NREL
NATIONAL RENEWABLE ENERGY LABORATORY





Integrated Models for Transmission & Distribution *plus*

Bonus 1: Unit Commitment + Planning

Bonus 2: Distribution Steady-State + PHIL

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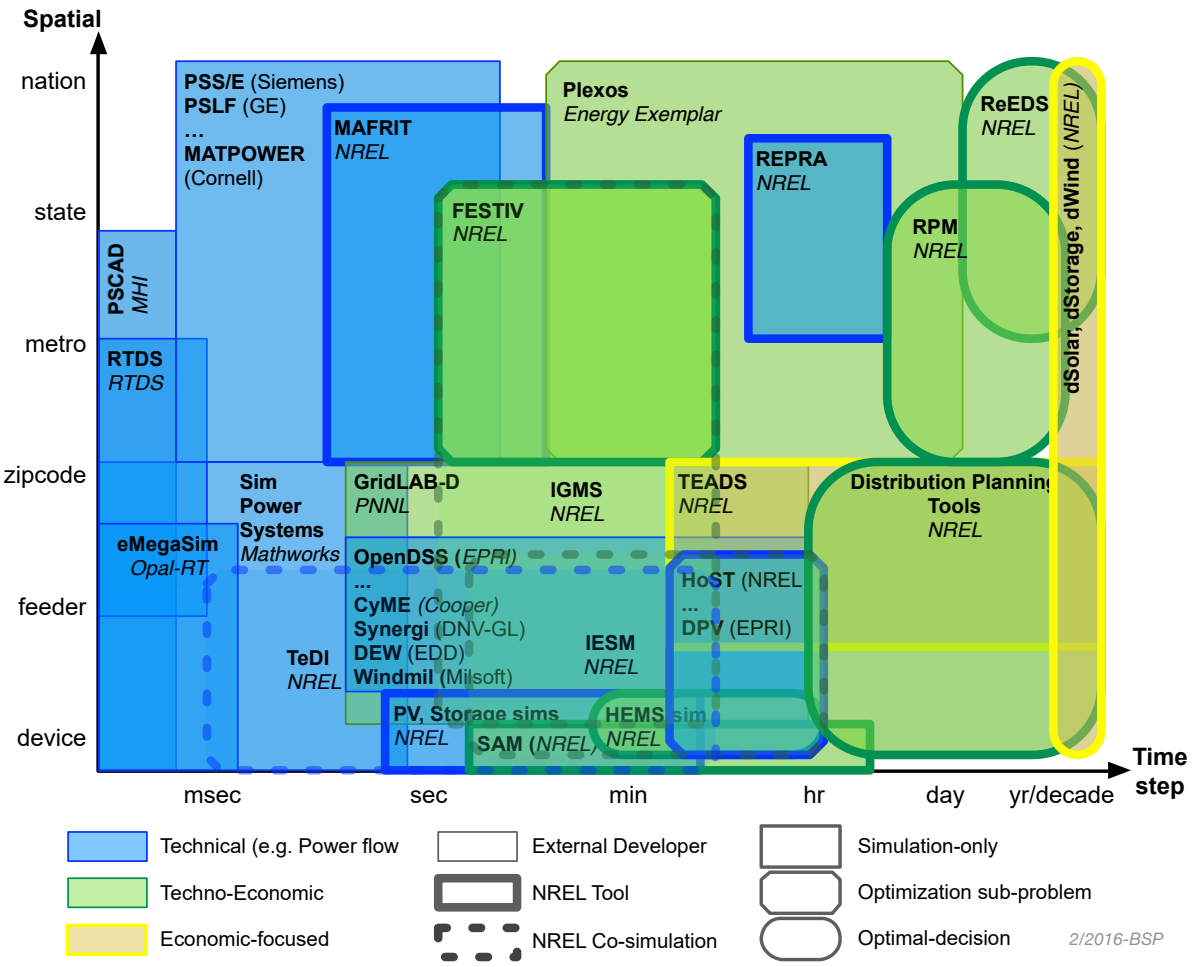
NREL/PR-5D00-66996

A map of power-systems simulation tools



- Markets
- Transmission
- Distribution
- Devices
- Hardware
- Co-simulation

- Transient
- Dynamic
- Steady-State
- Planning

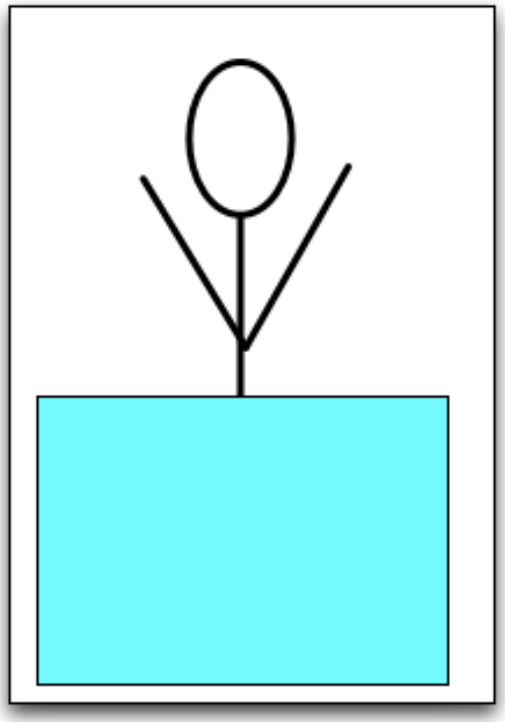
- Technical
- Economic
- Techno-economic

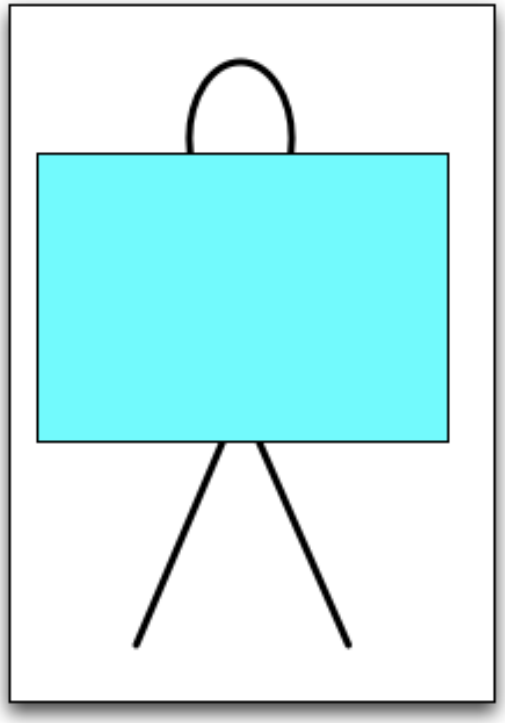
Palmintier, et al. Modeling and Simulation Tools for Analyzing High Penetrations of Variable Renewables in Electric Power Systems. Forthcoming NREL Technical Report

The short blanket problem

Domain A

Domain B

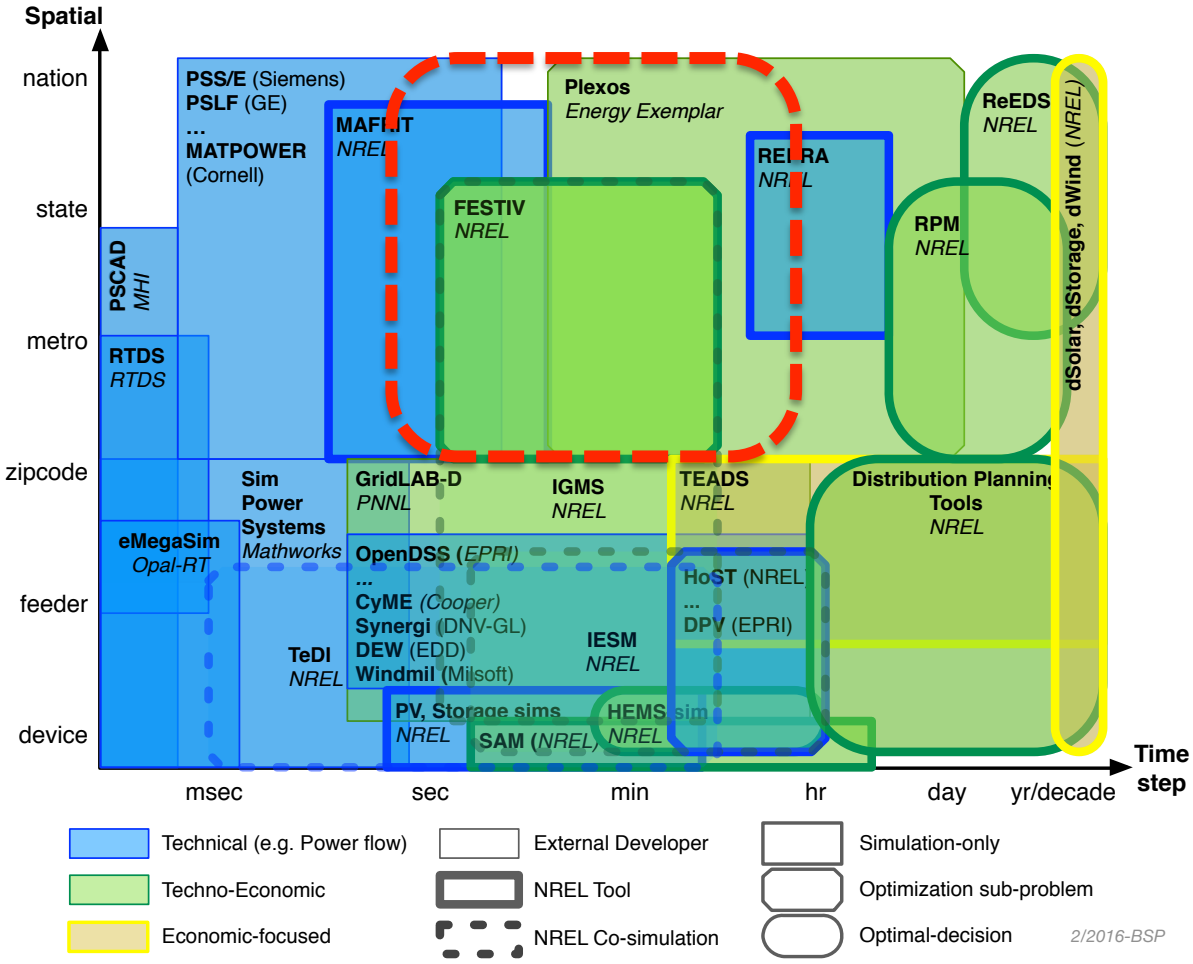




Solutions

- **Stretch the Blanket (Simplify)**
- **Use two blankets (Co-simulation)**
- **Use a bigger blanket (Bigger Computer)**

Flexibility in Planning: UC + Planning



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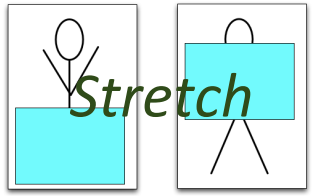
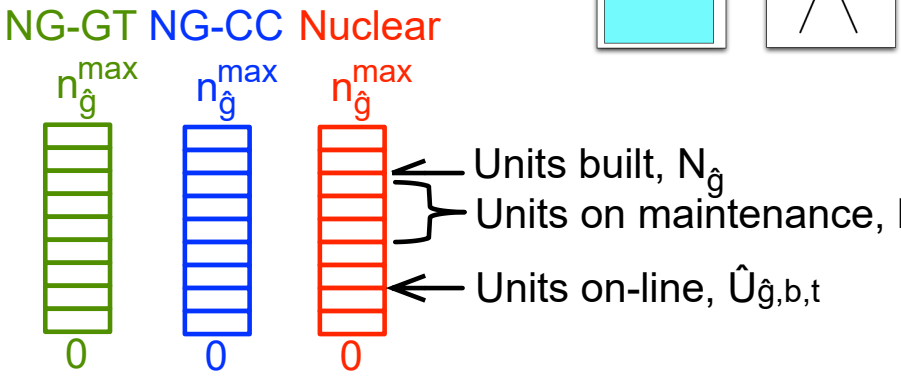
Flexibility in Planning: UC + Planning

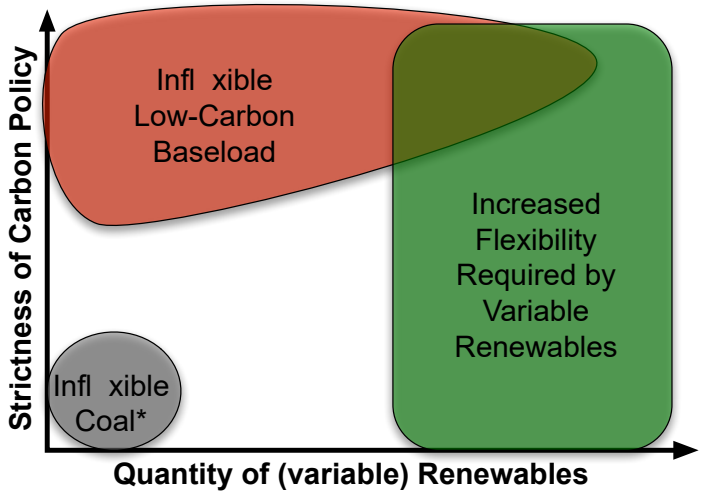
(When) does operational flexibility impact planning?



- Operational Flexibility
  - ➔ Unit Commitment

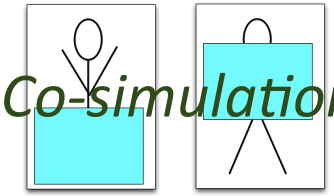
  With Planning
  - ➔ Clustered Integer UC
    - MILP
    - Fast (15-500x)
    - Maintains key unit-level details
      - Reserves
      - On/Off & minimum up/down time
      - Maintenance
    - Low errors (0.3-1.4% for planning)
- Results-- Flexibility Important for Planning with:
  - Strict Carbon Limits
  - High Variable Renewable Penetration

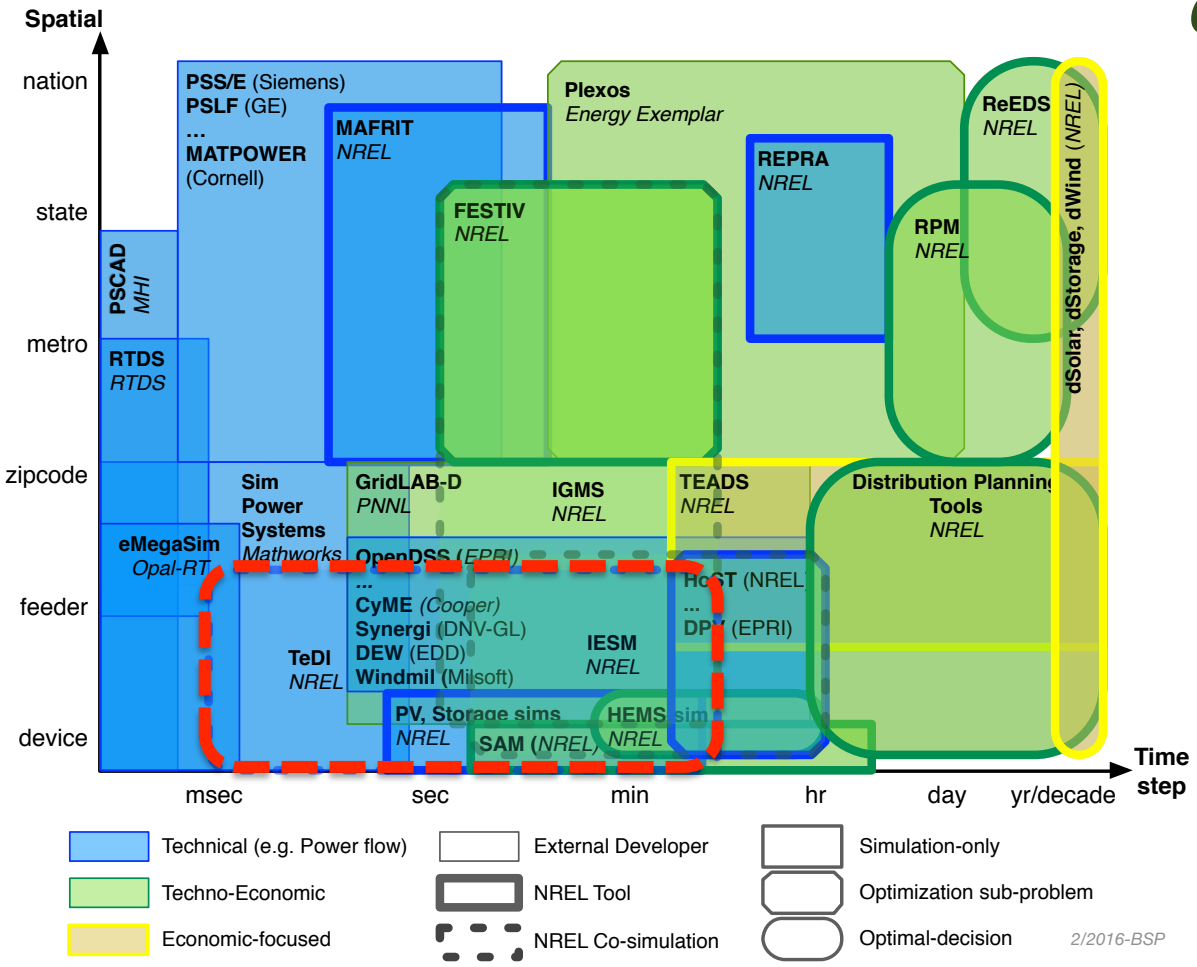




B. Palmintier and M. D. Webster, "Impact of Operational Flexibility on Electricity Generation Planning With Renewable and Carbon Targets," IEEE Transactions on Sustainable Energy, vol. 7, no. 2, pp. 672–684, Apr. 2016.

Power-Hardware-in-the-Loop Co-simulation



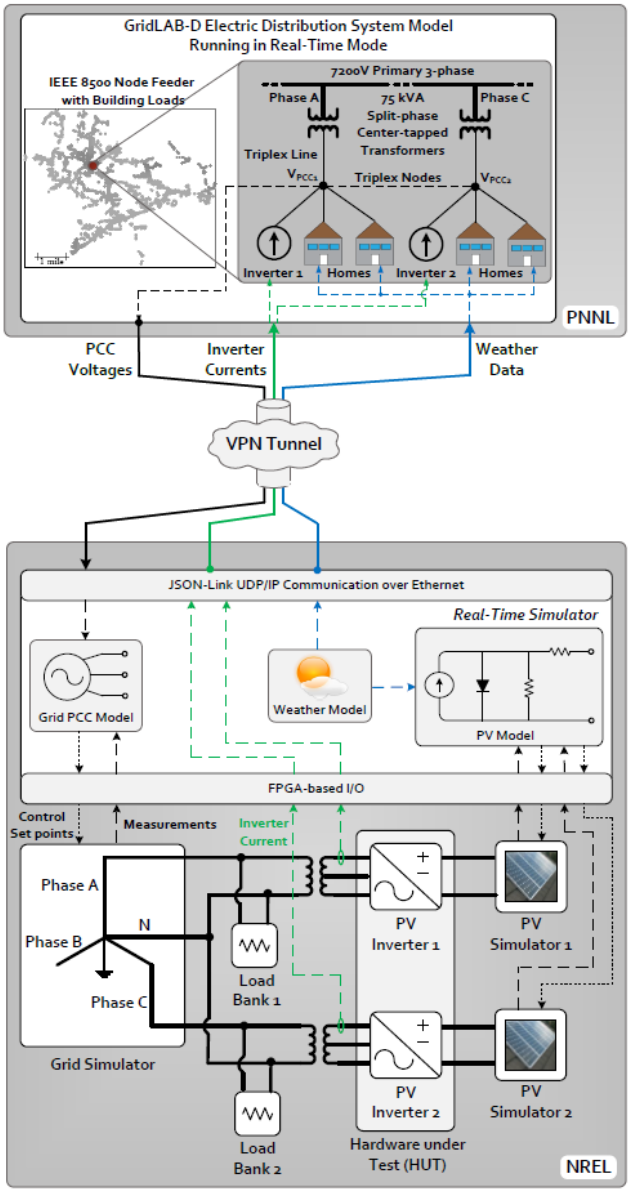


Palmintier, et al. Modeling and Simulation Tools for Analyzing High Penetrations of Variable Renewables in Electric Power Systems. Forthcoming NREL Technical Report

PHIL with Larger Grid Models – PHIL Co-simulation

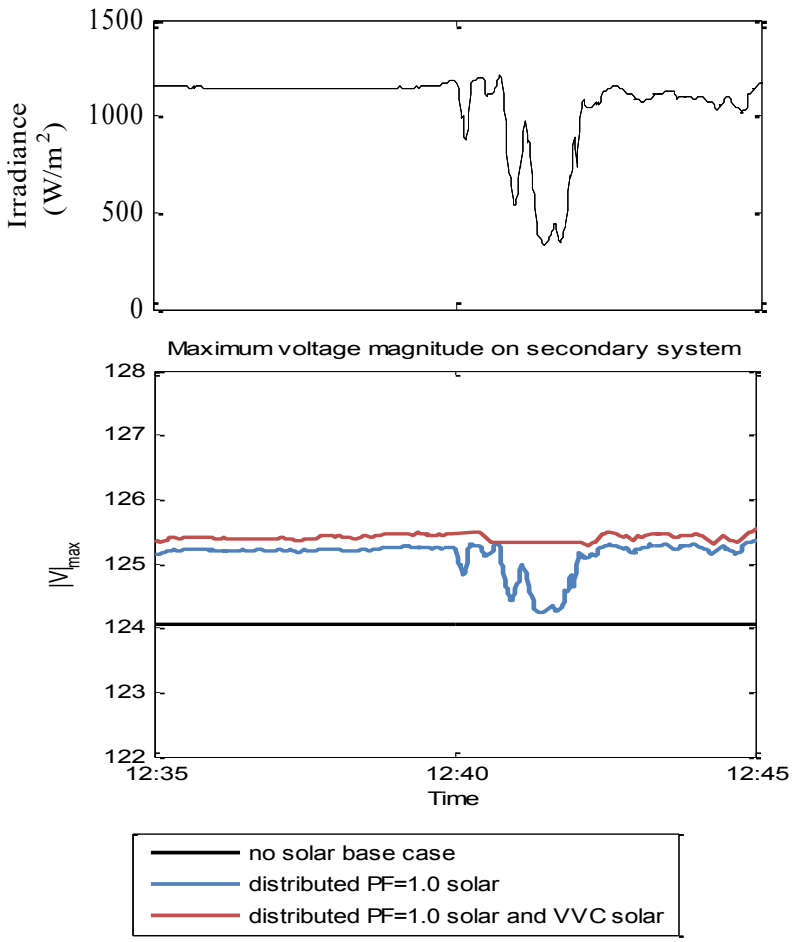
Combines actual hardware testing using PHIL with co-simulation of larger electric power grid using off-the-shelf modeling tools. Very flexible architecture enables multi-site testing (e.g. NREL links to PNNL and CSIRO), and scenario flexibility

- **Arbitrary Grid:** location, topology & equipment
  - Demo: IEEE 8500 and 123 with no hardware changes
- **Any scenario:** normal ops, faults, contingencies
  - Demo: Cloud transients, home thermal physics models
- **Actual hardware:** no proprietary models required
  - Demo: 2 advanced inverters at various points of common coupling
- **Multi-site:** hardware and/or simulation
  - Demo: PNNL (WA) link to NREL (CO)
  - CSIRO (Australia)



B. Palmintier, B. Lundstrom, S. Chakraborty, T. Williams, "A Power-Hardware-in-the-Loop Platform with Remote Distribution Circuit Co-simulation," IEEE Transactions on Industrial Electronics, 2015.

NREL-PNNL Remote PHIL Test Case: Three-phase Inverter

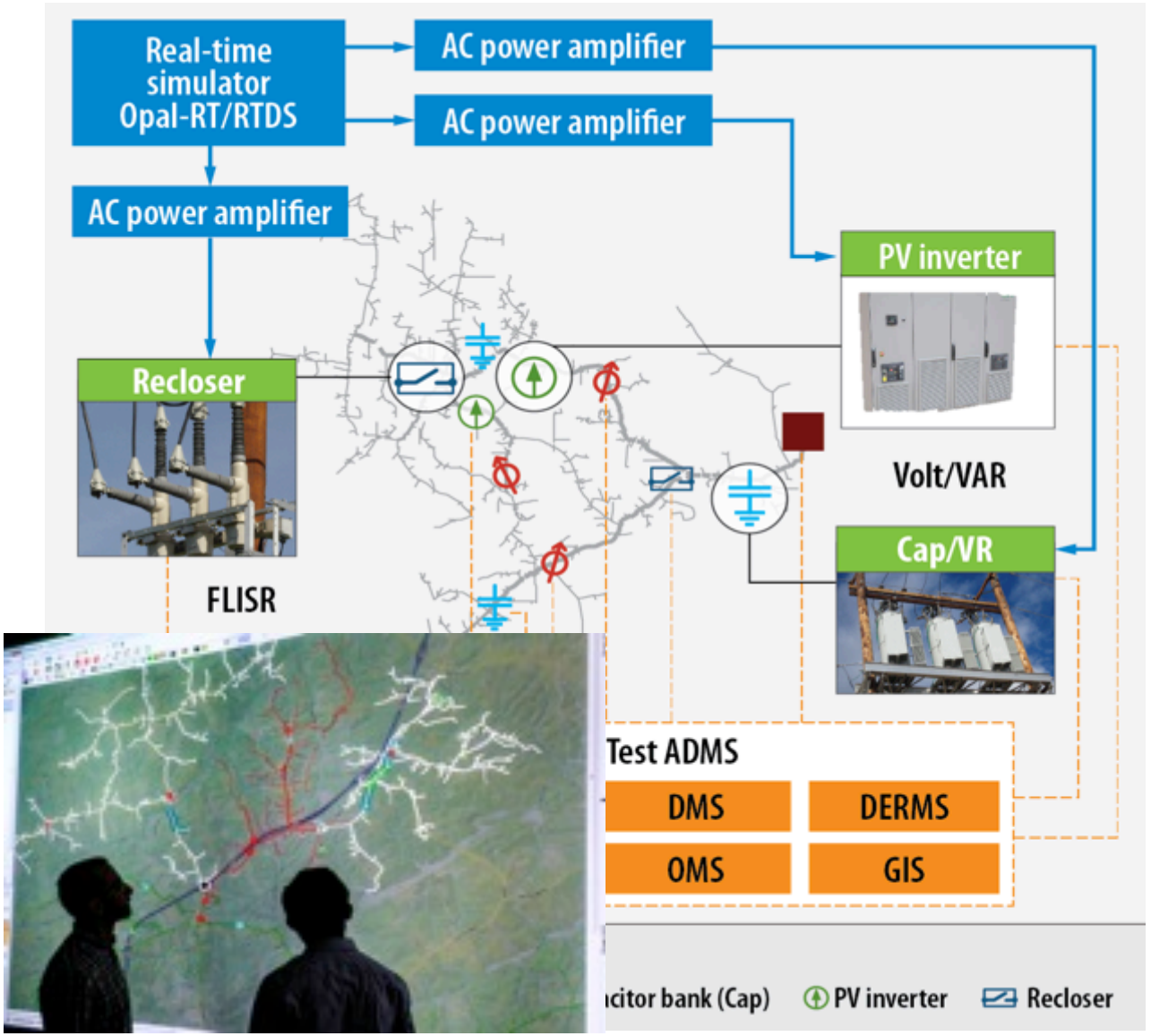


- IEEE 8500-node test feeder
  - One 7 kVA real-inverter output scaled up to 140 kVA in GridLAB-D simulation
  - This hardware inverter was operating in VVC
  - Added a large number small UPF inverters; combined output of 800 kW
- Cloud transient was implemented based on historical weather data
- The hardware inverter with VVC was capable of maintaining constant voltage on the secondary

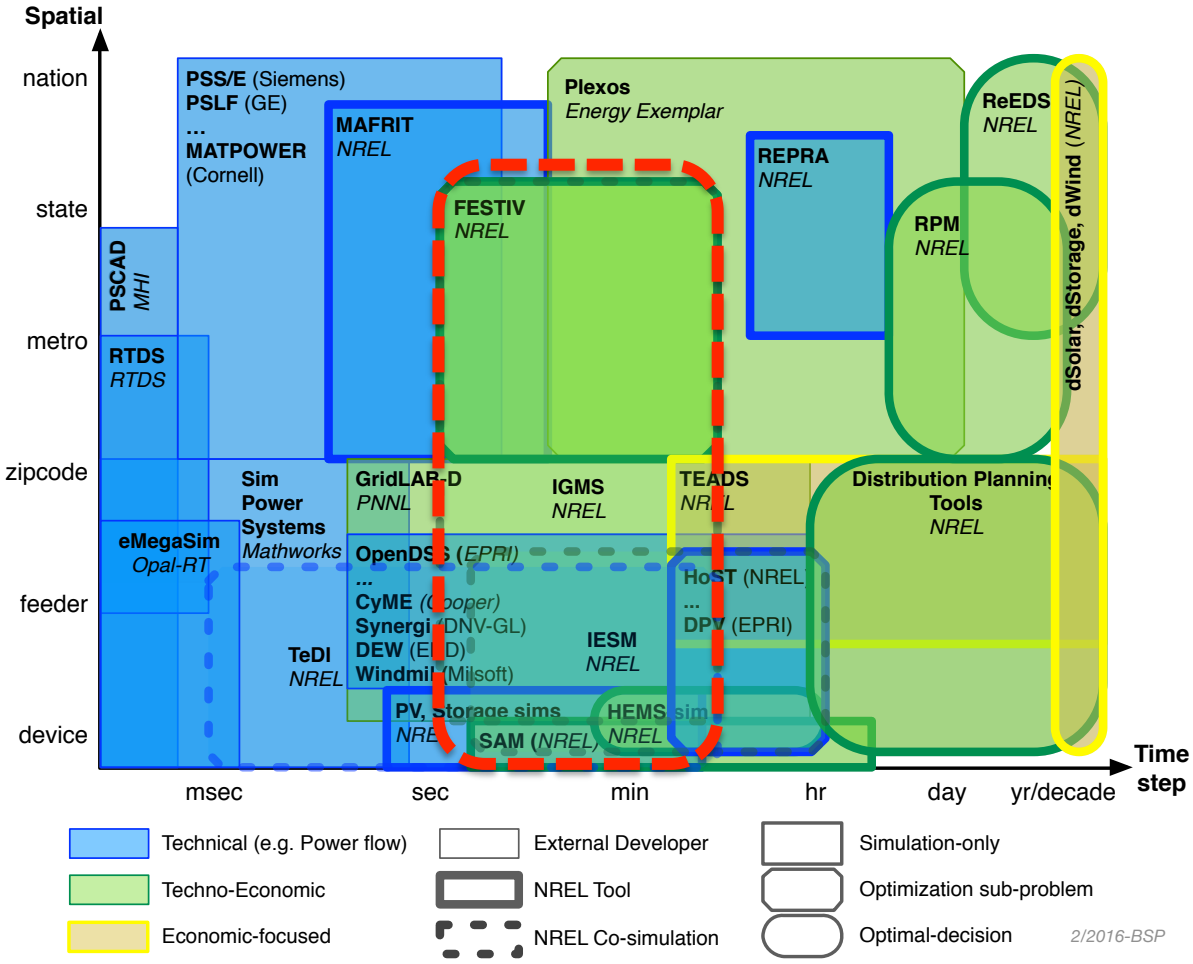
T. Williams, J. Fuller, B. Palmintier, B. Lundstrom, S. Chakraborty, "Examining Solar PV Control Systems with a Hardware-in-the-Loop Platform," in IEEE Photovoltaic Specialists Conference (PVSC), Denver, CO, 2014.

ADMS Testbed

- NREL is establishing a **national, vendor-neutral** Advanced Distribution Management System (ADMS) testbed to **accelerate industry development and adoption of ADMS capabilities**
- Enable utility partners, vendors, and researchers to evaluate existing and future ADMS use cases and integrate with HIL equipment



Integrated T+D



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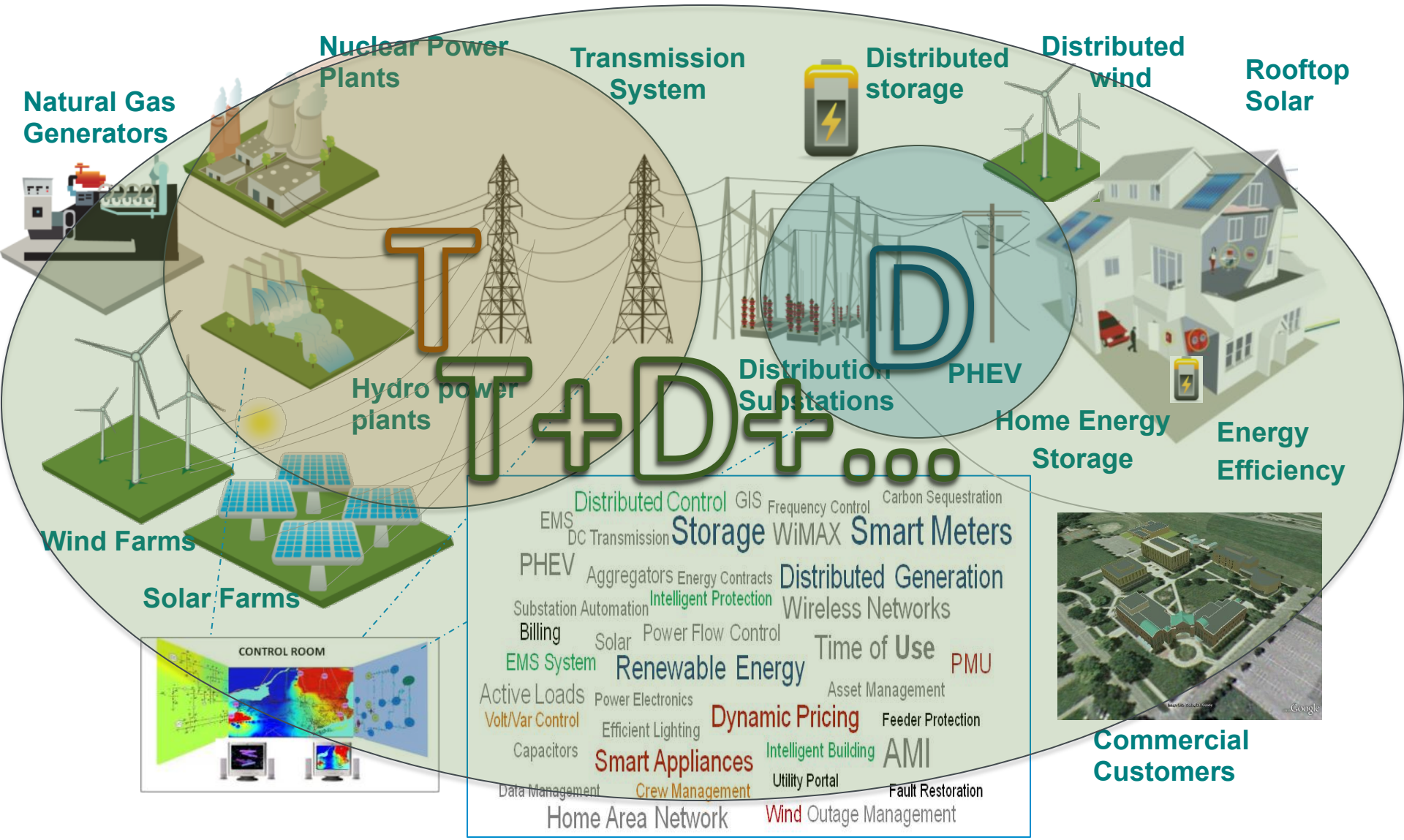
Integrated Simulation the Emerging Grid



Integrated T&D Grid Modeling System (IGMS)

Summary:

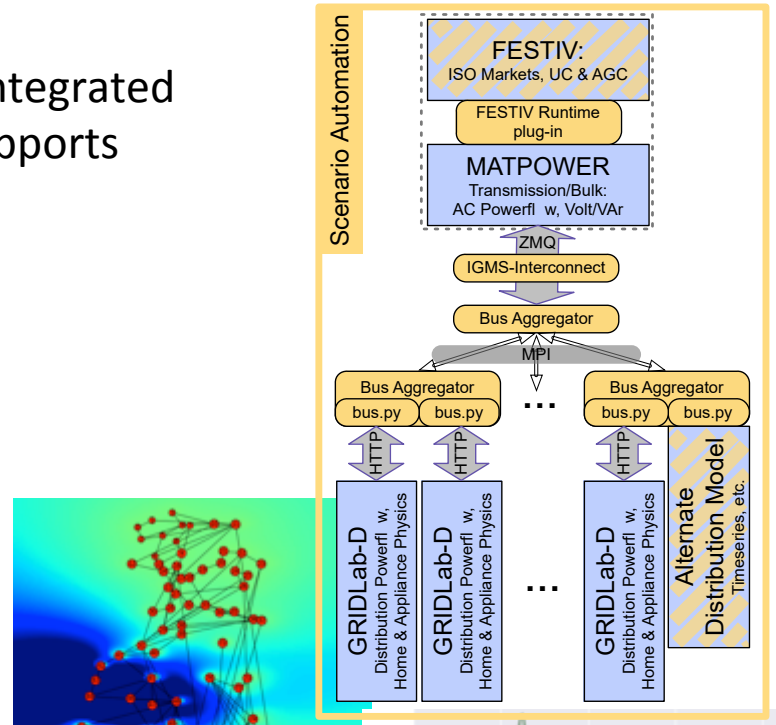
A next-generation analysis framework for full-scale integrated market+transmission+distribution simulation that supports millions of highly distributed energy resources.

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 DERs
- Semi-Automated import from PLEXOS, SynerGEE, & CyME

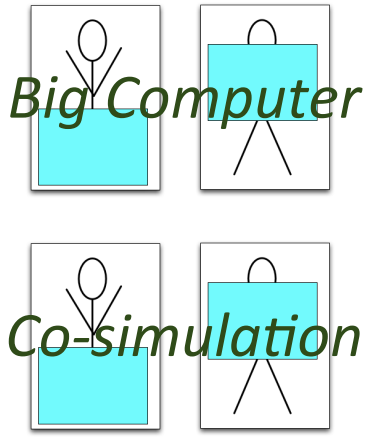
Example Applications

- **Past:** Analyze distributed PV support for grid operations
- **Successful Medium Scale Run(s):** 118 Transmission buses, 743 Distribution Feeders (PNNL taxonomy), >1M total buses, >600k homes. Highly-scalable
- **Current:** Wholesale price interaction of DERs
- **Future:**
  - Integrate Communications (ns-3, GMLC TDC project)
  - Alternative market, DR, and service architectures
  - Co-simulation with Hardware via PHIL



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

IGMS Report: NREL/TP-5D00-65550



How IGMS Works

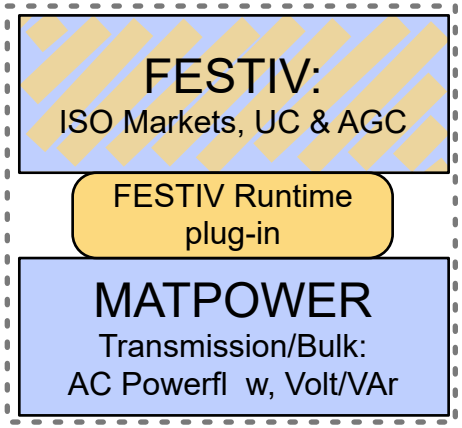
- Multi-Market
  - Day-Ahead Security-Constrained Unit Commitment (Daily)
  - Real-time SC Unit Commitment (Hourly)
  - Real-time SC Economic Dispatch (5-min)
  - AGC reserves

- US-style (currently):
  - Nodal prices
  - Coupled Reserve Markets

FESTIV:
ISO Markets, UC & AGC

FESTIV Tool: *E. Ela and M. O'Malley, "Studying the Variability and Uncertainty Impacts of Variable Generation at Multiple Timescales," IEEE Trans. Power Syst., vol. 27, no. 3, pp. 1324–1333, Aug. 2012.*

- Multi-Market:
  - Daily, Hourly, 5-min, AGC
- T: AC Powerflow (pos-seq, balanced)

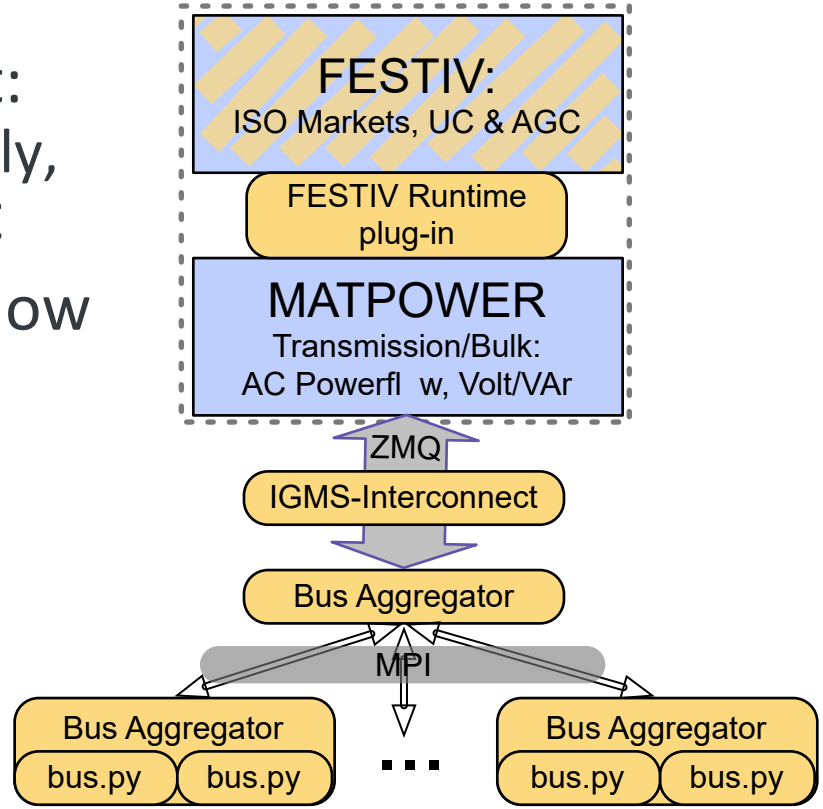


Every 4-60sec (AGC period)

Every 4-60sec (AGC period)

MATPOWER Tool: *Zimmerman, et al., "MATPOWER: Steady-State Operations, Planning, and Analysis Tools for Power Systems Research and Education," IEEE Transactions on Power Systems, vol. 26, no. 1, pp. 12–19, Feb. 2011.*

- Multi-Market:
  - Daily, Hourly, 5-min, AGC
- T: AC Powerflow (pos-seq, balanced)
- Nodal:
  - Voltage
  - Prices
  - (Services)



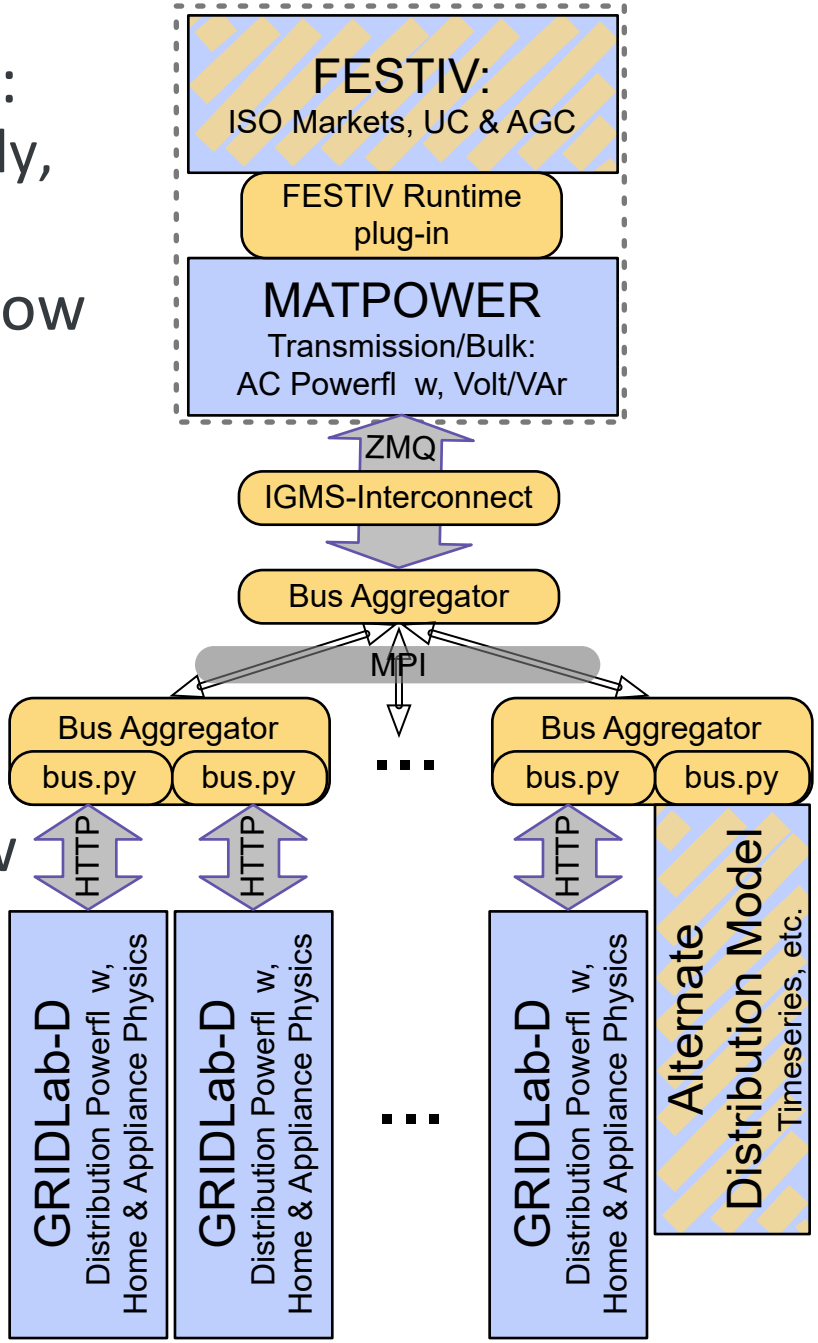
Every 4-60sec (AGC period)

Every 4-60sec (AGC period)

Bus.py Tool: *T. Hansen, B. Palmintier, S. Suryanarayanan, Maciejewski, and Siegel. "Bus.py: A GridLAB-D Communication Interface for Smart Distribution Grid Simulations", 2015 IEEE PES General meeting*

- Multi-Market:
  - Daily, Hourly, 5-min, AGC
- T: AC Powerflow (pos-seq, balanced)
- Nodal:
  - Voltage
  - Prices
  - (Services)
- D: Power flow (3ph, AC, unbalanced)
- Physics:
  - DERs
  - Load

Every 4-60sec (AGC period)

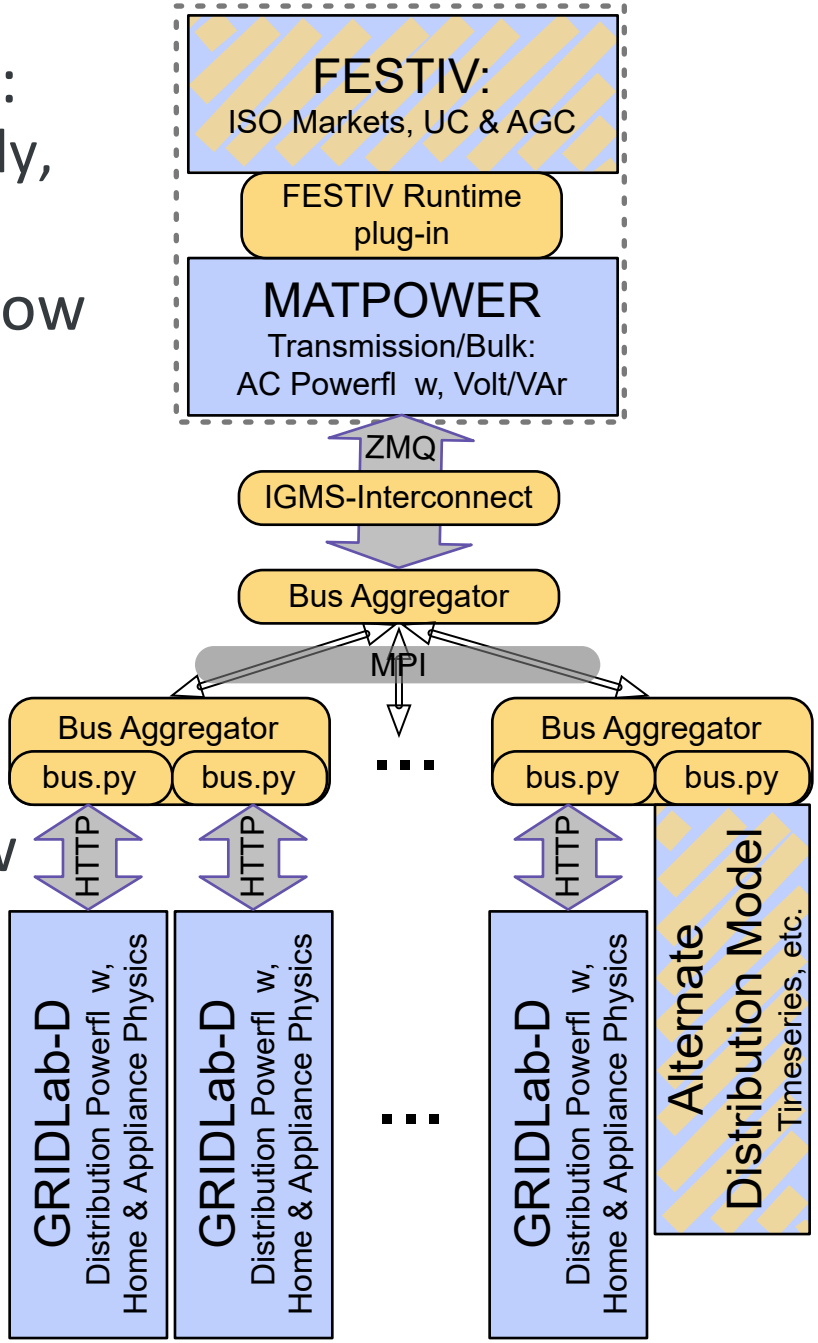


Every 4-60sec (AGC period)

GridLAB-D Tool:
Chassin, et al., "GridLAB-D: An Agent-Based Simulation Framework for Smart Grids," Journal of Applied Mathematics, vol. 2014, pp. 1–12, 2014.

- Multi-Market:
  - Daily, Hourly, 5-min, AGC
- T: AC Powerflow (pos-seq, balanced)
- Nodal:
  - Voltage
  - Prices
  - (Services)
- D: Power flow (3ph, AC, unbalanced)
- Physics:
  - DERs
  - Load

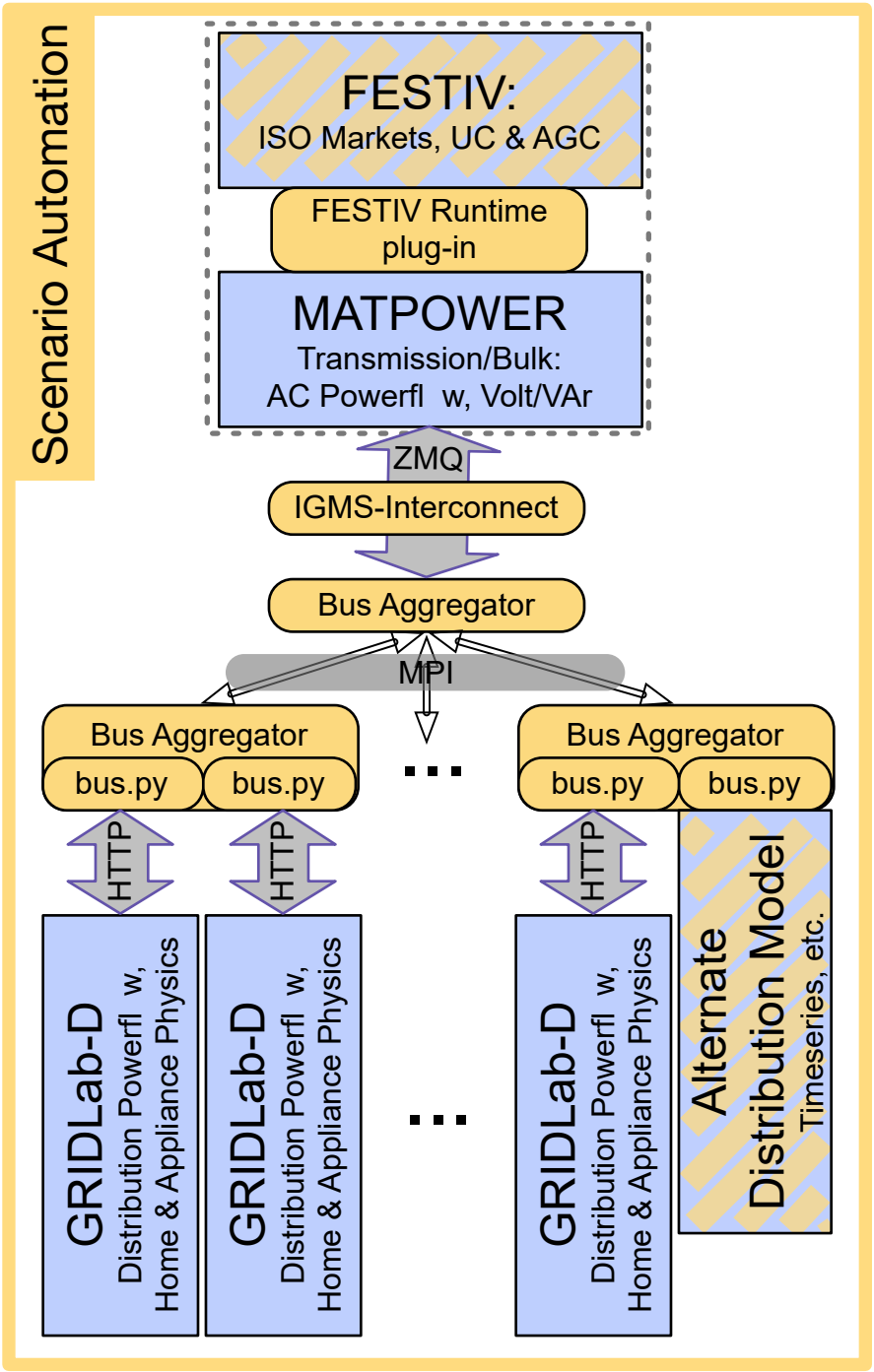
Every 4-60sec (AGC period)



- Return:
  - Power
  - Reactive
  - (Bids)

Every 4-60sec (AGC period)

IGMS Report:
NREL/TP-5D00-65550



Every 4-60sec (AGC period)

Every 4-60sec (AGC period)

IGMS Report:
NREL/TP-5D00-65550

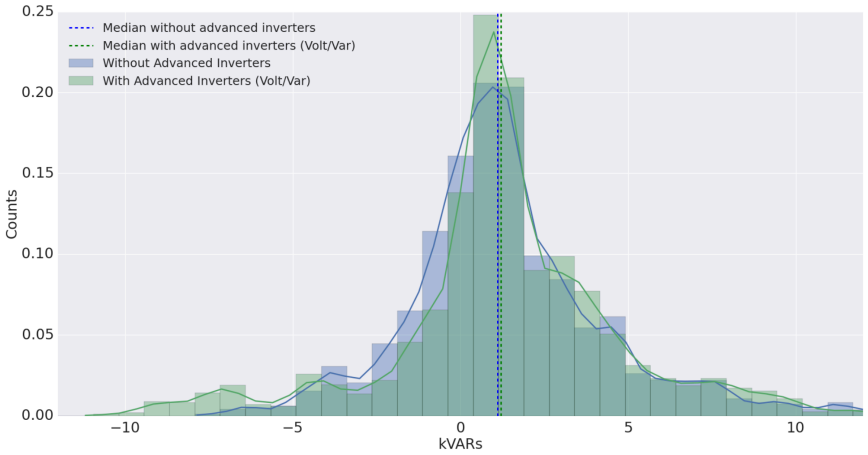
Representative IGMS Results

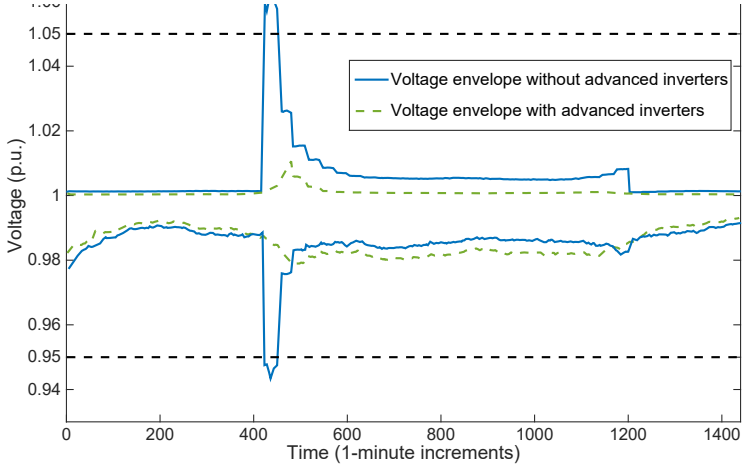
Note: Projects just starting now will be the first to use real utility data

Some Initial (Proof-of-Concept) Results

- Advanced DER Inverters: new Q demands largely met locally

- Advanced DER Inverters can help manage transmission voltages





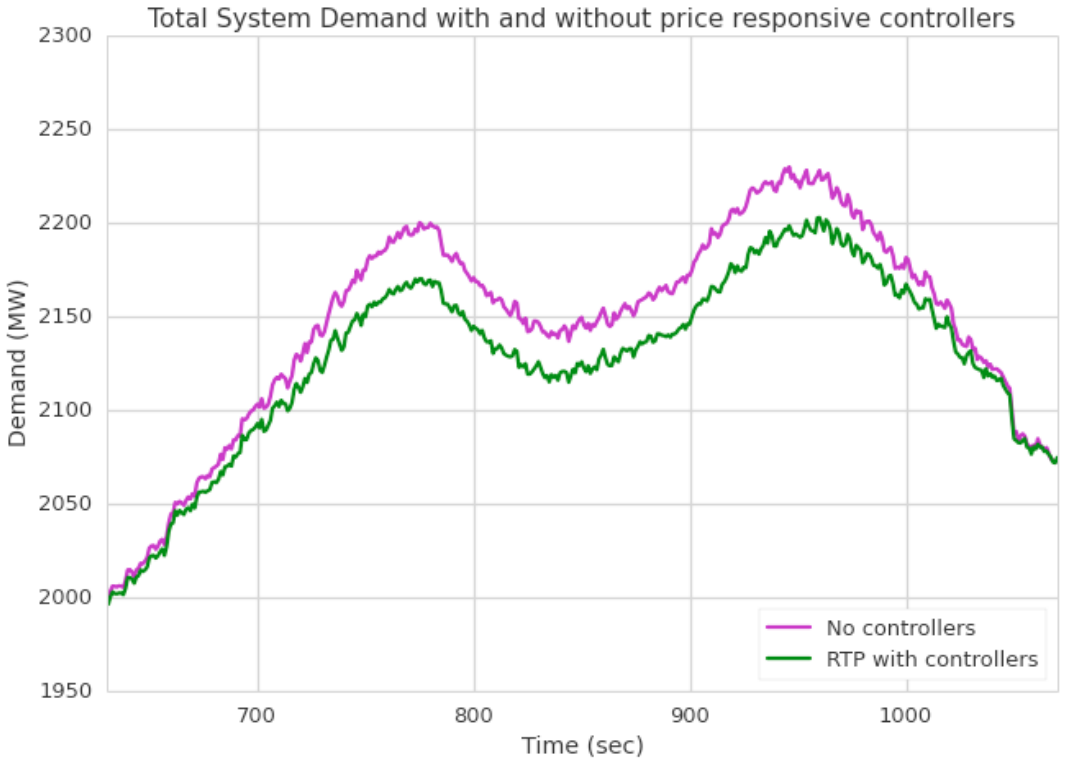
Solar Penetration (energy)	Visibility (Forecast)	Production Cost $1000s/day	CPS2 Violations	AACEE	ACE Std. Dev.
9%	none	Infeasible RTSCED at 10am simulation time			
9%	persistence	7,012	-	-	-
9%	perfect	5,636	-25%	-7%	-4%
14%	none	6,833	-	-	-
14%	persistence	6,558	-10%	-2%	-1%
14%	perfect	5,654	-22%	-23%	-13%

- Improved PV forecast: quantify interchange error & ACE impacts

On the Path to SunShot-Distribution: NREL/TP-5D00-65331

Bulk Impacts of DERs

- HVAC and Hot Water controllers in GridLAB-D
- System-wide demand impact



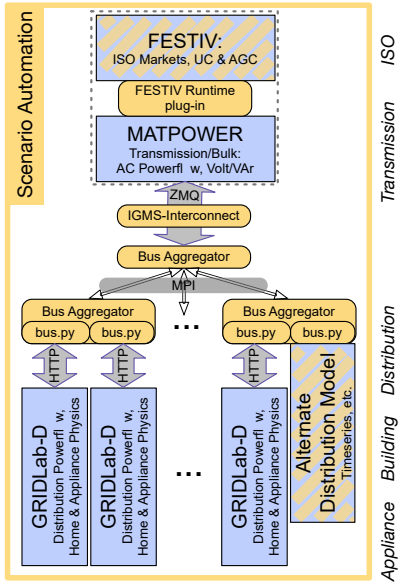
See: Palmintier et al. IEEE Transactions on Smart Grid (To Appear)

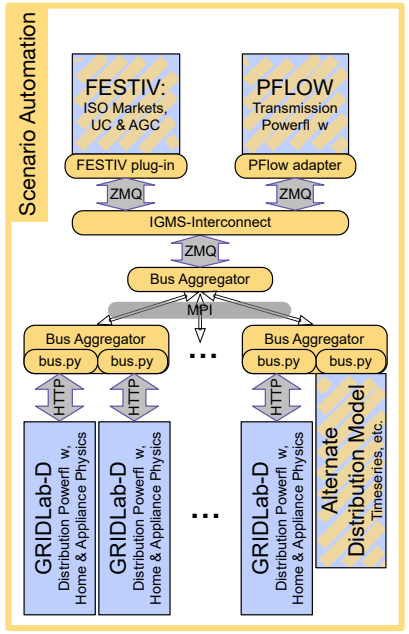
General Observations on Linking Models

1. Co-simulation is great for leveraging existing tools

- Lots of effort has gone into (sub) domain-specific tools.
  - (So use them)
  - Trusted by stakeholders
  - Continue to improve
- Allows focus on the "glue-ware"
  - Faster
  - Many frameworks
- Encourages Modularity
  - Swap/add models as needed

http://legomyphoto.wordpress.com/

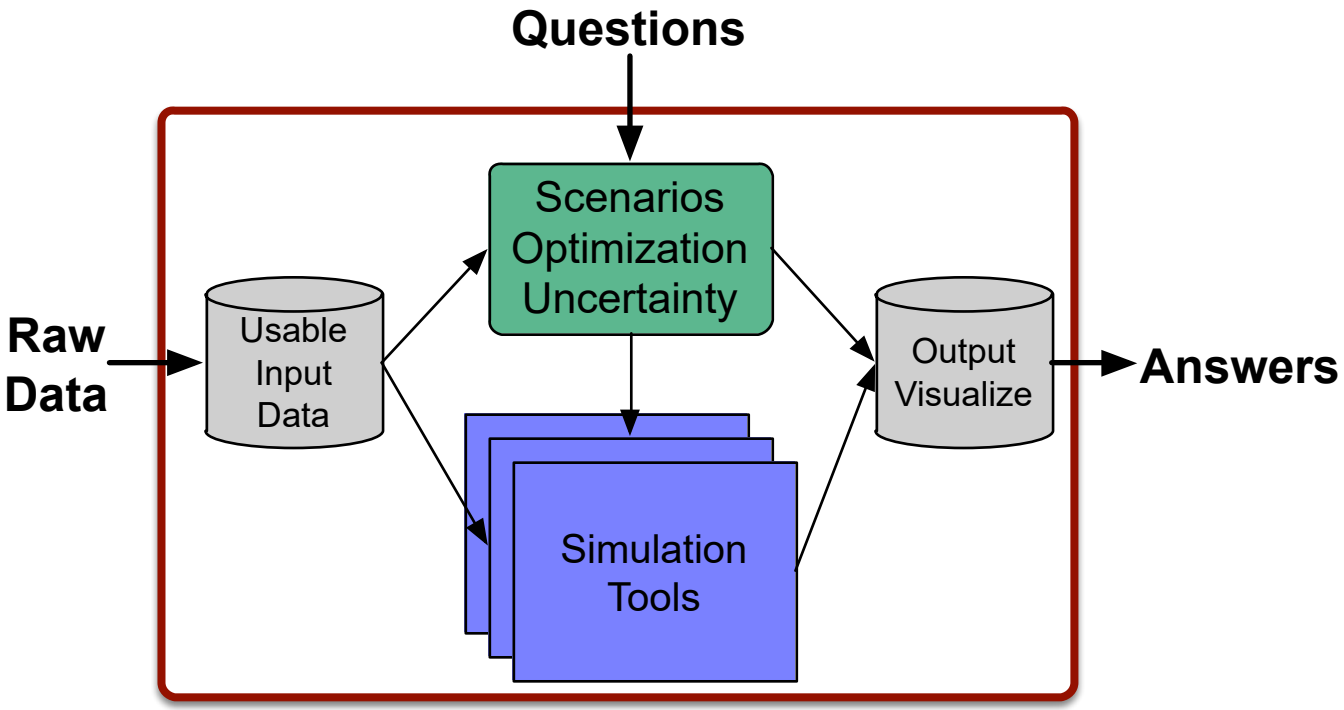




B. Palmintier, et al., "Experiences … with the Integrated Grid Modeling System (IGMS)," in *Power Systems Computation Conference (PSCC'16)*, Genoa, Italy, 2016.

2. It's not just the tool: Remember the Rest of the Workflow

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



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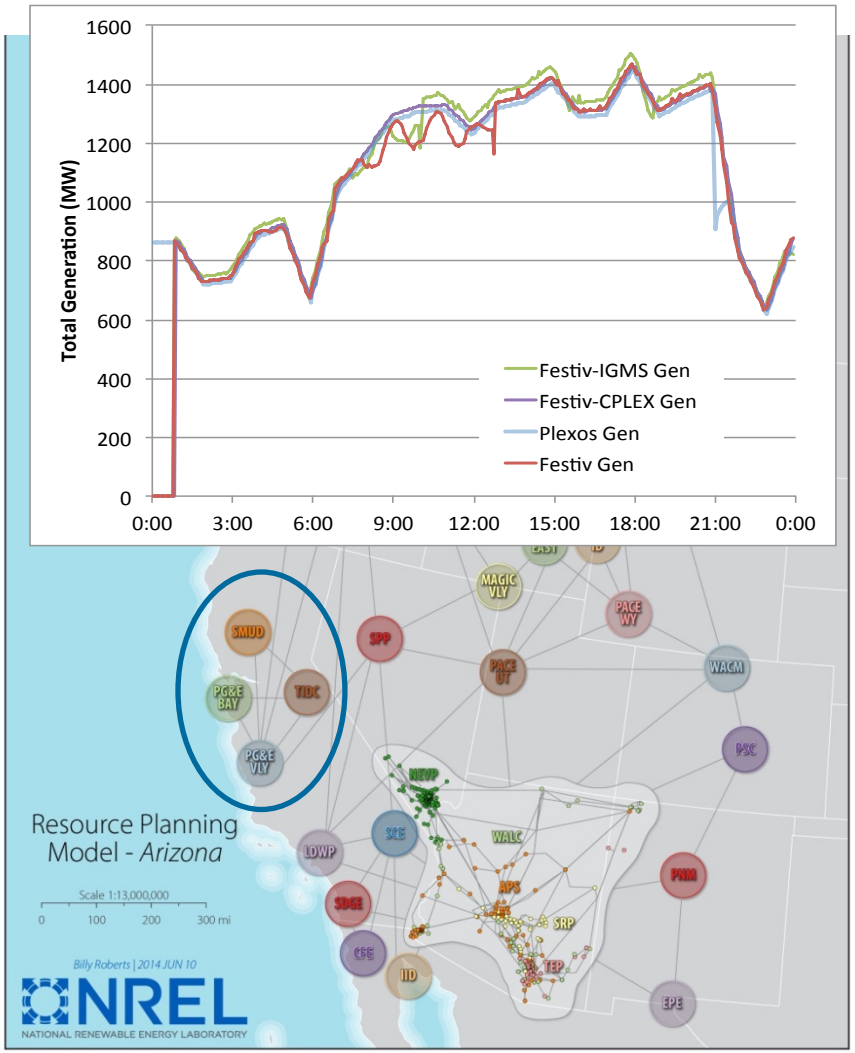
IGMS-Input Data Conversion

Distribution: SynerGEE and CYME to GridLAB-D

1. SynerGEE objects collected
2. Operated via syntax or mathematical conversions
3. Create GridLAB-D text element
4. Create ".glm" GridLAB-D file

POC: Julieta Giraldez

Transmission: PLEXOS to FESTIV – with RPM



IGMS Report: NREL/TP-5D00-65550

IGMS-Populating Feeders with Houses & PV

Scenario

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

Transmission

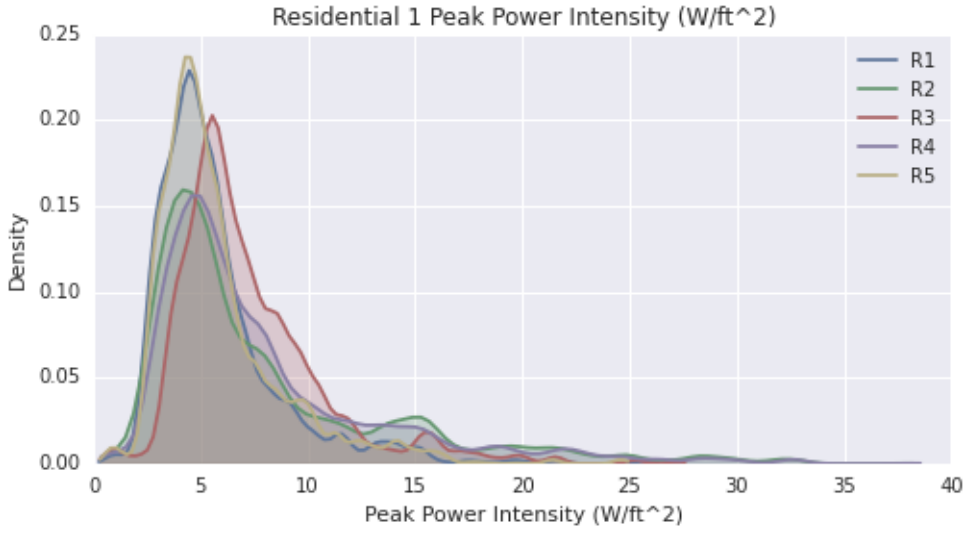
- FESTIV case
- IGMS-FESTIV model rules and configuration
- Startup .mat file

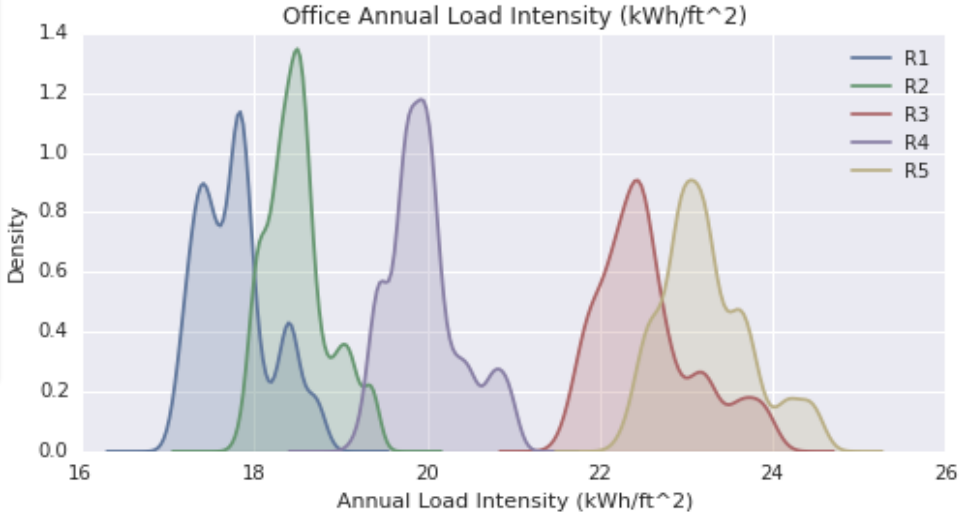
Distribution

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

bus.py setup

MultiNodeBus GridlabBus
ConstantBus FileBus

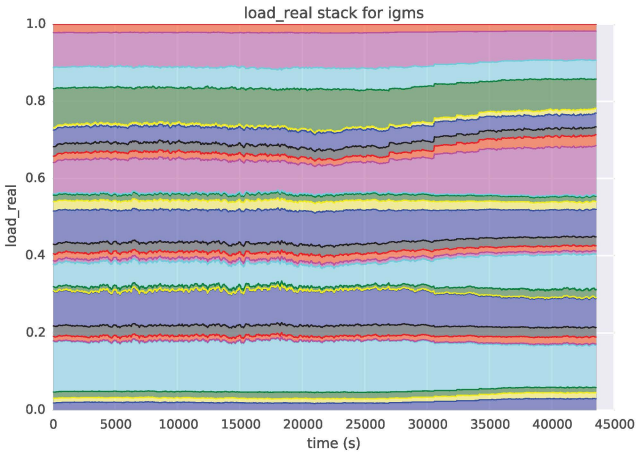


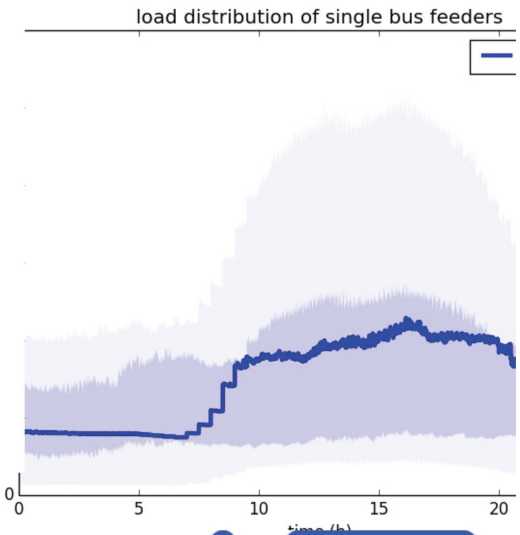


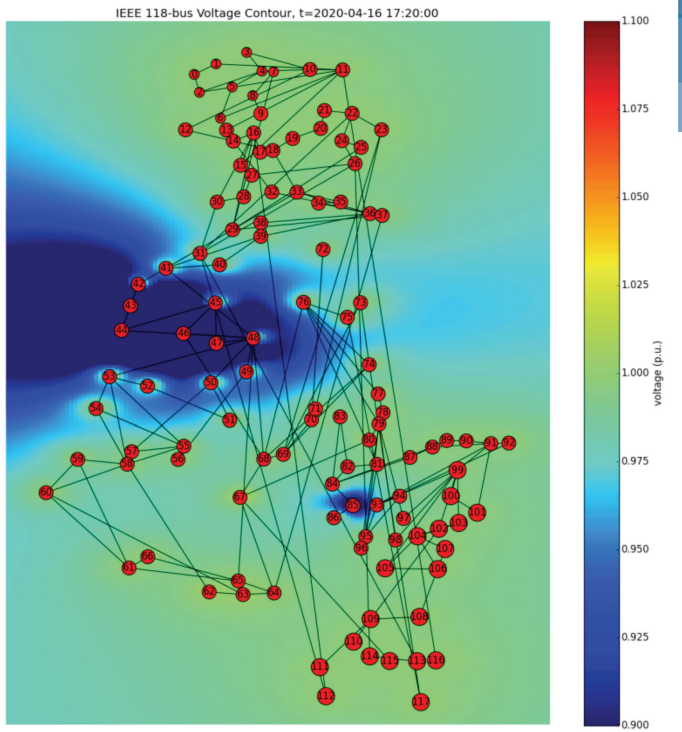
Core feeder processing built on evolved form of Open Modeling Framework

IGMS Report: NREL/ TP-5D00-65550

IGMS-Output Processing



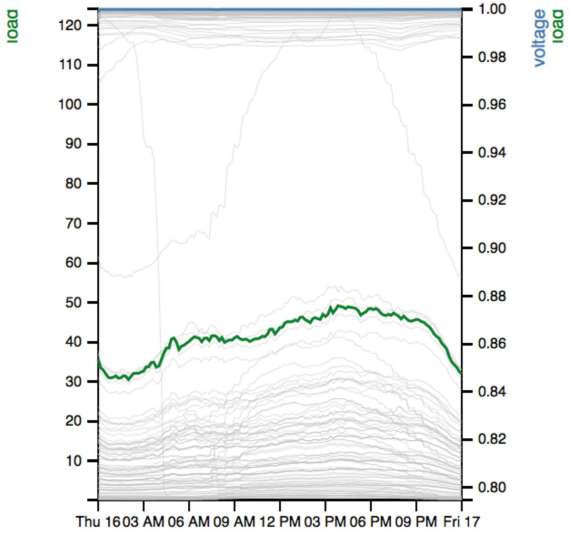


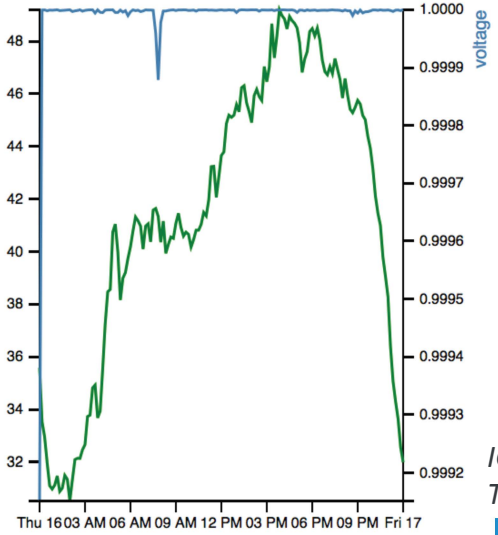


Load and Voltage

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

B56

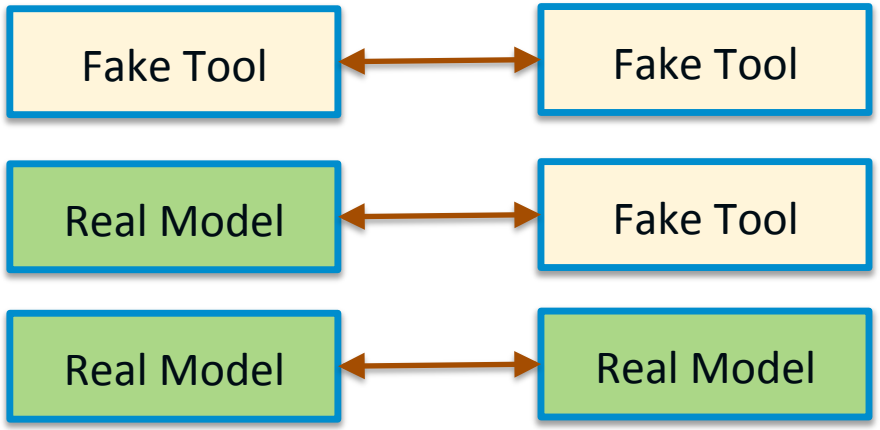




IGMS Report: NREL/ TP-5D00-65550

3. Modular Design also Simplifies Complex Development

- Co-simulation perspective: enables model swapping
- Also: Well-defined API advantages:
  - Multiple developers simultaneously
    - Easier merging in version control (you are using sofware version control, right? GIT is great)
  - Refine components separately
- And key: *TESTING*
  - Asynchronous development
  - Isolate problems



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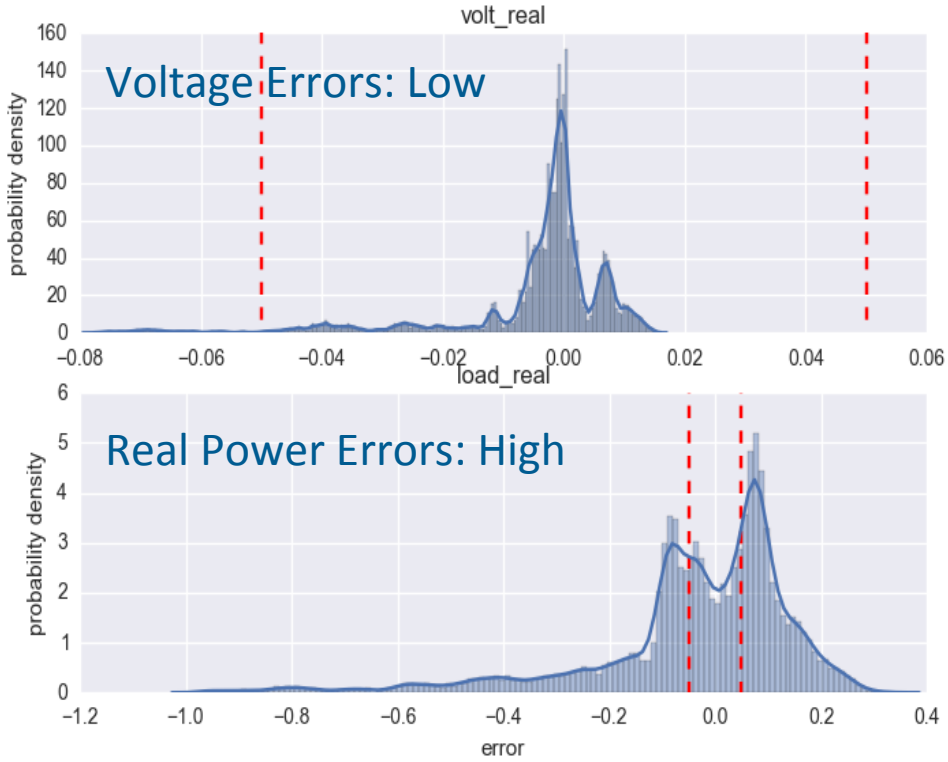
4. Big Models can inform smaller models

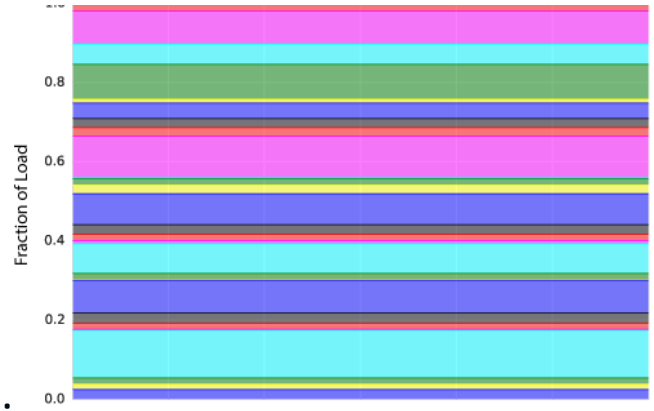
IGMS vs Separate Tools:

Largest difference separate vs

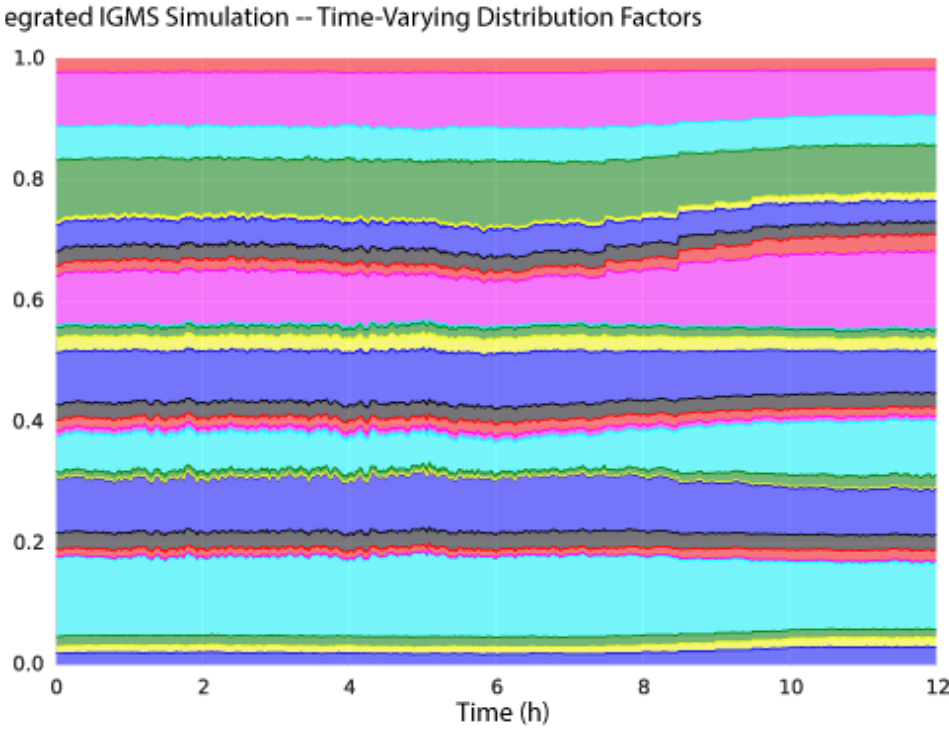
T+D : constant distribution factors



Traditional Transmission Models:



With IGMS:



Palmintier et al. "Integrated Grid Modeling System…" IEEE Transactions on Smart Grid (To Appear) and Palmintier et al. NREL/ TP-5D00-65550, Jan. 2016.

Future directions for T+D

- Enhanced T&D economic analysis in IGMS
  - Retail-Wholesale market interactions
  - DLMP development
- Real-world partners and validation
  - SuNLaMP T+D Tools with Argonne National Lab
- T+D+… Comms, Loads, Markets, etc.
  - DoE Grid Modernization T+D+C: with PNNL, LLNL, et al.
  - Opportunistic Hybrid Communication SuNLaMP (Bri-Mathias Hodge)
- Market interactions of DR: "Prosumer as price maker"
  - IGMS + IESM
- Power Hardware-in-the-Loop
  - ADMS testbed (Simulate power system)
  - ESIF Power Grid Hub
- Partnerships with NREL Analysis Group
  - high-distributed energy futures study
  - Future electricity system analysis

Full References

Integrated Grid Modeing System (IGMS) for T+D

- B. Palmintier, E. Hale, B.-M. Hodge, K. Baker, and T. Hansen, "Experiences integrating transmission and distribution simulations for DERs with the Integrated Grid Modeling System (IGMS)," in *Proceedings of the 19th Power Systems Computation Conference (PSCC'16)*, Genoa, Italy, 2016.
- B. Palmintier, E. Hale, T. Hansen, W. Jones, D. Biagioni, H. Sorensen, and B.-M. Hodge, "IGMS: An Integrated ISO-to-Appliance Scale Grid Modeling System," IEEE Transactions on Smart Grid, Special Issue on High Performance Computing (HPC) Applications for a More Resilient and Efficient Power Grid, (In Review)
- B. Palmintier, E. Hale, T. Hansen, W. Jones, D. Biagioni, K. Baker, H. Wu, J. Giraldez, H. Sorensen, M. Lunacek, N. Merket, J. Jorgenson, and B.-M. Hodge, "Integrated Distribution-Transmission Analysis for Very High Penetration Solar PV (Final Technical Report)," National Renewable Energy Laboratory, Golden, CO, NREL/TP-5D00-65550, Jan. 2016.
- B. Palmintier, "The Integrated Grid Modeling System (IGMS) for Combined Transmission and Distribution Simulation," presented at the Power and Energy Society General Meeting, Denver, CO, 29-Jul-2015. http://www.nrel.gov/docs/fy16osti/65552.pdf
- B. Palmintier, R. Broderick, B. Mather, M. Coddington, K. Baker, F. Ding, M. Reno, M. Lave, and A. Bharatkumar, "On the Path to SunShot: Emerging Issues and Challenges in Integrating Solar with the Distribution System," National Renewable Energy Laboratory, Golden, CO, NREL/TP-5D00-65331, May 2016.
- T. M. Hansen, R. Kadavil, B. Palmintier, S. Suryanarayanan, A. A. Maciejewski, H. J. Siegel, E. K. P. Chong, and E. Hale, "Enabling Smart Grid Cosimulation Studies: Rapid Design and Development of the Technologies and Controls," *IEEE Electrification Magazine*, vol. 4, no. 1, pp. 25–32, Mar. 2016.

Bonus Examples:

- B. Palmintier and M. D. Webster, "Impact of Operational Flexibility on Electricity Generation Planning With Renewable and Carbon Targets," IEEE Transactions on Sustainable Energy, vol. 7, no. 2, pp. 672–684,. 2016.
- B. Palmintier, B. Lundstrom, S. Chakraborty, T. Williams, "A Power-Hardware-in-the-Loop Platform with Remote Distribution Circuit Co-simulation," IEEE Transactions on Industrial Electronics, 2015.

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