Real-Time Decision-Making for Clean and Resilient Energy Systems

Bartolomeo Stellato

ISSNAF YI Strazzabosco Symposium, October 27 2022

Texas Power Grid collapsed after winter storm

Statewide power outages

Food/water shortages

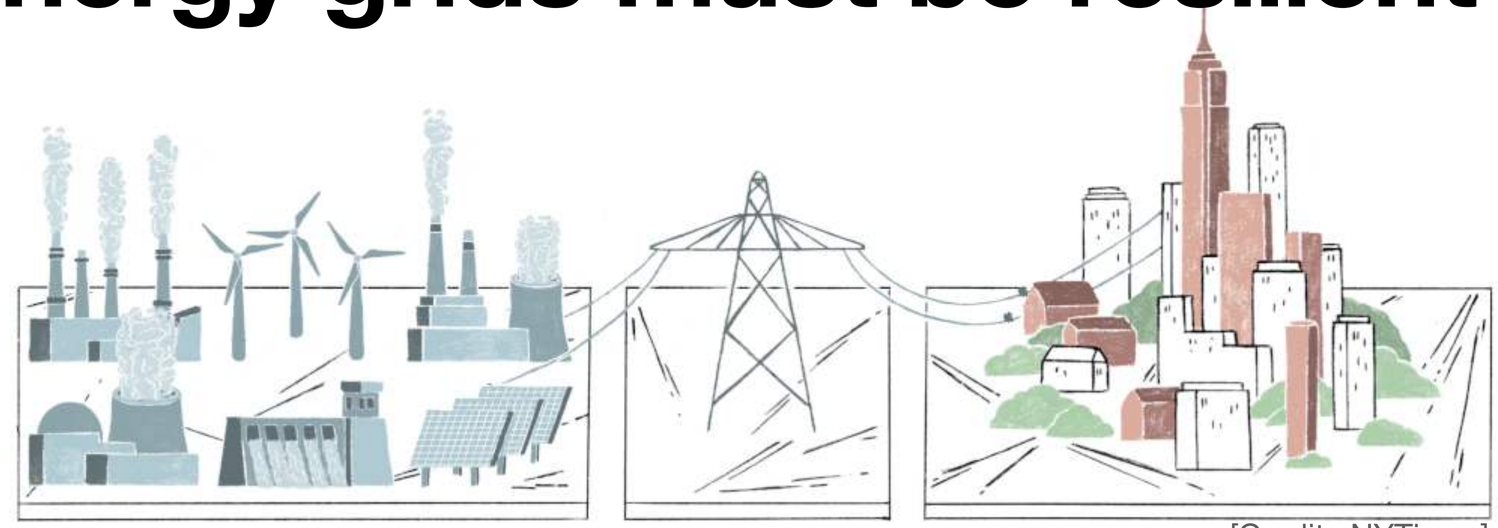
Property damage: $195 bln

Deaths: 246 - 702 (estimate)

Satellite images of Houston

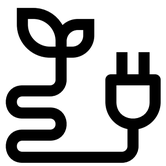
"Extreme Winter Weather Causes U.S. Blackouts". earthobservatory.nasa.gov. February 16, 2021.

Future energy grids must be resilient

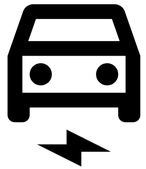


[Credits NYTimes]

Green energy transition



Renewables



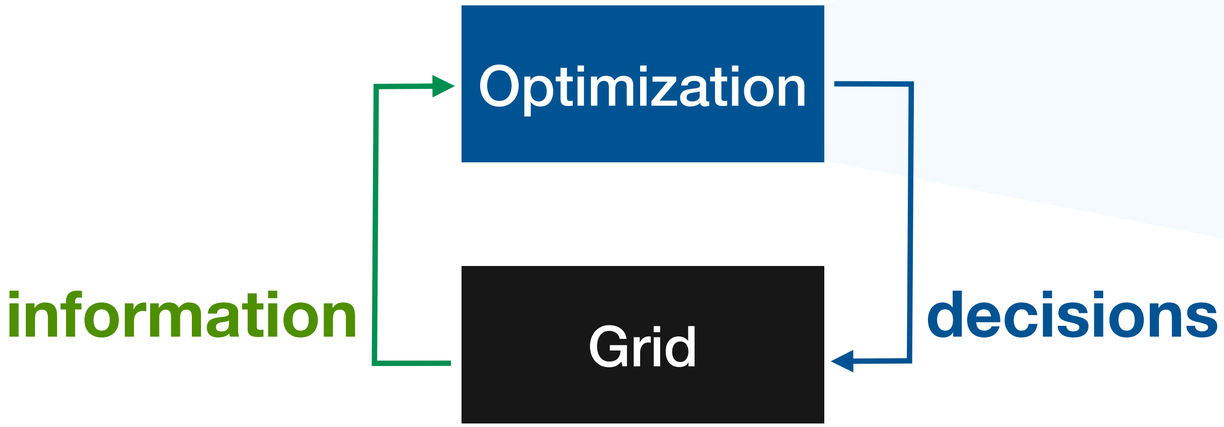
PEV

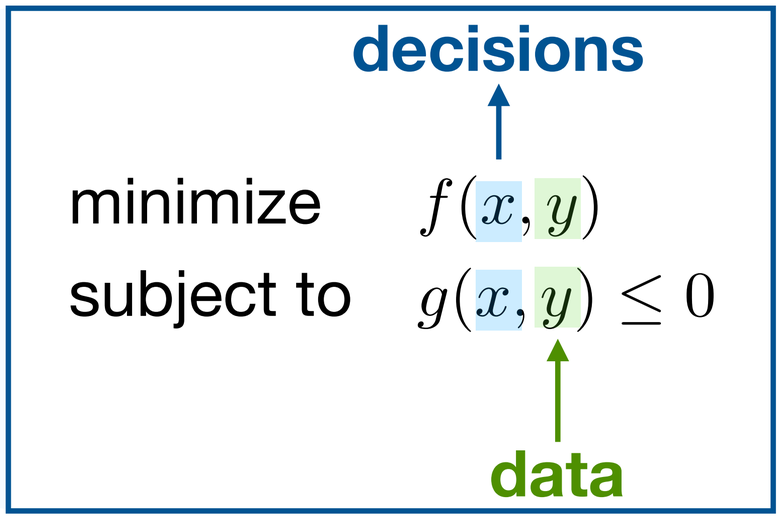
Uncertainty

Climate change

Can optimization make our grid more resilient?

Resilient grids via Real-Time Optimization

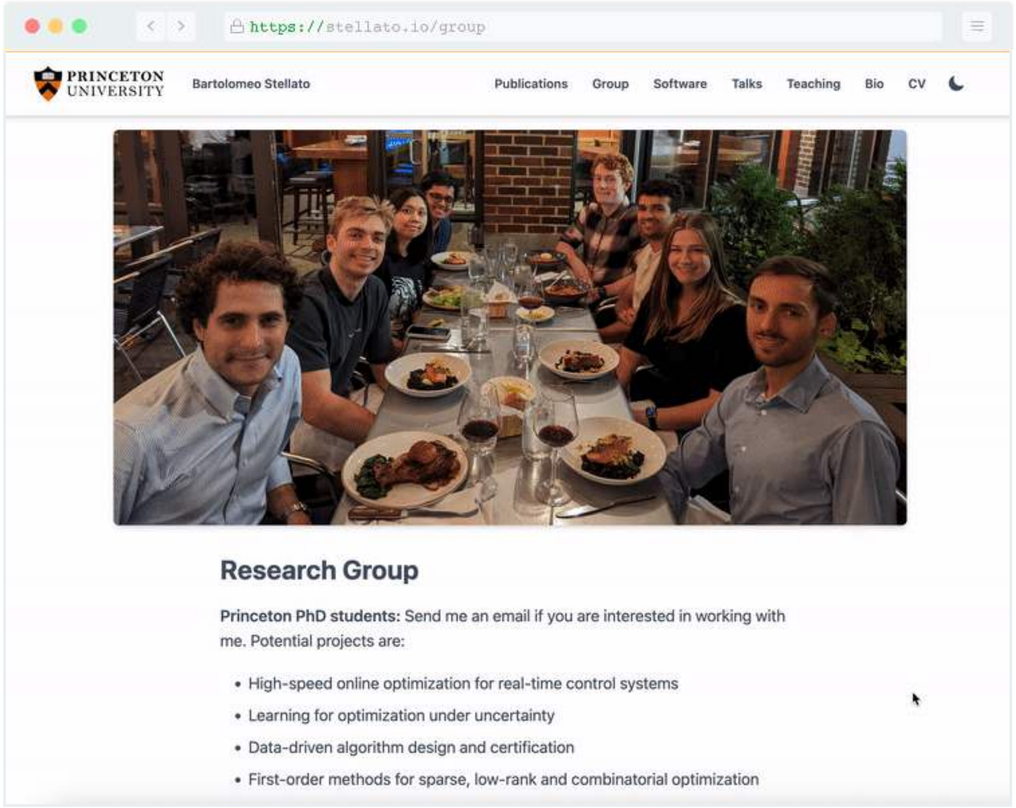




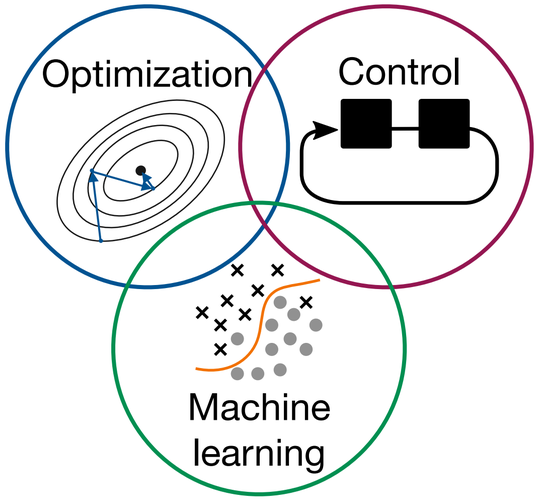
objective f: energy consumption, costs
constraints g: dynamics, physical limits

Re-planning in real-time is the key to adaptive resilient systems

Stellato research group @ Princeton University

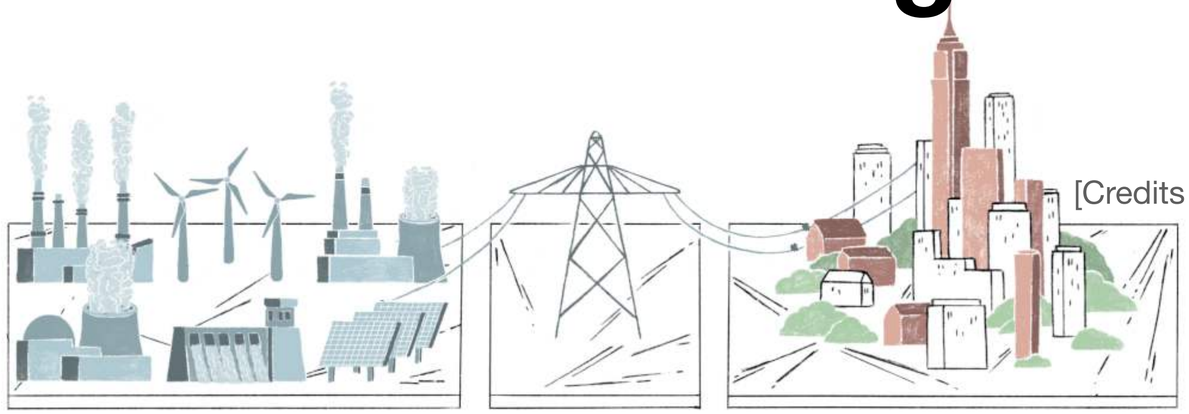


Develop **data-driven decision-making tools** for real-time optimization, machine learning, and optimal control.



sustainable energy applications

My recipe to tackle modern grid challenges



[Credits NYTimes]

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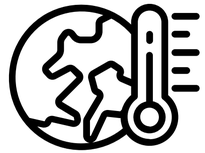
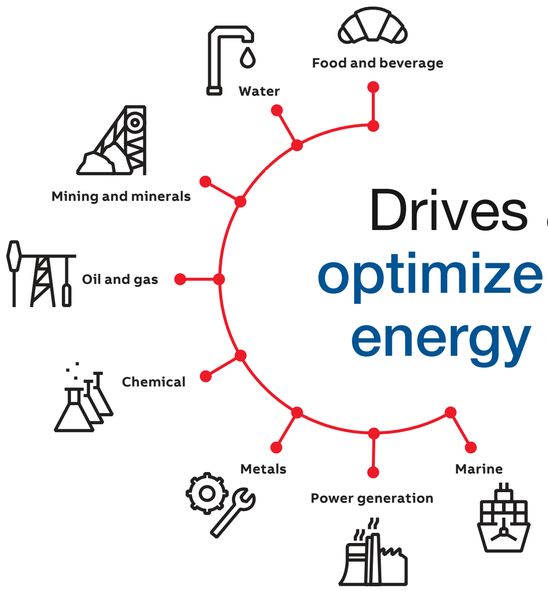


Climate change

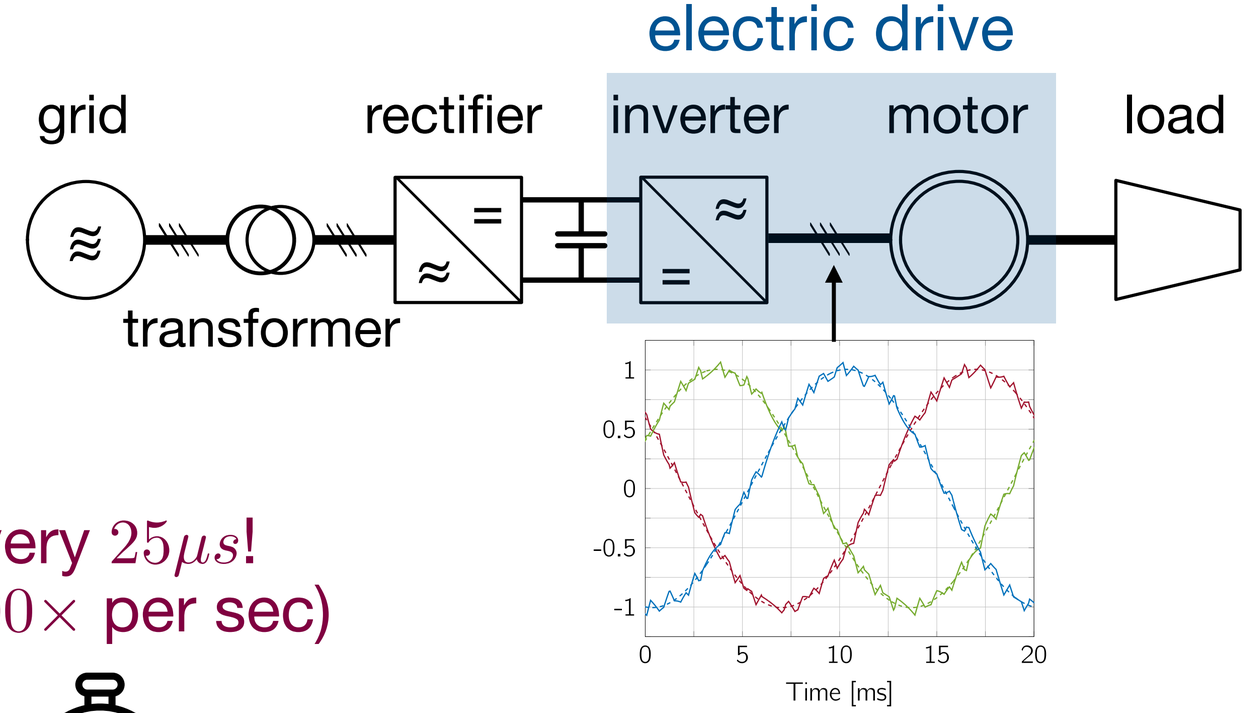
Fast optimization algorithms

Data-driven robust decision-making

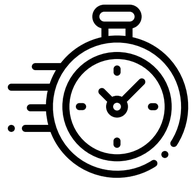
Optimizing energy consumption with Medium Voltage Drives



Drives are crucial to **optimize electric motor energy consumption**



... every $25\mu s$!
$(40,000\times$ per sec)



Collaboration with

ABB

Optimal Control via Approximate Dynamic Programming

minimize $\sum_{t=0}^{\infty} \gamma^t \ell(x_t)$ ← discounted objective $\mathrm{THD} + \delta f_{\mathrm{sw}}$

subject to $x_{t+1} = Ax_t + Bu_t$

$x_0 = x_{\mathrm{init}}$

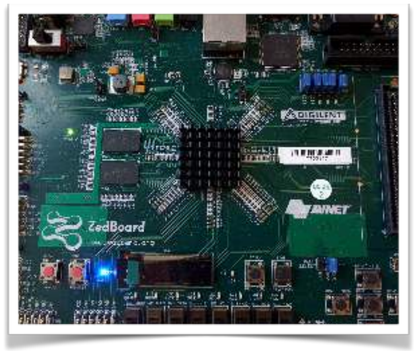
$x_t \in X, \quad u_t \in \{-1, 0, 1\}^3$ ← mixed-integer optimization (challenging to solve in real-time!)

Approximate Dynamic Programming

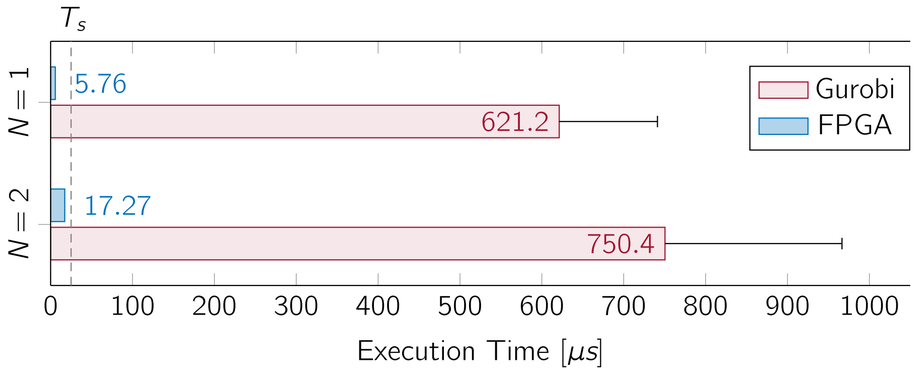
minimize $\sum_{t=0}^{N-1} \gamma^t \ell(x_t) + \gamma^N V(x_t)$ ← approximate value function (computed offline)

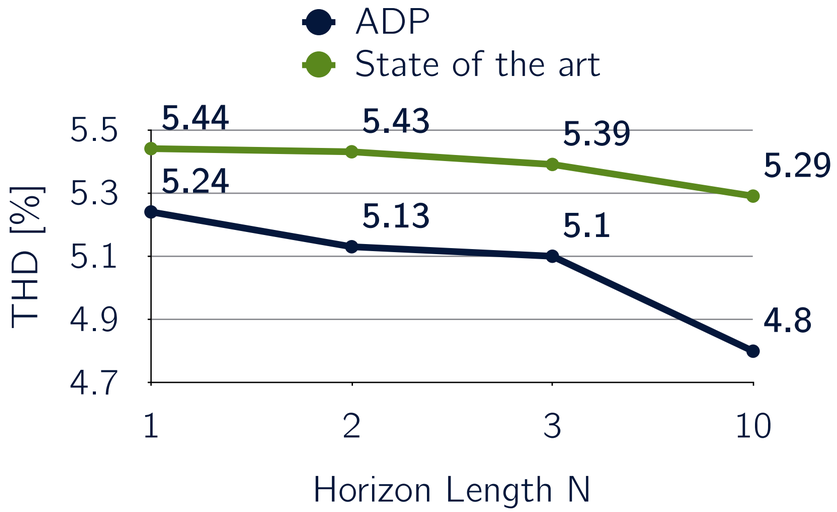
Real-time combinatorial optimization

Massively parallel
FPGA implementation



Solution time under $25\mu s$





Significant improvements

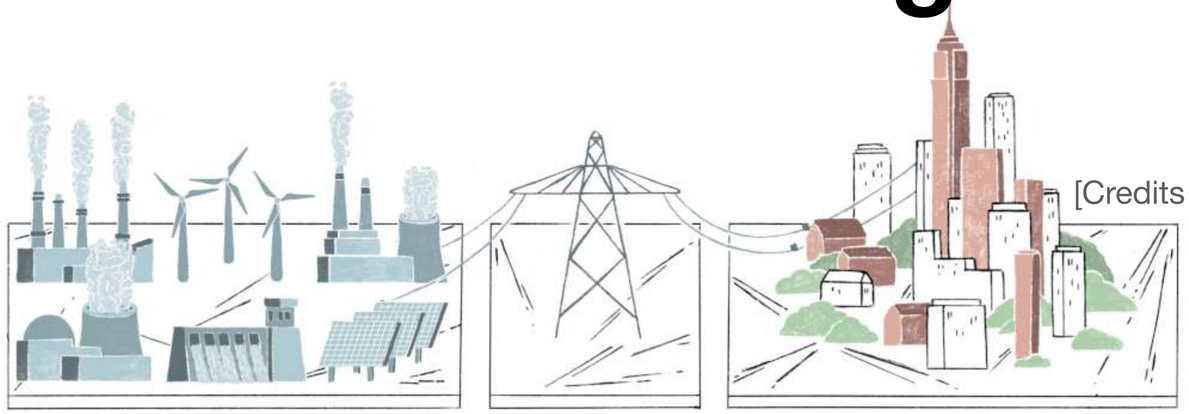
energy efficiency

lifespan of the electric motor

High-Speed Finite Control Set Model Predictive Control for Power Electronics
B. Stellato, T. Geyer, P. Goulart
IEEE Transactions on Power Electronics, 2017

First Place Paper Prize in IEEE Transactions in Power Electronics

My recipe to tackle modern grid challenges



[Credits NYTimes]

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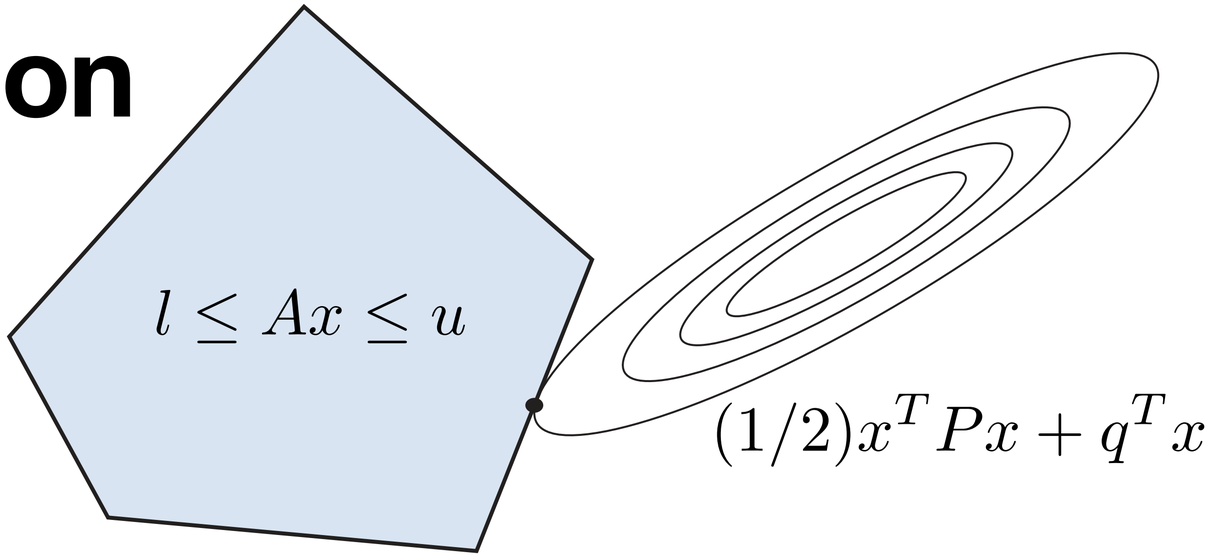
Data-driven robust decision-making

Quadratic optimization

Quadratic Optimization

minimize $(1/2)x^T Px + q^T x$

subject to $l \leq Ax \leq u$



Numerous applications

Core component in real-time optimization

OSQP Solver

Problem

$$\begin{array}{ll} \text{minimize} & (1/2)x^T P x + q^T x \\ \text{subject to} & l \leq Ax \leq u \end{array}$$

Algorithm in a nutshell

Linear system solve

Easy operations

$$x^{k+1} \leftarrow \text{Solve} \quad (P + \sigma I + \rho A^T A)x = \sigma x^k - q + A^T(\rho z^k - y^k)$$

$$z^{k+1} \leftarrow \Pi(Ax^{k+1} + \rho^{-1} y^k)$$

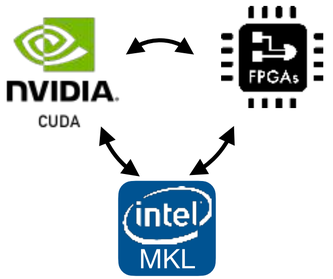
$$y^{k+1} \leftarrow y^k + \rho(Ax^{k+1} - z^{k+1})$$

always solvable!

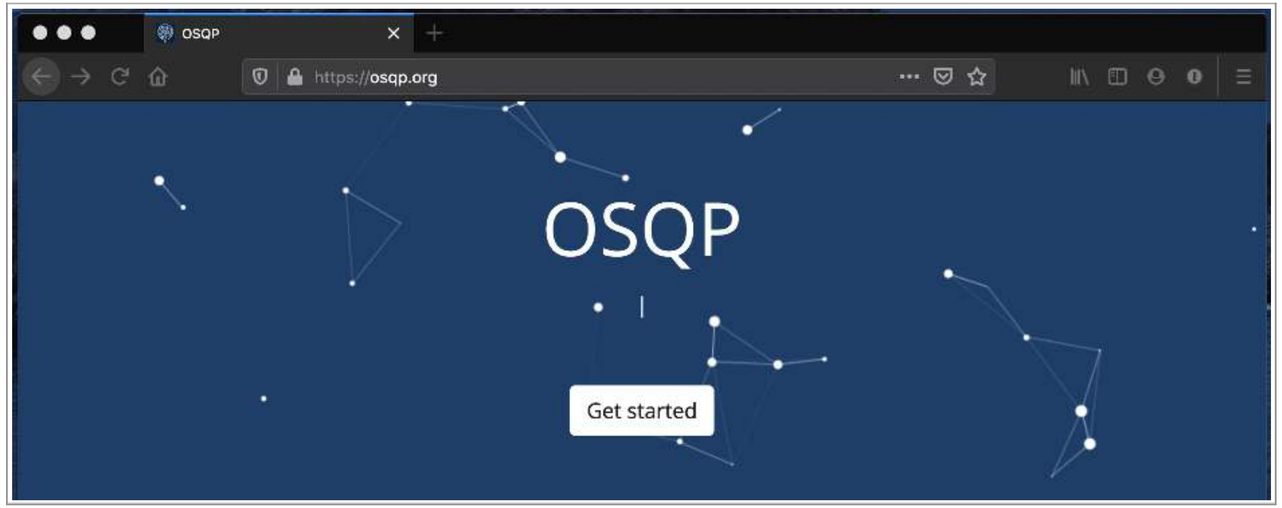
Efficient

Robust

Modular



OSQP



Academia

Industry

28 million downloads!

[https://pepy.tech/project/osqp]

OSQP: An Operator Splitting Solver for Quadratic Programs
B. Stellato, G. Banjac, P. Goulart, A. Bemporad, S. Boyd
Mathematical Programming Computation, 2020
(600 citations in 2 years)

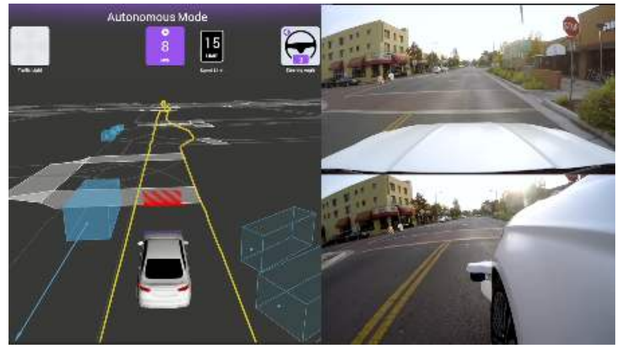
Mathematical Programming Computation
Best Paper Award

OSQP solver for sustainable energy

Optimal Trajectory Generation for Autonomous Vehicles

lyft Level 5

Baidu 百度 apollo



Electricity markets operations

Energy Exchange Istanbul

EXIST

Carbon-negative green houses

Smart grid operations

Optimization of grid-scale batteries (50 MW)

Gridmatic

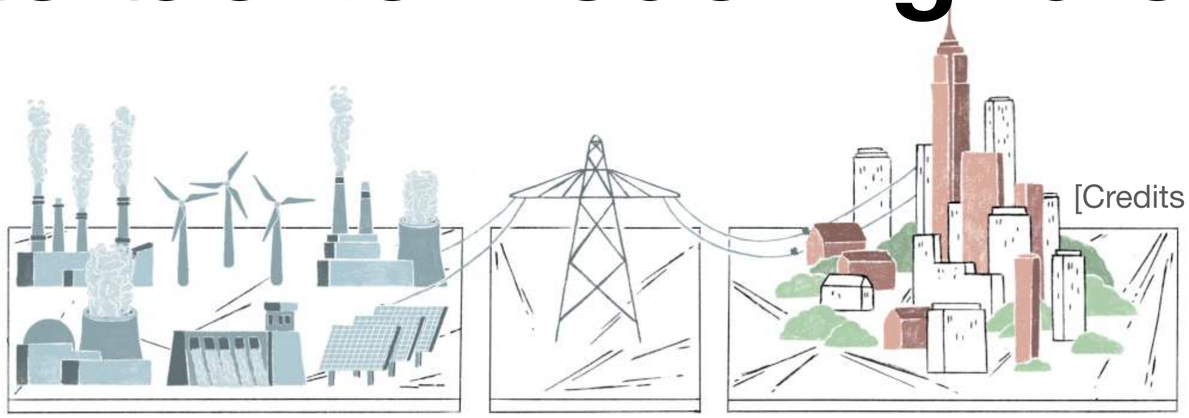
DECARBONIZING THE GRID
by optimizing clean energy

Large-scale Robust security-constrained Optimal Power Flow

GPU

Argonne NATIONAL LABORATORY

My recipe to tackle modern grid challenges



[Credits NYTimes]

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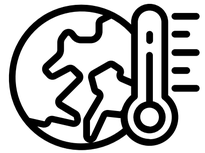

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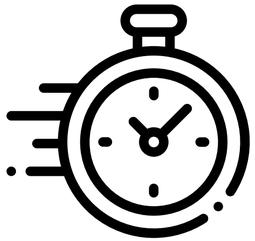


Data-driven robust decision-making

Uncertain energy distribution problems are hard

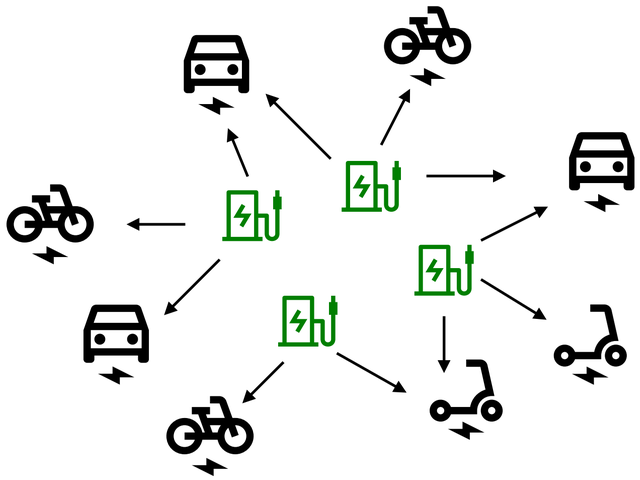
cost of opening charging stations

cost of energy distribution

$$\begin{array}{ll} \text{minimize} & c^T x + \mathbf{tr}(C^T X) \\ \text{subject to} & \mathbf{1}^T X_j = 1, \quad j = 1, \ldots, m \\ & (X^T)_i u \leq r_i x_i, \quad i = 1, \ldots, n \\ & x \in \{0,1\}^n, \quad X \in \mathbf{R}^{n \times m} \end{array}$$

vector of uncertain energy demands

capacity constraints

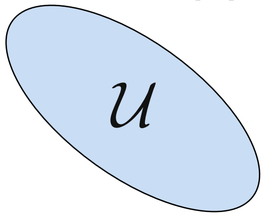


Hard to guarantee constraint satisfaction!

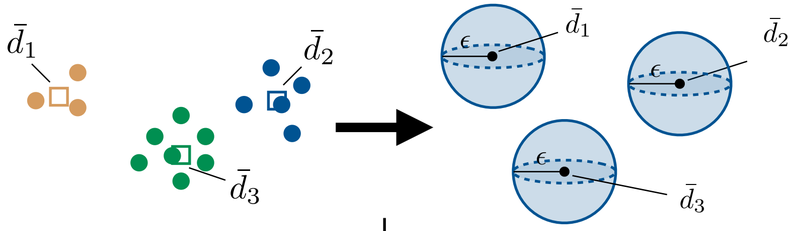
Mean Robust Optimization

Tradeoff between tractability and conservatism

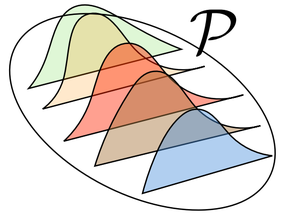
worst-case approach



data-driven approach



probabilistic approach



Robust Optimization

✓ Tractable

✗ Conservative

Mean Robust Optimization

Distrib. Robust Optimization

✓ Less conservative

✗ Intractable

- Clustering to **reduce dimensionality**
- **Same constraint satisfaction guarantees**

Mean Robust Optimization
I. Wang, C. Becker, B. Van Parys, B. Stellato
arXiv:2207.10820, 2022

INFORMS Computing Society Student Paper Award

Mean Robust Optimization to solve energy distribution problems

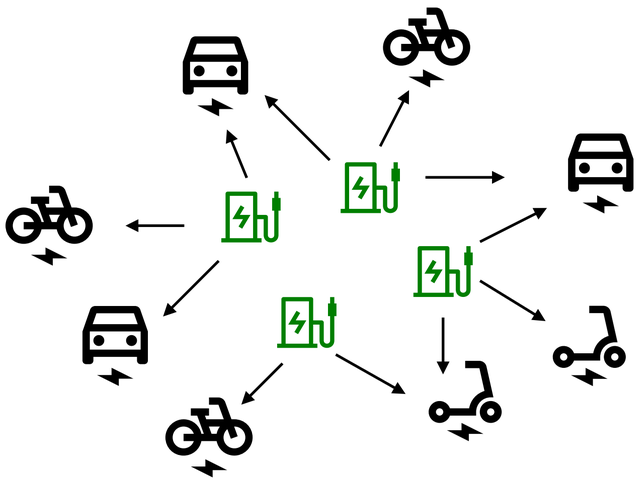
cost of opening charging stations

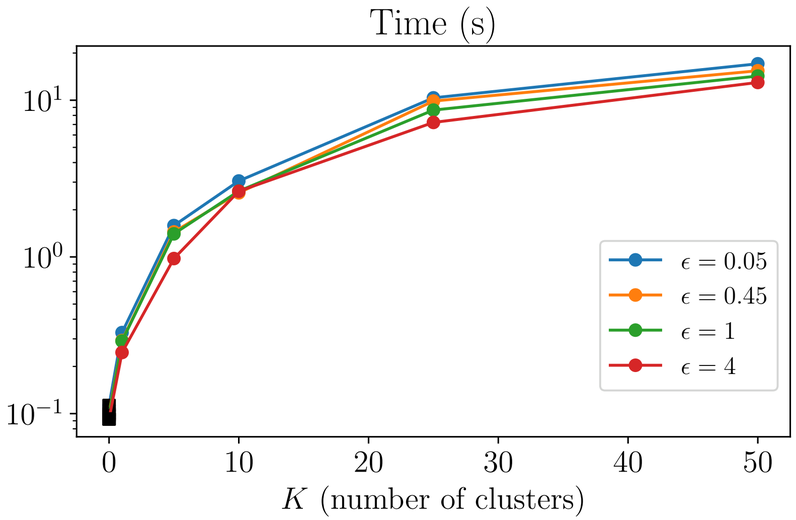
cost of energy distribution

$$\begin{aligned} \text{minimize} \quad & c^T x + \mathbf{tr}(C^T X) \\ \text{subject to} \quad & \mathbf{1}^T X_j = 1, \quad j = 1, \ldots, m \\ & (X^T)_i u \leq r_i x_i, \quad i = 1, \ldots, n \\ & x \in \{0,1\}^n, \quad X \in \mathbf{R}^{n \times m} \end{aligned}$$

capacity constraints

vector of uncertain energy demands





Drastic reduction in dimensionality

Same guarantees of constraint satisfaction

New project to design sustainable urban networks

PRINCETON UNIVERSITY

Metropolis Initiative

"Metropolis focuses on technological innovations that make cities more sustainable, resilient, and equitable."

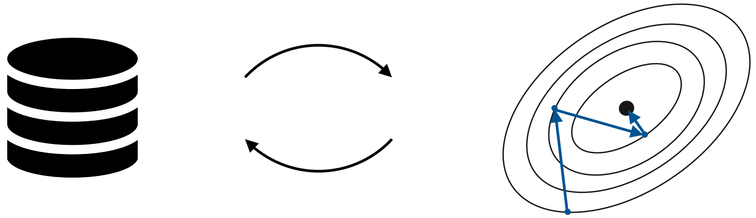
Towards Resilient Urban Networks with Differentiable Agent Decision Models

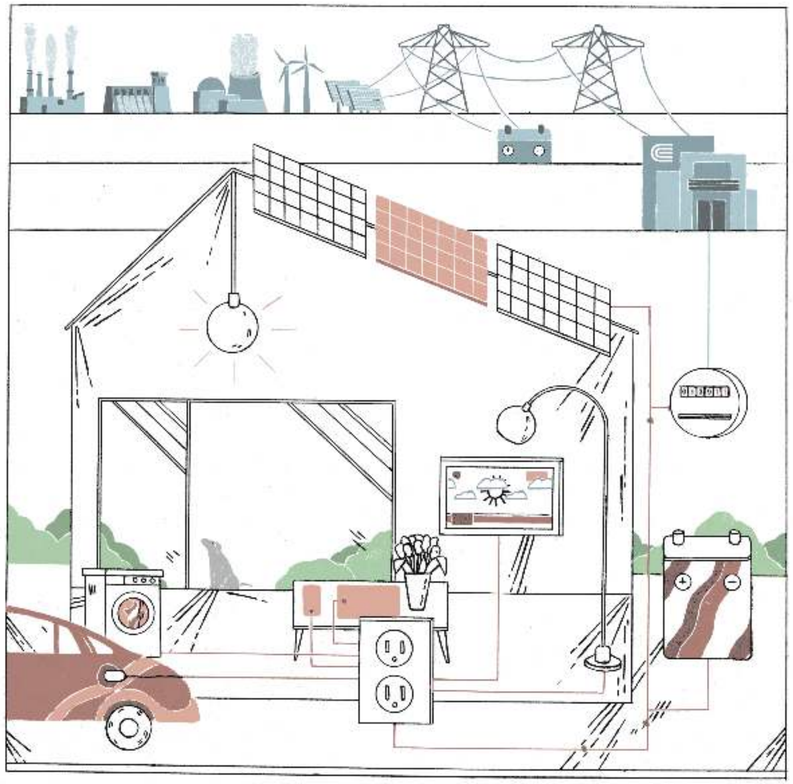
Jaime Fernandez Fisac

Gabriele Dragotto

A sustainable energy future…

Data and Optimization





[Credits NYTimes]

can help us transition to a **cleaner energy future**
and make our grid more

adaptive **safe**