Welcome

ENERGY SYSTEMS INTEGRATION

ESI optimizes the design and performance of electrical, thermal, fuel, and water pathways at all scales.

Autonomous Energy Grids Workshop

September 13 & 14

Agenda Day 1

September 13, 2017 – Day One
Salon E

7:30 - 8:00	Check In and Continental Breakfast	
8:00 – 8:45	Welcome - NREL Deputy Lab Director	Peter Green NREL
	Intro to Autonomous Energy Grids	Ben Kroposki NREL
8:45 – 9:45	Big Data Analytics – Speaker & Discussion	Georgios Giannakis Univ. of Minnesota
9:45 – 10:00	**Break**	
10:00 – 11:00	Big Data Analytics – Speaker & Discussion	David Culler UC Berkeley
11:00- 12:00	*Break Out Discussions – Big Data Analytics* Salons - F,G,H, & Keystone	
12:00 – 12:45		**Lunch**
12:45- 1:45	Optimization Theory – Speaker & Discussion	Steven Low Caltech
1:45 – 2:45	Optimization Theory – Speaker & Discussion	Angelia Nedich Arizona State Univ.
2:45 – 3:45	*Break Out Discussions – Optimization Theory* Salons - F G, H, & Keystone	
3:45 – 4:00	Travel and Check In at NREL NREL Shuttles provided	NREL- RSF Lobby
4:00 – 5:00	NREL ESIF Tour	

Agenda Day 2

<u>September 14, 2017 – Day Two</u>
Salon E

7:30 – 8:00	Continental Breakfast	
8:00 – 9:00	Control Theory – Speaker & Discussion	Sean Meyn Univ. of Florida
9:00 – 10:00	Control Theory – Speaker & Discussion	Mihailo Jovanovic USC
10:00 – 10:15	**Break**	
10:15 – 11:15	*Break Out Sessions – Control Theory* Salons - F, G, H, & Keystone	
11:15 – 12:00	**Lunch**	
12:00- 1:00	Complex Systems – Speaker & Discussion	Gil Zussman Columbia University
1:00 - 2:00	Complex Systems – Speaker & Discussion	Daniel Kirschen Univ. of Washington
2:00- 2:15	**Break**	
2:15- 3:15	*Break Out Sessions – Complex Systems* Salons – F, G, H, & Keystone	
3:15 - 4:15	Autonomous Energy Grids Bringing everything together	Ian Hiskens Univ. of Michigan
4:15 - 4:30	Workshop Summary – Salon E	

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Power Systems
Engineering Center

Autonomous Energy Grids

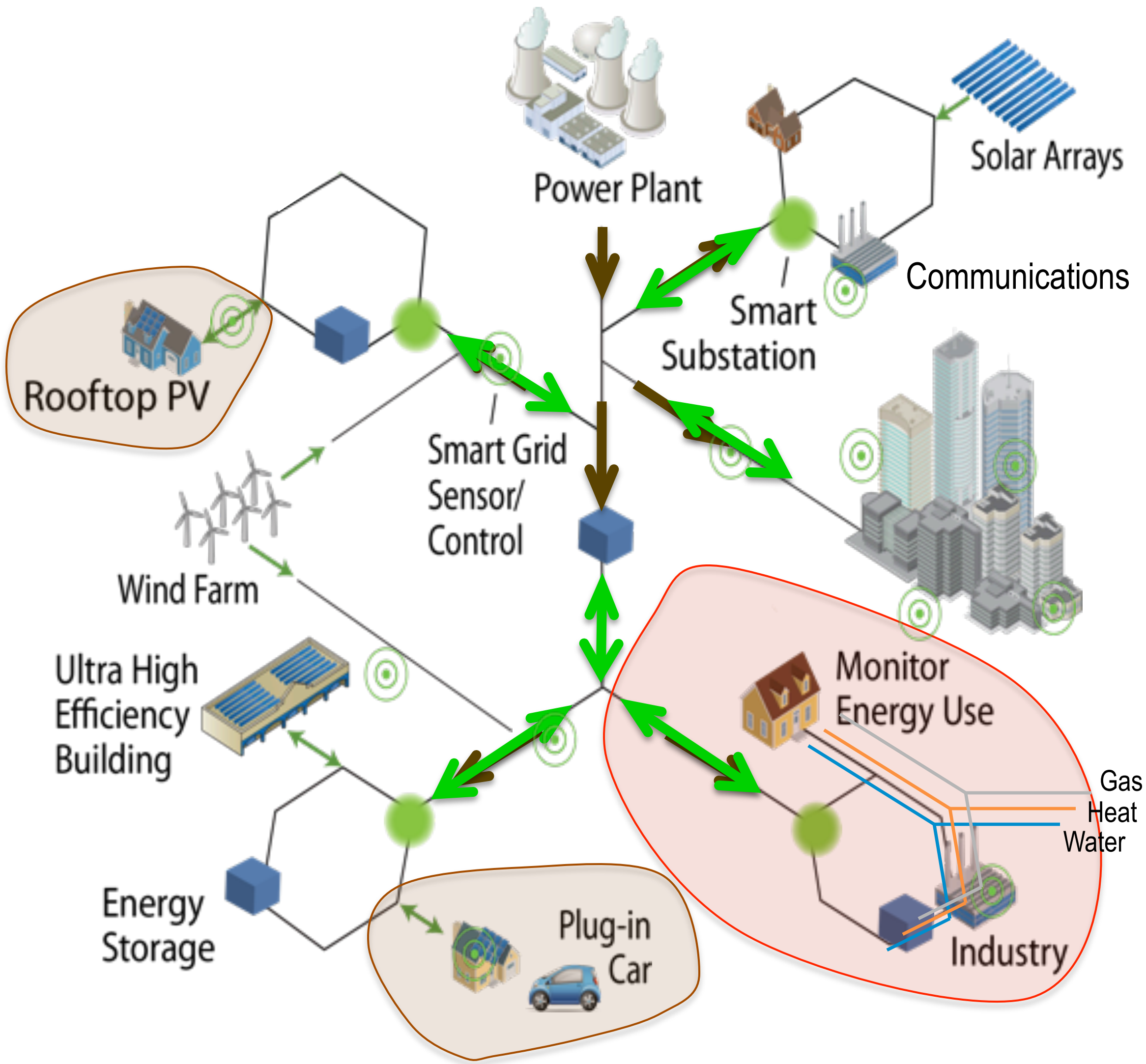
Ben Kroposki, PhD, PE, FIEEE

Director – Power Systems Engineering Center

https://www.nrel.gov/grid/

Autonomous Energy Grids

optimized for secure, resilient and economic operations

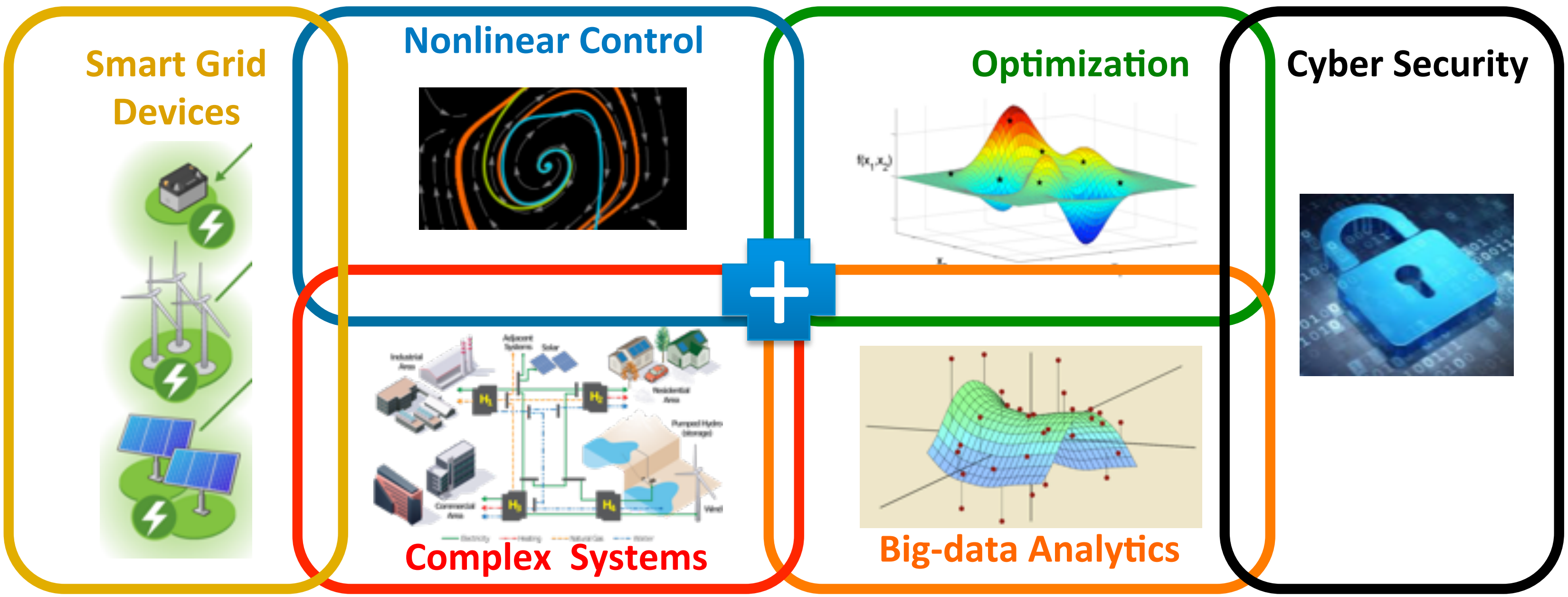


- Current power systems deliver electricity in one direction from large central plants to customer loads
- There is an increasing amount of distributed and variable generation, energy storage, and new loads being added to the grid - causing bi-directional power flows and voltage fluctuations that impact control and optimization
- New intelligence is being added to the grid through smart devices and communications - drastically increasing the amount of information available about grid conditions
- There is growing use of combined heat and power and natural gas generation – increasing interdependencies with the electrical grid and other domains
- All these contribute to cybersecurity and resilience concerns and solutions
- Our vision is to develop ***Autonomous Energy Grids*** that are optimized for secure, resilient, and economic operations through advanced science in controls, optimization, big-data analytics and complex systems

Creating Autonomous Energy Grids – Needs in Foundational Science

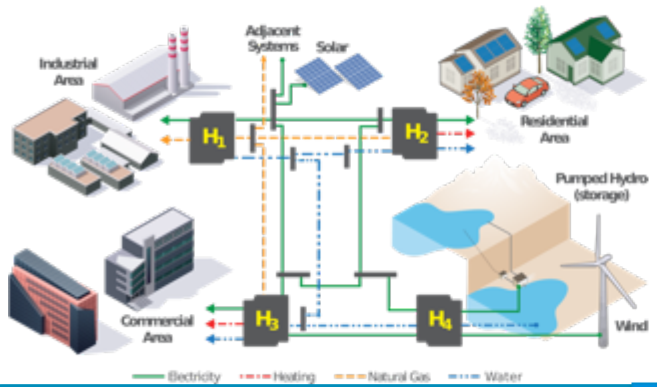
- Equivalent to autonomous vehicles, *"Autonomous Energy Grids"* do not require operators, can be extremely resilient (self-healing) and can optimize themselves for reliability and economic performance while integrating energy in all forms

- Need to advance foundational science to develop a common analytical framework for modeling, optimization, and control of complex systems at multiple spatial and temporal scales

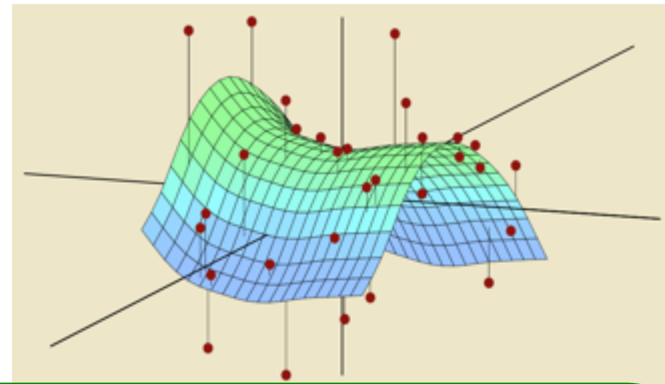


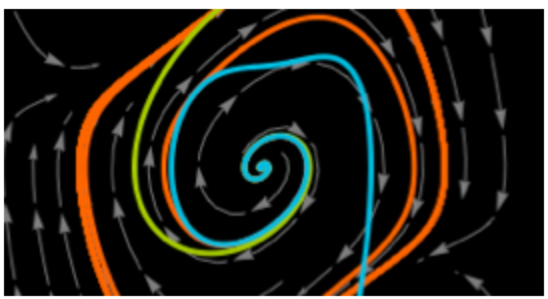
Workshop Focus - Technical Areas for Autonomous Energy Grids

Complex Systems Theory

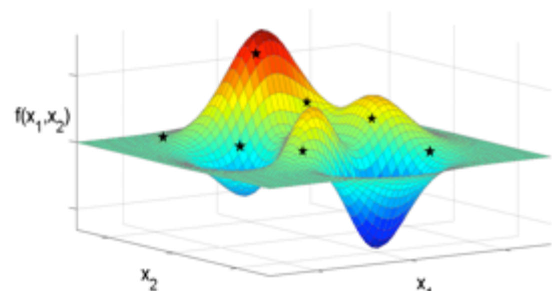


Big-data Analytics



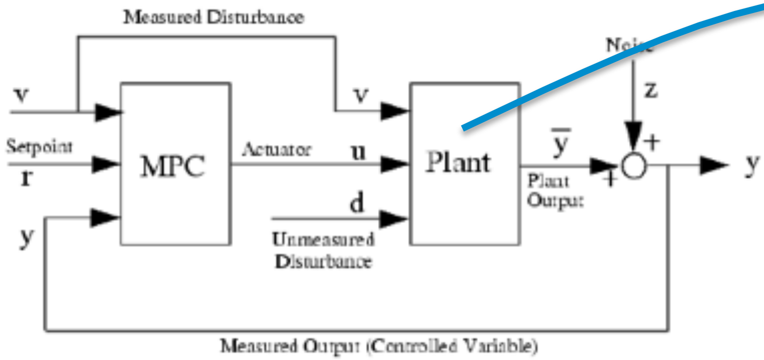


Nonlinear Control Theory



Optimization Theory

Non-Linear Control Theory



$$\min_{u_t,\ldots,u_{t+N-1}} \{\sum_{k=0}^{N-1} \|y_{t+k} - r(t)\|^2 + \rho\|u_{t+k} - u_r(t)\|^2)\}$$

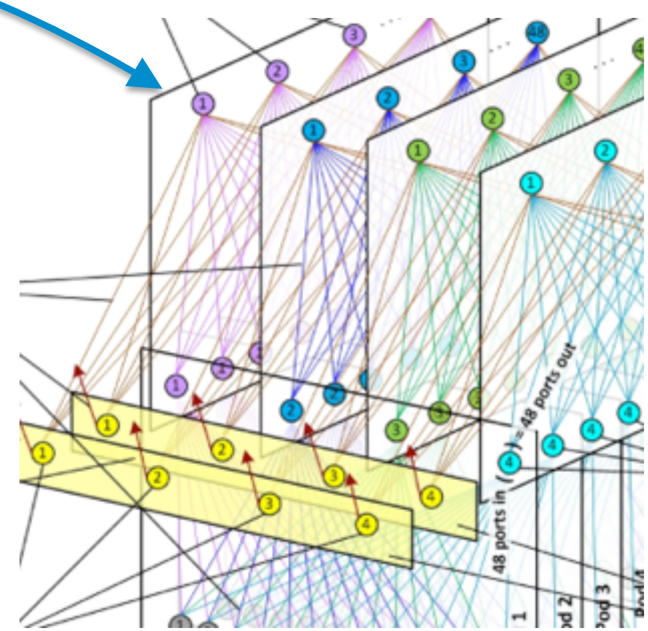
$$s.t.: x_{t+k+1} = f(x_{t+k}, u_{t+k})$$

$$y_{t+k} = g(x_{t+k}, u_{t+k})$$

$$u_{\min} \leq u_{t+k} \leq u_{\max}$$

$$y_{\min} \leq y_{t+k} \leq y_{\max}$$

$$x_t = x(t), k = 0, \ldots, N-1$$



Highly networked system

Advance core theory in:

- ❑ Stability of networked nonlinear systems
- ❑ Existence and uniqueness of ODE systems
- ❑ Nonlinear model predictive control
- ❑ Dynamic programming

Applications:

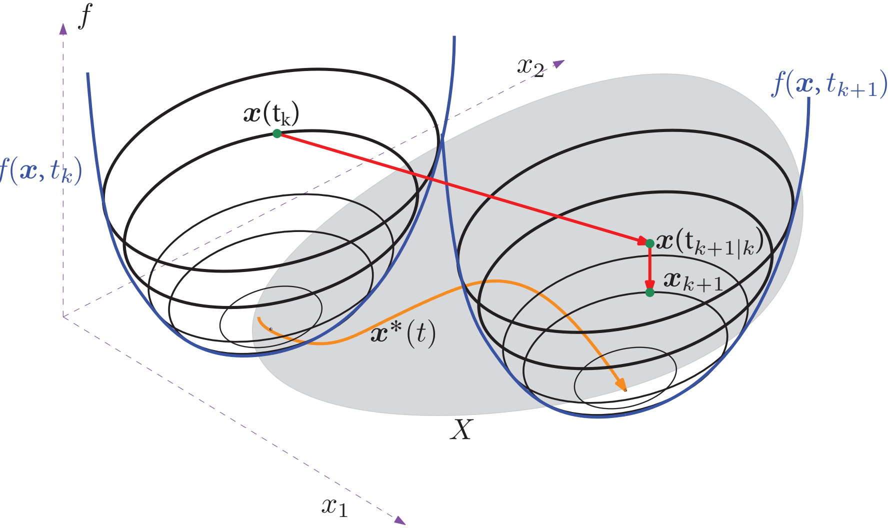
- ❑ Low-inertia energy systems
- ❑ Autonomous and fractal grids
- ❑ Autonomous electric vehicles

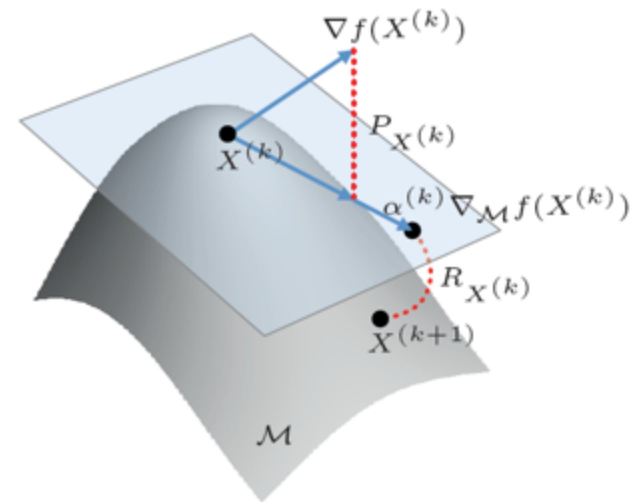
Optimization Theory

Convex
Optimization theory

$$\min_{\mathbf{x}\in\mathscr{X}} f_0(\mathbf{x},\mathbf{y}_0(\mathbf{x},t),t) + \sum_{n\in\mathscr{N}} f_n(\mathbf{x}_n,\mathbf{y}_0(\mathbf{x},t),t)$$
$$\text{subject to } \mathbf{h}(\mathbf{x},\mathbf{y}_h(\mathbf{x},t),t) = \mathbf{0}$$
$$\mathbf{g}(\mathbf{x},\mathbf{y}_g(\mathbf{x},t),t) \le \mathbf{0}$$

Nonconvex
optimization theory





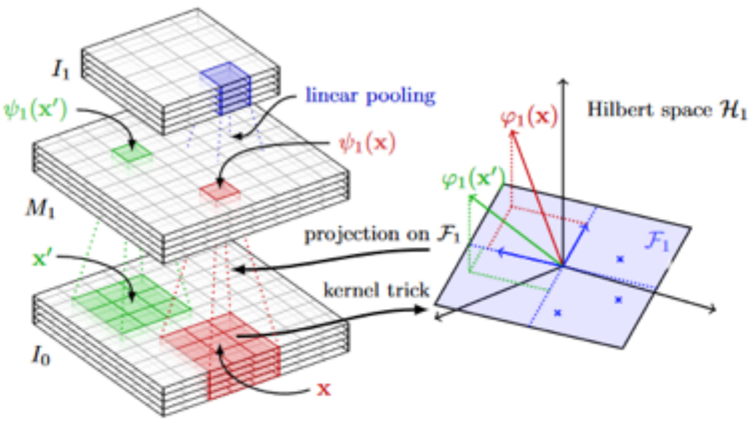
Advance core theory in:

- ❑ Dynamic and distributed optimization
- ❑ Optimization on manifolds
- ❑ Time-varying monotone operators
- ❑ Convex relaxation

Applications:

- ❑ Real-time optimization of power systems
- ❑ Transactive multi-energy systems
- ❑ Cyber-physical energy systems
- ❑ Electric (autonomous) vehicles

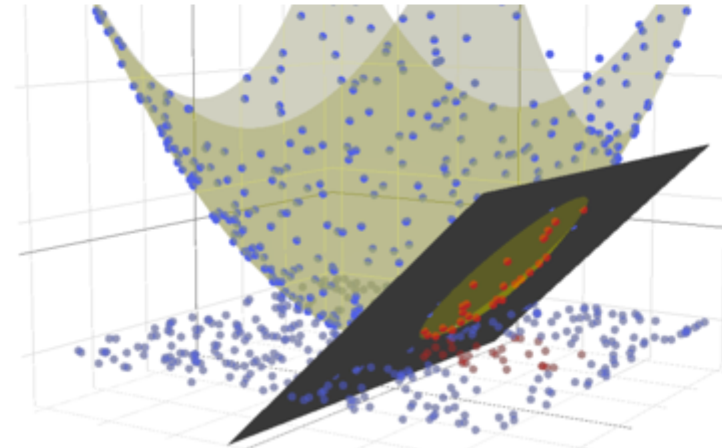
Big-data Analytics



Tensor decomposition

$$\mathbf{X} = \sum_{f=1}^{F} \mathbf{a}_f \circledcirc \mathbf{b}_f \circledcirc \mathbf{c}_f \Longleftrightarrow \mathbf{X}(i,j,k) = \sum_{f=1}^{F} \mathbf{a}_f(i)\mathbf{b}_f(j)\mathbf{c}_f(k)$$

$$= \sum_{f=1}^{F} \mathbf{A}(i,f)\mathbf{B}(j,f)\mathbf{C}(k,f), \quad \begin{cases} & i \in \{1,\cdots,I\} \\ \forall & j \in \{1,\cdots,J\} \\ & k \in \{1,\cdots,K\} \end{cases}$$



$$\hat{\boldsymbol{f}}_0 := \underset{\boldsymbol{f} \in \mathcal{R}\{\bar{\boldsymbol{K}}\}}{\arg\min} \frac{1}{S}\mathcal{L}(\boldsymbol{y} - \boldsymbol{\Phi f}) + \mu\Omega((\boldsymbol{f}^T \bar{\boldsymbol{K}}^{\dagger} \boldsymbol{f})^{1/2})$$

Matrix optimization

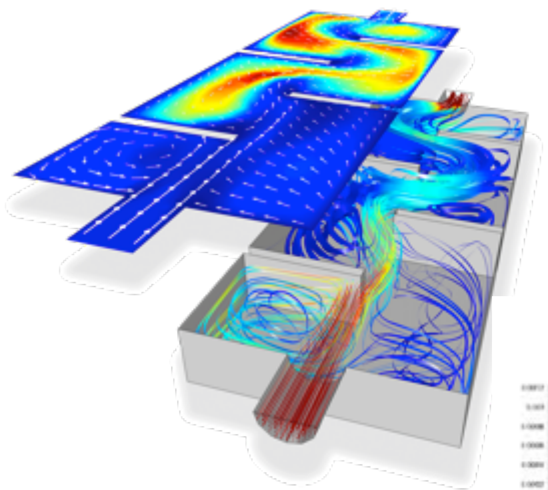
Advance core theory in:

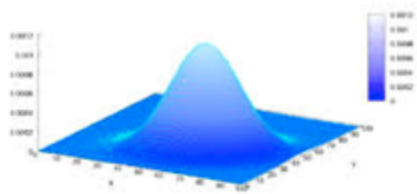
- ❑ Dynamic regret analysis
- ❑ Kernel-based data imputation and prediction
- ❑ Graphical models
- ❑ Dynamic Programming

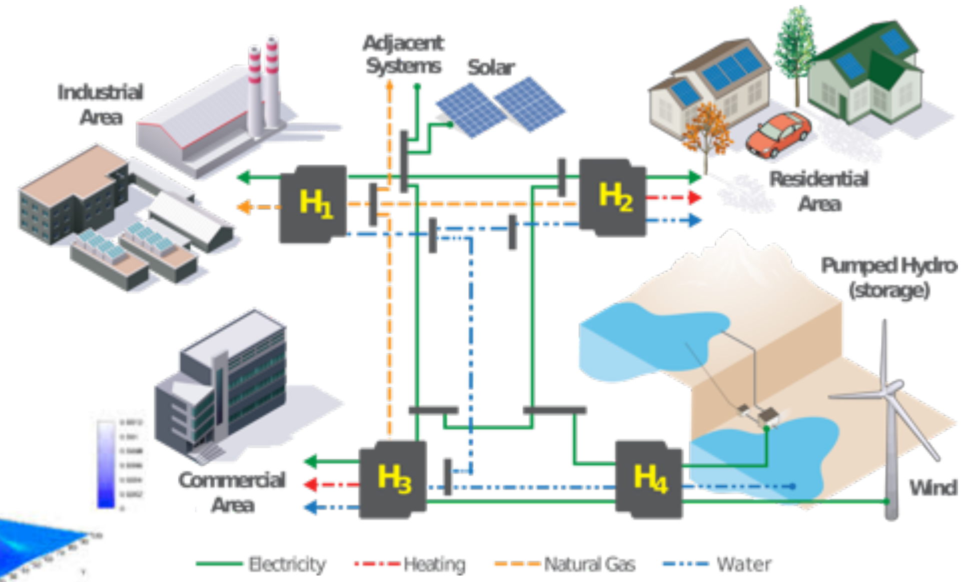
Applications:

- ❑ Forecasting at multiple time scales
- ❑ Anomaly detection and cybersecurity
- ❑ Energy data (de)compression
- ❑ Energy-customer behavioral science
- ❑ Autonomous dispatch center

Complex System Theory







$$T_{i,d}^{\text{in}+} = T_{i,d}^{\text{in}} + \theta_{i,d}(T_{i,d}^{\text{out}} - T_{i,d}^{\text{in}}) + \theta'_{i,d}\, p_{i,d}$$

$$\frac{\rho g}{\eta_{ij}} \hat{h}_{ij}^t q_{ij}^t = -\text{Re}\left(s_{\sigma(ij)}^t\right), \quad \forall ij \in \mathcal{P},\ \forall t = 1, \ldots, T.$$

Advance core theory in:

- ❑ Fixed-point methods for nonlinear equations
- ❑ Model reduction and approximation
- ❑ Uncertainty quantification
- ❑ Modeling of coupled infrastructures
- ❑ Full time spectrum modeling

Applications:

- ❑ Large-scale multi-energy systems
- ❑ Synthesis of dynamical models
- ❑ Feasibility studies
- ❑ Stochastic control and optimization
- ❑ Economical-dynamic analysis

Autonomous Energy Grids Workshop

This workshop seeks community engagement and input on the science and technical challenges that must be addressed to meet the emerging needs of Autonomous Energy Grids.

Over the two days, we will explore advances in non-linear control theory, optimization theory, big data analytics, and complex system modeling.

Identify the gaps and challenges in theory and computation related to that are need to achieve Autonomous Energy Grids

Identify research tools and capabilities needed to meet these challenges.


Enjoy the Workshop!