Transactive Control in Transportation Systems

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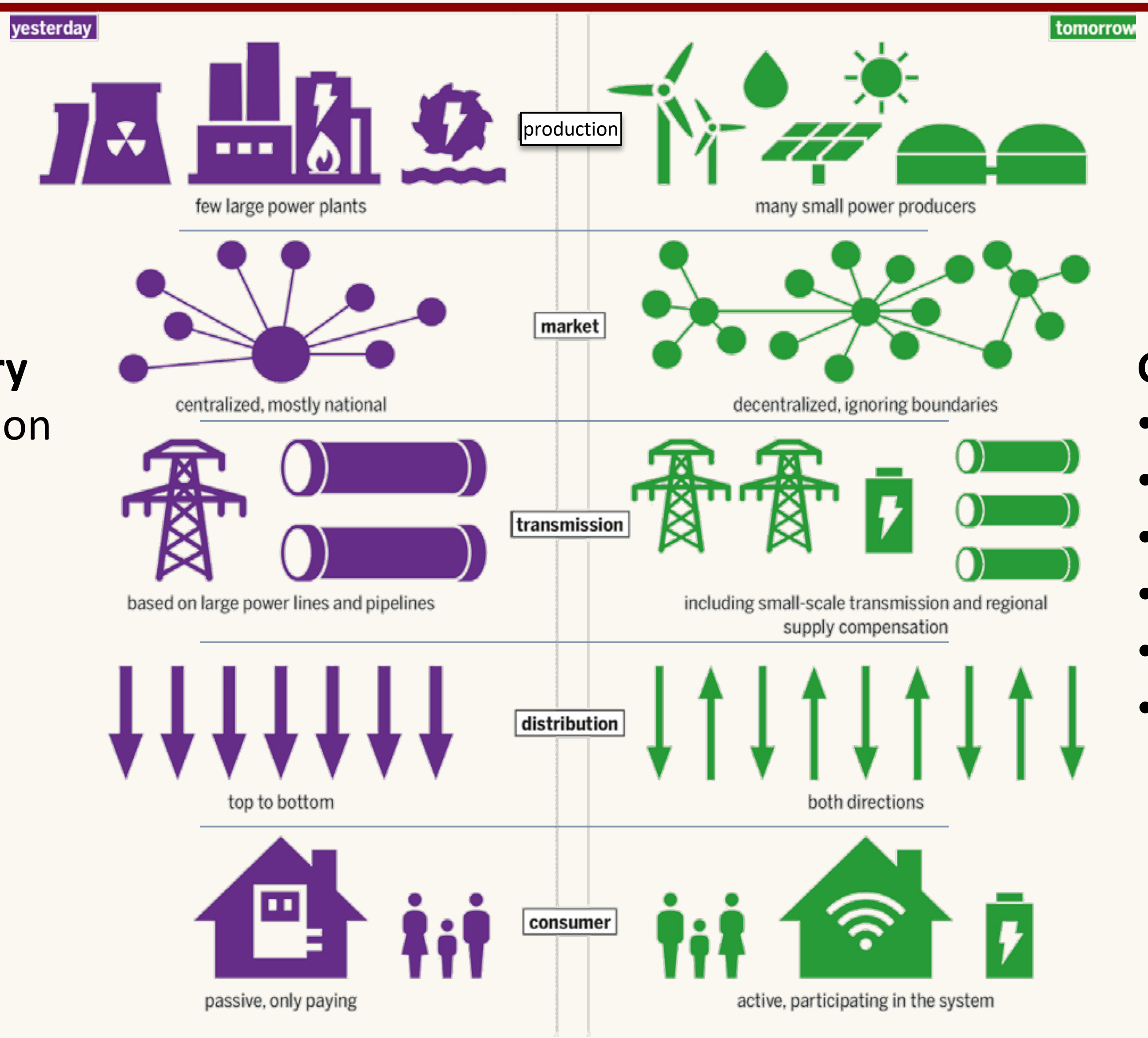
(collaborative work with D'Achiardi, Guan, Tseng, Yanakiev, Mazumder, and Pilo)

Workshop on Autonomous Energy Systems, August 19-20, 2020

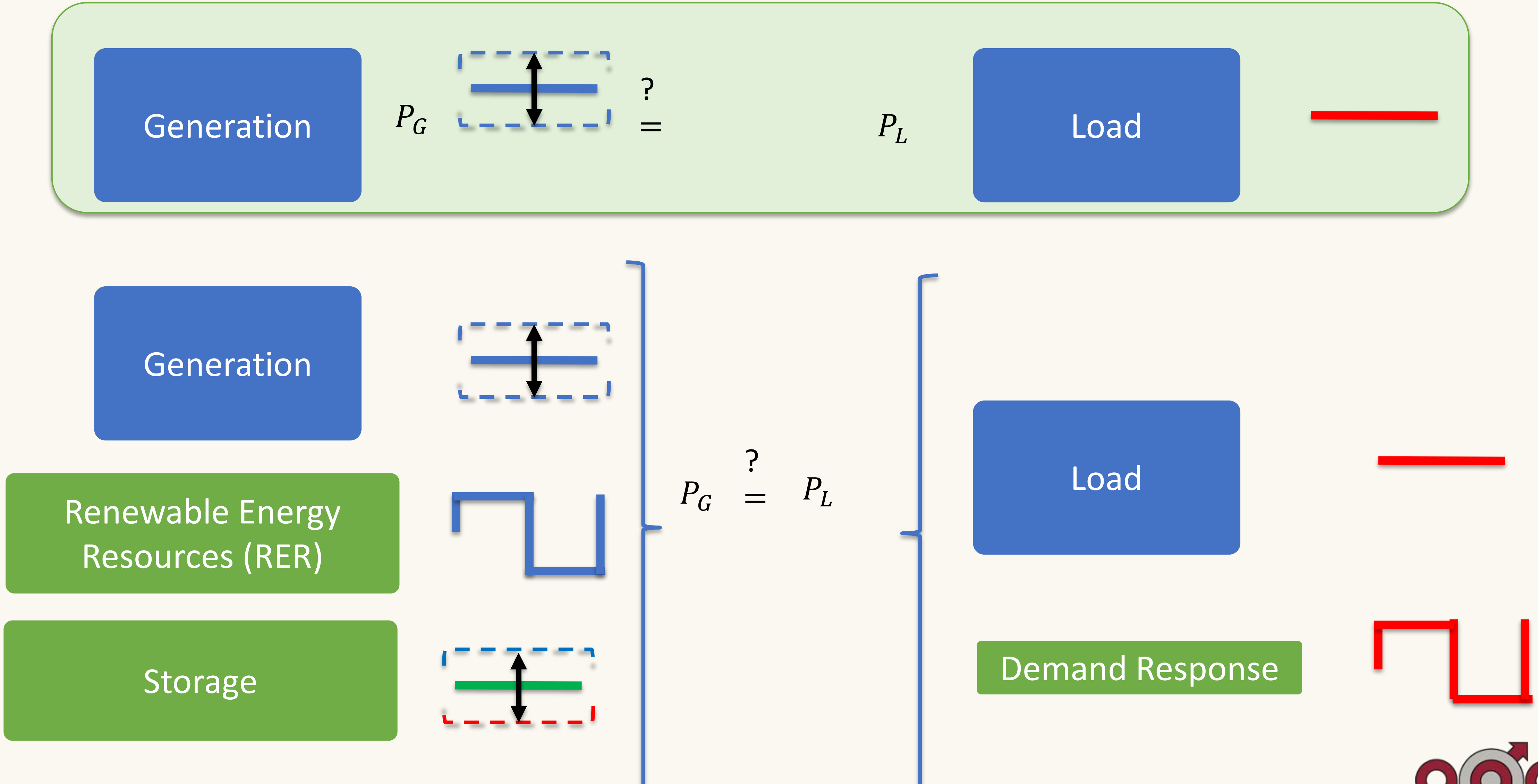
Paradigm Shift

Grid of the 20th Century
- Centralized generation
- Limited visibility
- Passive loads
- Limited resilience
- Passive Edge

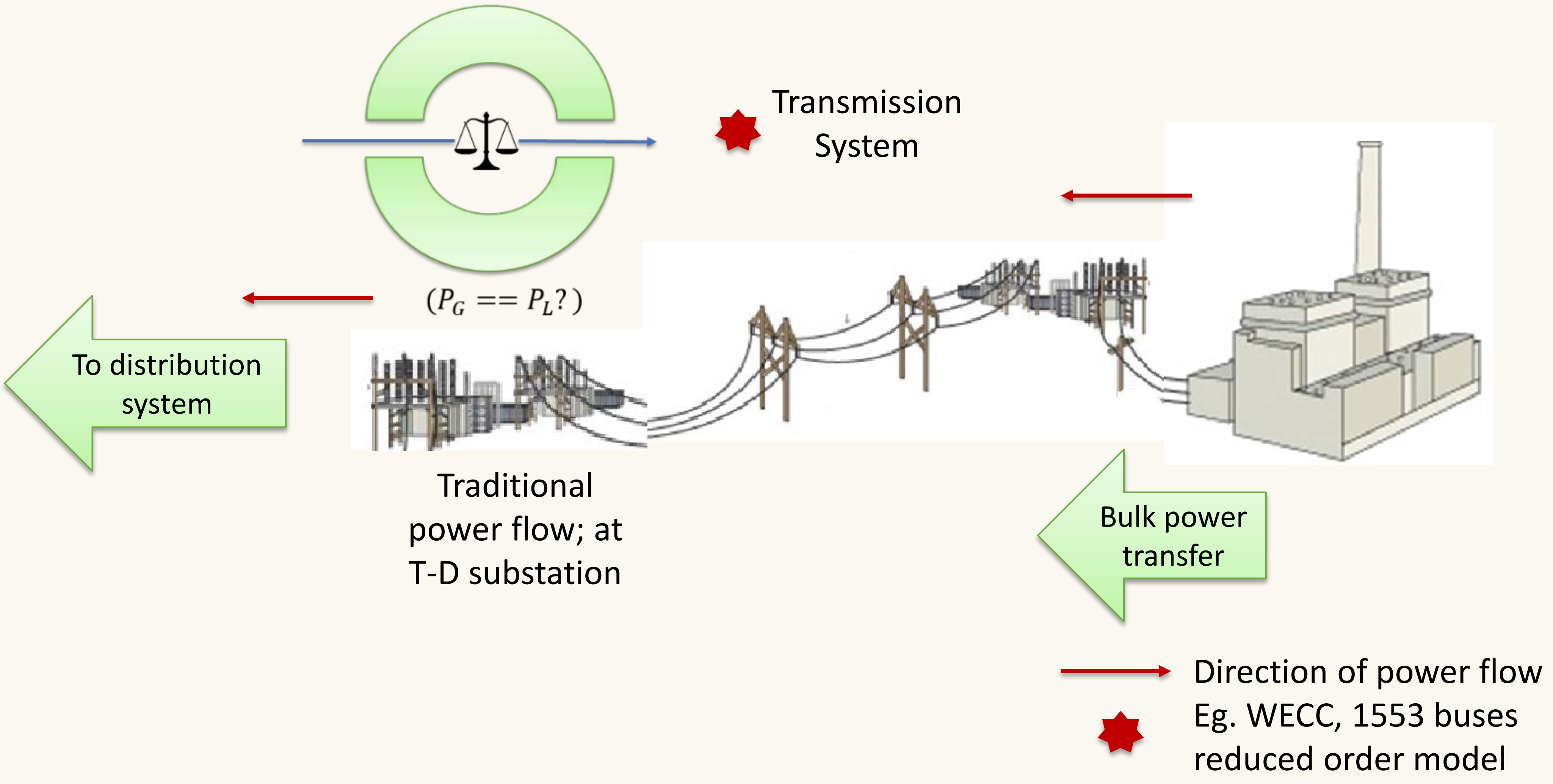


Grid of the 21st Century
- Distributed generation
- Visibility with varied sensors
- Controllable loads
- Intelligent edge
- Dynamic
- Billions of controllable nodes

Power Balance: Becoming Dynamic

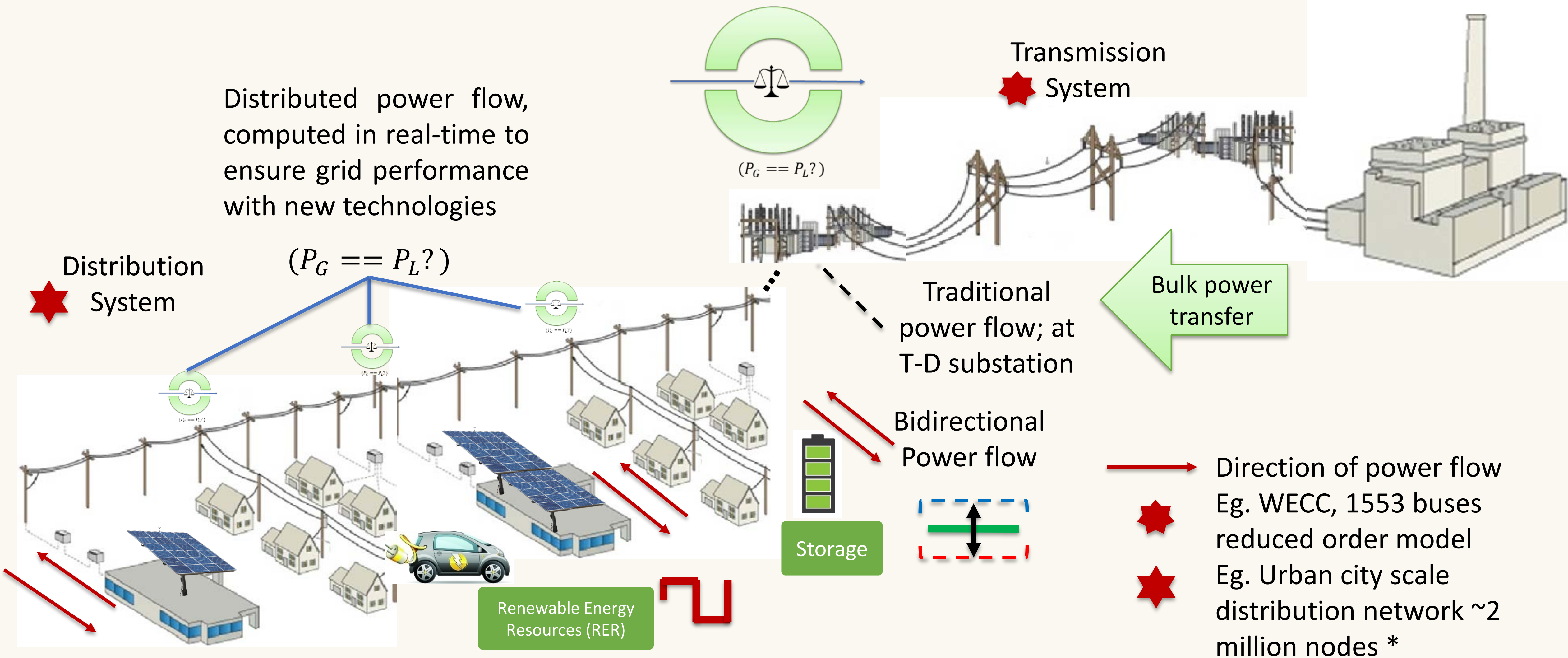


Power Balance: Traditional



Power Balance: Becoming Distributed

Distributed power flow, computed in real-time to ensure grid performance with new technologies



Direction of power flow

- Eg. WECC, 1553 buses reduced order model
- Eg. Urban city scale distribution network ~2 million nodes *

* M. Zhao, R. V. Panda, S. S. Sapatnekar and D. Blaauw, Trans. on Computer-Aided Design of Integrated Circuits and Systems, Feb. 2002

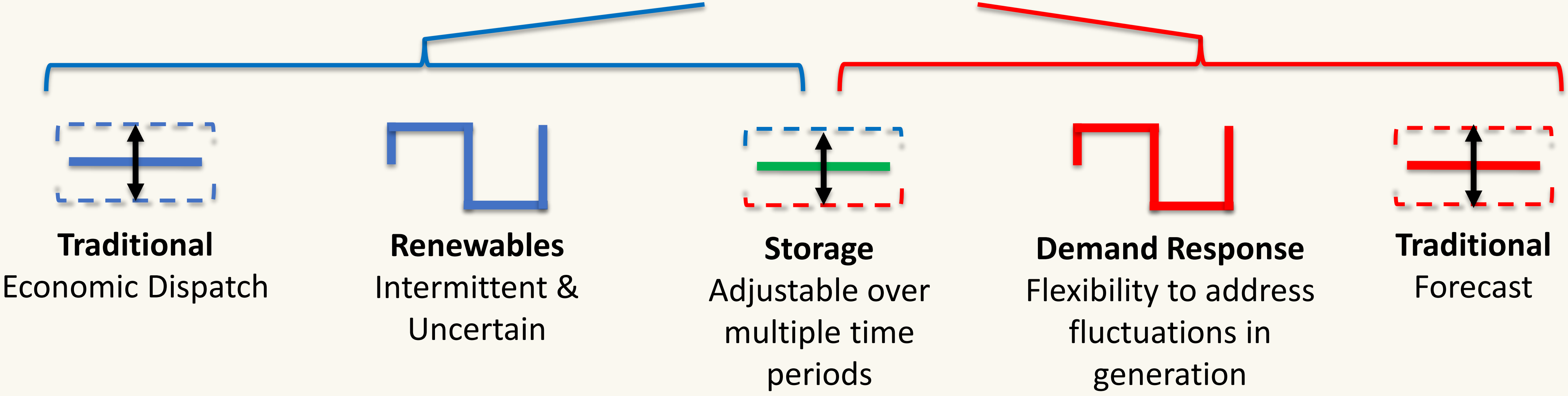
This Talk: Distributed Optimization Using Trains

- Transactive Control in Transportation Systems
- Co-optimization of train scheduling and grid-scheduling
  - Railway grid Dynamic Market Mechanism ($rDMM$)
  - Train Dispatch
- Simulations – Amtrak Northeast Corridor (NEC)
- Co-optimization of interdependent infrastructures
  - Wind Power Producers & Natural Gas Producers
  - Electricity and NG Markets
- Summary

TRANSACTIVE CONTROL

Story of Demand Response

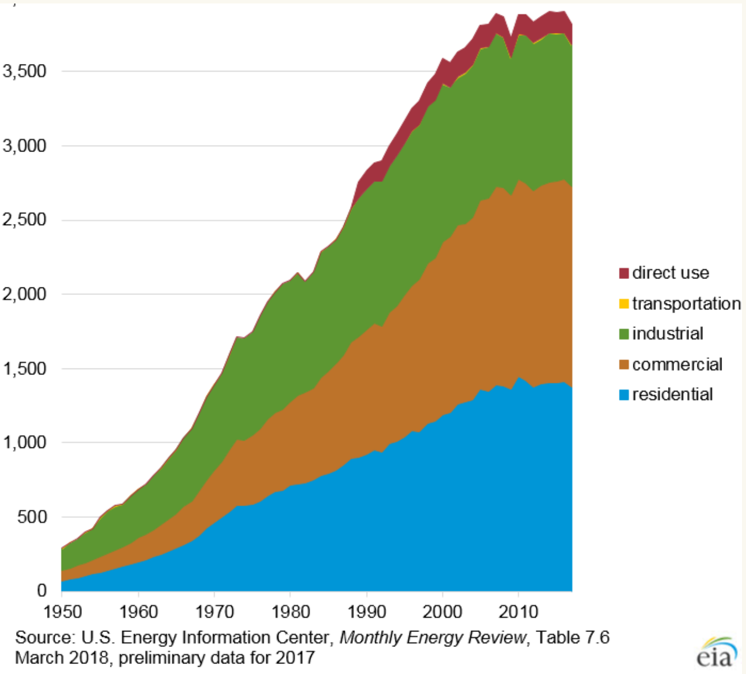
Generation = Demand



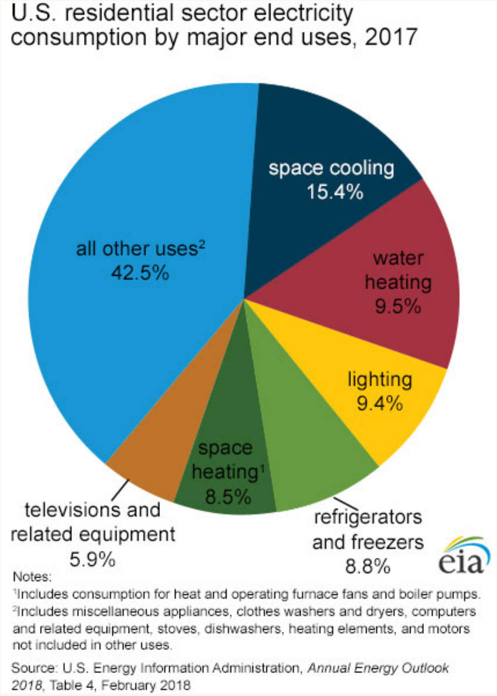
- Modern grid characterized by increased penetration of renewables energy resources (RERs) leading to intermittent supply
- Storage is a great resource, but fast-acting storage is still expensive
- Flexible demand is needed to ensure power balance and cost efficiency

Demand Response

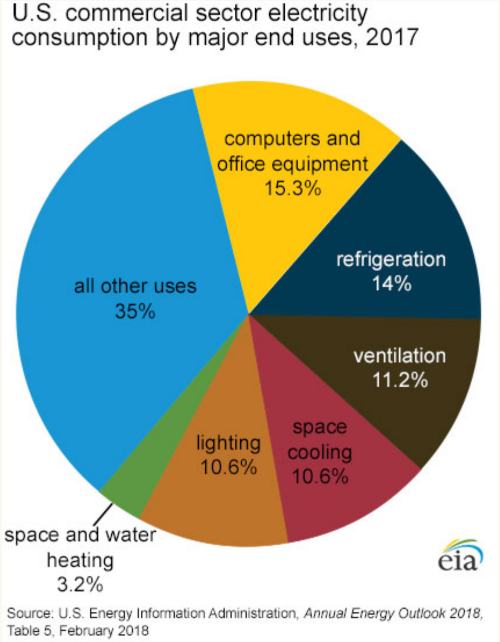
- Voluntary change in the energy consumption of an electric utility customer to better match the demand for power with the supply.
- Most ISOs and Utilities offer incentive DR programs (e.g. PJM and PG&E)
- DR taxonomies based on the end-users' sectors: residential, commercial buildings, industrial, and transportation



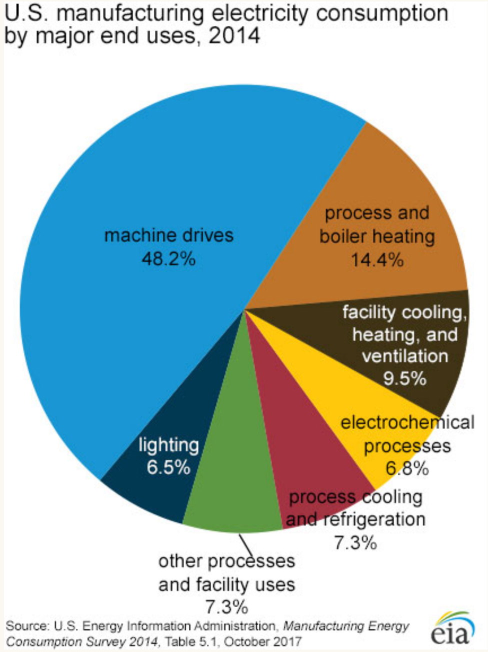
Residential



Commercial buildings

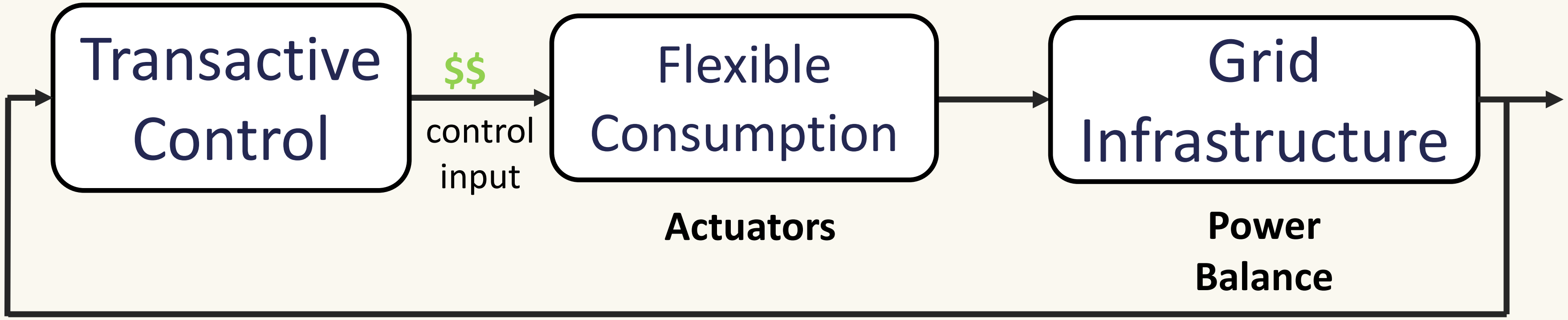


Industrial



Transactive Control

Transactive control: A mechanism through which system- and component-level decisions are made through economic **transactions** between the components of the system, in conjunction with or in lieu of traditional controls.*



Transactive energy: A system of economic and control mechanisms that allows the dynamic balance of supply and demand across the entire electrical infrastructure using value as a key operational parameter.**

* Gridwise Architectural Council, 1982 ; ** NIST, 2017

Transactive Control in Smart Grids

Timeline

1980	Reid Smith: **Contract Networks**
1980	Fred Schweppe: **Homeostatic Utility Control**
2003	PNNL: **Transaction-based Control**
2004	PNNL/GWAC: **Transactive Control**
2007	PNNL: **Olympic Peninsula Project** (demo)
2009	Cazalet: (T)*EMIX* **Transactive Energy**
2012	Kiani + Annaswamy: **Hierarchical Transactive Control (DMM)**
2012	GWAC: **Transactive Energy Conferences**
2015	Annaswamy + Nudell: **Transactive Control: What's in a Name?**
2015	GWAC: **Transactive Energy** (Framework Report – V1)

Pacific Northwest Demonstration Project

What:

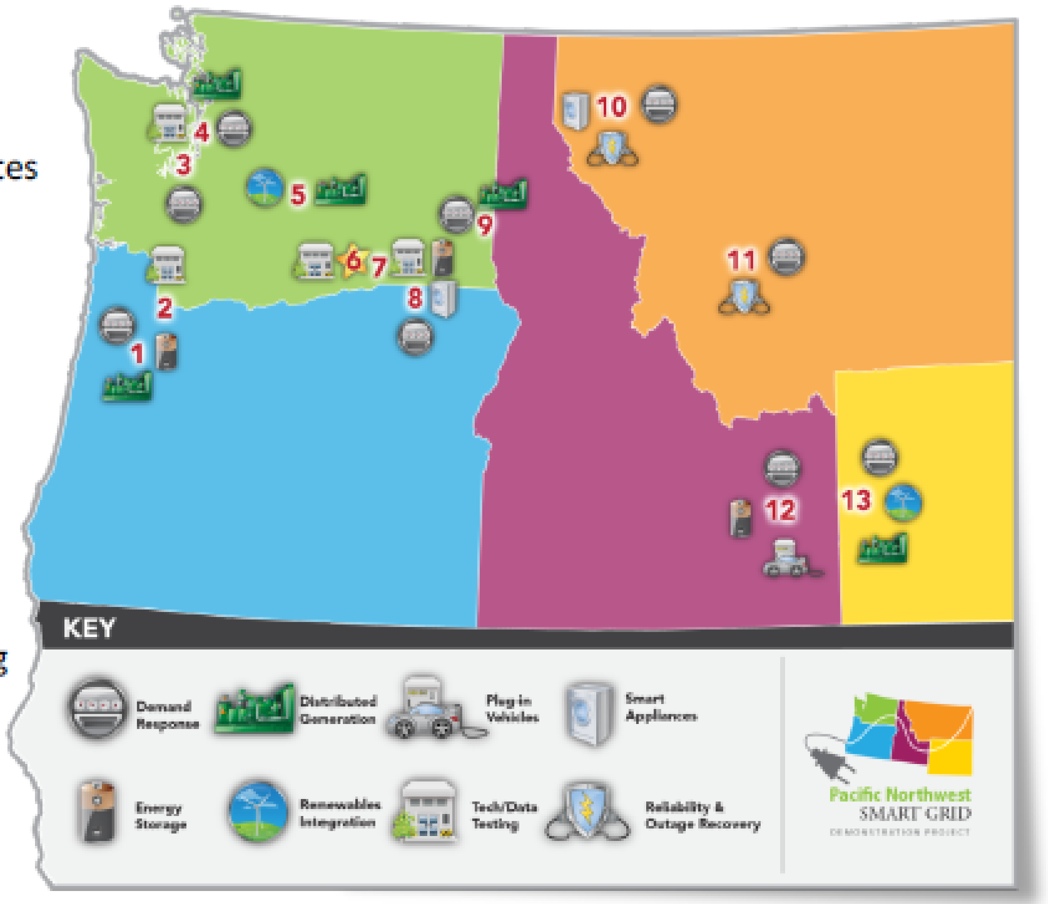
- $178M, ARRA-funded, 5-year demonstration
- 60,000 metered customers in 5 states

Why:

- Quantify costs and benefits
- Develop communications protocol
- Develop standards
- Facilitate integration of wind and other renewables

Who:

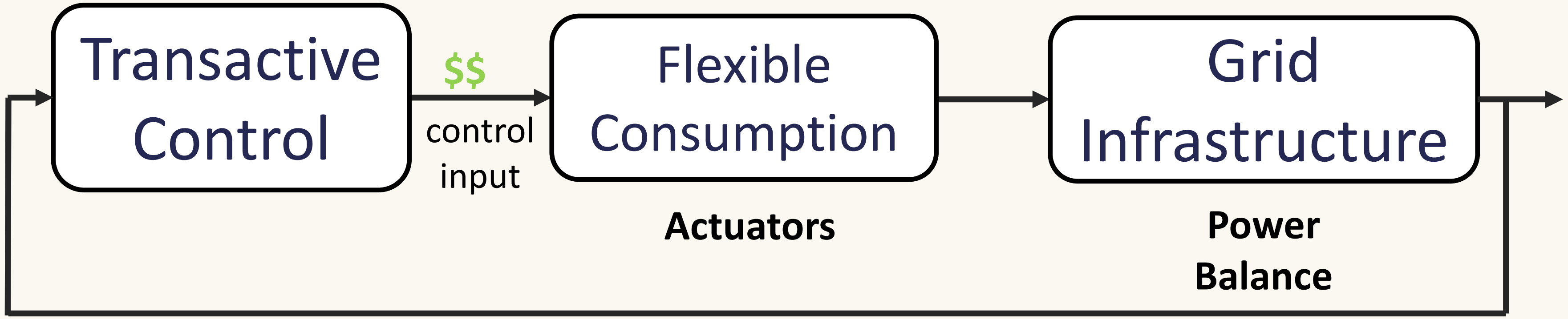
Led by Battelle and partners including BPA, 11 utilities, 2 universities, and 5 vendors

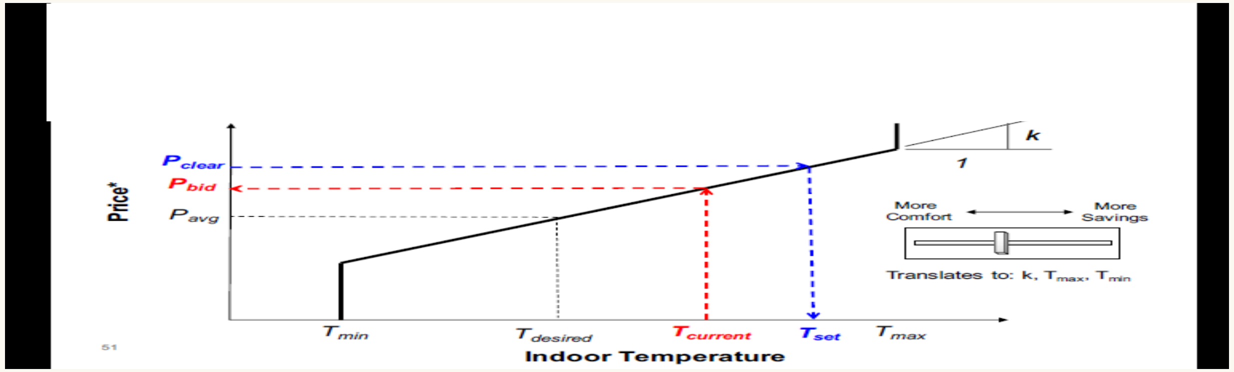


Reference: Courtesy Jakob Stoustrup, Tutorial, American Control Conference, 2016

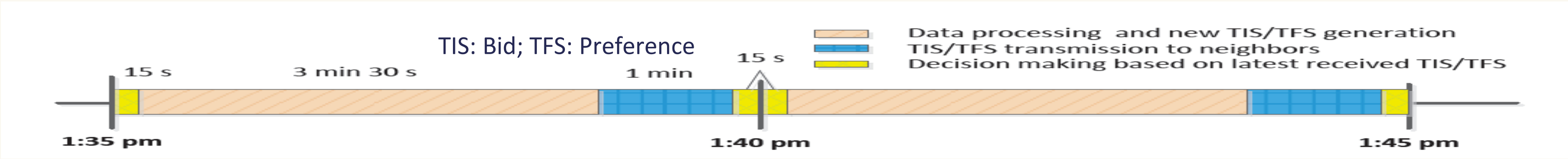
Transactive Control

A mechanism through which system- and component-level decisions are made through economic **transactions** between the components of the system, in conjunction with or in lieu of traditional controls

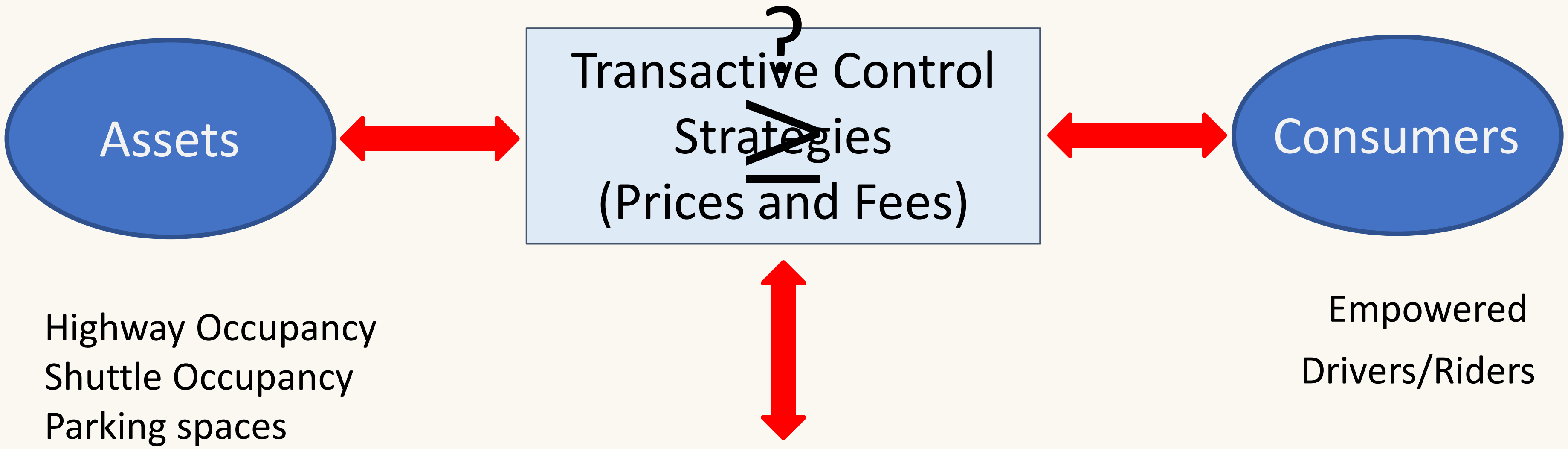




(From J. Stoustrup, Tutorial, ACC Workshop, 2016)



Transactive Control in Transportation Systems



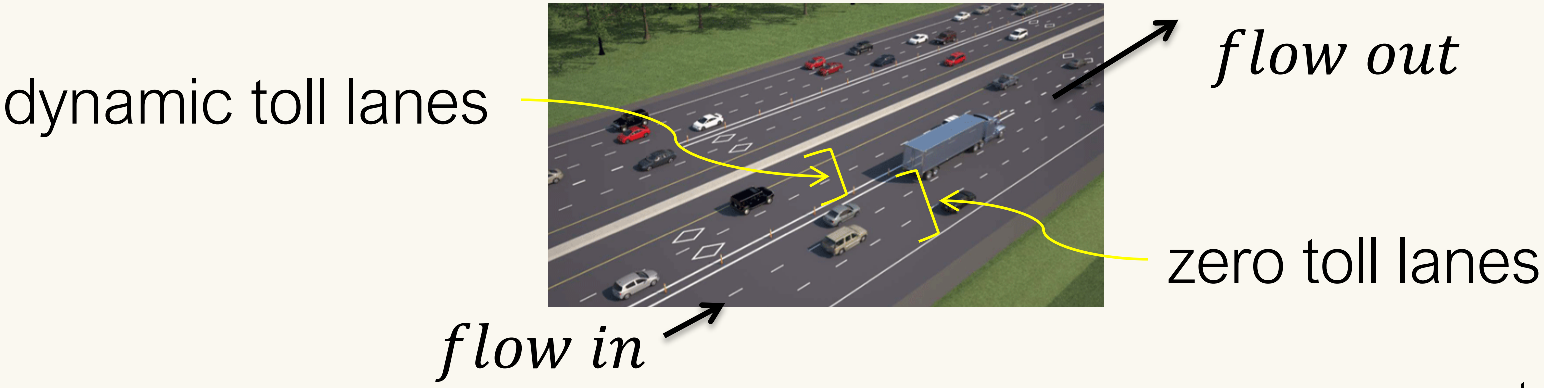
Highway Occupancy
Shuttle Occupancy
Parking spaces
Taxis

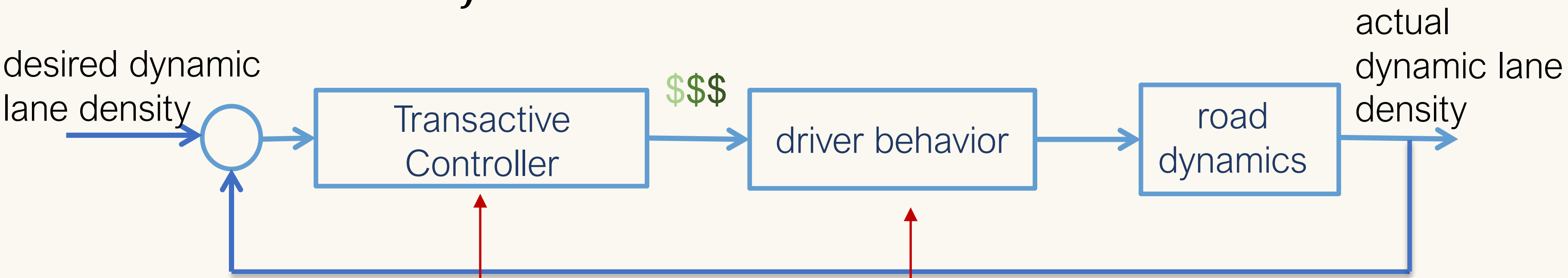
Efficient Resource Utilization

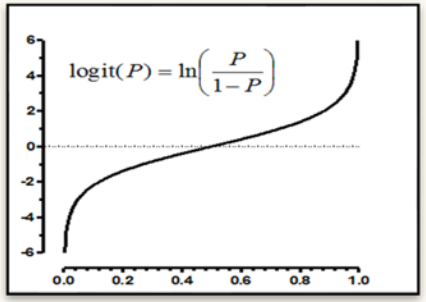
Empowered
Drivers/Riders

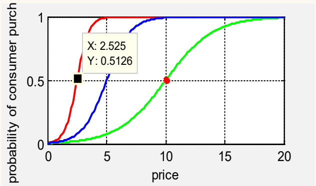
Example 1: Dynamic Toll-pricing for congestion reduction
Example 2: Shared Mobility on Demand using Dynamic Routing and Pricing

Toll pricing controller*







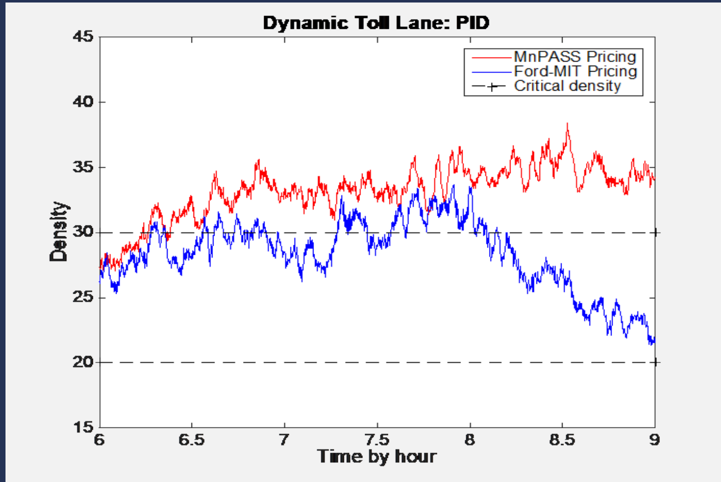


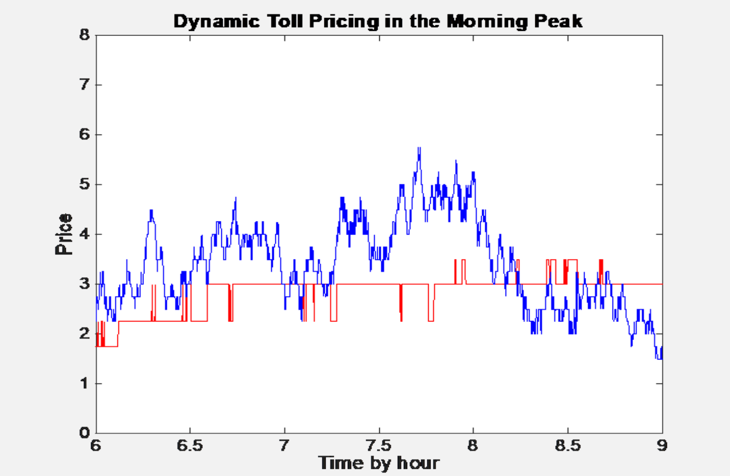
- Logistic Function
- Identify parameters
- Use inverse nonlinearity in the price-controller

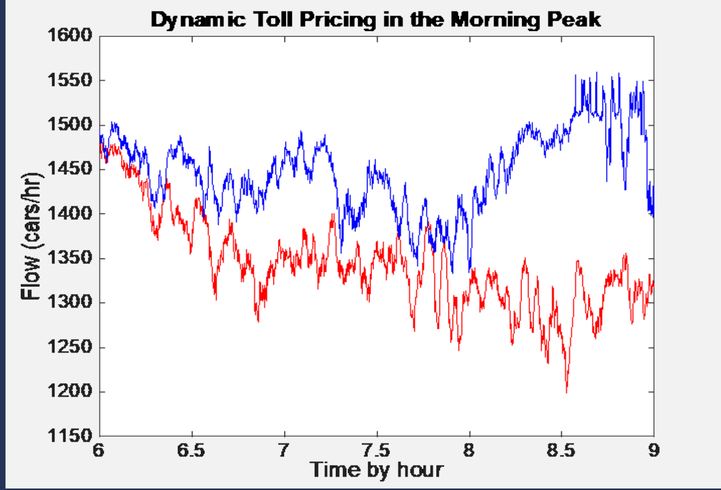
* *A. M. Annaswamy, Y. Guan, H. E. Tseng, H. Zhou, T. Phan and D. Yanakiev, "Transactive Control in Smart Cities," in Proceedings of the IEEE, vol. 106, no. 4, pp. 518-537, April 2018.*

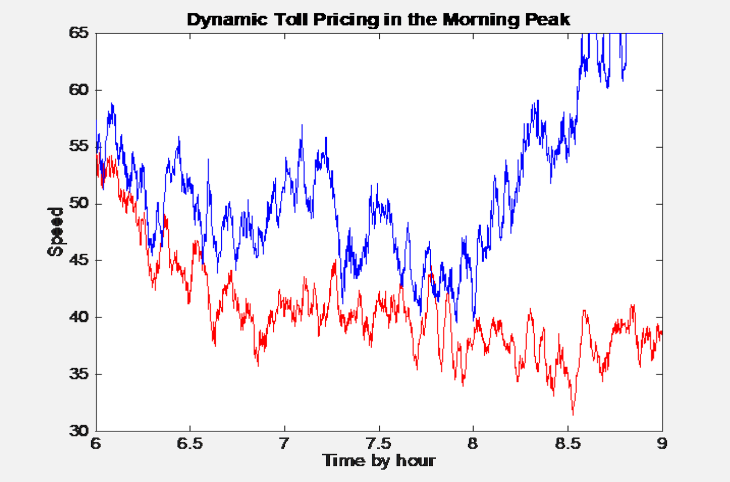
Response to High Input Flow

High input flow is introduced in the middle of the operating period to test the systems' ability to prevent congestion. Our model-based control (blue) is successful in keeping the HOT density low compared to MnPASS (red).

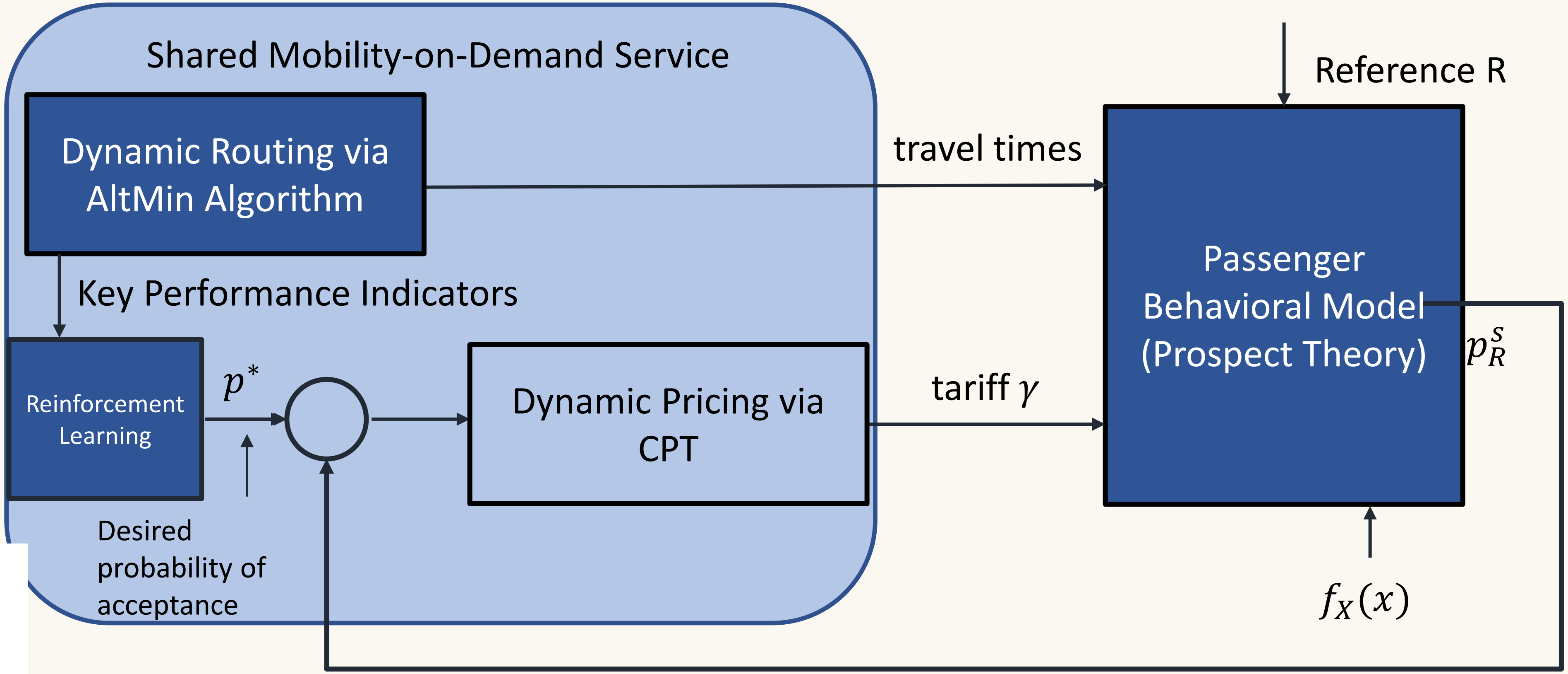


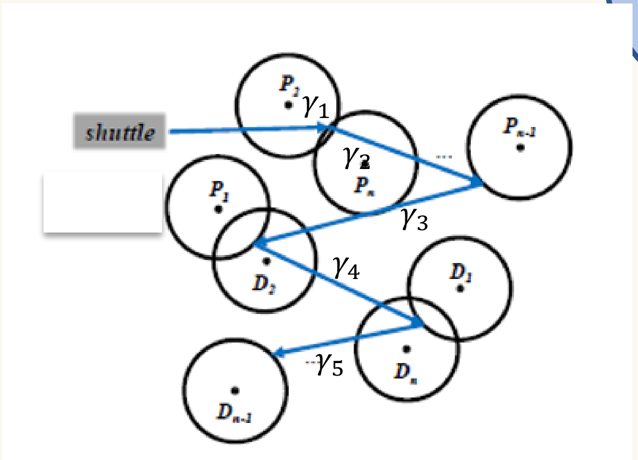






Transactive Control in Shared Mobility*





p_R^s: subjective probability of acceptance framed by R

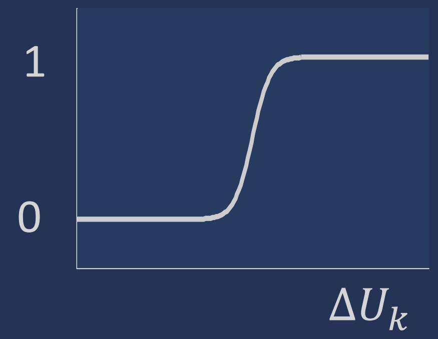
* Y. Guan, A. M. Annaswamy and H. Eric Tseng, "Cumulative Prospect Theory Based Dynamic Pricing for Shared Mobility on Demand Services," 2019 IEEE 58th CDC, 2019.

Passenger Acceptance: Utility Function

- **Utility function (for passenger k)**

$$U_{a_k} = a + b_p \cdot WalkT_{pk} + b_w \cdot WaitT_k + b_r \cdot RideT_k + b_d \cdot WalkT_{dk} + \gamma \cdot \rho_k$$

- **Discrete choice model (two alternatives; U_{a_k}, U'_{a_k})**
  - **Probability of acceptance: $p_{a_\mathbf{k}}$**



$$p_{a_\mathbf{k}} = \frac{1}{1 + e^{-\rho \Delta U_\mathbf{k}}}, \qquad \Delta U_\mathbf{k} = U_{a_k} - U'_{a_k}$$

Conventional Utility Theory (contd.)

- Several alternatives with utilities $U_{a_1}, \ldots, U_{a_n}$
- Corresponding probabilities $p_1, \ldots, p_n$

Utility function of ride-sharing

$$u_i = \sum_{j=1}^{m} U_{a_i}{}^j p_i{}^j$$

$$U_{a_k} = f(\tau), \qquad \tau \in [t_p^1, t_p^2]$$

$$u_i = \int_{t_p^1}^{t_p^2} U_a(\tau) p_i(\tau) d\tau$$

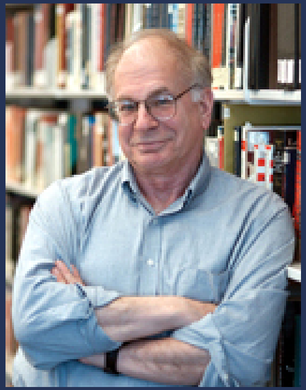
u_1: Utility function of taking a private car;

u_n: Utility function of taking a bus

- Not adequate if uncertainty is large

Prospect Theory – Decision under Uncertainty

- The theory was created in 1979[1] and developed in 1992[2] by Kahneman and Tversky
- Winner of Nobel Prize in Economics in 2001
- One of the foundations of behavioral economics
- Captures how human beings make decisions under risk

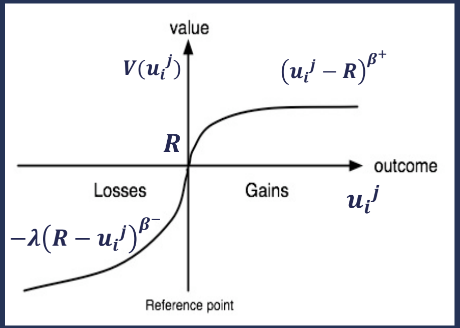


Daniel Kahneman

Amos Tversky

1. Kahneman, Daniel, and Amos Tversky. "Prospect theory: An analysis of decision under risk." Handbook of the fundamentals of financial decision making: Part I. 2013. 99-127.
2. Tversky, Amos, and Daniel Kahneman. "Advances in prospect theory: Cumulative representation of uncertainty." *Journal of Risk and uncertainty* 5.4 (1992): 297-323.

Prospect Theory for Mode Choice*



- In prospect theory*: $$u_i = \sum_{j=1}^{m} V(u_i{}^j)\pi(p_i{}^j)$$

- Human beings are irrational in two ways:

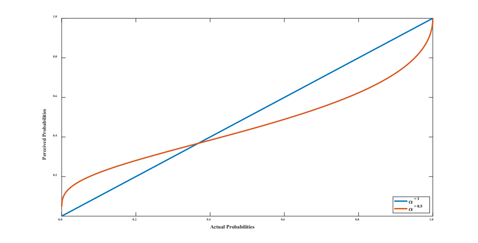
1. How do we perceive utility $V(u_i{}^j)$: loss aversion - losses hurt more than the benefit of gains

$$V(u_i{}^j) = \begin{cases} (u_i{}^j - R)^{\beta^+}, & \text{if } u_i{}^j > R \\ -\lambda(R - u_i{}^j)^{\beta^-}, & \text{if } u_i{}^j < R \end{cases}$$

R: Frames the problem; $\lambda > 1$

2. How do we assess probability $\pi(p_i{}^j)$: overreact to small probability events and underreact to large probability events

$$\pi(p_i{}^j) = \exp\left(-(-ln p_i{}^j)^{\alpha}\right), \qquad \alpha < 1$$



* Kahneman and Tversky, 1992

Prospect Theory for Shared Mobility

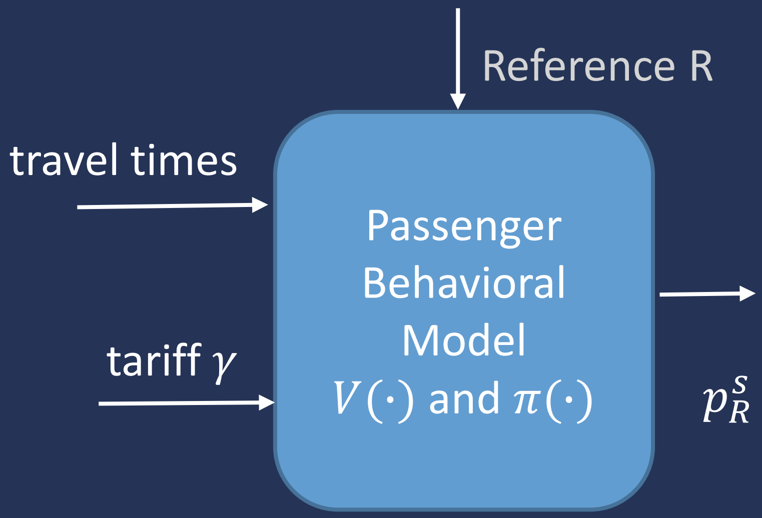
- The utility function is a combination of time and price:

$$u = a + b_p T_{walk} + b_w T_{wait} + b_r T_{ride} + \gamma\rho$$

- $\tau \in \left[t_p^1, t_p^2\right], u: u(\tau); \tau$: Shuttle arrival interval

$$U_R^S = \int_{-\infty}^{R} V(u) \frac{d}{du}\{\pi[F_U(u)]\}du + \int_{R}^{\infty} V(u) \frac{d}{du}\{-\pi[1 - F_U(U)]\}du$$

- R: reference
- $F(\tau) = \int_{-\infty}^{\tau} df(\tau)$ - Cumulative Distribution Function (CDF)
  - Extract from demand pattern and historical data
  - $F(\tau)$ exists but unknown



Objective probability of acceptance

$$p^o = \frac{e^{U^o}}{e^{U^o} + e^{A^o}}$$

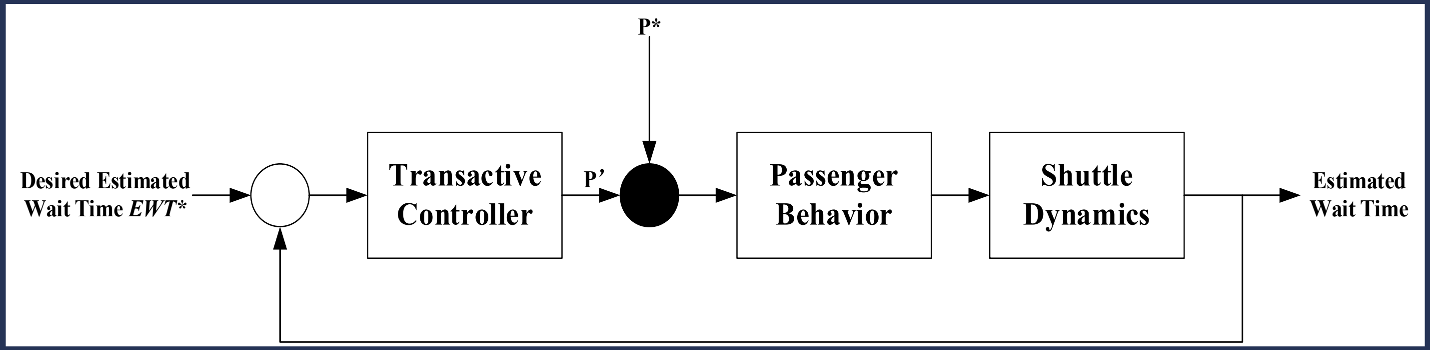
U^o and A^o: objective utility of the SMoDS and the alternative

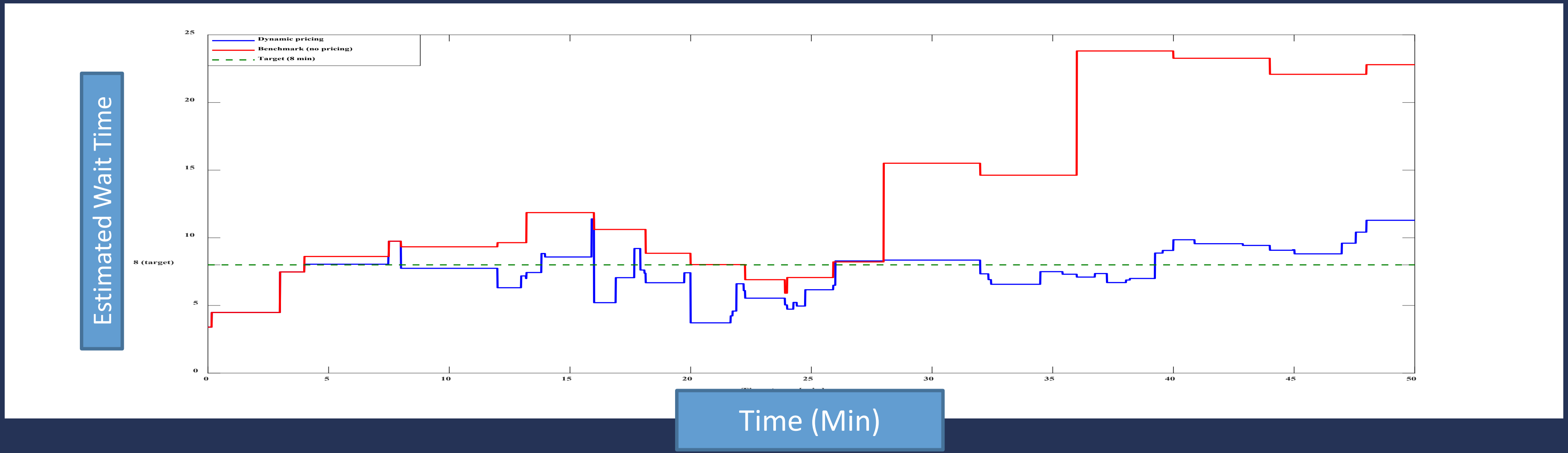
Subjective probability of acceptance

$$p_R^S = \frac{e^{U_R^S}}{e^{U_R^S} + e^{A_R^S}}$$

U_R^S and A_R^S: subjective utility of the SMoDS and the alternative

Results*

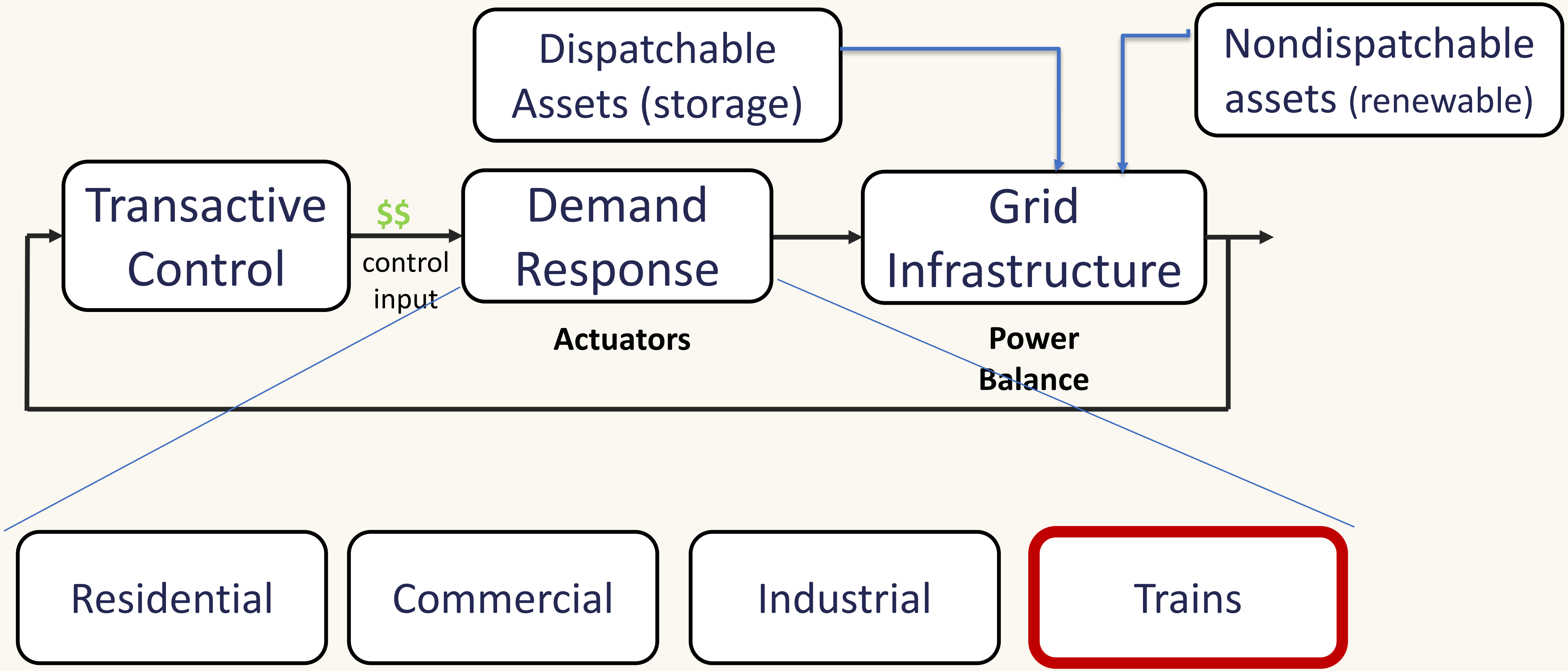




* A. M. Annaswamy, Y. Guan, H. E. Tseng, H. Zhou, T. Phan and D. Yanakiev, "Transactive Control in Smart Cities," in Proceedings of the IEEE, vol. 106, no. 4, pp. 518-537, April 2018.

CO-OPTIMIZATION OF GRID-SCHEDULING AND TRAIN-SCHEDULING

Transactive Control in Power Grids



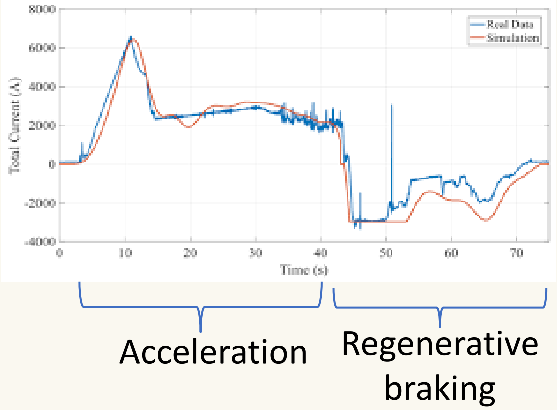
* D. D'Achiardi, A.M. Annaswamy, S.K. Mazumder, and E. Pilo, Transactive Control of Electric Railways, http://arxiv.org/abs/2006.08119

Smart Railway Technologies

- Automation technologies yield trains that can follow optimal trajectories
  - e.g. Positive Train Control (PTC) in US Northeast Corridor
- Train operators maintain a schedule margin to meet timeliness objectives
  - 15% margins on US schedules, 7% in Europe [1]
- Bidirectional power flow enabled by regenerative braking in electric trains (deceleration ≡ inject power into the grid)
- Integration of Distributed Energy Resources (DERs)
  - Reduce operational costs
  - Reduce carbon footprint
  - Improve resiliency (e.g. return trains to stations during blackouts)

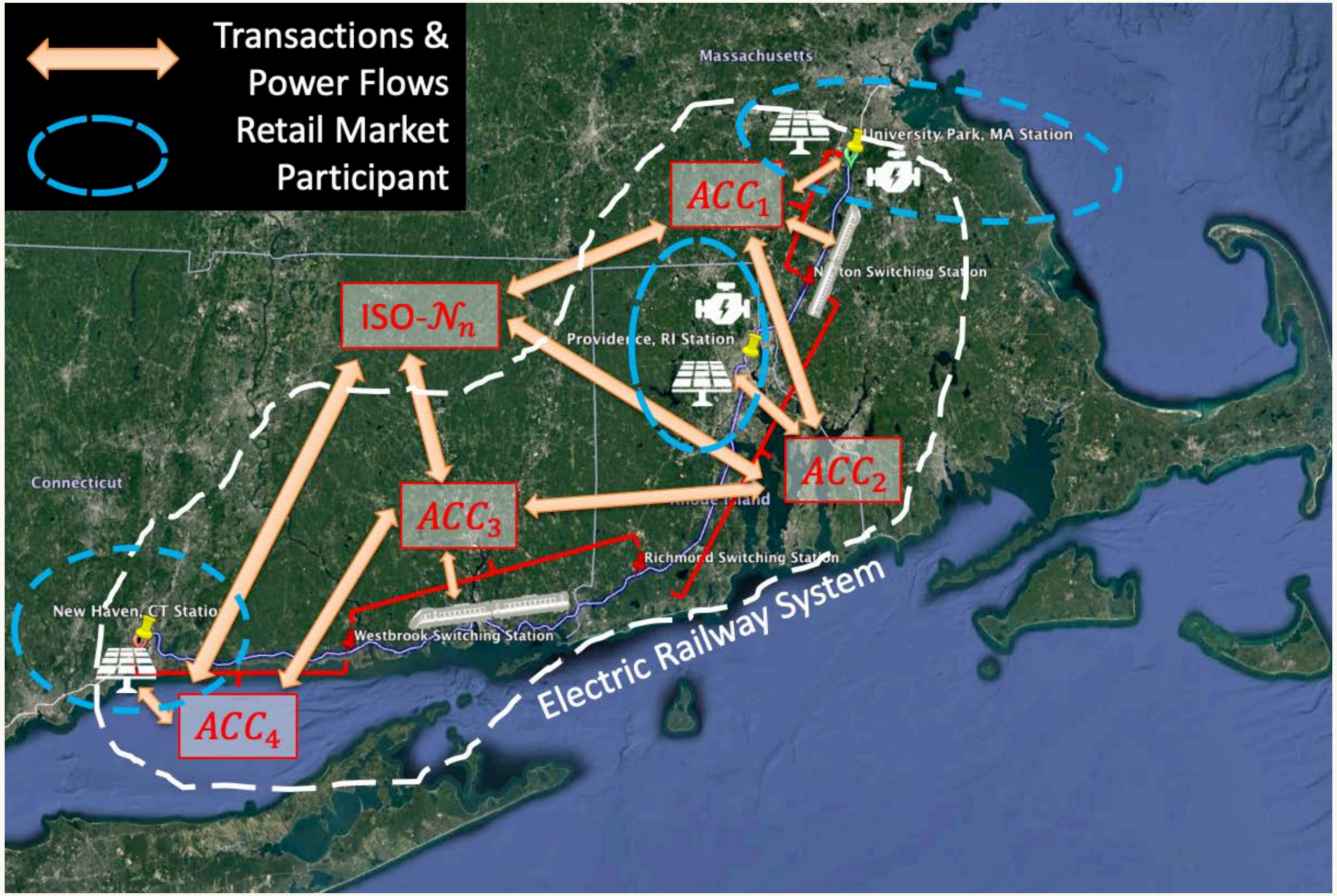
4rail.net

ConEd: NYC Subway 7 Line



[1] Transit Matters. "Regional Rail for Metropolitan Boston." Boston, MA. URL: http://transitmatters.org/regional-rail-doc

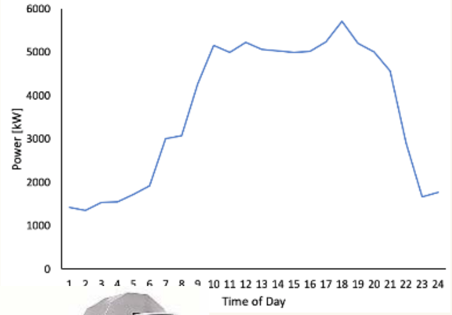
An Example: Trip from Boston to New Haven



- University Park, MA → Providence, RI → New Haven, CT
- 4 dispatch regions → 4 Area Control Centers (ACC)
- Each ACC faces hourly energy pricing from utility service
- Several dispatchable DERs at each ACC
- Goal: Grid (DER)+Train optimization

DERs at University Park Station, MA

Electric load estimate –NREL SAM



1.6MW$_e$
CHP

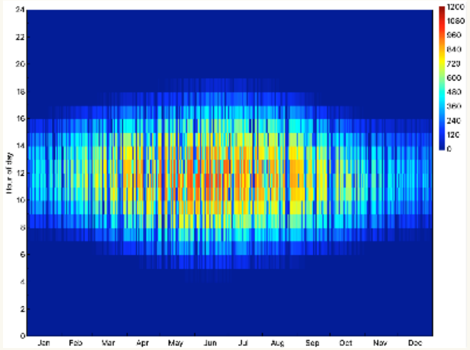
ENGINE TYPE	UNITS	CG170-16	
Electrical power [2]	kW$_e$	1,550	
Mean effective pressure	bar psi	18.2	264
Thermal output (+/-8 %) [3]	kW Btu/m	1,589	2,003
Electrical efficiency [2]	%	43.0	
Thermal efficiency [3]	%	43.7	
Total efficiency	%	86.7	

$NO_x \leq 500$ mg/Nm^3, 1 g/bhp-h

2.8MW$_{DC}$ PV Array

Solar Irradiance [W/m^2]

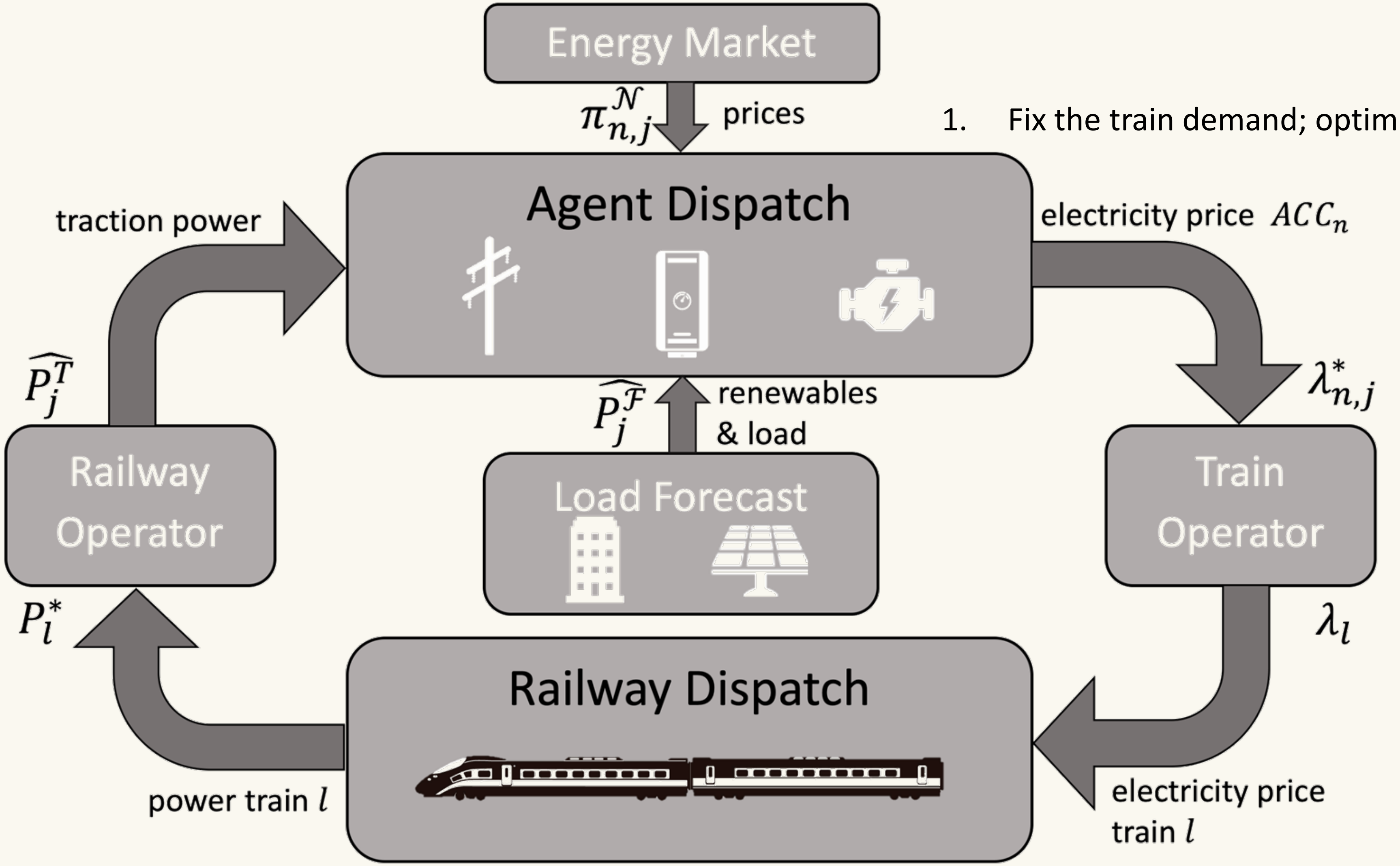
NREL SAM



Amtrak NEC Train track

A 2-step optimization approach*

1. Fix the train demand; optimize DER dispatch



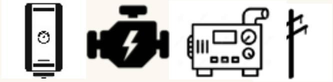
2. Fix the electricity price; optimize train dispatch

* D. D'Achiardi, A.M. Annaswamy, S.K. Mazumder, and E. Pilo, Transactive Control of Electric Railways, http://arxiv.org/abs/2006.08119

Step 1: DER dispatch using DMM*

$$\min_{y_i, i \in \mathcal{A}_n} \sum_{i \in \mathcal{A}_n} J_i(y_i)$$

cost minimization

$\mathcal{A}_n$: 

s.t.

$$h_e = \hat{P}^{re} + \hat{P}^{T} + \hat{P}^{e} - \sum_{i \in \mathcal{A}_n} g_i^e(y_i) = 0$$

power balance

$$h_{th} = \hat{P}^{th} - \sum_{i \in \mathcal{A}_n} g_i^{th}(y_i) = 0$$

thermal balance

$$\underline{y_i} \le y_i \le \overline{y_i}$$

capacity constraints

A Dynamic Market Mechanism Approach to OPF:

$$L(x, \rho, \gamma) = f(x) + \rho^T h(x) + \gamma^T g(x)$$

$$x(k+1) = x(k) - \alpha_1 \nabla_x L(x^k, \rho^k, \gamma^k)$$

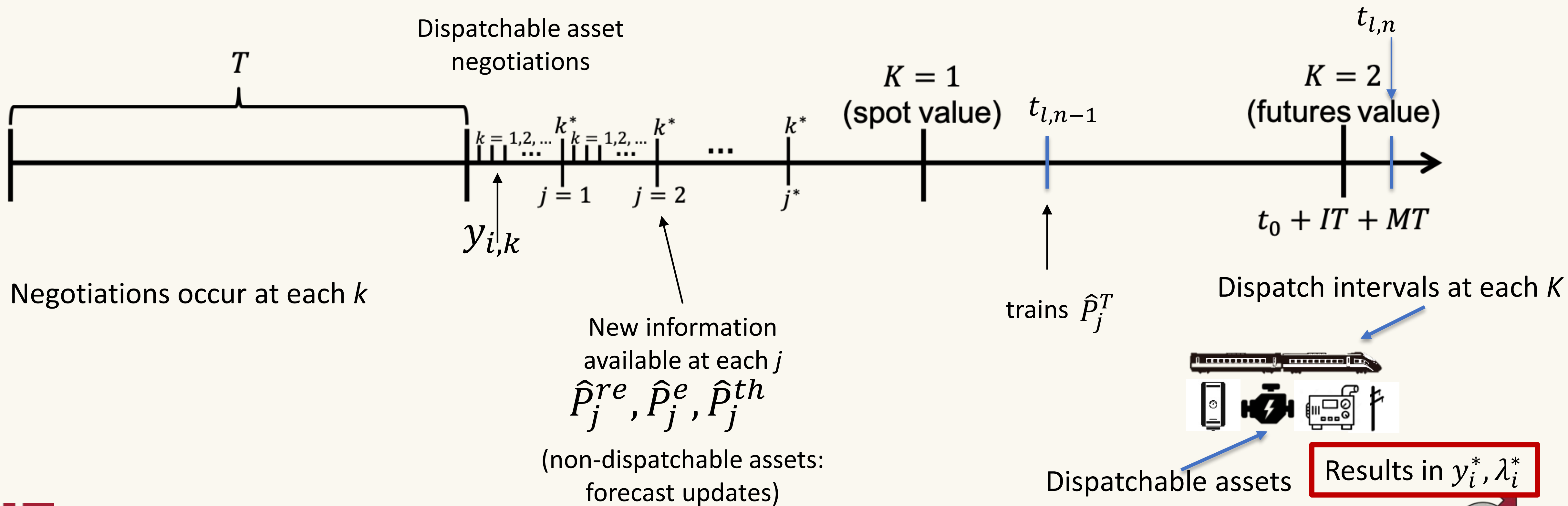
$$\rho(k+1) = \rho(k) - \alpha_2 \nabla_\rho L(x^k, \rho^k, \gamma^k)$$

* A. Kiani and A.M. Annaswamy. "A Dynamic Mechanism for Wholesale Energy Market: Stability and Robustness", IEEE Trans. Smart Grid ,2014.

Step 1: DER dispatch using DMM

DMM: Dynamic Market Mechanisms – allows real-time information regarding renewables and loads to be incorporated.*

Primal update: $$y_i^{k+1} = y_i^k - \beta_{y_i}\left(\nabla_{y_i} J_i(y_i^k) + \left[\nabla_{y_i} h^e\right]^T \lambda_{e,j}^k - \left[\nabla_{y_i} h^{th}\right]^T \lambda_{th,j}^k\right)$$



*A.B. Kiani, A.M. Annaswamy, and T. Samad, "A Hierarchical Transactive Control Architecture for Renewables Integration in Smart Grids" in IEEE Trans. Smart Grid, 2014.

Step 2: Train Dispatch

$$\min_{P_l(\tau)} \int_{\tau=t_0}^{\tau=t_f} P_l(\tau)\lambda_l(\tau)d\tau \quad \text{given } \lambda_l(\cdot)$$

Cost Minimization Objective

Results in $P^*_{1,1}, P^*_{1,2}, P^*_{1,3}, P^*_{2,3}$

s.t. $m\,\ddot{x}_l + F_{DF,l}(\dot{x}_l) + m_l g sin(\alpha(x_l)) = F_{T,l}\left(\frac{P_l}{\dot{x}_l}\right),$ — train motion dynamics

$\underline{P_l} \leq P_l \leq \overline{P}_l,$ — power bounds

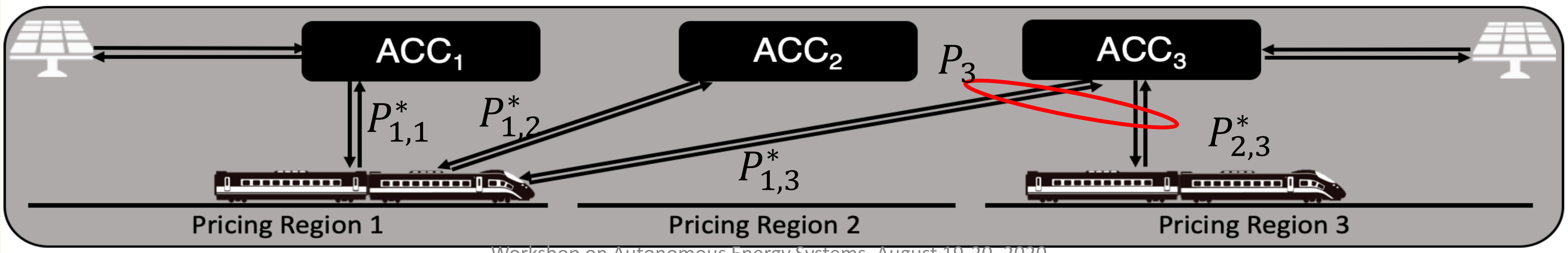
$\underline{F_{T,l}} \leq F_{T,l} \leq \overline{F}_{T,l},$ — traction force bounds

$\underline{a_l} \leq \ddot{x}_l \leq \overline{a}_l,$ — acceleration bounds

$\underline{v_l} \leq \dot{x}_l \leq \overline{v}_l,$ — speed bounds

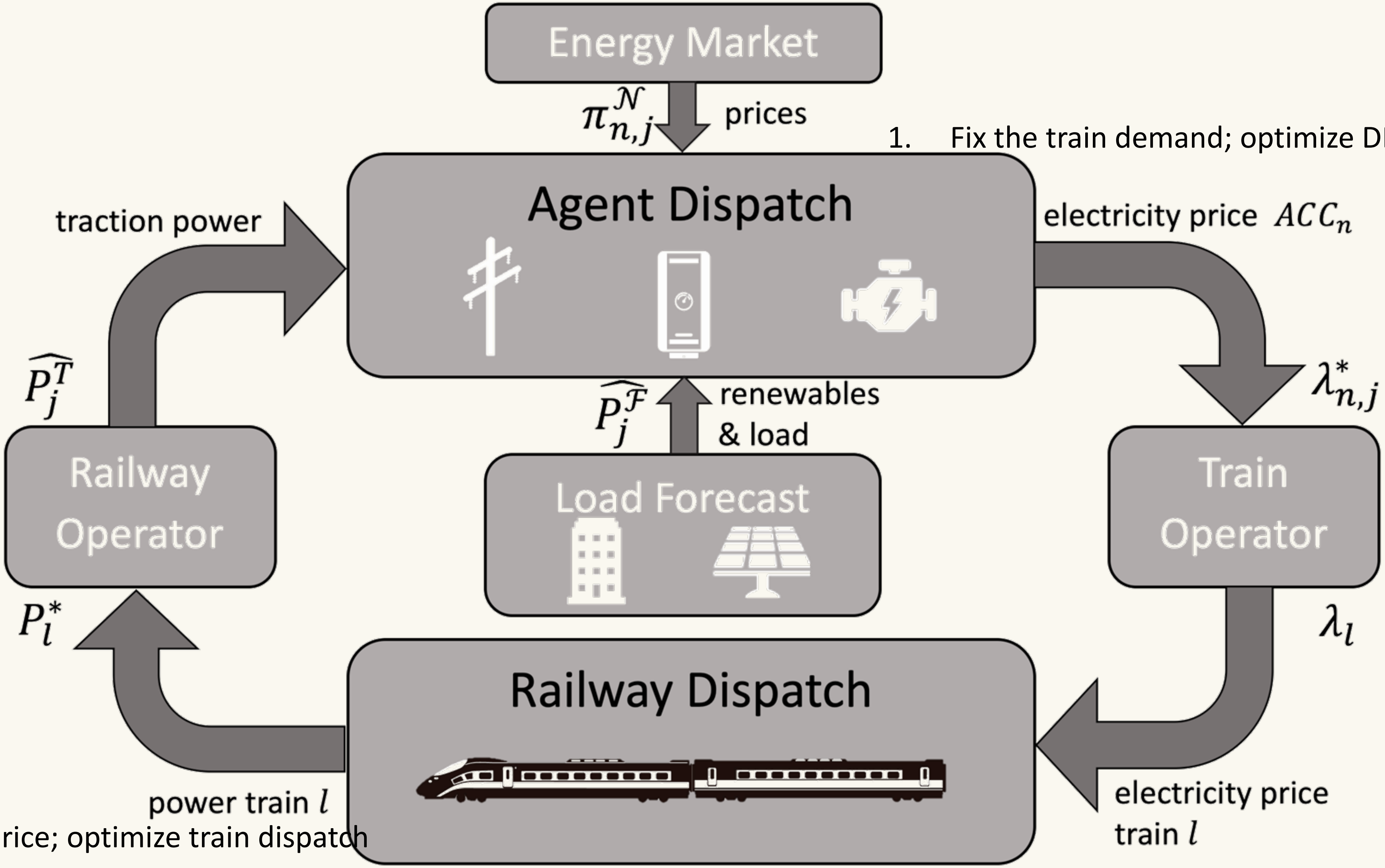
$t_{l,a}(s) \geq \underline{t_l}(s),$ — minimum arrival time station s

$t_{l,d}(s) \leq \overline{t}_l(s),$ — maximum departure time station s



A 2-step optimization approach*

1. Fix the train demand; optimize DER dispatch

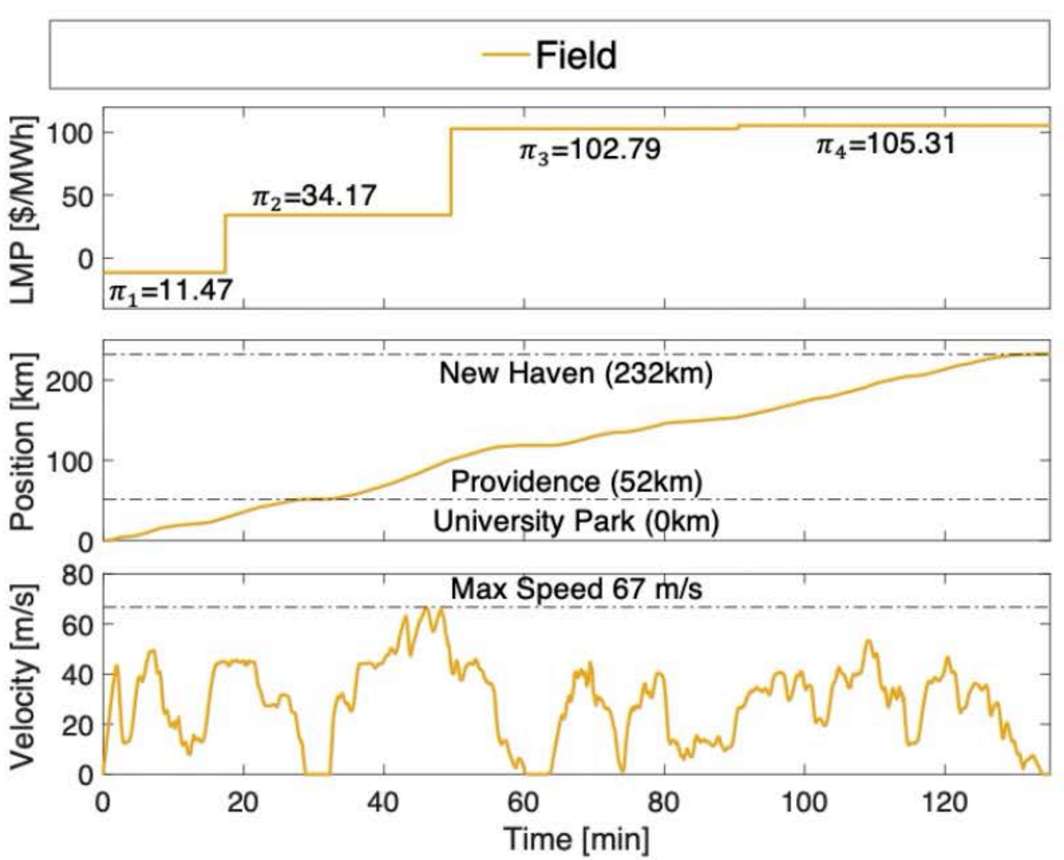


2. Fix the electricity price; optimize train dispatch

* D. D'Achiardi, A.M. Annaswamy, S.K. Mazumder, and E. Pilo, Transactive Control of Electric Railways, http://arxiv.org/abs/2006.08119

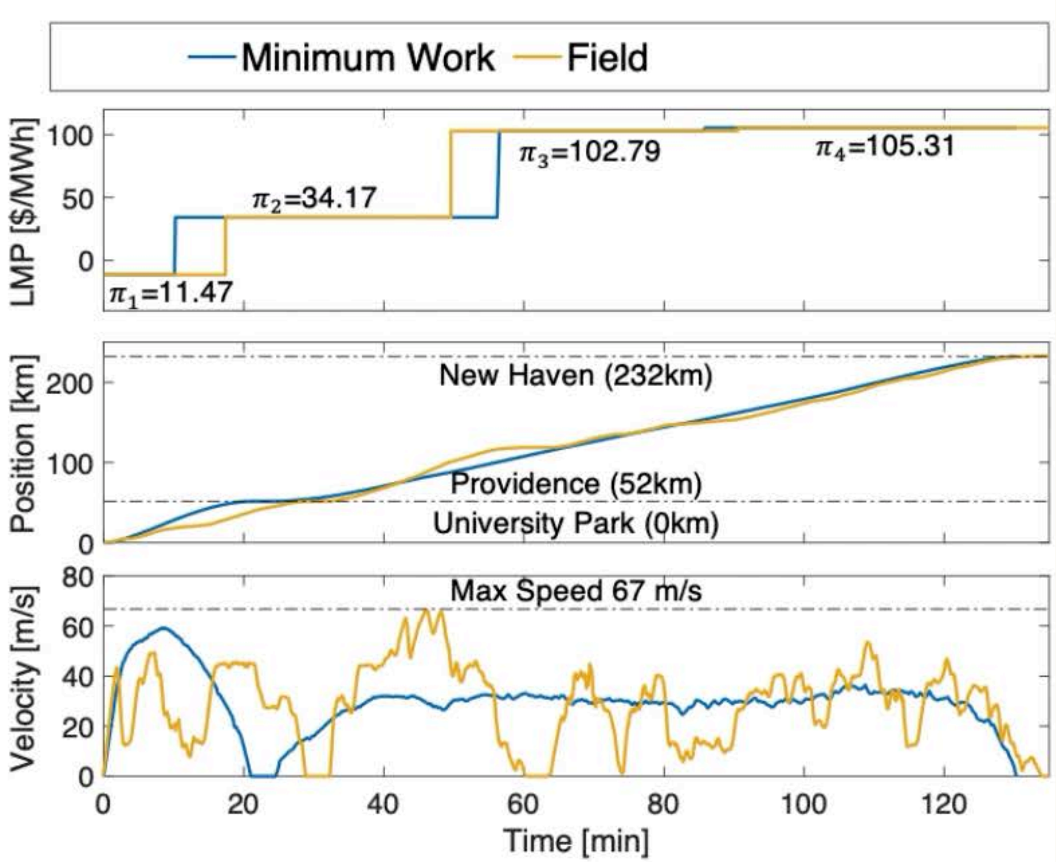
CO-OPTIMIZATION OF GRID-SCHEDULING AND TRAIN-SCHEDULING

Simulations – Train Location & Dispatch Profiles



Field data: Yields a total trip-cost of $200

Simulations – Train Location & Dispatch Profiles



62% energy cost reduction from field to minimum work (train only optimization) ($200→$76)

Simulations – train location & dispatch profiles

- Distributed Optimization approach (grid+train) results in a 80% cost reduction per trip compared to field ($200→$40)
- A 47% trip-cost reduction compared to a minimum work (train-only optimization)

CO-OPTIMIZATION OF INTER-DEPENDENT INFRASTRUCTURES

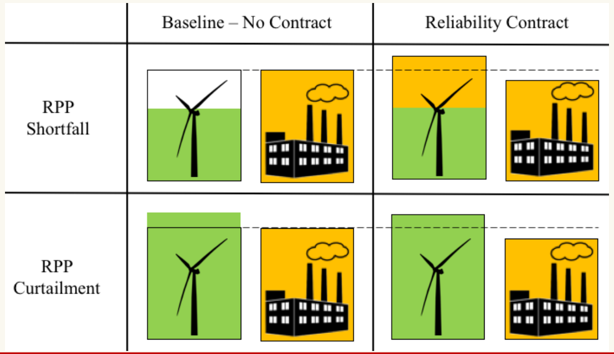
Renewable and Natural Gas Power Plant Partnerships*

Problem

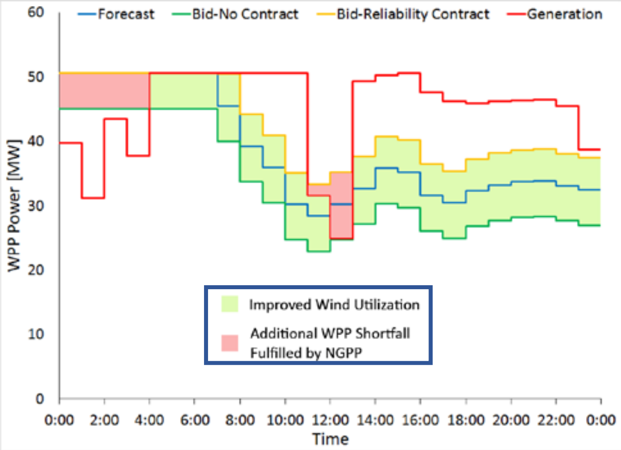
- Urgent need to accommodate renewables
- Speculation: Renewables will need to be dispatched (not treated as negative load)
- Speculation: Penalties $\lambda_p = \alpha\lambda_{DA}$, $\alpha > 1$ for unmet commitments
  - **may discourage renewable utilization**

Approach

Secondary market to cover unmet commitments at lower cost $\pi_{RC} = \beta\lambda_{DA}$, $\beta < \alpha$



Results



α = 1.5. β = 1.09

Renewable utilization increase from 74% to 88%

Yearly profits increase by $863 thousand for each party

Impact

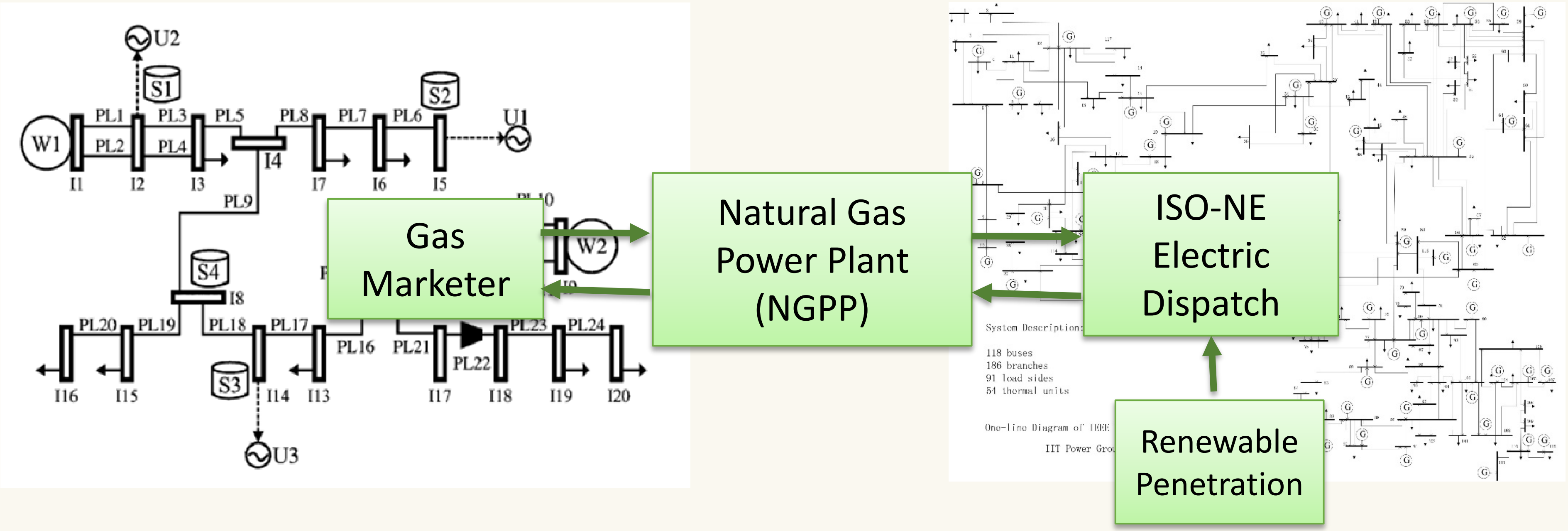
- Reliability contracts “firm up” commitments
- NGPPs benefit from exclusive energy rights to RPP shortfalls.
- RPPs benefit from reduced penalty payments
  (1) more aggressive bidding
  (2) higher renewable utilization

* D. D'Achiardi, N. Aguiar, S. Baros, V. Gupta and A. M. Annaswamy. Reliability Contracts Between Renewable and Natural Gas Power Producers. In *IEEE Transactions on Control of Network Systems, 2019*

Interdependency between NG and Electricity Networks – Market Flow*

Natural Gas Network

IEEE 118-bus Electricity Network



NGPP bids to ISO

NGPP gets dispatched amount to produce

Bilateral transaction between marketer and NGPP

Adjustments to dispatch in real time markets

- Two main issues: (a) Market misalignment (b) Unequal access to gas between NGPPs (GenCos) and RCITs (LDCs)
- Analysis of vulnerabilities was carried out.

* N. Nandakumar and A. M. Annaswamy, "Impact of increased renewables on natural gas markets in eastern United States," in *Journal of Modern Power Systems and Clean Energy*, May 2017

Summary

Distributed Optimization Using Trains

- Transactive Control in Transportation Systems
- Co-optimization of train scheduling and grid-scheduling
  - Railway grid Dynamic Market Mechanism ($rDMM$)
  - Train Dispatch
- Simulations – Amtrak Northeast Corridor (NEC)
- Co-optimization of interdependent infrastructures
  - Wind Power Producers & Natural Gas Producers
  - Electricity and NG Markets

A recent "9 pm for 9 minutes" event in India on April 9, 2020

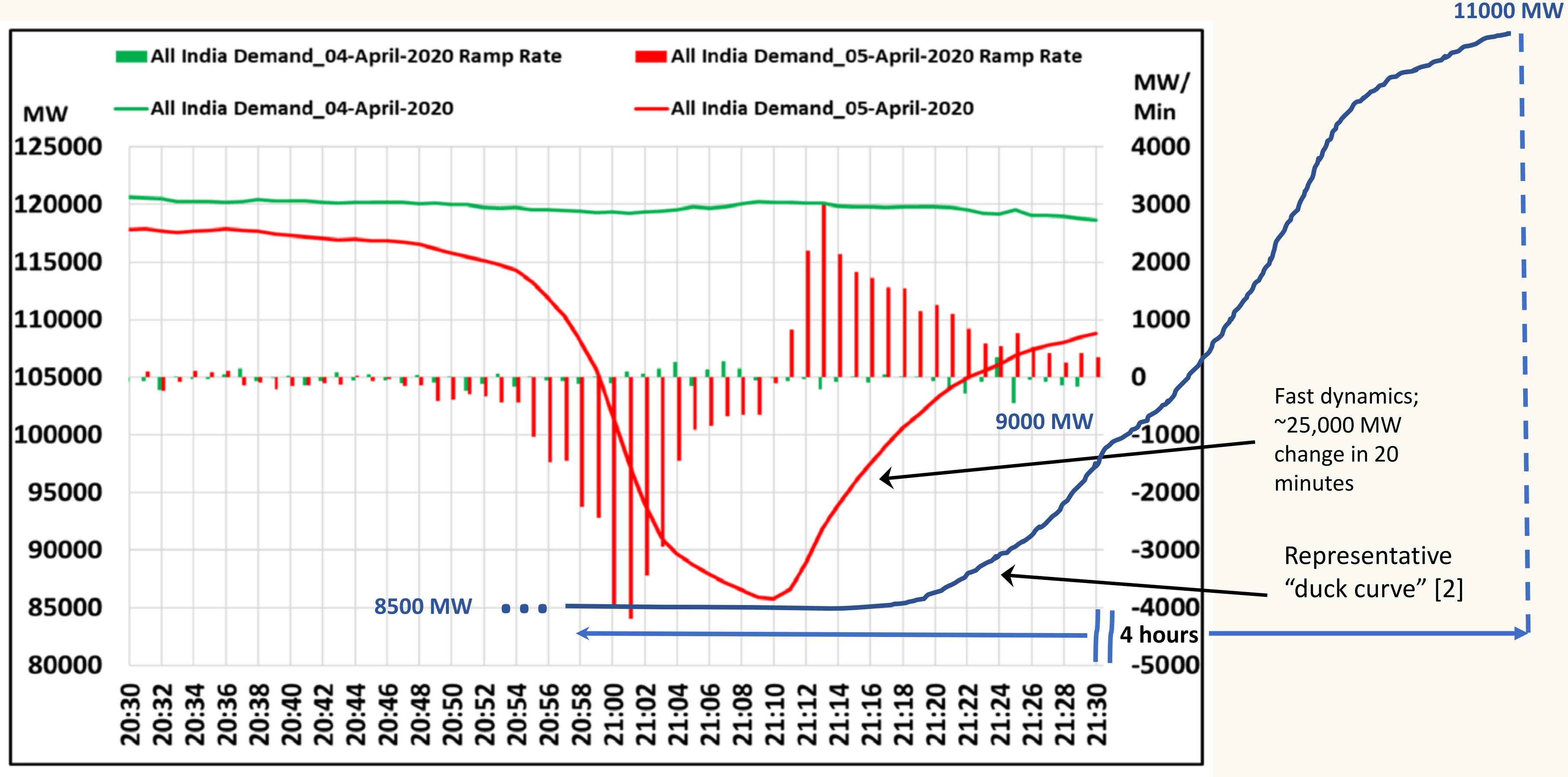
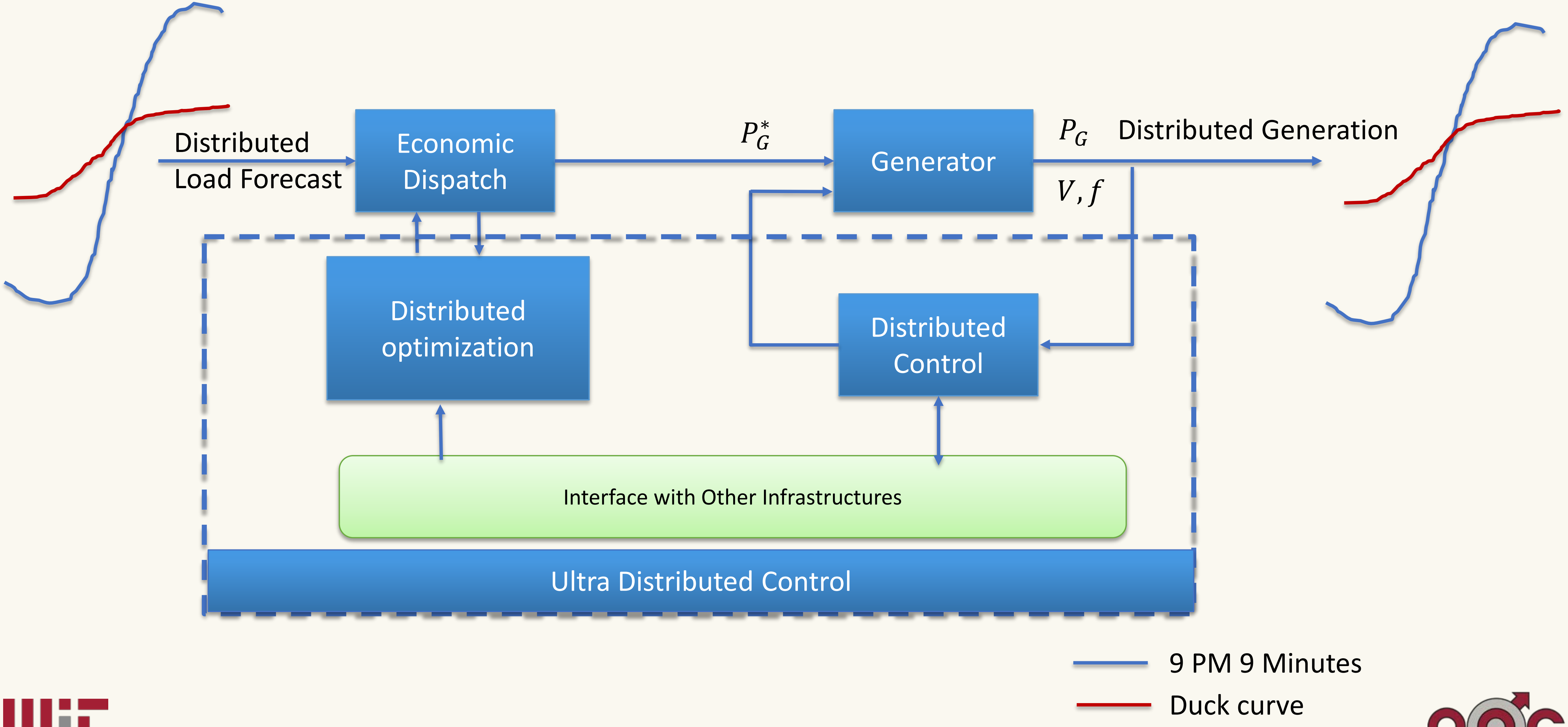


Figure 11: All India Demand Trend during the lights off event [1]

[1] Report on Pan India Lights Off Event 9 PM 9 Minutes [https://posoco.in/wp-content/uploads/2020/05/Report-on-Pan-India-Lights-Off-Event-9-PM-9-Minutes-on-5th-April-2020.pdf]

[2] ISO-NE Duck Curve [https://pv-magazine-usa.com/2018/05/08/the-duck-curve-comes-to-new-england/]

What's next? Towards Ultra-Distributed Control



THANK YOU!