

# Electricity Supply

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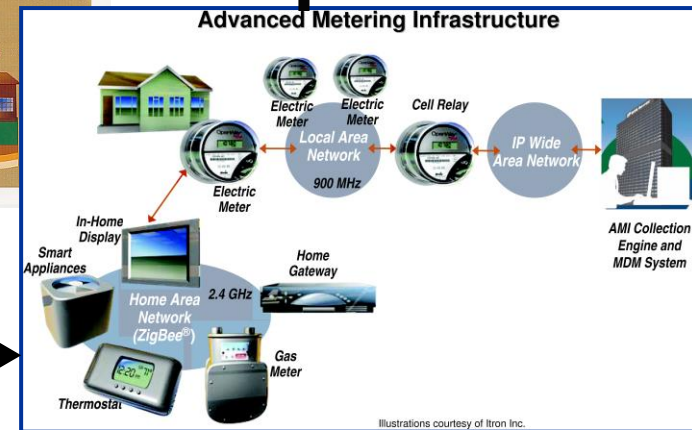
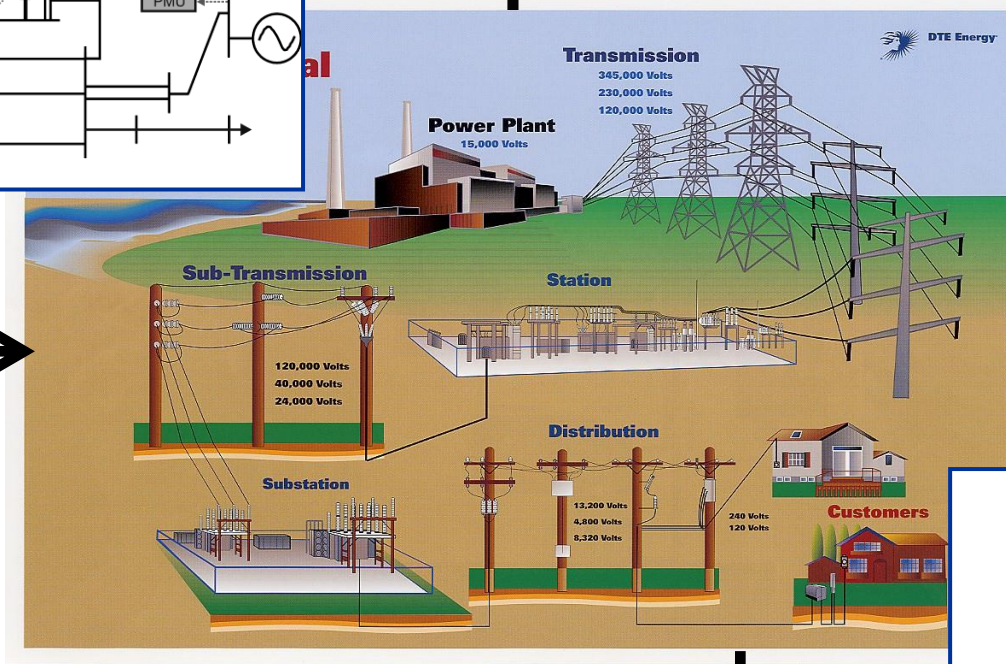
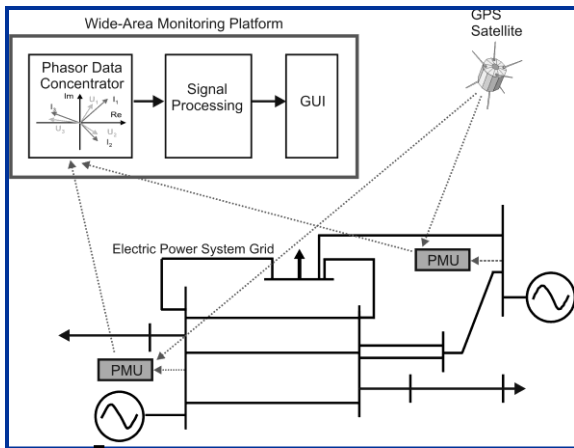


NSF FORCES Kickoff  
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# Enhanced control of power systems

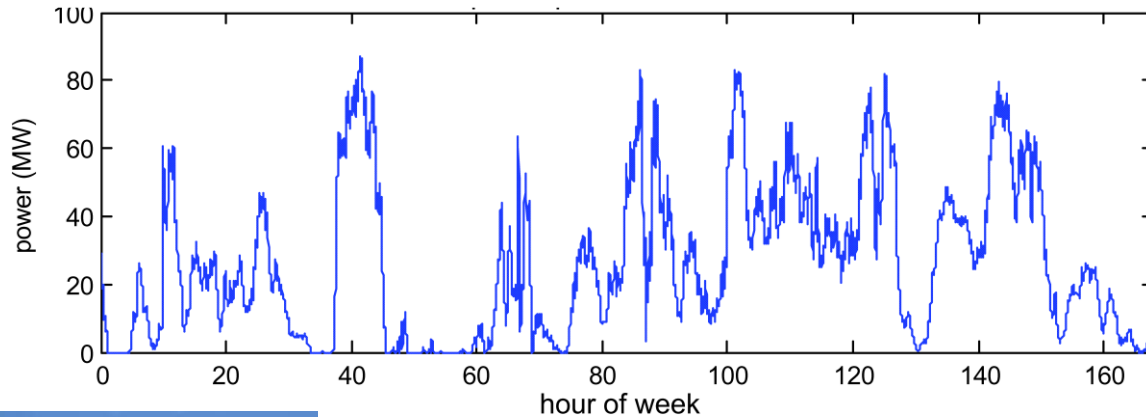
- Phasor measurement units
- Wide area monitoring and control

- Advanced metering infrastructure
- Fully responsive load control

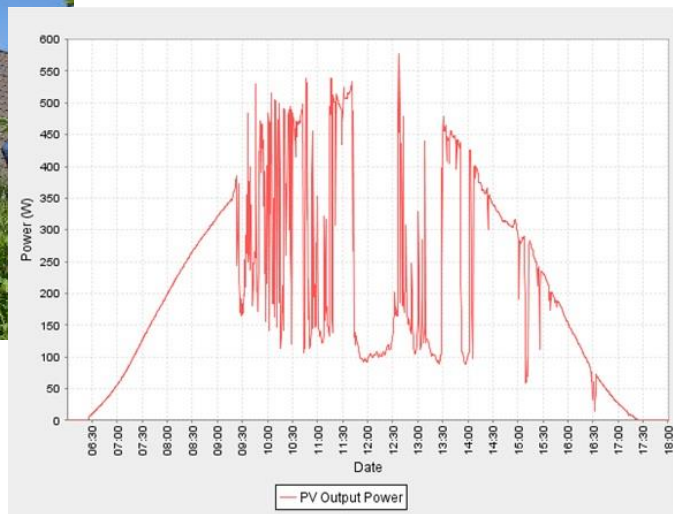


# Why enhance the grid?

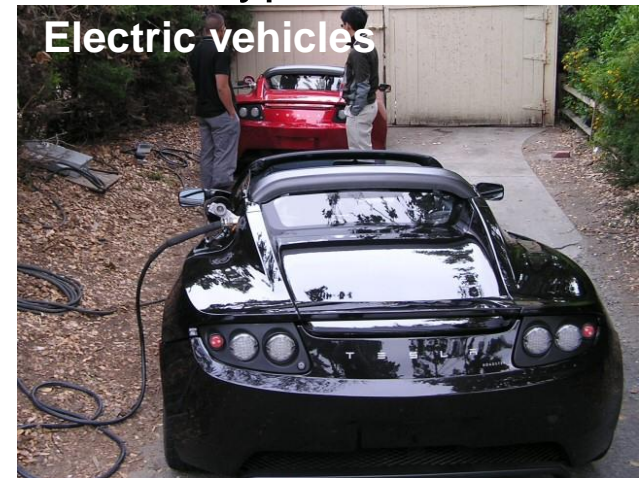
Increased generation from renewable sources.



- 100 MW wind plant at Buffalo Ridge, MN.
- 1 minute power production, mid-summer.



New types of loads.



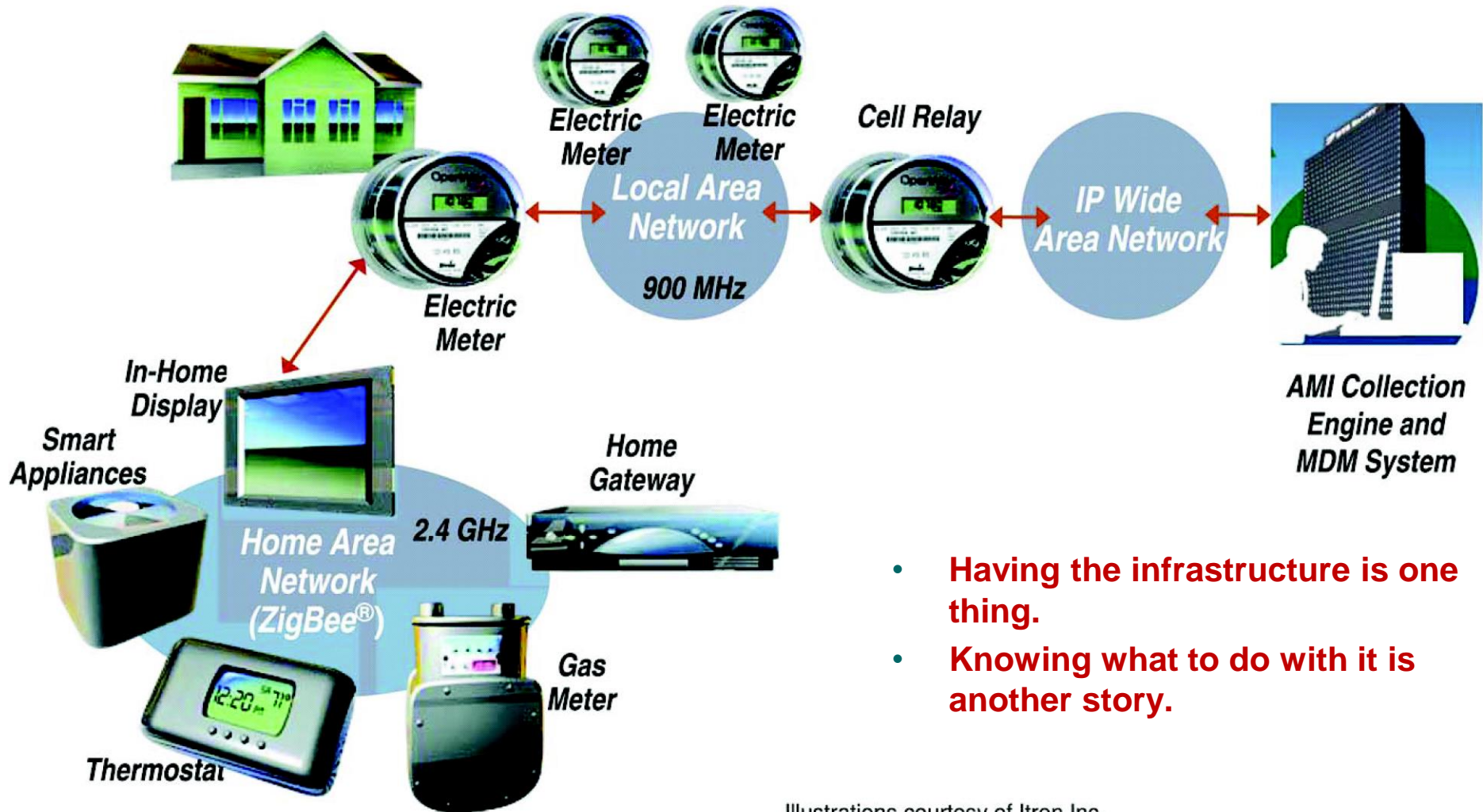
# Motivation

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- Current paradigm:
  - Load is an exogenous input.
  - Generation tracks deviations from the forecast.
  - Voltage profile is relatively constant.
- Increasingly difficult as renewable generation grows.
  - Generation is not designed to be highly manoeuvrable.
  - Distribution voltages can be quite volatile.
- Benefits of load scheduling.
  - Large scale: valley filling.
  - Local: transformer overload prevention.
- Ubiquitous communications facilitates control of highly distributed loads.
  - And energy storage (if costs reduce.)
- Increasing levels of uncertainty.



# Advanced metering infrastructure (AMI)

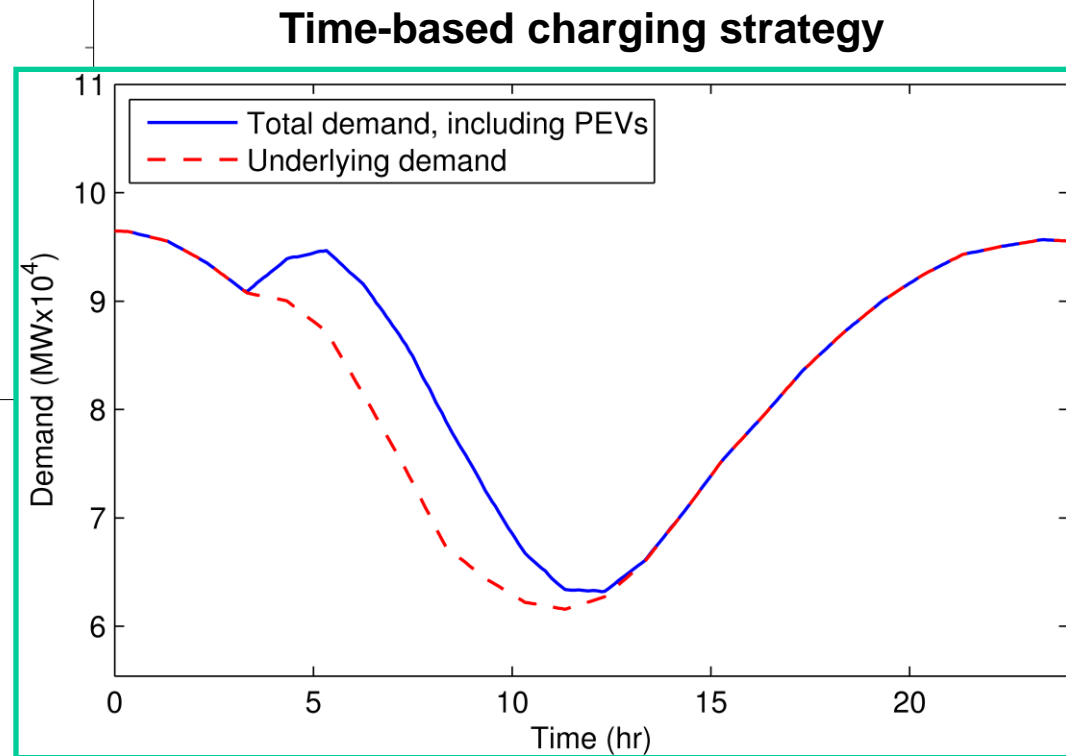
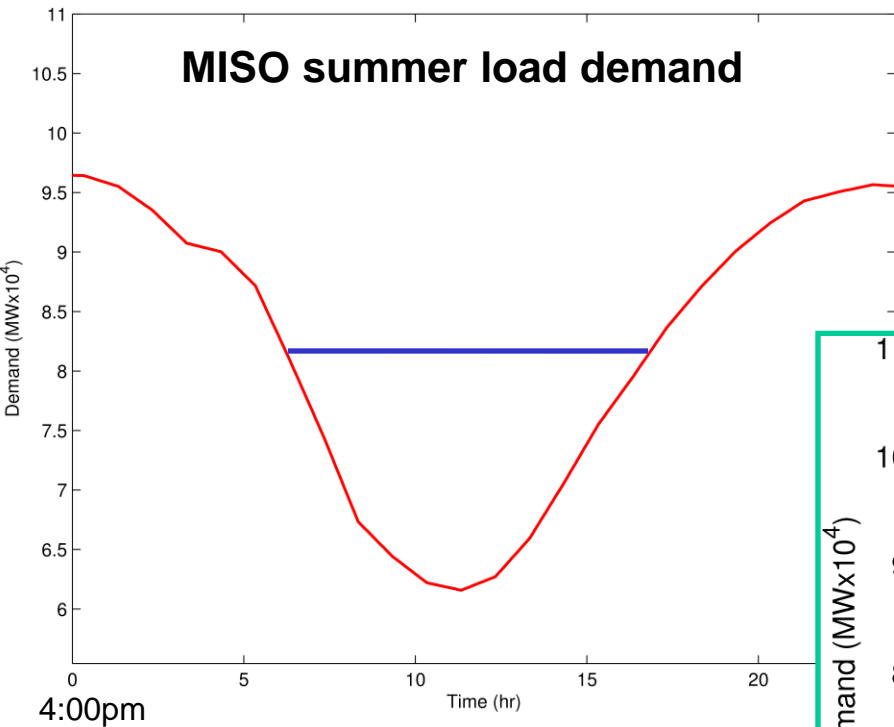


- **Having the infrastructure is one thing.**
- **Knowing what to do with it is another story.**

Illustrations courtesy of Itron Inc.

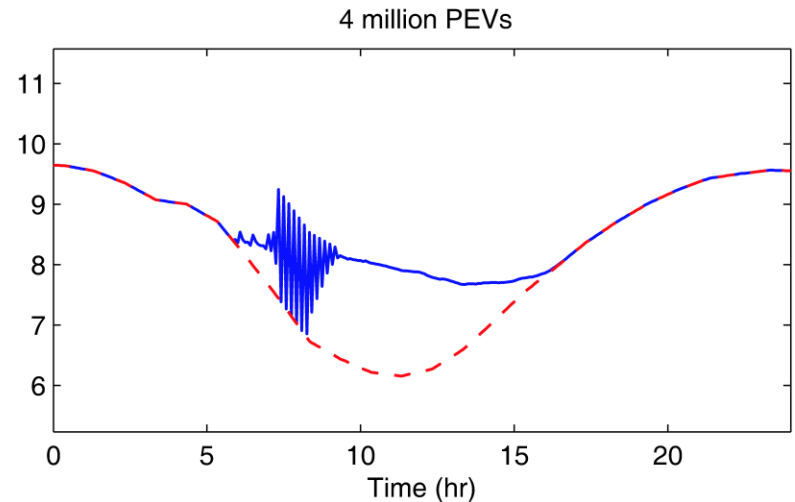
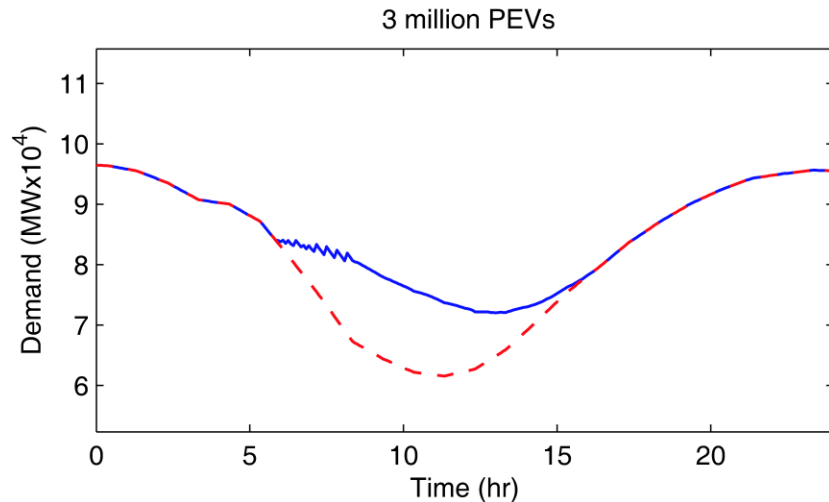
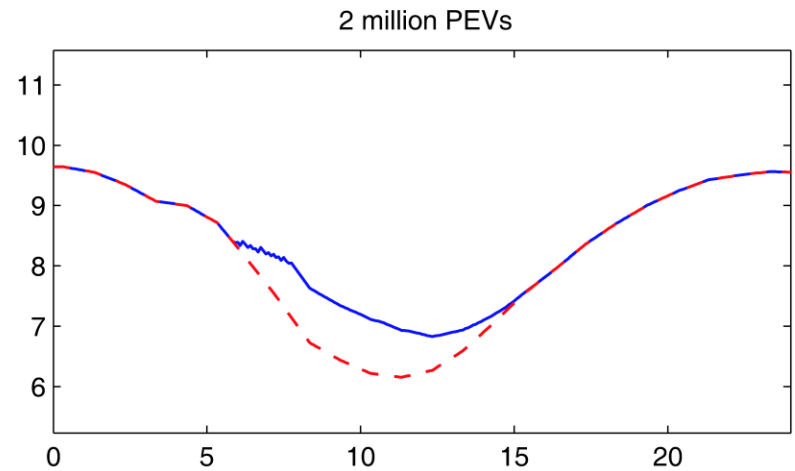
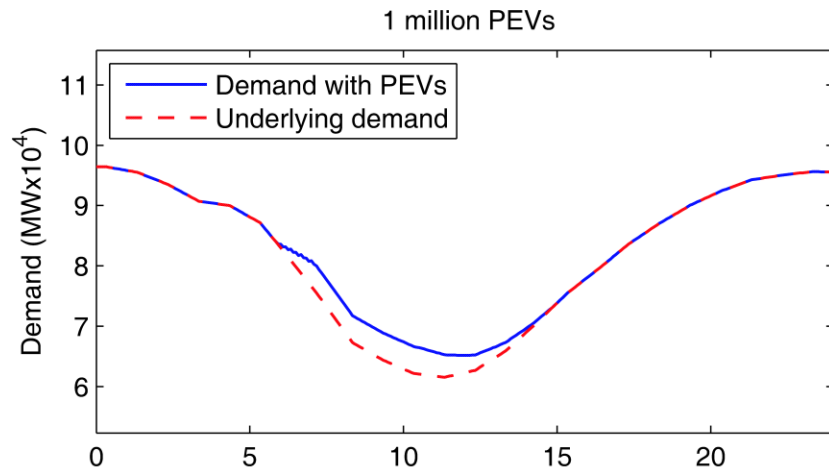
# Electric vehicle charging

- Charging control strategies will be vitally important for ensuring large-scale adoption of plug-in EVs does not cause generation scheduling problems.



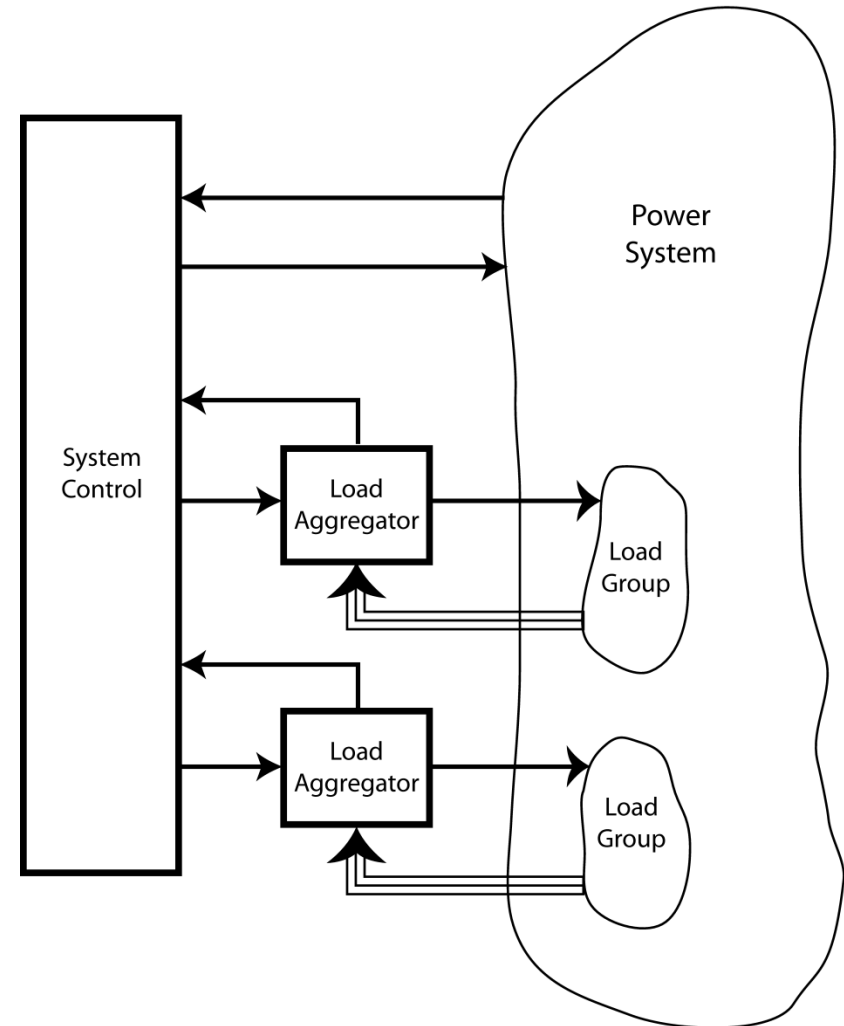
# Electric vehicle charging (continued)

## Price-based charging strategy



# Load control

- Competing objectives:
  - Local control objective, e.g.,
    - Maintain temperature close to setpoint.
    - Deliver required charge to PEV by specified time.
  - System service, e.g., balance renewable generation output.
- Load control strategies must be consistent with the legacy system operating philosophy.
- Centralized control of large numbers of loads is impractical.

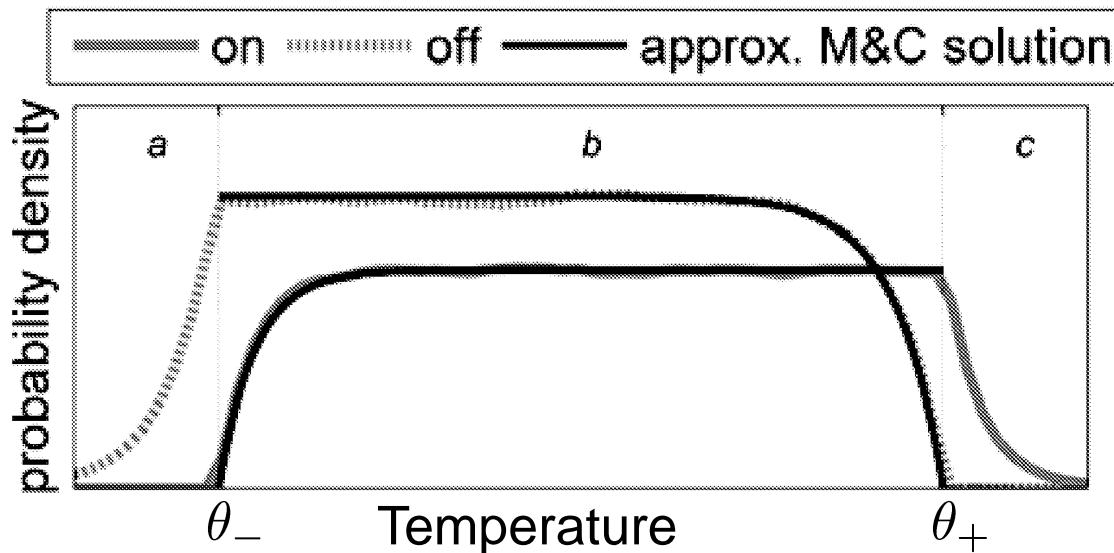




# Load control: hysteresis-based devices

- Steady-state temperature distribution for 10,000 cooling loads.
- Temperature behavior of each device is modeled according to:

$$\theta_{n+1} = a\theta_n + (1 - a)(\theta_{amb} - m_n K) + w_n$$



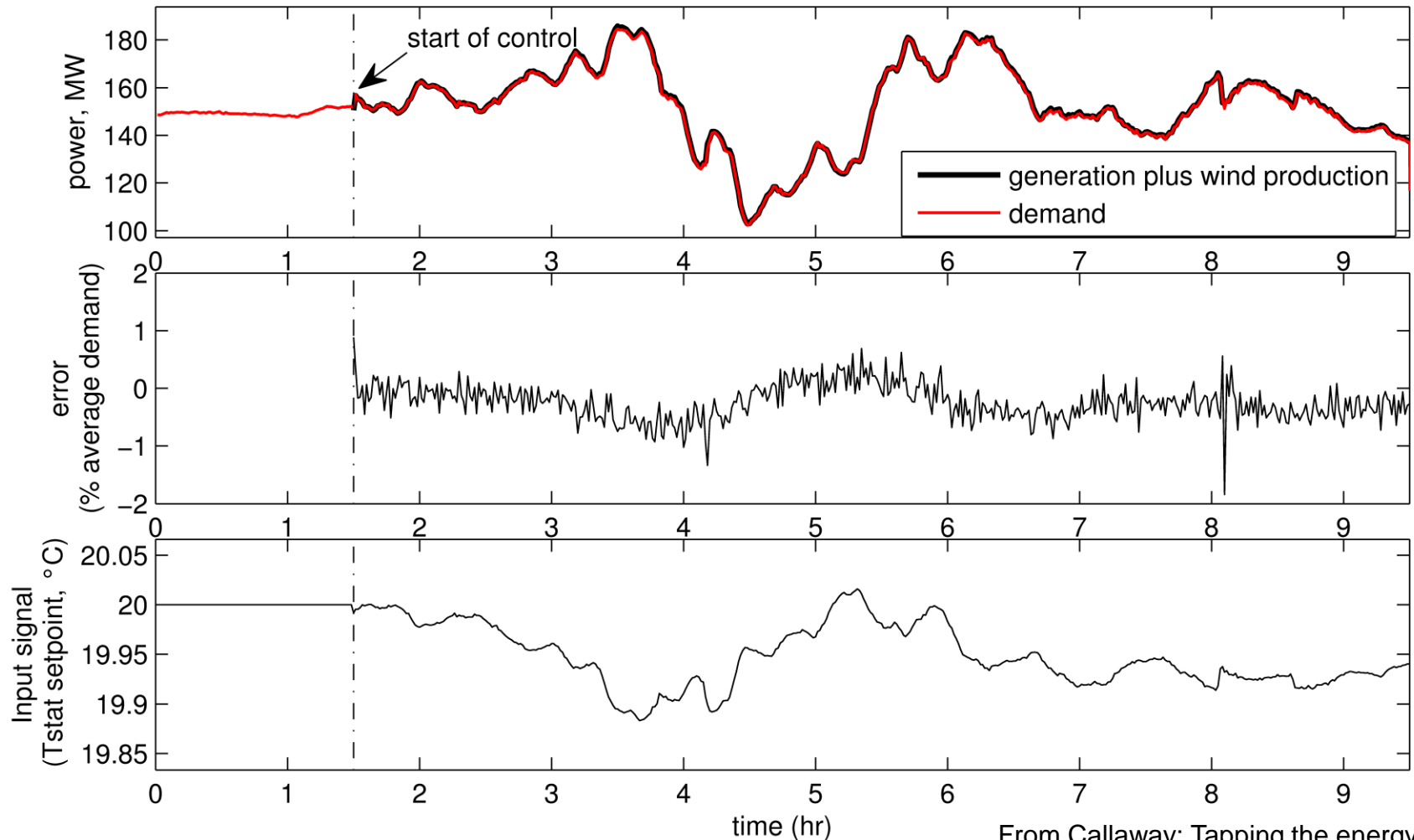
- **Control strategy:**
  - Increase load by lowering set-point.
  - Decrease load by raising set-point.

From Callaway: Tapping the energy storage potential in electric loads.

- These ideas can be adapted to controlling large numbers of plug-in electric vehicles.
- Recent work has shown that such controls can induce period-doubling bifurcations.

# Load control: tracking wind variations

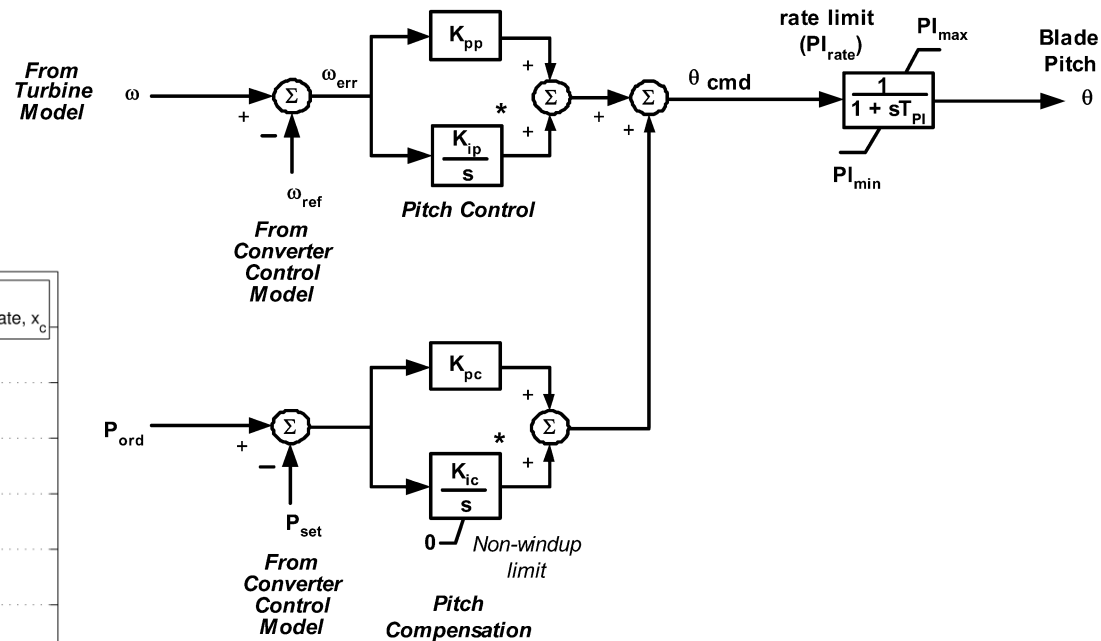
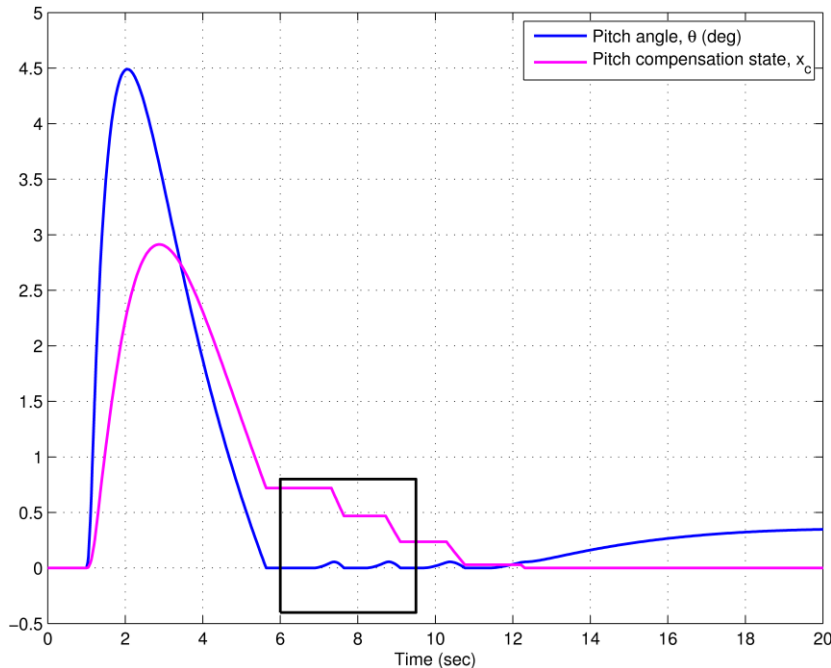
- Controlling 60,000 AC loads to follow wind variations.



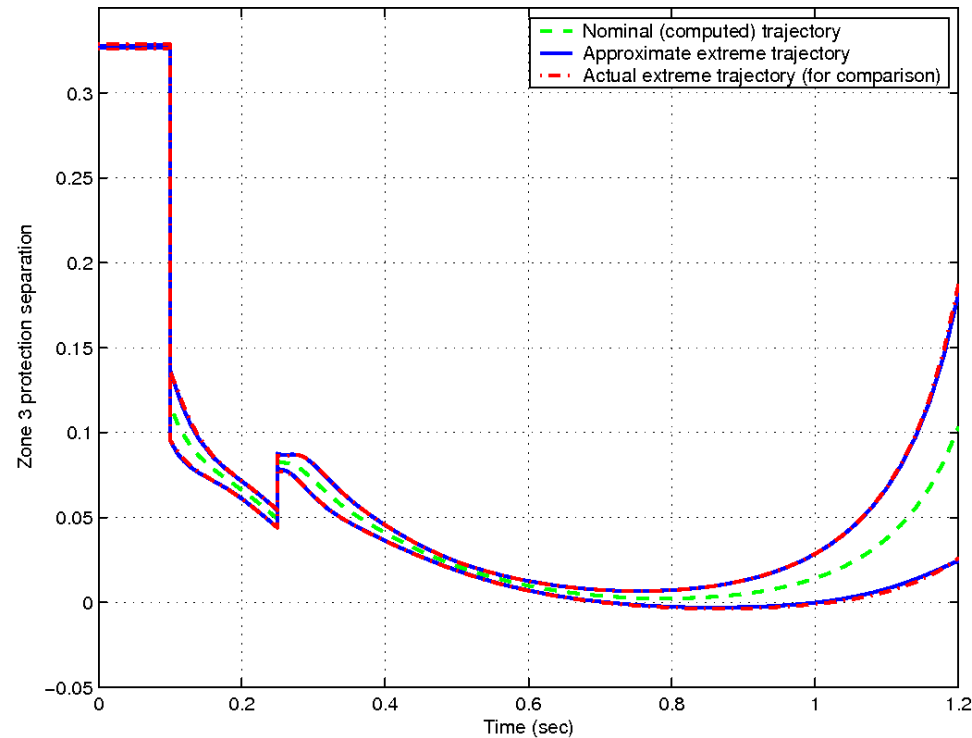
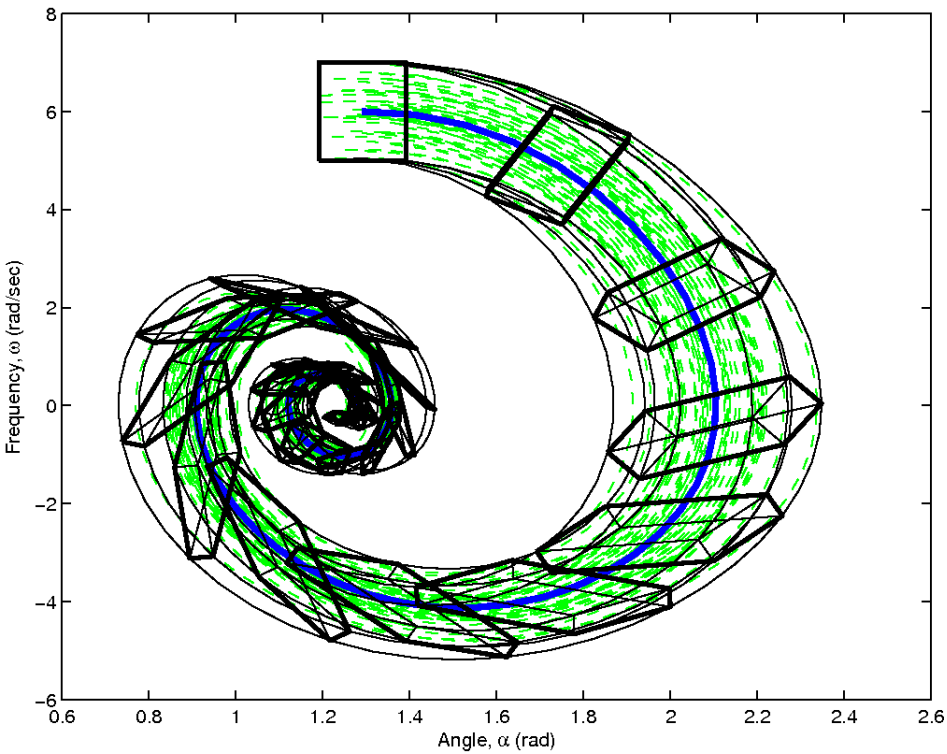
From Callaway: Tapping the energy storage potential in electric loads.

# Increasingly complex models

- Industry-standard wind-turbine model gives deadlock.



# Uncertainty assessment



# Conclusions

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- Large-scale renewable generation will challenge current power system operating strategies.
  - System-wide: generation and transmission utilization.
  - Locally: overloads and voltage regulation.
- Significant actuation can be achieved through coordinated control of large numbers of highly distributed loads.
  - Issues:
    - Technical: control structure, latency, interoperability, data security, ...
    - Social: incentives for consumers to participate in (non-disruptive) fast-acting, demand response schemes.
- Newer power system devices involve disparate time-scales.
  - Natural to model as hybrid dynamical systems.
  - Model verification is fundamentally important.
- Power system dynamic analysis must consider uncertainty in parameters that govern both cyber and physical behavior.