Autonomous Energy Systems

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

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National Renewable Energy Laboratory

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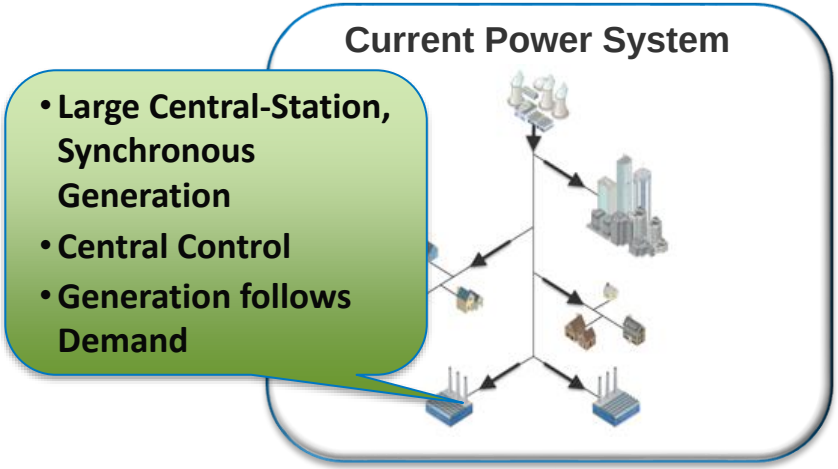
April 7, 2020

Disclaimer

Transformation of the Power System



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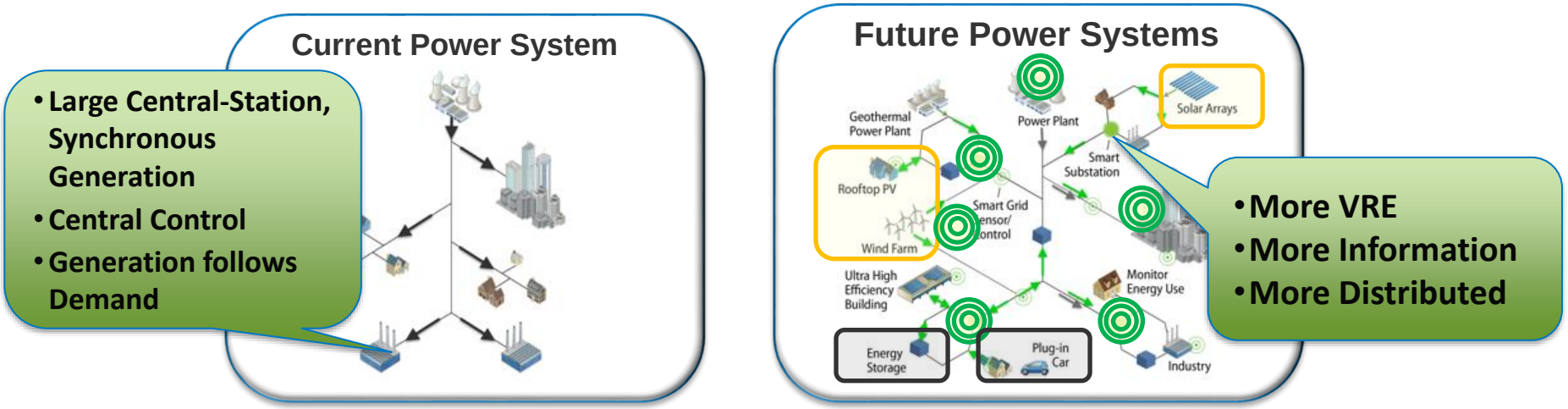


- Increasing levels of wind and solar – variable and power electronics based
- More use of Communications, Controls, Data, and Information (e.g. Smart Grids) – can have interoperability and cybersecurity issues
- Other new distributed technologies: EVs, Distributed storage, Flexible Loads
- Increasing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

Is the Grid getting too complex to control?

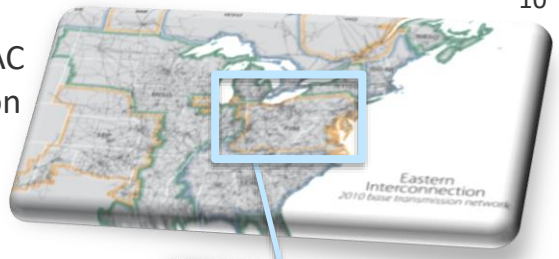
Current Grid

Central Control
10^4 Bulk Generators

Synchronous AC Interconnection

Regional Transmission Operator -
Market/ Reliability Coordinator

Local Utility -
Transmission/ Subtransmission/ Bulk Generation



5 min markets
4 sec power flows

Local Utility Distribution

Industry/ Commercial/ Residential

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

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

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

Distributed, Hierarchical Control

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

Millions

1000s

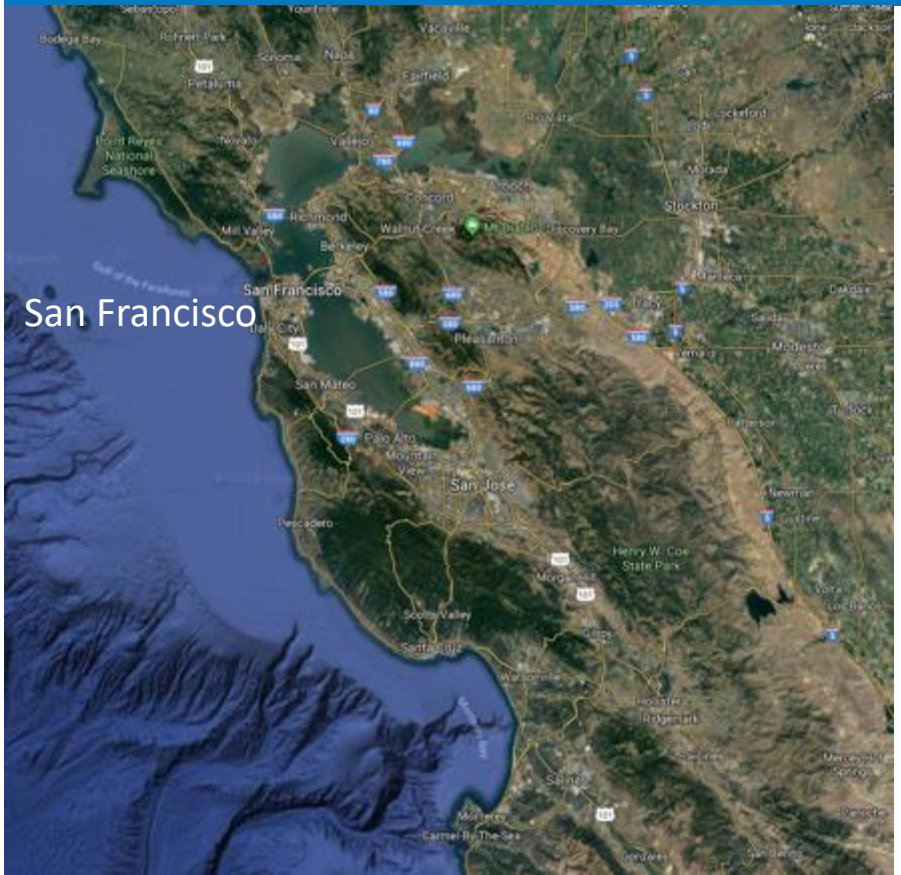
1-100

Virtual Emulation

Flatirons Campus

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.

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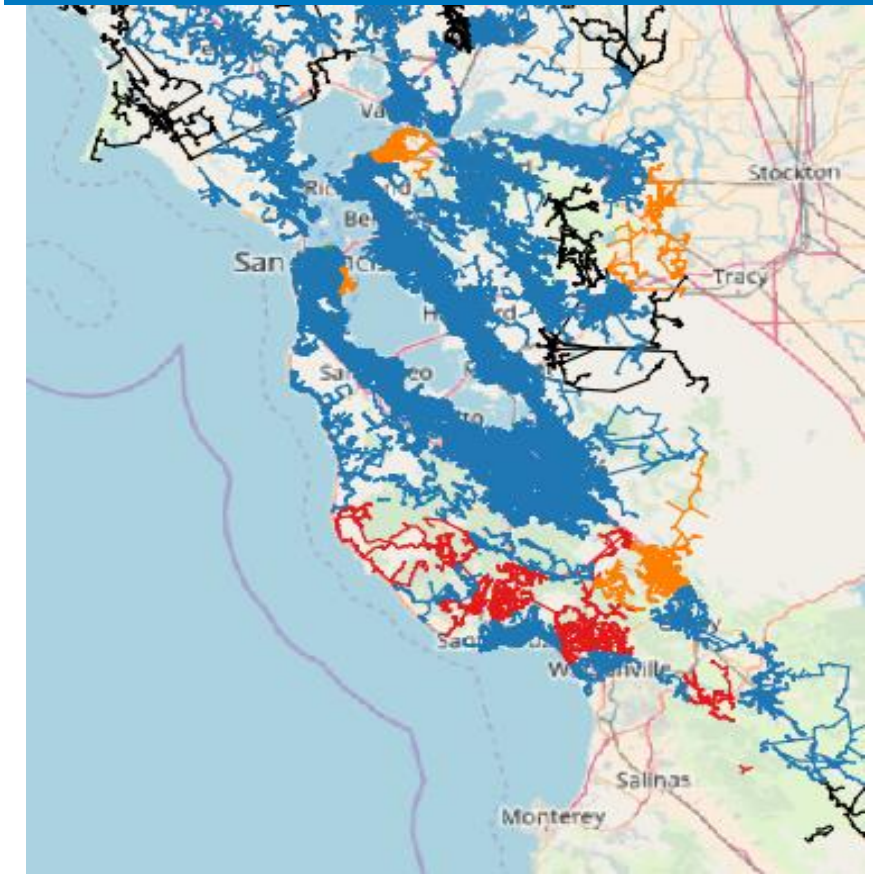

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Optimize and control massively deployed DER in real-time.

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

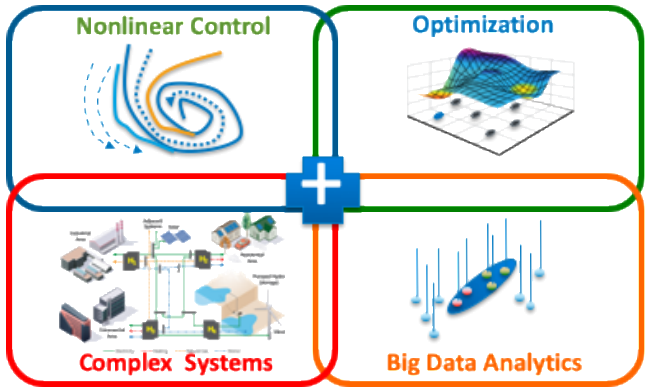
Nobody knows how to do this!

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

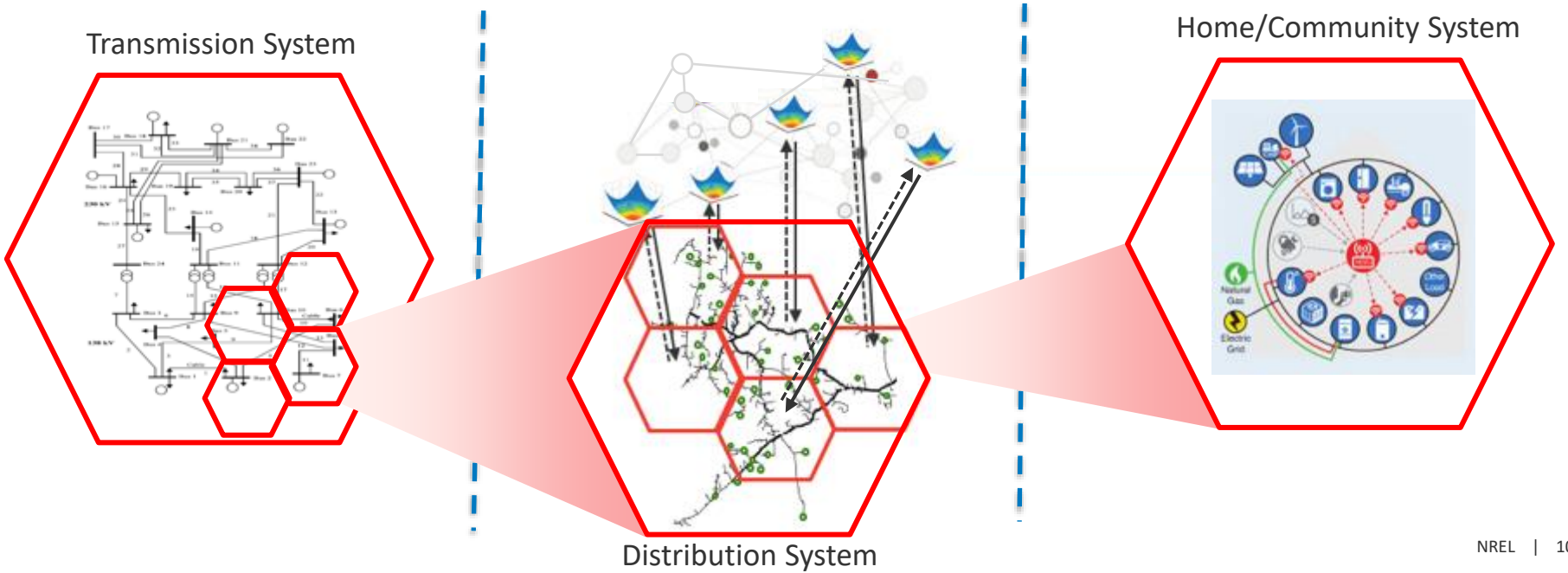
- **Bridge the gap between control theory and optimization theory** and **propose a unified theoretical approach** that builds on contemporary advances in control, optimization, and parallel computing
- Develop distributed optimization **algorithms that can run in real-time** (1s) across full system
- **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**



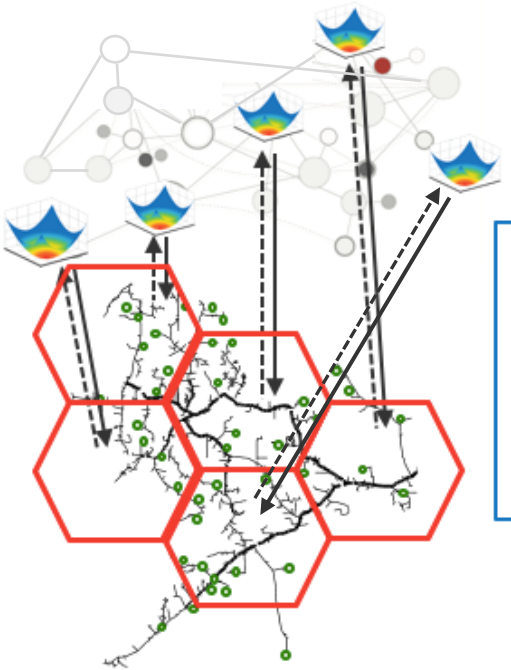
Formulating new math to address challenges

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



Distributed Control and Optimization



Real-time optimization with missing model parameters

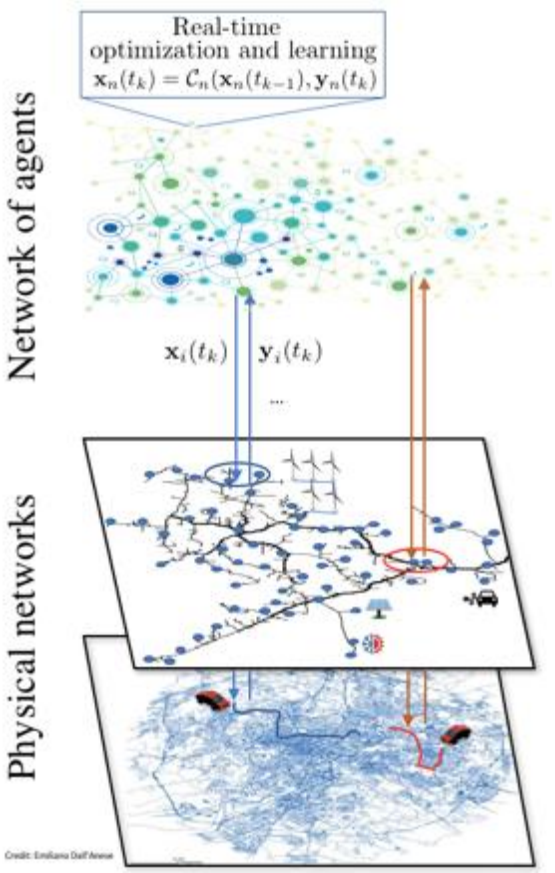
- *"Online Optimization with Feedback",* A. Bernstein, E. Dall'Anese, and A. Simonetto accepted to ***IEEE Transactions on Signal Processing***
- *"Online Optimization as a Feedback Controller: Stability and Tracking",* M. Colombino, E. Dall'Anese and A. Bernstein, submitted to ***IEEE Transactions on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

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

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.

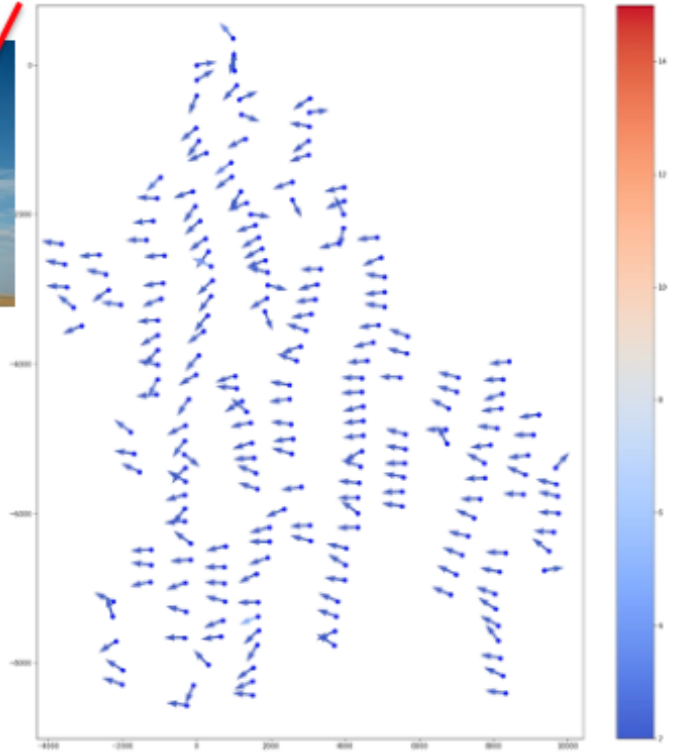
$$x_i^{k+1} = \underset{x_{p(i)}}{\text{argmin-RL(n)}}\, f_i(x_i) + y_k^{k,T}(x_i - \bar{x}^k) + \frac{\rho}{2}\|x_i - \bar{x}^k\|^2$$
$$y^{k+1} = y^k + \rho(x_i^{k+1} - \bar{x}^{k+1}),$$

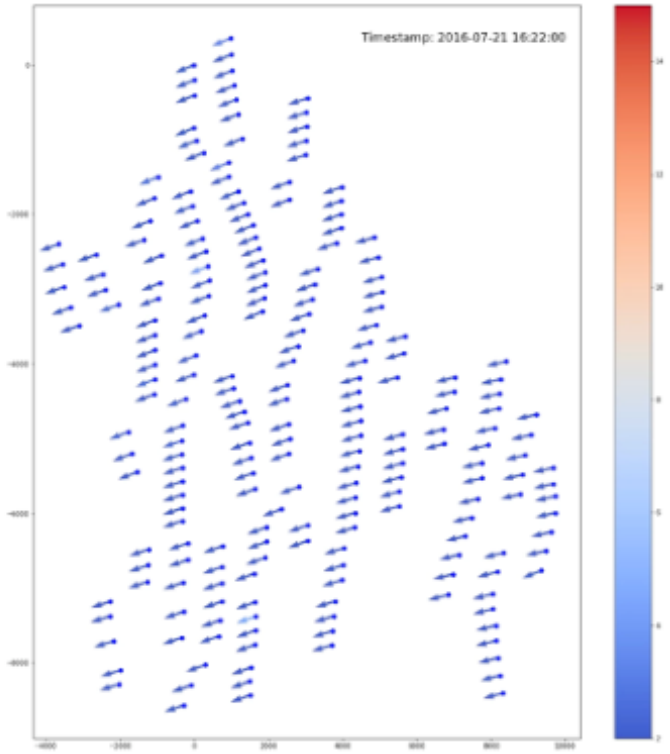
This Paper introduced a ADMM-RL controller to train wind turbines and water heater controls

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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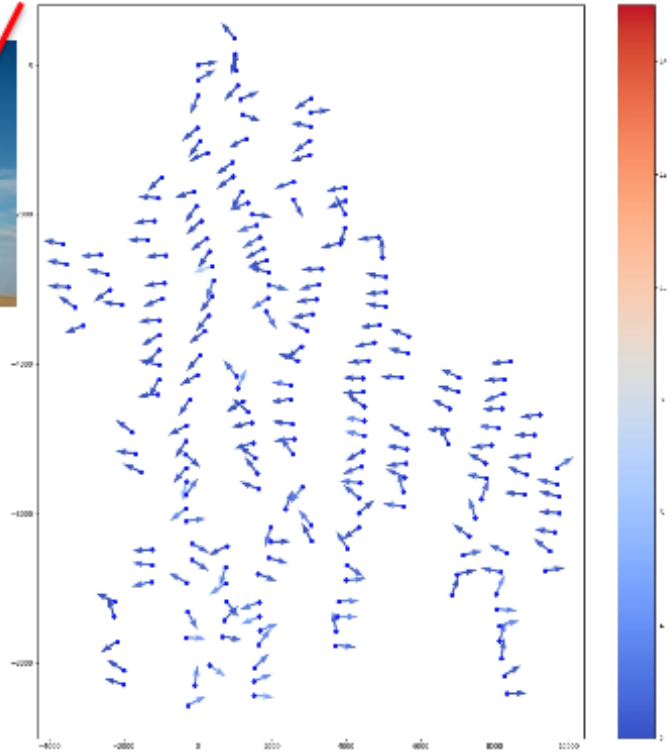

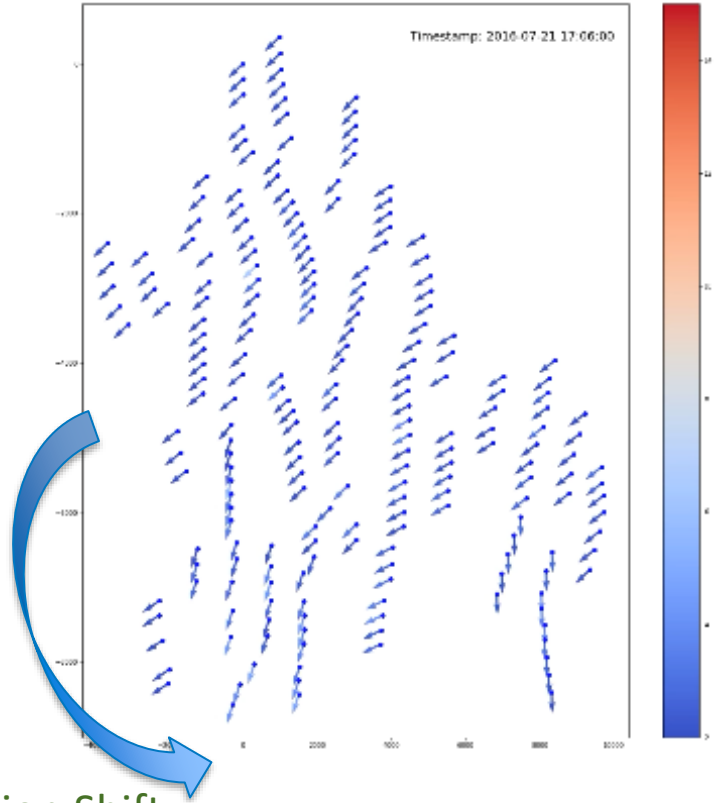

Wind Direction Shift

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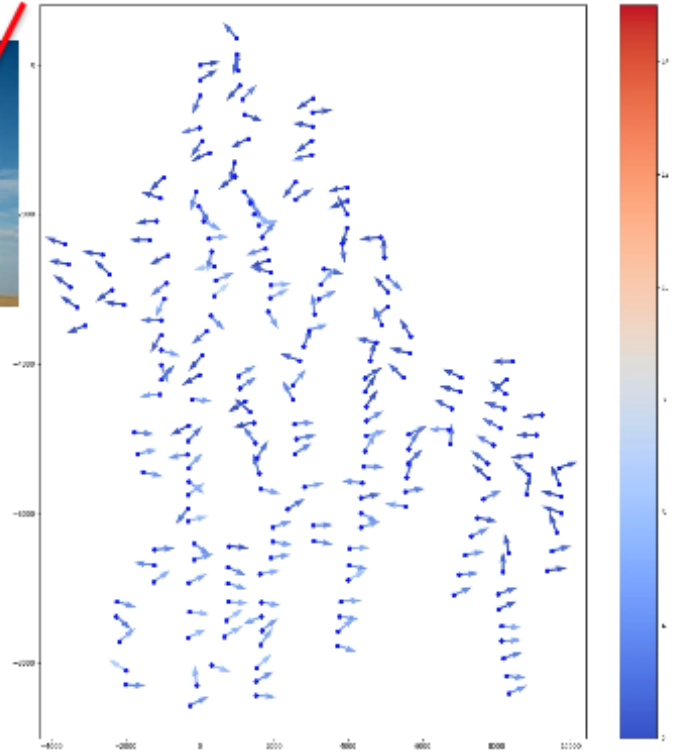

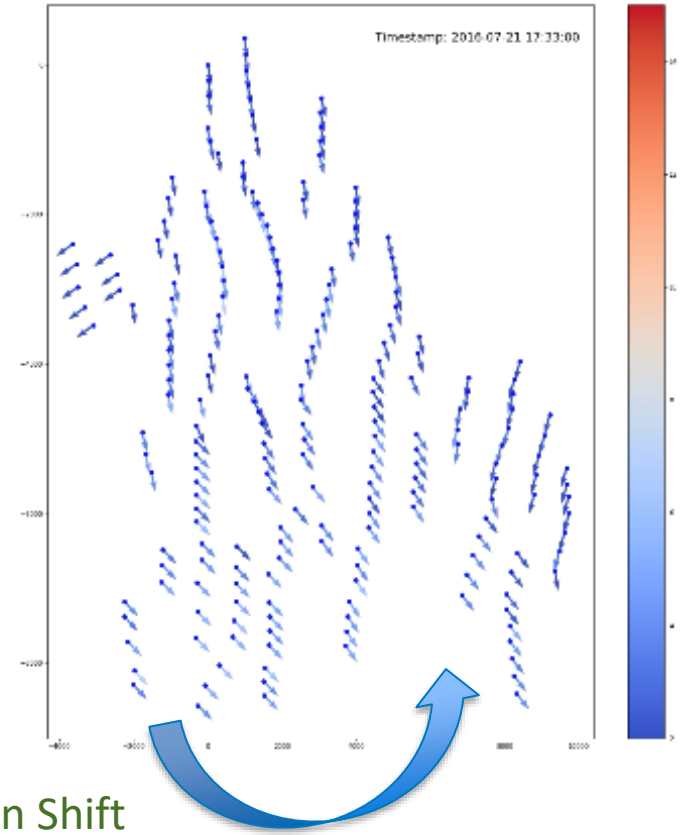

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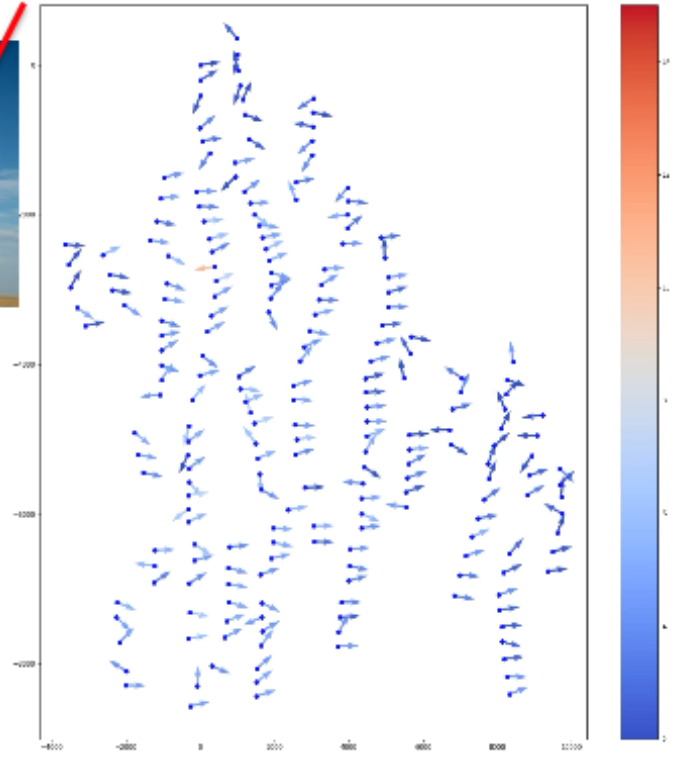

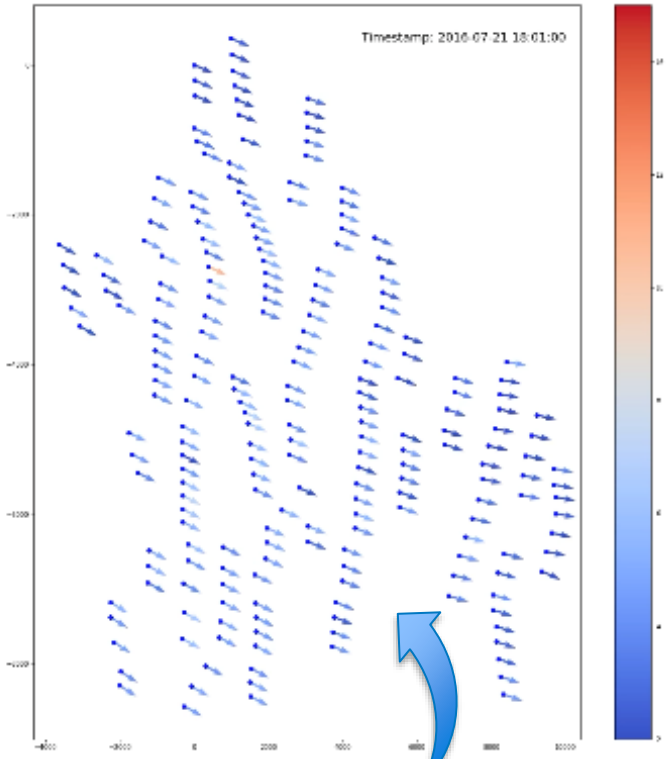

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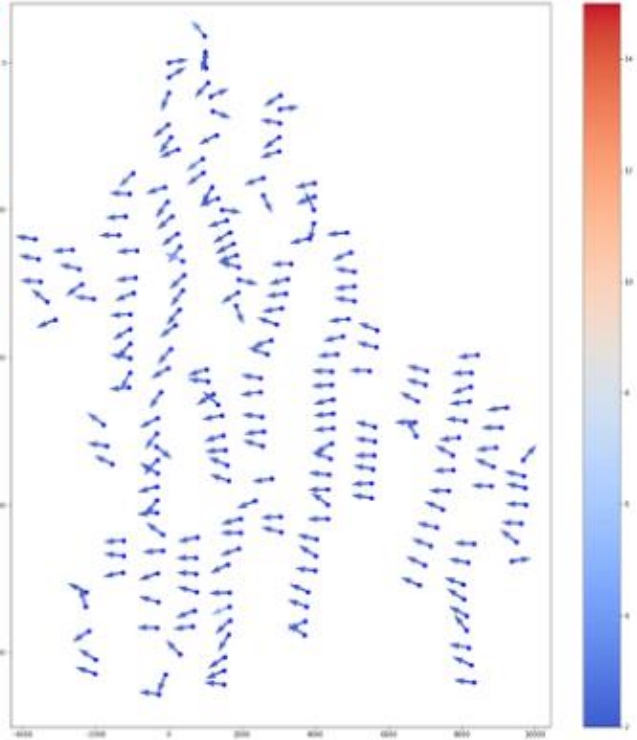
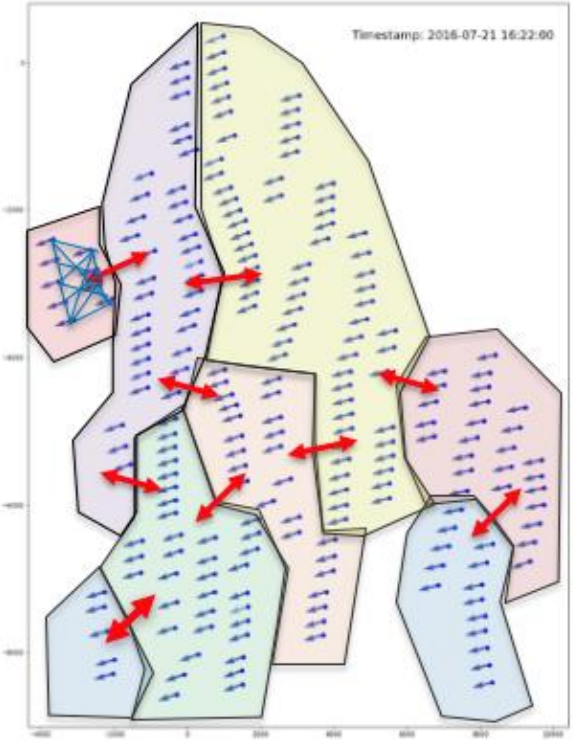
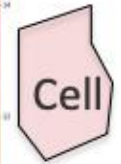


Distributed Wind Farm Control





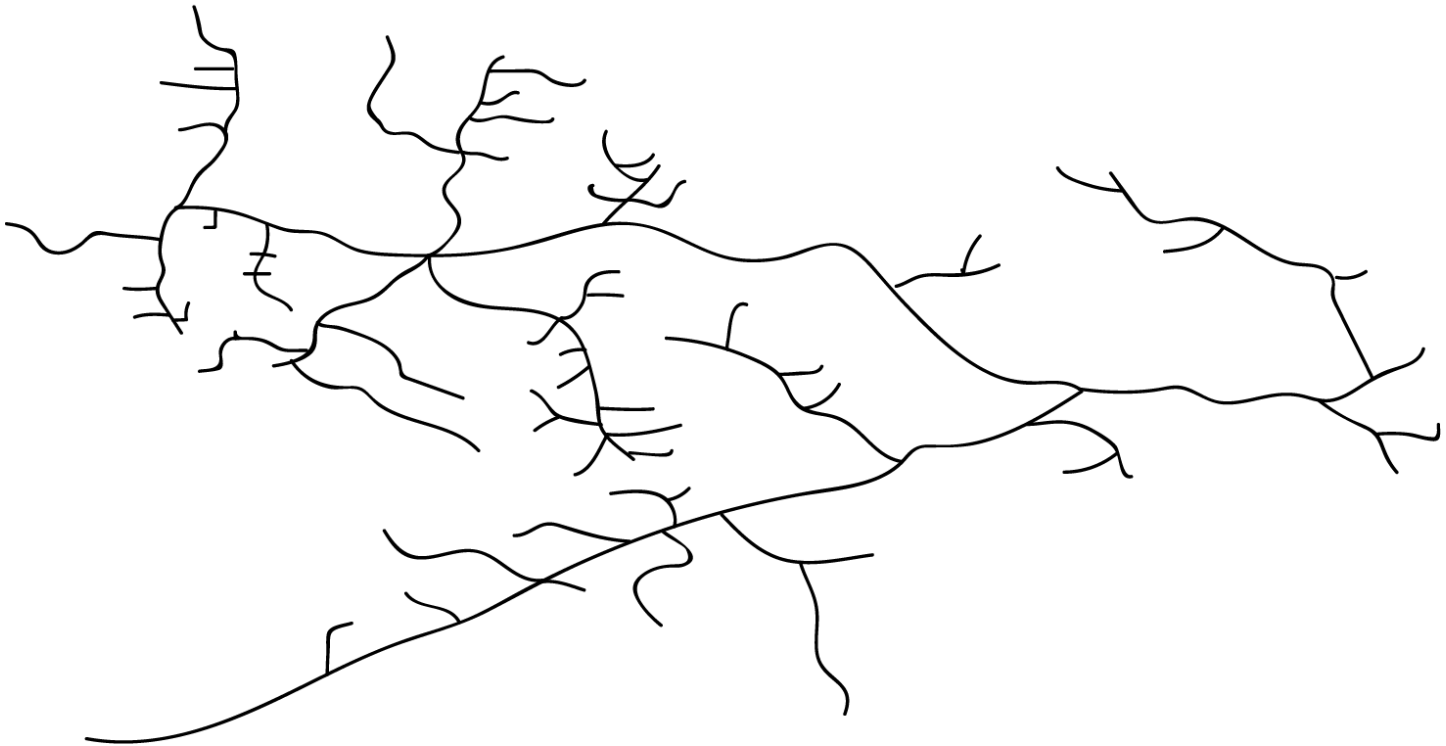
Intracellular Comms

Intercellular Comms

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

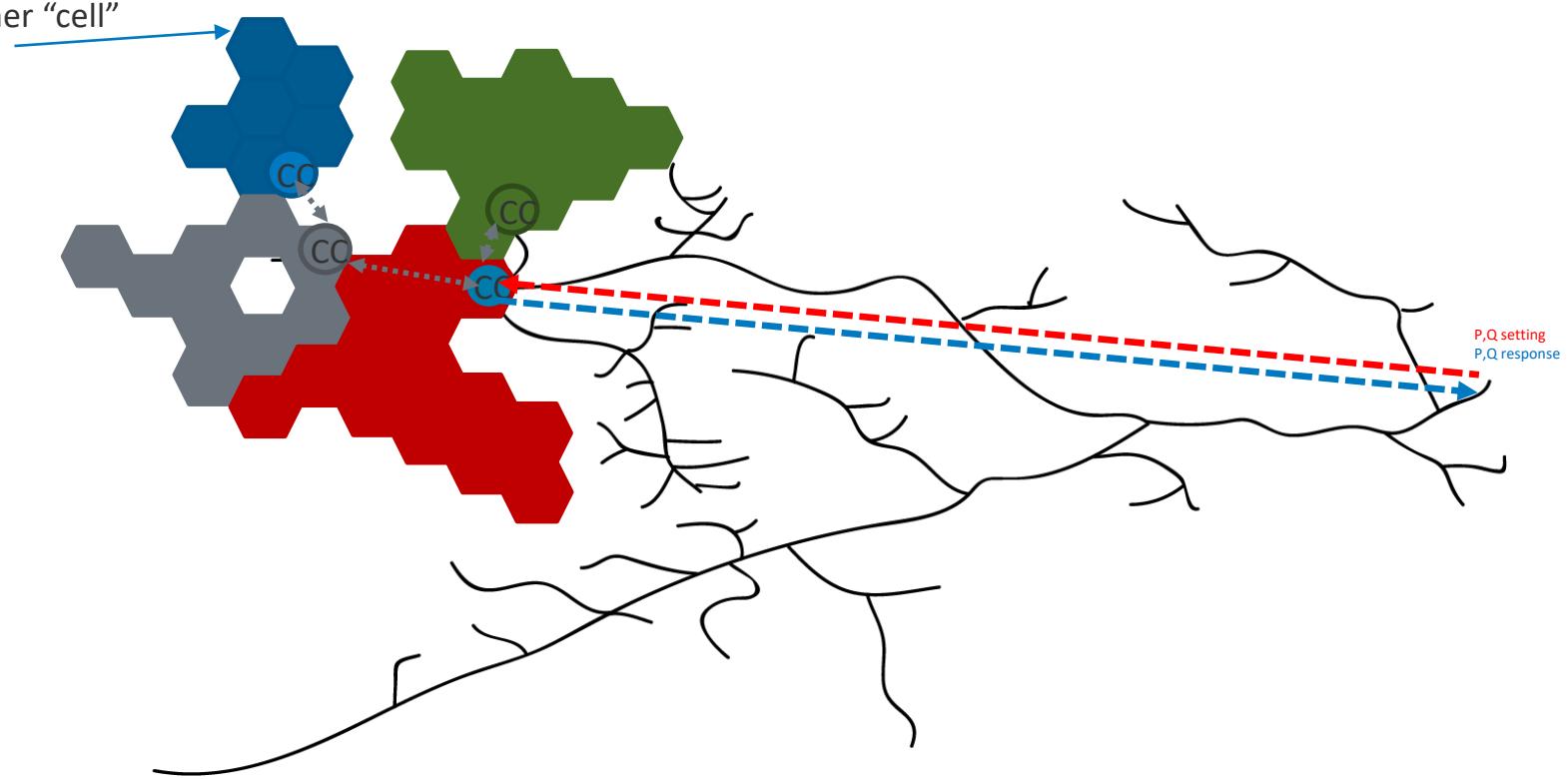
Let’s look a little closer – a single distribution circuit

Complex system simulation with new optimization and controls



Complex system simulation with new optimization and controls

Color coding represent the next higher “cell”



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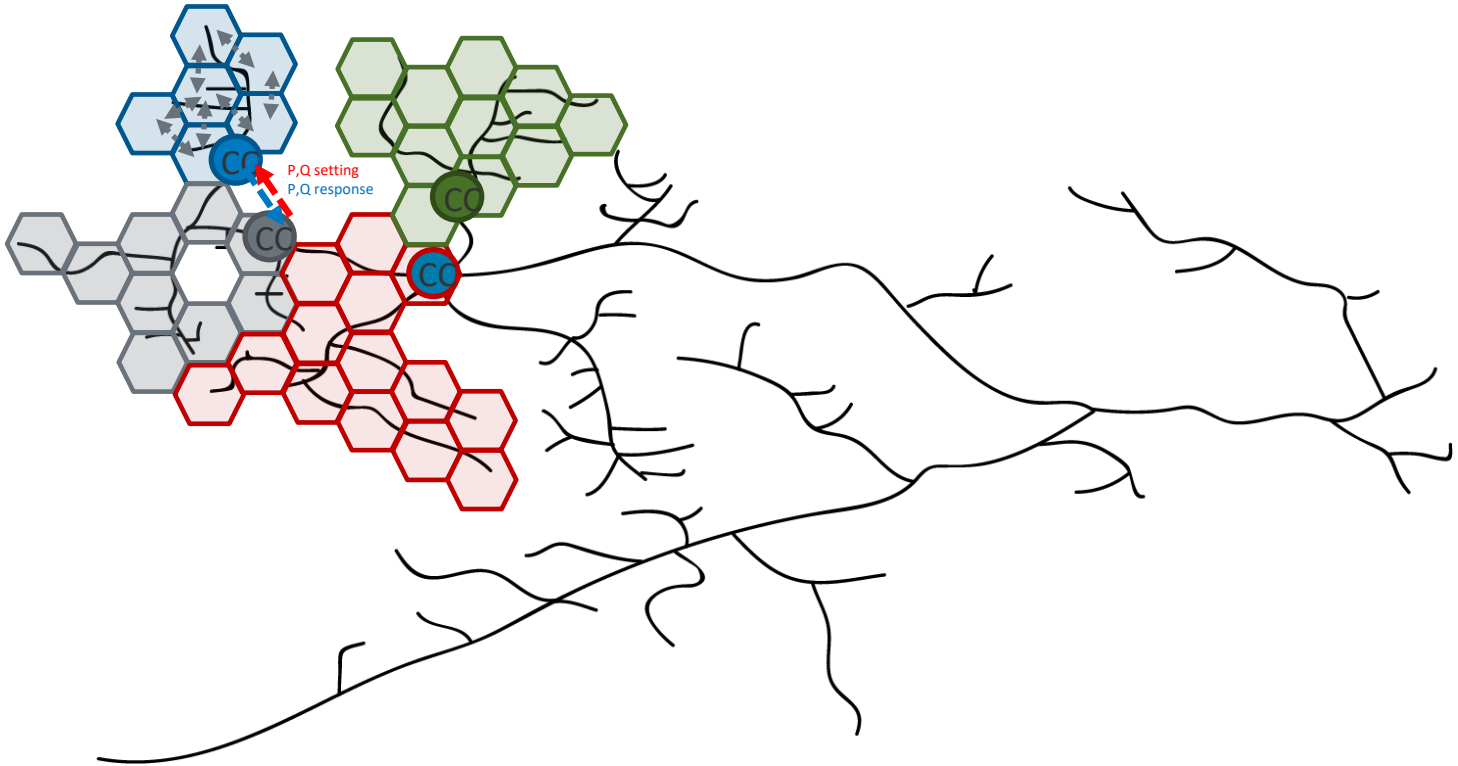

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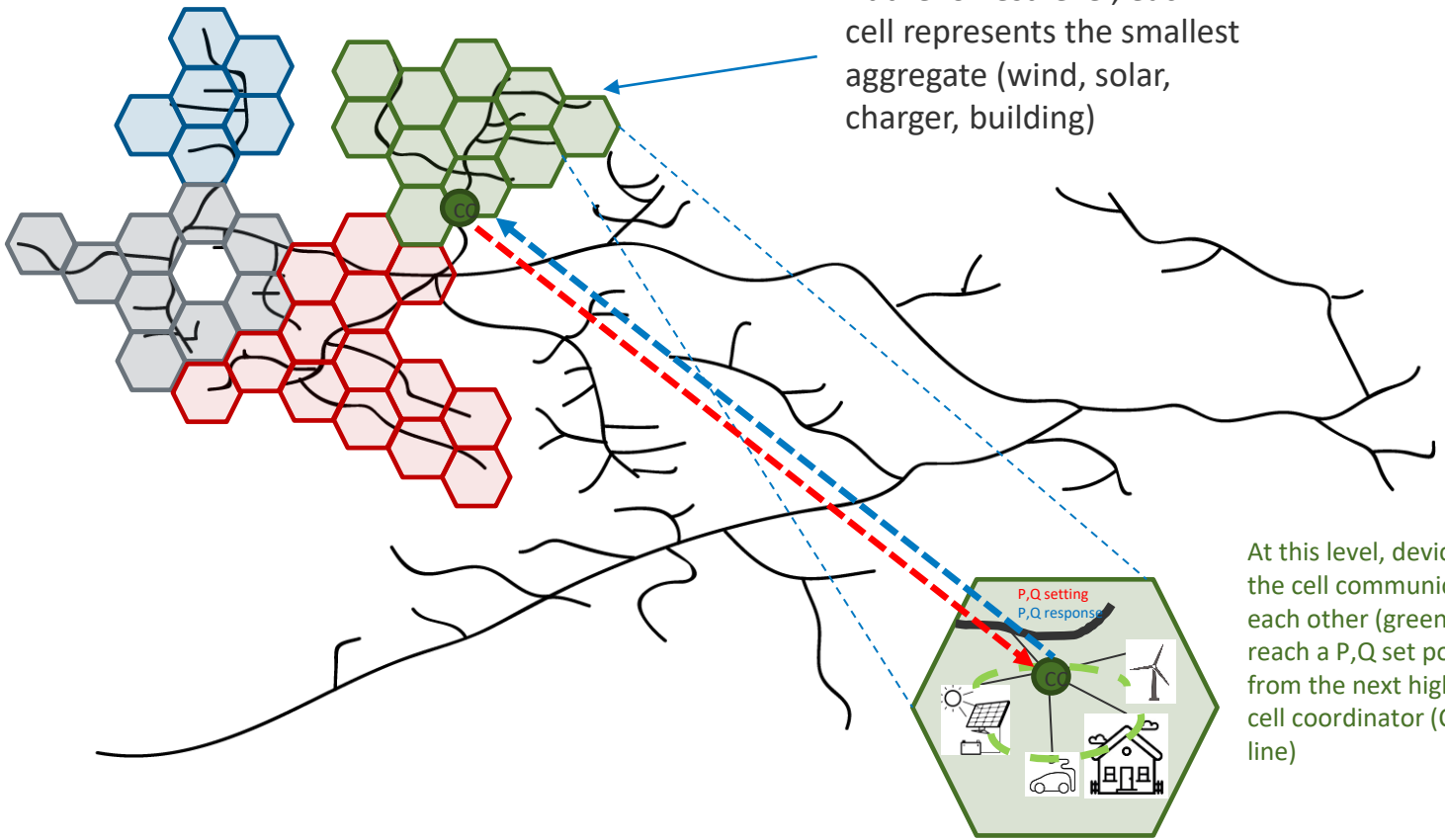
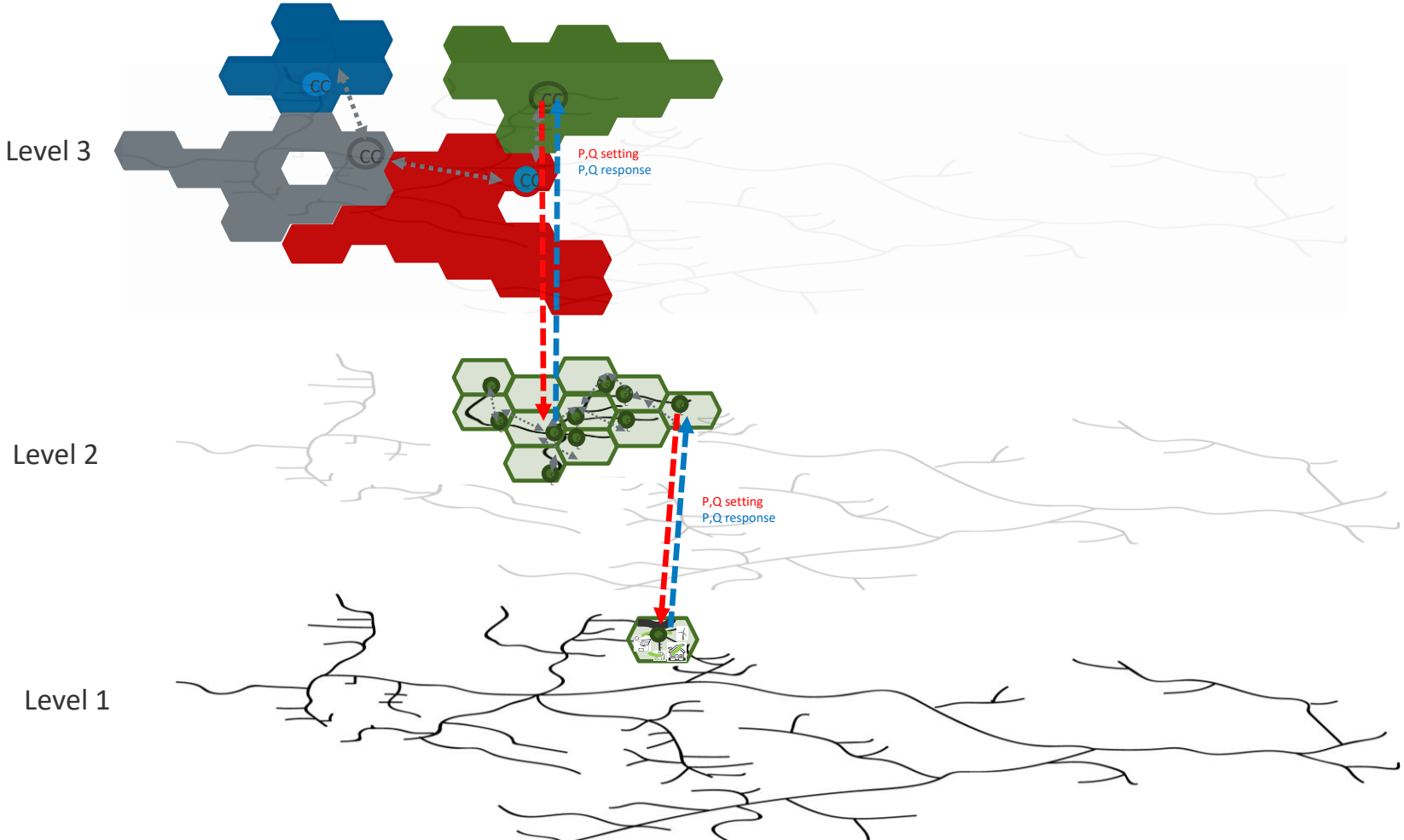
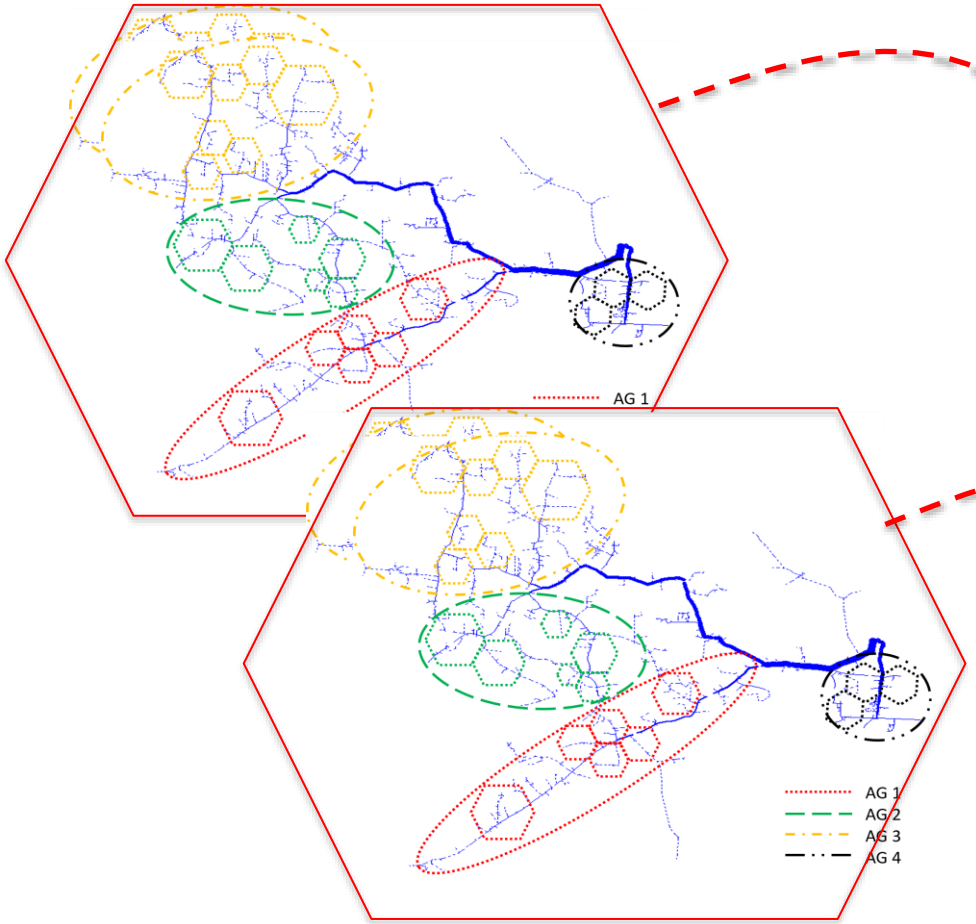
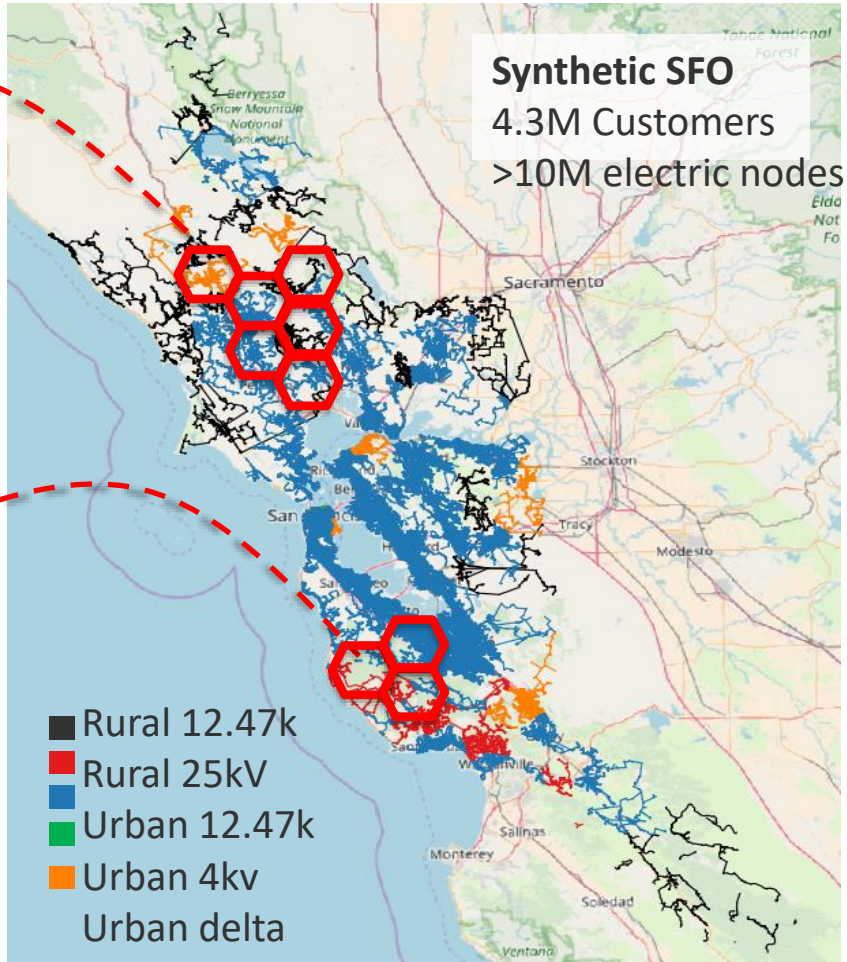


In 3D


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

Moving Back to the Metropolitan Scale





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


Energy Systems Integration Facility (ESIF)

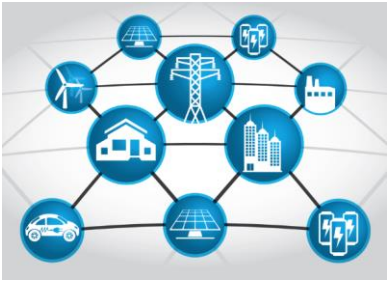
Shortening the time between innovation and practice

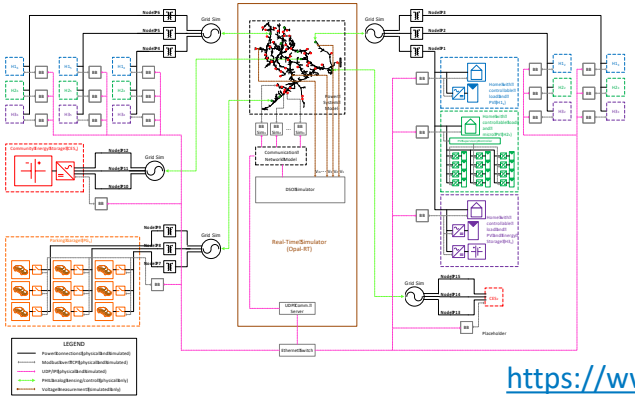
ESIF Unique Capabilities

- 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

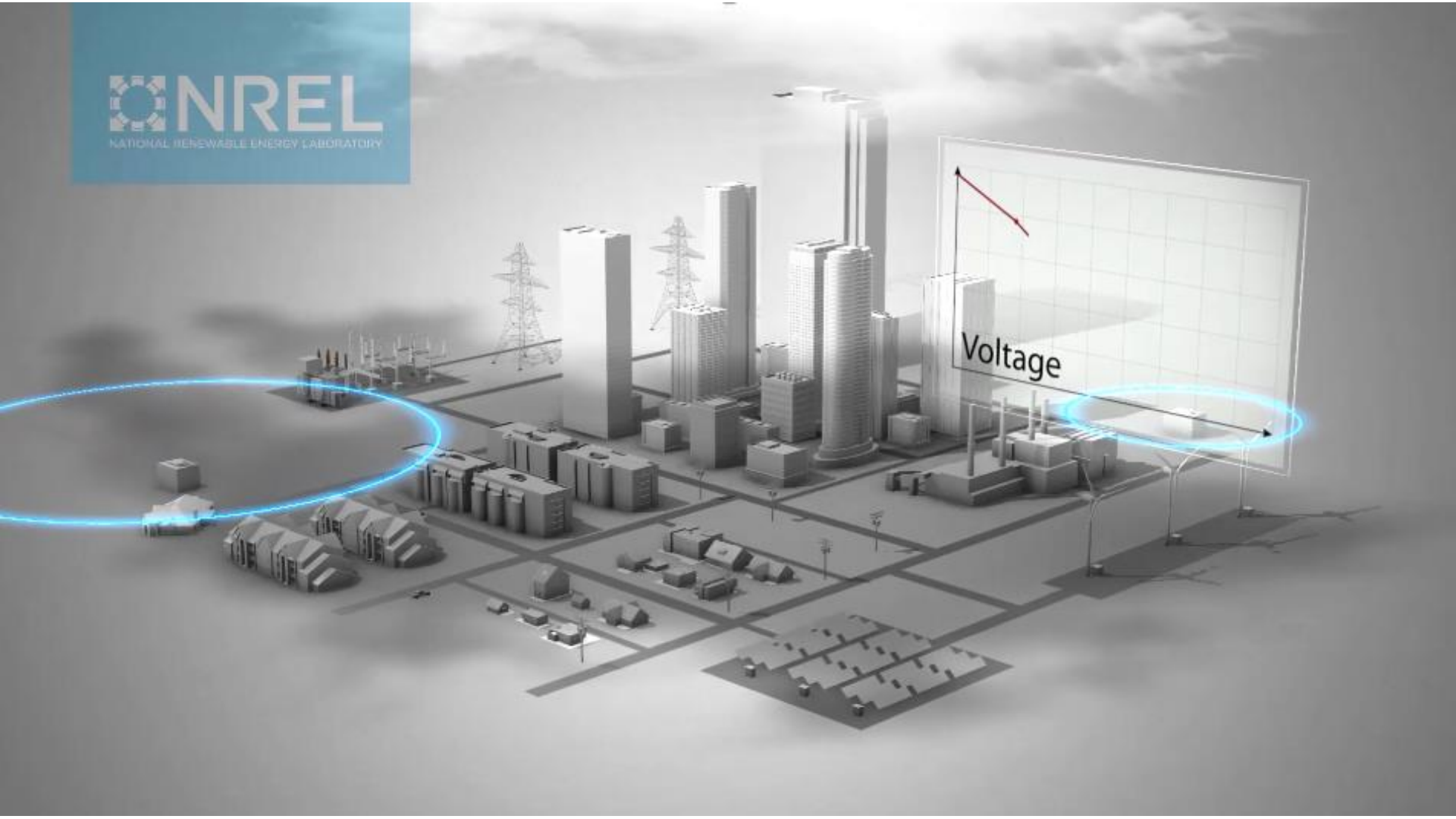
https://www.youtube.com/watch?v=In4HtG6XypU

Let’s Look to the Future

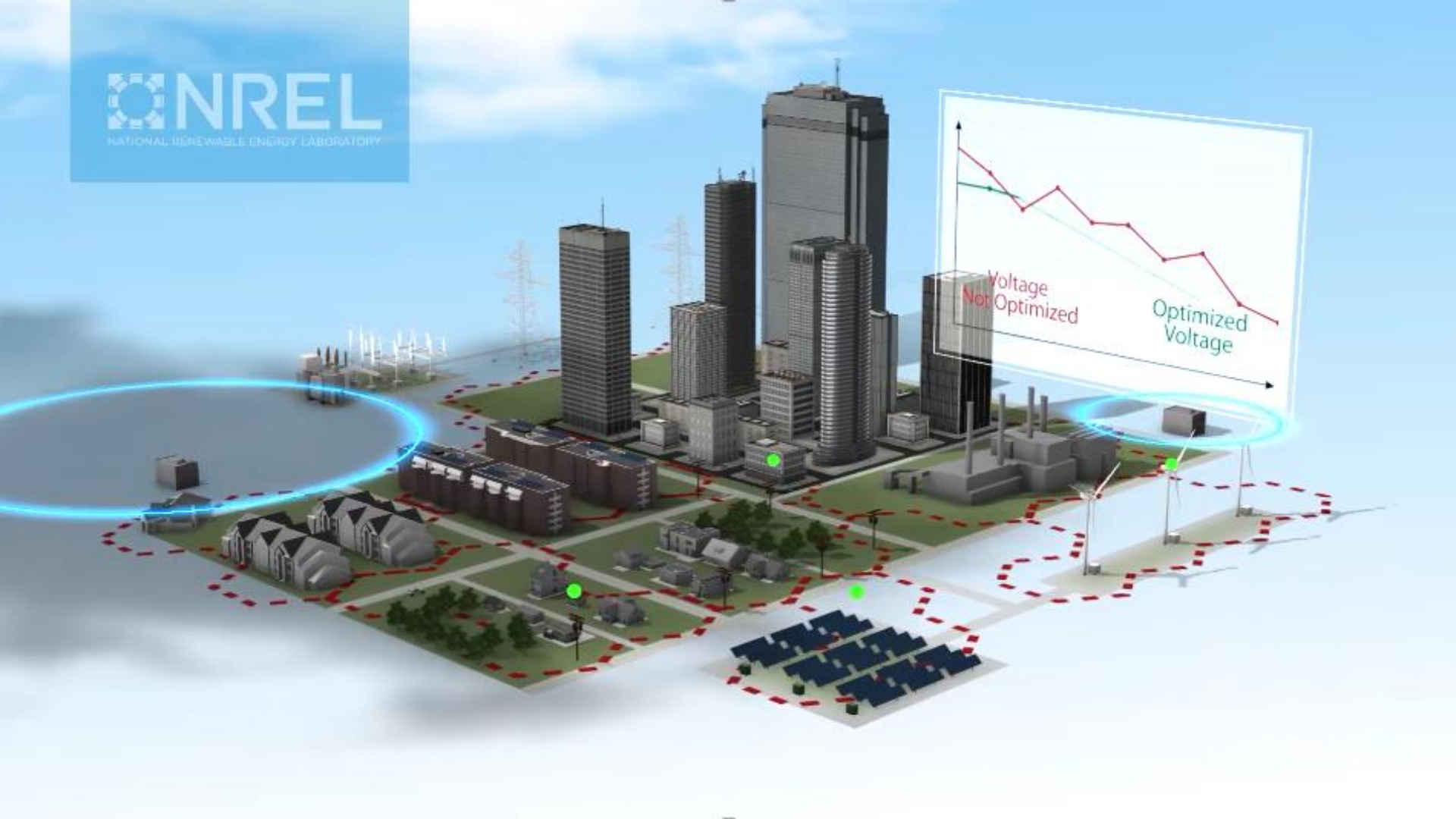
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

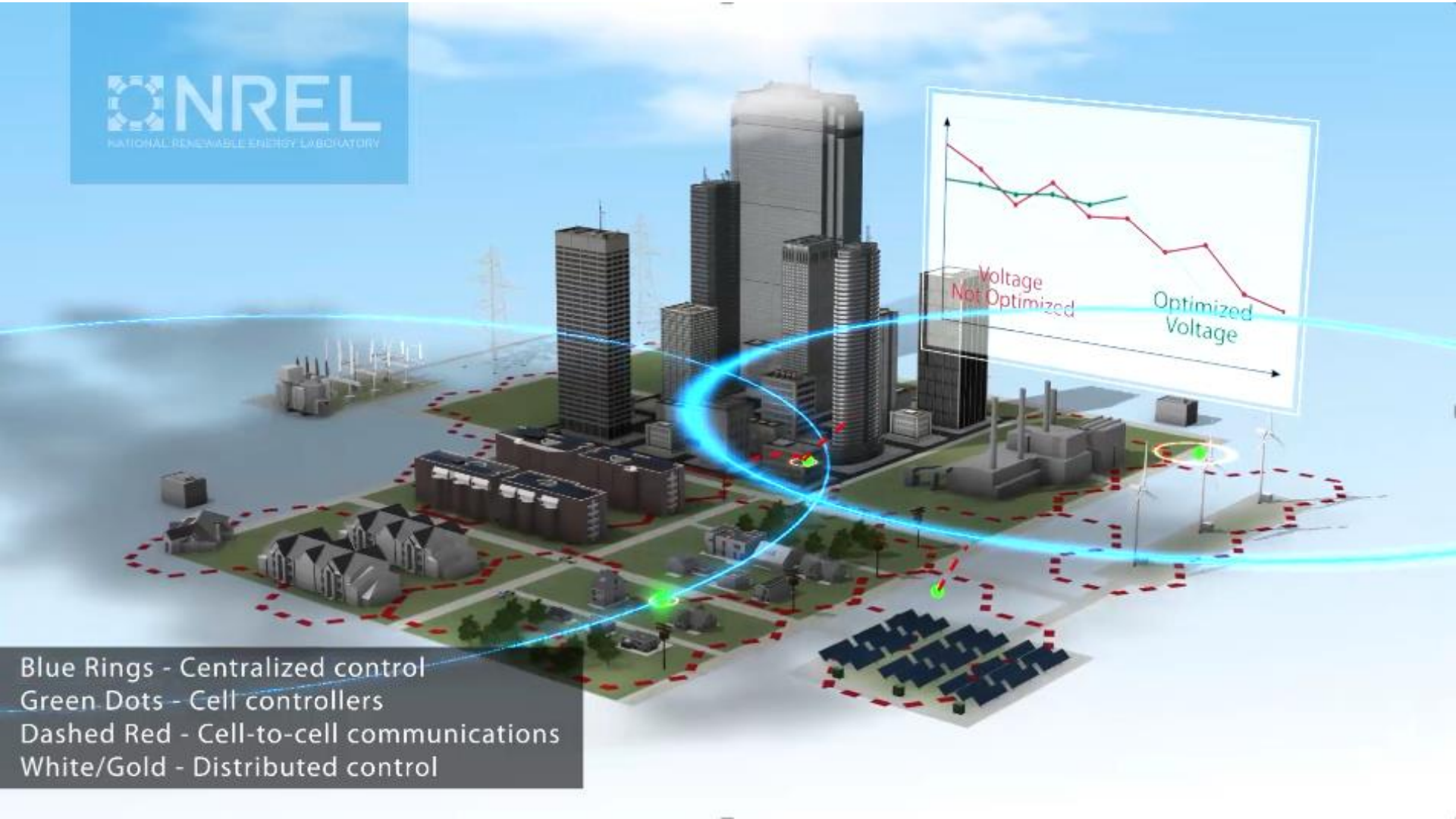
Autonomous Energy Grids

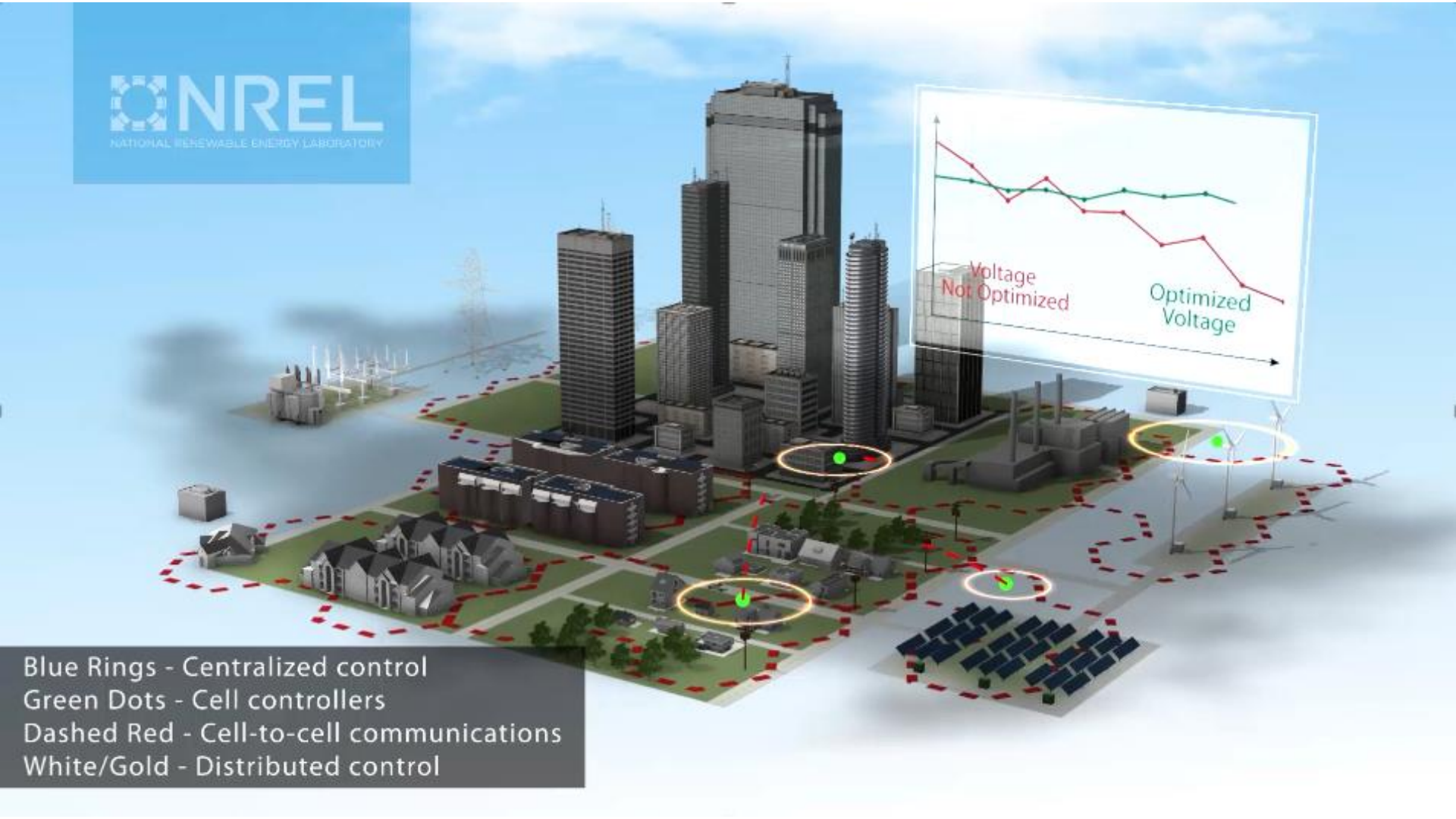
NREL is a national laboratory of the U.S. Department of Energy,
Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.


NREL
NATIONAL RENEWABLE ENERGY LABORATORY
Voltage


NREL
NATIONAL RENEWABLE ENERGY LABORATORY
Voltage
Blue Rings - Centralized control


NREL
NATIONAL RENEWABLE ENERGY LABORATORY
Voltage
Not Optimized
Optimized
Voltage


NREL
NATIONAL RENEWABLE ENERGY LABORATORY
Voltage
Not Optimized
Optimized
Voltage
Blue Rings - Centralized control
Green Dots - Cell controllers
Dashed Red - Cell-to-cell communications
White/Gold - Distributed control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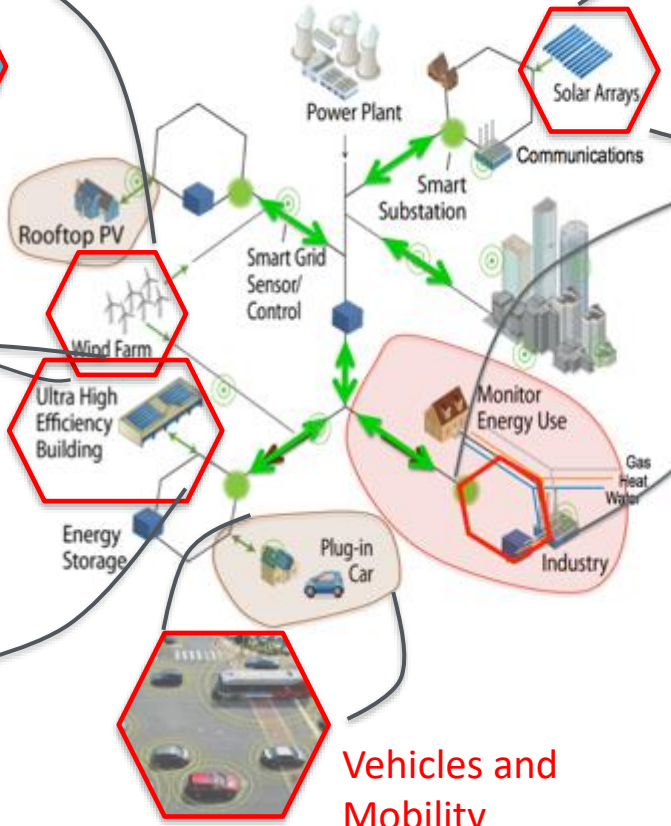
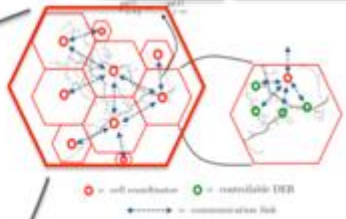
Transforming ENERGY through Autonomous Energy Systems

Advanced Wind Plants

Advanced Solar Plants





Autonomous Energy Grids

Grid Interactive Efficient Buildings

Vehicles and Mobility

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

Thank you

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