Carnegie Mellon

A Queueing Based Scheduling Approach for Load Management in Electrical Energy Systems: The Case of Electric Vehicle Charging

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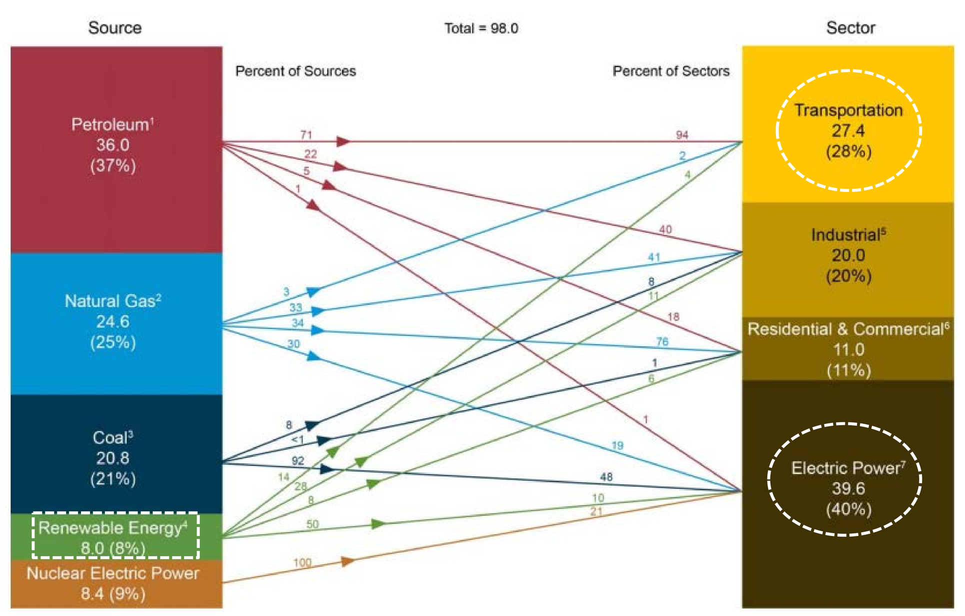
Motivation

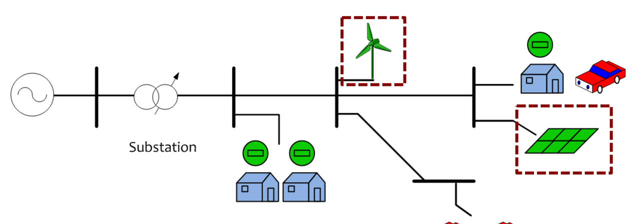
- Growing popularity of EV can cause severe stress on the existing infrastructure
- The need to implement *demand dispatch* to absorb intermittent renewable generation
- Radical transformation of the power system and increased level of uncertainties
- Wide availability of information and communication technology

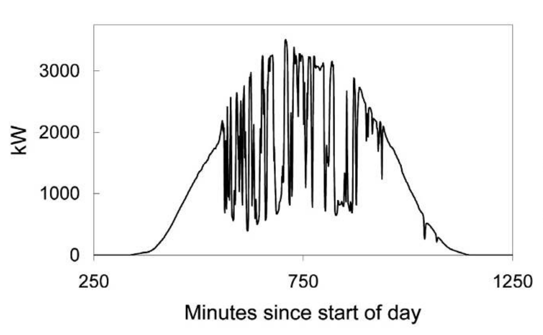
Big Picture – Large Scale and Lots of Uncertainties

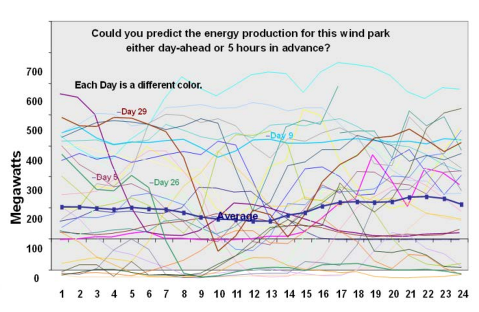
- The U.S. Energy Consumption in 2010



- Intermittency of Renewable Generation







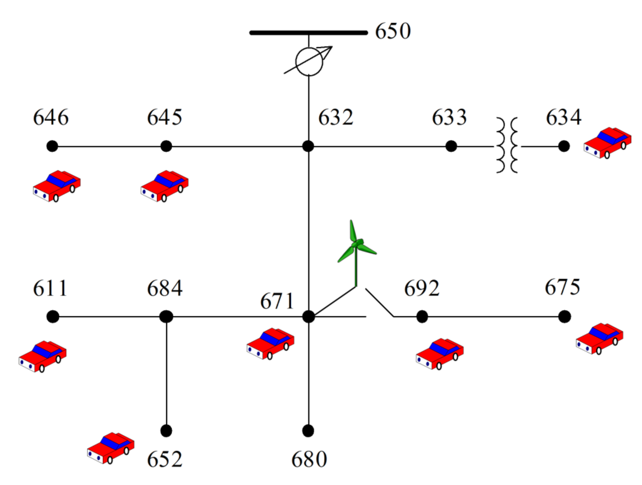
Transportation electrification is a huge issue.

Big potential for integrating renewable energy sources!

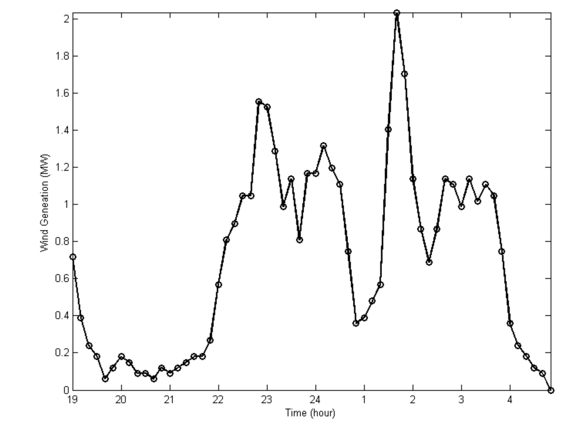
High intermittency and big operation challenge!

Simulation Results

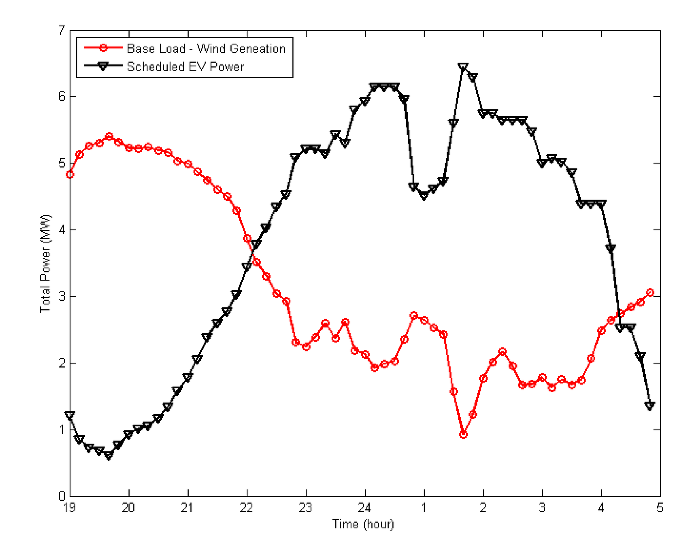
Constant Cost Charging



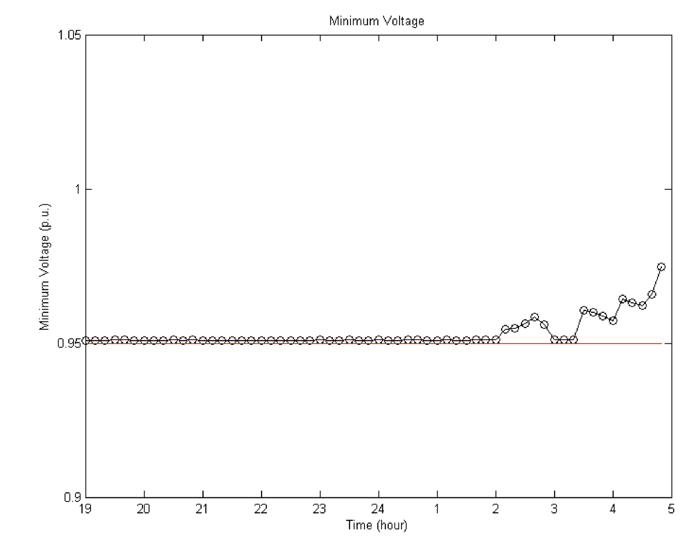
IEEE 13-bus system



Wind power generation

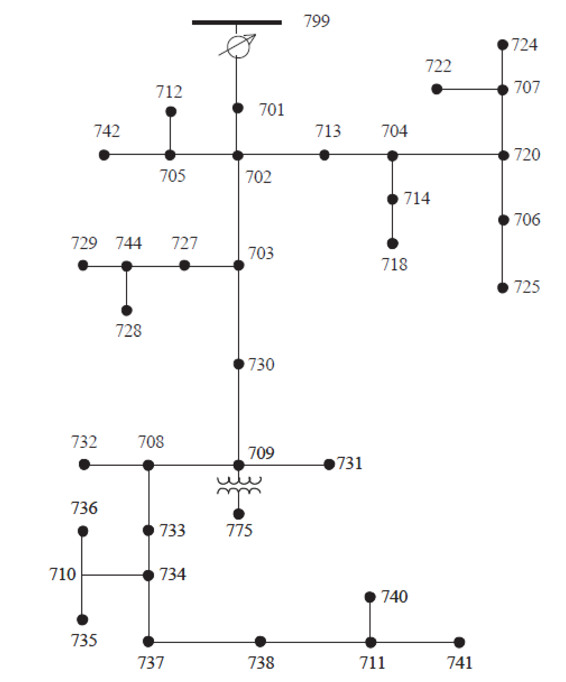


Total load profile

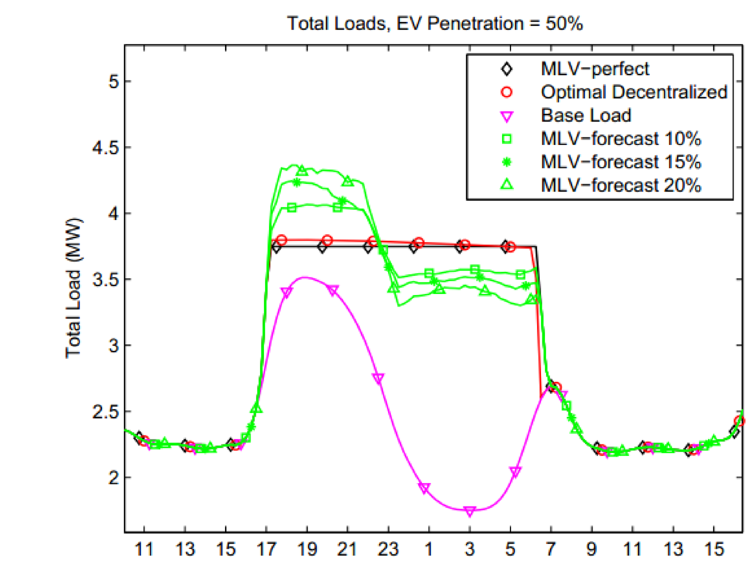


Voltage profile

Minimum Variance Charging



IEEE 37-bus system



Total load profile

Advantages of the proposed max-weight approach:

- Reliable and secure power system operation
- Rigorous theoretical guarantee on asymptotic optimality
- Low complexity
- Robustness against uncertainties

Queueing Based Scheduling Approach to the EV Charging Problem

EV Battery Queueing Model

Key observation: *EV loads are delay-tolerant.*

$$U_i(n) = [U_i(n-1) - \sigma_i(n)\eta_i\Delta t]^+ + A_i(n)$$

Charging power — Energy discharge

Goal of the EV charging scheduler (DSO):

- Secure operation of the power system
- Small EV battery queues
- Minimum charging cost

Formulation of the EV Charging Problem

$$\text{minimize}_{\{\boldsymbol{\sigma}(n)\}} \quad \limsup_{T\to\infty} \frac{1}{T}\sum_{n=1}^{T} c(\boldsymbol{\sigma}(n);\boldsymbol{p}(n))$$ — General cost function

$$\text{subject to} \quad U_i(n) = [U_i(n-1) - \eta_i\sigma_i(n)\Delta t]^+ + A_i(n)$$ — EV queueing dynamics

For each time slot n:

$$P_i + \sigma_i = V_i \sum_{k\in\mathcal{N}_i} V_k[G_{ik}\cos(\theta_i-\theta_k) + B_{ik}\sin(\theta_i-\theta_k)]$$

$$Q_i = V_i \sum_{k\in\mathcal{N}_i} V_k[G_{ik}\sin(\theta_i-\theta_k) - B_{ik}\cos(\theta_i-\theta_k)]$$ — AC power flow (with renewable)

$$V_i^{\min} \le V_i \le V_i^{\max}$$ — Voltage constraints

$$\sigma_i^{\min} \le \sigma_i \le \sigma_i^{\max}$$ — Charging circuit constraints

$\sigma_i = 0$ if EV i not available, — Driving pattern or regulation input

All queues are **stable**

Large scale, highly non-convex, stochastic optimization problem!

Max-Weight EV Dispatch *(Optimal Power Flow)*

$$\boldsymbol{\sigma}(n) \in \arg\max_{\boldsymbol{\sigma}\text{ is feasible}} \sum_{i=1}^{N} \big(U_i(n)\big)^{\alpha}\eta_i\sigma_i - \beta(n)c(\boldsymbol{\sigma};\boldsymbol{p}(n))$$

Maximize queue weighted charging power — **Larger queues, charge more**

Minimize charging cost — **Higher cost, charge less**

Simple algorithm, but highly nontrivial for analysis and performance guarantees!

Theorem: [Li *et al.* 11, 12] Under the myopic scheduling, we have

1) $\limsup_{T\to\infty} \frac{1}{T}\sum_{n=1}^{T} c(\boldsymbol{\sigma}(n);\boldsymbol{p}(n)) \le c^\star$ with probability 1.

2) All queues are rate stable.

Key technique: *fluid limits* [Dai95][Prabhakar00][Meyn07]

'Inferring properties about stochastic systems from deterministic systems'

References

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