On the Control of Active End-nodes in the Smart Grid

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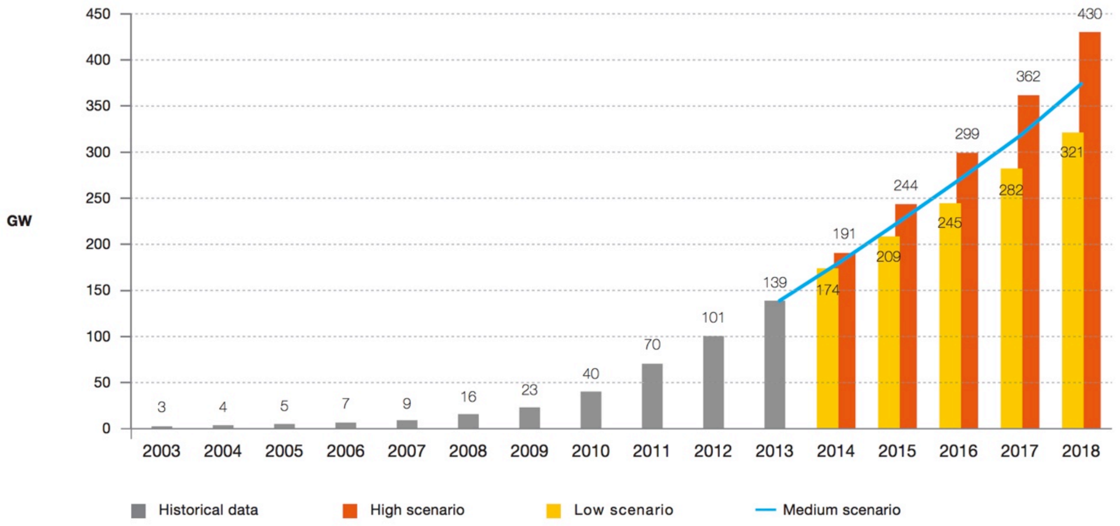
Active End-nodes are Being Rapidly Deployed

- Solar PV systems
  - – smart inverters
- Electric vehicles
  - – smart chargers
- Storage systems
  - – smart controllers



Global PV Cumulative Capacity

Source: EPIA, Global Market Outlook

Critical Challenges

- Increased uncertainty
  - Intermittent renewable generation
  - Mobility of electric vehicles
  - Requires additional operating reserves
    - *costly* and *inefficient*

- Decreased reliability
  - Branch and transformer congestion
  - Over-voltage and under-voltage conditions
  - Reverse power flow
  - …

Control is Necessary yet Challenging!

- Traditional grid control mechanisms are inadequate to reliably and economically control the active end-nodes
  - High active end-node penetration in distribution networks
  - Spatial and temporal uncertainties
  - Competing objectives of system operators and customers

Contributions

- Studied *three* problems:
  - Accommodating high penetration of EVs in distribution networks
  - Accommodating high penetrations of PVs and elastic loads in low-voltage distribution networks
  - Energy procurement and allocation in a grid-tied solar-powered EV charging station

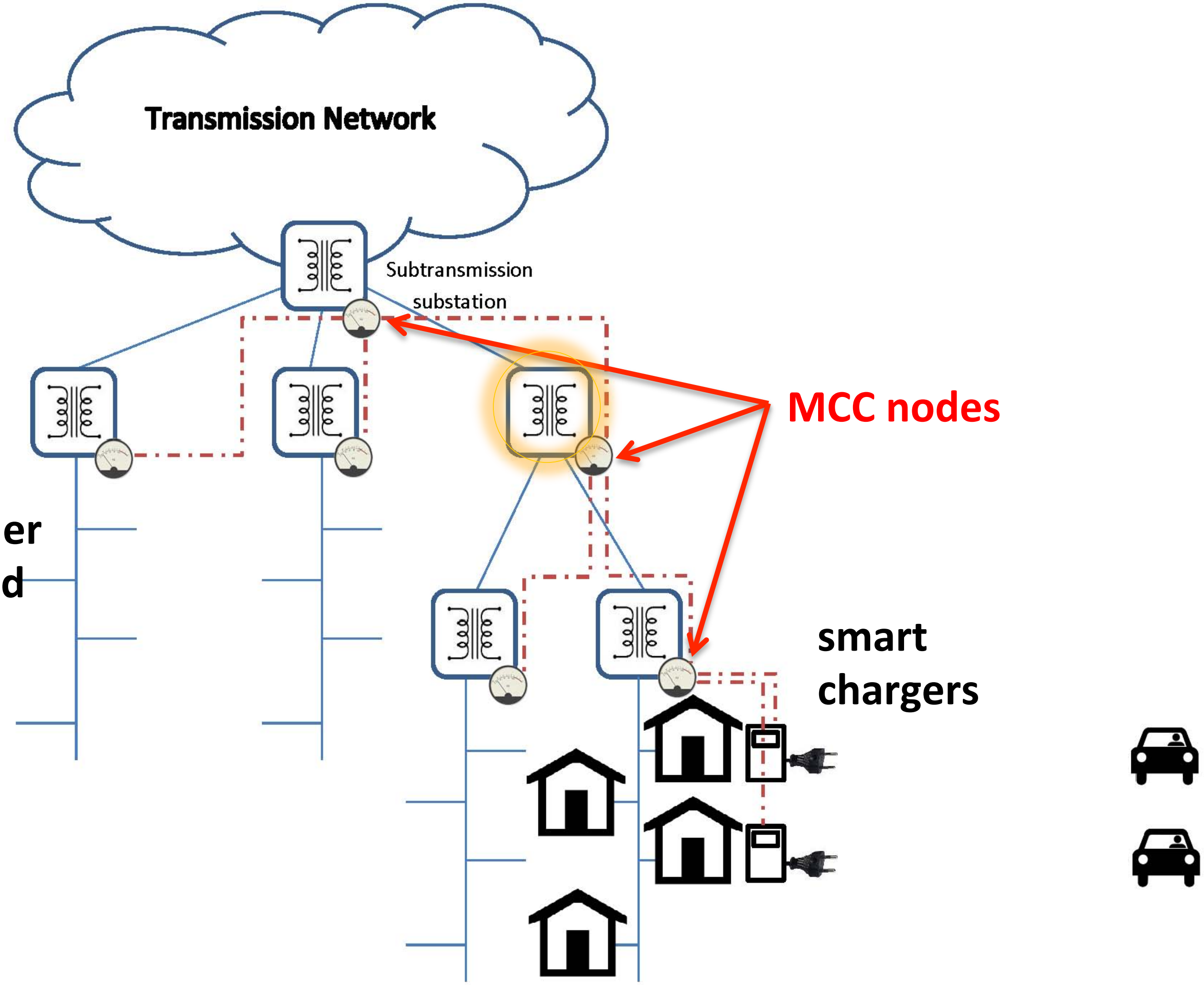
Contributions – cont'd

- Two distributed algorithms for the control of active end-nodes at scale
  - using near real-time measurements
  - balance system-level and user-level objectives
  - meet system constraints

- Optimal charging strategy for grid-tied solar-powered EV charging stations

EV Charging Control in Distribution Networks

System Model



MCC nodes

every line or transformer has a rated capacity and a setpoint

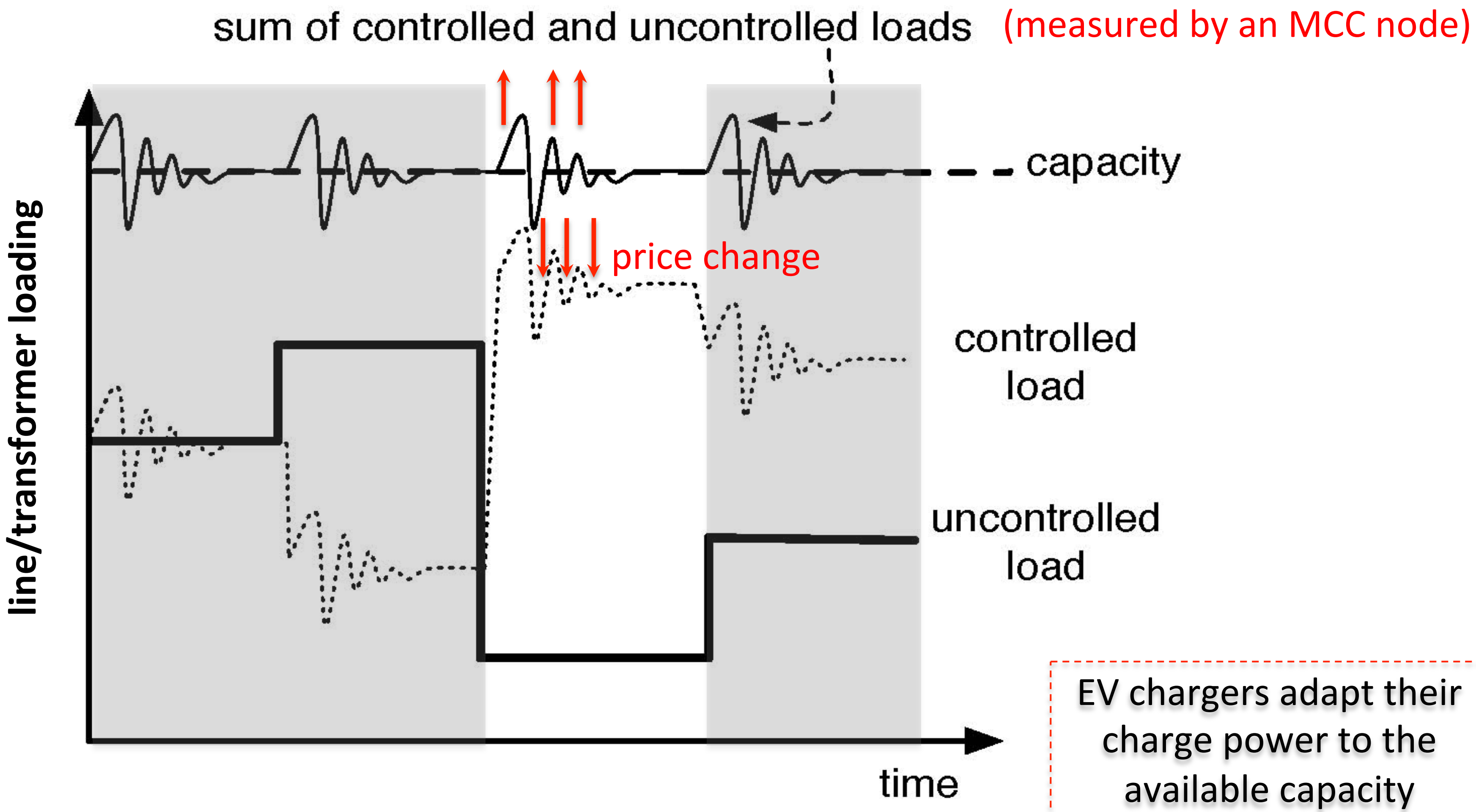
smart chargers

Prior Work

- Solving an OPF problem (day-ahead)
  [Vlachogiannis09, Clement-Nyns10, Mehboob14, Sharma14, …]
  - precise model of the distribution network
  - EV arrival and departure times
  - EV point of connection

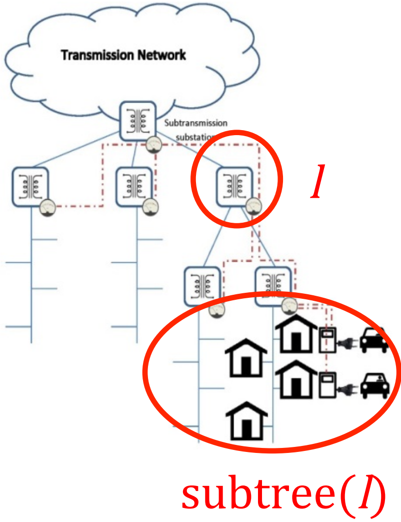
- Near real-time control
  - Centralized **[Deilami11, Shao12, …]**
    - not scalable
  - Decentralized **[Hermans12, Hilshey12, Fan12, Studli12, Wen12, Gan13, …]**
    - different objectives
    - distribution network model

TCP-inspired Control



EV chargers adapt their charge power to the available capacity

Proportionally Fair Allocation



A single snapshot optimization problem:

$$\max_{rate} \sum_{s \in \mathcal{S}} \log(rate_s)$$

subject to

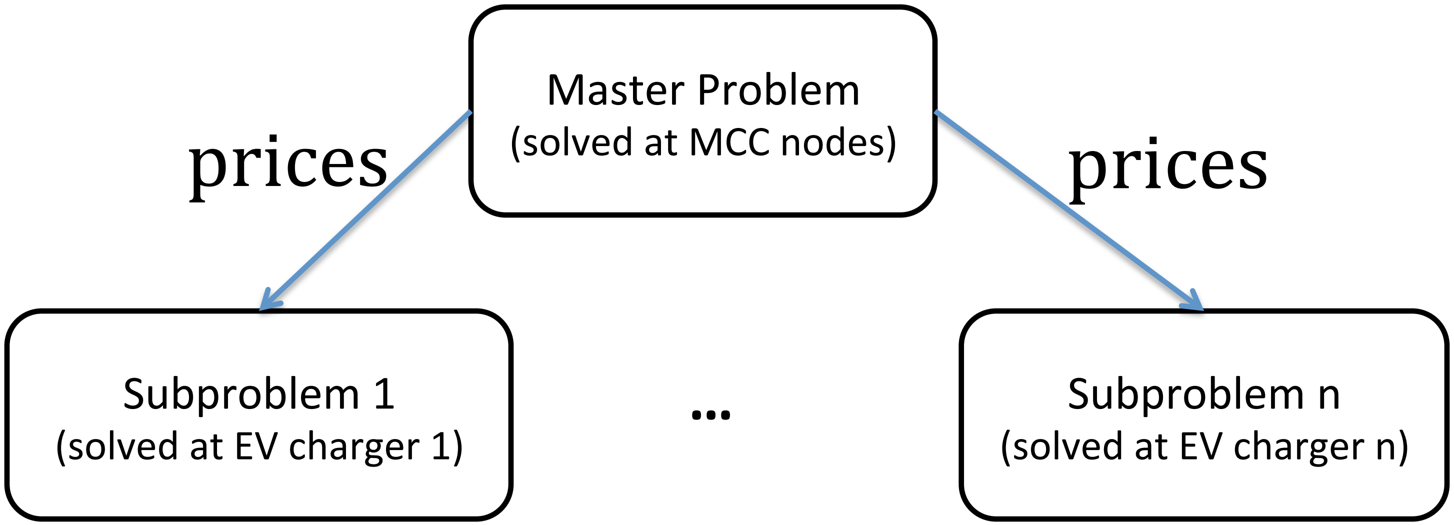
$$0 \leq rate_s \leq maxrate_s \qquad \forall s \in \mathcal{S}$$

$$EV\ load_l + home\ load_l \leq setpoint_l \qquad \forall l \in \mathcal{L}$$

Similar to **[Yaïche00] [Low99], [Kelly98]**

Dual Decomposition

Phase 1



Master Problem
(solved at MCC nodes)

prices

prices

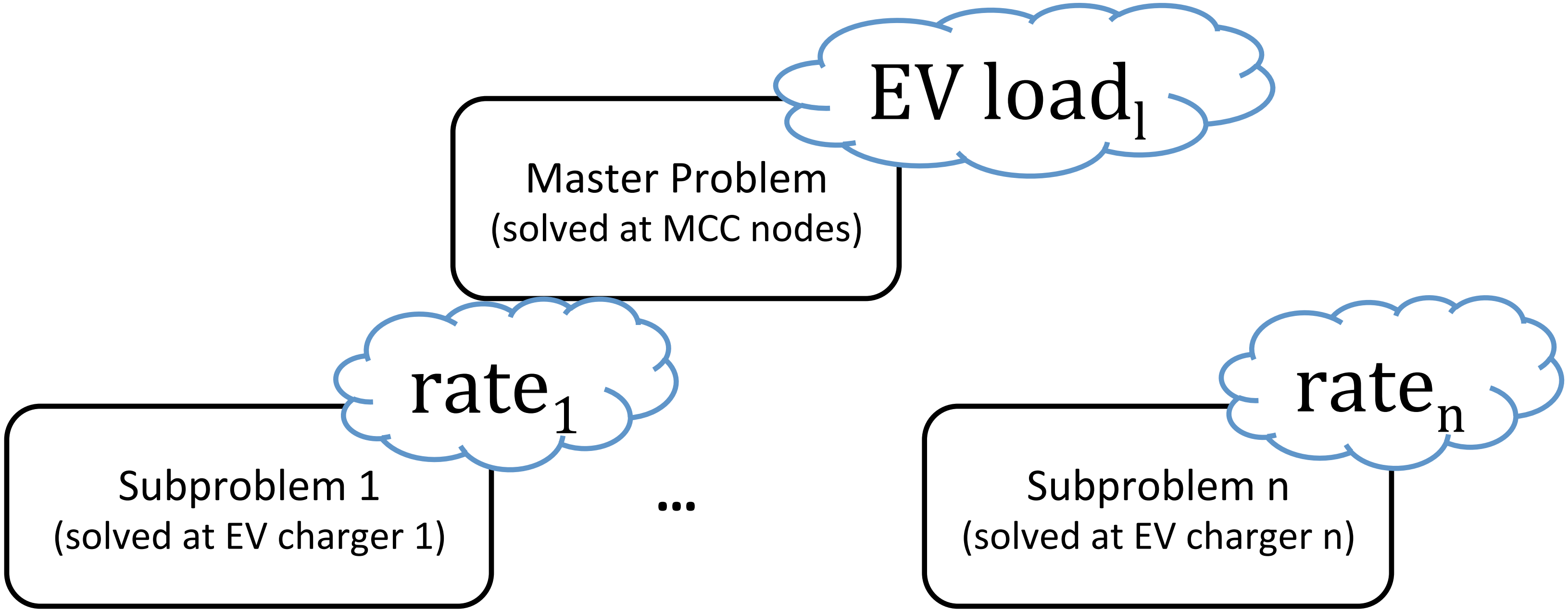
Subproblem 1
(solved at EV charger 1)

…

Subproblem n
(solved at EV charger n)

Dual Decomposition – cont'd

Phase 2



EV load_l

Master Problem
(solved at MCC nodes)

rate_1

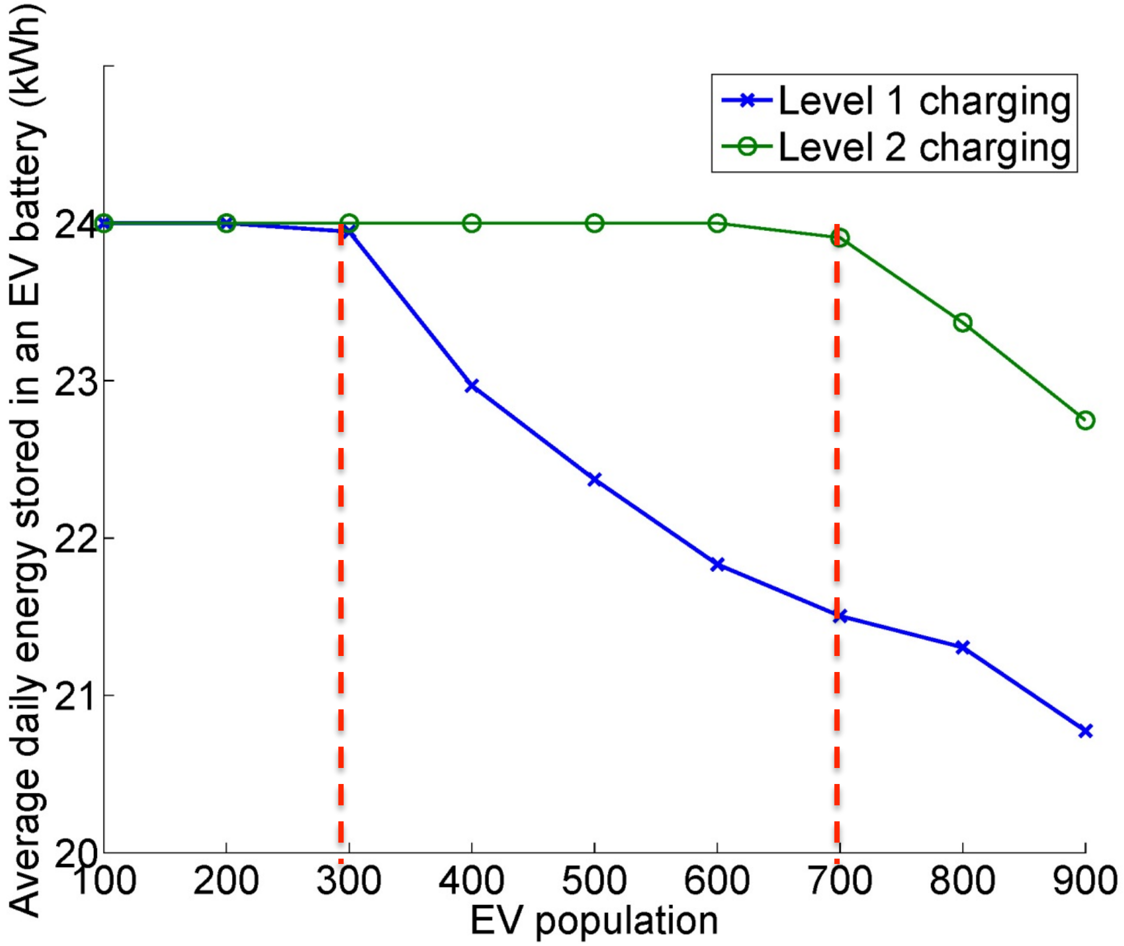
rate_n

Subproblem 1
(solved at EV charger 1)

…

Subproblem n
(solved at EV charger n)

Average Energy Stored in EVs with Control



For an acceptable level of overload, only 70 EVs could be fully charged without control

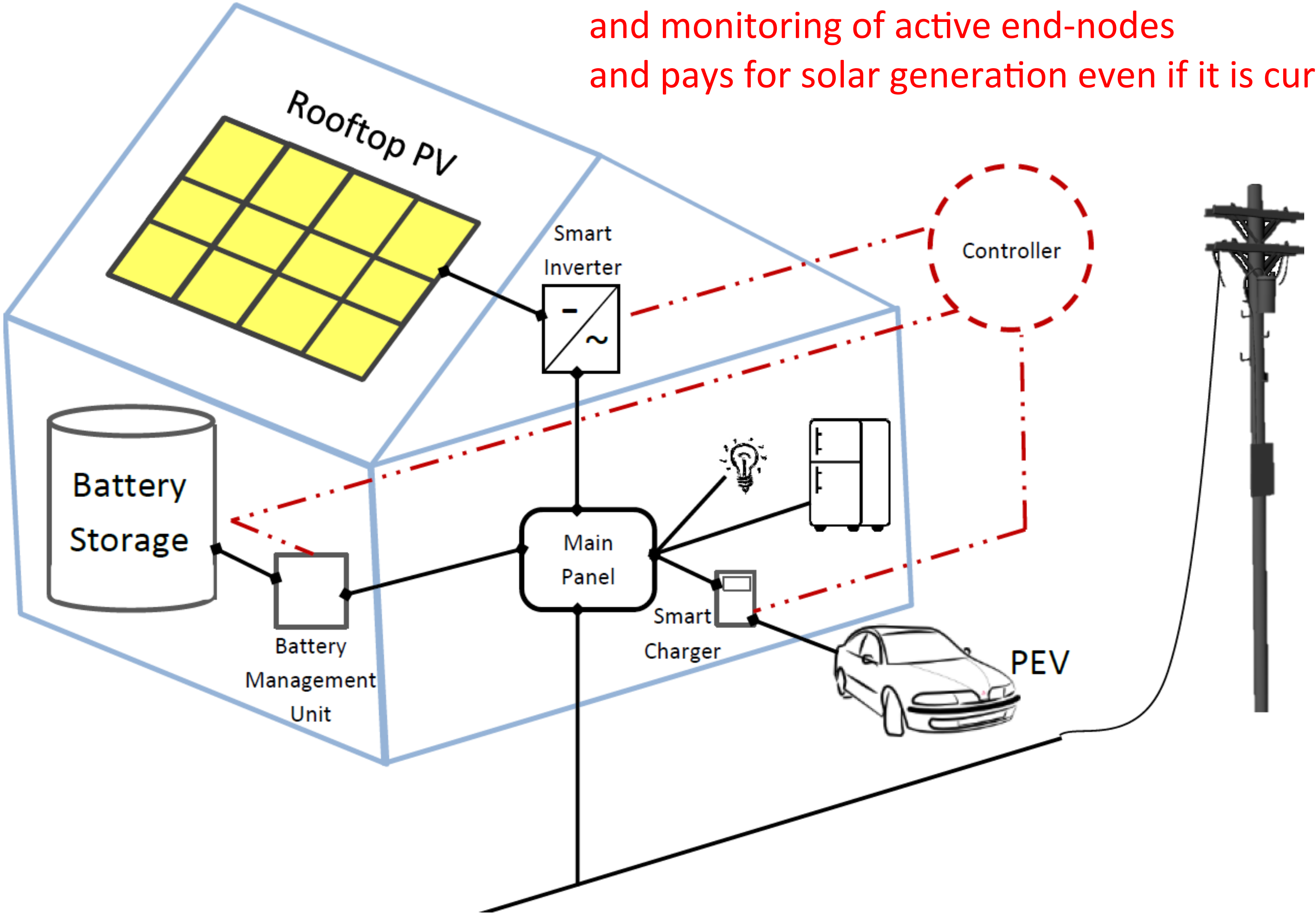
Insights

- Congestion control methods developed for computer networks are applicable, with some changes, to EV charging control
- MCC nodes are needed primarily at hotspots
- Distributed control algorithm scales well with the size of the distribution network and the number of chargers
- Limitations:
  - Slow convergence in some cases
  - Does not address voltage problems
  - Cannot deal with renewable generation or storage

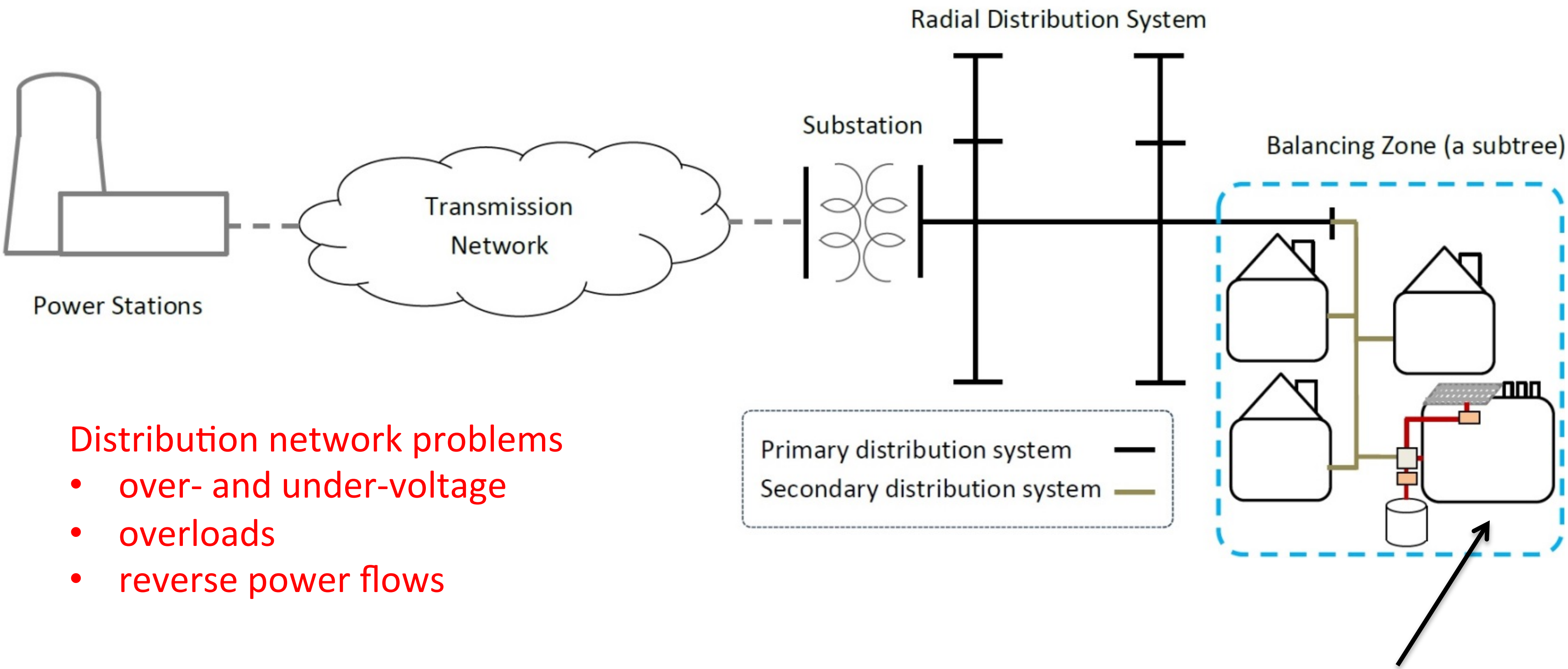
Optimal Control of Active End-nodes in Distribution Networks

System Model

Assumption: the utility is granted remote control and monitoring of active end-nodes and pays for solar generation even if it is curtailed



System Model – cont'd



Distribution network problems

- over- and under-voltage
- overloads
- reverse power flows

small business with active end-nodes

Mitigating Solutions for Utilities

- Upgrading distribution networks
- Curtailing solar PV generation
- Controlling active end-nodes
  - Storing/consuming excess solar generation
  - Sharing within each balancing zone

Prior Work

- DER integration in the smart grid **[Paudyal11]**
  - Control taps and capacitors
  - Different objectives
  - Unbalanced distribution network model

- Volt/VAR control in the distribution network **[Turitsyn10, Farivar12, Farivar13]**
  - Control PV inverters

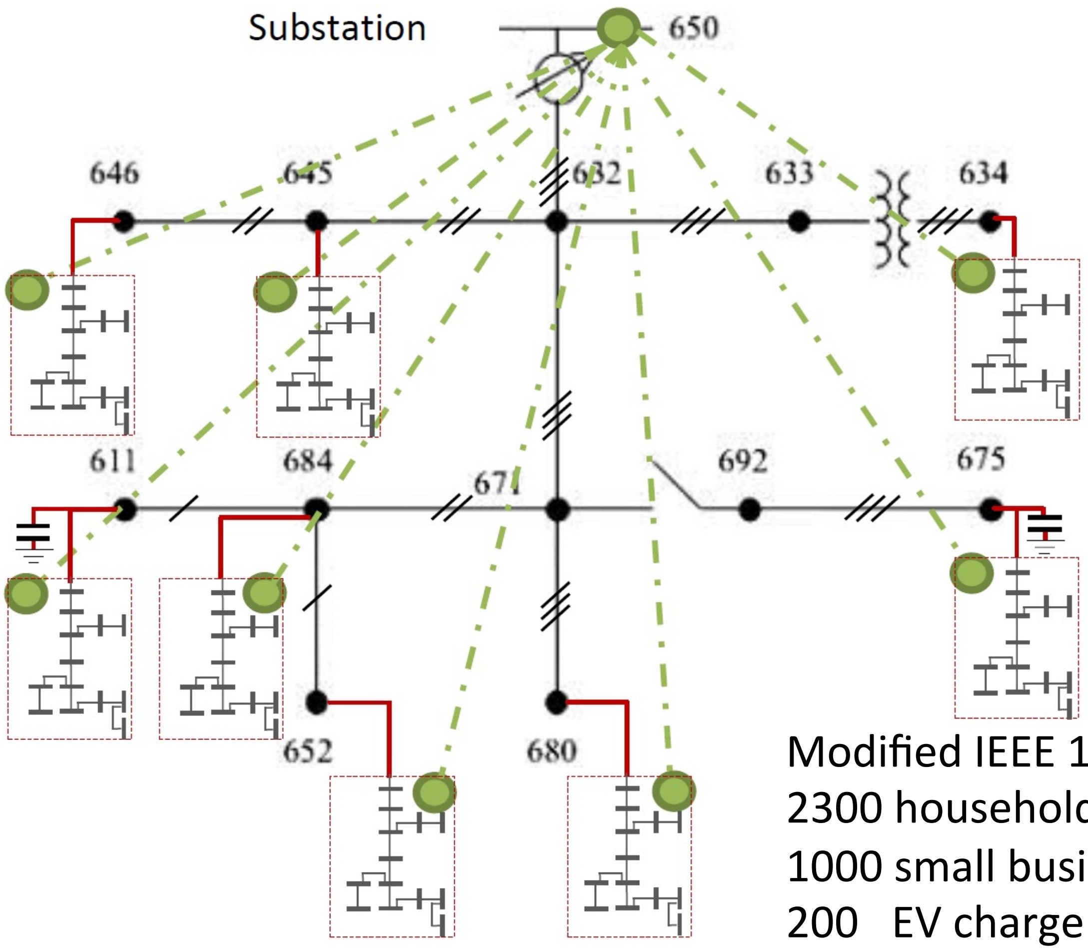
Our Approach

- Myopic
- Hierarchical
  - at two different levels: substation, balancing zone
- Relies on real-time measurements
- Incorporates a linearized power flow model
  - voltage, capacity, and reverse flow constraints

Objectives

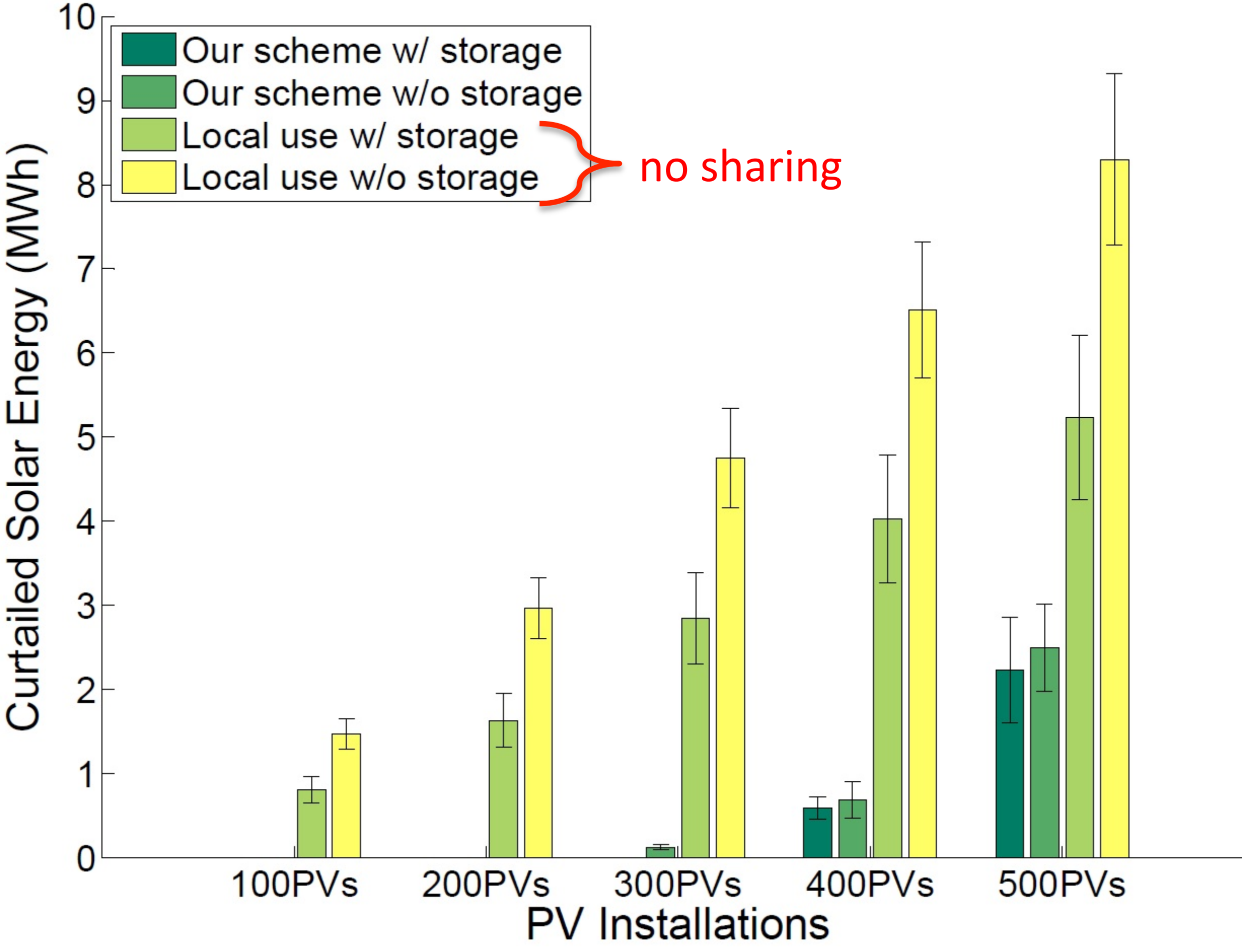
- Maximize revenue of the utility
  - i.e., maximize power allocated to elastic loads while providing fairness to elastic loads
- Minimize curtailment of solar power
- Minimize carbon emissions
  - i.e., minimize use of conventional (grid) power

Test Distribution Network



Modified IEEE 13 bus test feeder
2300 households
1000 small businesses
200 EV chargers
{100,200,300,400,500} PVs+Storage

Curtailed Solar Energy vs. PV Penetration Rate

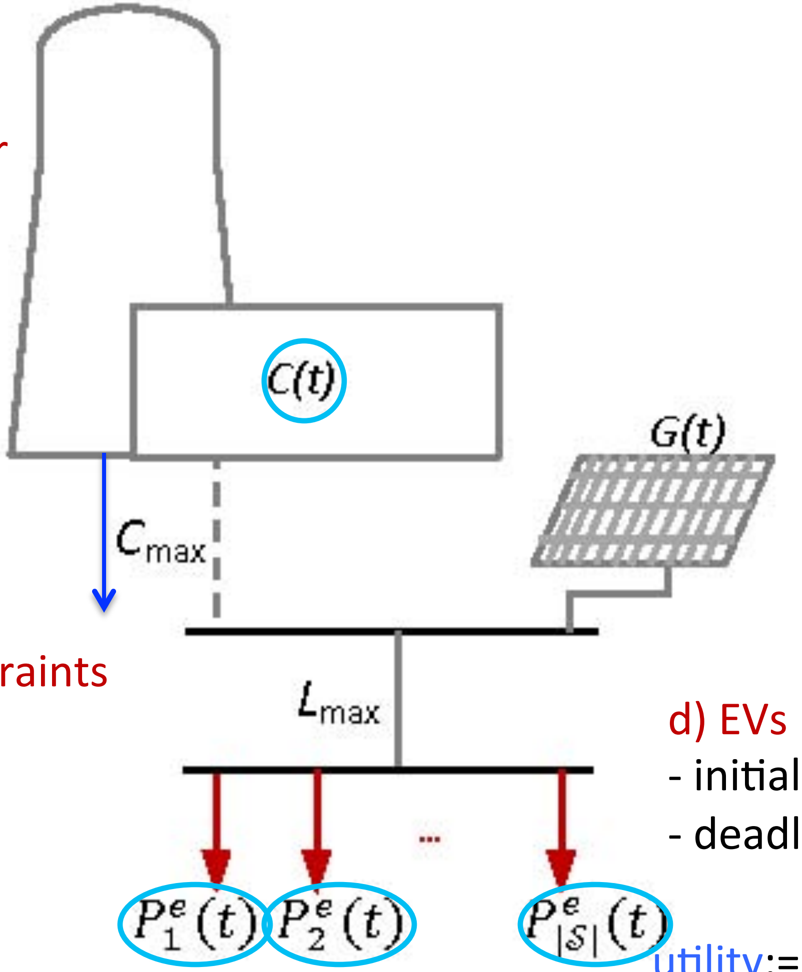


Insights

- The synergy between EV chargers and PV inverters can be used to cancel out their effects on distribution feeders
- Using a linearized power flow model, the optimal control can be computed in near real-time
- This approach does not require deployment of expensive MCC nodes
- Limitations:
  - The substation controller can be a bottleneck
  - Balanced radial distribution network model

Optimal Policies for Solar-Powered Charging Stations

System Model



a) conventional power
the carbon footprint of
conventional power
is assumed to be a
convex function of C(t)

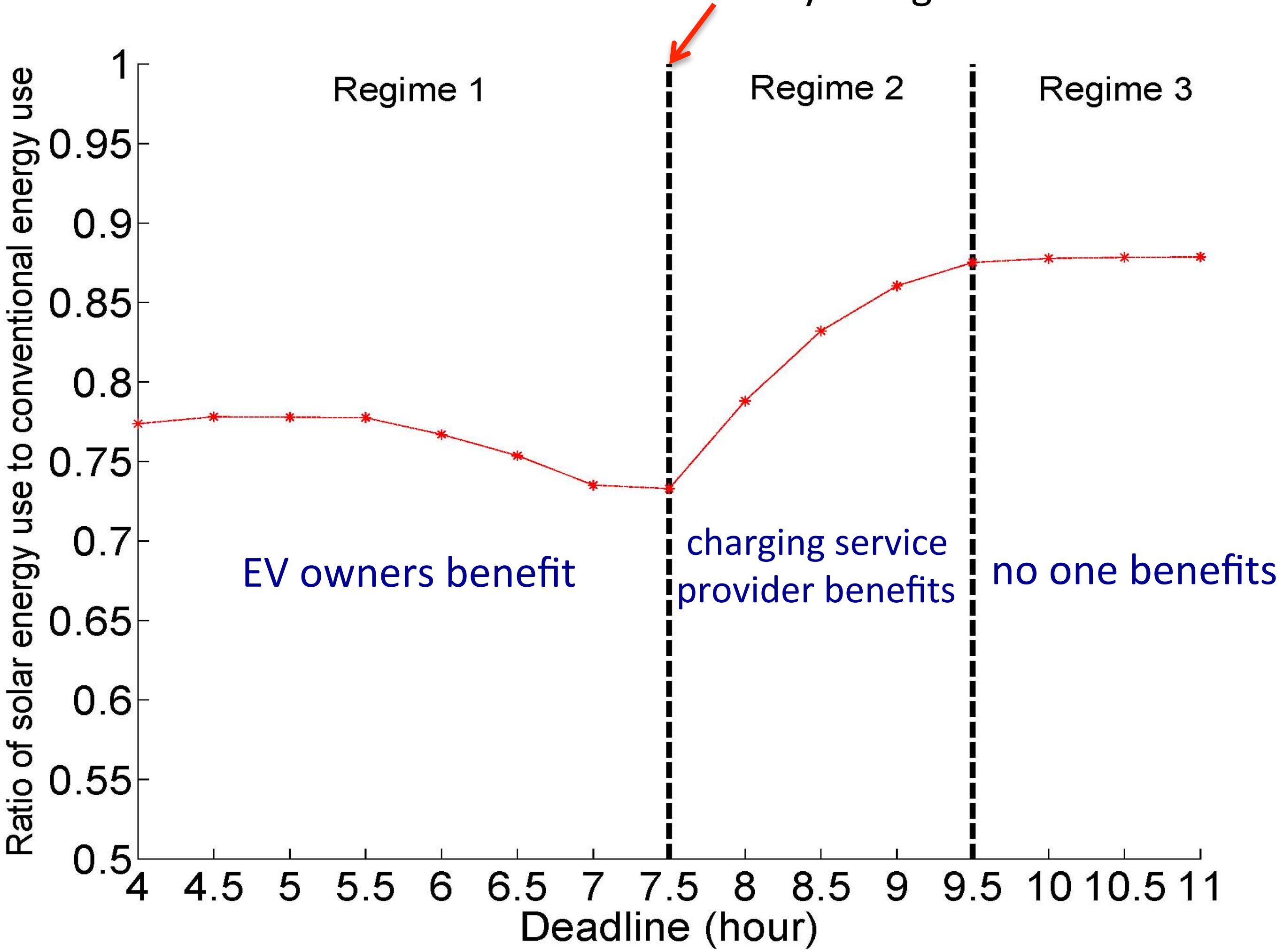
b) on-site solar generation
but no storage

c) feeder constraints

d) EVs
- initial state of charge
- deadline (set by owners)

utility:= energy_stored/initial_demand

Insights



EVs are fully charged

EV owners benefit

charging service provider benefits

no one benefits

Conclusions

Summary of Contributions

- A real-time distributed control scheme for fair power allocation to EV chargers based on measurements of feeder/transformer loading
  - A novel approach in this space

- A hierarchical control scheme for active end-nodes based on linearized power flow equations and real-time measurements of loads and states of the active end-nodes

- A cost-minimizing charging strategy for a solar-powered EV charging station

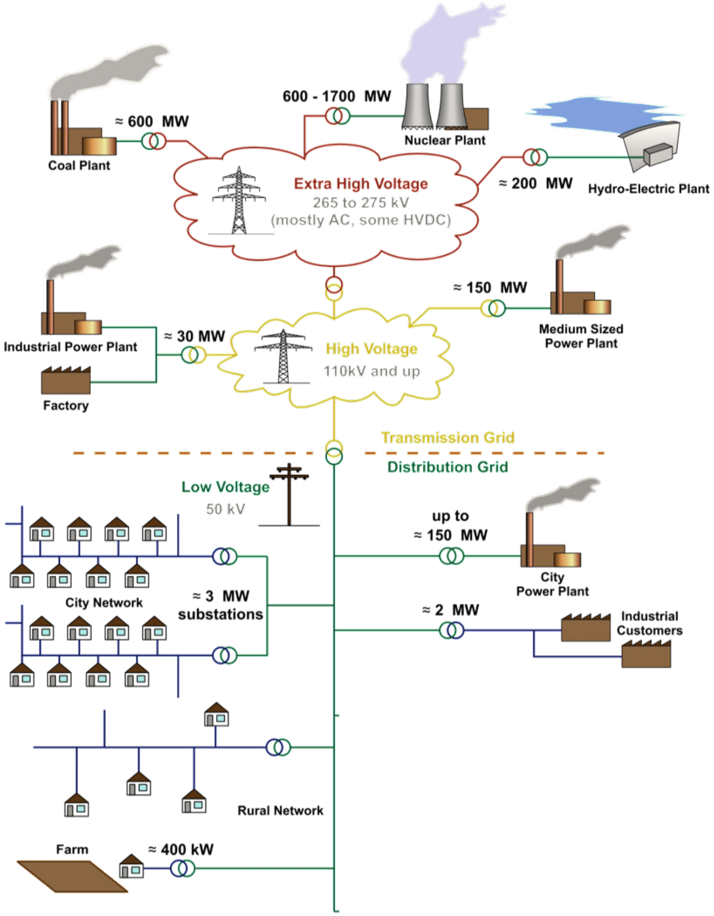
BACK UP SLIDES

Future Work

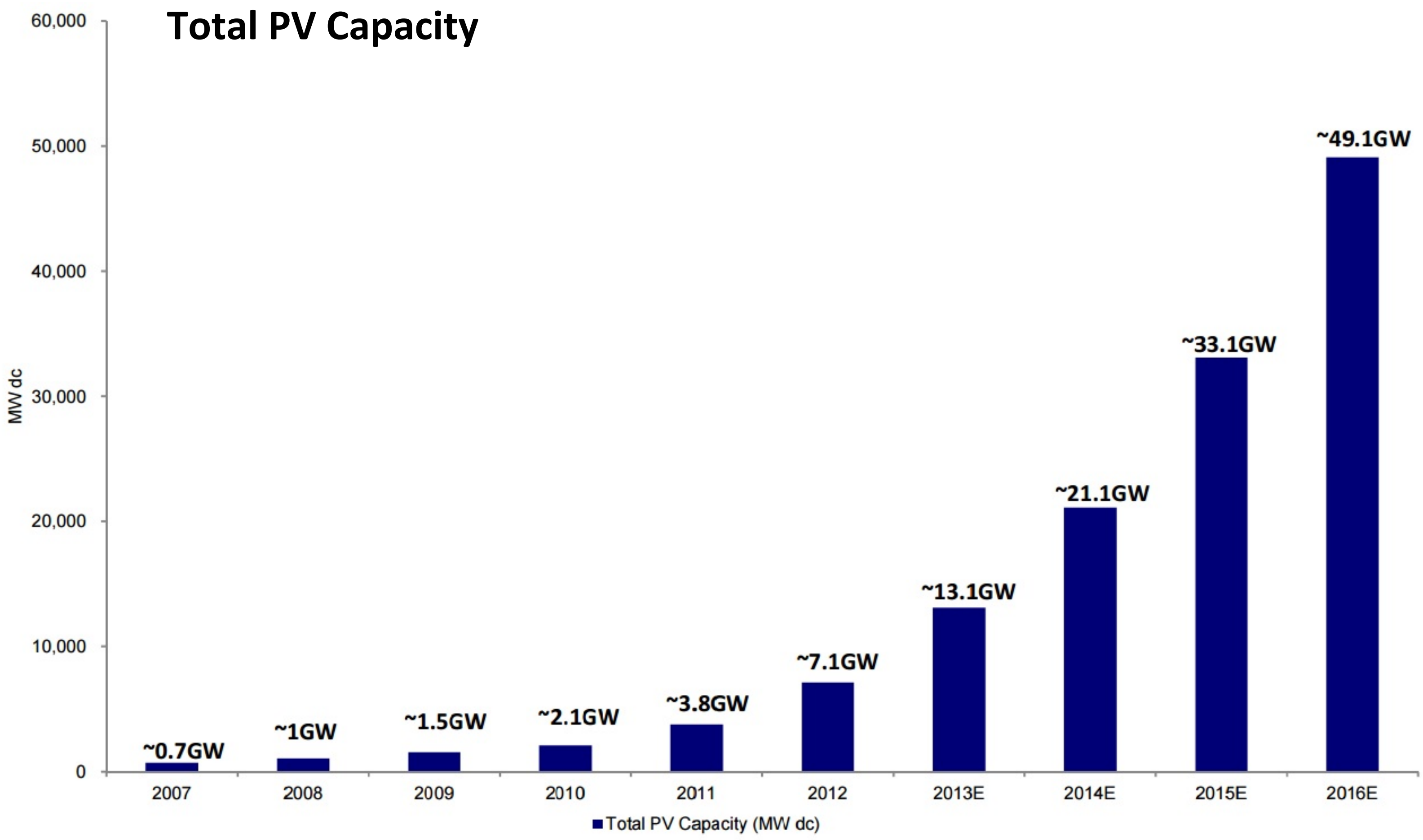
a) Using a Faster Distributed Algorithm to Control EV Charging
b) TCP-style Control for Active End-nodes
c) Generalizing to Unbalanced Multi-phase Distribution Systems
d) Optimizing Switching Operations of Load Tap Changers and Capacitors
e) Model Predictive Control for the Public EV Charging Station

Traditional Grid is Inefficient and Under-utilized

- Peak demand happens just a few hours a year
- Power generation facilities, and transmission and distribution networks are overprovisioned to ensure reliability
- Distribution networks are poorly monitored and controlled

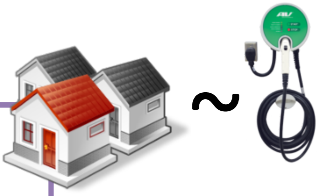


Exponential Growth of Solar PV Capacity



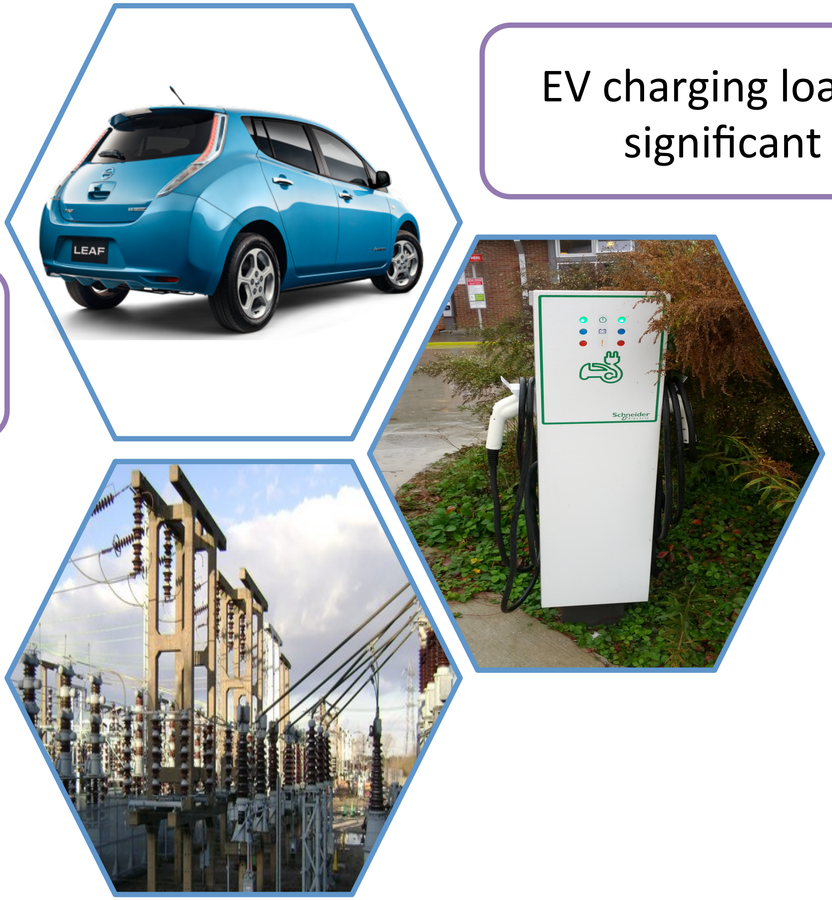
Source: Deutsche Bank

Electric Vehicle Charging



EV charging load is significant

spatial & temporal uncertainties



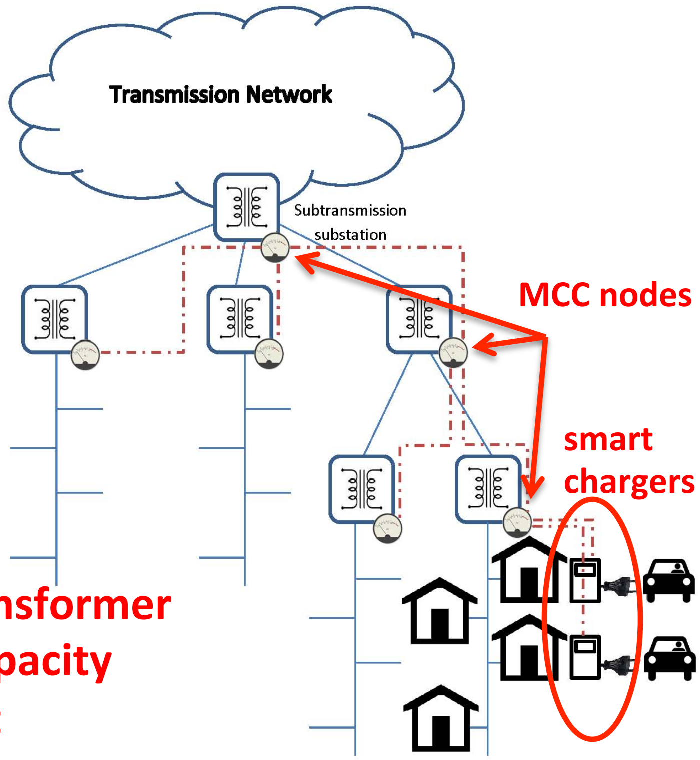
feeder & transformer overloading

System Model

Measurement, communications, and control (MCC) nodes

- measure branch power flow/transformer load,
- generate some feedback, and
- send to downstream nodes and smart chargers

in every time slot

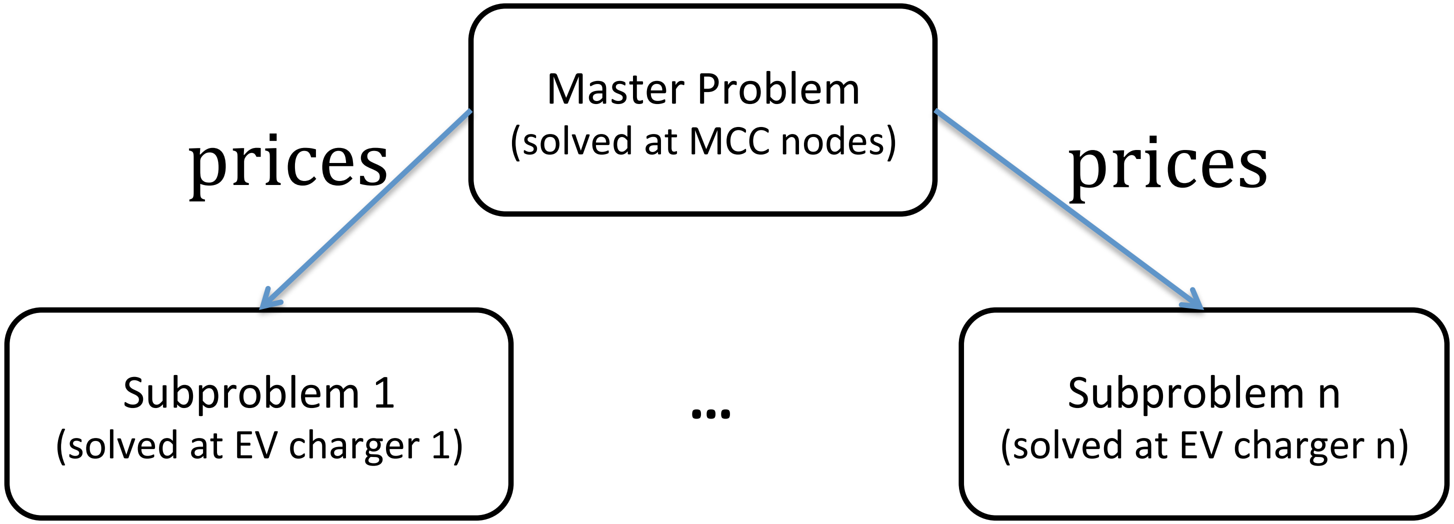


MCC nodes

smart chargers

every line/transformer has a rated capacity and a setpoint

Dual Decomposition & Control Rules



prices

Master Problem
(solved at MCC nodes)

prices

Subproblem 1
(solved at EV charger 1)

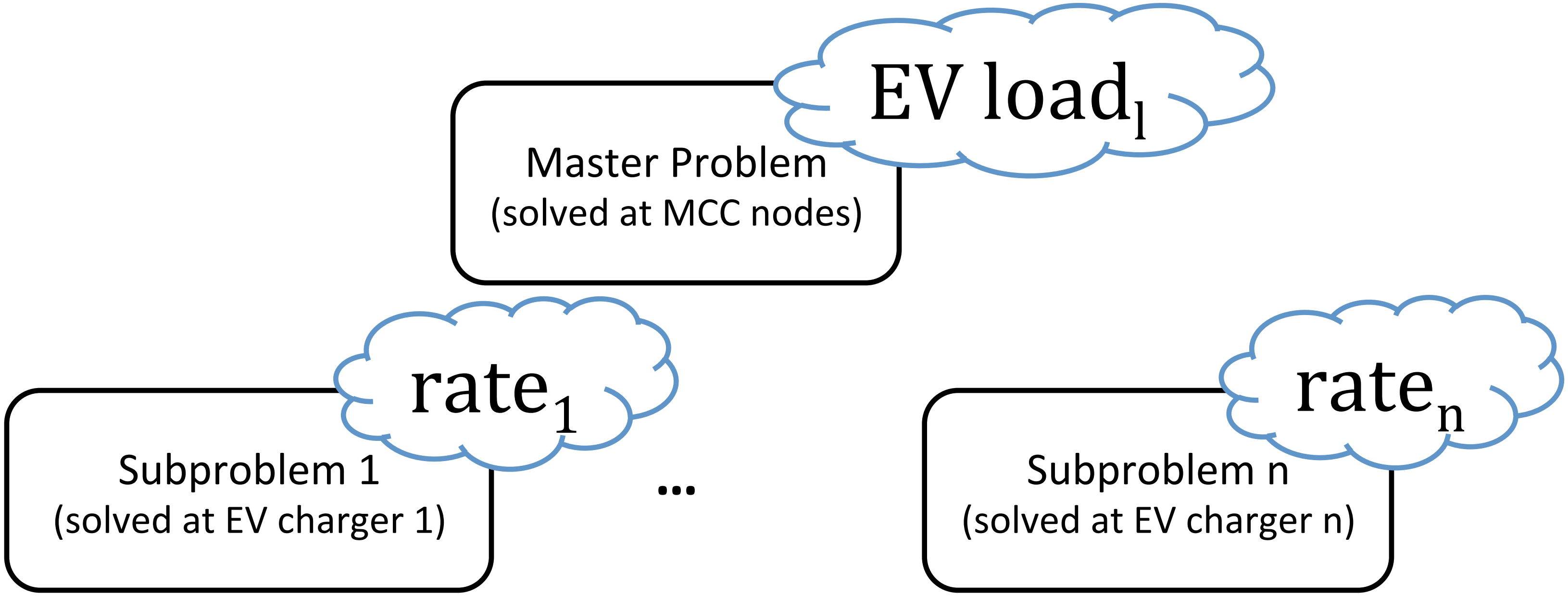
…

Subproblem n
(solved at EV charger n)

1. MCC nodes update congestion prices and send them to downstream EV chargers

$$price_l \leftarrow \max\{price_l - \boxed{stepsize} \times (setpoint_l - load_l), 0\}$$

Dual Decomposition & Control Rules



EV load_l

Master Problem
(solved at MCC nodes)

rate_1

Subproblem 1
(solved at EV charger 1)

…

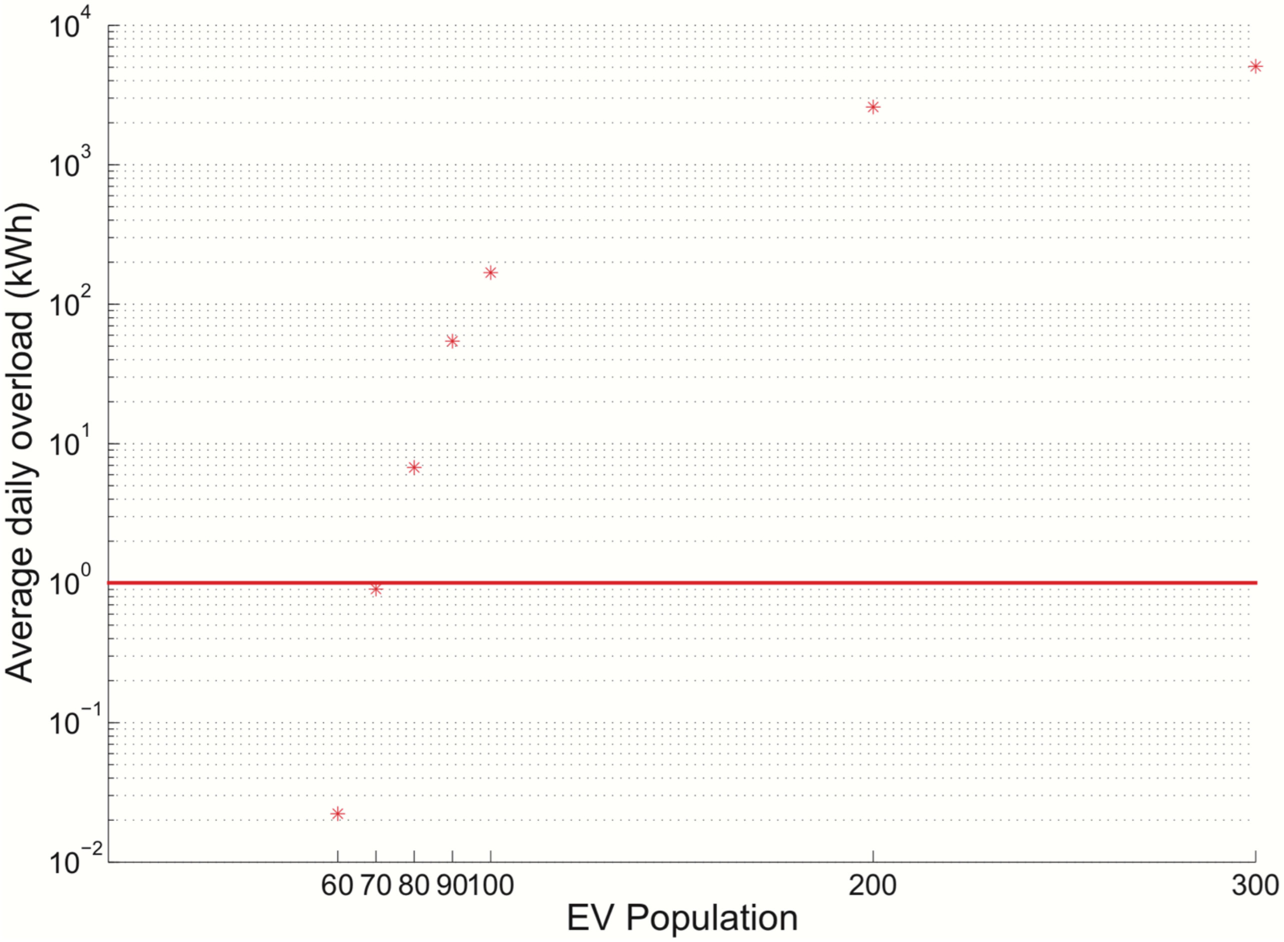
rate_n

Subproblem n
(solved at EV charger n)

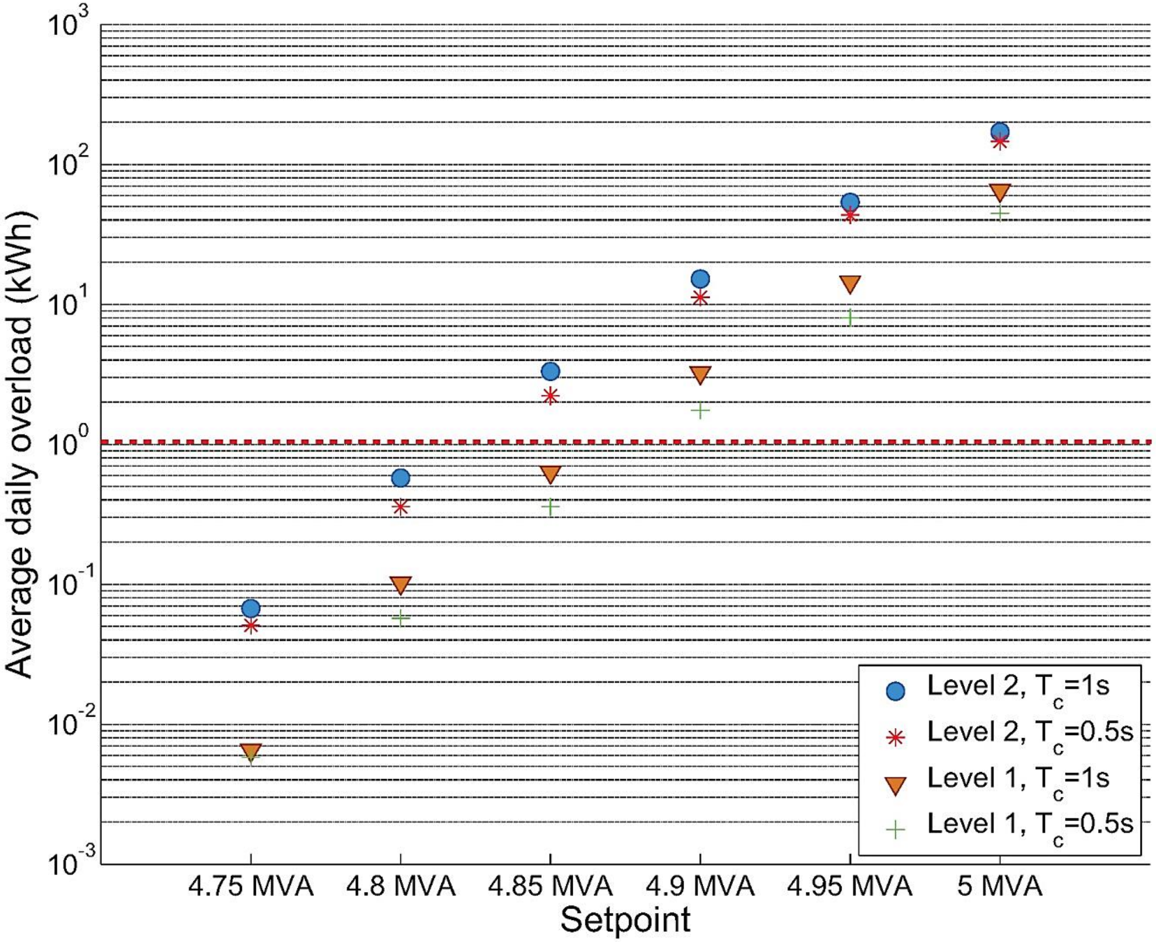
Phase 2: New rates are obtained from solving subproblems using new congestion prices

$$rate_s \leftarrow \min\left\{\frac{1}{path\ price_s}, maxrate_s\right\}$$

Average Daily Overload without Control

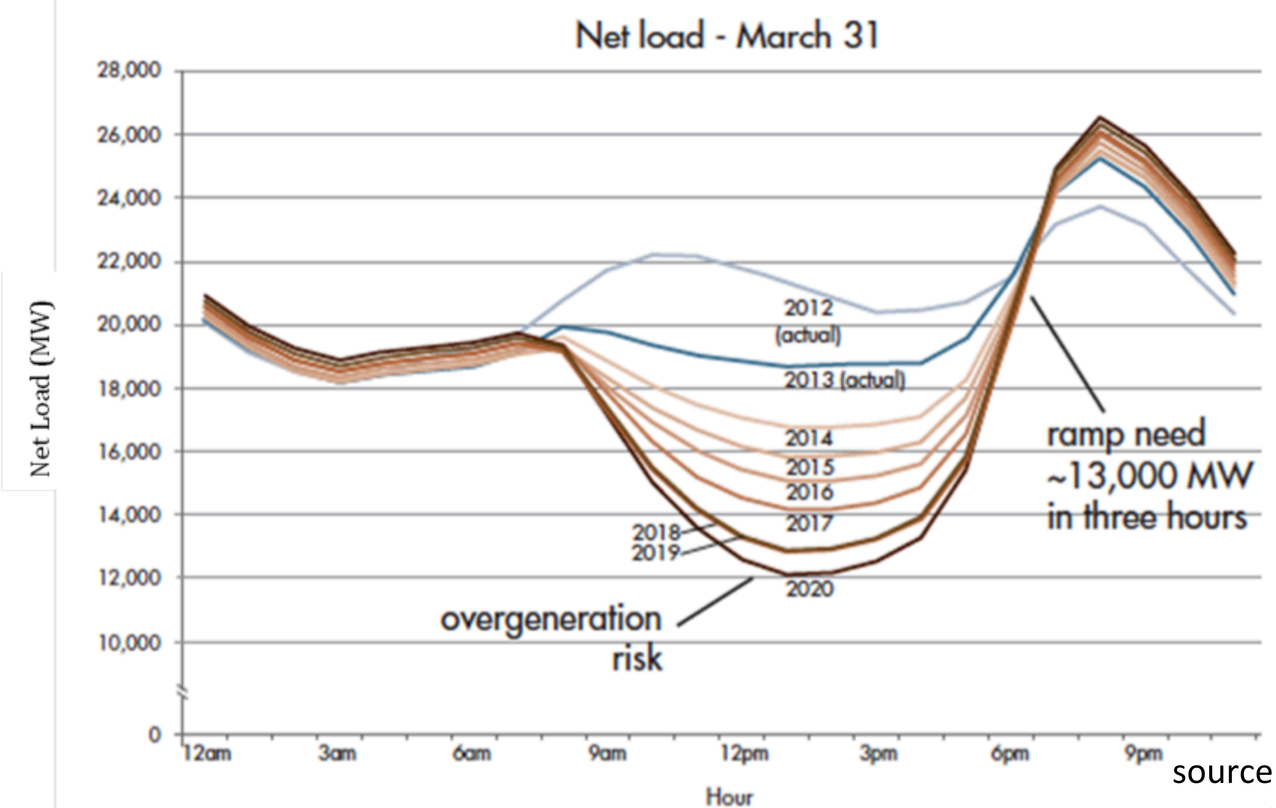


Choosing the Setpoint



High Penetration of Residential Solar Power has Wide Ramifications

in addition to overvoltage and reverse flow at the distribution level



source: http://www.caiso.com/Documents/FlexibleResourcesHelpRenewables_FastFacts.pdf

Mitigating Solutions for Utilities

Storage

Curtailment

Sharing

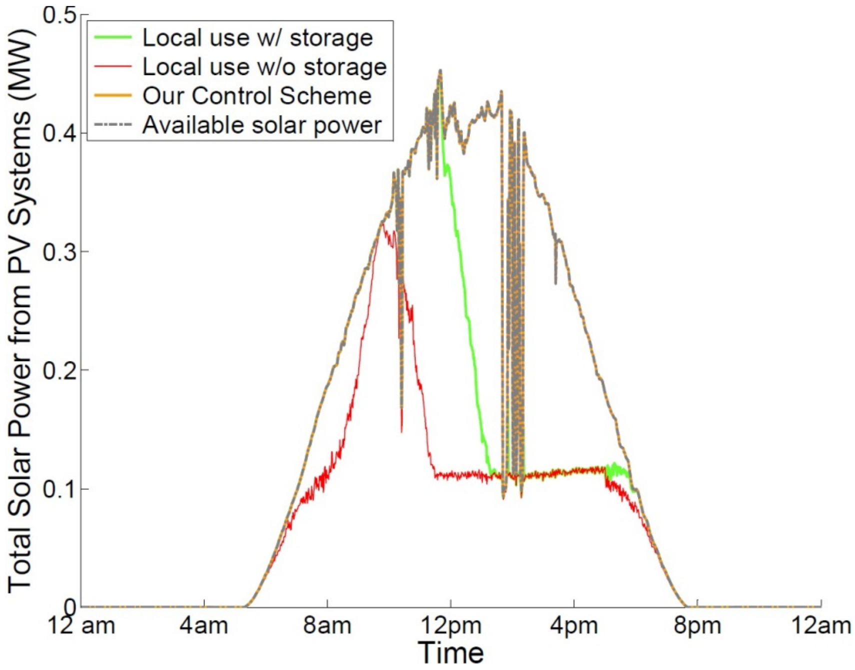
Network Upgrade

Demand Elasticity

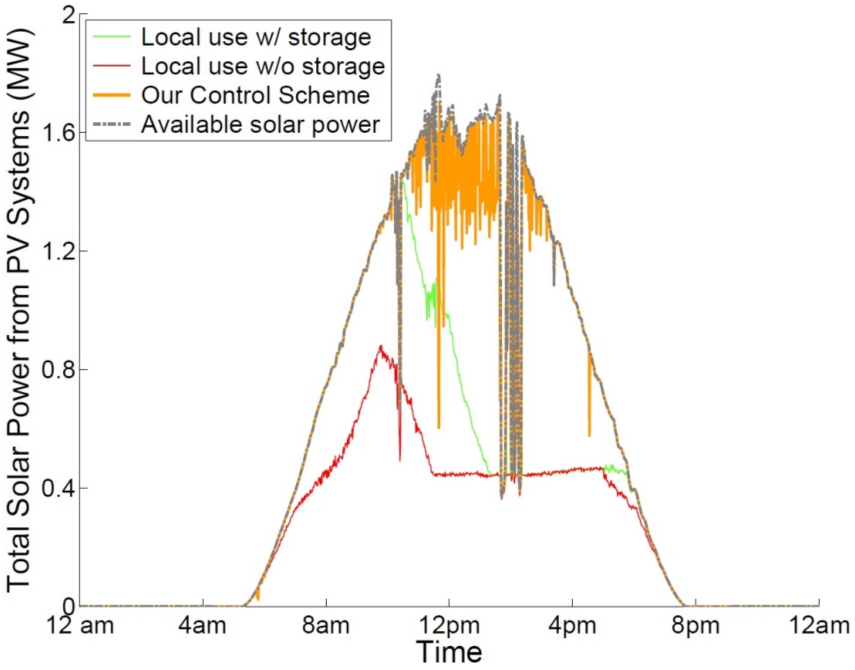
Balancing supply and demand where and to the extent that is possible using new technologies

Results

100 PV panels (3% penetration)



400 PV panels (12% penetration)



Requirements

1. On-site solar generation should not negatively affect the utility of an EV owner
2. Carbon emissions must be minimized
3. Power allocation must be fair to users

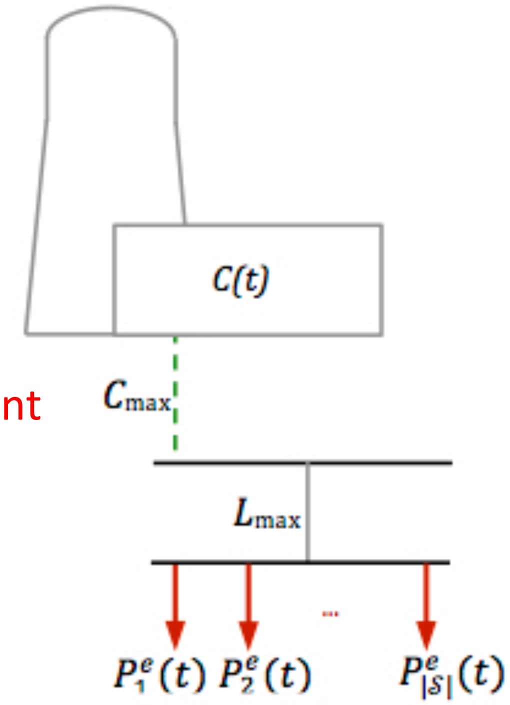
This is a multi-objective optimization problem!

Offline Algorithm

- Has three steps:
  - Compute the worst-case utility, assuming no solar (satisfying the first requirement)
  - Compute the carbon-minimizing power allocation to meet the worst-case utility, given the amount of solar power available (satisfying the second requirement)
  - Allocate the available power fairly among the users (satisfying the third requirement)

Step 1: Compute the Worst-Case Utility

Convex optimization



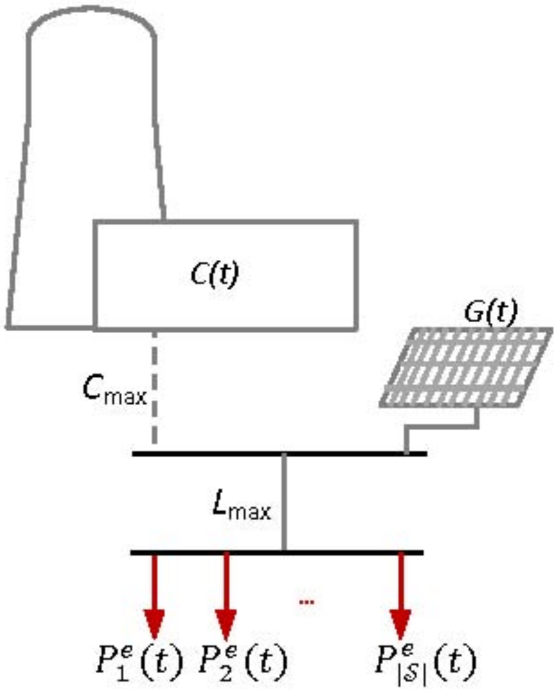
binding constraint

Input: EV arrival times, initial demands, and deadlines

Output: energy supplied to every EV, i.e., the worst-case utility of every EV

Step 2: Find the Carbon-Minimizing Dispatch

Linear programming

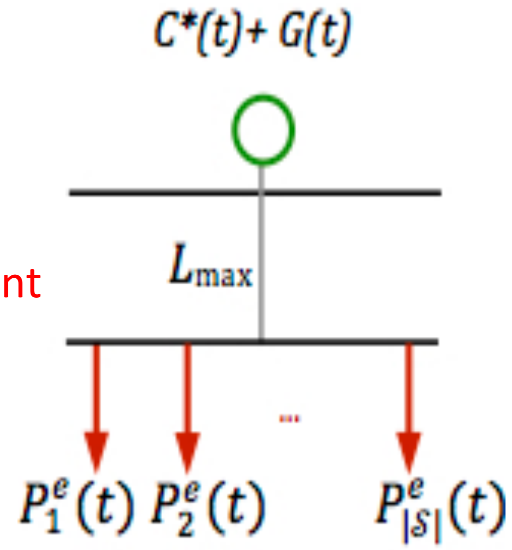


Input: worst-case utilities, incoming solar radiation

Output: optimal use of grid power - C*(t)

Step 3: Compute the Fair Allocation of Available Power

Convex optimization



binding constraint

Input: worst-case utilities, total available power

Output: fair energy allocation to EVs, never less than before