



Autonomous Energy Systems

A vision of the future grid integrating massive amounts of distributed energy resources

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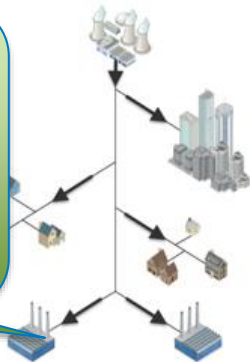
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Transformation of the Power System

Current Power System

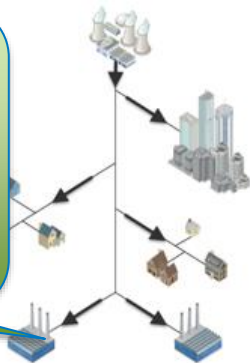
- Large Central-Station, Synchronous Generation
- Central Control
- Generation follows Demand



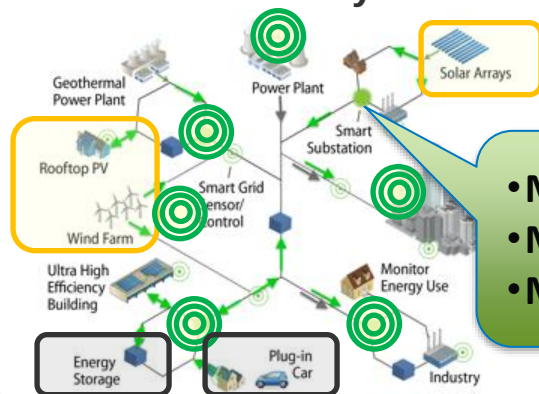
Transformation of the Power System

Current Power System

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- Central Control
- Generation follows Demand



Future Power Systems



- 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

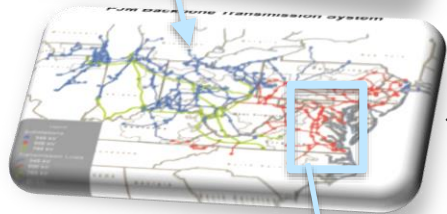
Is the Grid getting too complex to control?

Current Grid

Central Control
 10^4 Bulk Generators

Synchronous AC
Interconnection

Regional
Transmission
Operator -
Market/
Reliability
Coordinator
Local Utility -
Transmission/
Subtransmission/
Bulk Generation



Local Utility
Distribution

Industry/
Commercial/
Residential



- 128M Households in US
- 6M Commercial buildings
- + Industry and Transportation



5 min markets
4 sec power
flows

Is the Grid getting too complex to control?

Current Grid

Central Control
 10^4 Bulk Generators

Distributed, Hierarchical Control

10^8 Generators, Storage, Active Loads
1 sec optimizations at each level

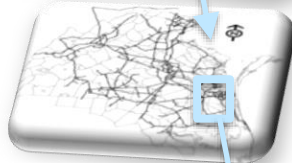
Synchronous AC
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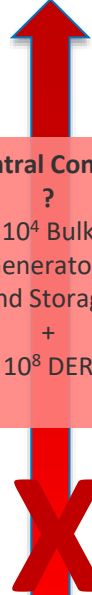


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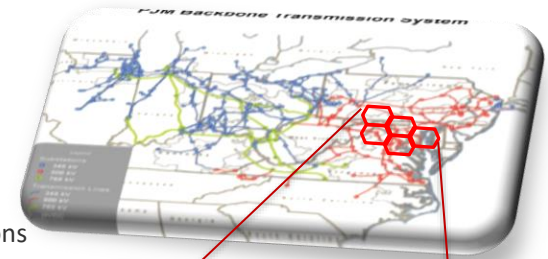


Central Control
?
 10^4 Bulk
Generators
and Storage
+
 10^8 DER

- 128M Households in US
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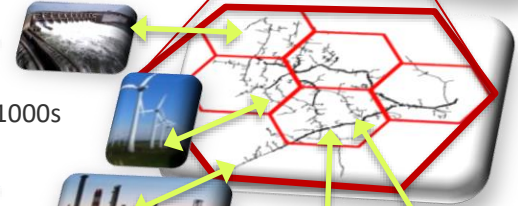


Millions



Virtual
Emulation

1000s



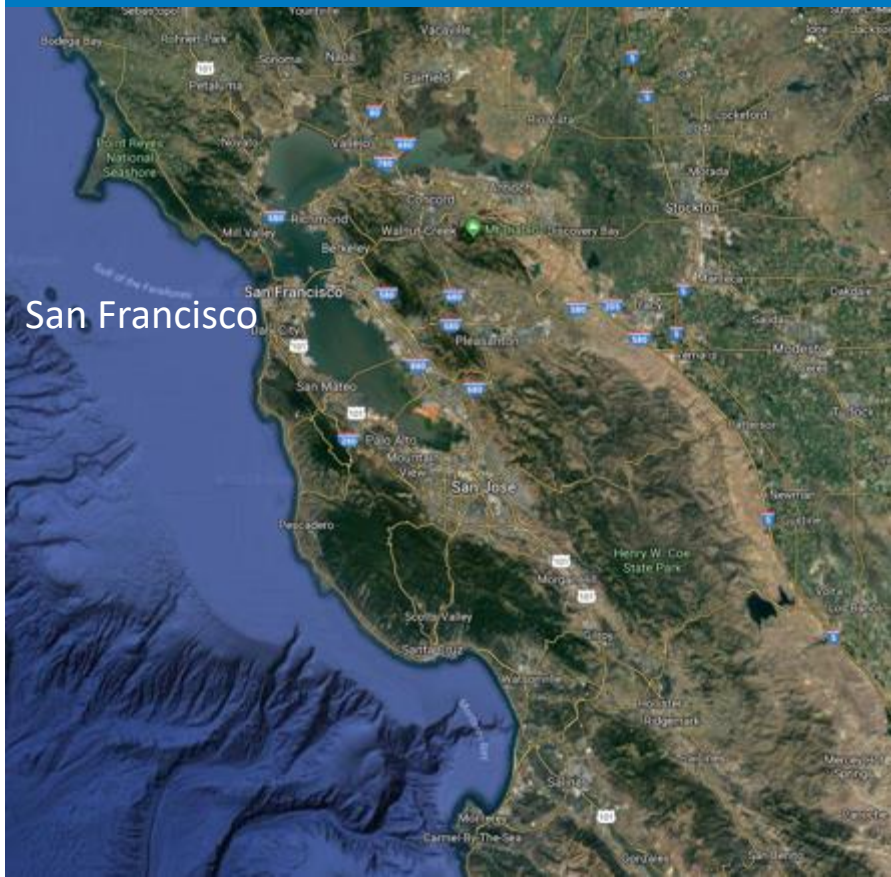
Flatirons
Campus

1-100



ESIF

What are we trying to achieve in the Autonomous Energy Systems Project?



Distributed Energy Resources (DER) =

- Generation (solar, wind, fuel cells, generators)
- Storage = Batteries, Ice storage
- Loads = Buildings, Homes
- Mobility = EVs, Chargers

Optimize and control massively deployed DER in real-time.

- **Generation (solar, wind, fuel cells, generators)**
- **Storage = Batteries, Ice storage**
- **Loads = Buildings, Homes**
- **Mobility = EVs, Chargers**

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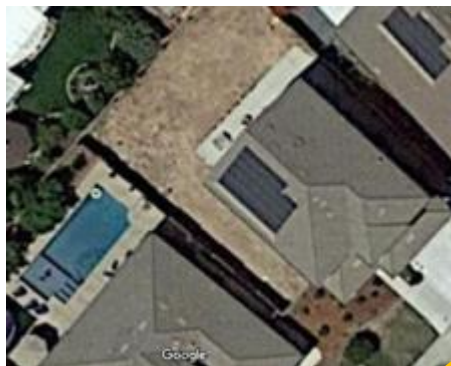
Example: SF Bay Area

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

Nobody knows how to do this!

Transforming **ENERGY** through Autonomous Energy Systems

Home



Neighborhood



Community/Town

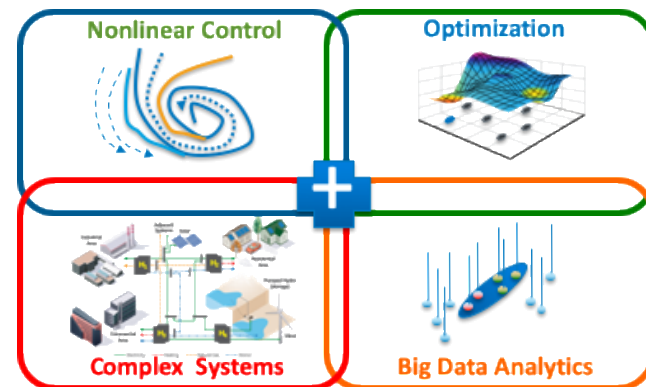


Large City



Develop framework to enable scalable control and optimization of all energy resources across several domains (grids, buildings, transport, renewables) and scales

- **Bridge the gap between control theory and optimization theory and propose a unified theoretical approach** that builds on contemporary advances in control, optimization, and parallel computing
- Develop distributed optimization **algorithms that can run in real-time** (1s) across full system
- **Ensure a computationally affordable, optimal, resilient, and reliable distributed operation** with the objective to enable flexible operation and maintain stability and optimality
- **Validate the results in relevant real-world applications**

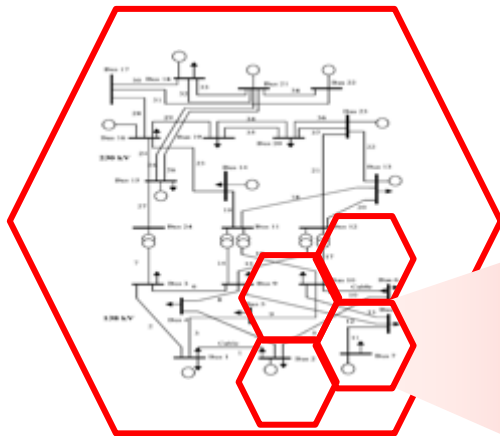


Formulating new math to address challenges

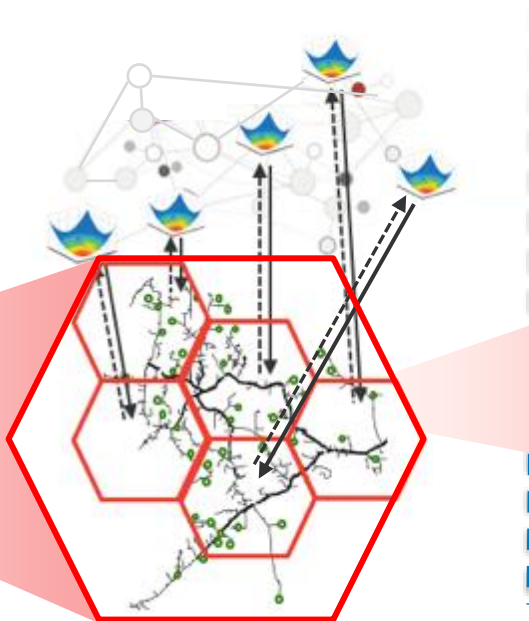
Challenges that are being addressed:

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

Transmission System



Distribution System



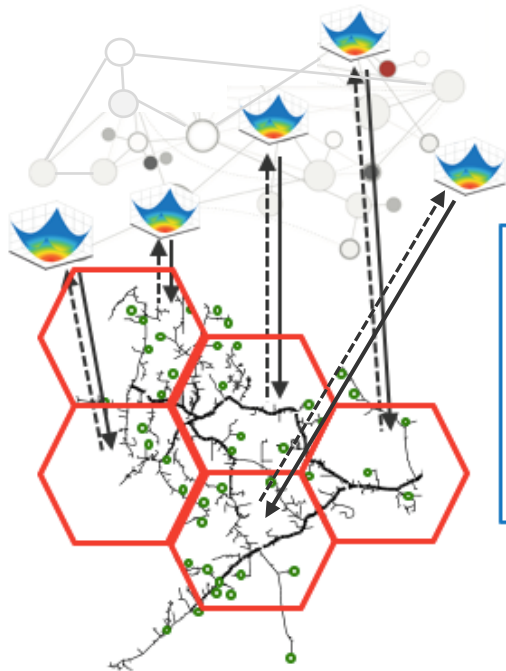
Home/Community System



Distributed Control and Optimization

Real-time optimization with missing model parameters

- "Online Optimization with Feedback", A. Bernstein, E. Dall'Anese, and A. Simonetto accepted to *IEEE Transactions on Signal Processing*
- "Online Optimization as a Feedback Controller: Stability and Tracking", M. Colombino, E. Dall'Anese and A. Bernstein, submitted to *IEEE Transactions on Control of Network Systems*

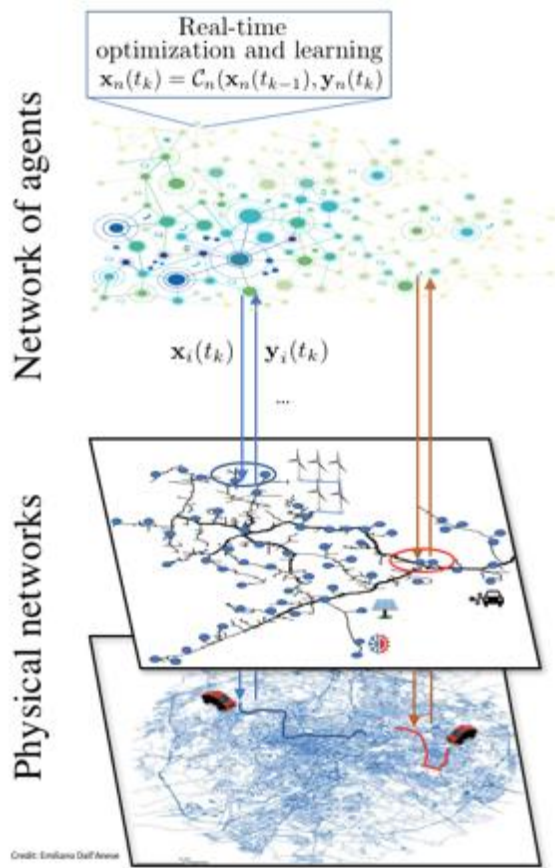


$$\begin{aligned} \min_{\mathbf{x}, \mathbf{p}_i, \mathbf{q}_i} \quad & f_{net}(\mathbf{x}) + \sum_{DERs} f_i(\mathbf{p}_i, \mathbf{q}_i) \\ \text{subject to} \quad & \mathbf{p}_i, \mathbf{q}_i \in \mathcal{Y}_i \quad \forall i, \\ & \mathbf{h}_i(\mathbf{p}_i, \mathbf{q}_i) = \mathbf{0} \quad \forall i, \\ & \mathbf{g}_i(\mathbf{p}_i, \mathbf{q}_i) \leq \mathbf{0} \quad \forall i, \\ & \mathbf{h}_{net}(\mathbf{x}, \mathbf{p}, \mathbf{q}) = \mathbf{0} \\ & \mathbf{g}_{net}(\mathbf{x}, \mathbf{p}, \mathbf{q}) \leq \mathbf{0} \end{aligned}$$

Unique Impactful Results

- Unique results in terms of convergence/stability of the algorithms for **real-time/ closed-loop optimization** algorithms that utilize measurements
- New mathematical framework for driving dynamic system to **optimal time-varying solutions**

Integration of Data Analytics - Formulating new math (ADMM-RL)



Combining Distributed Optimization and Learning (data-driven optimization)

- "Distributed Reinforcement Learning with ADMM-RL", Peter Graf, Jennifer Annoni, Christopher Bay, Dave Biagioni, Devon Sigler, Monte Lunacek, Wesley Jones submitted to the **ACC Conference**

Alternating Direction Method of Multipliers (ADMM)

Decomposition-coordination procedure in which the solutions to small local subproblems (optimization) are coordinated to find a solution to a large global problem.

$$\begin{aligned} &\text{minimize } f(x) + g(z) \\ &\text{s.t. } Ax + Bz = c \end{aligned}$$

$$\begin{aligned} &\text{minimize } \sum_i f_i(x_i) \\ &\text{s.t. } x_i = z. \end{aligned}$$



Reinforcement Learning (RL)

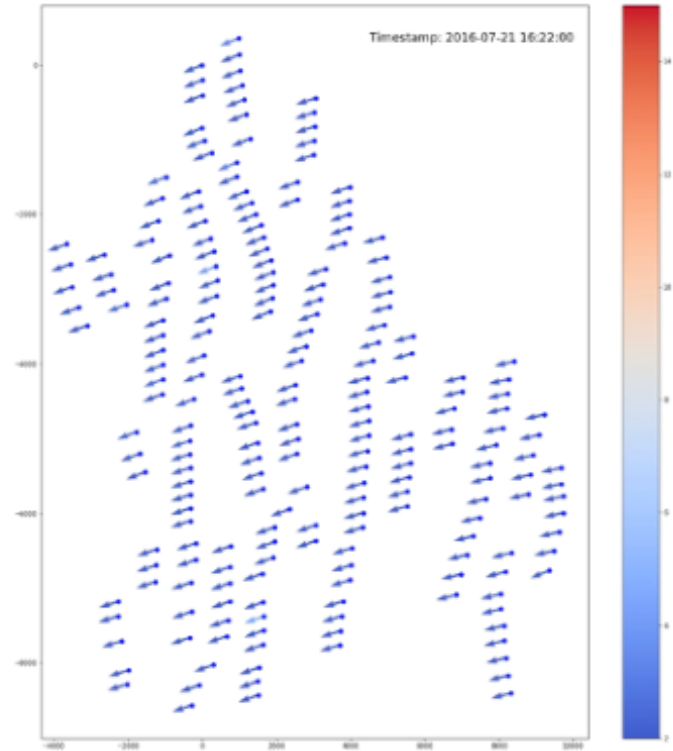
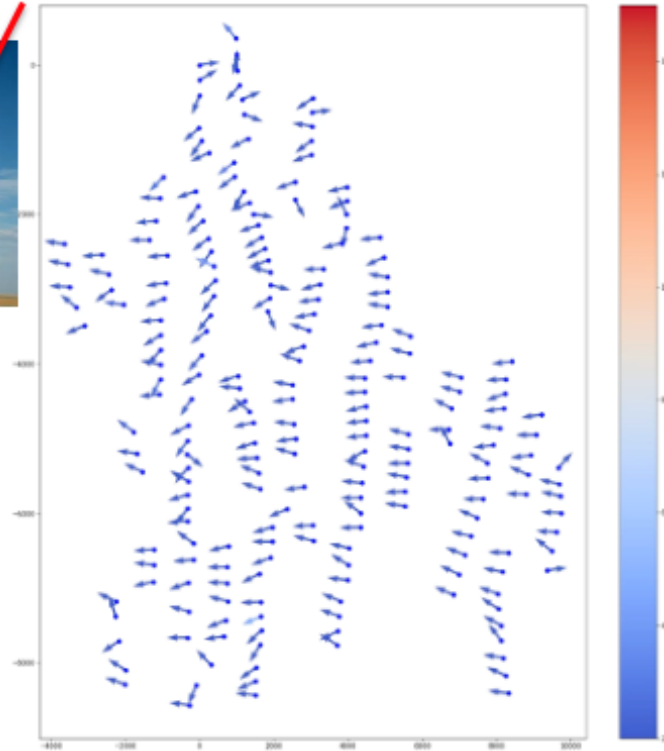
Learner discovers what action yields maximum reward.

$$\begin{aligned} x_i^{k+1} &= \underset{x_{P(i)}}{\operatorname{argmin-RL}(n)} f_i(x_i) + y_k^{k,T} (x_i - \bar{x}^k) + \\ &\quad \frac{\rho}{2} \|x_i - \bar{x}^k\|^2 \\ y^{k+1} &= y^k + \rho(x_i^{k+1} - \bar{x}^{k+1}), \end{aligned}$$

Application – Distributed Control of Wind Farms

Typical Wind Farm Control

(Each turbine moves based on local wind measurements)

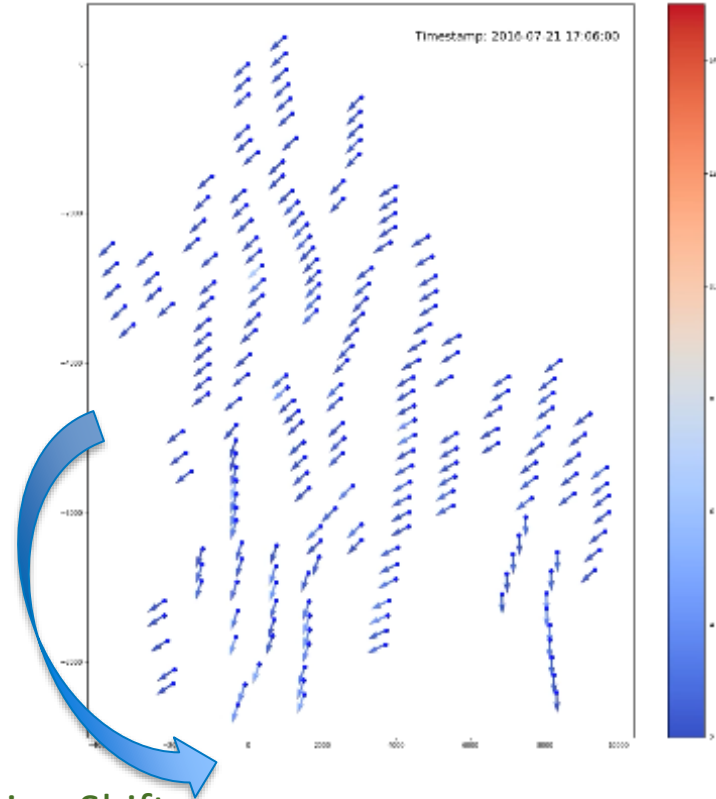
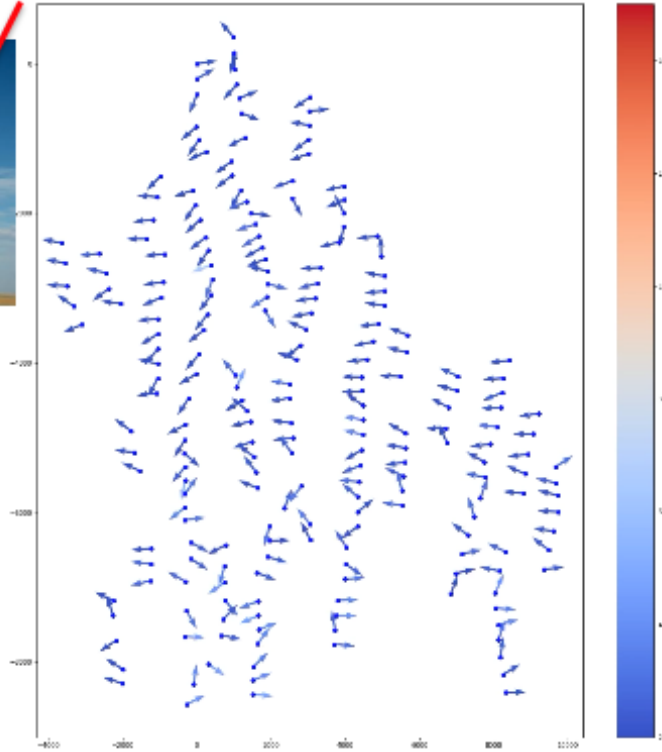


https://www.youtube.com/watch?v=nYV_LH46ZOU

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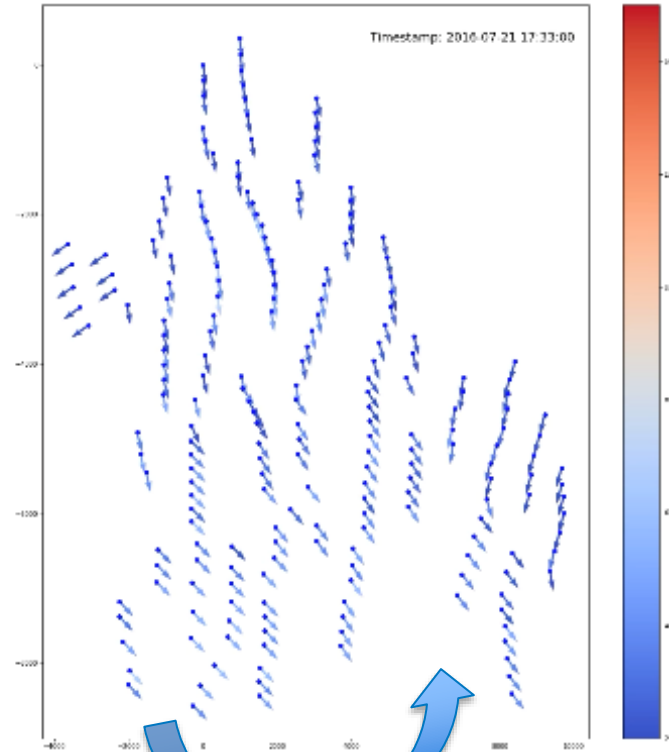
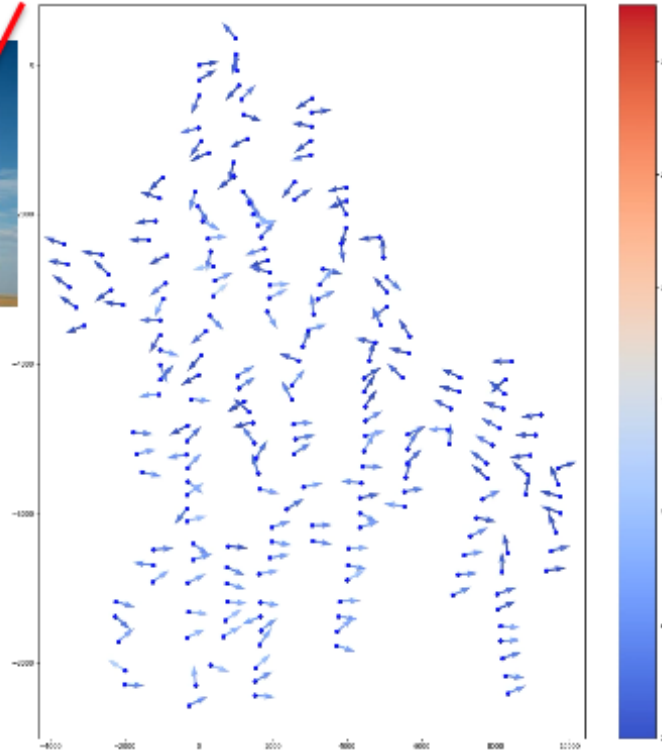


Wind Direction Shift

Application – Distributed Control of Wind Farms

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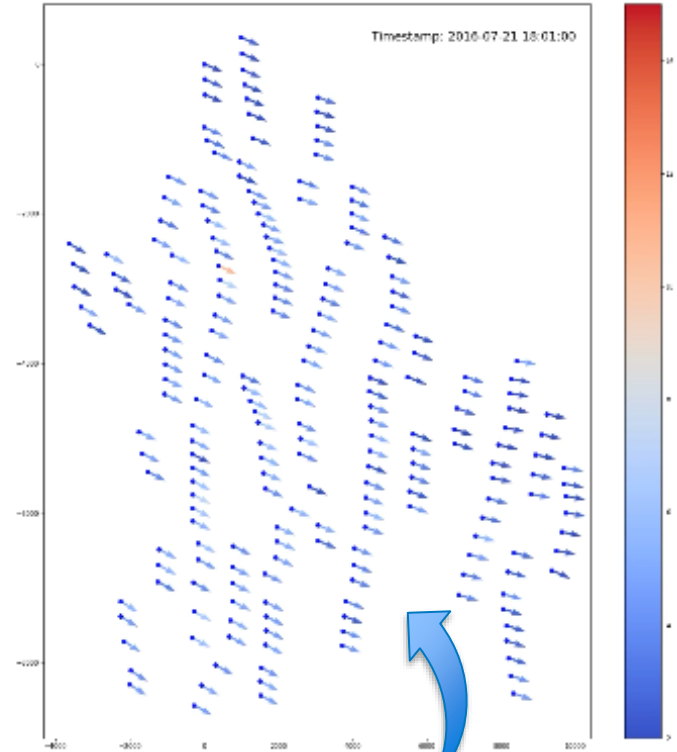
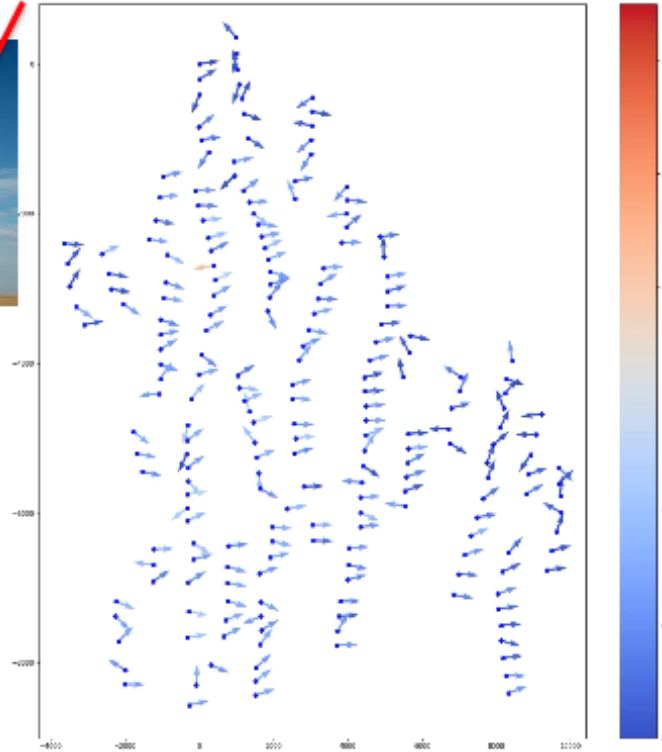


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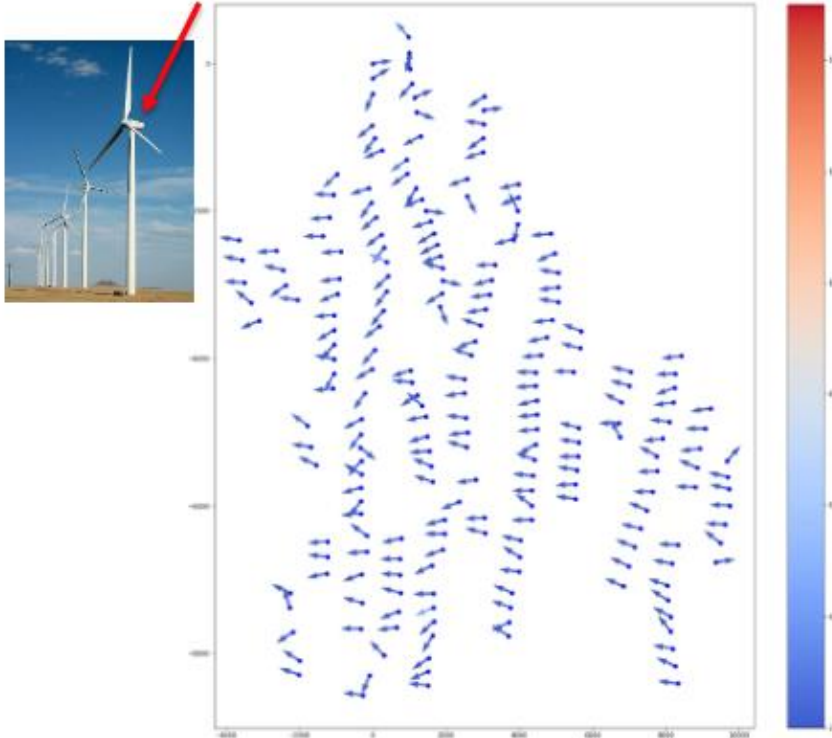


Wind Direction Shift

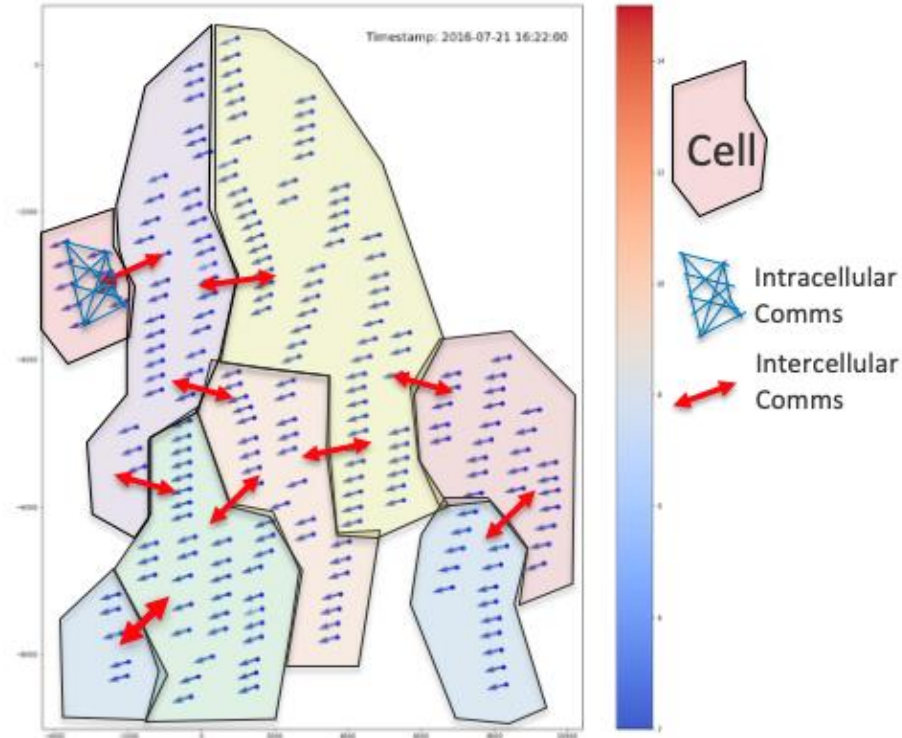
Application – Distributed Control of Wind Farms

Typical Wind Farm Control

(Each turbine moves based on local wind measurements)



Distributed Wind Farm Control



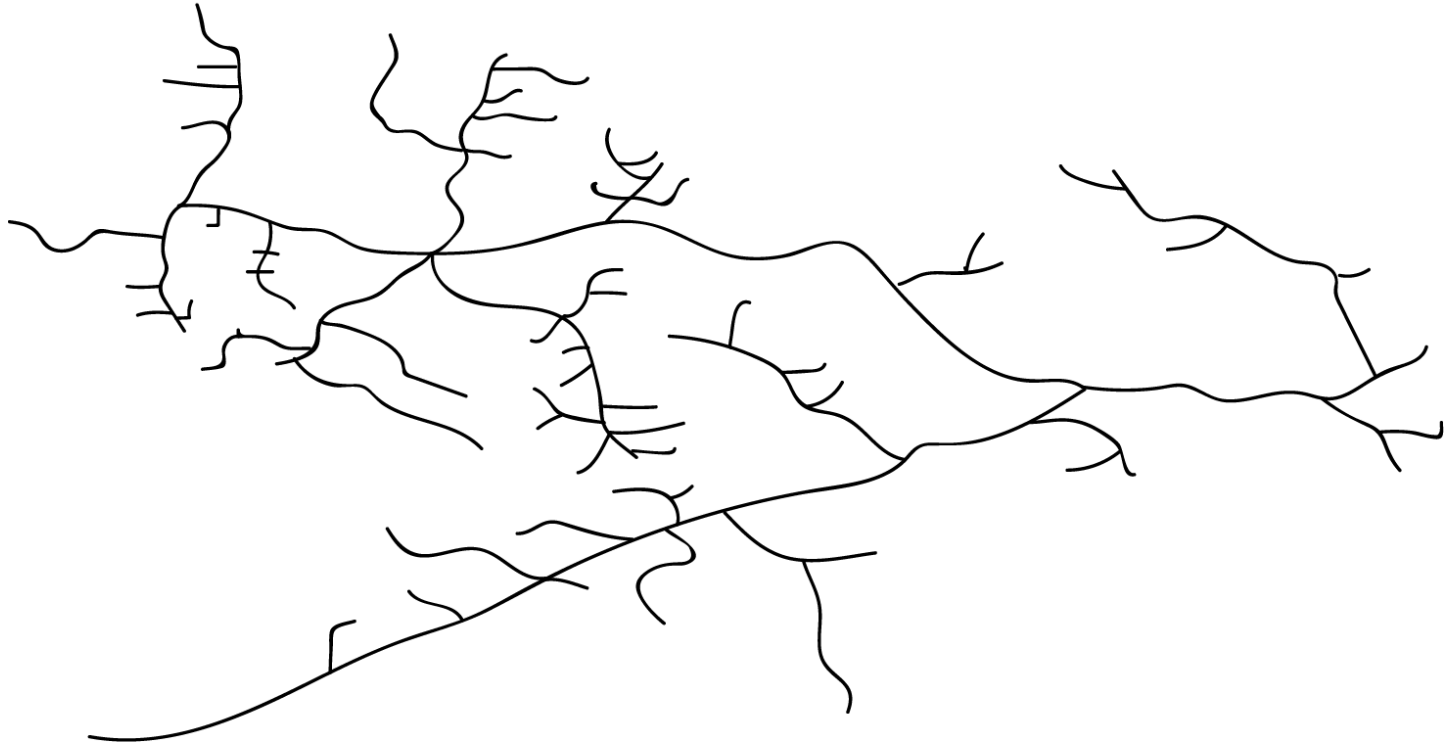
- Solution from Central Control of **13.75min** to Distributed Control of **2s**
- **Allowing ~2% more energy production annually**

Let's look a little closer

– a single distribution circuit

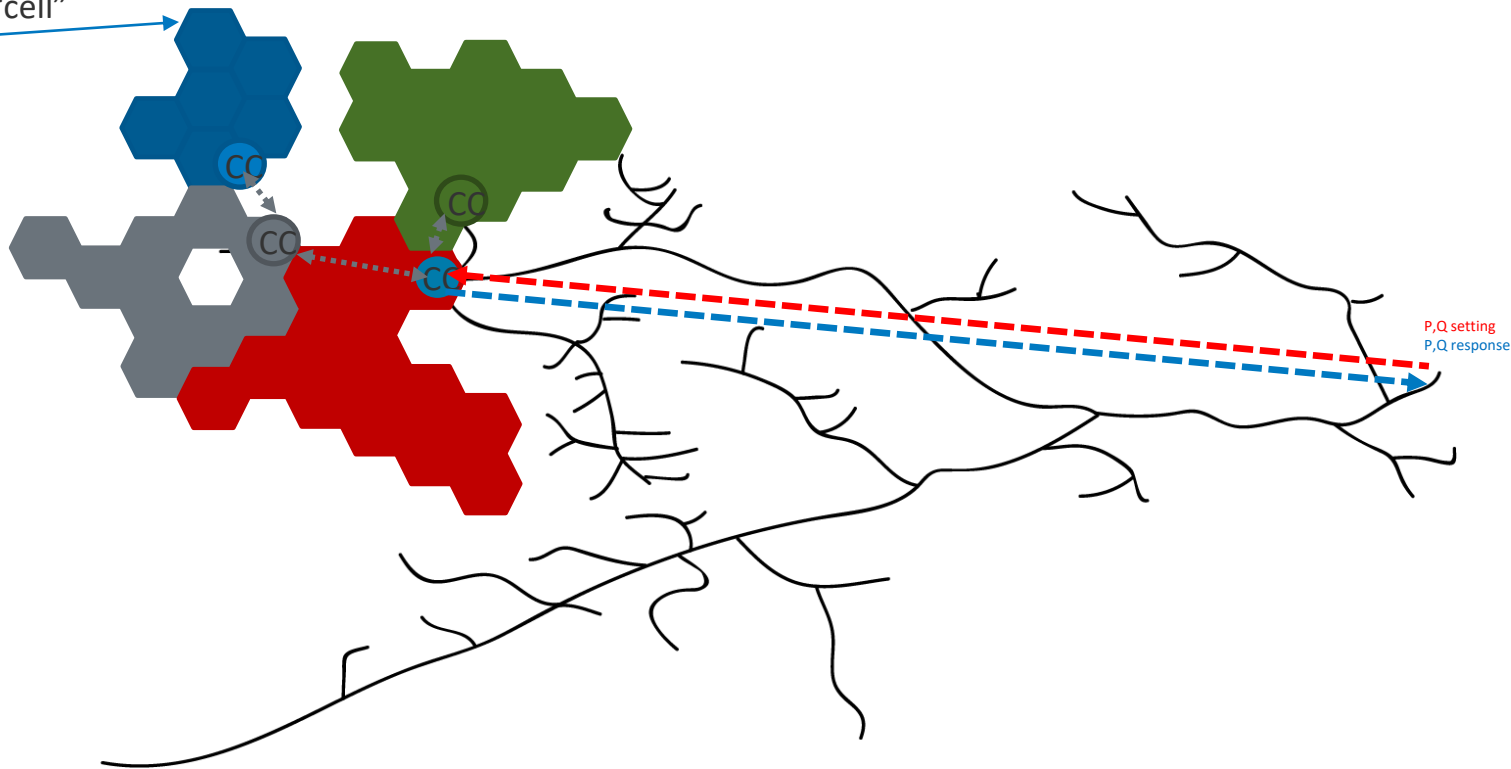


Complex system simulation with new optimization and controls

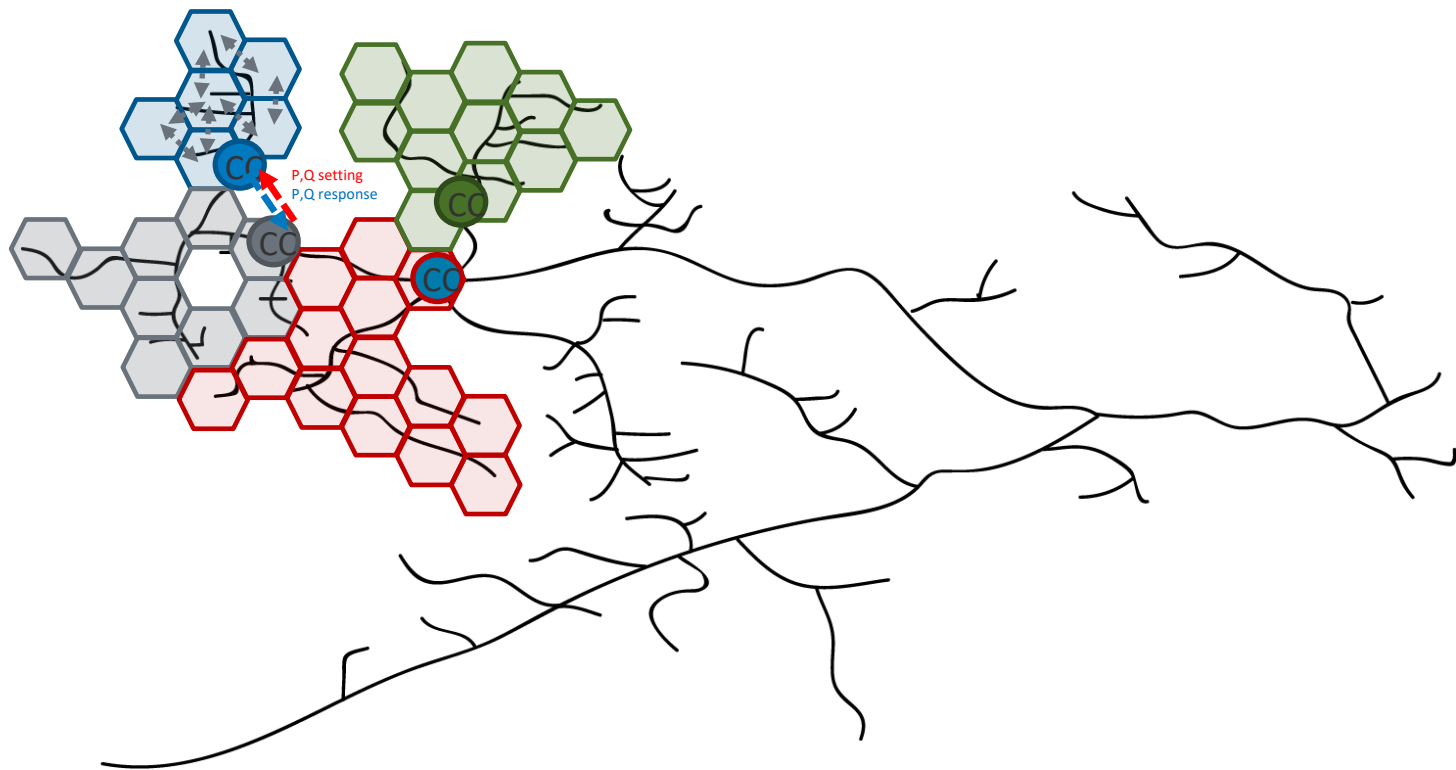


Complex system simulation with new optimization and controls

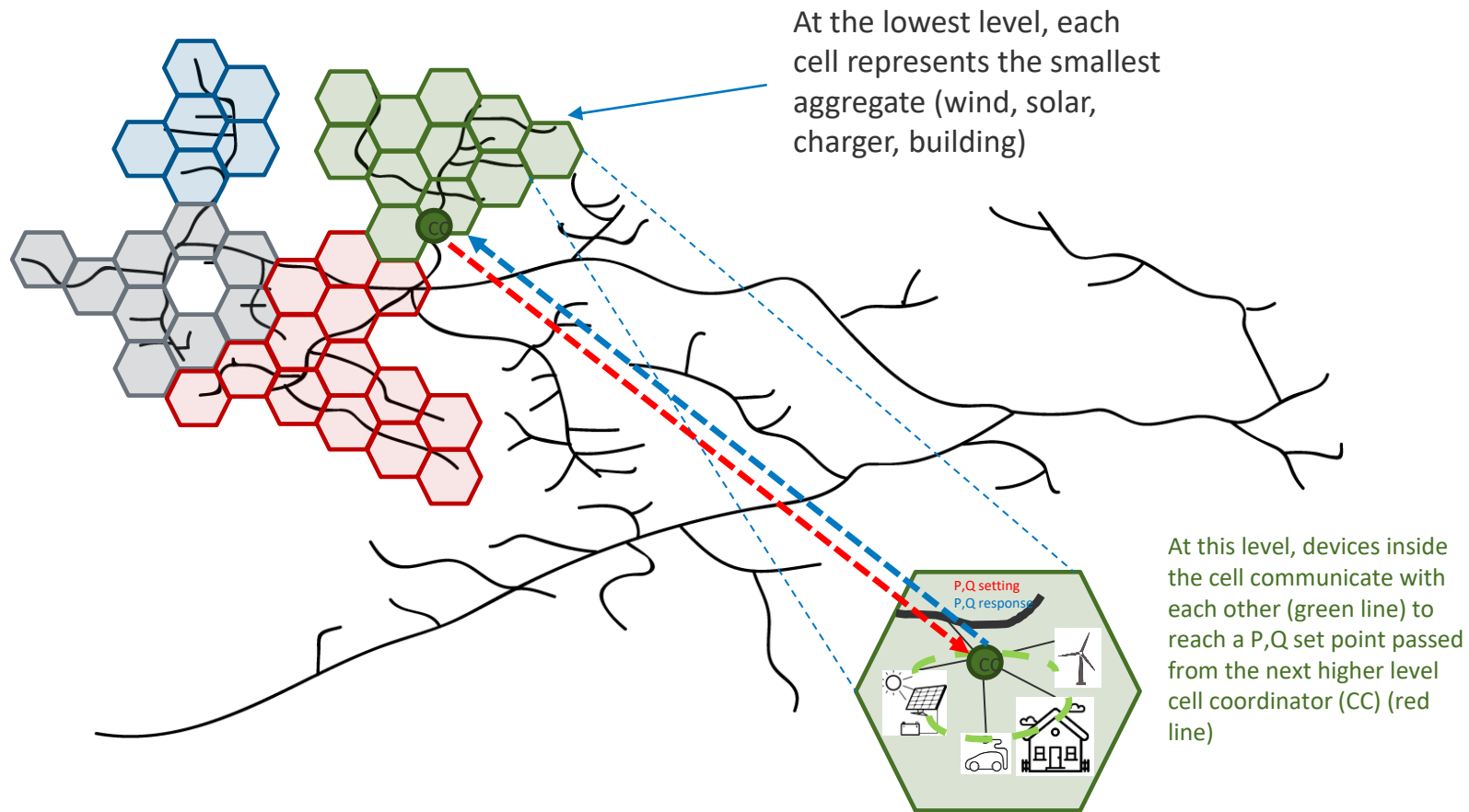
Color coding represent the
next higher "cell"



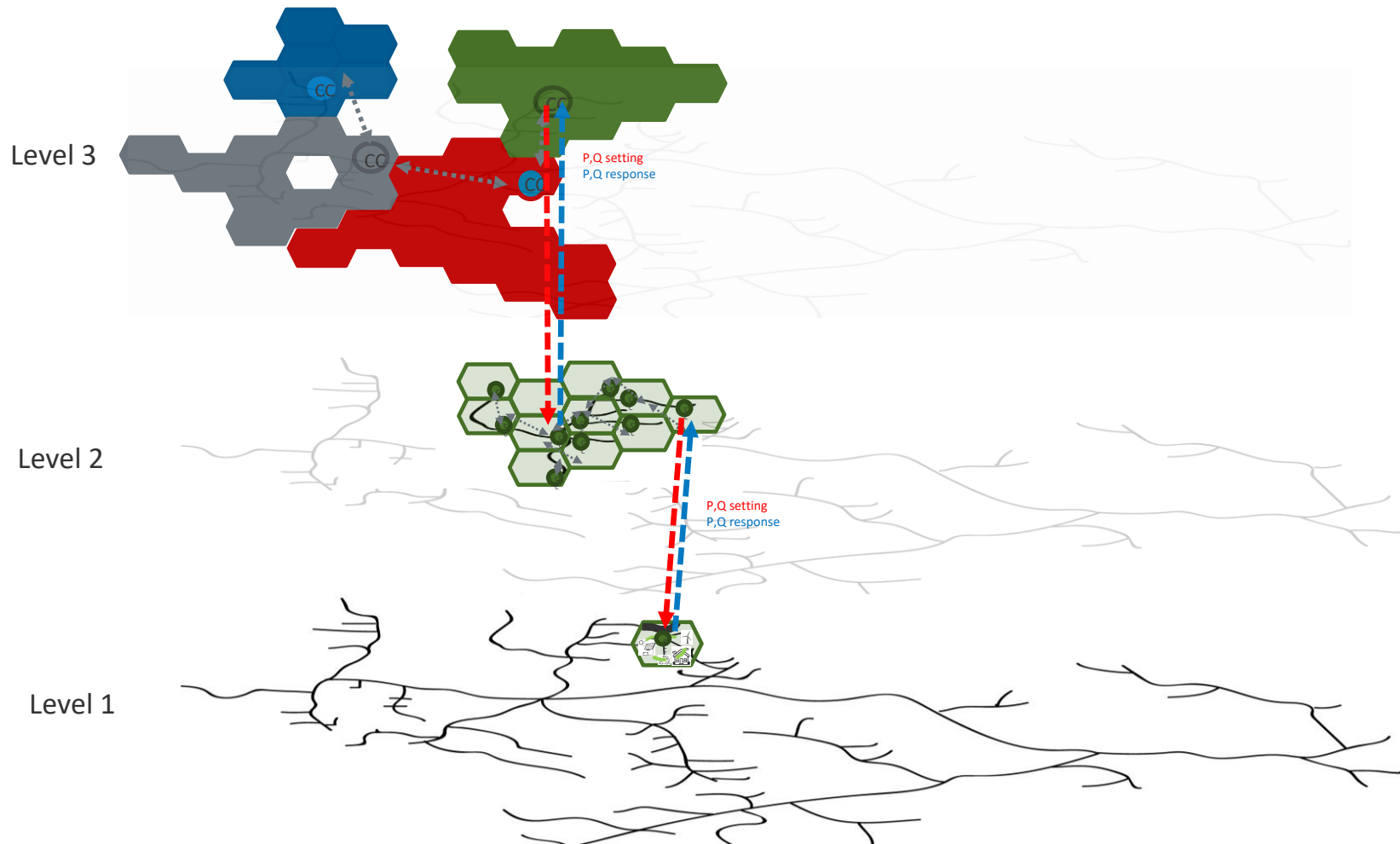
Complex system simulation with new optimization and controls



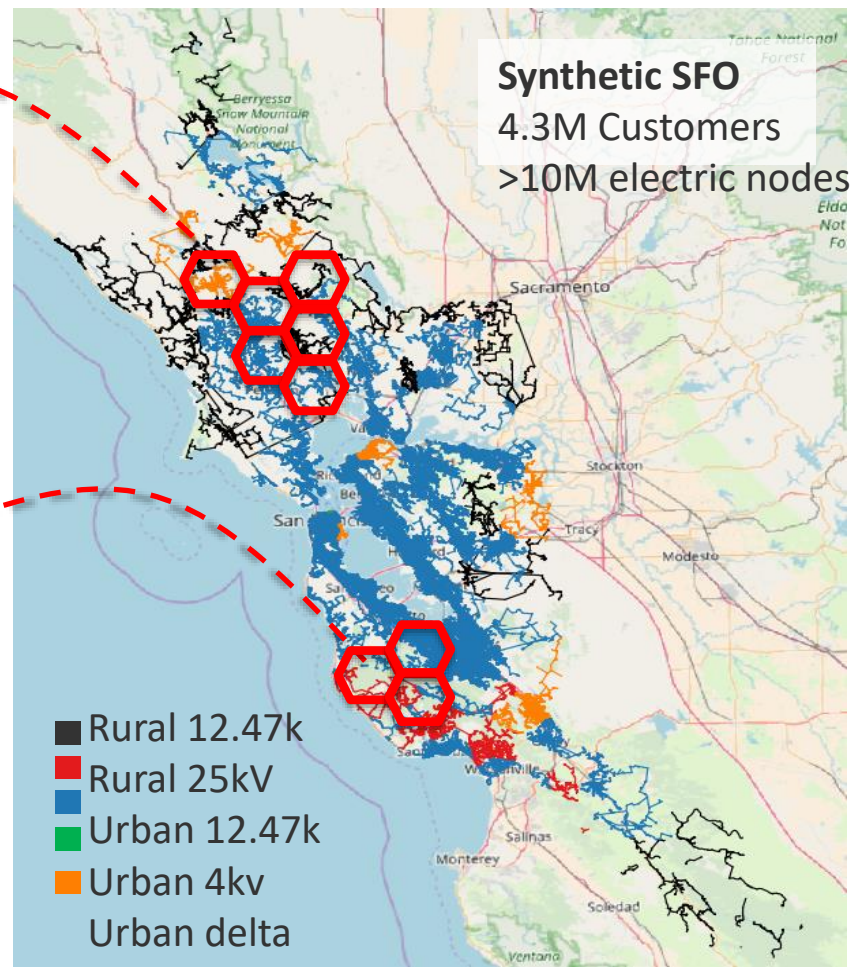
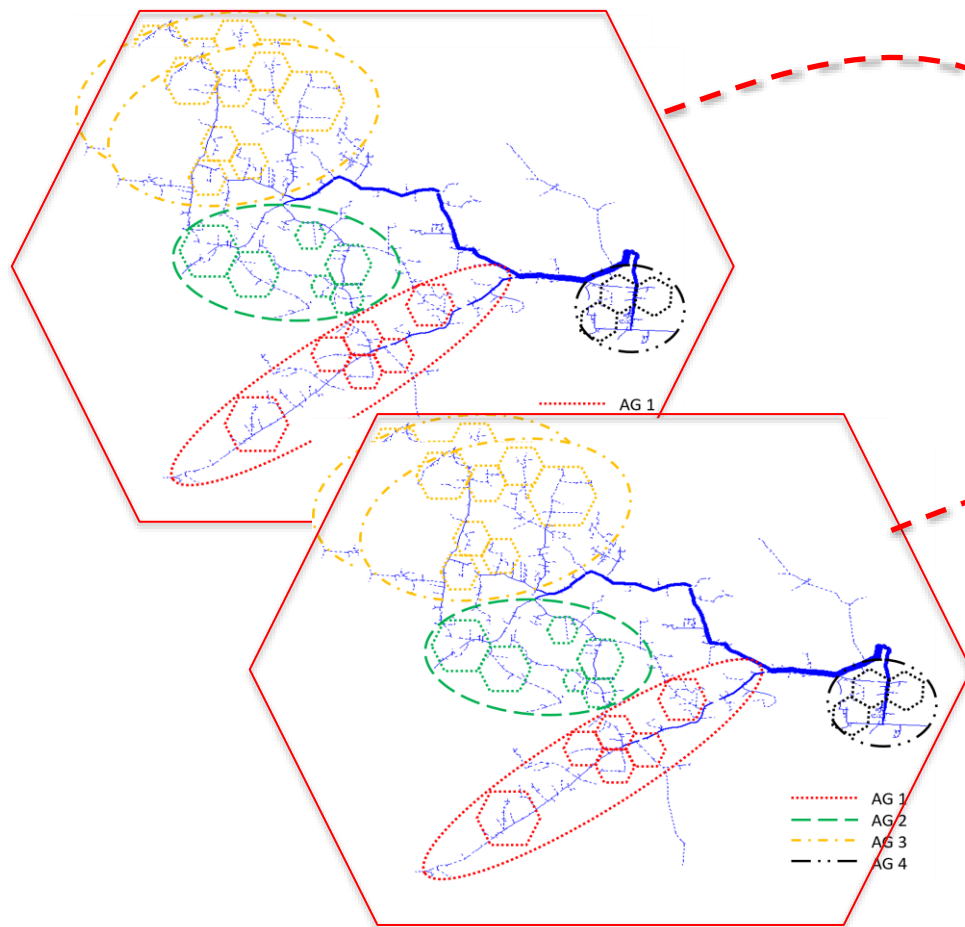
Complex system simulation with new optimization and controls



In 3D



Moving Back to the Metropolitan Scale



All that Simulation was nice, but can you
show me it really works?



Energy Systems Integration Facility (ESIF)





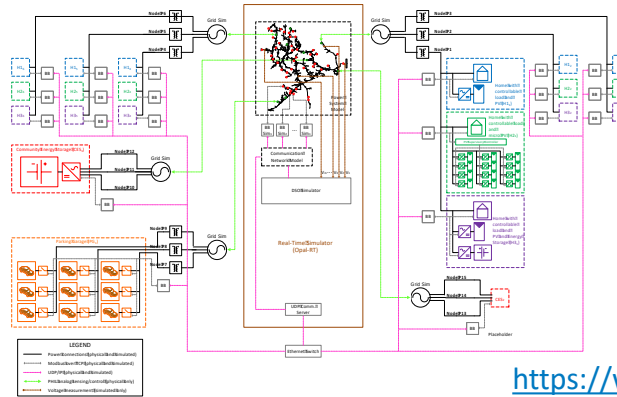
Shortening the
time between
innovation and
practice

ESIF Unique Capabilities

- Multiple parallel AC and DC experimental busses (MW power level) with grid simulation and loads
- Flexible interconnection points for electricity, thermal, and fuels
- Medium voltage (15kV) microgrid test bed
- Virtual utility operations center and visualization rooms
- Smart grid testing lab for advanced communications and control
- Interconnectivity to external field sites for data feeds and model validation
- Petascale HPC and data mgmt system in showcase energy efficient data center
- **MW-scale Power hardware-in-the-loop (PHIL) simulation capability to test grid scenarios with high penetrations of clean energy technologies**

ARPA-E NODES: Large-Scale PHIL Experiment

The largest ever number of connection points in a single PHIL experiment!



**Network Optimized
Distributed Energy Systems
(NODES)**

arpa·e
CHANGING WHAT'S POSSIBLE

<https://www.youtube.com/watch?v=In4HtG6XypU>

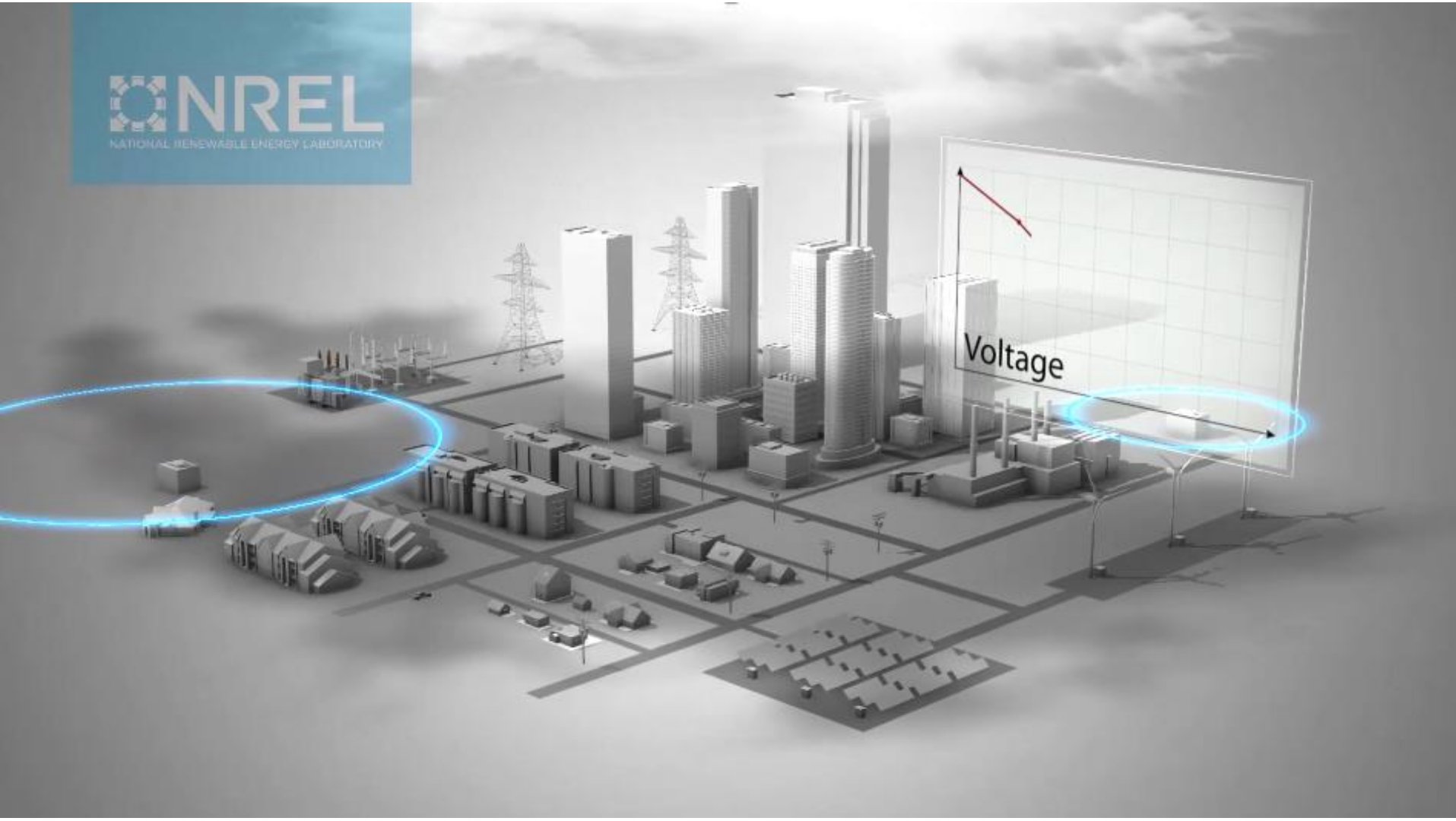
Let's Look to the Future

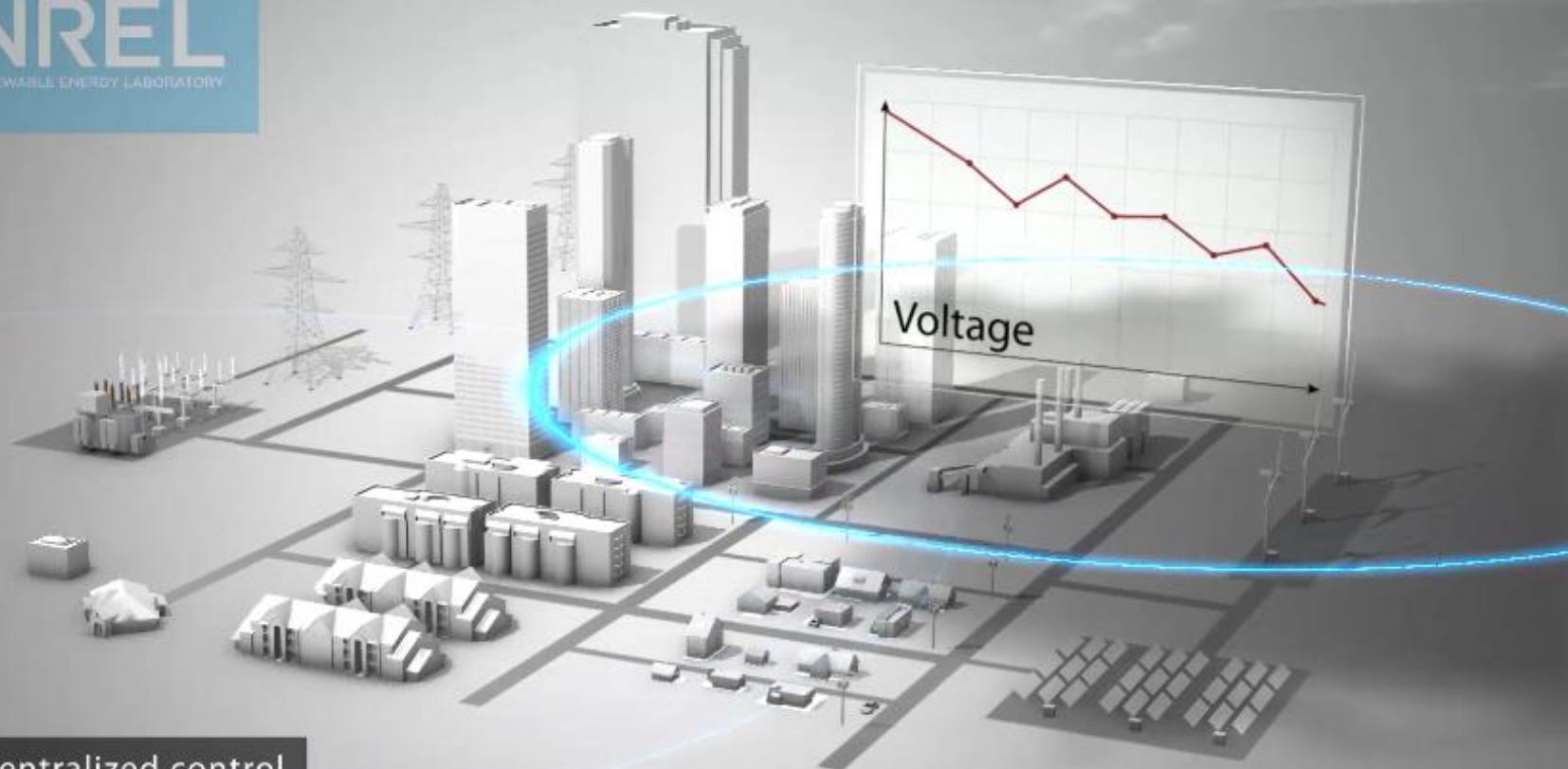




Autonomous Energy Grids

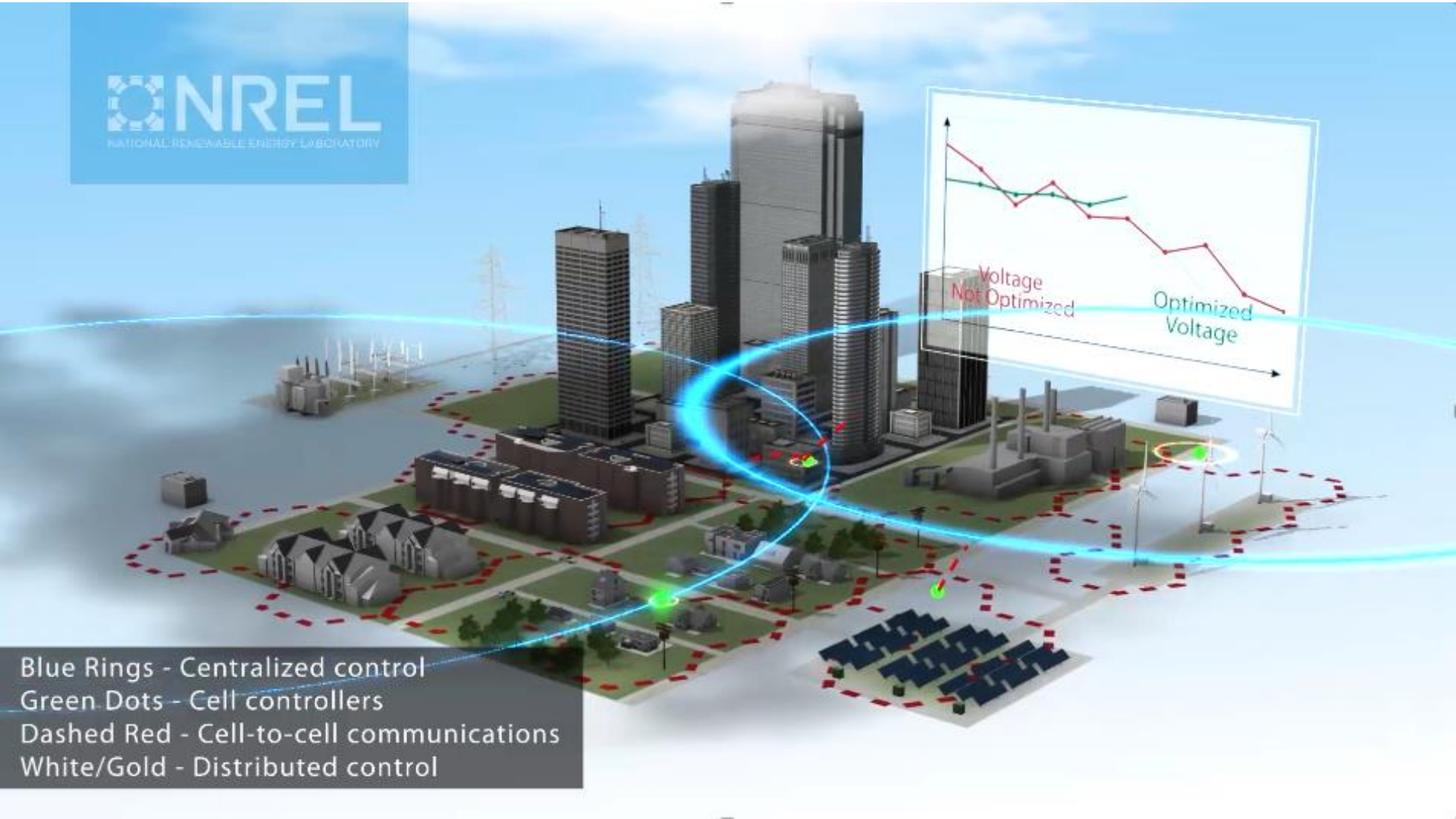
NREL is a national laboratory of the U.S. Department of Energy,
Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.



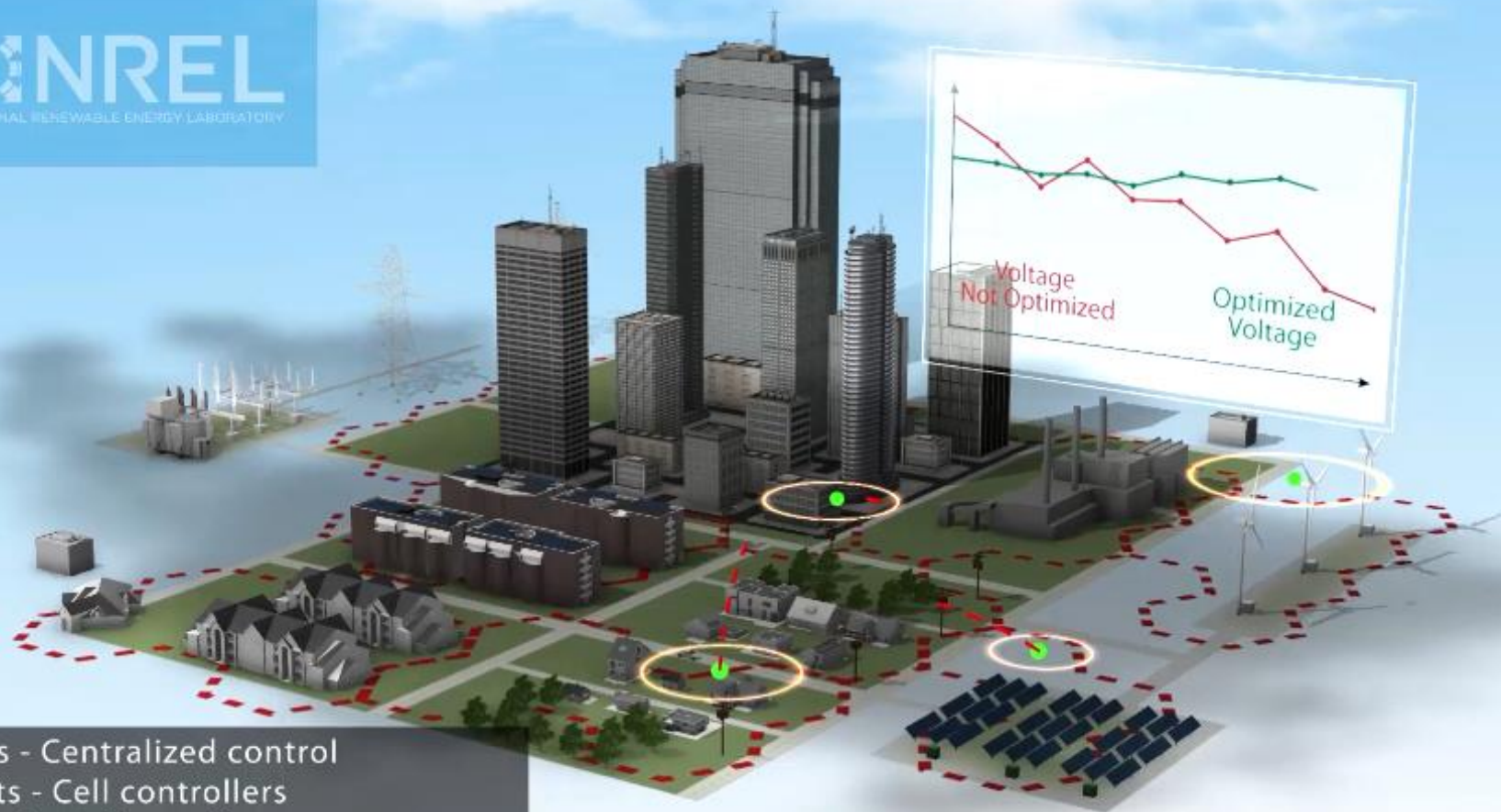


Blue Rings - Centralized control



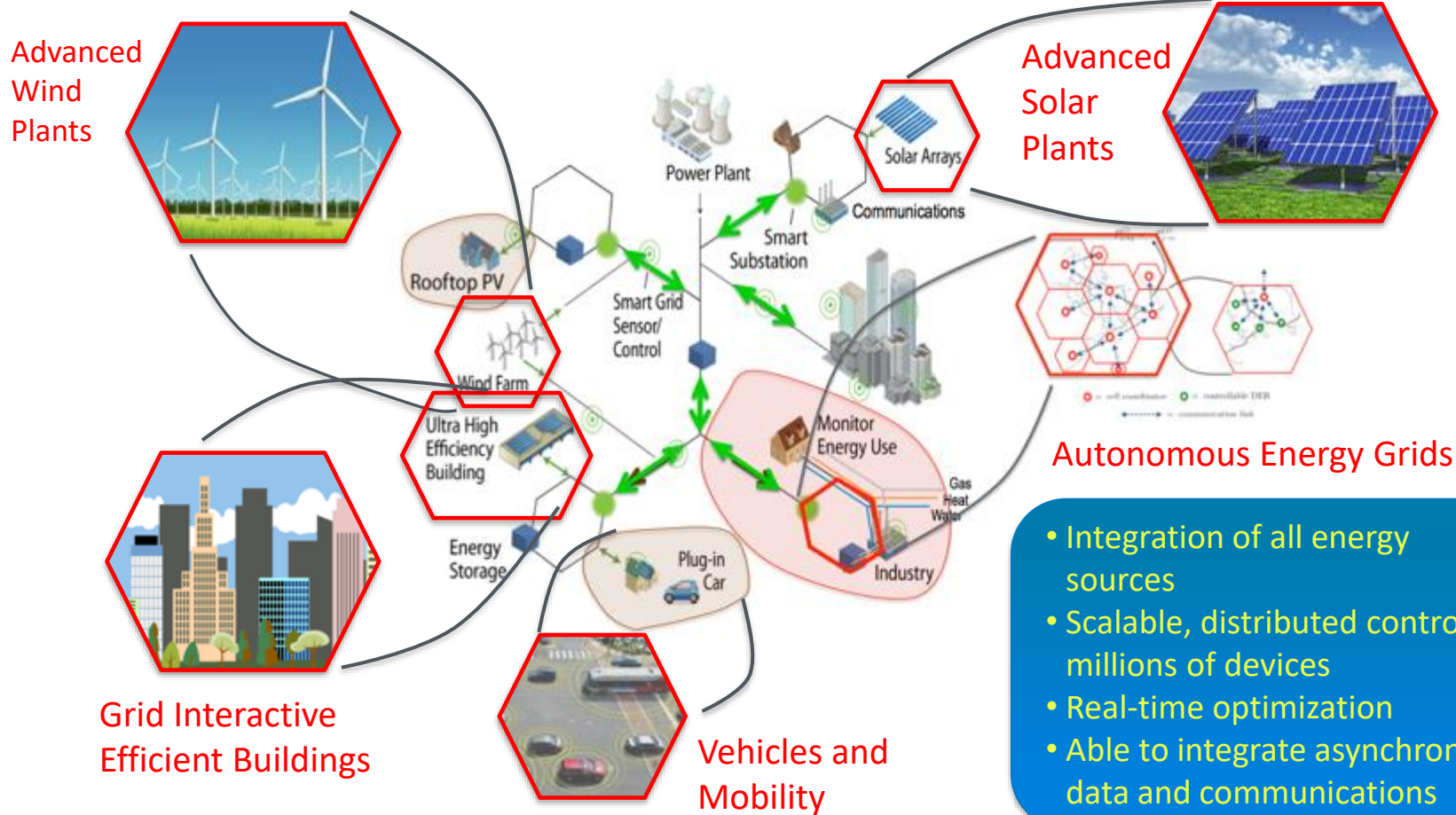


Blue Rings - Centralized control
Green Dots - Cell controllers
Dashed Red - Cell-to-cell communications
White/Gold - Distributed control



Blue Rings - Centralized control
Green Dots - Cell controllers
Dashed Red - Cell-to-cell communications
White/Gold - Distributed control

Transforming **ENERGY** through Autonomous Energy Systems



Thank you

www.nrel.gov/grid/autonomous-energy.html