NREL Transforming ENERGY

Autonomous Energy Systems

August 2020

Presenter: Benjamin Kroposki

AES NREL Team:

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- **Power Systems** - Andrey Bernstein, Guido Cararo, Yue Chen, Chin-Yao Chang, Bri-Mathias Hodge, Huaiguang Jiang, Yingchen Zhang , Xinyang Zhou , Bai Cui
- **Wind** - Jennifer King, Chris Bay
- **Transportation** - Brennan Borlaug, Kalpesh Chaudhari, Rob Fitzgerald, Venu Garikapati, Yanbo Ge, Matt Moniot, Clement Rames, Nick Reinicke, Jinghui Wang, Eric Wood
- **Buildings** - Venkatesh Chinde, Bill Livingood, Rohit Chintala

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- Emiliano Dall'Anese (Univ of Colorado-Boulder), M. Hong (Univ of Colorado-Boulder), Steven Low (CalTech), Ian Hiskens (Univ. of Michigan), Sean Meyn (Univ. og Florida)

Autonomous Energy Systems Workshop

Welcome to the third in our series of Workshops on **Autonomous Energy Systems**

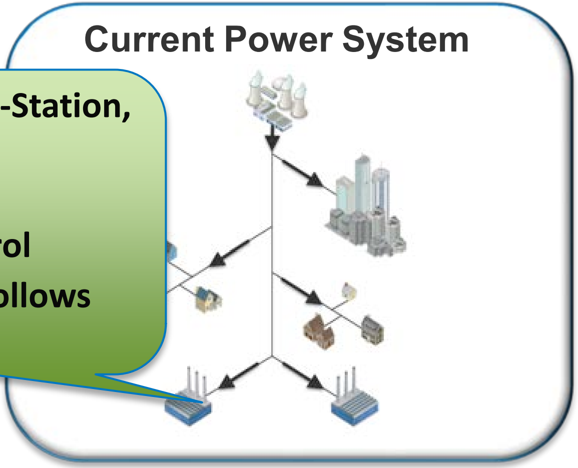
By focusing on basic research in optimization theory, control theory, big data analytics, and complex system theory, we aim to develop a flexible planning and operation framework that can keep pace with the complexity of modern energy systems.

Prior workshop material can be found at:
https://www.nrel.gov/grid/autonomous-energy.html

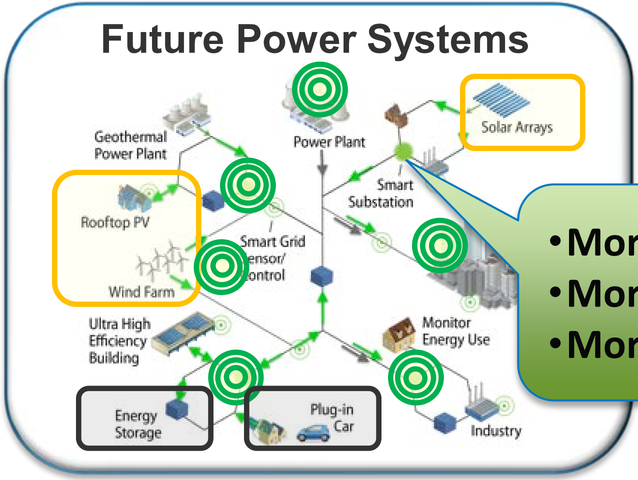
Innovative Optimization and Control Methods for Highly Distributed Autonomous Systems
April 11-12, 2019
https://www.nrel.gov/grid/innovative-optimization-control-methods.html

Autonomous Energy Grids Workshop
September 13-14, 2017
https://www.nrel.gov/grid/autonomous-energy-grids-workshop.html

Transformation of the Power System



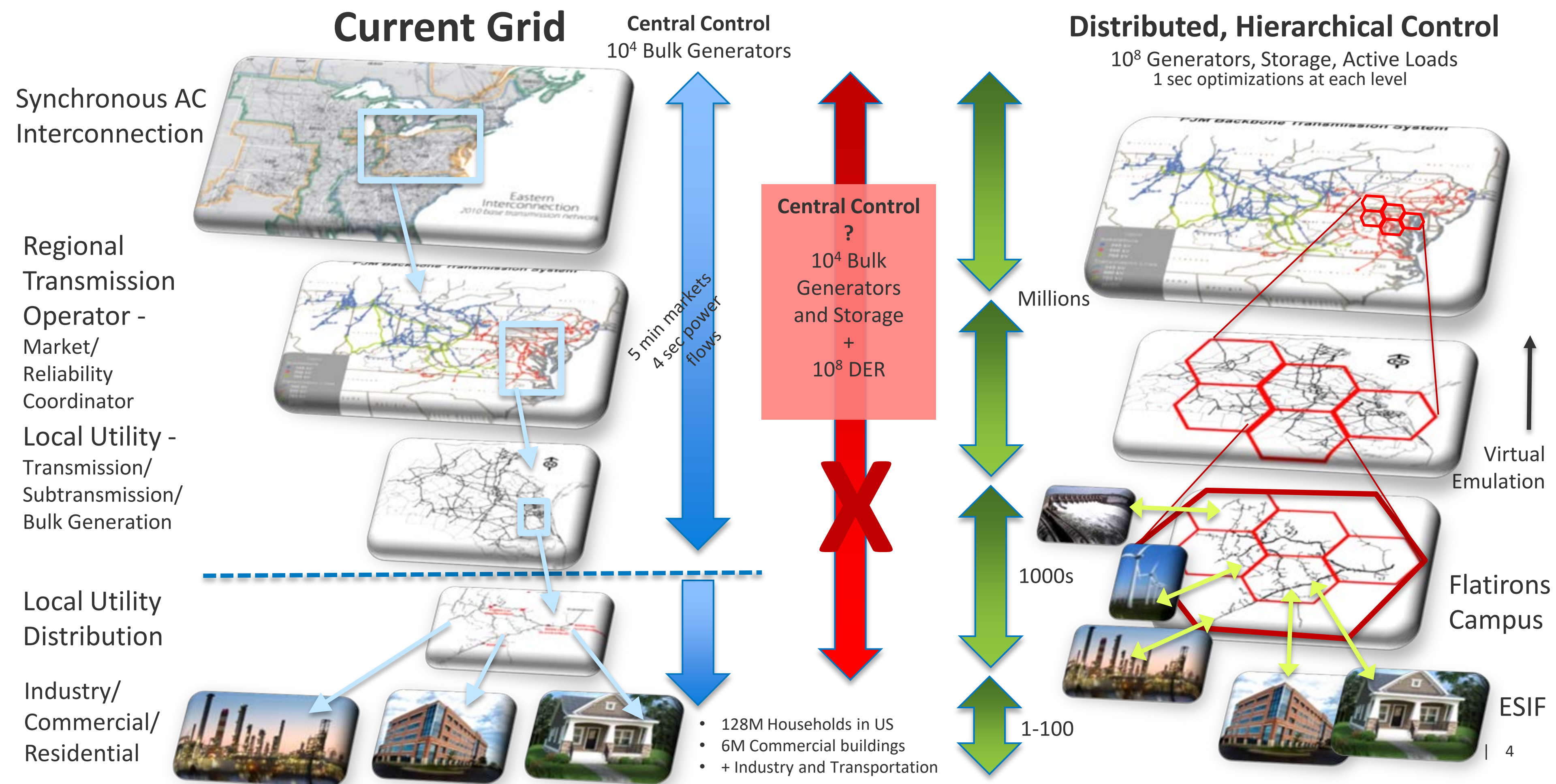
- Large Central-Station, Synchronous Generation
- Central Control
- Generation follows Demand



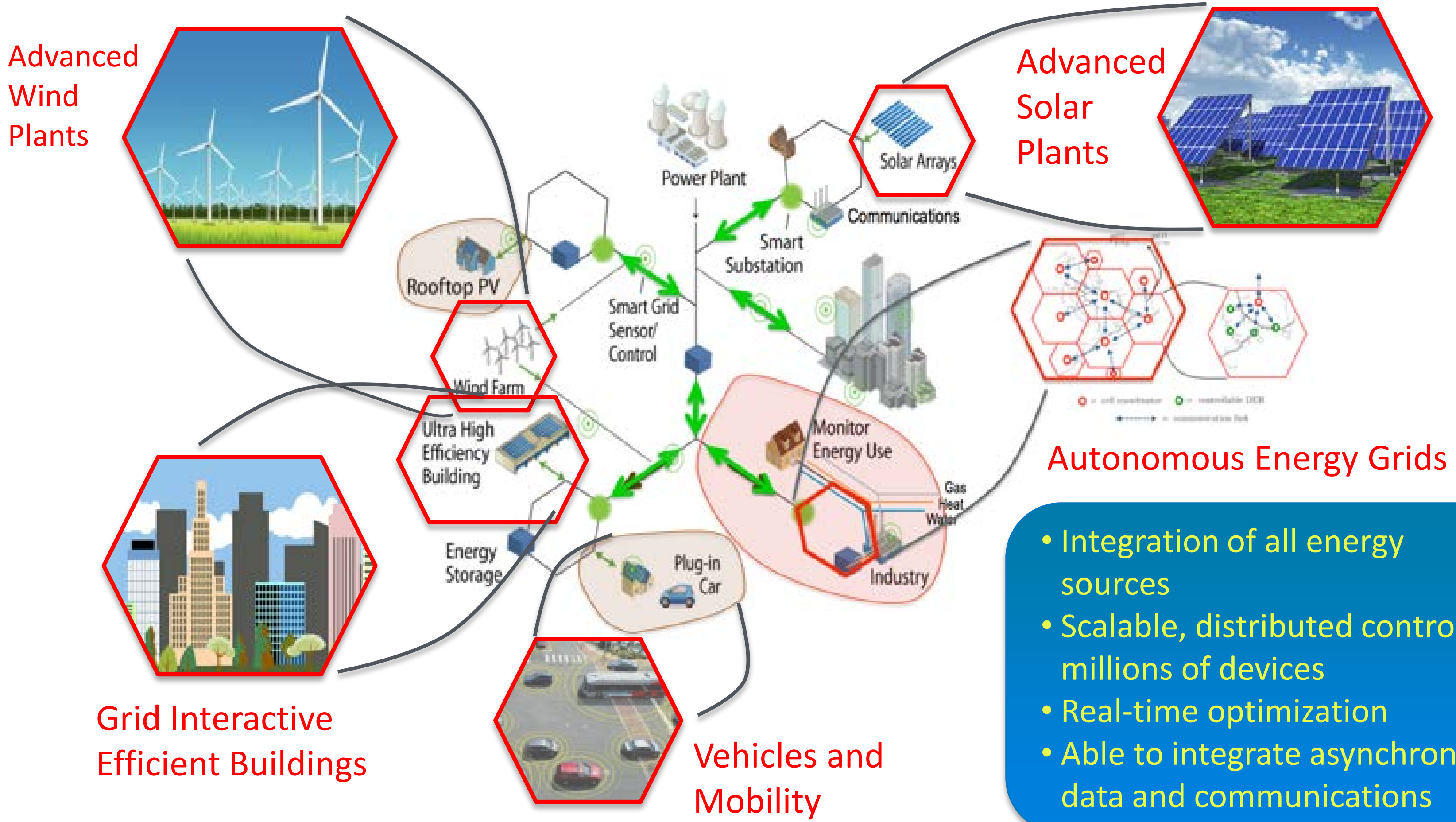
- More VRE
- More Information
- More Distributed

- Increasing levels of wind and solar – variable and power electronics based
- More use of Communications, Controls, Data, and Information (e.g. Smart Grids) – can have interoperability and cybersecurity issues
- Other new distributed technologies: EVs, Distributed storage, Flexible Loads
- Increasing interdependencies between electricity grids and other infrastructures
- Becoming highly distributed and more complex to operate

Is the Grid getting too complex to control?

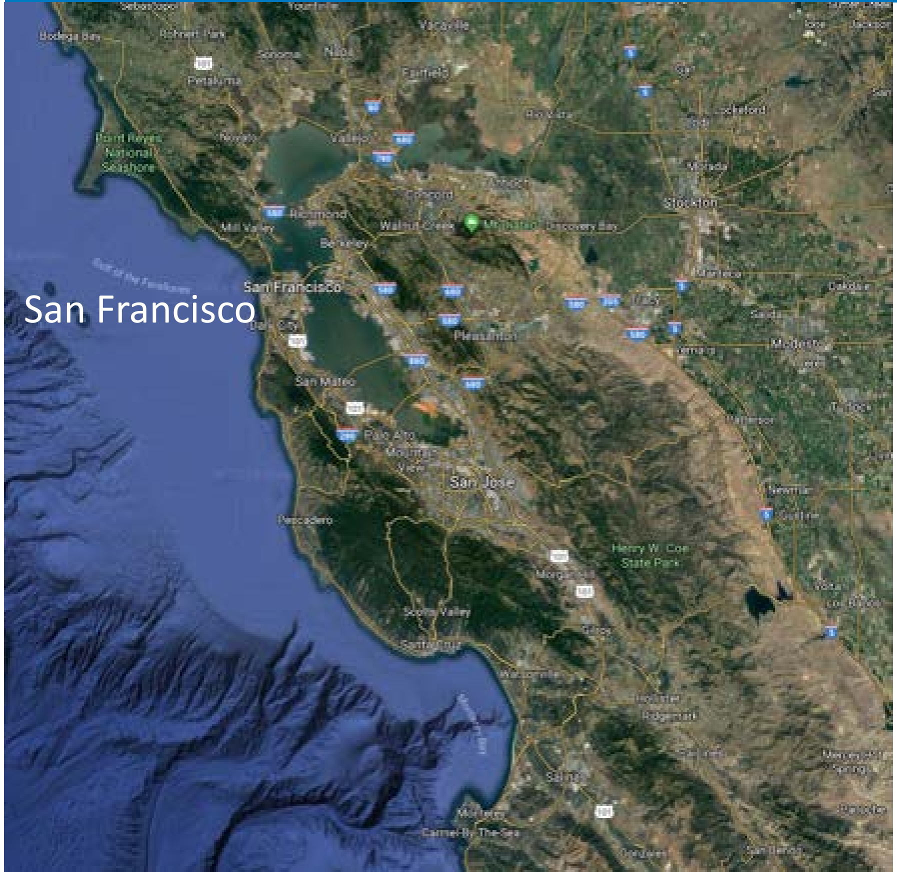


Transforming ENERGY through Autonomous Energy Systems



- Integration of all energy sources
- Scalable, distributed control of millions of devices
- Real-time optimization
- Able to integrate asynchronous data and communications

AES – Defining a large cross-cutting project objective



Optimize and control massively deployed, distributed energy resources (generation, storage, loads, mobility) in real-time.

Example: Bay Area

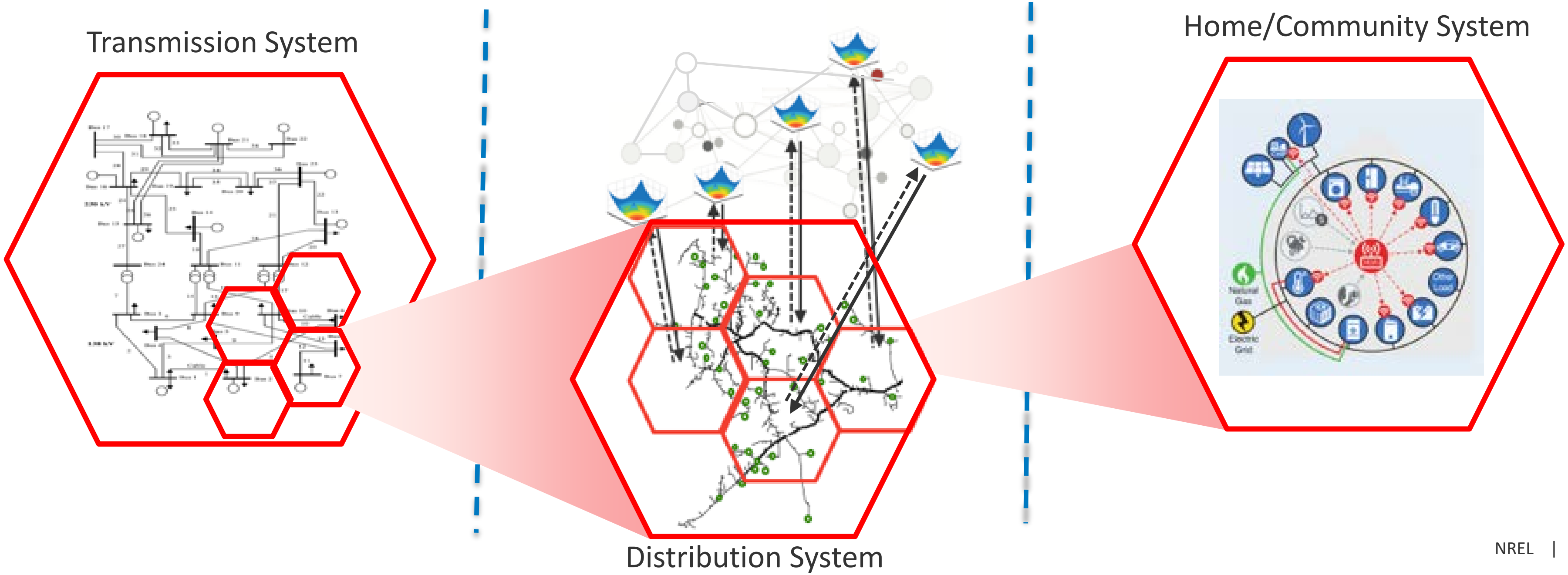
- Grid has more than 10 million electric nodes at distribution level
- 4.3 million Customers – each with PV, storage, smart homes, plug-in EVs = 20 million controllable devices

Nobody knows how to do this!

Formulating new math to address challenges

Challenges that are being addressed:

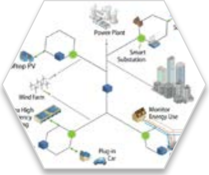
1. **Distributed** – Needs to be fast enough to operate in real-time (On-line)
2. **Scalable** – Needs to be able to control millions of devices (Hierarchical)
3. **Data Aware** – Make best use of time-varying asynchronous measurements



Autonomous Energy Systems

Applications

Power Grids



Transportation

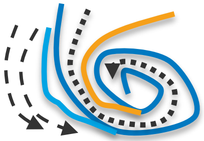
Buildings

Renewables

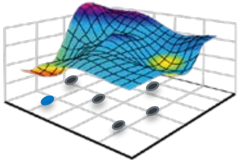
Common Problems:

- Real-time controls and optimization
- Hundreds to millions of control points
- Asynchronous data and communications
- Multi-domain systems (complex) and stochastic systems (variable renewables, consumer/occupant behavior)

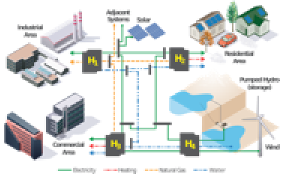
Nonlinear Control



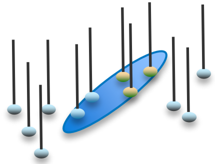
Optimization



Complex Systems

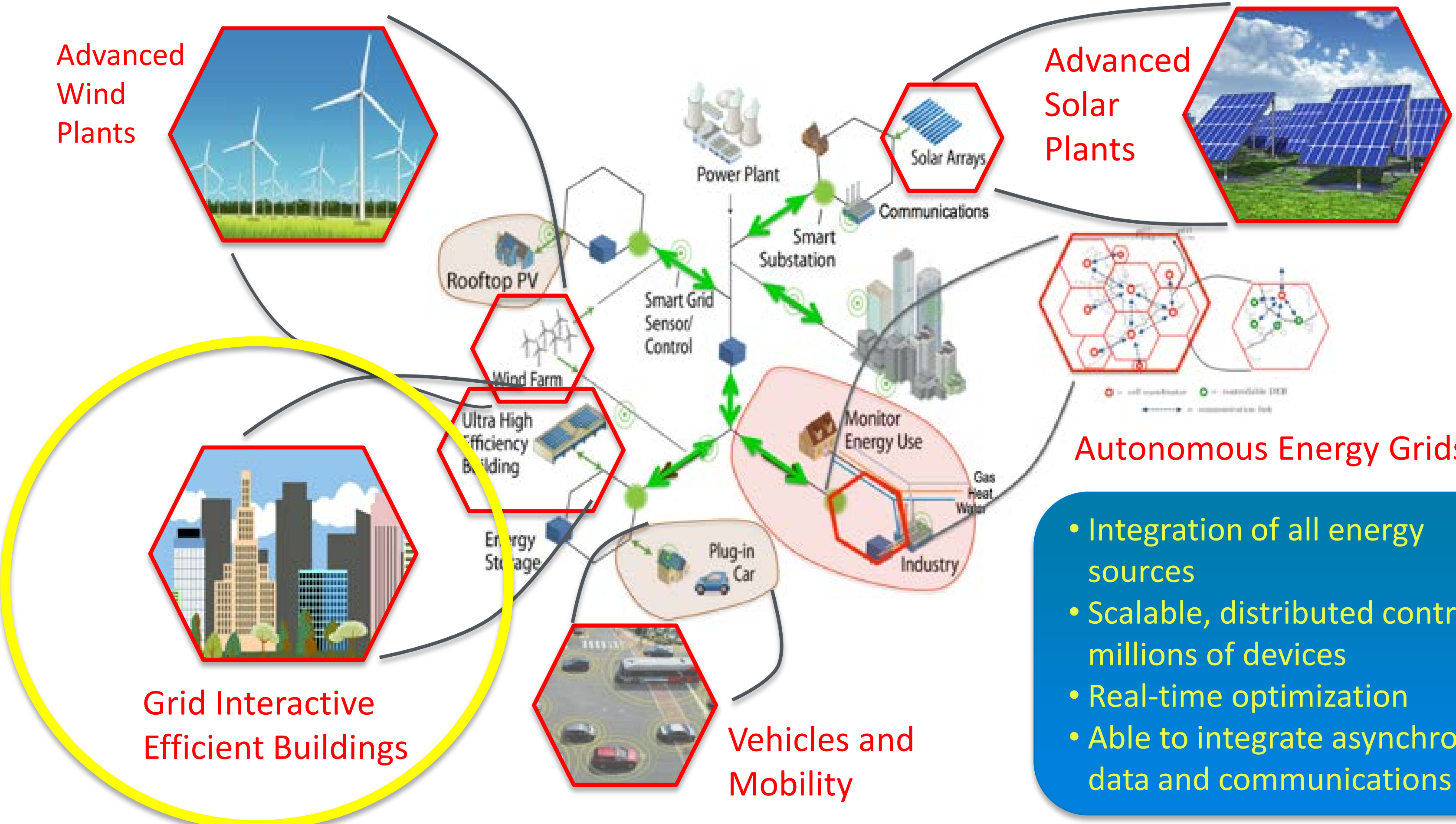


Big Data Analytics



Buildings

Transforming ENERGY through Autonomous Energy Systems



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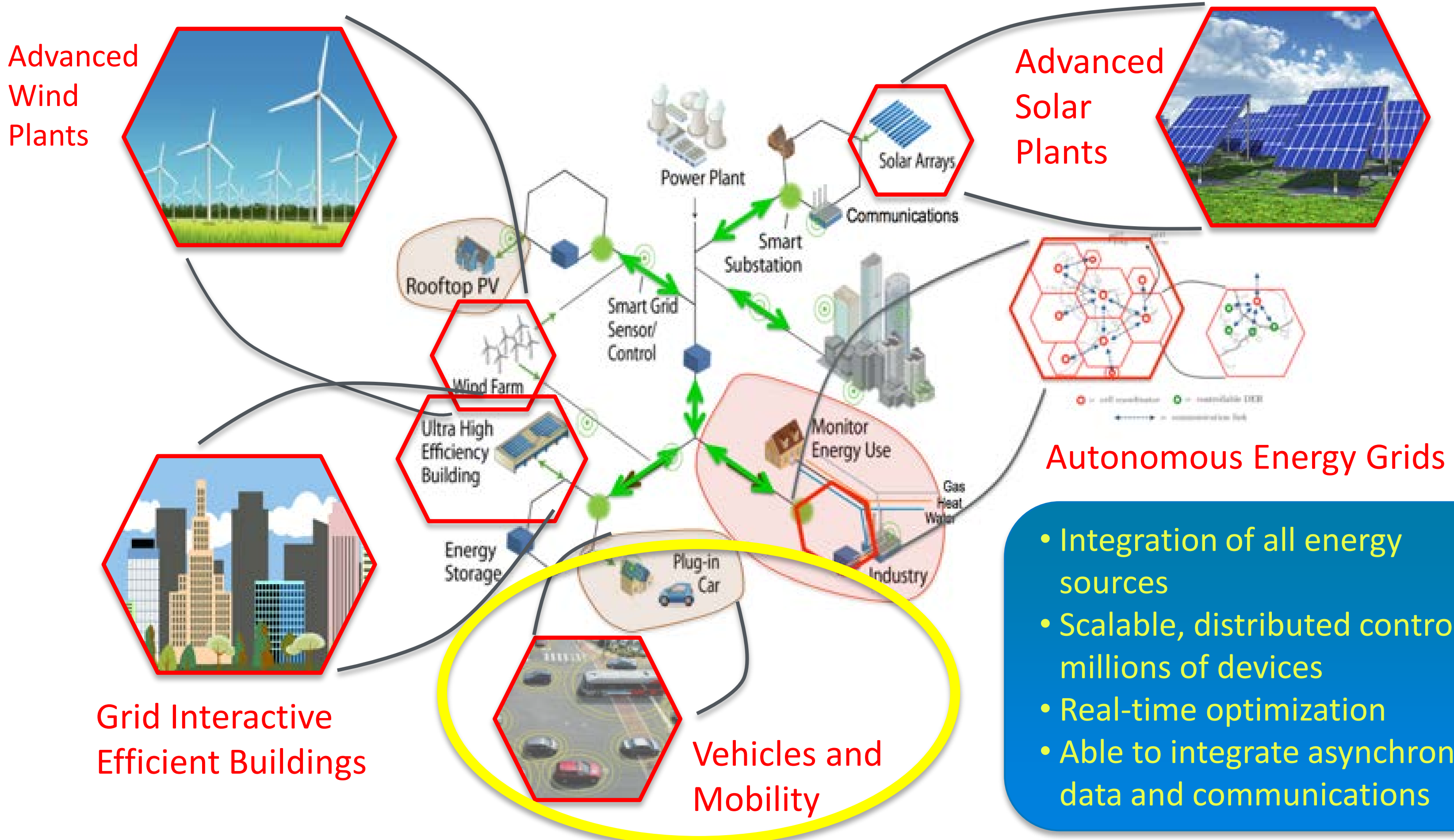
- Scalable, distributed control of millions of devices
- Real-time optimization
- Able to integrate asynchronous data and communications

Transportation

Transforming ENERGY through Autonomous Energy Systems



- Integration of all energy sources
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Transportation Integration

- Developed EV fleet control - Highly Integrated Vehicle Ecosystem (HIVE)

- Charge control (consensus charging)

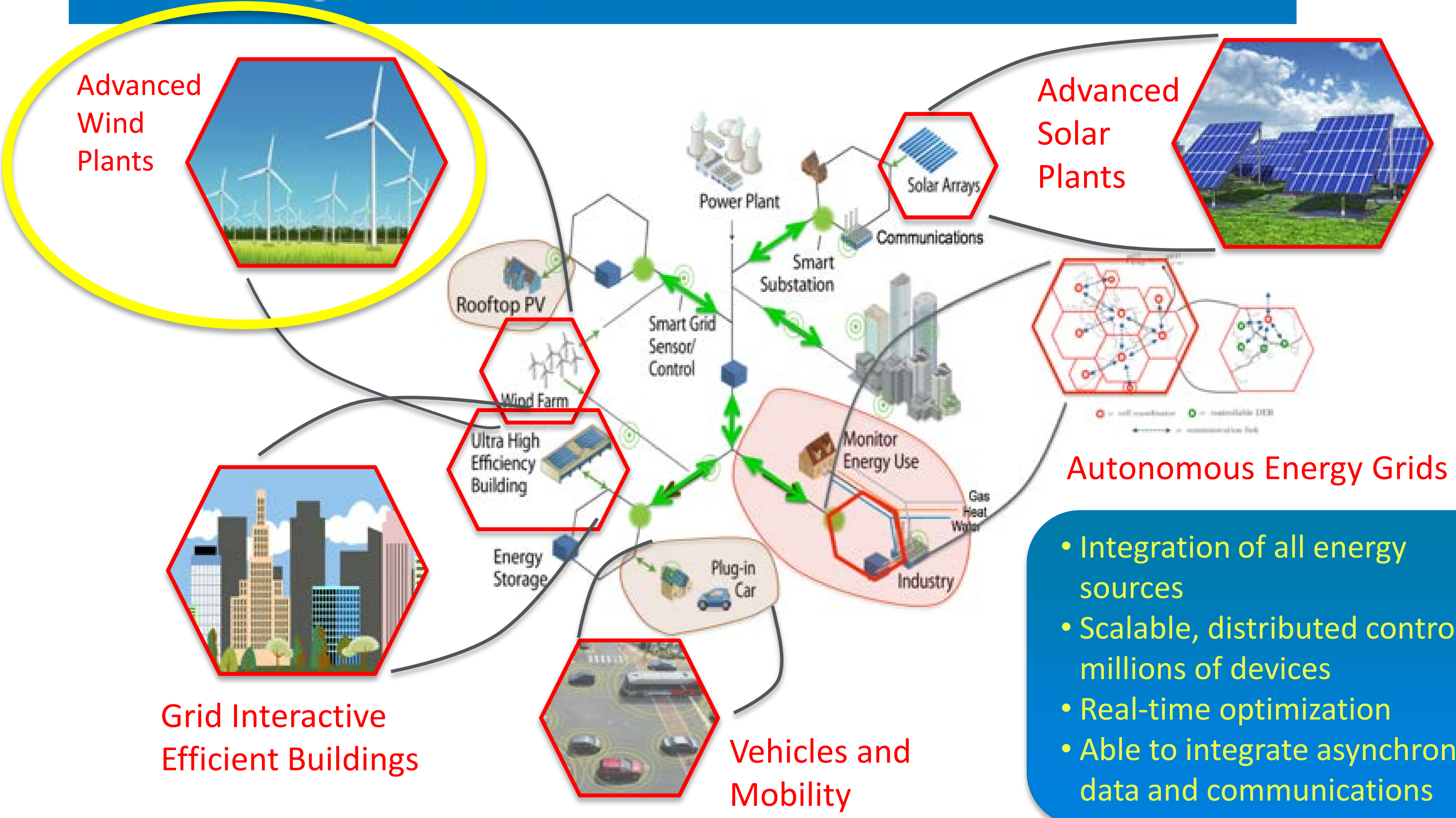
Fleet Operation (Austin)

Ride Austin TNC Data

Web link

Renewable Energy

Transforming ENERGY through Autonomous Energy Systems



- Integration of all energy sources
- Scalable, distributed control of millions of devices
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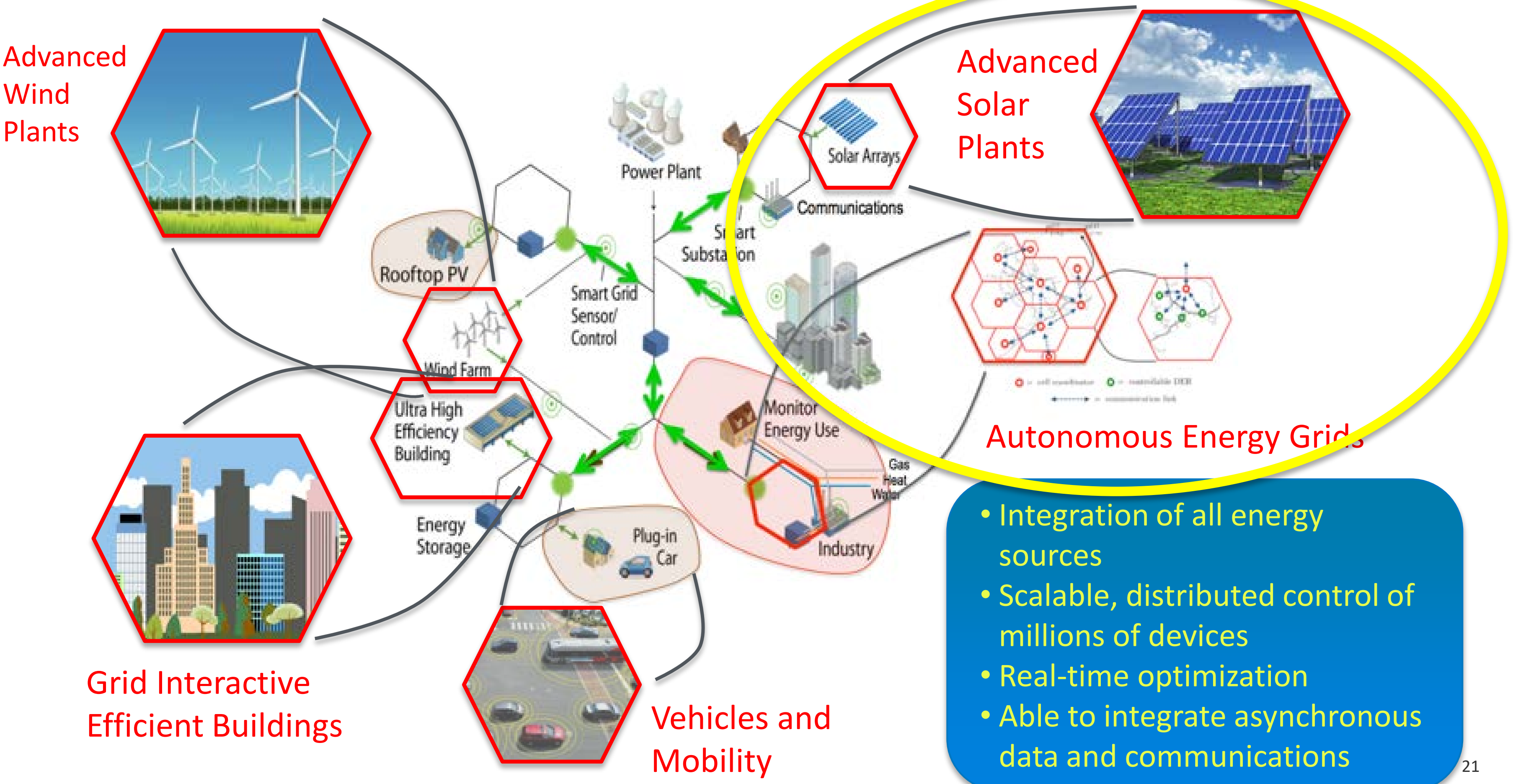
Application – Distributed Control of Wind Farms

Grids and Optimization

Transforming ENERGY through Autonomous Energy Systems



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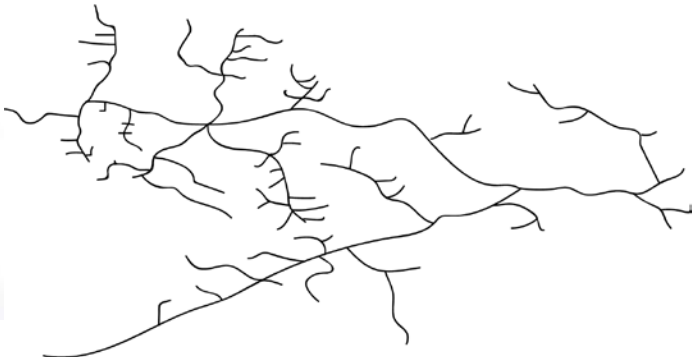
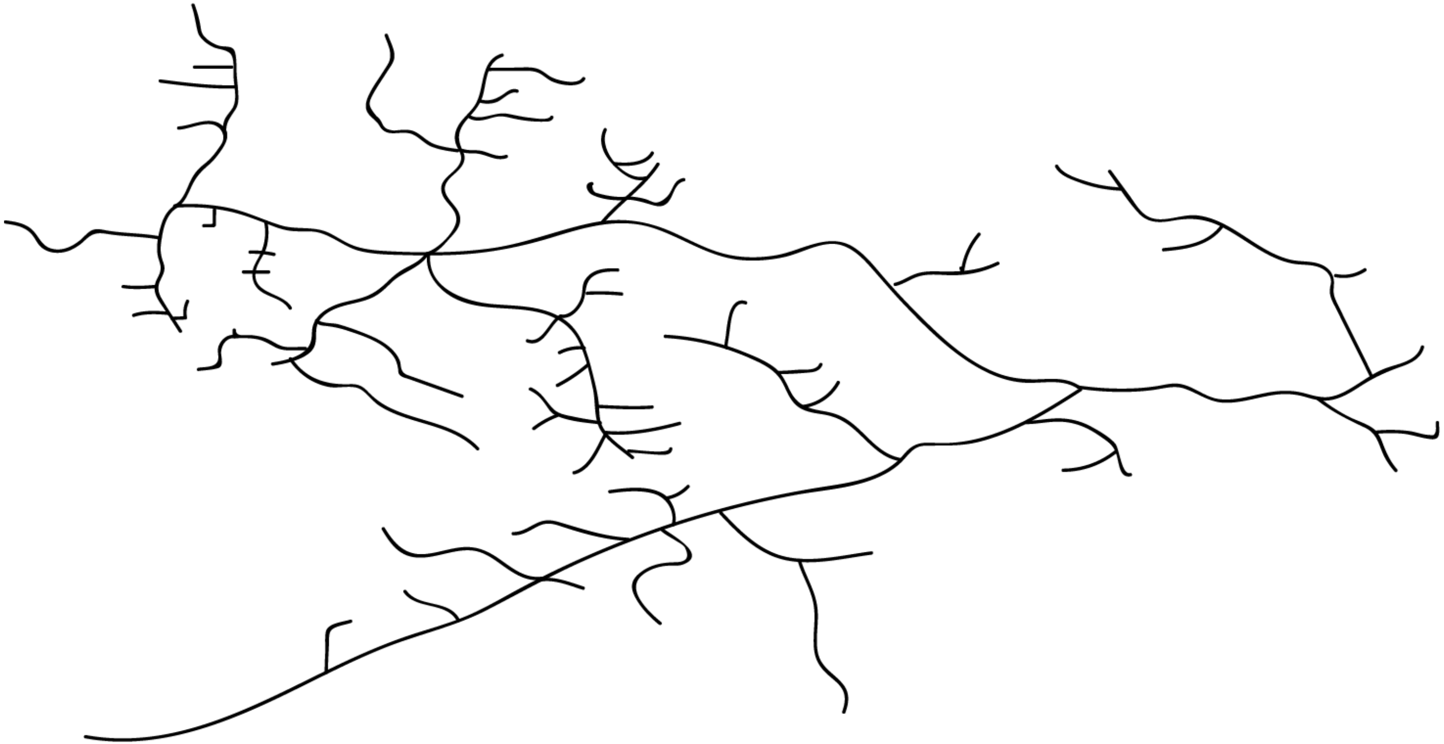
Let's look a little closer
– a single distribution circuit

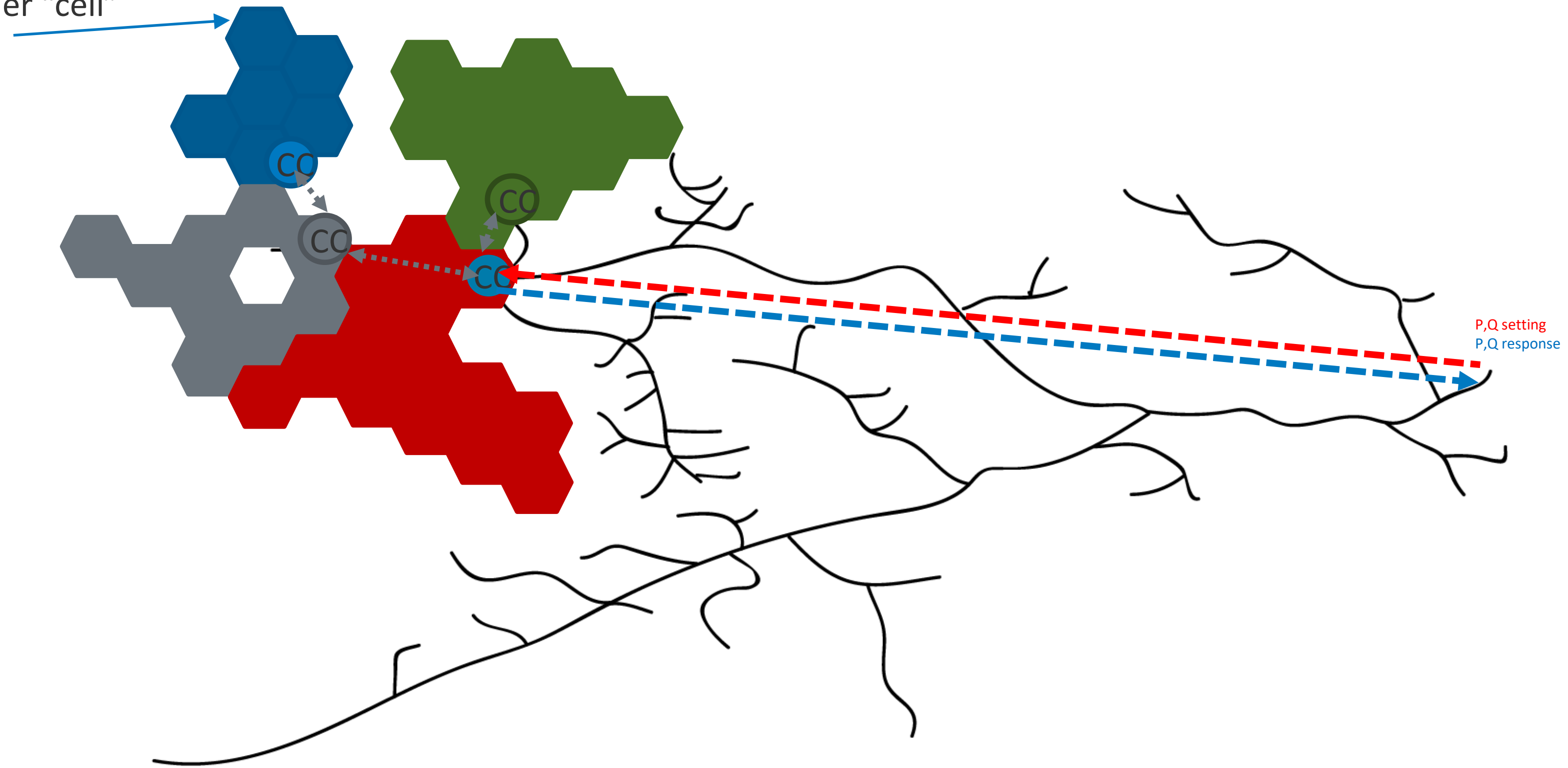


Complex system simulation with new optimization and controls

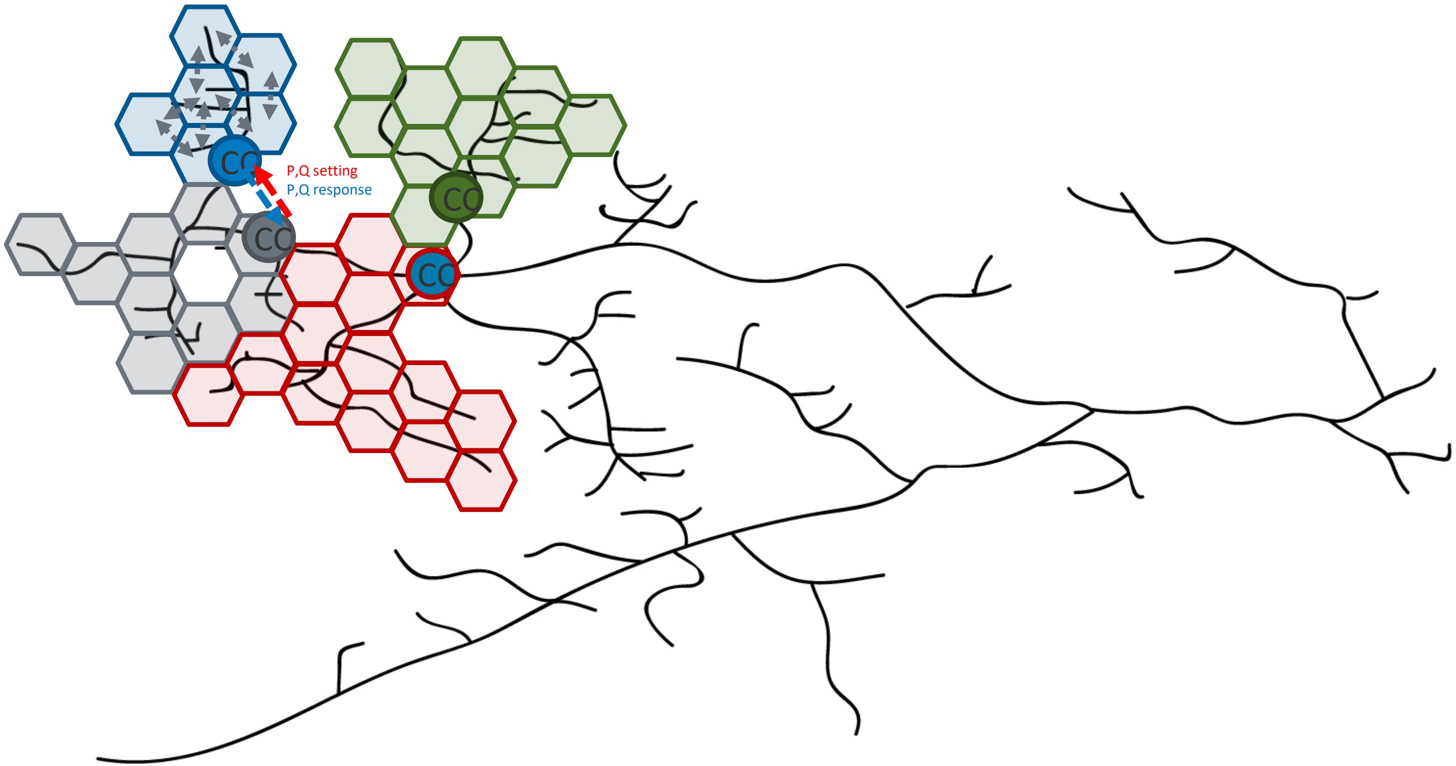


Complex system simulation with new optimization and controls

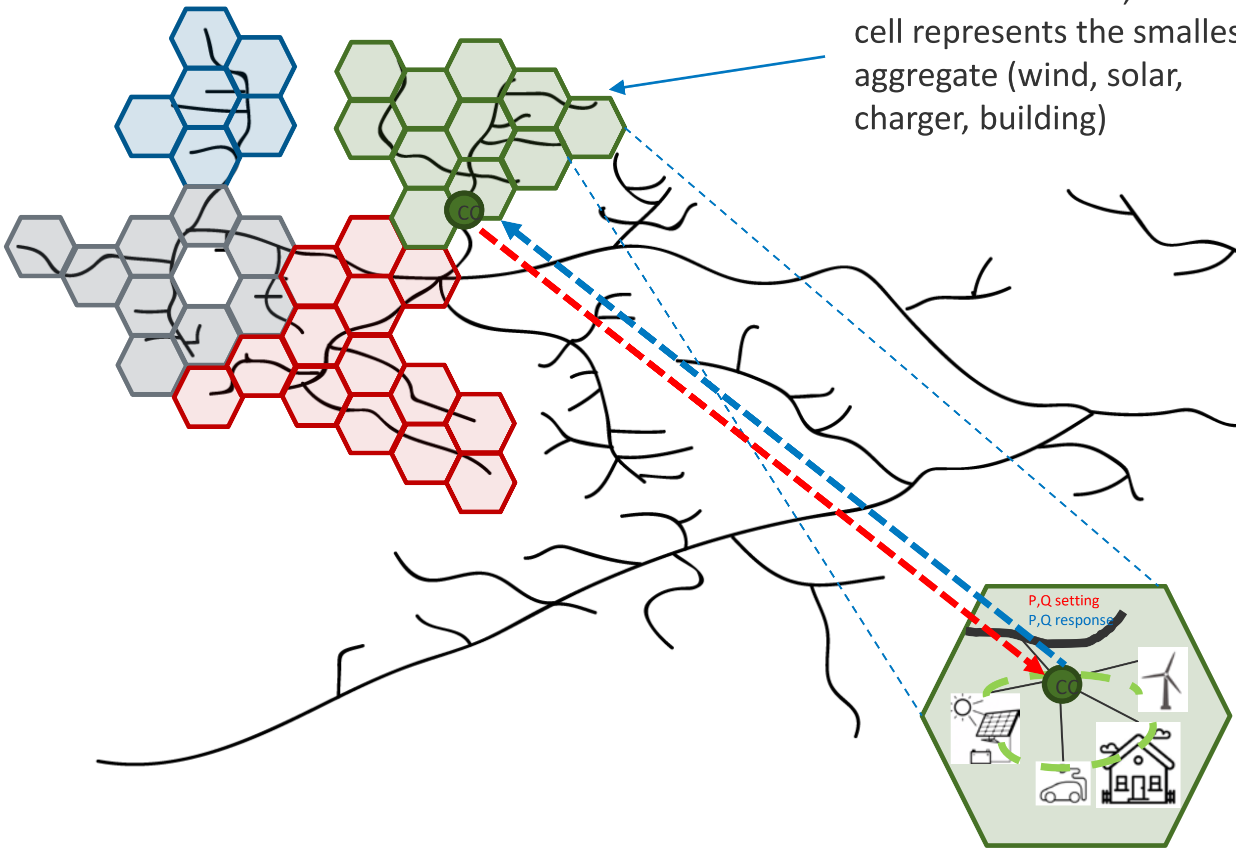
Color coding represent the next higher "cell"



Complex system simulation with new optimization and controls



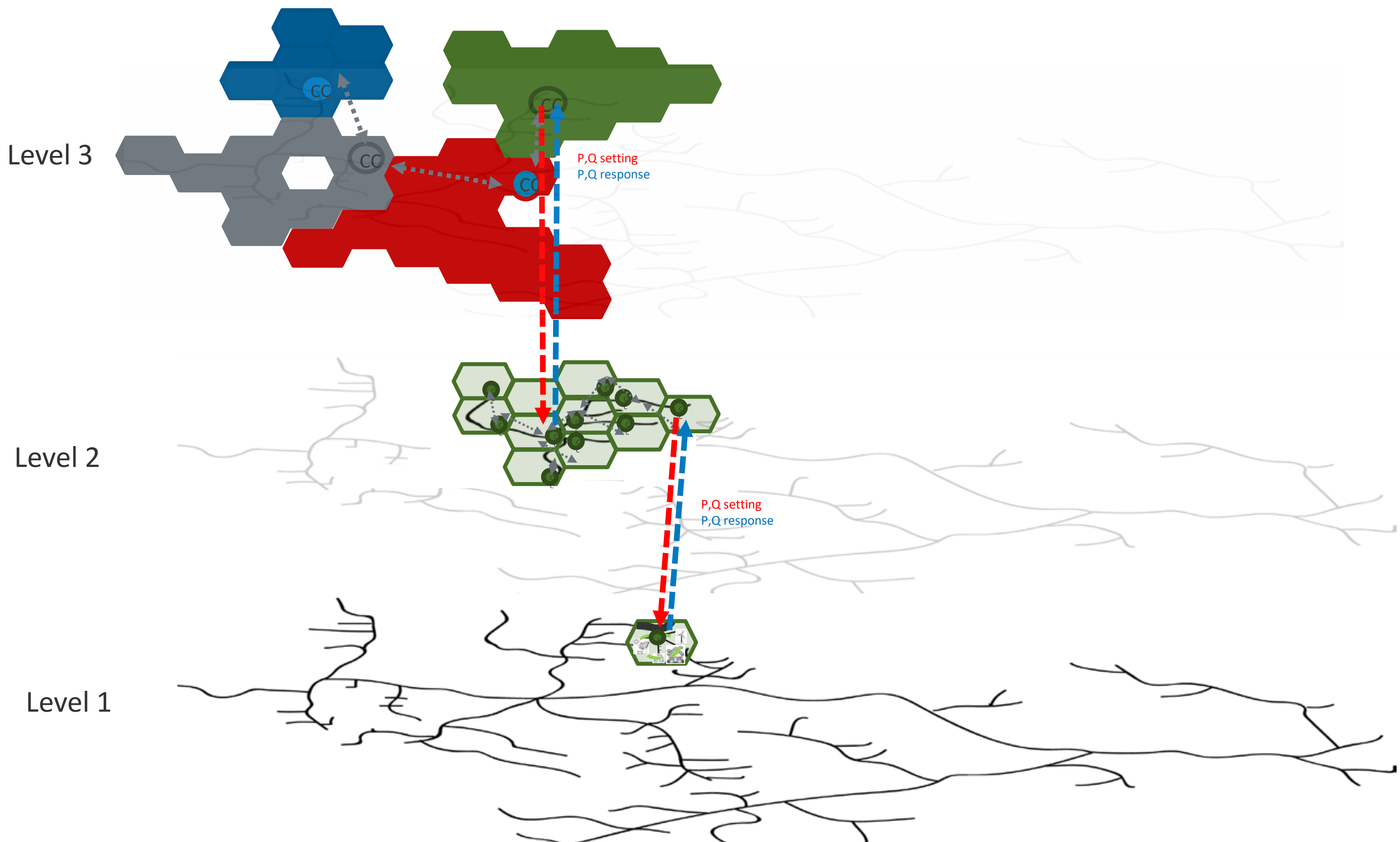
Complex system simulation with new optimization and controls



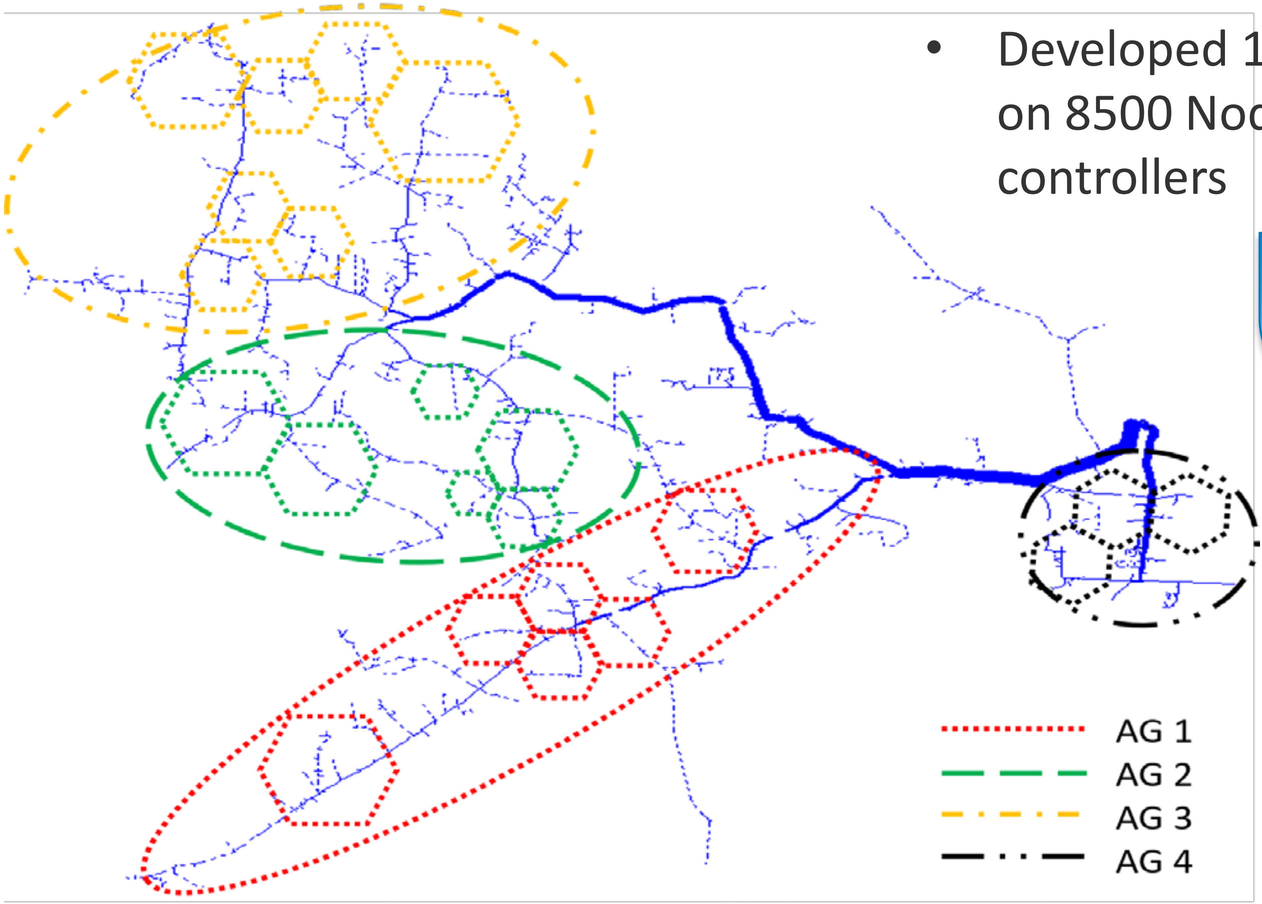
At the lowest level, each cell represents the smallest aggregate (wind, solar, charger, building)

At this level, devices inside the cell communicate with each other (green line) to reach a P,Q set point passed from the next higher level cell coordinator (CC) (red line)

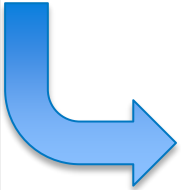
In 3D


Level 3
CC
CC
CC
CC
P,Q setting
P,Q response
Level 2
P,Q setting
P,Q response
Level 1

Complex system simulation with new optimization and controls

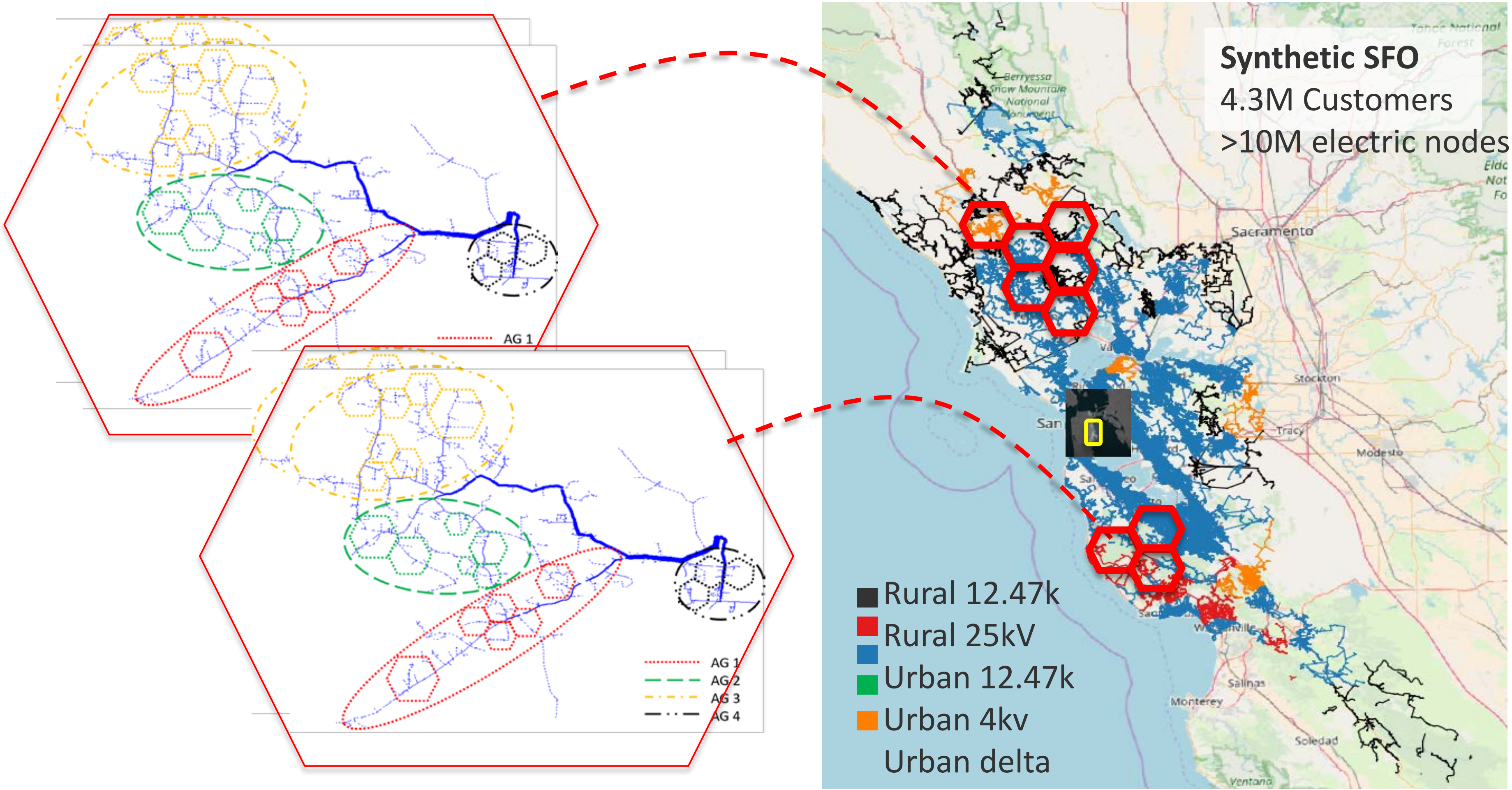


- Developed 144 cells and multi-cells on 8500 Node System with 12,000 controllers



Simulations the size of the Bay Area

Pulling it all together….



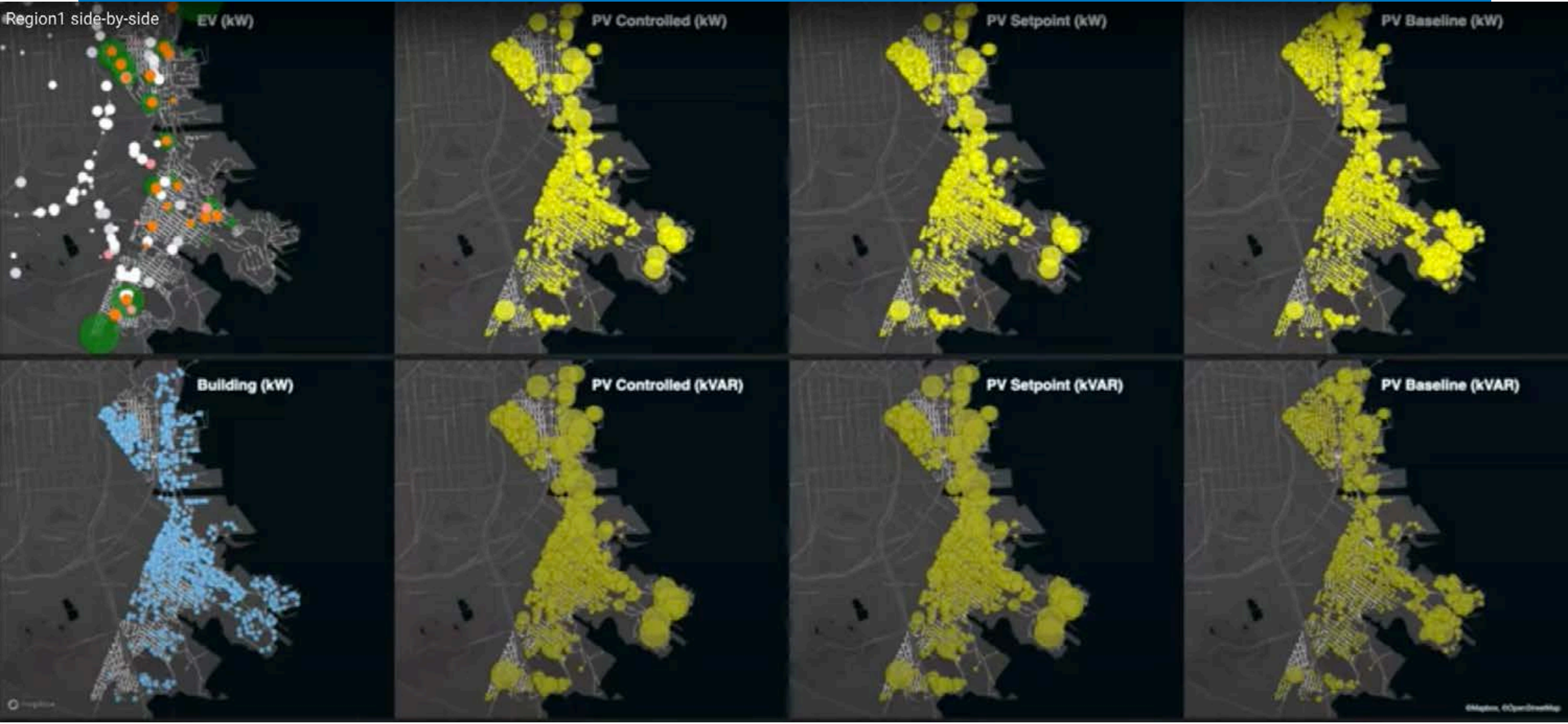
Bay Area Simulations

PV Generation

Building Loads

EV Routing and Charging Loads

Bay Area Simulations – Comparing Baseline to AES Controller



Bay Area Simulations

Comparing Controls at different physical scales

AES Project Presentation at this Workshop

- Computation-Efficient Optimization Algorithm for Autonomous Energy Systems - ***Xinyang Zhou and Chin-Yao Chang, NREL***
- Distributed monitoring and control of load tap changer dynamics - ***Andrey Bernstein and Bai Cui, NREL***
- Autonomous Energy System Simulation Capabilities – Ultra-Large Scale DER Deployment - ***Jen King, NREL***
- Scalable Distributed Model Predictive Control for Building and Renewable Energy Systems - ***Rohit Chintala and Christopher Bay, NREL***
- Online optimization as feedback control for dynamical systems - ***Emiliano Dall'Anese, University of Colorado - Boulder***
- Modeling and Management of Electric Vehicle Loads - ***Matt Moniot and Kalpesh Chaudhari, NREL***

AES Publications

1. Bernstein, A., E. Dall'Anese, and A. Simonetto, *"Online Primal-Dual Methods With Measurement Feedback for Time-Varying Convex Optimization",* IEEE Transactions on Signal Processing, Volume: 67 , Issue: 8 , April 2019, https://ieeexplore.ieee.org/document/8631190

2. Colombino, M., E. Dall'Anese and A. Bernstein *"Online Optimization as a Feedback Controller: Stability and Tracking",* IEEE Transactions on Control of Network Systems, March 2019, https://ieeexplore.ieee.org/document/8673636

3. Zhang, K., W. Shi, H. Zhu, E. Dall'Anese, and T. Basar, *"Dynamic Power Distribution System Management with a Locally Connected Communication Network",* IEEE Journal of Selected Topics in Signal Processing, Volume: 12 , Issue: 4 , August 2018, https://ieeexplore.ieee.org/document/8360012

4. H. Jiang, Y. Zhang, Y. Chen, C. Zhao. J.Tan, *"Power-Traffic Coordinated Operation for Bi-Peak Shaving and Bi-Ramp Smoothing -A Hierarchical Data-Driven Approach"*, Applied Energy Journal, https://www.sciencedirect.com/science/article/pii/S0306261918308869

5. Zhou, Xinyang, Zhiyuan Liu, Wenbo Wang, Changhong Zhao, Fei Ding, Lijun Chen *"Hierarchical Distributed Voltage Regulation in Networked Autonomous Grids",* Proc. of American Control Conference, July 2019. https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=8814670

6. Colombino, M., Emiliano Dall'Anese, Andrey Bernstein, *"Online optimization as a feedback controller: Stability and Tracking",* IEEE Transactions on Control of Network Systems, March 2019 https://ieeexplore.ieee.org/document/8673636

7. Chang, Chin-Yao, Marcello Colombino, Jorge Corté, Emiliano Dall'Anese, *"Saddle-flow dynamics for distributed feedback-based optimization",* IEEE Control Systems Letters, Volume: 3 , Issue: 4 , October 2019 https://ieeexplore.ieee.org/document/8723549

8. Graf, Peter, Jennifer Annoni, Christopher Bay, Dave Biagioni, Devon Sigler, Monte Lunacek, Wes Jones, *"Distributed Reinforcement Learning with ADMM-RL",* 2019 American Control Conference (ACC), July 2019, https://ieeexplore.ieee.org/document/8814892

AES Publications

9. Annoni, Jennifer, Christopher Bay, Kathryn Johnson, Paul Fleming, *"Short-Term Forecasting Across a Network for the Autonomous Wind Farm"* 2019 American Control Conference (ACC), July 2019, https://ieeexplore.ieee.org/document/8814394

10. Annoni, Jennifer, Emiliano Dall'Anese, Mingyi Hong, Christopher Bay, *"Efficient Distributed Optimization of Wind Farms Using Proximal Primal-Dual Algorithms"*,2019 American Control Conference (ACC), July 2019, https://ieeexplore.ieee.org/document/8814655

11. Annoni, Jennifer, Bay, Christopher, Johnson, Kathryn, Dall'Anese, Emiliano, Quon, Eliot, Kemper, Travis, Fleming, Paul, *"Wind direction estimation using SCADA data with consensus-based optimization"* Wind Energy Science, June 2019. https://www.wind-energ-sci.net/4/355/2019/

12. Bernstein, A., Dall'anese, E., and Simoinetto, A. *"Online primal-dual methods with measurement feedback for time-varying convex optimization"*, IEEE Transactions on Signal Processing, 2019, January 2019, https://ieeexplore.ieee.org/document/8631190

13. Bernstein, A., Y.Chen, M. Colombino, E. Dall'Anese, P. Mehta, S. Meyn, "Quasi-Stochastic Approximation and Off-Policy Reinforcement Learning", 2019 IEEE 58th Conference on Decision and Control (CDC), December 2019. https://ieeexplore.ieee.org/document/9029247

14. J. Song, E. Dall'Anese, A. Simonetto, and H. Zhu, *"Dynamic Distribution State Estimation Using Synchrophasor Data*," IEEE Transactions on Smart Grid, Vol 11, Issue 1, January 2020. https://ieeexplore.ieee.org/document/8847472

15. Zhou, Xinyang, Zhiyuan Liu, Changhong Zhao, Lijun Chen. *"Accelerated Voltage Regulation in Multi-Phase Distribution Networks Based on Hierarchical Distributed Algorithm"*, IEEE Transactions on Power System, Vol 35, Issue 3, May 2020. https://ieeexplore.ieee.org/document/8879622

16. Zhou, Xinyang, Zhiyuan Liu, Changhong Zhao, Yi Guo, Lijun Chen *"Gradient-Based Multi Area Distributed Distribution System State Estimation"*, IEEE Transactions on Smart Grid. https://ieeexplore.ieee.org/document/912205

AES Publications

17. Zhang, Xiangyu, Dave Biagioni, Peter Graf, Jennifer King. *"Cooperative Load Scheduling for Multiple Aggregators Using Hierarchical ADMM.",* 2020 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT), February 2020 https://ieeexplore.ieee.org/document/9087678

18. Jiang, H., Y. Gu, Y. Xie, R. Yang, and Y. Zhang, *"Solar Irradiance Capturing in Cloudy Sky Days – A Convolutional Neural Network Based Image Regression Approach",* IEEE Access, Vol. 8, January 2020, https://ieeexplore.ieee.org/document/8970273

19. Cavraro, G., A. Bernstein, R. Carli, S. Zampieri, *"Distributed Minimization of the Power Generation Cost in Prosumer-Based Distribution Networks"*, 2020 American Control Conference, Denver, CO, July 2020 https://ieeexplore.ieee.org/document/9147784

20. Ajalloeian, A., A. Simonetto, E. Dall'Anese, *"Inexact Online Proximal-gradient Method for Time-varying Convex Optimization",* 2020 American Control Conference, Denver, CO, July 2020 https://ieeexplore.ieee.org/document/9147467

21. Stanfel, P., Johnson, K., King, J., Bay, C., *"A Distributed Reinforcement Learning Yaw Control Approach for Wind Farm Energy Capture Maximization."* 2020 American Control Conference, Denver, CO, July 2020. https://ieeexplore.ieee.org/document/9147946

22. Chen, Y., A. Bernstein, A. Devraj, S. Meyn, *"Model-Free Primal-Dual Methods for Network Optimization with Application to Real-Time Optimal Power Flow",* 2020 American Control Conference, Denver, CO, July 2020. https://ieeexplore.ieee.org/document/9147814

23. Chen, Y and Bernstein, A., "Data-Driven Linear Parameter-Varying Modeling and Control of Flexible Loads for Grid Services", 2020 American Control Conference, Denver, CO, July 2020. https://ieeexplore.ieee.org/document/9147261

24. Zamzam, A., Y. Liu, A. Bernstein, "Model-Free State Estimation Using Low-Rank Canonical Polyadic Decomposition", IEEE Control System Letters, Vol 5., No. 2, April 2021, https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=9123942

AES Publications

25. Cavraro, G., A. Bernstein, “Bus Clustering for Distribution Grid Topology Identification”, IEEE Transactions on Smart Grid, April 2020, https://ieeexplore.ieee.org/document/9076710

26. Cavraro, G. A. Bernstein, V. Kekatos, Y. Zhang, “Real-Time Identifiability of Power Distribution Network Topologies With Limited Monitoring”, April 2020, https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=8754743

27. Network Topologies With Limited Monitoring”, IEEE Control Systems Letters, Vol, 4, No. 2, April 2020. https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=8754743

28. Cavraro, G, E. Dall’Anese, A. Bernstein, “Dynamic Power Network State Estimation with Asynchronous Measurements”, 2019 IEEE Global Conference on Signal and Information Processing (GlobalSIP), November 2019 https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=8969267

Additional AES Submitted Publications

- Guo, Yi, Xinyang Zhou, Changhong Zhao, Yue Chen, Tyler H. Summers and Lijun Chen. “Solving Optimal Power Flow Problems Feedback for Distribution Networks with State Estimation”, 2020 American Control Conference. https://arxiv.org/abs/1909.12763
- A. Simonetto, E. Dall’Anese, J. Monteil, and A. Bernstein, “Personalized Optimization with User’s Feedback”, submitted to Automatica, 2019 https://arxiv.org/abs/1905.00775
- V. Chinde, Hirsch, A., Livingood, W., and Florita, A. “Simulating Grid Services Provided by Flexible Building Loads: State of the Art and Needed Improvements” submitted to BUILD SIMUL, https://doi.org/10.1007/s12273-020-0687-1
- Y. Zhang, E. Dall'Anese, and M. Hong, "Proximal-ADMM For Time-varying Network Optimization," Submitted to IEEE Trans. on Control of Network Systems, https://arxiv.org/abs/2005.03267
- G. Bianchin, J. I. Poveda, and E. Dall'Anese, "Online Optimization of Switched LTI Systems Using Continuous-Time and Hybrid Accelerated Gradient Flows," Automatica, submitted August 2020, under review. [Online] available at: https://arxiv.org/abs/2008.03903
- G. Cavraro, E. Dall'Anese, J. Comden, and A. Bernstein, "Online State Estimation for Systems with Asynchronous Sensors," IEEE Trans. on Automatic Control, submitted May 2020, under review. [Online] Available at: https://arxiv.org/pdf/2006.00628

Thank you

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