Develop the ability to answer the following analysis questions:

1. Home energy management systems (HEMS) benefits to homeowners? Under various tariff structures?
2. Impacts on household comfort?
3. Impacts on utility net income?
4. Physical impacts on distribution system?

IESM is a Co-Simulation Tool



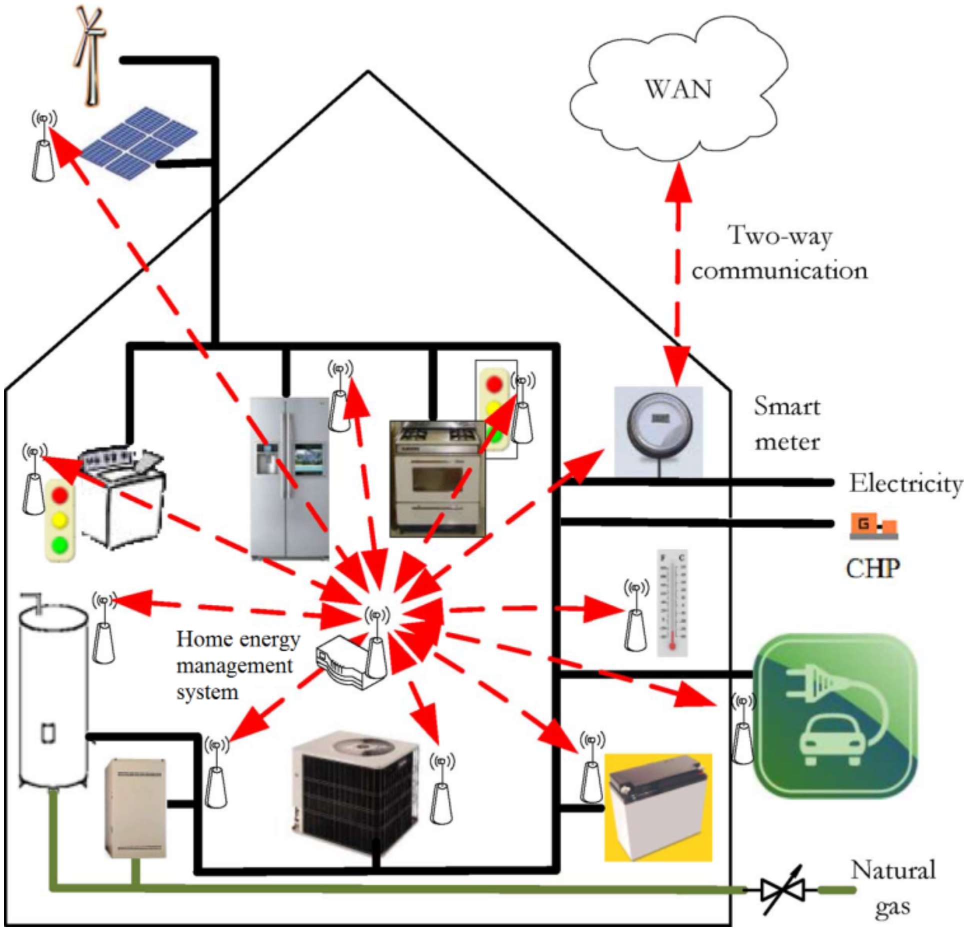
Home Energy Management System (HEMS)

Partnered with FY14 HEMS LDRD

Simultaneous optimization of
- Energy cost
- Discomfort

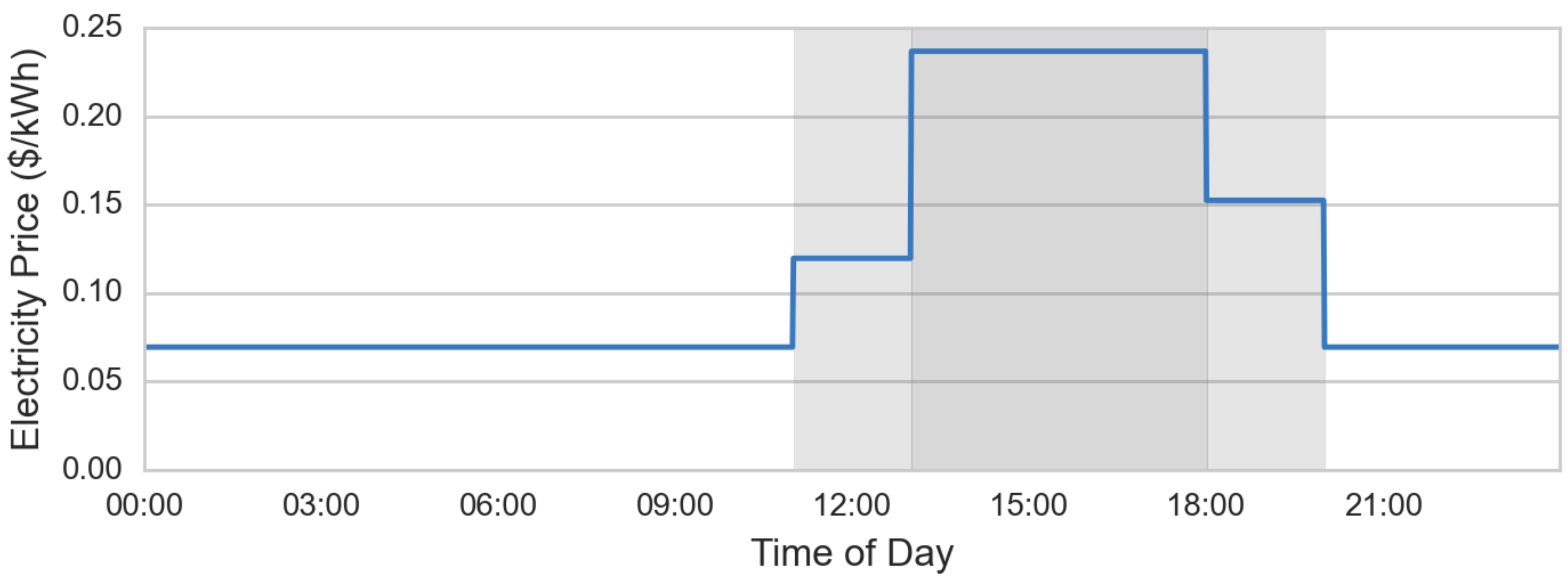
Also possible
- Energy use
- Carbon footprint
- Peak energy use

Predictive
- Net load
- Price
- Weather

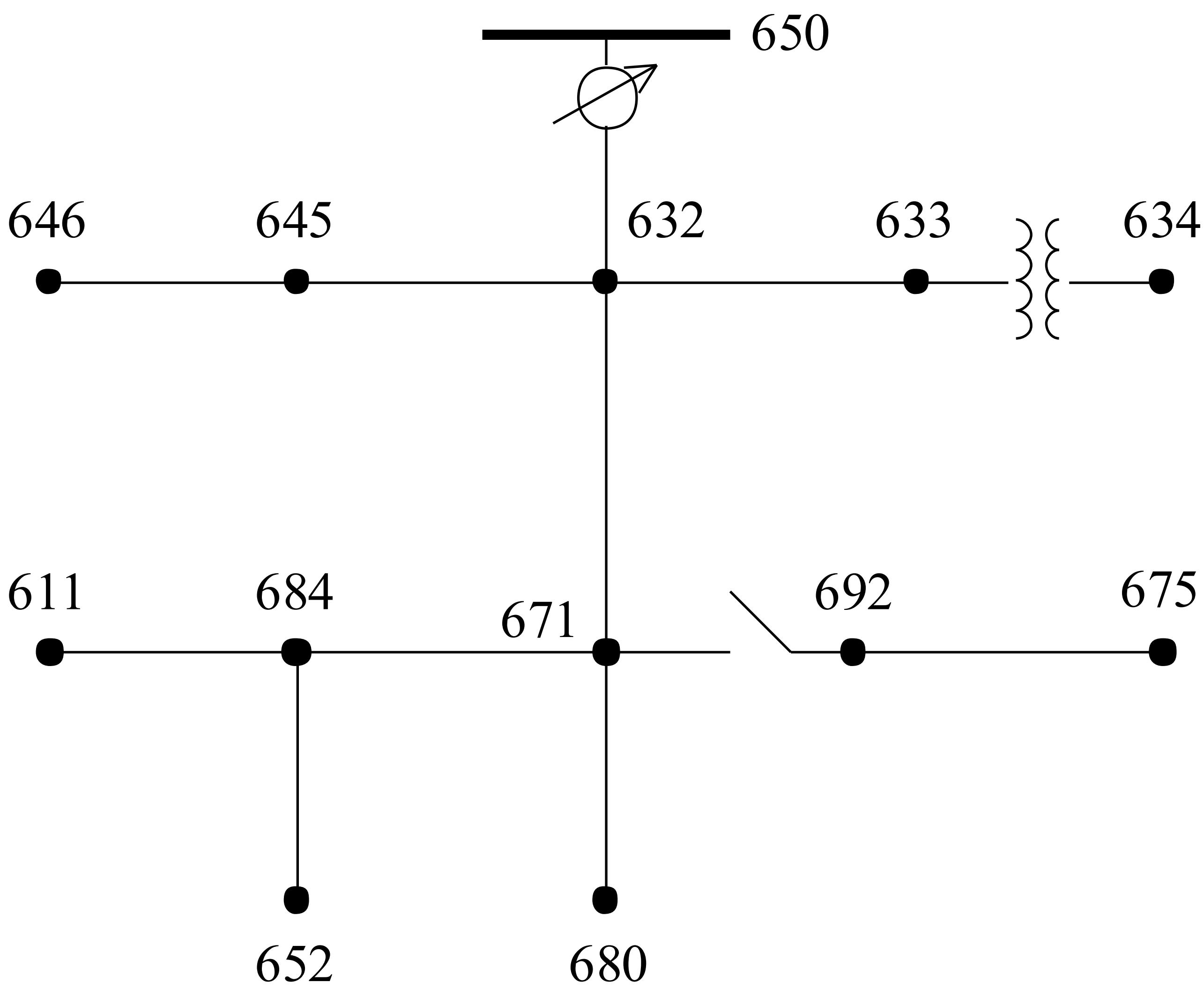


Analyzed Benefits of HEMS

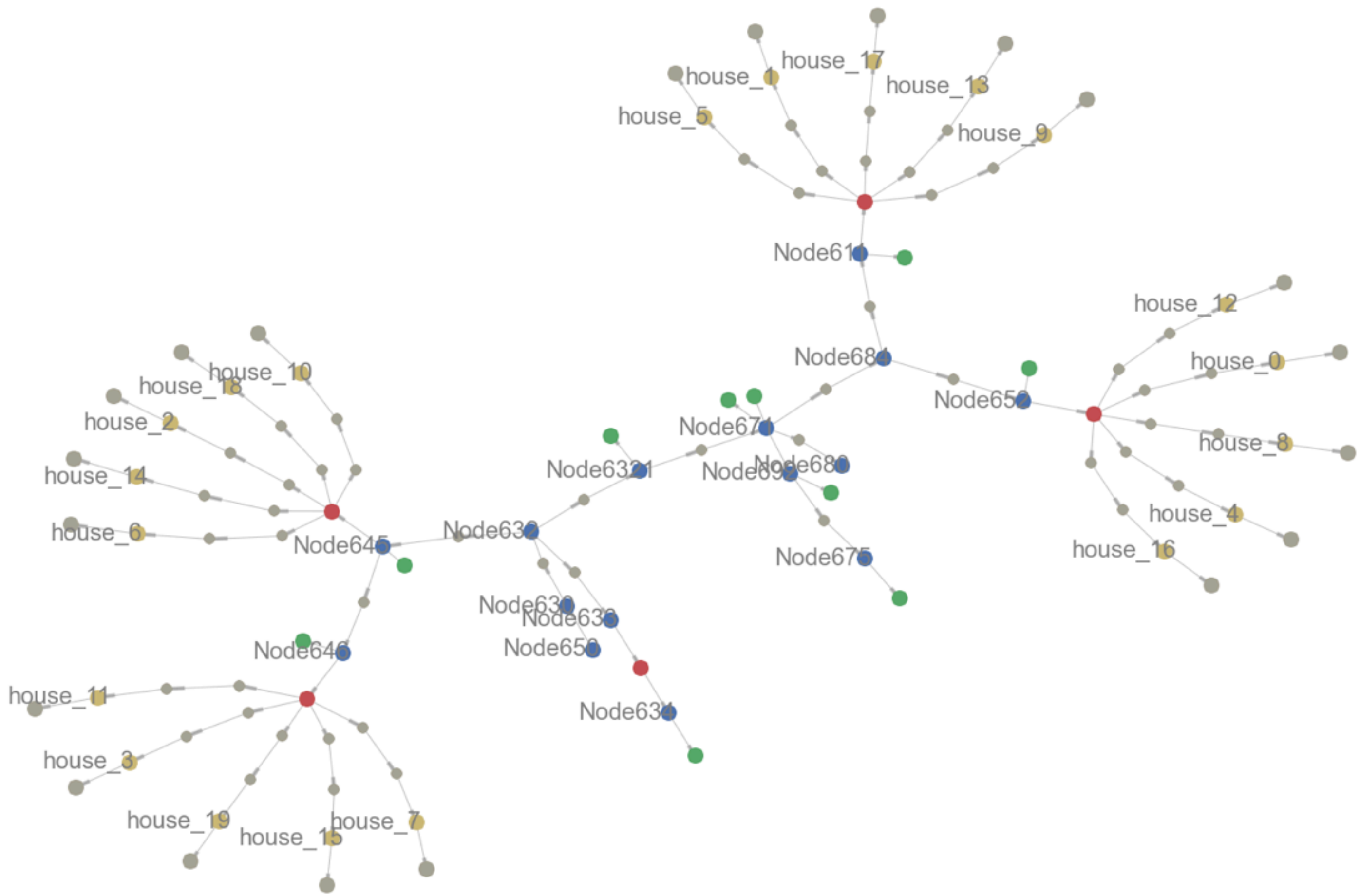
- HEMS controlling air conditioning set point
- Duke Energy residential TOU pricing from rate case information (Weekdays)
- Weekends have flat prices at lowest rate



IEEE 13-node feeder

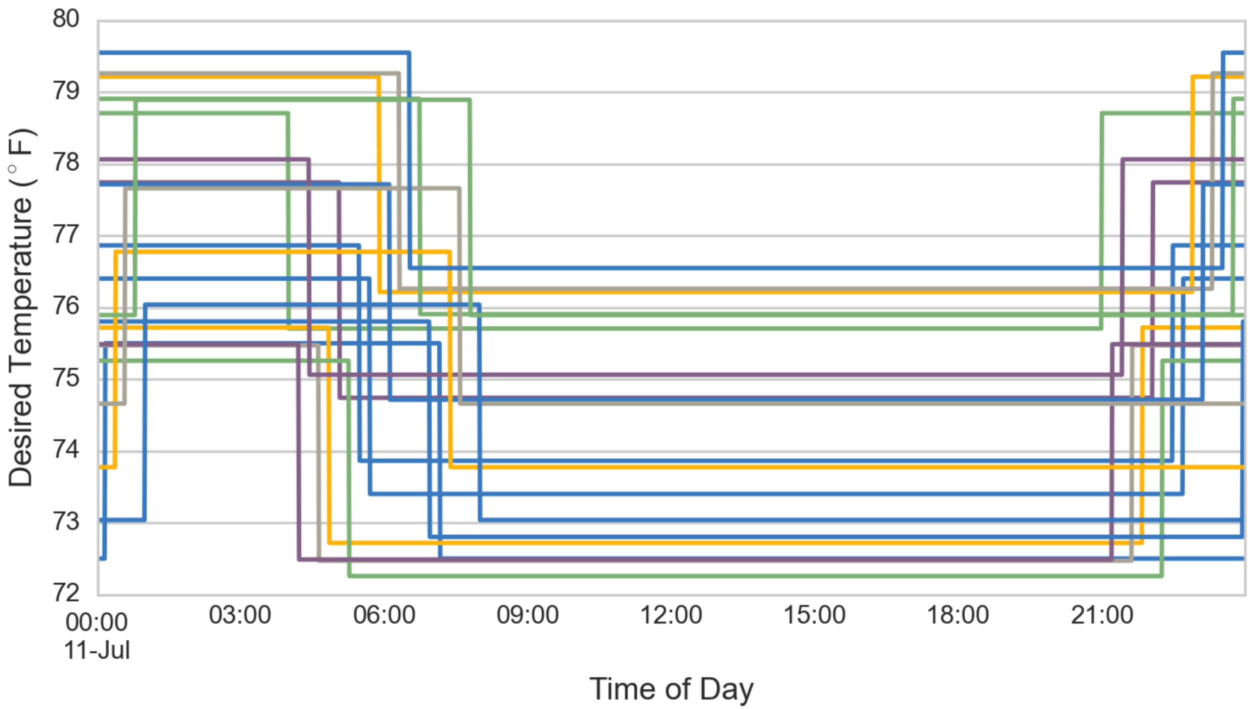


20 Houses on the IEEE 13-Node Feeder



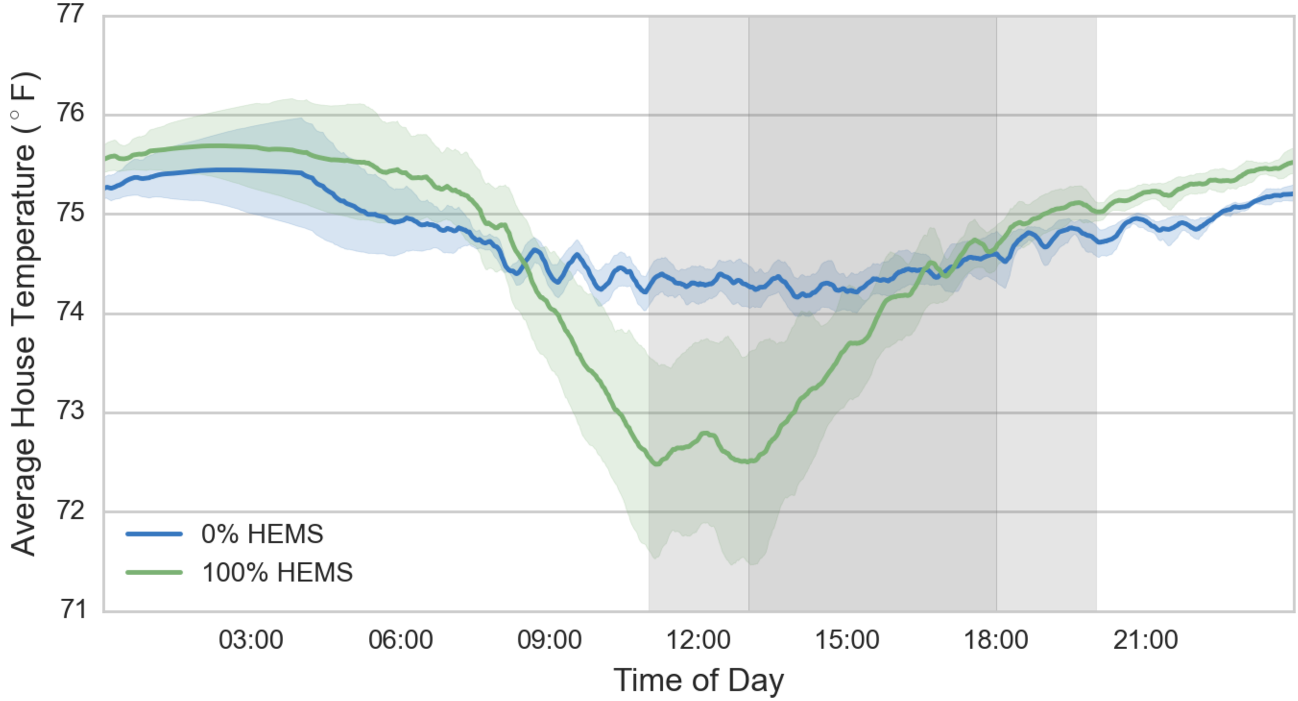
39

Varied House Temperature Schedules



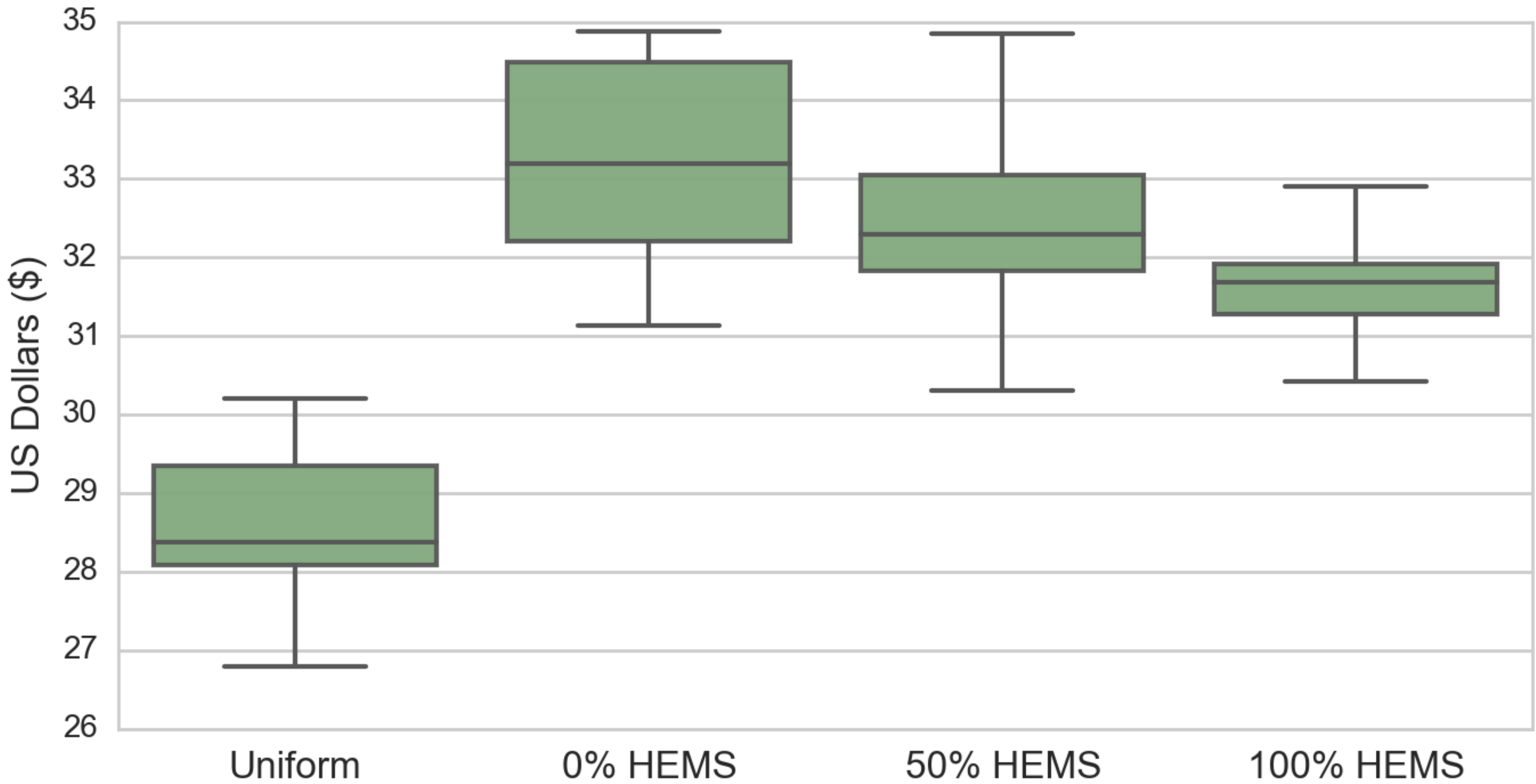
- Daytime temperatures: 72 - 77° F
- Start time: 4:00 and 8:00 AM
- Nightime mode after 16 hours – temperature increased by 3°F

HEMS Pre-Cools Houses



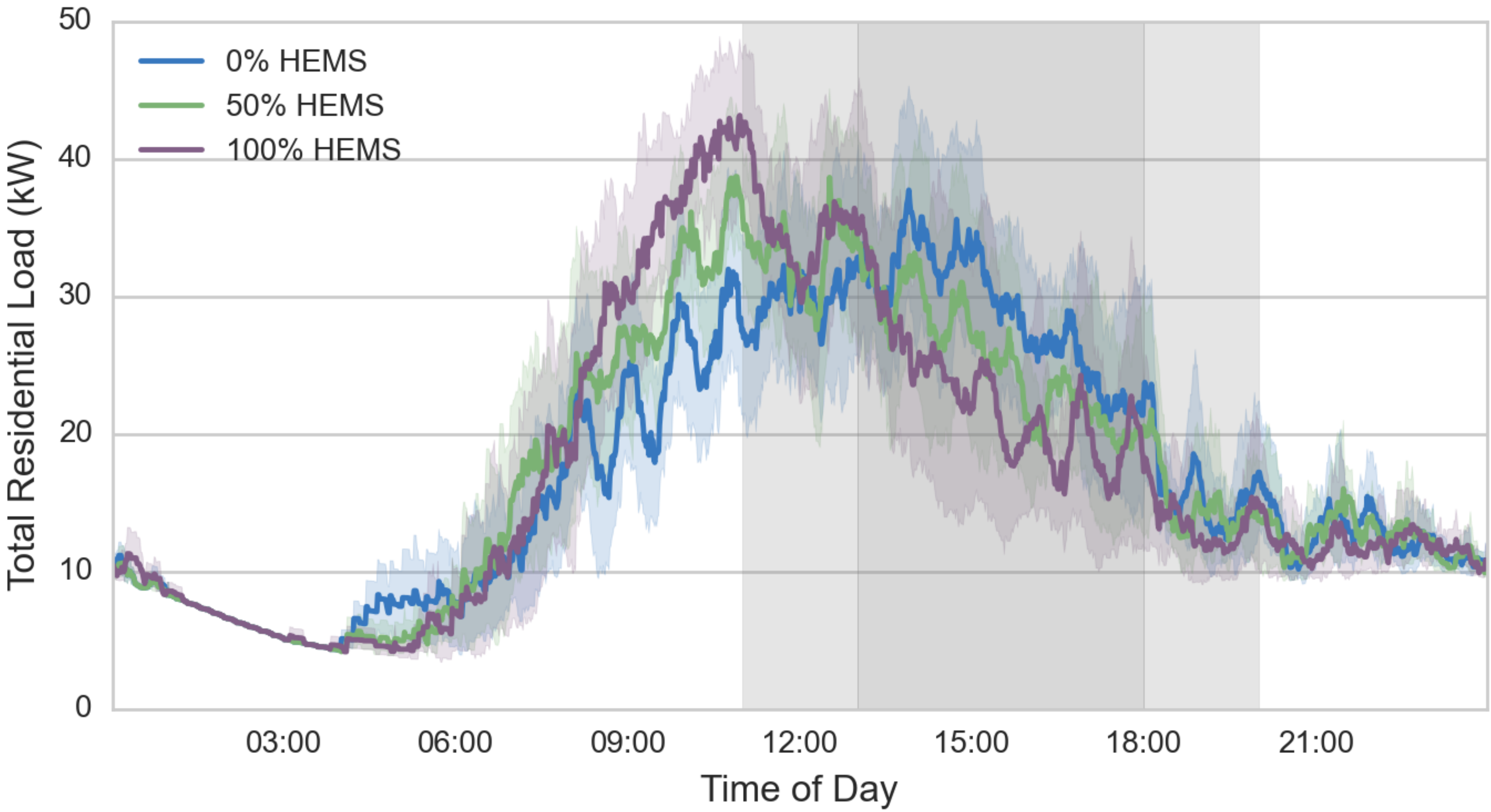
- **Average temperature about 2°F lower during shoulder period**
- **HEMS limits: desired temperature +0°F / -5°F**

HEMS Enables Cost Savings



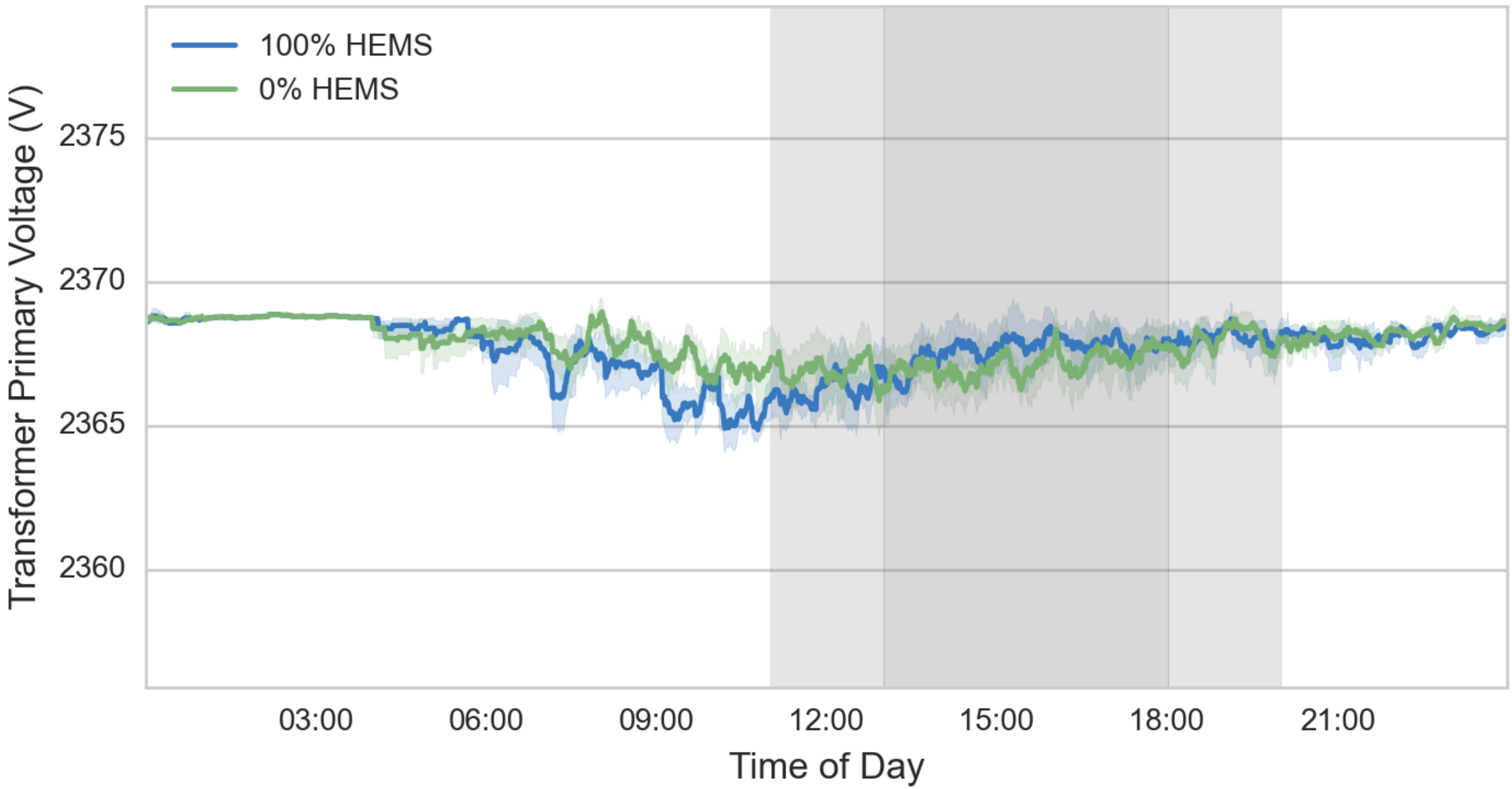
- **Average bill reduced by 5%**
- **Cumulative load is essentially unchanged**

Cooling Load Shifts Earlier & Peaks Higher



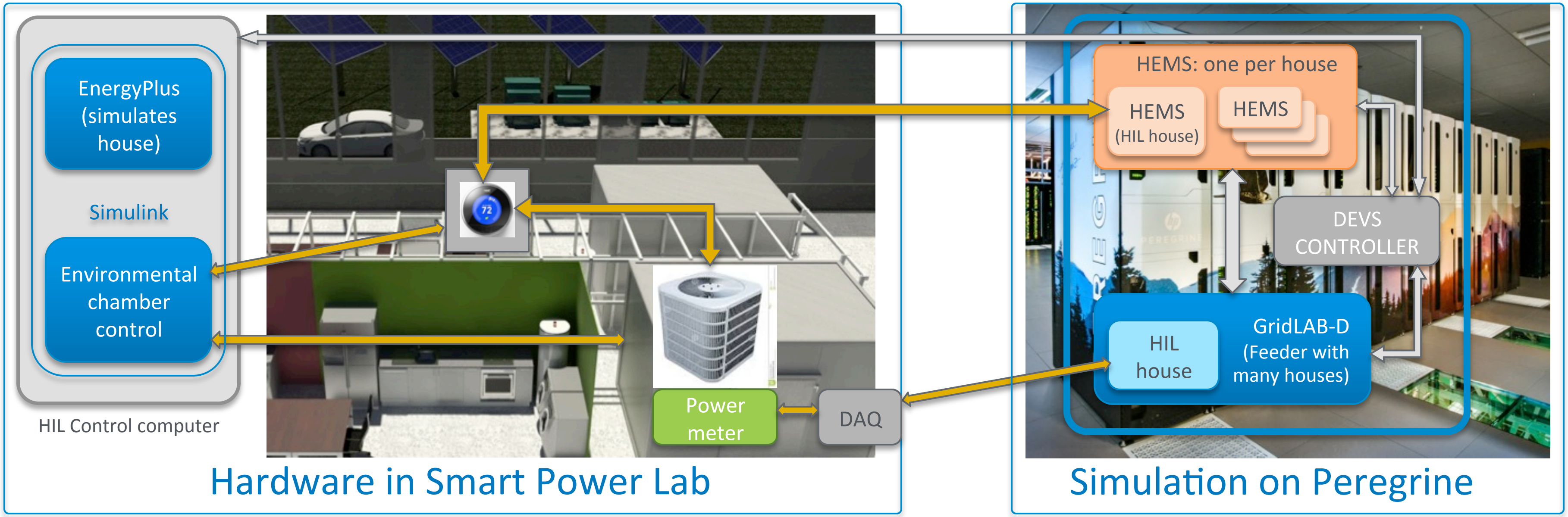
Could be mitigated by coordinated HEMS penetration, coordinated operation, and/or alternative pricing

And Causes Deeper Voltage Sag



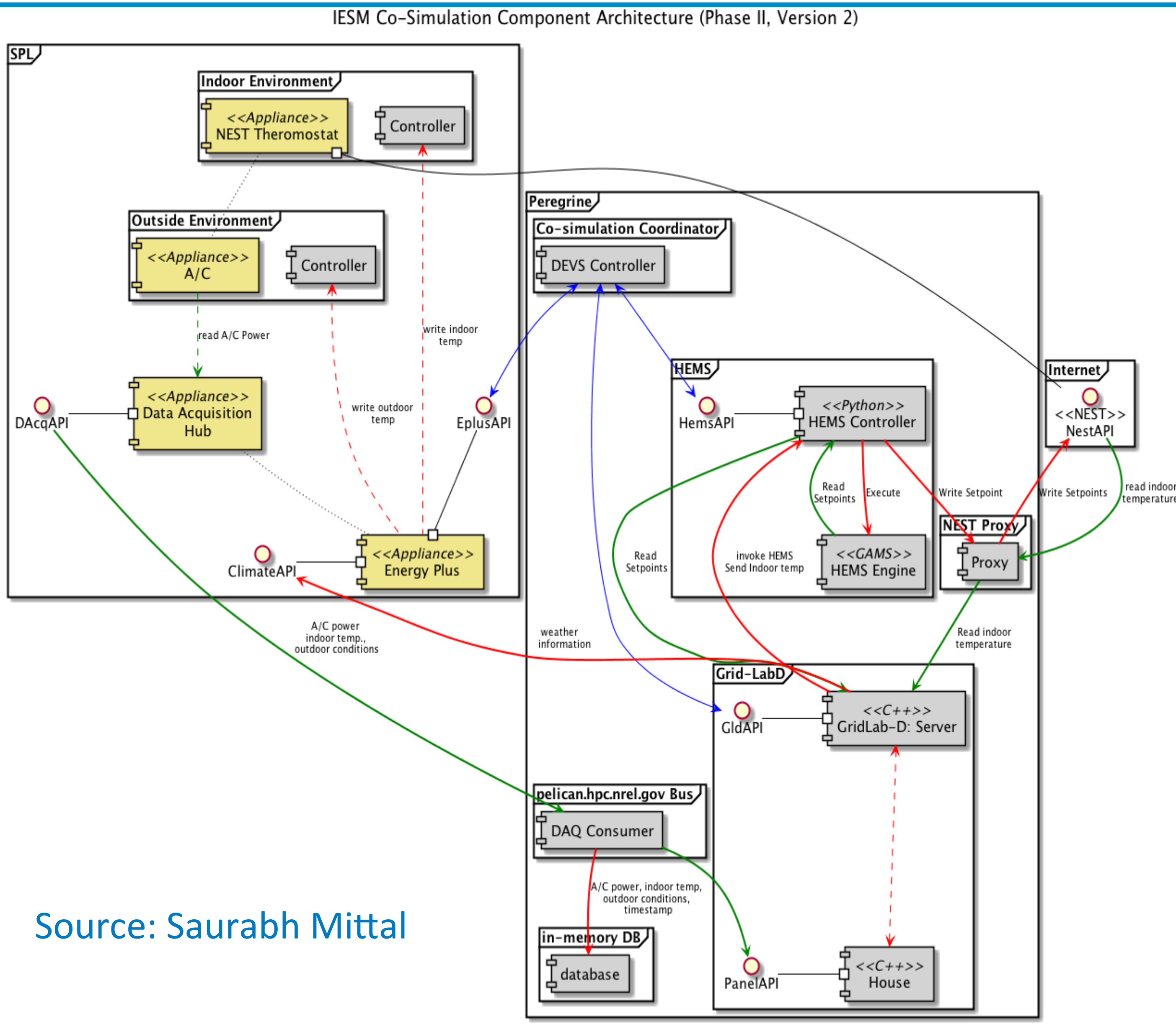
Node 646: Nominal load of 230 kW; 90% load fixed and 10% supplies the 5 houses that are simulated.

IESM Hardware in the Loop Testing



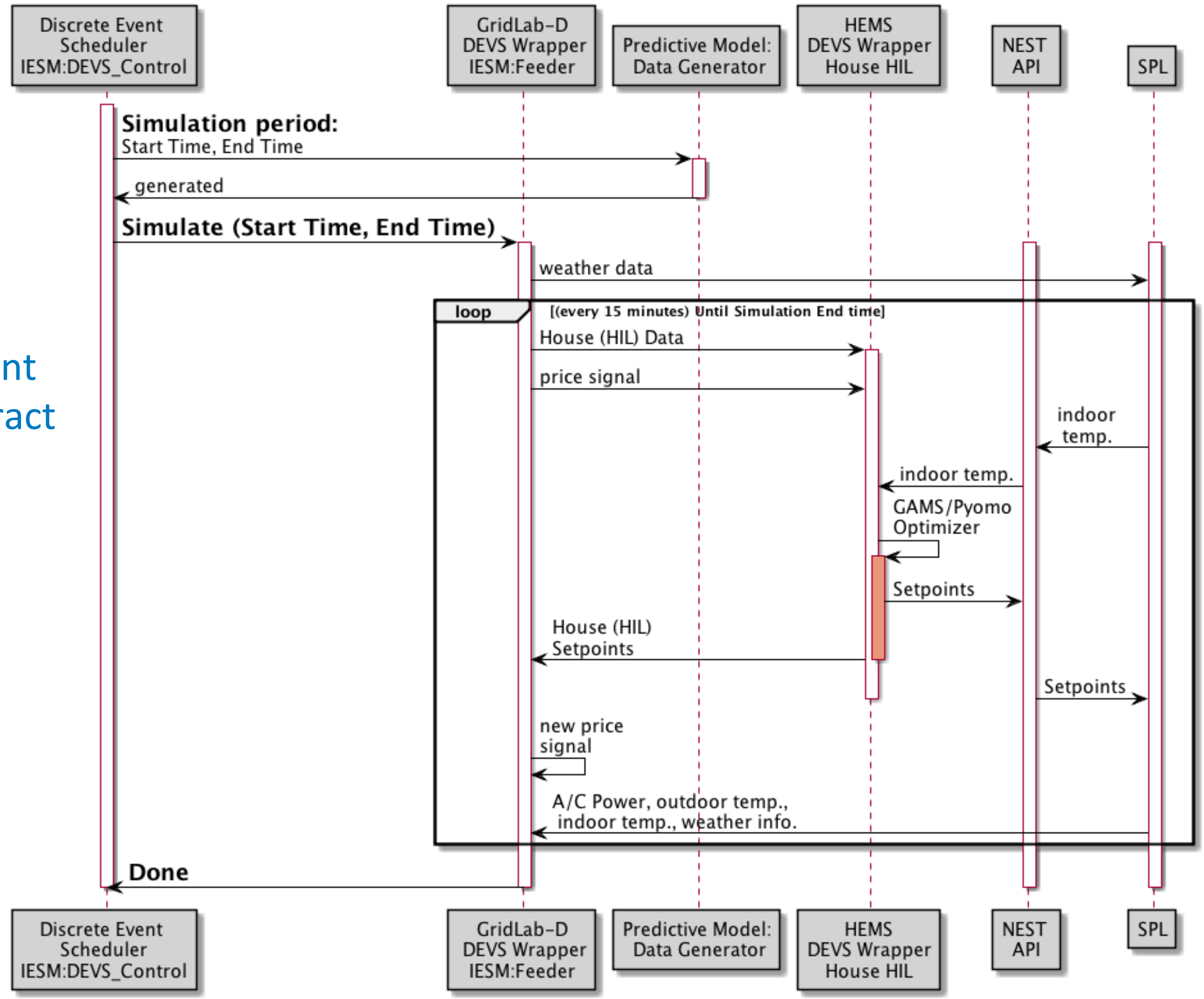
- Simulation on Peregrine of 13 node IEEE test feeder with 20 homes
- One home : air conditioner replaced with hardware in Smart Power Lab (SPL)
- EnergyPlus simulation of home in SPL
- HEMS controlling air conditioner in the lab

Co-Simulation Component Diagram



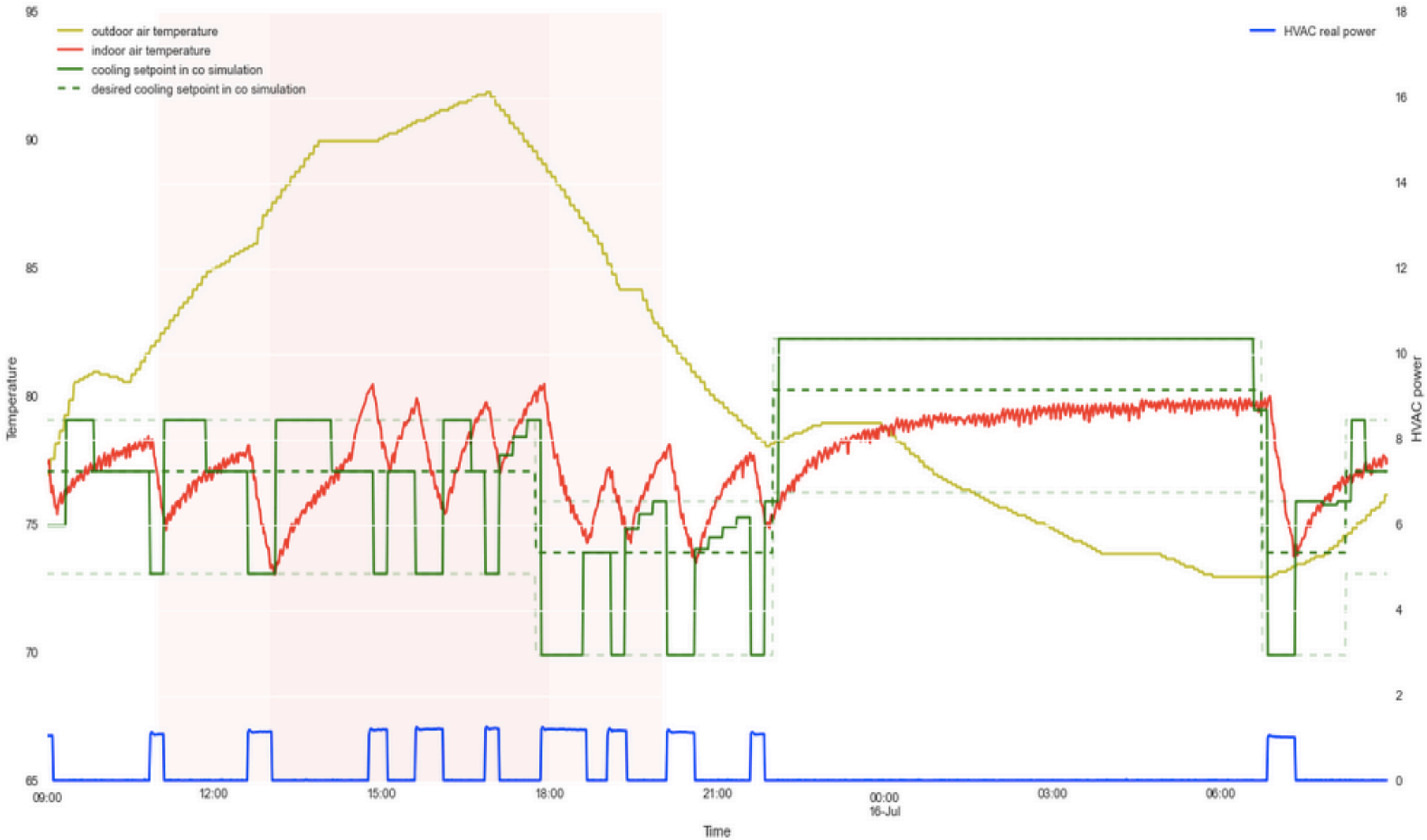
Source: Saurabh Mittal

Data Management and Sequencing

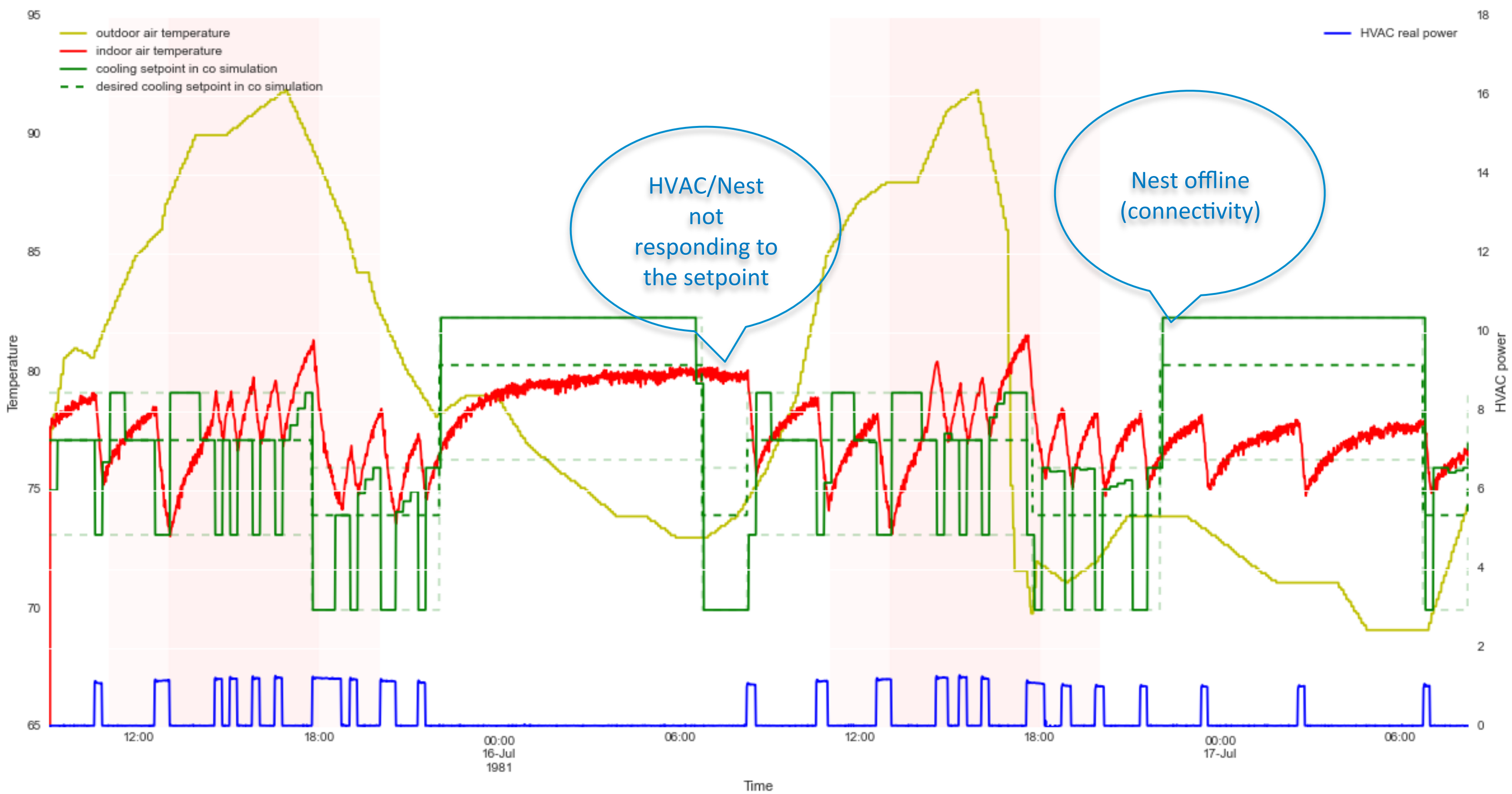


Uses Discrete-event Scheduler in abstract time

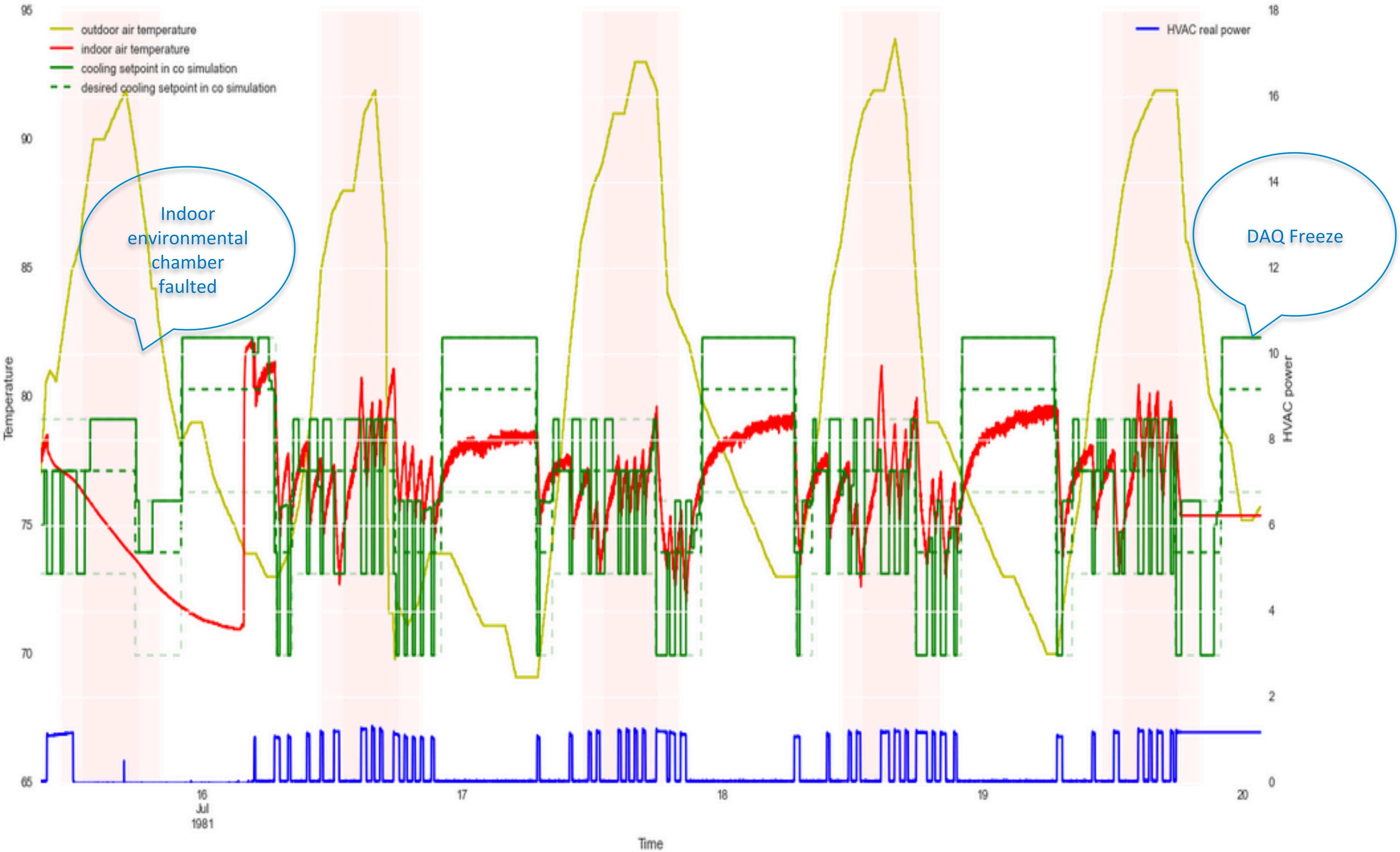
Run #6: Successful 1-Day Run



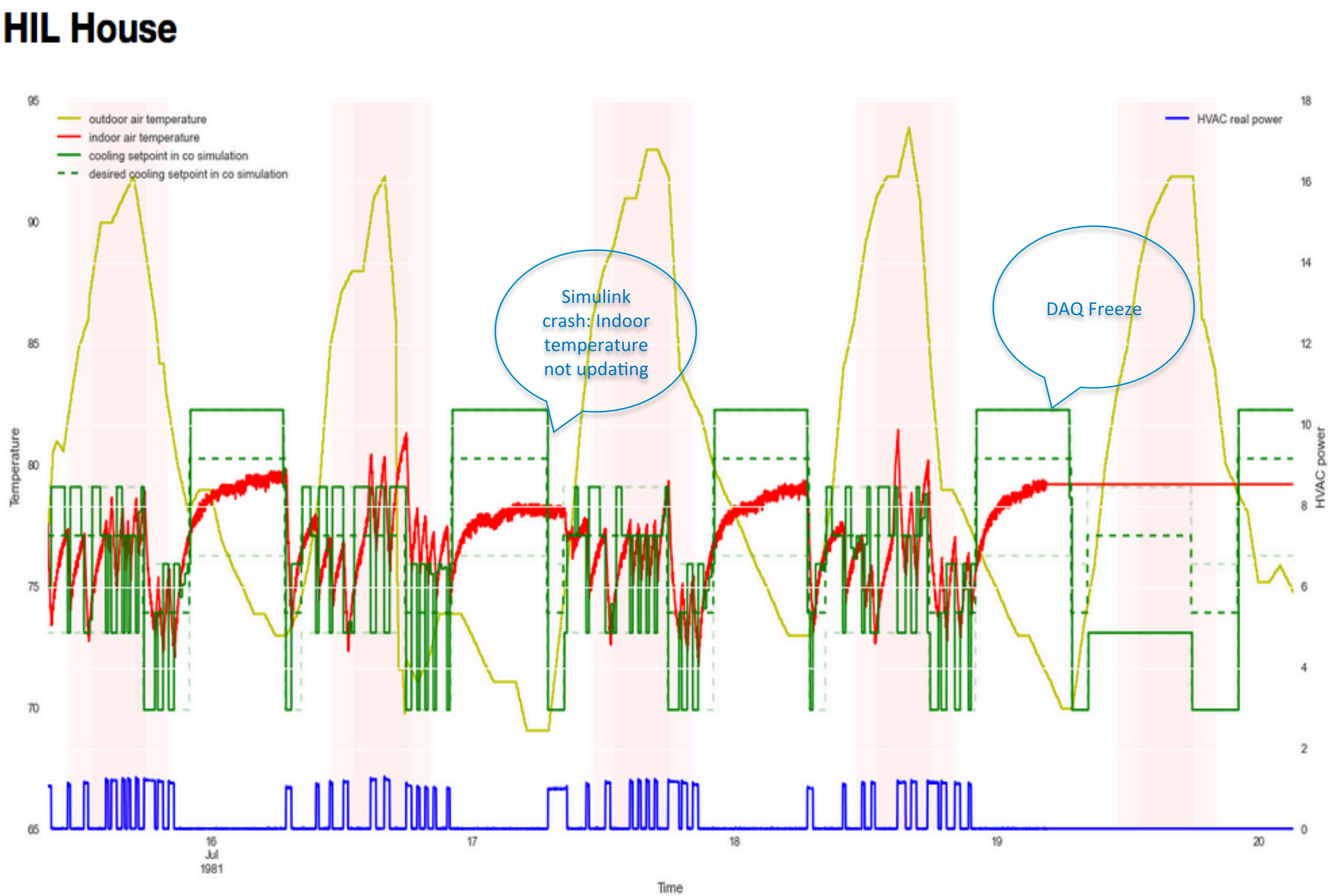
Run #5: 2-Day Run



Run #7 – Multiday Results

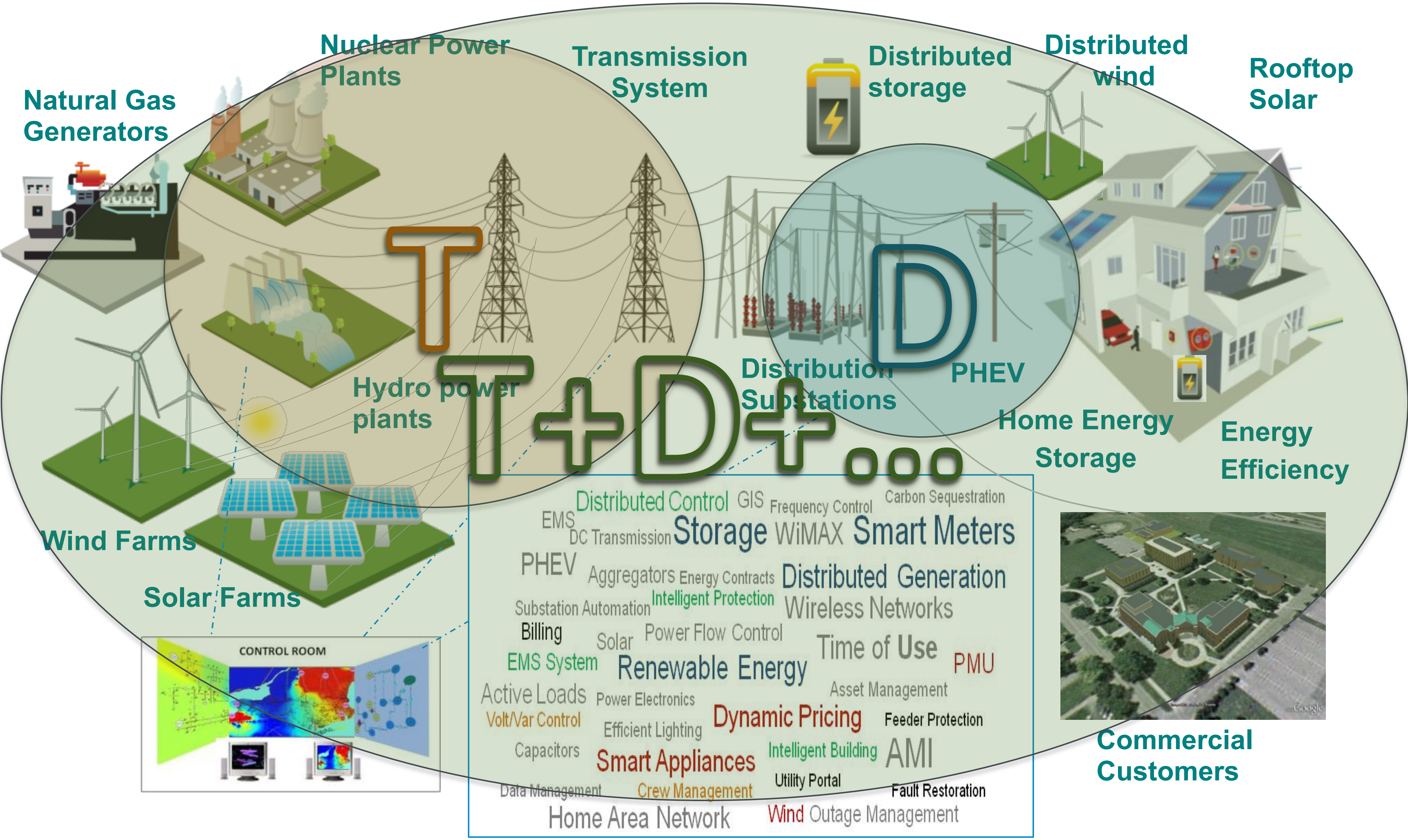


Run #10 – Multiday Results

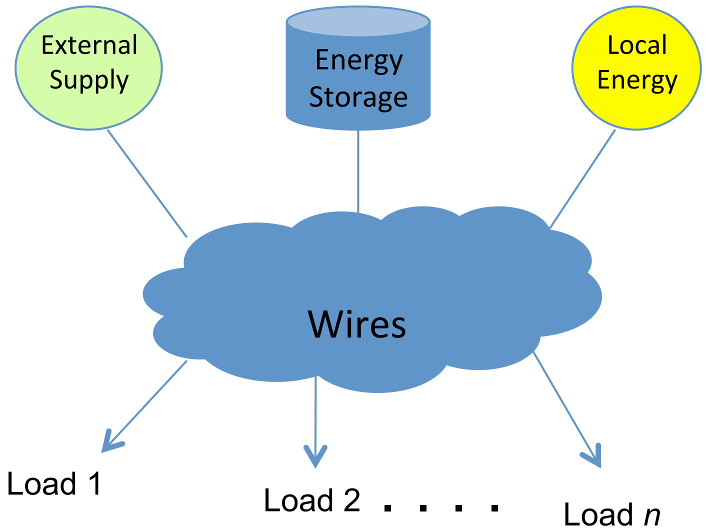


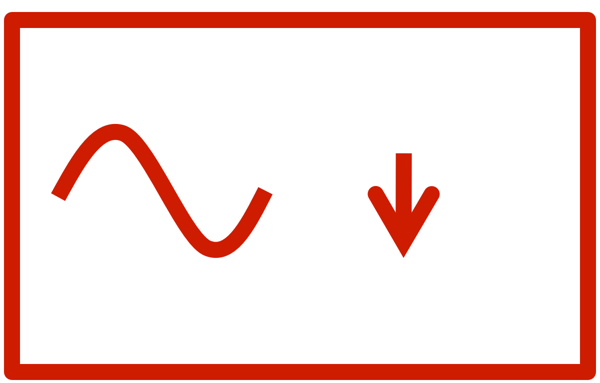
Integrated T&D

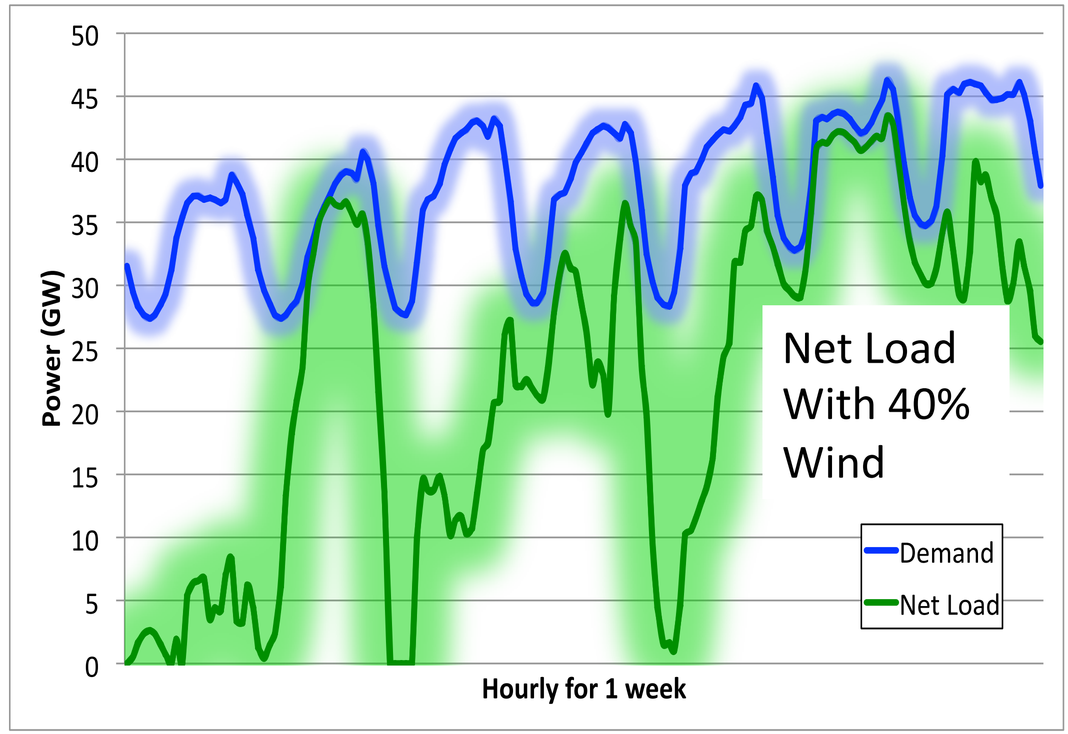
The Emerging, Integrated Grid



Prosumers and Net Energy



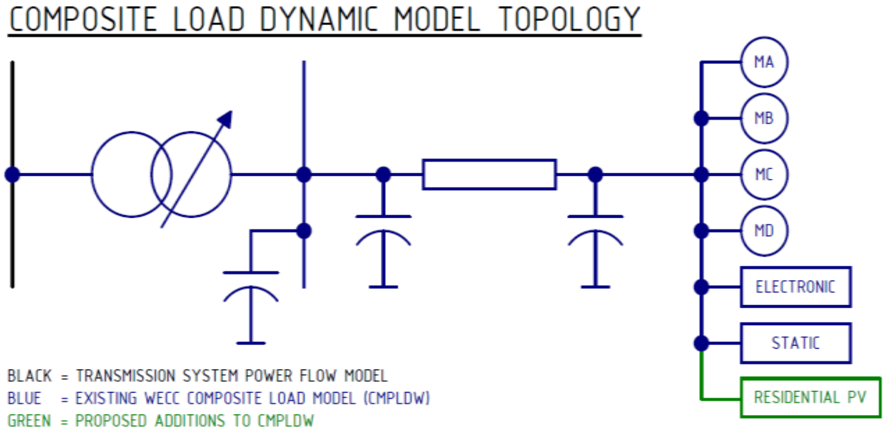




Net Load = Demand - Wind

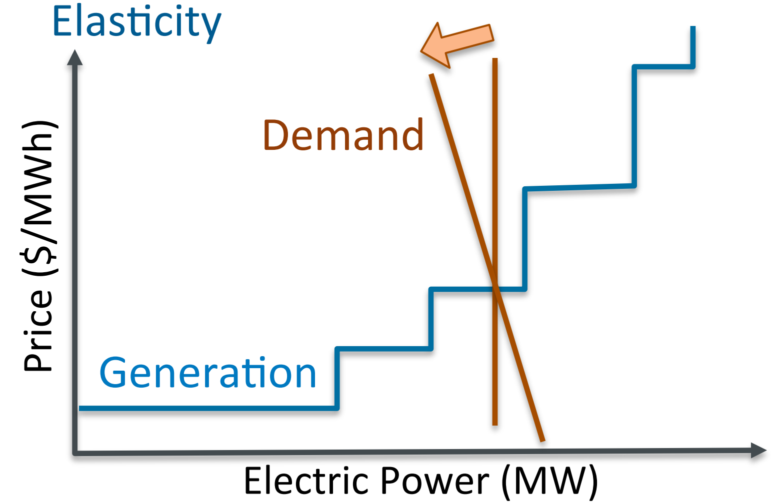
(Aggregated) Modeling of DERs

WECC



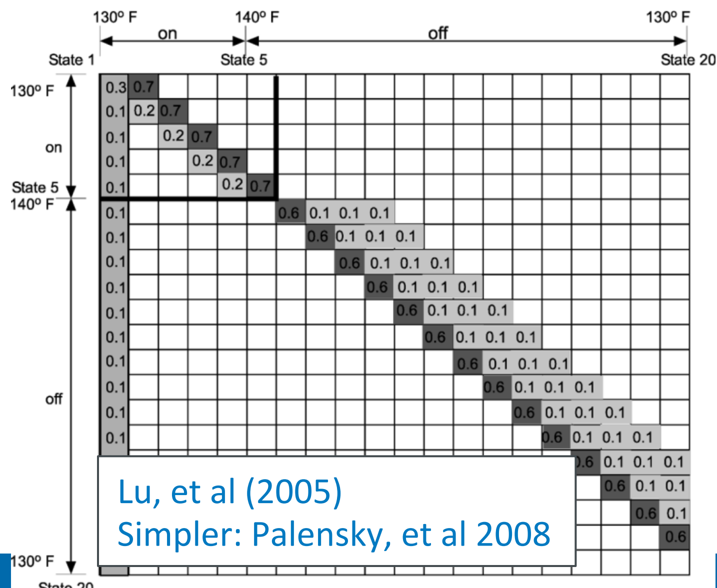
Kosterev, et al 2008. PV added: Ellis, et al (2011)

Elasticity

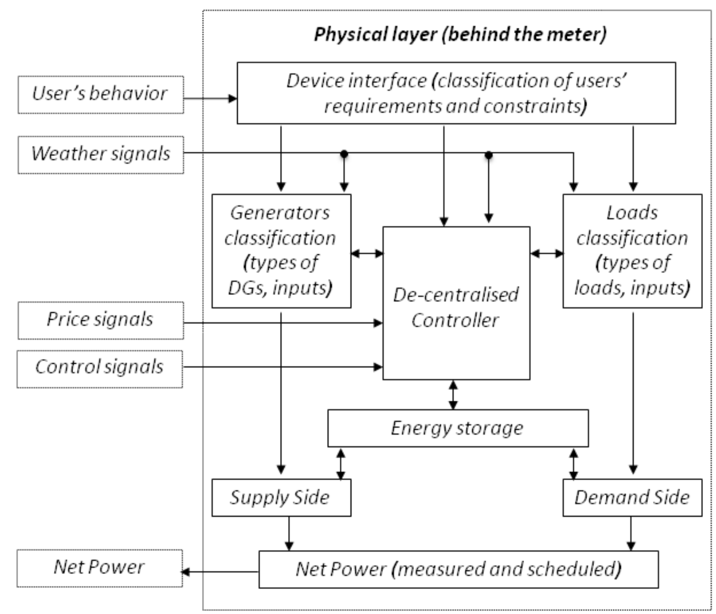


$$P_{start} = P_{season} P_{hour} P_{social-random}$$

Paatero & Lund (2005). Similar: Huang, Hodge, et al (2011)



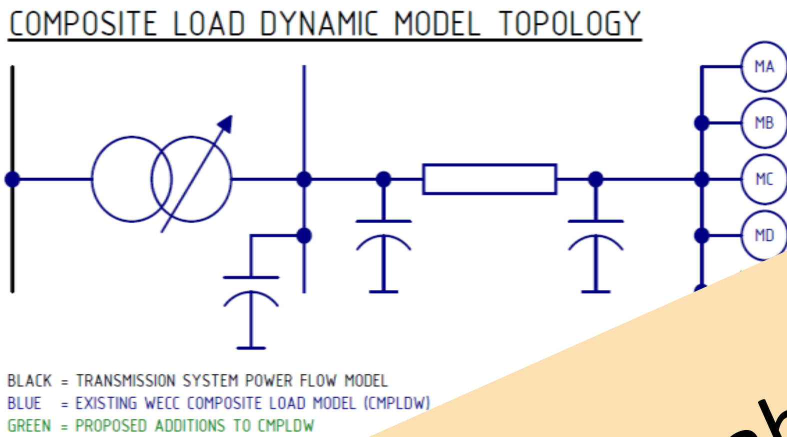
Lu, et al (2005)
Simpler: Palensky, et al 2008



Lampropoulos, et al 2010. Similar: Illic 2010

(Aggregated) Modeling of DERs

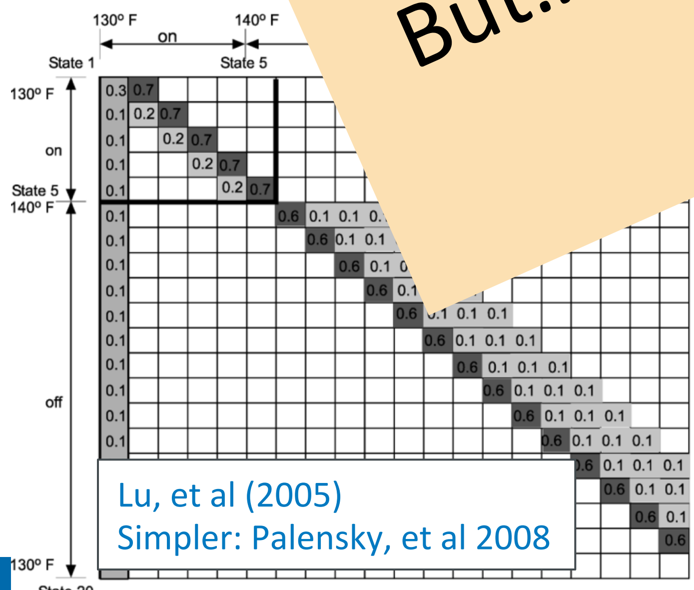
WECC



Kosterev, et al 2008. PV a

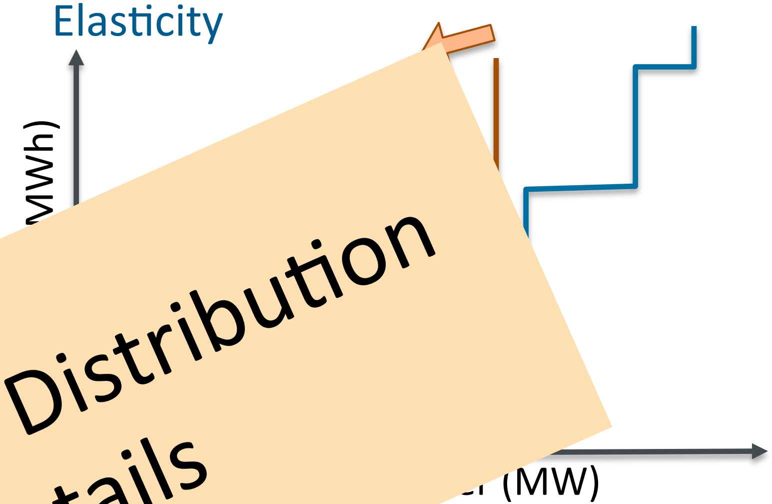
$P_{start} = P_s$

Paatero & Lund

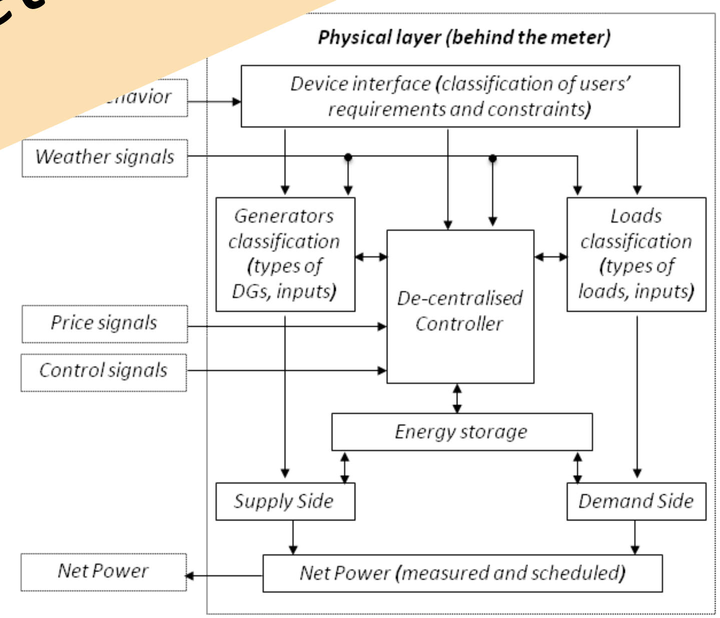


Lu, et al (2005)
Simpler: Palensky, et al 2008

Elasticity



But... What about Distribution System Details



Lampropoulos, et al 2010. Similar: Illic 2010

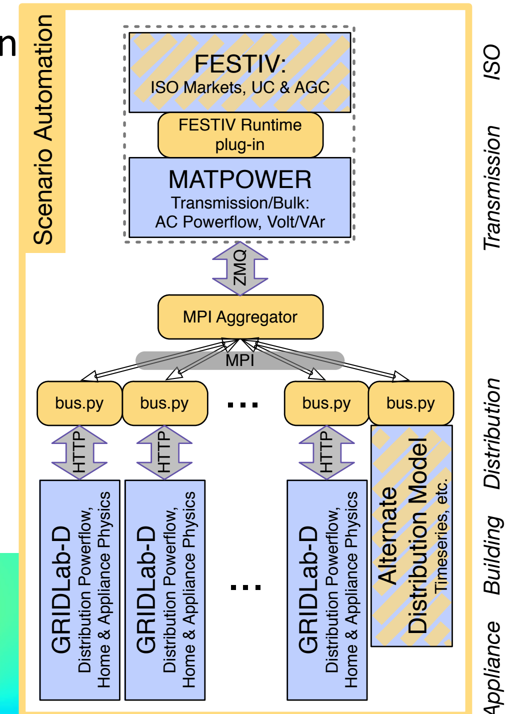
Research Questions

- *DER-Wholesale market interactions*
- *Can **ISO**-level **visibility of DGPV** reduce required bulk system **reserve requirements** while maintaining reliability standards?*
- *To what extent can high penetration **DER-bulk** system **reactive power and voltage** interactions?*
- *Spatial ride-through (V and freq)*
- *What are the bulk operational impacts of advanced **distributed control algorithms**?*
- *Physical limits to Demand Response*

NREL's Integrated T&D Grid Modeling System (IGMS)

Summary:

A next-generation analysis framework for full-scale transmission&distribution modeling that supports millions of highly distributed energy resources.



End-to-End T&D Modeling Capability

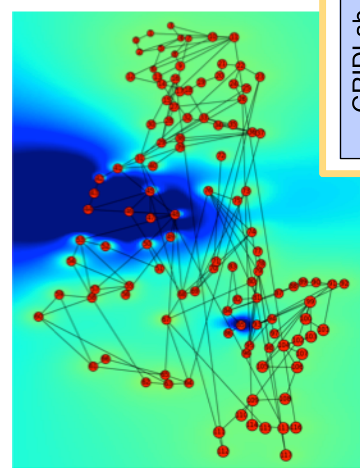
- detailed multi-period wholesale markets (including LMPs)
- generator/reserve dispatch (AGC)
- AC Powerflow (bulk transmission)
- Full unbalanced 3-ph power flow for 100s-1000s of distribution feeders
- Physics based end-use models of buildings and end-use loads.

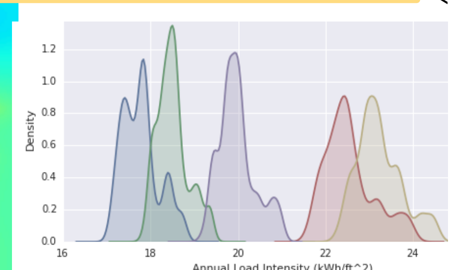
Example Applications

- **Current**: Analyze distributed PV support for grid operations
- **Future:**
  - Simulate smart grid storage, PV, and demand response
  - Simulate alternative market and service architectures
  - Co-simulation with Hardware via PHIL
  - Connect to Advanced DMS/EMS systems

Highlights

- **Successful Medium Scale Run(s): 118 Transmission buses, 743 Distribution Feeders** (PNNL taxonomy)**, >1M total buses, >600k homes**
- **FY15 DoE Solar-SI funded (following FY14 LDRD):**
  - Automated output processing and visuals
  - Semi-Automated import from PLEXOS, SynerGEE, & CyME
  - Comparison of IGMS to stand-alone tools
- **FY16+ (part of >8 proposed projects):**
  - Grid Modernization: T+D+C team, other
  - Enhanced Market/Tariff/EMS support



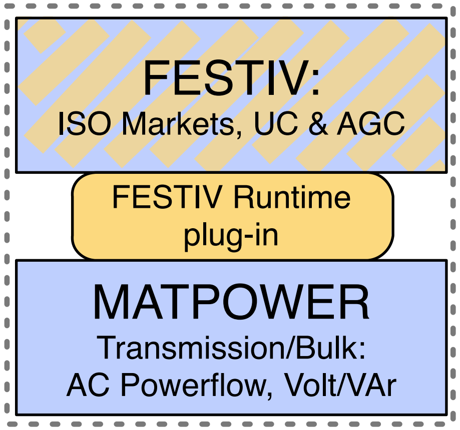


NREL's Integrated Grid Modeling System (IGMS) provides a first-of-a-kind co-simulation with transmission-level markets, 1000s of distribution feeders, and 1Ms of DERs

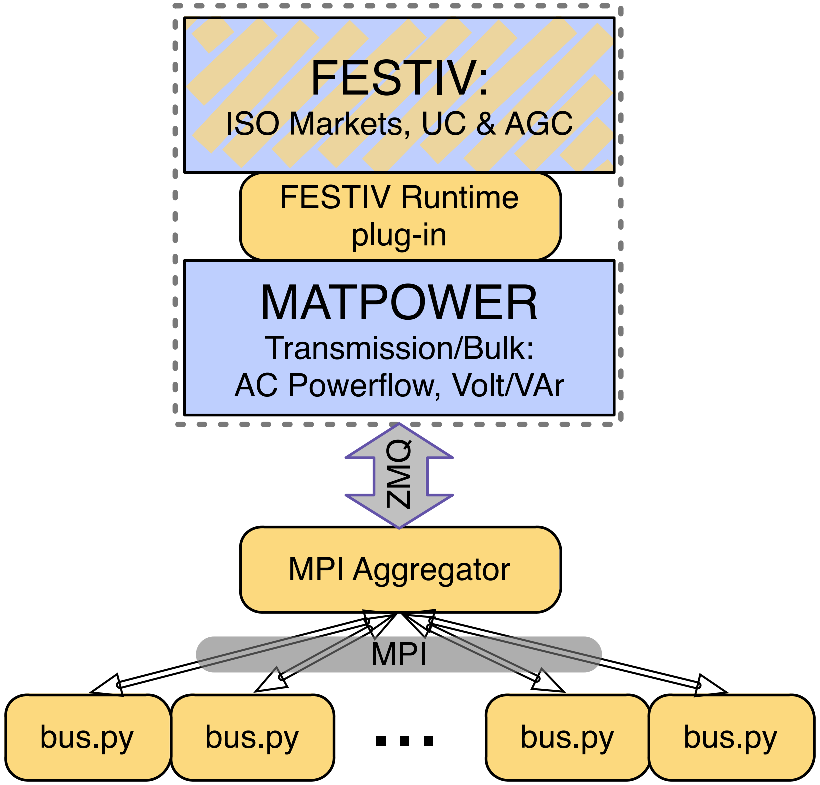
FESTIV:
ISO Markets, UC & AGC

- Day-Ahead Commitment
- Real-time Commitment
- Real-time Dispatch
- AGC reserves

- AC Powerflow (pos-seq, balanced)

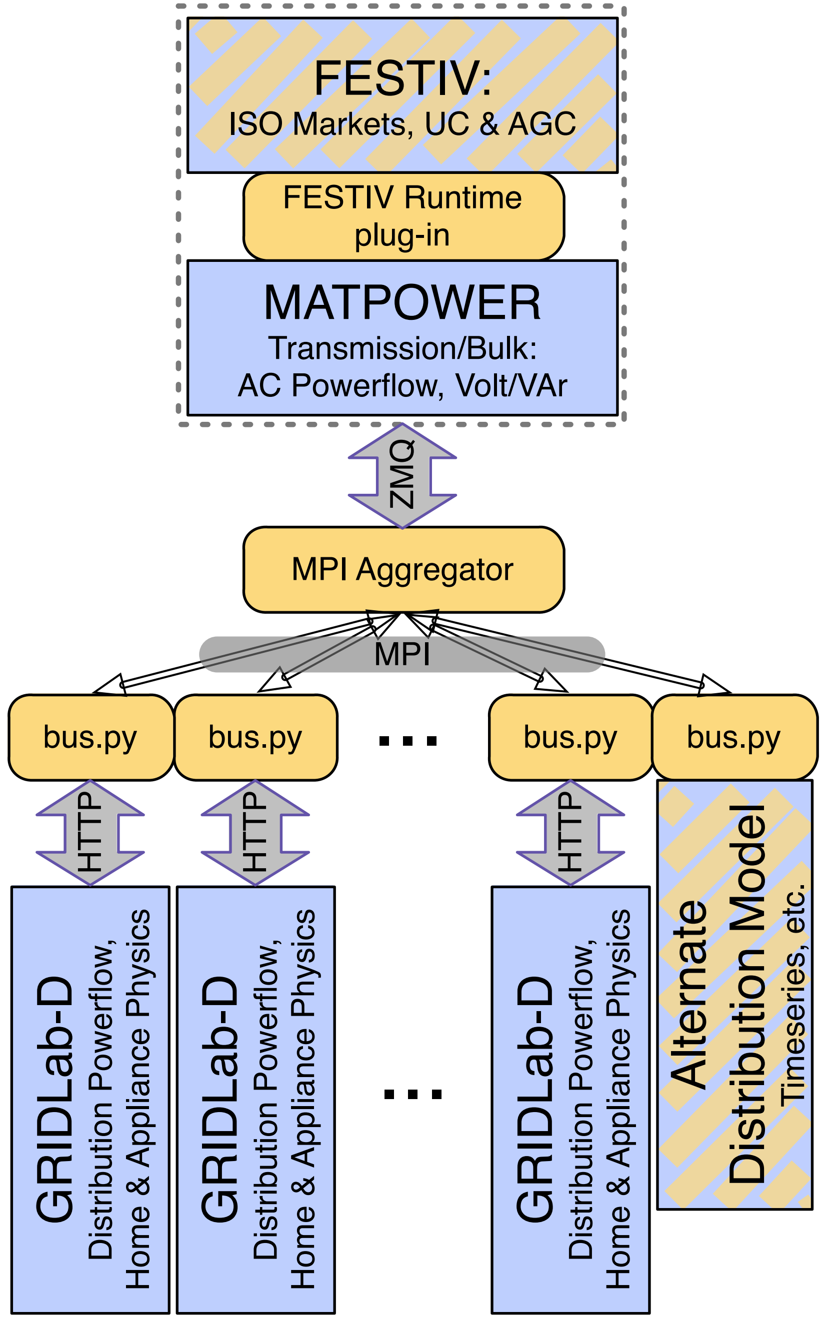


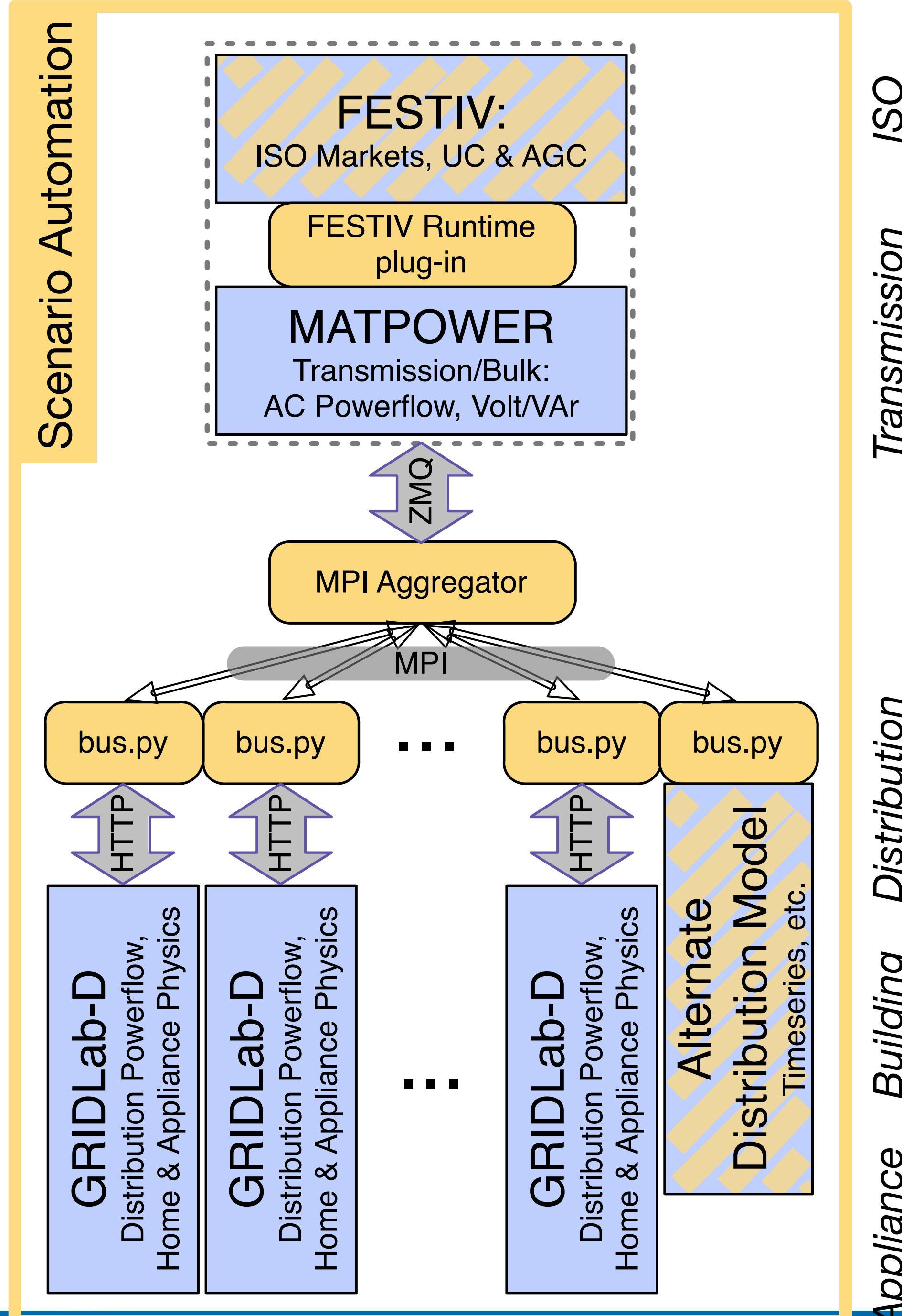
- Nodal:
  - Prices
  - Services
  - Voltage



- Return:
  - Power
  - Reactive
  - (Bids)

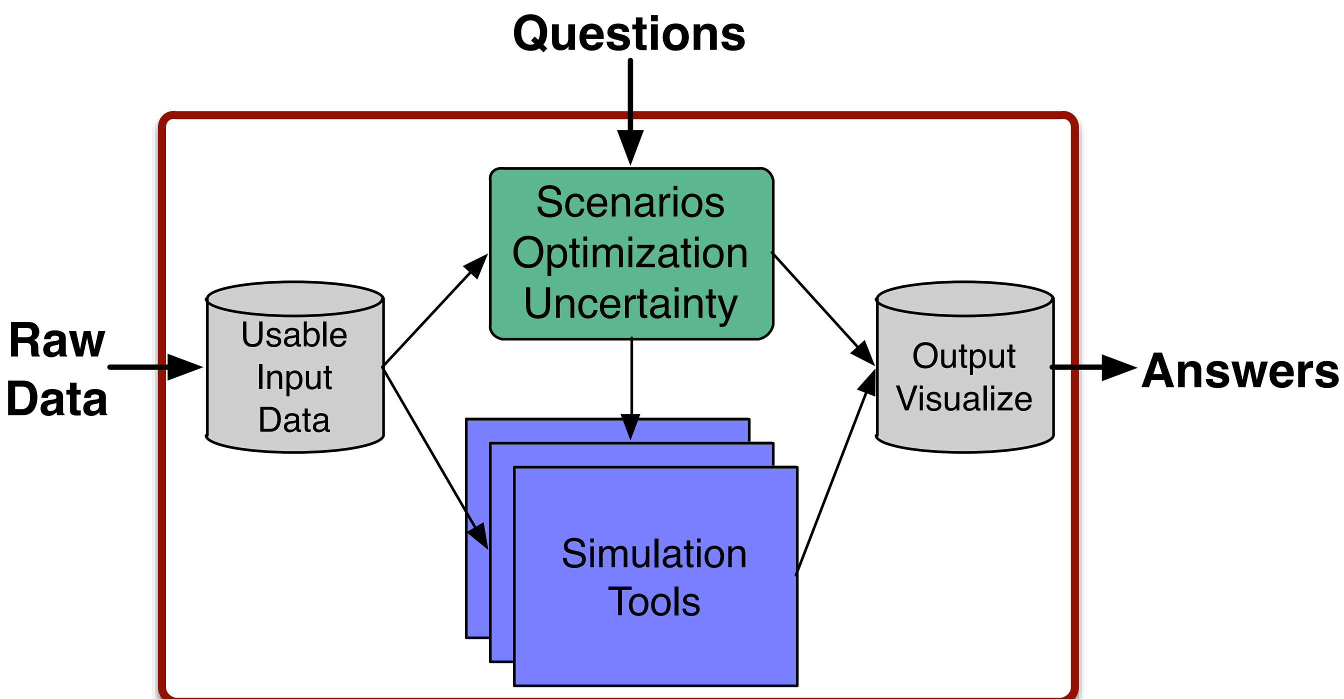
- 3-ph unbalanced powerflow
- Physics:
  - DERs
  - Load




Scenario Automation
FESTIV:
ISO Markets, UC & AGC
FESTIV Runtime plug-in
MATPOWER
Transmission/Bulk:
AC Powerflow, Volt/VAr
ZMQ
MPI Aggregator
MPI
bus.py
bus.py
...
bus.py
bus.py
HTTP
HTTP
HTTP
GRIDLab-D
Distribution Powerflow,
Home & Appliance Physics
GRIDLab-D
Distribution Powerflow,
Home & Appliance Physics
...
GRIDLab-D
Distribution Powerflow,
Home & Appliance Physics
Alternate
Distribution Model
Timeseries, etc.
ISO
Transmission
Distribution
Building
Appliance

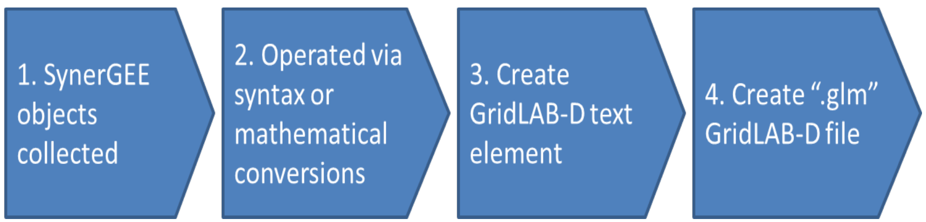
Analysis Workflow

Often the simulation itself is the "easy" part, compared to set-up and output analysis



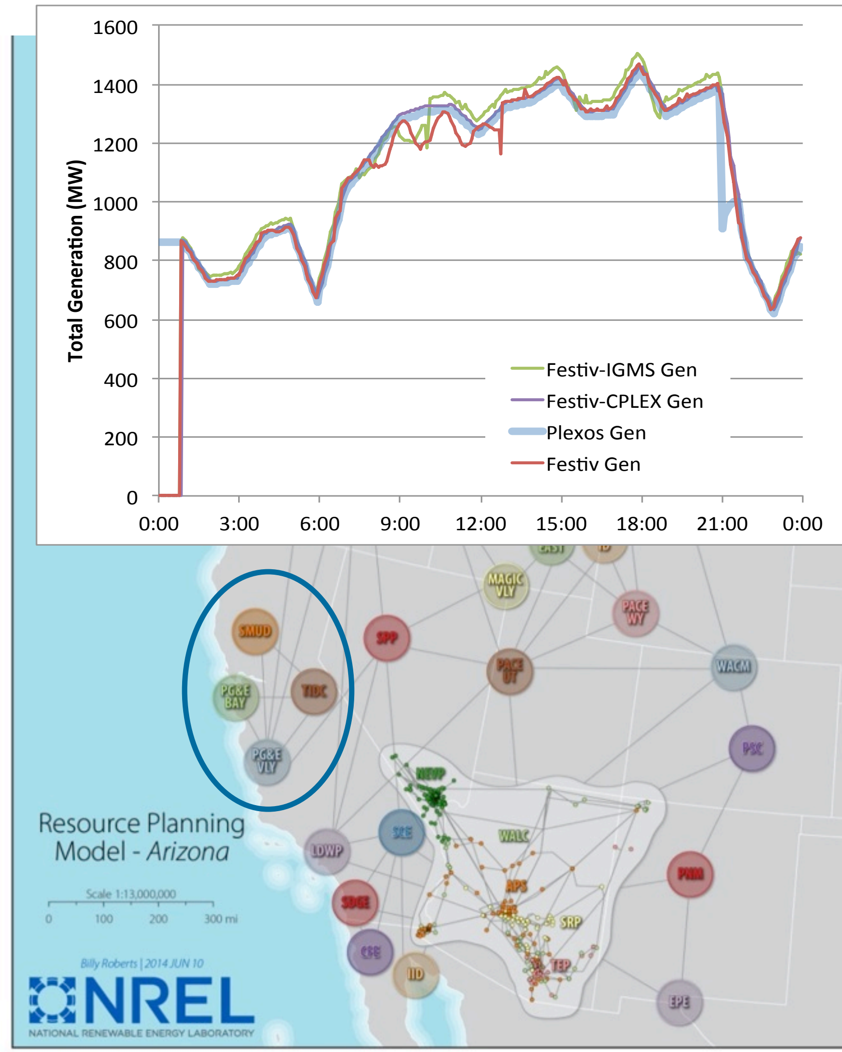
IGMS-Input Data Conversion

Distribution: SynerGEE and CYME to GridLAB-D



POC: Julieta Giraldez

Transmission: PLEXOS to FESTIV – with RPM



IGMS-Populating Feeders with Houses & PV

Scenario

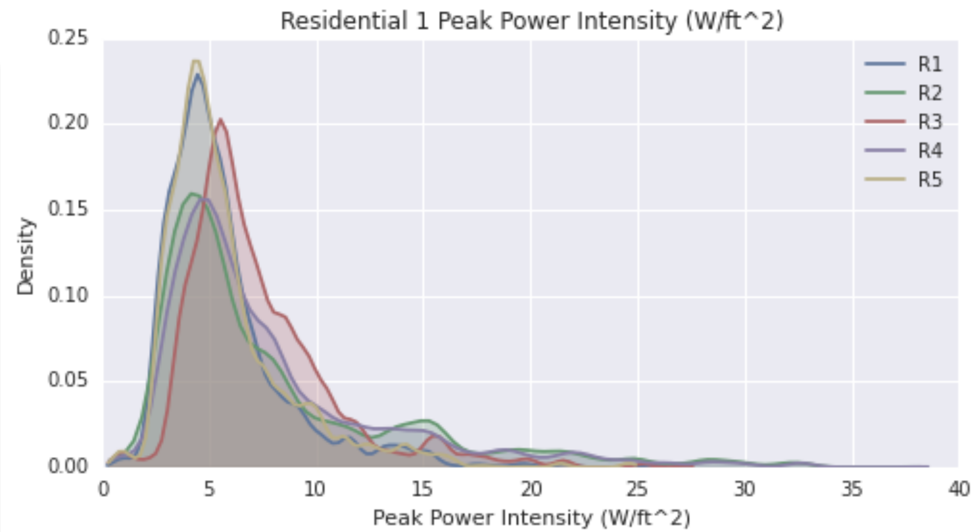
```
sim start: 4/16/2020
sim duration: 1 d
sim timestep: 1 min
```

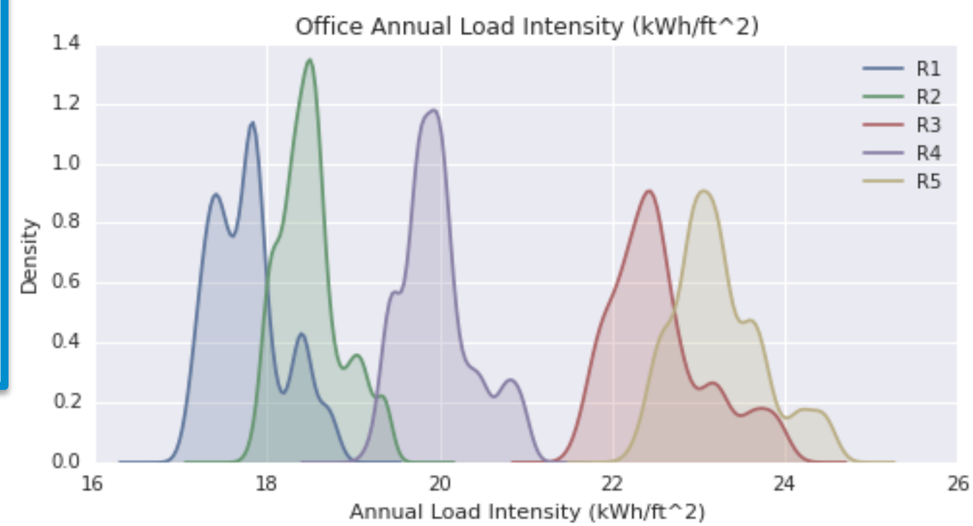
Transmission
- FESTIV case
- IGMS-FESTIV model rules and configuration
- Startup .mat file

Distribution
- Assign feeder models to nodes
- glmgen options for populating GridLAB-D
- LHS sampling

bus.py setup

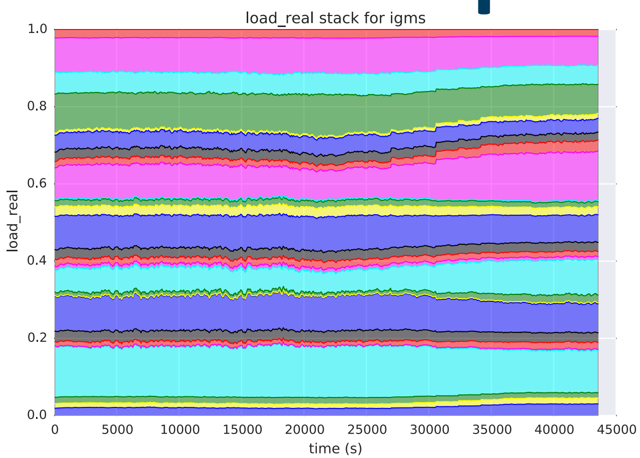
```
MultiNodeBus GridlabBus
ConstantBus FileBus
```

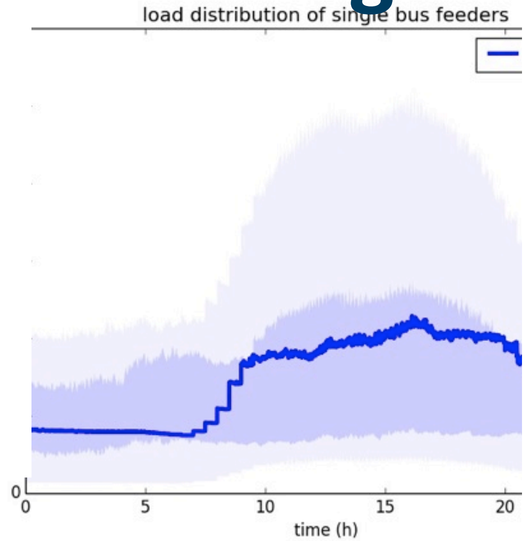


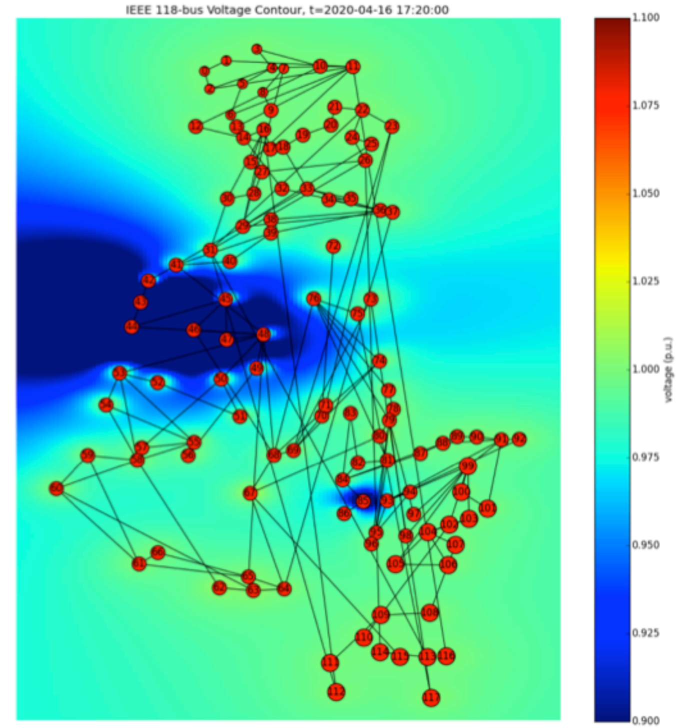


Core feeder processing built on evolved form of Open Modeling Framework

IGMS-Output Processing

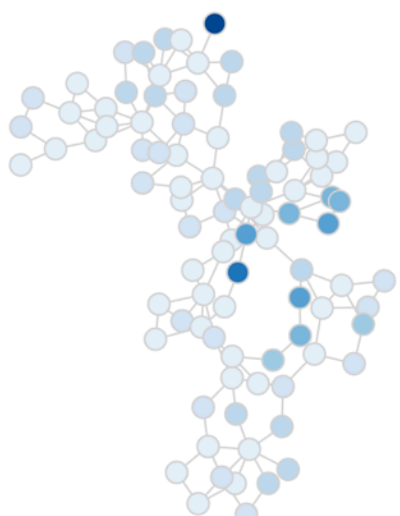


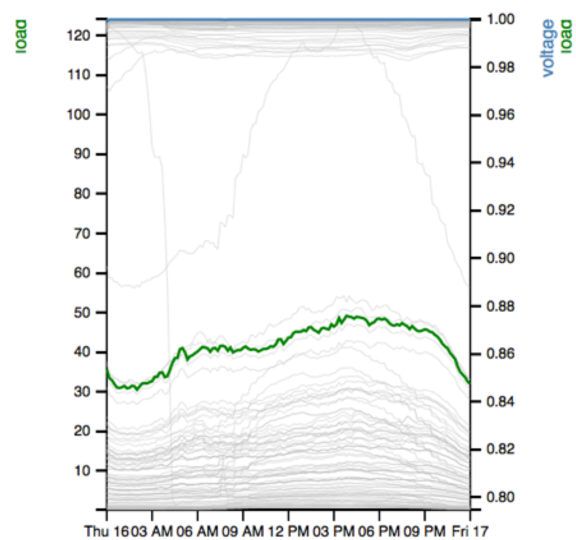


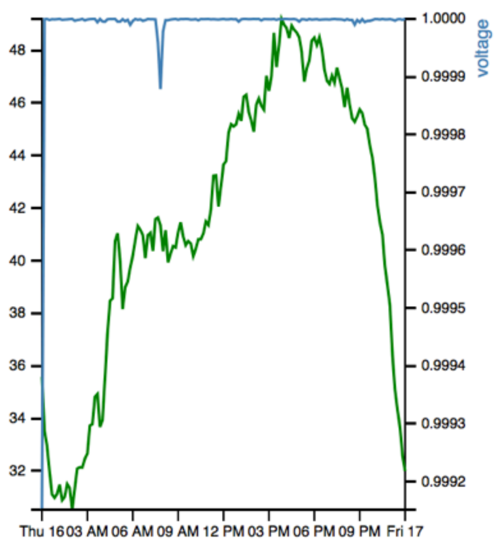


Load and Voltage

The B56 nodes in the graph are colored by their maximum change in voltage, where darker colors have a greater change.

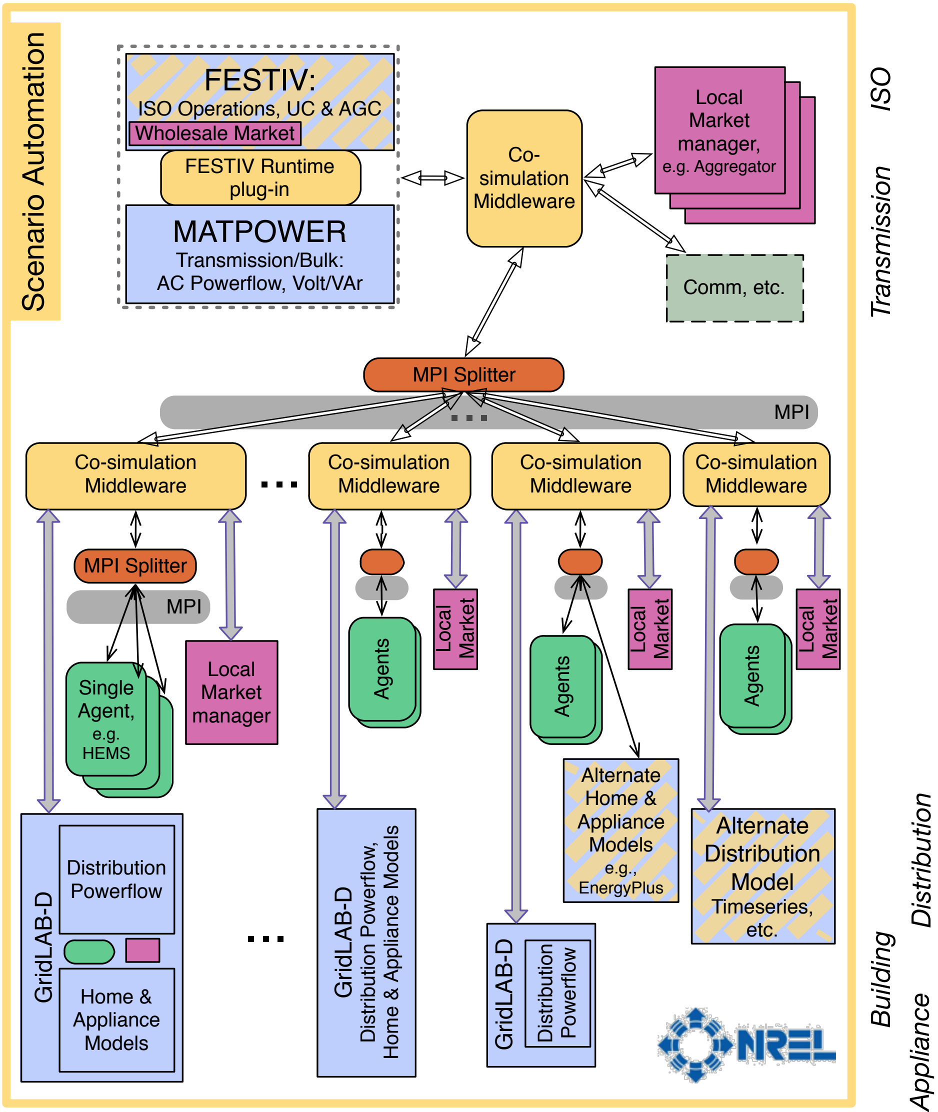






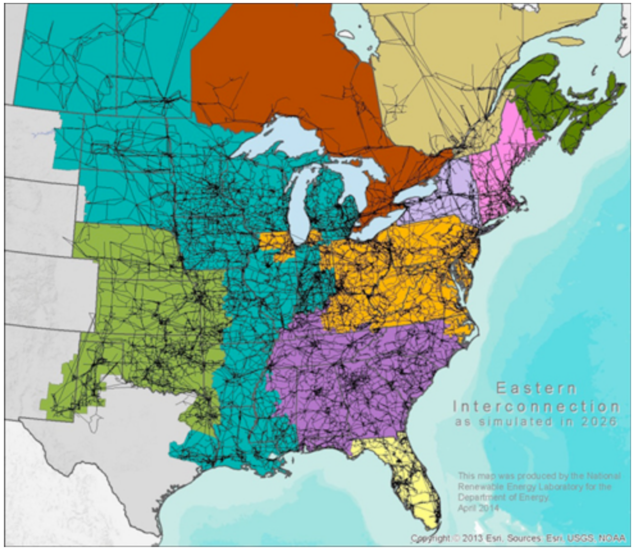
IGMS + IESM: Prosumer as Price maker

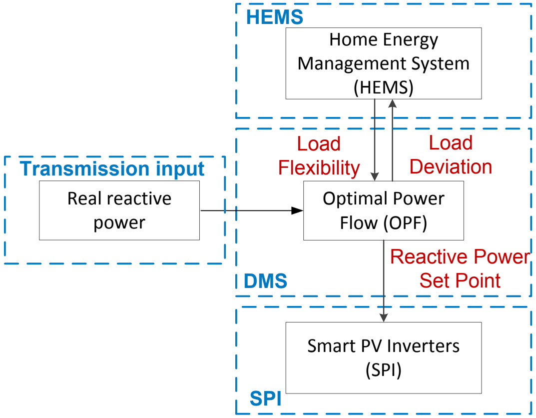
- **Strong Complements:**
  - IGMS: Bulk + many D
  - IESM: D + many HEMS
- **Potential:**
  - ISO - Smart Appliance
  - Bulk + Distribution Market Interactions
  - Shared Hierarchical, Scalable Co-simulation



Other HPC for planning efforts at NREL

- Time domain parallelization of (very) large PLEXOS production cost—nodal EI: 60k (Clayton Barrows and Aaron Townsend)
- Distributed Energy Scheduler—control framework simulations in IGMS (Emiliano Dall'Anese)
- Energy+ and PLEXOS for DR (Elaine Hale)





Future directions for T+D

- **IGMS + IESM = "Prosumer as price maker"**
- **Enhance economic analysis in IGMS**
  - Retail-Wholesale market interactions
  - Customer and utility accounting
- **T+D+… Comms, Loads, Markets, etc.**
- **Large-scale simulations for Power Hardware-in-the-Loop**

Questions

Thanks!

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