PEV Coordination Through Market Prices and Network Use-of-System Charges

An overview of research on power system challenges with many PEVs

Ilan Momber


SETS Joint Doctorate:

♦ 2nd HEI: Royal Institute of Technology (KTH), Stockholm
♦ Home HEI: Instituto de Investigación Tecnológica (IIT), Madrid
The SETS JD is an international programme offered by six different universities in a consortium.
The SETS Joint Doctorate
More Information

Duration
Standard duration: 4 years, from September 2012 onwards.

Timetable
Full-time dedication.

Credits
Training activities consist in at least 60 ECTS credits regarding doctoral courses.

Degree
A Joint degree awarded by Comillas Pontifical University, Delft University of Technology and KTH Royal Institute of Technology.

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The following talk:

An overview of research on power system challenges with high PEV penetrations


PEVs in the Big Picture

Why the PEV may be part of future systems:

- Human mobility and the individual transport sector need to adapt to mitigate emissions impact
- Modern power systems with large shares of vRES call for flexible demand, storage and reserve
- PEVs are highly efficient
- PEV penetration low, but growing
1 Background Info and Concepts
   - Qualitative Foundation of Work: Regulatory Aspects
   - PEV in Future Power Systems

2 PEV Coordination with DLC
   - Market Participation Under Uncertainty
     - Risk Management
     - Expected Value of Aggregation
   - PEV Charging Schedules for Efficient Network Use
     - Pricing Network Capacity with DSO’s LRMC
     - Temporal and Spatial PEV Charging Alignment

3 PEV Coordination with ILC
   - KKT-Optimality
     - Comparing Retail Price Alternatives of the Aggregator
   - Affine Demand and Strong Duality
     - Endogenous Hourly Retail Prices

4 Final Remarks
PEV in Future Power Systems
A Brief Overview at a Glance

Electricity Market - PEV Aggregator
- Takes market decisions on multiple trading floors
- Exposed to uncertainty in prices, fleet availability and demand

MV/LV Distribution Grid - DSO
- Network expansion planning
- Operates the grid in secure conditions (voltages, line currents)
- Calculates network use-of-system fees

PEV Mobility - Final customers
- Drive and connect at supply points
- Require energy for mobility
Qualitative Basis of Work
Regulatory Aspects of Power Systems

FP7 MERGE - WP5, titled:

**Regulatory Framework and Business Models for Efficient PEV Integration**

- For further reading: a conference Momber et al. [2011a], and a journal Gómez et al. [2011] paper, as well as a book chapter Momber et al. [2013]
- Project deliverables are online and accessible: notably MERGE D5.2 Momber et al. [2011b] and MERGE D5.3 Michel Rivier et al. [2012],
- Good overview document: EES-UETP workshop for Ph.D. students Ilan Momber [2011].
EPS Regulatory Aspects
An overview of qualitative assertions
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An overview of qualitative assertions
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4 Final Remarks
Similar Problems in EPS Research
Self-Scheduling of a PEV fleet via the Aggregator

- Short-term planning challenge of such a PEV Aggregator is a combination of known power system problems:
  - Bathurst and Strbac [2003]: wind power producer with energy storage,
  - Carrión et al. [2007]: a large consumer (with on-site generation),
  - Carrión et al. [2009]: a retailer with stochastic demand, as well as
  - Morales et al. [2010] and Pineda-Morente [2011]: a conventional producer with resource unavailability.

- The here presented model can analyze, how price uncertainty and mobility-caused PEV unavailability affect optimal market involvement and profit functions of this future agent.

- Individual single firm perspective of decision maker.
Sources of Uncertainty
Modelling the short-term future

Market Price Uncertainty
Challenge: capturing characteristics such as daily/weekly seasonality, high frequency and high volatility.

Uncertainty from PEV Mobility
Open Question: is a future fleet of PEV going to exhibit similar patterns as today’s ICE propelled mobility?
Market Price Uncertainty

Econometrics: SARIMA and GARCH time series models for short-term forecasting.

Uncertainty from PEV Mobility

Scenario generation based on available data from mobility patterns reported in household travel surveys, such as the German *Mobilität in Deutschland* (MID).

Dallinger and Wietschel [2012]
Stylized Decision Framework
General Market Clearing Structure in a Weekly Time Frame

\( \lambda^B_{h49} : \) Clearing of Balancing Market for next hour: 49h

\( \lambda^D_{d1} : \) Clearing for all 24h of day \( d_1 \)

Futures Contracting
Stylized Decision Framework

PEV Multi-Market and Client Interactions

Day-Ahead Market

\[ e_h \cdot \lambda^D_h \]

\[ e_{h}^\wedge \cdot \lambda^D_h \]

PEV Aggregator

\[ \sum_{v \in V} e_{v,h,\omega}^\wedge \cdot \gamma_{h}^\wedge \]

\[ \sum_{v \in V} e_{v,h,\omega}^\vee \cdot \gamma_{h}^\vee \]

Balancing Market

\[ e_{h,\omega}^{B+} \cdot \lambda_{h,\omega}^- \]

\[ e_{h,\omega}^{B-} \cdot \lambda_{h,\omega}^+ \]

Client Side
Mathematical Formulation

Objective Function

The self-scheduling problem in (1) seeks the risk-neutral maximization of expected profits from scenario-weighted day-ahead transactions $\Pi^D_\omega$, and imbalance settlements $\Pi^B_\omega$, client-side retail to PEV $\Pi^C_\omega$ as a price taker in combination with a weighted measure of the CVaR:

Maximize $\mathbb{E}\{\Pi^{Tot}_\omega\} + \beta \cdot \text{CVaR}$

$$= \sum_{h \in H} \left[ \pi_\omega \sum_{\omega \in \Omega} \left( \Pi^D_{h,\omega} + \Pi^B_{h,\omega} + \Pi^C_{h,\omega} \right) \right] + \beta \cdot \text{CVaR}, \quad (1)$$

where the different components break down as follows:

$\forall h, \omega : \Pi^D_{h,\omega} = \left[ \left( e^{D}_{h,\omega} \frac{\bar{\tau}}{\tau} - e^{D}_{h,\omega} / \tau \right) \lambda^D_{h,\omega} \right], \quad (2)$

$\forall h, \omega : \Pi^B_{h,\omega} = \left[ e^{B-}_{h,\omega} \lambda^-_{h,\omega} - e^{B+}_{h,\omega} \lambda^+_{h,\omega} \right], \quad (3)$

$\forall h, \omega : \Pi^C_{h,\omega} = \sum_{v \in V} \left[ e^{RT}_{v,h,\omega} \gamma - e^{RT}_{v,h,\omega} \bar{\gamma} \right] \quad (4)$

and $\text{CVaR} = \frac{1}{\theta - 1} \sum_{\omega \in \Omega} \pi_\omega \cdot \gamma_\omega. \quad (5)$
Mathematical Formulation

Main Constraints

∀ h, ω : \( \sum_{v \in V} [e_{v, h, \omega}^{RT, \vee} - e_{v, h, \omega}^{RT, \wedge}] = (e_{h, \omega}^{\vee} - e_{h, \omega}^{\wedge}) + (e_{h, \omega}^B - e_{h, \omega}^B) \), \hspace{1cm} (6)

∀ v, h, ω : \( e_{v, h, \omega}^{SOC} = e_{v, h-1, \omega}^{SOC} + (e_{v, h, \omega}^{RT, \vee} \eta_v^{\wedge}) - (e_{v, h, \omega}^{RT, \wedge} \eta_v^\vee) - \rho_{v, h, \omega} \), \hspace{1cm} (7)

∀ h, ω, ω' : \( e_{h, \omega}^D = e_{h, \omega'}^D, \quad e_{h, \omega}^{\wedge} = e_{h, \omega'}^{\wedge} \), \hspace{1cm} (8)

∀ v, h, ω : \( e_{v, h, \omega}^{RT, \vee} + e_{v, h, \omega}^{RT, \wedge} \leq \nu_{v, h, \omega} \cdot \overline{P}_v \), \hspace{1cm} (9)

∀ v : \( e_{v, 0}^{SOC} = \nu_v^{SOC}, \quad e_{v, |\mathcal{H}|}^{SOC} = \phi_v^{SOC} \), \hspace{1cm} (10)

∀ v, h, ω : \( \overline{E}_v \leq e_{v, h, \omega}^{SOC} \leq \overline{E}_v \), \hspace{1cm} (11)

∀ ω : \( -\Pi_\omega^{Tot} + \zeta - \iota_\omega \leq 0 \), \hspace{1cm} (12)

∀ ω : \( \iota_\omega \geq 0 \). \hspace{1cm} (13)
Implementation
MatLab $\leftrightarrow$ GAMS via GDX
Applying the Model
The Value of Flexibility and Aggregation

EVPEV-F:

The value of flexibility is the difference to the no-control case:

\[ z_{\text{flex}} = \frac{z_{\text{DLC}} - z_{\text{noC}}}{z_{\text{noC}}} = 33.1\% . \]

EVPEV-A:

<table>
<thead>
<tr>
<th>Sub-Fleetsize</th>
<th>( V^k )</th>
<th>1000</th>
<th>250</th>
<th>40</th>
<th>25</th>
<th>10</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td># Aggregations</td>
<td>(</td>
<td>K</td>
<td>)</td>
<td>1</td>
<td>4</td>
<td>25</td>
<td>40</td>
</tr>
<tr>
<td>( z_{\text{sf}} = \sum_k \left[ \mathbb{E} \left{ \Pi^\text{Tot}_k \right} + \beta \cdot \text{CVaR}_k \right] []</td>
<td>16.894</td>
<td>16.711</td>
<td>16.484</td>
<td>16.009</td>
<td>14.467</td>
<td>13.613</td>
<td></td>
</tr>
<tr>
<td>EVPEV-A ( z_{\text{agg}} ) []</td>
<td>-</td>
<td>0.183</td>
<td>0.410</td>
<td>0.885</td>
<td>2.427</td>
<td>3.282</td>
<td></td>
</tr>
<tr>
<td>Relative EVPEV-A ( \frac{z_{\text{agg}}}{z_{\text{DLC}}} ) [%]</td>
<td>-</td>
<td>1.08%</td>
<td>2.43%</td>
<td>5.24%</td>
<td>14.37%</td>
<td>19.42%</td>
<td></td>
</tr>
</tbody>
</table>
Managing Exposure
Conditional Value at Risk Effects

Cum. Prob. $F(x) = \sum_{\omega} \pi_{\omega} : \Pi_{\omega} < x$

- $\Pi_{\omega}^{Total, \beta=0.01}$
- $\Pi_{\omega}^{Total, \beta=0.2}$
- $\Pi_{\omega}^{Total, \beta=3.98}$

Scenario Profit $\Pi_{\omega}$ [EUR]
Managing Risk
Trading of Expected Profit

\[ \text{Conditional Value at Risk} \quad [\text{EUR}] \]

\[ \text{Expected Profit} \ E[\Pi_{\text{Tot}}] \quad [\text{EUR}] \]

\[ \beta = 0.01 \]
\[ \beta = 0.08 \]
\[ \beta = 0.02 \]
\[ \beta = 0.04 \]
\[ \beta = 0.06 \]

\[ \beta = 0.13 \]
\[ \beta = 0.02 \]
\[ \beta = 0.31 \]

\[ \beta = 0.47 \]
\[ \beta = 0.72 \]
\[ \beta = 1.1 \]
\[ \beta = 1.69 \]
\[ \beta = 2.6 \]
\[ \beta = 3.98 \]

Ilan Momber ( Sets JD: IIT-KTH)
The cost of the lines are allocated taking into account the used capacity \((a)\) in terms of current flow as well as the extent of use \((b)\), which refers to the marginal participation of the network users. For active power the network UoS prices at node \(n\) are derived as:

\[
C^n_{UoS} = \sum_l C^{tot}_l \frac{I_l}{I_l^{n,lim}} \cdot \left( \sum_{n' \in N} \left( \frac{\partial I_l}{\partial P_{n'}} P_{n'} + \frac{\partial I_l}{\partial Q_{n'}} Q_{n'} \right) \right),
\]

where \(C^{tot}_l\) denotes the total cost of line \(l\), \(I_l/I_l^{n,lim}\) is the used capacity of this line, \(\partial I_l/\partial P_{n'}\) and \(\partial I_l/\partial Q_{n'}\) are the partial derivatives of the current with respect to active \(P_{n'}\) and reactive \(Q_{n'}\) power components of network user \(n'\).
Hence, with these types of prices, the cost attributed to network use caused by the fleet of vehicles billed to the aggregator by the DSO would be formulated as follows:

\[
\forall \omega : \kappa_\omega = \sum_{n \in N} (u_{n,\omega} - u'_{n,\omega}) C_n^{UoS},
\]  

with

\[
\forall v, h, n, \omega : u_{n,\omega} \geq e_{v,h,n,\omega}^{RT, \forall},
\]

\[
\forall v, h, n, \omega : u'_{n,\omega} \geq e_{v,h,n,\omega}^{RT, \overline{\forall}},
\]
Applying Network Prices
Network Data: Prices for On- & Off-Peak, Feeder Topology

### Network UoS Tariffs as Prices Related to the Used Capacity

<table>
<thead>
<tr>
<th>Node $n$</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C^{U\circ S}_{n,h \in H^{on}} [\text{€/kW max per day}]$</td>
<td>0.388</td>
<td>0.438</td>
<td>0.470</td>
<td>0.504</td>
<td>0.536</td>
<td>0.556</td>
<td>0.586</td>
<td>0.602</td>
<td>0.616</td>
</tr>
<tr>
<td>$C^{U\circ S}_{n,h \in H^{off}} [\text{€/kW max per day}]$</td>
<td>0.194</td>
<td>0.219</td>
<td>0.235</td>
<td>0.252</td>
<td>0.268</td>
<td>0.278</td>
<td>0.293</td>
<td>0.301</td>
<td>0.308</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Node $n$</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
<th>17</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C^{U\circ S}_{n,h \in H^{on}} [\text{€/kW max per day}]$</td>
<td>0.640</td>
<td>0.678</td>
<td>0.618</td>
<td>0.522</td>
<td>0.532</td>
<td>0.514</td>
<td>0.538</td>
<td>0.624</td>
</tr>
<tr>
<td>$C^{U\circ S}_{n,h \in H^{off}} [\text{€/kW max per day}]$</td>
<td>0.320</td>
<td>0.339</td>
<td>0.309</td>
<td>0.261</td>
<td>0.266</td>
<td>0.257</td>
<td>0.269</td>
<td>0.312</td>
</tr>
</tbody>
</table>

Network Topology of Urban MV Feeder as in Gonzalez and Gómez, 2008
Applying Network Prices
Expected Day-Ahead and Real-Time Charging
Applying Network Prices

Expected Battery State-of-Charge

[Graphs showing expected battery state-of-charge over time with different energy levels for various time slots.]
Applying Network Prices
Expected Total Charging per Node and Problem Summary

<table>
<thead>
<tr>
<th></th>
<th>Obj. Fn. Value</th>
<th>CPU Time*</th>
<th>Total Iterations</th>
<th>Equations</th>
<th>Non-Zeros</th>
<th>Real Variables</th>
<th>Binary Variables</th>
<th>Integer Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 1: Market Signals Only</td>
<td>0.418</td>
<td>0.093 s</td>
<td>583</td>
<td>30 349</td>
<td>184 789</td>
<td>52 452</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Run 2: With Grid Signals</td>
<td>0.418</td>
<td>0.172 s</td>
<td>1 753</td>
<td>79 333</td>
<td>283 549</td>
<td>53 268</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

*GAMS® Build 24.0.1; CPLEX™ 12.5.0; 64-bit MS Windows© 7; 8.00 GB RAM; Intel® Core™ i7-3770 CPU @ 3.4 GHz
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Control Approaches
Direct vs. Indirect Load Control

### Direct Load Control
- Guille and Gross [2009]
- Bessa and Matos [2013]
- Vagropoulos and Bakirtzis [2013]
- Ilan Momber et al. [2014a]

### Indirect Load Control
- Dallinger and Wietschel [2012]
- Vandael et al. [2013]
- Ilan Momber et al. [2014b]

Gabriel, S.A. et al. [2012]
Bi-Level Decision Making
The Aggregator Leads the PEV via Prices

Maximize Expected Profits

Determine
Optimal Market Bids
Retail Prices

Minimize Mobility Cost

Determine
SOC, Demand
Charging Schdl.
Maximize \[ z_{UL} = f_{UL} \left( e_{h, v}^{D, v}, \gamma_{h}^{v} \right) = \sum_{h \in H} \left( \Pi_{h}^{C} + \kappa_{h}^{D} \right), \quad (18) \]

with:

\[ \kappa_{h}^{D} = - \left[ e_{h, v}^{D, v} \cdot \lambda_{h}^{D} \right], \quad (19) \]

\[ \Pi_{h}^{C} = \sum_{v} \left[ e_{v, h}^{RT, v} \cdot \gamma_{h}^{v} \right], \quad (20) \]

\[ \forall h : \sum_{v \in V} \left[ e_{v, h}^{RT, v} \right] = \left( e_{h, v}^{D, v} \right), \quad (21) \]

\[ \forall h : \gamma_{h}^{v} = \lambda_{h}^{D} + m. \quad (22) \]
Min.

\[ z_{LL} = f_{LL}(e_{v,h}^{RT} e_{v,h}^{SOC} e_{v,h}^{NSE} e_v^{UoS,off} e_v^{UoS,off}) \]

\[ = \sum_v \left( \sum_h \left[ e_{v,h}^{RT,\vee} \cdot e_{v,h}^{SOC} \cdot e_{v,h}^{NSE} \cdot \Xi_v + e_v^{UoS,on,\vee} \cdot e_v^{UoS,on} + e_v^{UoS,off,\vee} \cdot e_v^{UoS,off} \right] + e_v^{R,T,v} - \nu_{v,h} \cdot P_v \leq 0 : \mu_{g^1} \right) \]

\[ \forall v, h: \quad g^1 = e_{v,h}^{RT,\vee} - \nu_{v,h} \cdot P_v \leq 0 : \mu_{g^1} \]  \hspace{1cm} (24)

\[ \forall v, h: \quad g^2 = e_{v,h}^{SOC} - E_v \leq 0 : \mu_{g^2} \]  \hspace{1cm} (25)

\[ \forall v, h: \quad h^1 = \left[ e_{v,h}^{RT,\vee} + e_{v,h}^{NSE} \right] \cdot \eta_v \cdot e_{v,h}^{SOC} \cdot \rho_{v,h} + e_{v,h-1}^{SOC} + t_{SOC} = 0 : \theta_{v,h} \]  \hspace{1cm} (26)
Affine Demand formulation
LL formulation with total affine demand

To make the charging schedule responsive to the retail prices, \( \gamma^v_h \) determines the total demand per vehicle, which is given by:

\[
\sum_h e^v_{v,h} = e^\text{tot}_v
\]  
(27)

\[
D_v \leq e^\text{tot}_v \leq \overline{D}_v,
\]  
(28)

with \( \overline{D}_v = \overline{E}_v - \nu_{v,\text{SOC}} + \sum_h \rho_{v,h} \) and \( \underline{D}_v = \underline{\phi}^\text{SOC} - \nu_{v,\text{SOC}} + \sum_h \rho_{v,h} \). In-between its bounds, \( e^\text{tot}_v \) follows an affine relationship with the mean hourly retail price \( \frac{1}{|H|} \sum_h \gamma^v_h \), in which the slope \( \alpha \) is given by:

\[
\alpha_v = \frac{\overline{D}_v - \underline{D}_v}{\Xi_v - \overline{\lambda}^D} = \frac{\overline{E}_v - \underline{\phi}^\text{SOC}}{\Xi_v - \overline{\lambda}^D},
\]  
(29)

where \( \overline{\lambda}^D \) is the mean day-ahead market price during off-peak periods
\[
\frac{1}{|H^\text{on}|} \sum_{h \in H^\text{off}} \lambda^D_h. \]

Below this price, the problem is designed to be infeasible, as it is unlikely that a strategic aggregator would not require a significant margin above its procurement cost.
Affine Price-Demand Relationship
Parametrizing the LL level Demand Response

Mean Retail Price:
\[ \frac{1}{|\mathcal{H}|} \sum h \gamma h \]

Total Demand:
\[ e_{\text{tot}} \]

Supplied Energy
--- Non-Supplied Energy
∀ \( v \) \( \mathbf{h}^3 = \sum_h D_v \alpha_v \cdot (\bar{\gamma}_v - \lambda_D) \left[ e_{v,h}^{RT,v} + e_{v,h}^{\text{NSE}} \right] + s_v = 0 \cdot \theta_v^3 \), \hspace{2cm} (30)

∀ \( v \) \( \mathbf{g}^3 = D_v - \sum_h (e_{v,h}^{RT,v} + e_{v,h}^{\text{NSE}}) \leq 0 : \mu_{g^3}^v \), \hspace{2cm} (31)

∀ \( v \) \( \mathbf{g}^4 = \sum_h e_{v,h}^{\text{NSE}} - D_v \leq 0 : \mu_{g^4}^v \). \hspace{2cm} (32)

∀ \( v, h \in \mathcal{H}^\text{on} \) : \( \mathbf{g}^5 = e_{v,h}^{RT,v} - e_v^{\text{UoS, on},v} \leq 0 : \mu_{g^5}^{v,h} \), \hspace{2cm} (33)

∀ \( v, h \in \mathcal{H}^\text{off} \) : \( \mathbf{g}^6 = e_{v,h}^{RT,v} - e_v^{\text{UoS, off},v} \leq 0 : \mu_{g^6}^{v,h} \). \hspace{2cm} (34)
Given the price interface $\gamma^V_{h}$,

- the lower level problem is linear
- and thus convex

- It can be replaced (recast) by its corresponding K-K-T-conditions
  - these are necessary and sufficient optimality conditions
  - OPcOP $\Rightarrow$ MPCC

- The recast MPCC might not be easily solvable
  - because the feasible region is not generally convex
  - non-linearities and binary variables might require ad-hoc solution techniques
Bi-Level Formulation

K-K-T Conditions of Optimization Problem in Standard Form

\[
\begin{align*}
\min_x & \ f(x) \\
\text{s.t.} & \ g_i(x) \geq 0, \ i = 1, 2, \ldots, m & : \ \theta_{v,h,i} \\
& \ h_j(x) = 0, \ j = 1, 2, \ldots, p & : \ \mu_{v,h,j} \\
\end{align*}
\]

\[
\nabla f(\bar{x}) + \sum_{i=1}^{m} \bar{\theta}_i \nabla g_i(\bar{x}) + \sum_{j=1}^{p} \bar{\mu}_j \nabla h_j(\bar{x}) = 0 \quad (35)
\]

\[
\forall i = 1, 2, \ldots, m : \ g_i(\bar{x}) \geq 0, \ \bar{\theta}_i \geq 0, \ \bar{\theta}_i \nabla g_i(\bar{x}) = 0 \quad (36)
\]

\[
\forall j = 1, 2, \ldots, p : \ h_j(\bar{x}) = 0, \ \bar{\mu}_j : \ \text{free} \quad (37)
\]

with:

- (35): stationarity
- (36): feasibility and complementarity for inequalities
- (37): feasibility for the equalities
NLP Lower Level Recast
KKT-Stationarity and Strong Duality are Applied

Lagrangian Derivative Stationarity Components

\[ \nabla L (\hat{\cdot}) = \nabla f (\hat{\cdot}) + \theta^T \cdot \nabla g (\hat{\cdot}) + \mu^T \cdot \nabla h (\hat{\cdot}) = 0 \]  

(38)

Strong Duality Theorem

\[ c^T x = \lambda^T b \]  

(39)

Nicer Formulation without Complementarity
The only non-linear terms in the problem are now the multiplication of:

- price and demand
  - in the UL objective function
  - in the LL primal objective function
- dual of affine-demand constraint with sum of prices
  - in the LL dual objective function

All non-linear terms are bi-linear and involve $\gamma_h$

Discretizing $\gamma_h$ with reasonable granularity (step size $\Delta \gamma = .001$, i.e. .1 euro cent for example) should do the trick

If only hourly prices with a fixed margin are considered, discretizing the margin avoids $|k| \cdot |h - 1|$ binary variables
Case Study Description

Structure

Small case study example
1) excluding network pricing
2) including network UoS tariff
3) aggregator competition

General Settings:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>H</td>
<td>$</td>
</tr>
<tr>
<td>$H^{on}$</td>
<td>{7, ..., 22}</td>
<td></td>
</tr>
<tr>
<td>$H^{off}$</td>
<td>{1, ..., 6} $\cup$ {23, 24}</td>
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</tr>
<tr>
<td>$</td>
<td>V</td>
<td>$</td>
</tr>
<tr>
<td>$\lambda^D$</td>
<td>0.034</td>
<td>€ /kWh</td>
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<tr>
<td>$\frac{1}{</td>
<td>H</td>
<td>} \sum_{h \in H} \lambda^D_h$</td>
</tr>
<tr>
<td>$C^{UoS, on}$</td>
<td>0.04</td>
<td>€/ kW</td>
</tr>
<tr>
<td>$C^{UoS, off}$</td>
<td>0.08</td>
<td>€/ kW</td>
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## Small-Scale Case

### Mobility and PEV Parameters

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<tr>
<td>$E_v$</td>
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<tr>
<td></td>
<td>12.5</td>
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<tr>
<td>$\eta_v$</td>
<td>.94</td>
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<tr>
<td></td>
<td>.96</td>
<td>+/-</td>
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<tr>
<td></td>
<td>.98</td>
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<tr>
<td>$P_v$</td>
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<tr>
<td>$\bar{\phi}^{SOC}$</td>
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<td>kWh</td>
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<tr>
<td>$D_v$</td>
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<td>$\bar{D}_v$</td>
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<td>kWh</td>
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</table>

![Graph](image)
Numerical Results

Detailed Schedules

Energy [kWh]

Hours [h]

v1 Charging
v2 Charging
v3 Charging

v1 SOC
v2 SOC
v3 SOC
Conclusions

Take home lessons and future work

- The regulatory framework matters: unbundling is important in EU

- In the **Direct Load Control** approach
  - there is a value of flexibility to markets
  - fleet aggregation size may matter
  - conditional value at risk
  - network capacity prices smoothen schedule

- In the **Indirect Load Control** approach
  - optimal retail price levels can be found endogenously
  - energy prices of aggregator compete with network capacity prices

- **Future Work**
  - Decomposition Techniques
  - Apply to different networks and mobility scenarios
    - scalability: larger fleets - more uncertainty
  - Study competition on retail market: EPECs
Many Thanks for Your Attention!

(Madrid)  (Stockholm)


References III
Literature Cited


Ilan Momber, Sonja Wogrin, and Tomás Gómez. An MPEC for electricity retail alternatives of plug-in electric vehicle (PEV) aggregators. In *18th Power Systems Computation Conference (PSCC)*, Wroclaw, Poland, August 2014b. IEEE.


References V

Literature Cited


"Standing on the shoulders of giants."
– Isaac Newton, 1676.

"I think there is a world market for maybe five computers."
– Thomas Watson, IBM, 1943.

"There is no reason anyone would want a computer in their home."

“If I had asked people what they wanted, they would have said faster horses.”