CPS: Synergy: Architectural and Algorithmic Solutions for Large Scale PEV Integration into Power Grids

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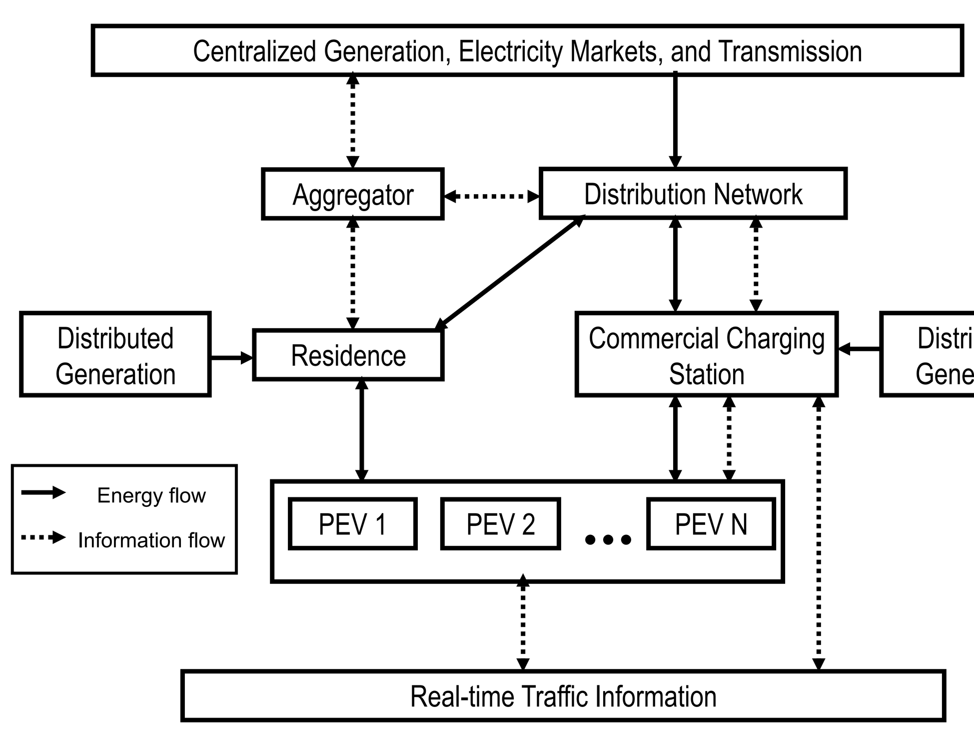
Project Objectives

What will be the effecton power grid of large scale PEV integration?

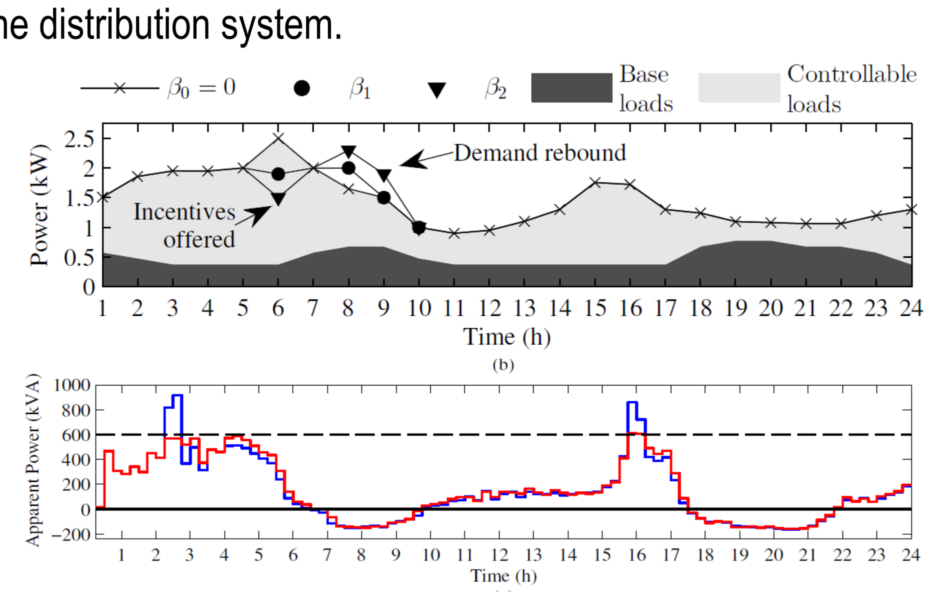
1. Commercial charging v/s residential charging
2. Charging with V2G v/s charging without V2G



PEV Ecosystem

Demand Response through Residential Charging

- Mitigation of distribution overloads via a decentralized framework in which the aggregator seeks to maximize its profits while the consumers minimize their costs in response to time-varying prices, and additional incentives provided to mitigate potential overloads in the distribution system.



base load

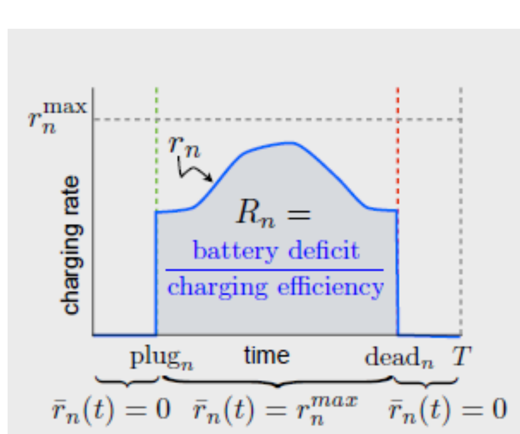
$$\min \sum_{t=1}^{T}\left(D(t)+\sum_{n=1}^{N} r_n(t)\right)^2$$

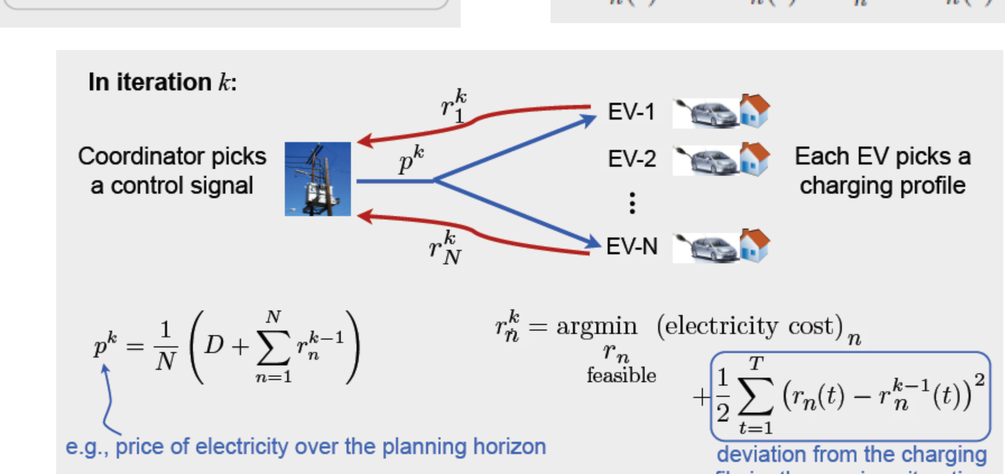
s.t. $0 \le r_n(t) \le \bar{r}_n(t)$ (rate constraint)

$\sum_{t=0}^{T} r_n(t) = R_n$ (capacity constraint)

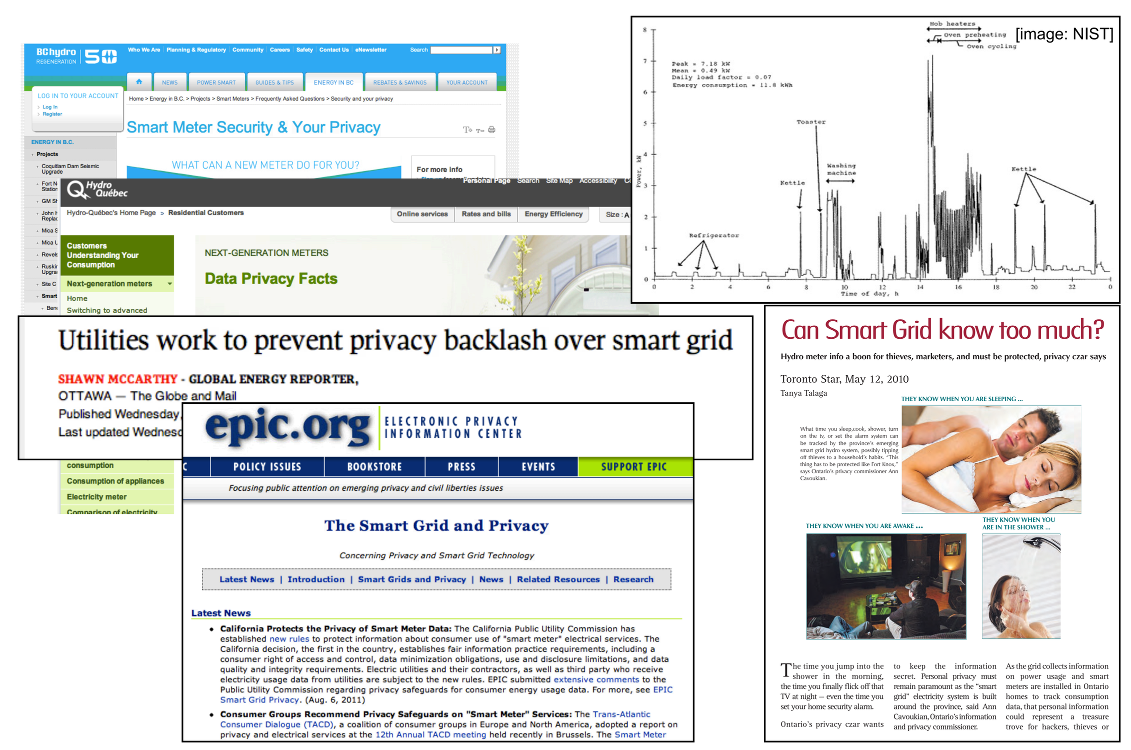
over the variables

$r_n(t)$ for $t = 1,\ldots,T,\ n = 1,\ldots,N$





Privacy in Demand Response Algorithms



1. Regret Minimization Algorithms to minimize data communication

Customer Cost:

$$c_i^k = \left(\sum_{j=1}^{N} x_j^k + D^k\right)^T x_i^k$$

Electricity Price

Utility Company Cost:

$$c_u^k = \sum_{t\in T}\left(\sum_{j=1}^{N} x_j^k(t) + D^k(t)\right)^2$$

Unknown and Uncertain Base Load

Regret: (k: Index for different days)

$$R_i := \sum_{k=1}^{K} c_i^k(x^k) - \min_{x\in F_i}\sum_{k=1}^{K} c_i^k(x, x_{-i}^k)$$

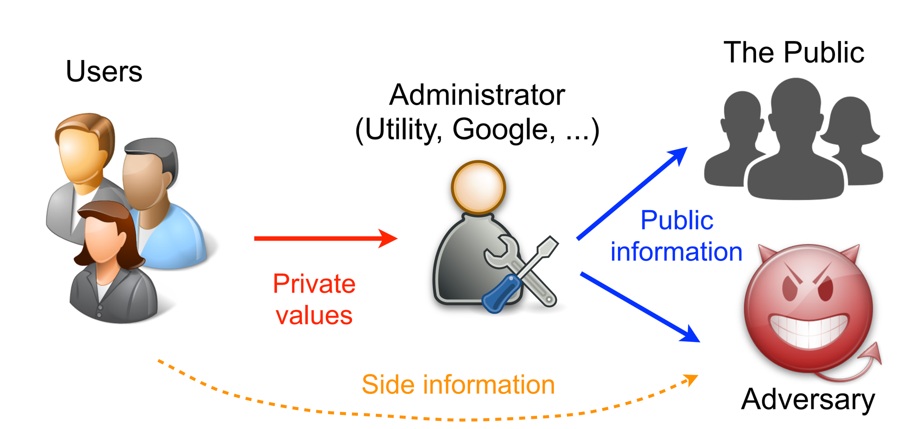
Use gradient projection to minimize both customer and utility company regret

$$x_i^{k+1} = \mathbf{Proj}\left(x_i^k - \eta_i^k \nabla c_i^k(x_i^k)\right)$$

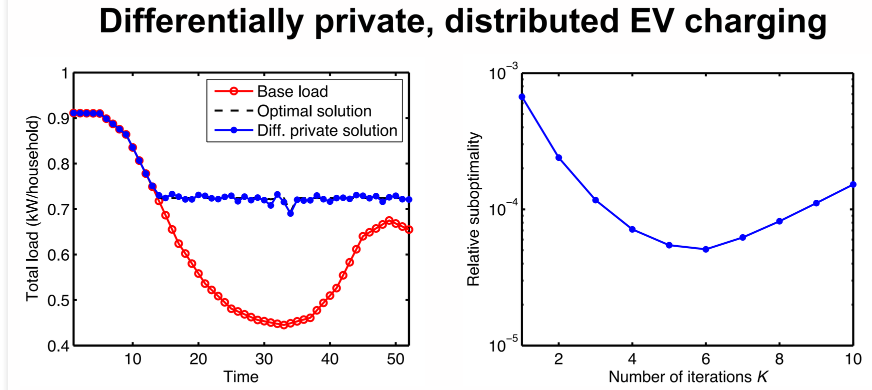
Update only once at the end of the day

- Theorem: The average charging profiles and the pricing policy converge to a Nash equilibrium

2. Differential Private algorithms



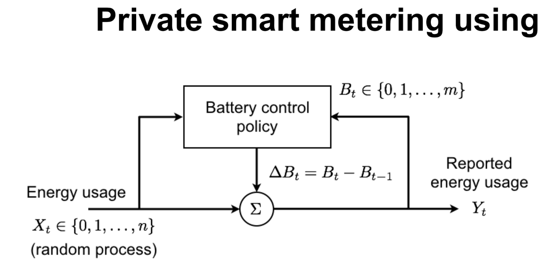
Differentially private, distributed EV charging



Add Laplace noise to protect privacy

Privacy vs. sub-optimality tradeoffs

Private smart metering using storage



Mutual information I(X;Y) as a metric of privacy

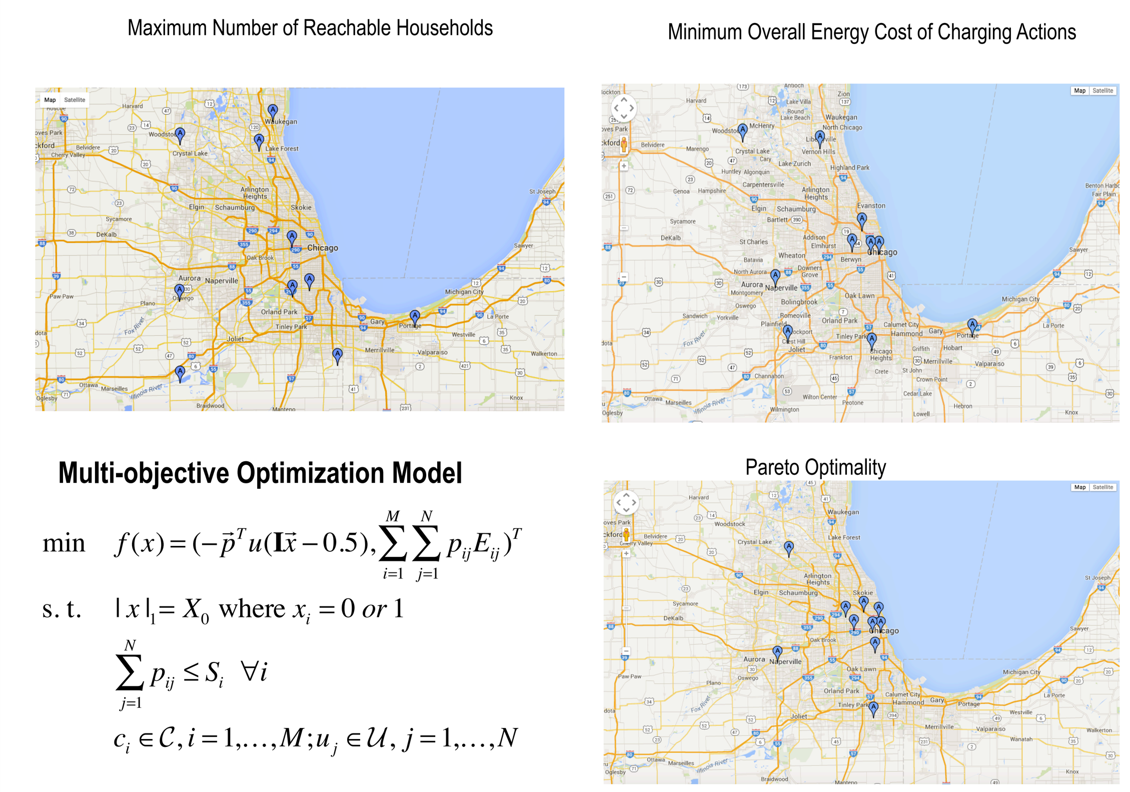
$$\mathbb{P}(\hat{X}(Y) \neq X) \geq \frac{H(X) - I(X;Y) - 1}{\log_2|\mathcal{X}|}$$

Probability of the attacker making an error

$\mathcal{X}$: alphabet of X

Commercial Charging Stations

1. Multi-objective energy-aware charging station placement



Multi-objective Optimization Model

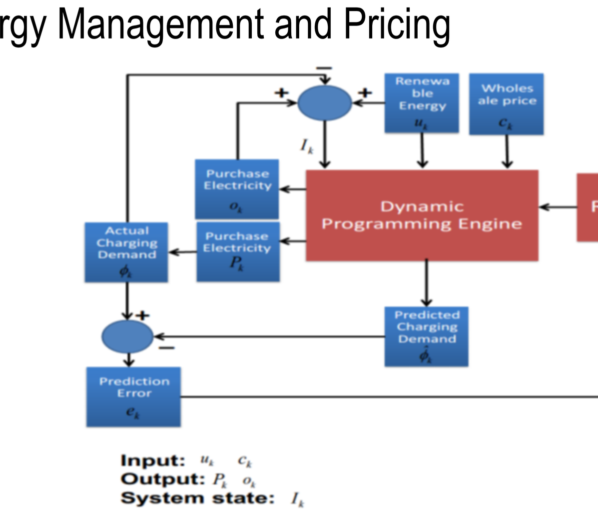
$$\min\ f(x) = (-\vec{p}^T u(\mathbf{I}\vec{x} - 0.5), \sum_{i=1}^{M}\sum_{j=1}^{N} p_{ij}E_{ij})^T$$

s.t. $|x|_1 = X_0$ where $x_i = 0$ or 1

$\sum_{j=1}^{N} p_{ij} \le S_i\ \ \forall i$

$c_i \in \mathcal{C}, i = 1,\ldots,M; u_j \in \mathcal{U}, j = 1,\ldots,N$

2. Energy Management and Pricing



Approach:

(1) Employ a linear regression model to estimate the spatio-temporal charging demand

(2) Construct an optimization framework, taking into account, electricity wholesale market, energy storage, renewable energy integration, and user satisfaction;

(3) Apply dynamic programming (DP) to derive the optimal charging prices and electricity purchase at each selling horizon.

Results:

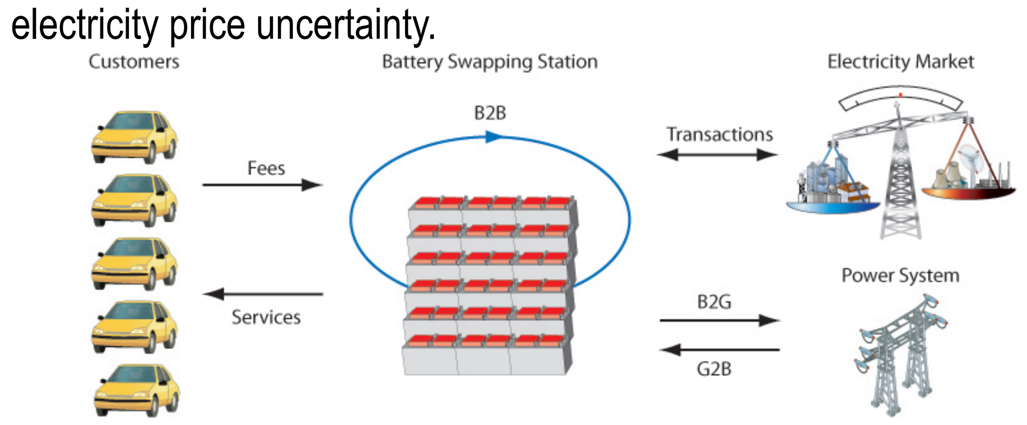
(1) DP algorithm achieves increased profit (up to 9%) compared to greedy algorithm;

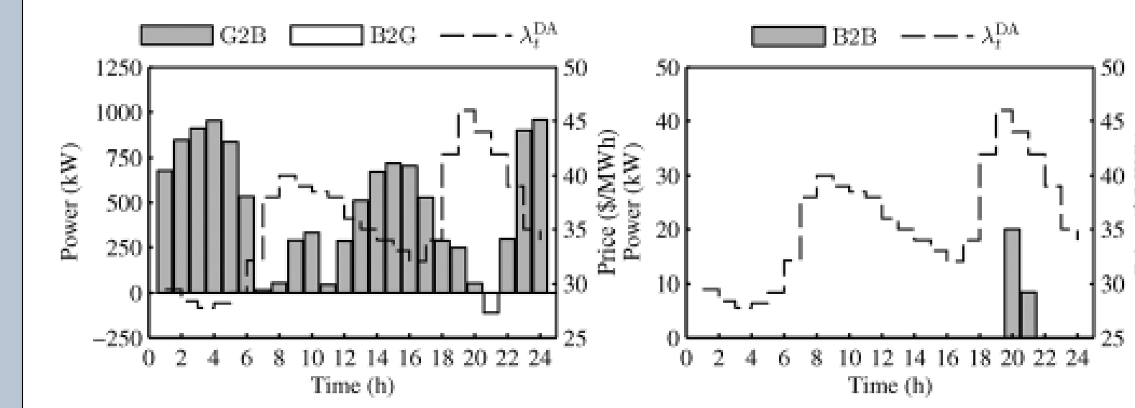
(2) An electricity storage is beneficial for protecting charging station from volatile wholesale prices and improving profits;

(3) Charging station chooses different electricity purchase strategies (aggressive or conservative) according to different energy storages costs (low or high).

3. Battery Swapping Station

An optimization framework for the operating model of battery swapping stations. The proposed model considers the day-ahead scheduling process. Battery demand uncertainty is modeled using inventory robust optimization, while multi-band robust optimization is employed to model electricity price uncertainty.

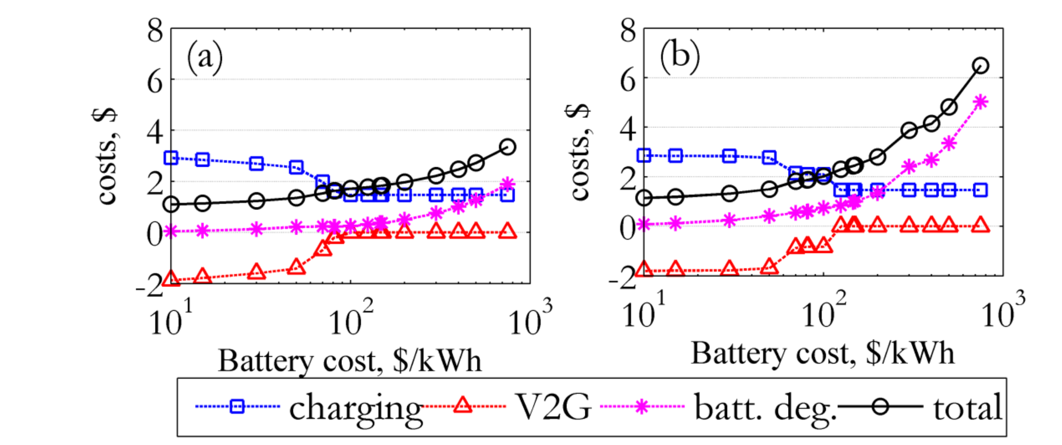




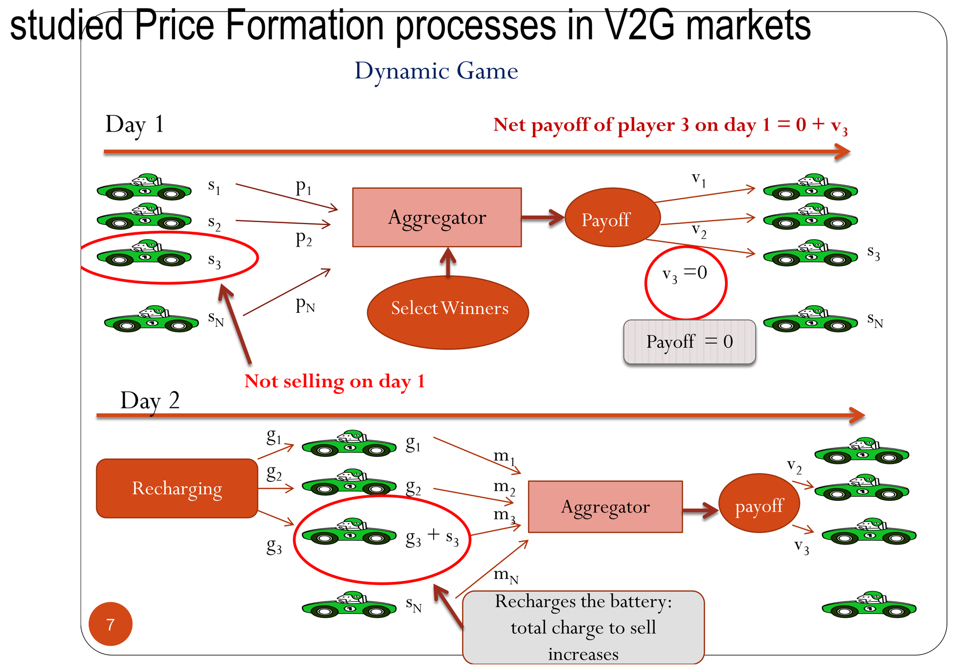
Service Provision through V2G

The provision of services from EVs could reduce the useful life of the battery and thus introduce a cost that needs to be taken into account when scheduling the charging of these EVs. The objective function explicitly takes into account the cost of battery degradation (chemistry and class dependent) not only when used to provide services to the system but also in terms of the EV utilization for motion.

$$\min\left\{\sum_{t\in T}\left[\lambda_t^{min}\Delta t\sum_{v\in V}\left(c_{v,t} - d_{v,t}\eta_v^D\right)\right] + z_0\Gamma_0 + \sum_{t\in T} q_{0t}\right\}$$

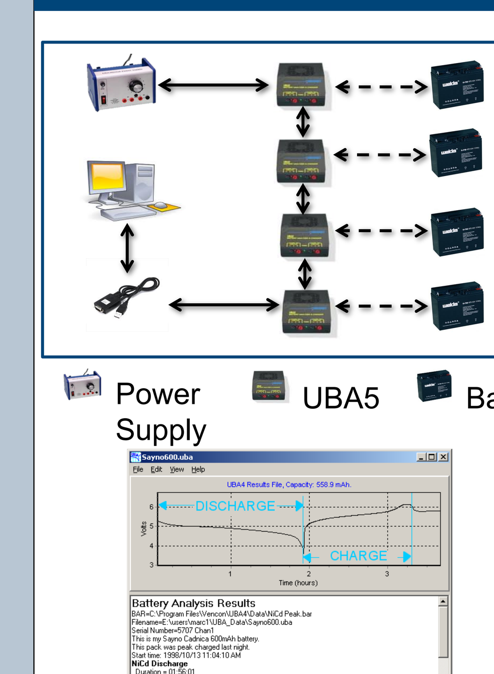


Also studied Price Formation processes in V2G markets



Theorem 1: A strategy combination of the form π where $\pi_i(s) = \bar{p}_i(s, \pi)$ for all $s \in S$ is a Markov Perfect Equilibrium for the game described in Section II.

New Undergraduate Lab



- Emulation of a charging station for research and teaching
- Vehicle representation: battery
- Vehicle modes: charge (in station) and discharge (on road)
- Allows to demo scheduling and discharge curves as well as different charge options
- Allows to study effects on different battery types
- Allows to study longevity of a battery as function of charging characteristics