Integration of Plug-In Electric Vehicles in Renewable-Dominated Power Systems

Miguel Carrión

Escuela de Ingeniería Industrial, Toledo, Spain

Motivation

- It is expected a high increment of the number of PEVs

Plug-in Electric Vehicles

Drawbacks of using Electrical Vehicles

- Consumers acceptance (uncertainty)
- Reduced autonomy
- Small diversity of electrical vehicles (nowadays)
- Technological evolution (uncertainty)
- Need of charging point at home
- Reduced number of outdoor charging points
- High purchase cost

Advantages of Using Electrical Vehicles

- Increase of the energetic independence
- Reduction of the effects of the environmental issue (reduction of contaminant emissions)
- Increase of the energetic efficiency (well to wheel)
- Reduction of noise pollution

Impact in Power Systems

- A large increment in the number of electrical vehicles:
  - Is it affordable by a power system?
  - What are the consequences? (electricity prices, CO_2 emissions, generating mix,…)

Plug-in Electric Vehicles (EVs) in power systems

- Active research topic
  - W. Kempton, S. E. Letendre, 1997
  - J. Tomic, W. Kempton, 2007
  - H. Lund and W. Kempton, 2008
  - C. K. Ekman, 2011
  - D. Dallinger and M. Wietshel, 2011
  - M. A. Ortega, F. Bouffard and V. Silva, 2013
  - K. Seddig, P. Jochem and W. Fitchner, 2014

Objective

- Analysis of the incorporation of a significant number of EVs in a power system with a large penetration of renewable energy
  - Controlled/Uncontrolled charge of EVs
  - Stochastic dispatch model

PEVs modeling

- PEVs are equipped with a large battery that is charged from the grid
- Definition of several groups of PEVs with similar behavior patterns
- The time interval in which PEVs can be charged is defined for each group
- Initial battery status of each group is estimated (daily distance driven, consumption per km, etc.)

Charge modeling

- Uncontrolled charge
  - Charging process is not controlled by the ISO
- Grid-to-vehicle control (G2V)
  - Charging process is controlled by the ISO
- Vehicle-to-grid control (V2G)
  - Charging and discharging processes are controlled by the ISO

Stochastic dispatch model

- Stochastic dispatch model that co-optimizes simultaneously energy and reserve

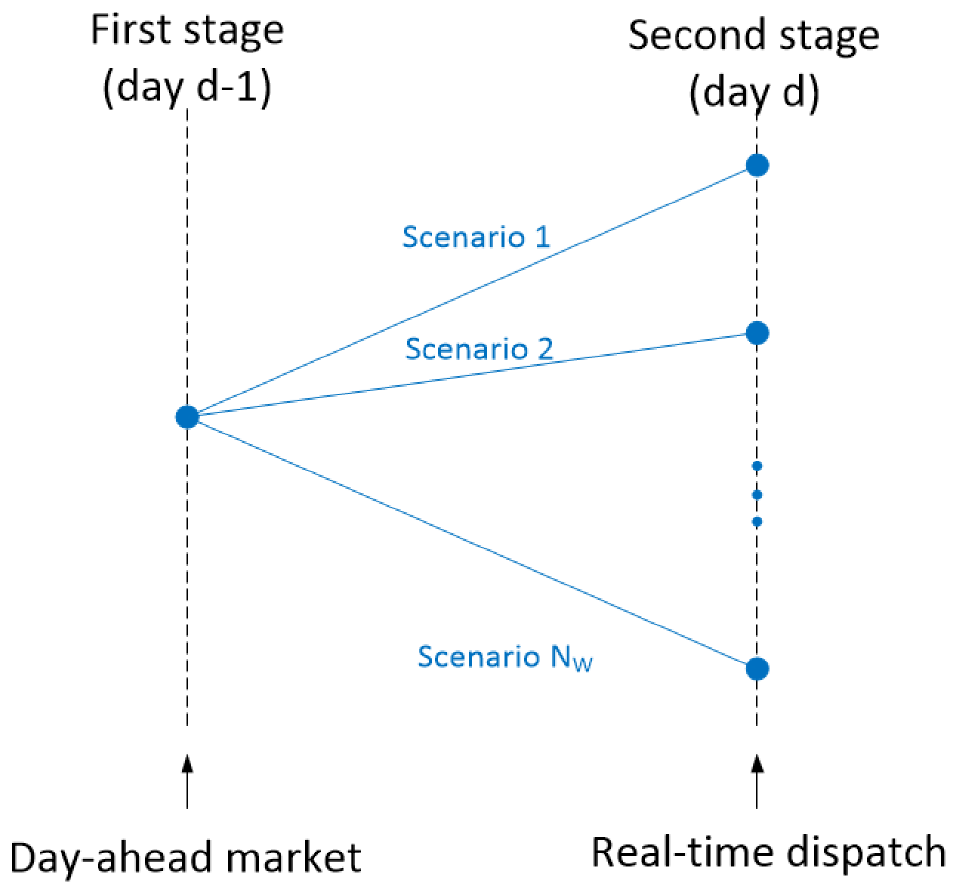
  (Pritchard et al., 2010, Morales et al., 2012, Domínguez et al., 2014)

  - Energy scheduling (Day-ahead schedule)
    - Pool prices
  - Real-time operation (Real-time dispatch)
    - Balancing prices

Decision stages

- Two-stage stochastic programming model
  - First stage:
    - Energy schedule
    - Uncontrolled charge of PEVs (additional inelastic load)
  - Second stage:
    - Reserve deployment (changes in the energy schedule)
    - Controlled charge/discharge of PEVs (decided by ISO)
      - Charge: Down reserve
      - Discharge: Up reserve

Decision framework



Model assumptions

- Smart grid framework
- Inelastic loads
- Linear generating-side offers
- Minimum power outputs equal to zero
- DC model of the transmission network
- Reserve capacity bids are not considered
- Equipment failures are not considered

Uncertainty

- Uncertain parameters
  - Demand
  - Renewable resources (wind, PV)
  - PEV demand

- Modelled using a set of scenarios

Optimization problem

Minimize Expected generation costs

Subject to:

- Technical constraints
- Reserve deployment constraints
- Power flow constraints
  - Power balance on day-ahead schedule
- Power balance for deviations in the real-time dispatch
  - State-of-charge of PEVs

Objective function

Day-ahead energy costs

$$
\text{Minimize}_{\Theta}
$$

$$
\sum_{t \in S^{\mathrm{T}}} \left(\sum_{c \in S^{\mathrm{C}}} C_c^{\mathrm{CO}} p_{ct}^{\mathrm{C,Disp}} + \sum_{h \in S^{\mathrm{H}}} C_h^{\mathrm{HO}} p_{ht}^{\mathrm{H,Disp}} \right)
$$

$$
+ \sum_{\omega \in S^{\Omega}} \pi_{\omega} \sum_{t \in S^{\mathrm{T}}} \left(\sum_{c \in S^{\mathrm{C}}} C_c^{\mathrm{CO}} \left(r_{ct\omega}^{\mathrm{CDu}} - r_{ct\omega}^{\mathrm{CDd}} \right) + \sum_{h \in S^{\mathrm{H}}} C_h^{\mathrm{HO}} \left(r_{ht\omega}^{\mathrm{HDu}} - r_{ht\omega}^{\mathrm{HDd}} \right) \right.
$$

$$
\left. + \sum_{n \in N} C_n^{\mathrm{UD}} p_{nt\omega}^{\mathrm{UD}} \right)
$$

Reserve deployment energy costs

Load shedding costs

Technical constraints

$$0 \le p^{\mathrm{C}}_{ct\omega} \le P^{\mathrm{C}}_{\max,c}, \quad \forall c \in S^{\mathrm{C}}, \forall t \in S^{\mathrm{T}}, \forall \omega \in S^{\Omega}$$

$$p^{\mathrm{C}}_{ct\omega} - p^{\mathrm{C}}_{ct-1,\omega} \le P^{\mathrm{C}}_{\mathrm{up},c}, \quad \forall c \in S^{\mathrm{C}}, \forall t \in S^{\mathrm{T}}, \forall \omega \in S^{\Omega}$$

$$p^{\mathrm{C}}_{ct-1,\omega} - p^{\mathrm{C}}_{ct,\omega} \le P^{\mathrm{C}}_{\mathrm{down},c}, \quad \forall c \in S^{\mathrm{C}}, \forall t \in S^{\mathrm{T}}, \forall \omega \in S^{\Omega}$$

Thermal units

$$0 \le p^{\mathrm{H}}_{ht\omega} \le P^{\mathrm{H}}_{\max,h}, \quad \forall h \in S^{\mathrm{H}}, \forall t \in S^{\mathrm{T}}, \forall \omega \in S^{\Omega}$$

Hydro units

$$p^{\mathrm{R}}_{rt\omega} + p^{\mathrm{RS}}_{rt\omega} = U^{\mathrm{R}}_{rt\omega} P^{\mathrm{R}}_{\max,r}, \quad \forall r \in S^{\mathrm{R}}, \forall t \in S^{\mathrm{T}}, \forall \omega \in S^{\Omega}$$

$$p^{\mathrm{R}}_{rt\omega}, p^{\mathrm{RS}}_{rt\omega} \ge 0, \quad \forall r \in S^{\mathrm{R}}, \forall t \in S^{\mathrm{T}}, \forall \omega \in S^{\Omega}$$

Renewable units

Reserve constraints

$$0 \leq r_{ct\omega}^{\mathrm{CDu}} \leq R_{ct}^{\mathrm{CSu}}, \quad \forall c \in S^{\mathrm{C}}, \forall t \in S^{\mathrm{T}}, \forall \omega \in S^{\Omega}$$

$$0 \leq r_{ct\omega}^{\mathrm{CDd}} \leq R_{ct}^{\mathrm{CSd}}, \quad \forall c \in S^{\mathrm{C}}, \forall t \in S^{\mathrm{T}}, \forall \omega \in S^{\Omega}$$

$$p_{ct\omega}^{\mathrm{C}} = p_{ct}^{\mathrm{C,Disp}} + r_{ct\omega}^{\mathrm{CDu}} - r_{ct\omega}^{\mathrm{CDd}}, \quad \forall c \in S^{\mathrm{C}}, \forall t \in S^{\mathrm{T}}, \forall \omega \in S^{\Omega}.$$

Thermal units

$$0 \leq r_{ht\omega}^{\mathrm{HDu}} \leq R_{ht}^{\mathrm{HSu}}, \quad \forall h \in S^{\mathrm{H}}, \forall t \in S^{\mathrm{T}}, \forall \omega \in S^{\Omega}$$

$$0 \leq r_{ht\omega}^{\mathrm{HDd}} \leq R_{ht}^{\mathrm{HSd}}, \quad \forall h \in S^{\mathrm{H}}, \forall t \in S^{\mathrm{T}}, \forall \omega \in S^{\Omega}$$

$$p_{ht\omega}^{\mathrm{H}} = p_{ht}^{\mathrm{H,Disp}} + r_{ht\omega}^{\mathrm{HDu}} - r_{ht\omega}^{\mathrm{HDd}}, \quad \forall c \in S^{\mathrm{H}}, \forall t \in S^{\mathrm{T}}, \forall \omega \in S^{\Omega}.$$

Hydro units

Power flows

$$p^{\mathrm{L}}_{\ell t\omega} = \frac{1}{X_\ell}\left(\theta_{O(\ell)t\omega} - \theta_{F(\ell)t\omega}\right), \quad \forall \ell \in S^{\mathrm{L}}, \forall t \in S^{\mathrm{T}}, \forall \omega \in S^{\Omega}$$

$$-P^{\mathrm{L}}_{\max,\ell} \leq p^{\mathrm{L}}_{\ell t\omega} \leq P^{\mathrm{L}}_{\max,\ell}, \quad \forall \ell \in S^{\mathrm{L}}, \forall t \in S^{\mathrm{T}}, \forall \omega \in S^{\Omega}$$

$$-\pi/2 \leq \theta_{nt\omega} \leq \pi/2, \quad \forall n \in S^{\mathrm{N}}, \forall t \in S^{\mathrm{T}}, \forall \omega \in S^{\Omega}$$

Power balance on day-ahead schedule

$$\sum_{c \in S_n^{\mathrm{C}}} p_{ct}^{\mathrm{C,Disp}} + \sum_{h \in S_n^{\mathrm{H}}} p_{ht}^{\mathrm{H,Disp}} + \sum_{r \in S_n^{\mathrm{R}}} p_{rt}^{\mathrm{R,Disp}} - \sum_{\ell \in S_{\mathrm{O},n}^{\mathrm{L}}} p_{\ell t}^{\mathrm{L,Disp}} + \sum_{\ell \in S_{\mathrm{F},n}^{\mathrm{L}}} p_{\ell t}^{\mathrm{L,Disp}} =$$

$$= P_{nt}^{\mathrm{D,Exp}} + \boxed{\sum_{k \in S_n^{\mathrm{K}}} \left(1 - \gamma_{kn}^{\mathrm{EV}}\right) P_{knt}^{\mathrm{EV,Exp}}} \quad \boxed{(\lambda_{nt})}$$

$$\forall n \in S^{\mathrm{N}}, \forall t \in S^{\mathrm{T}}$$

Power balance for deviations in the real-time dispatch

$$\sum_{c\in S_n^{\mathrm{C}}}\left(r_{ct\omega}^{\mathrm{CDu}}-r_{ct\omega}^{\mathrm{CDd}}\right)+\sum_{h\in S_n^{\mathrm{H}}}\left(r_{ht\omega}^{\mathrm{HDu}}-r_{ht\omega}^{\mathrm{HDd}}\right)+\sum_{r\in S_n^{\mathrm{R}}}\left(p_{rt\omega}^{\mathrm{R}}-p_{rt}^{\mathrm{R,Disp}}\right)$$

$$-\sum_{\ell\in S_{\mathrm{O},n}^{\mathrm{L}}}\left(p_{\ell t\omega}^{\mathrm{L}}-p_{\ell t}^{\mathrm{L,Disp}}\right)+\sum_{\ell\in S_{\mathrm{F},n}^{\mathrm{L}}}\left(p_{\ell t\omega}^{\mathrm{L}}-p_{\ell t}^{\mathrm{L,Disp}}\right)+p_{nt\omega}^{\mathrm{UD}}=$$

$$=P_{nt\omega}^{\mathrm{D}}-P_{nt}^{\mathrm{D,Exp}}+\sum_{k\in S_n^{\mathrm{K}}}\left(1-\gamma_{kn}^{\mathrm{EV}}\right)\left(P_{knt\omega}^{\mathrm{EV}}-P_{knt}^{\mathrm{EV,Exp}}\right)$$

$$+\sum_{k\in S_n^{\mathrm{K}}}p_{knt\omega}^{\mathrm{BC}}-\sum_{k\in S_n^{\mathrm{K}}}p_{knt\omega}^{\mathrm{BD}}\quad(\lambda_{nt\omega}^{\mathrm{B}})$$

$$\forall n\in S^{\mathrm{N}},\forall t\in S^{\mathrm{T}},\forall\omega\in S^{\Omega}$$

State-of-charge constraints

$$p^{\mathrm{BS}}_{knt\omega} = \gamma^{\mathrm{EV}}_{kn} P^{\mathrm{BS},0}_{knd\omega} N^{\mathrm{EV}}_{kn}, \quad \forall k, \forall n, t = t^{\mathrm{O}}_{kd} - 1, \forall d, \forall \omega$$

$$p^{\mathrm{BS}}_{knt\omega} = p^{\mathrm{BS}}_{knt-1,\omega} + \alpha^{\mathrm{BC}}_{k} p^{\mathrm{BC}}_{knt\omega} - \frac{1}{\alpha^{\mathrm{BD}}_{k}} p^{\mathrm{BD}}_{knt\omega}, \quad \forall k, \forall n, t = t^{\mathrm{O}}_{kd}, \dots, t^{\mathrm{F}}_{kd}, \forall d, \forall \omega$$

$$0 \le p^{\mathrm{BC}}_{knt\omega} \le \gamma^{\mathrm{EV}}_{kn} P^{\mathrm{BPT}}_{\max} N^{\mathrm{EV}}_{kn}, \quad \forall k, \forall n, t = t^{\mathrm{O}}_{kd}, \dots, t^{\mathrm{F}}_{kd}, \forall d, \forall \omega$$

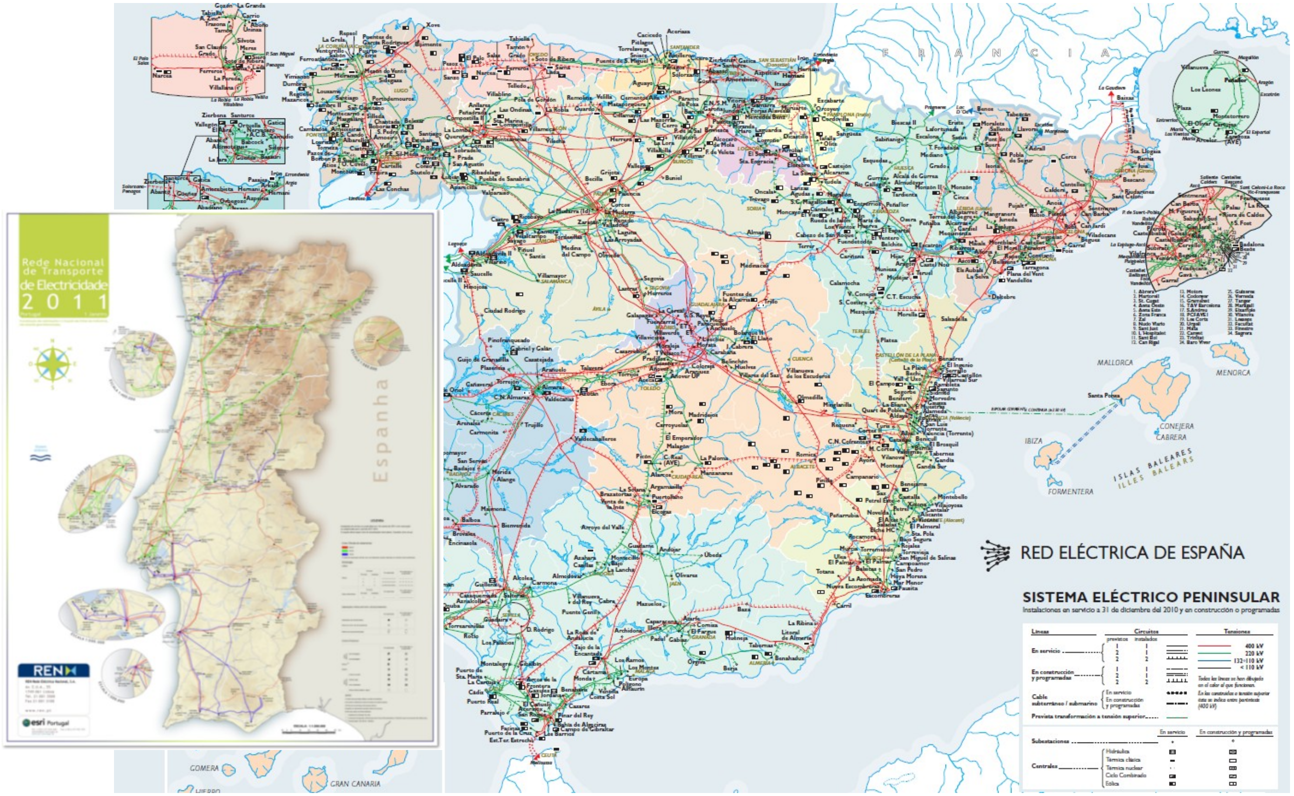
$$0 \le \frac{1}{\alpha^{\mathrm{BD}}_{k}} p^{\mathrm{BD}}_{knt\omega} \le p^{\mathrm{BS}}_{knt\omega}, \quad \forall k, \forall n, t = t^{\mathrm{O}}_{kd}, \dots, t^{\mathrm{F}}_{kd}, \forall d, \forall \omega$$

$$0 \le p^{\mathrm{BD}}_{knt\omega} \le \gamma^{\mathrm{EV}}_{kn} P^{\mathrm{BPT}}_{\max} N^{\mathrm{EV}}_{kn}, \quad \forall k, \forall n, t = t^{\mathrm{O}}_{kd}, \dots, t^{\mathrm{F}}_{kd}, \forall d, \forall \omega$$

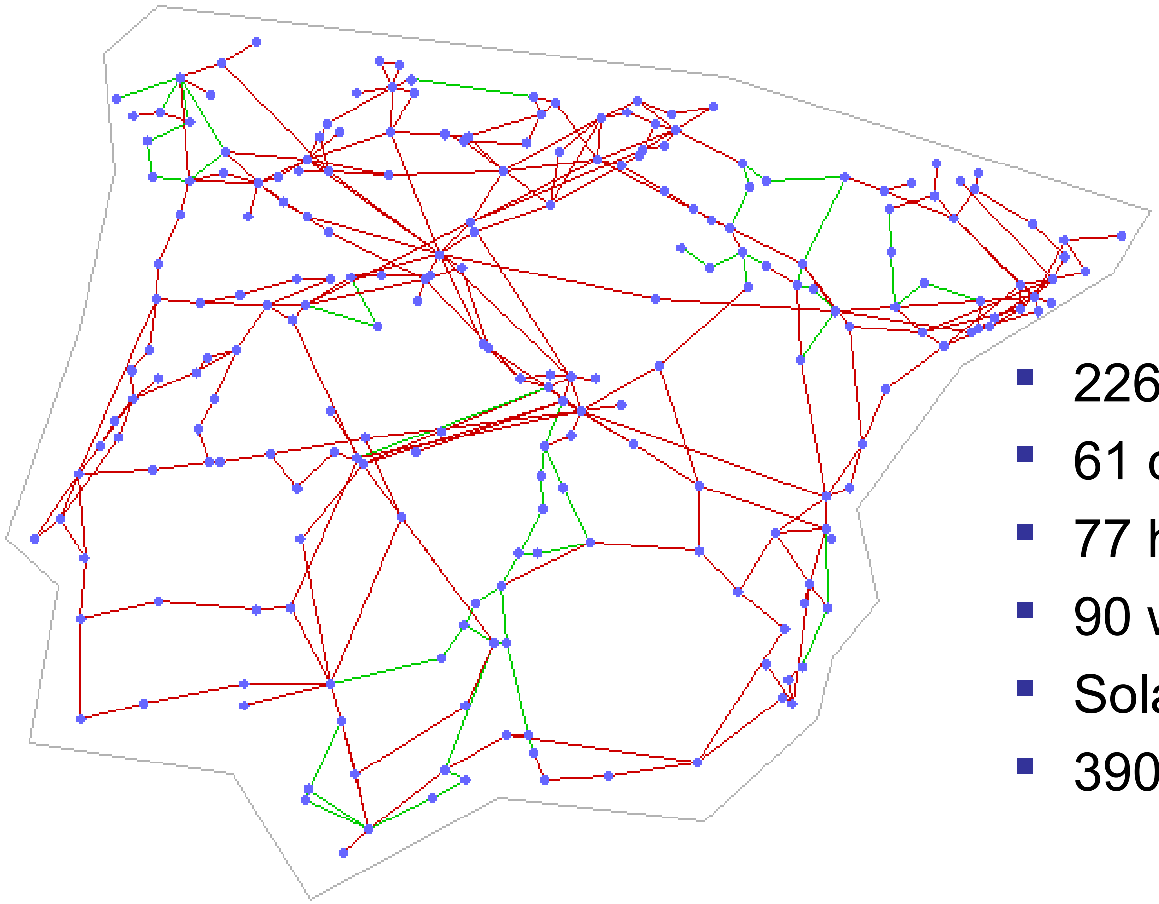
$$p^{\mathrm{BS}}_{knt\omega} = \gamma^{\mathrm{EV}}_{kn} P^{\mathrm{BS}}_{\max,k} N^{\mathrm{EV}}_{kn}, \quad \forall k, \forall n, t = t^{\mathrm{F}}_{kd}, \forall d, \forall \omega$$

Case study

- Iberian Power System (MIBEL)



Input data

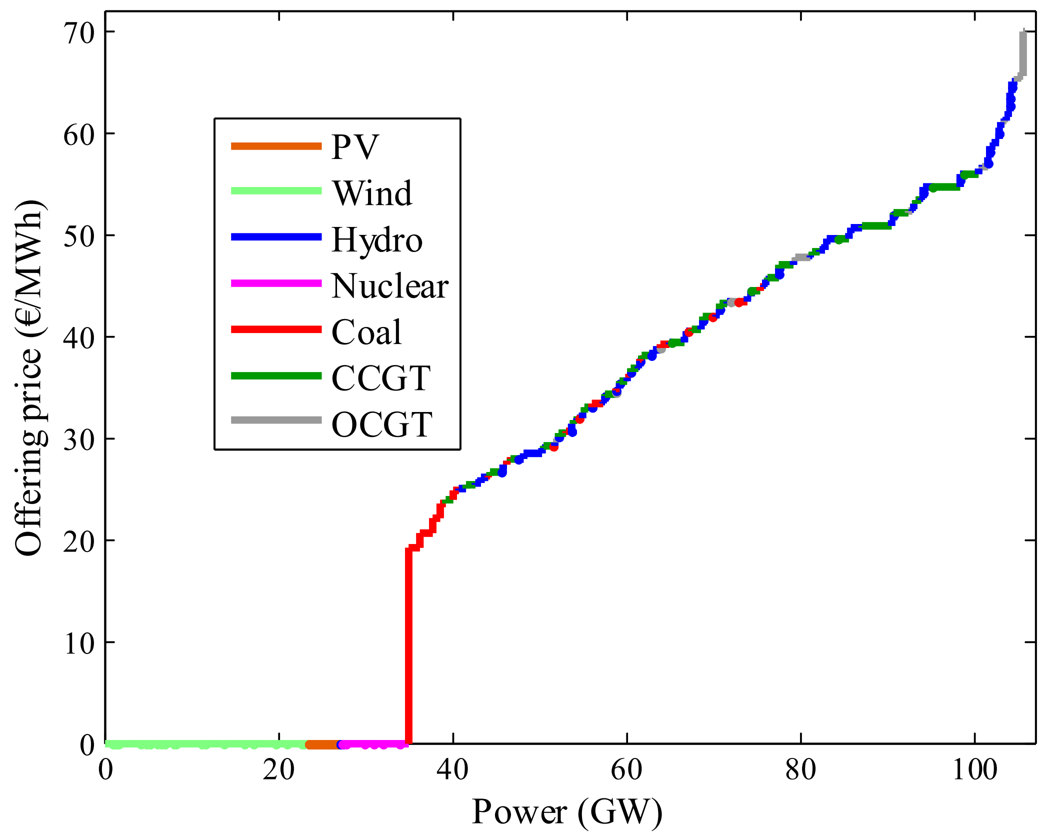


- 226 buses
- 61 conventional generating units
- 77 hydro units
- 90 wind units
- Solar PV distributed per node
- 390 transmission lines

Transmission system based on the equivalent of the European System
(Zhou and Bialek, 2005)

Input data

Technology	Capacity (GW)
Nuclear	7.655
Coal	12.519
Gas	5.532
Combined Cycle	31.914
Hydro	21.077
Wind	23.456
PV	3.677
Total	**105.830**



Input data

- PEVs demand
  - Battery capacity: 22 kWh
  - Efficiency of charging/discharging: 0.88
  - Consumption: 0.18 kW/km
  - Charge rate: 7.2 kW (SAE J1772 low)
  - Number of vehicles: 30 millions
    - Percentage of PEVs: 30 %

Input data

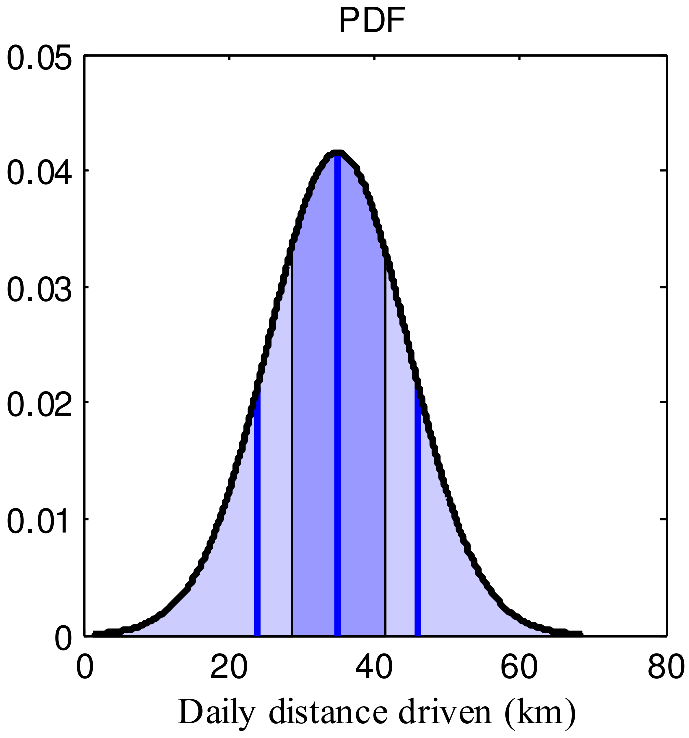
- PEVs demand
  - 3 groups (from mobility studies)

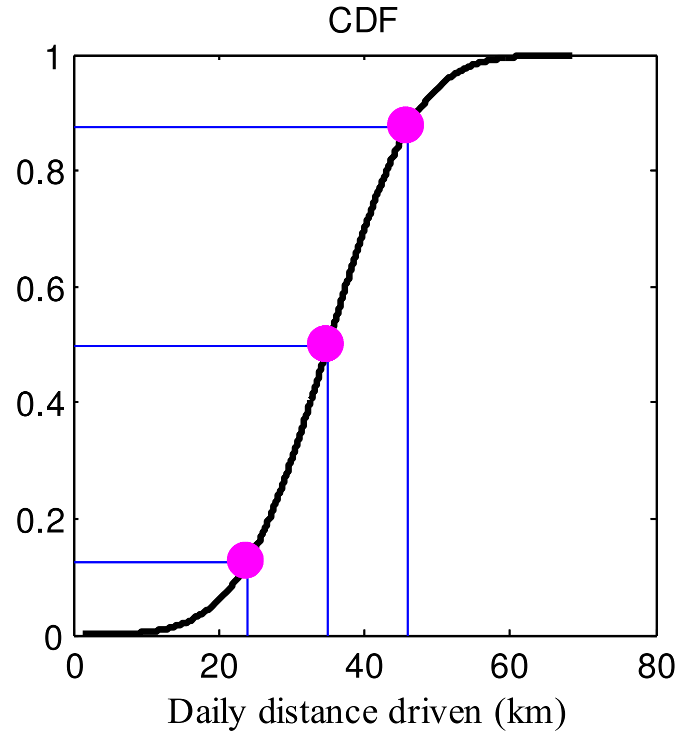
Type	Beginning hour	Ending hour	Duration	Percentage of PEVs
1	16:00	7:00 (next day)	16 hours	45 %
2	21:00	7:00 (next day)	11 hours	40 %
3	2:00	21:00	19 hours	15 %

Input data

- Daily driven distance: N(35,9.6)

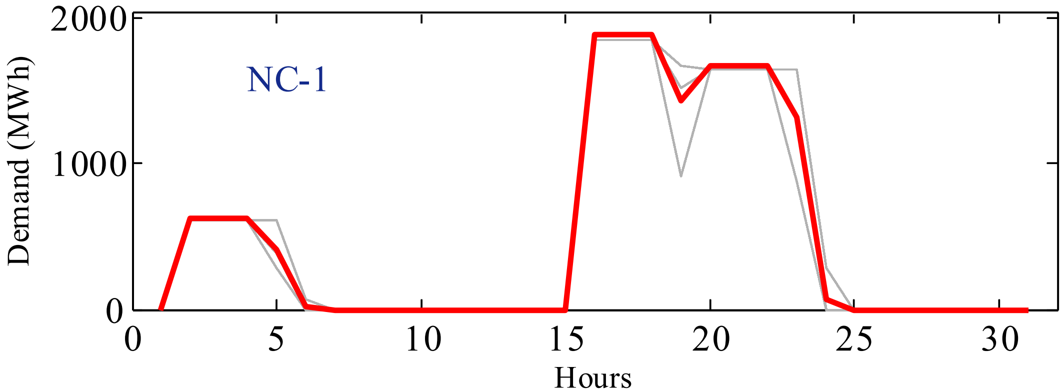
  (G. Tal, M. A. Nicholas, J. Davies, J. Woodjack, 2014)



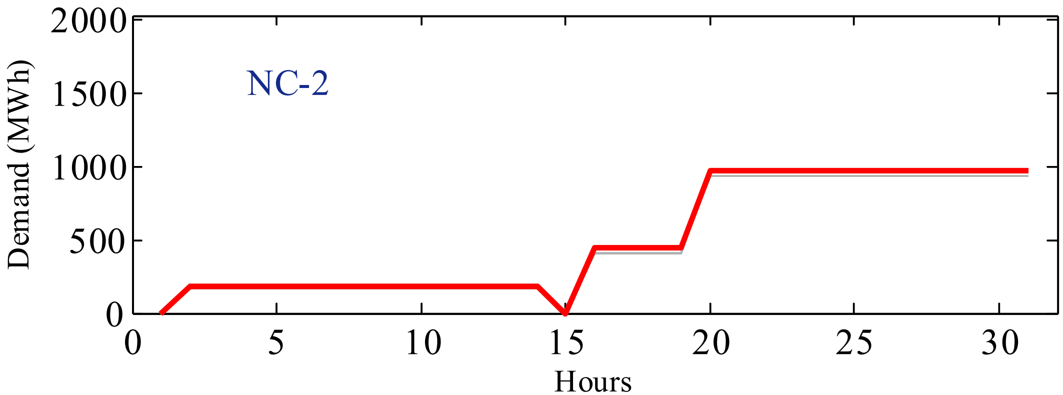


Input data

❑ PEVs demand



- **NC-1**: Charging starts when PEVs are available to be charged
  - ➢ Demand peaks

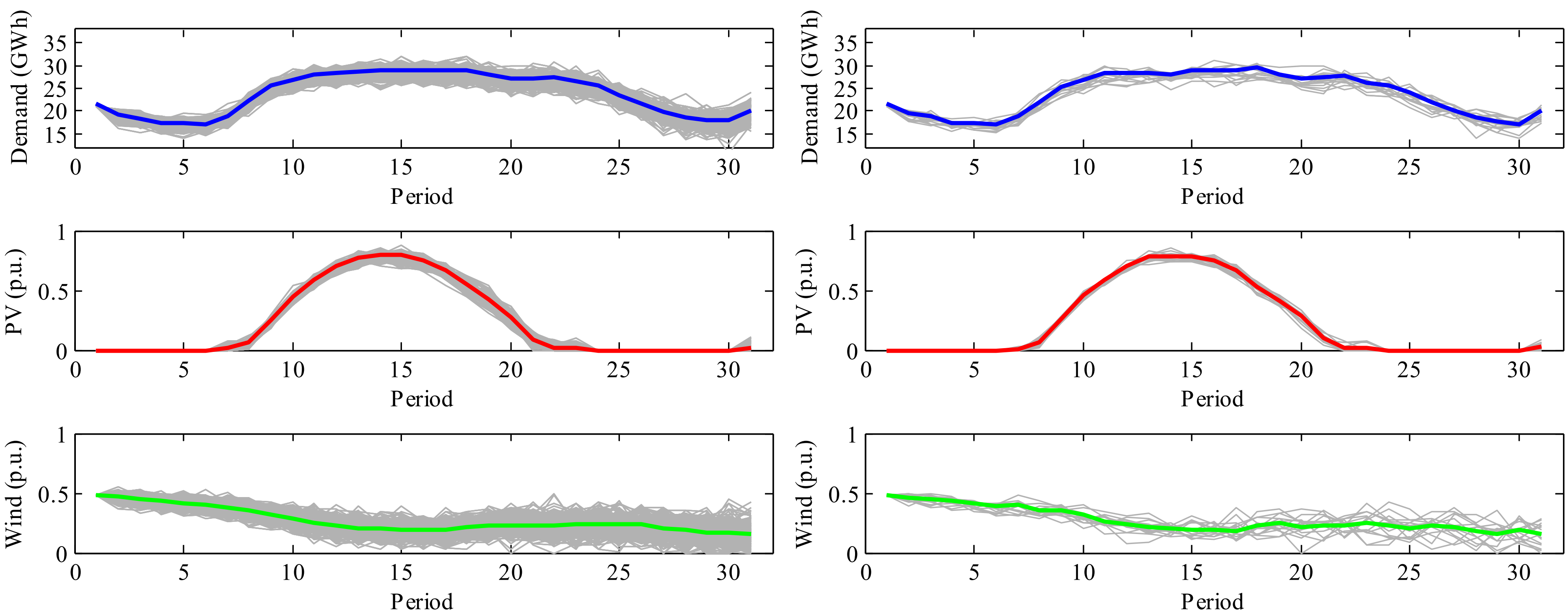


- **NC-2**: Charging is evenly distributed during all periods in which PEVs are available to be charged
  - ➢ Smooth demand

Input data

- Uncertain parameters (Morales et al., 2009)

Initial set (600 scenarios) → Final set (15 scenarios)



Solution

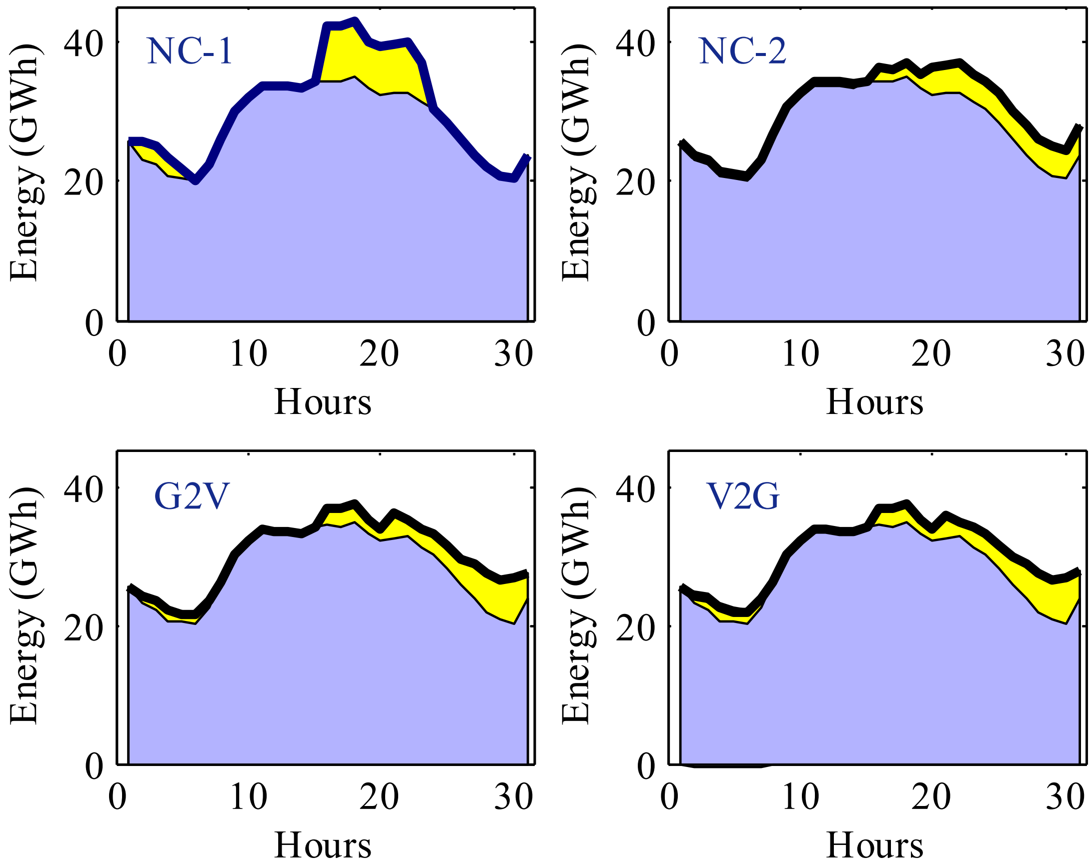
- Computational size
  - Constraints: 1.8 millions
  - Continuous variables: 1.6 millions
- CPLEX 12.2.0.1
  - Server with four 2.9 GHz and 250 GB of RAM
- Solution time
  - Between 1.3 and 4.5 hours

Expected generation costs

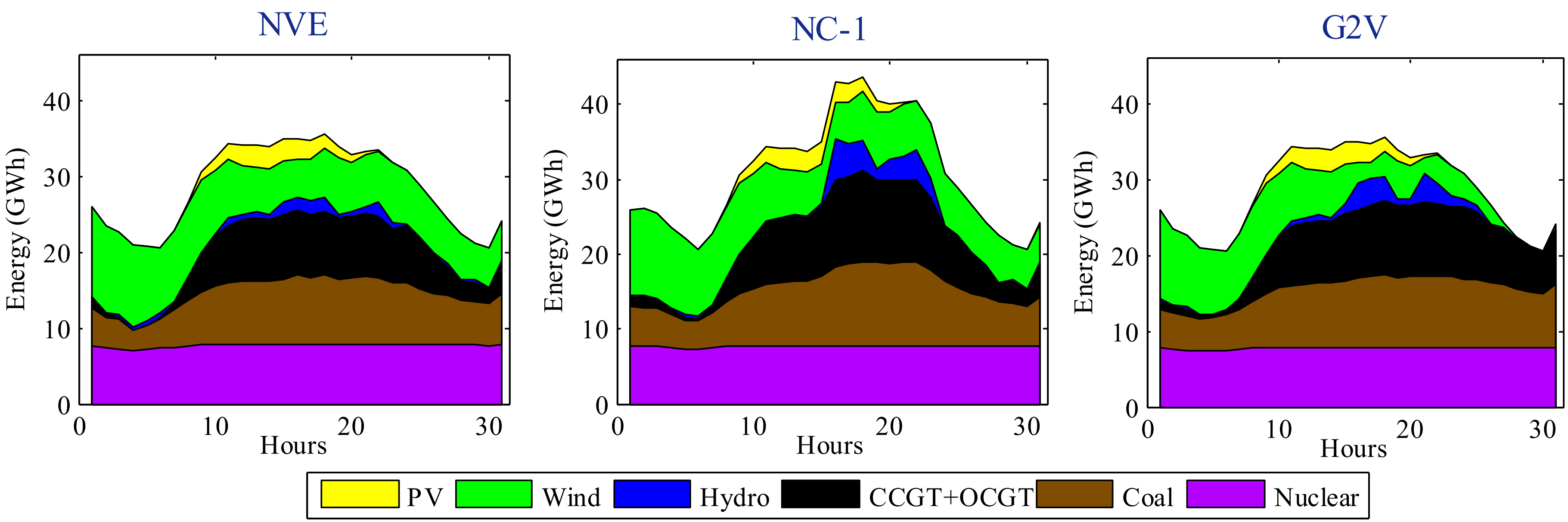
	Non-PEV	NC-1	NC-2	G2V	V2G
Expected cost (M€)	11.480	13.830	13.638	13.359	13.342

- Increment of 7.6% in the total demand (66.4 GWh)
- The expected cost increases between 16.2 and 20.5%
- The coordination G2V reduces the cost between 3.4 and 2.0%
- V2G does not outperform G2V significantly (0.1%)

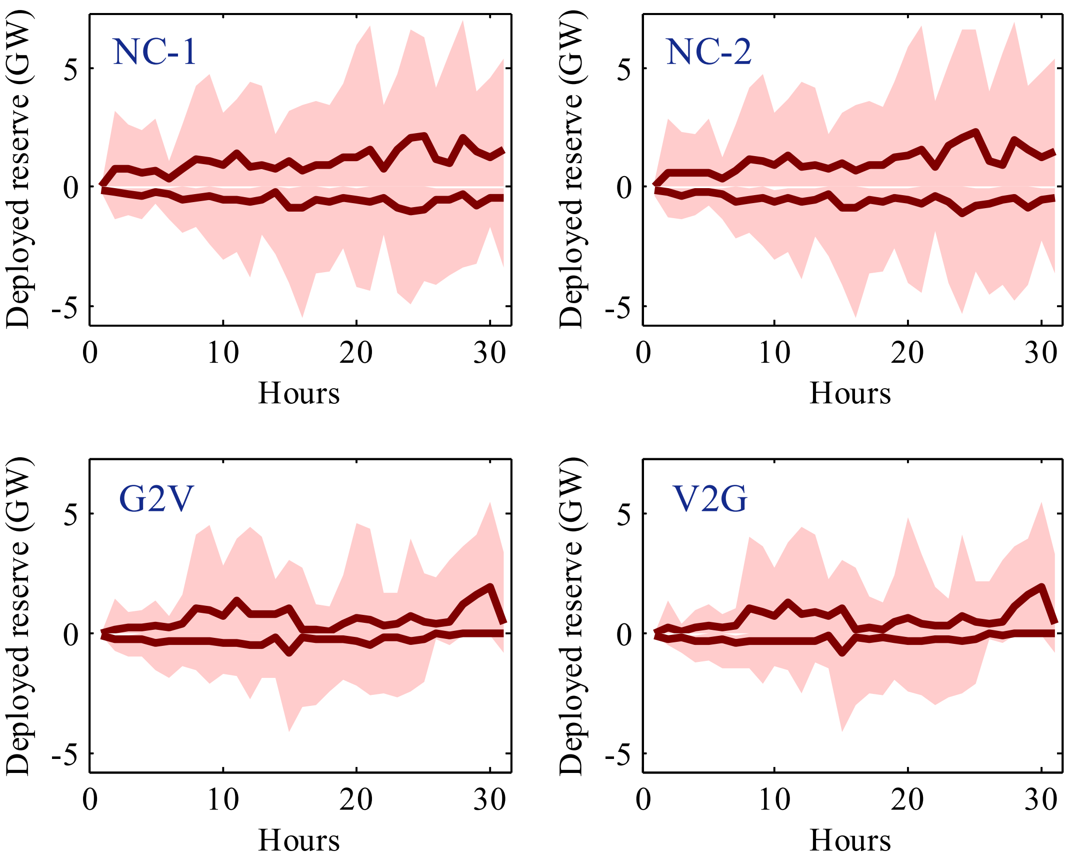
Expected demand profile



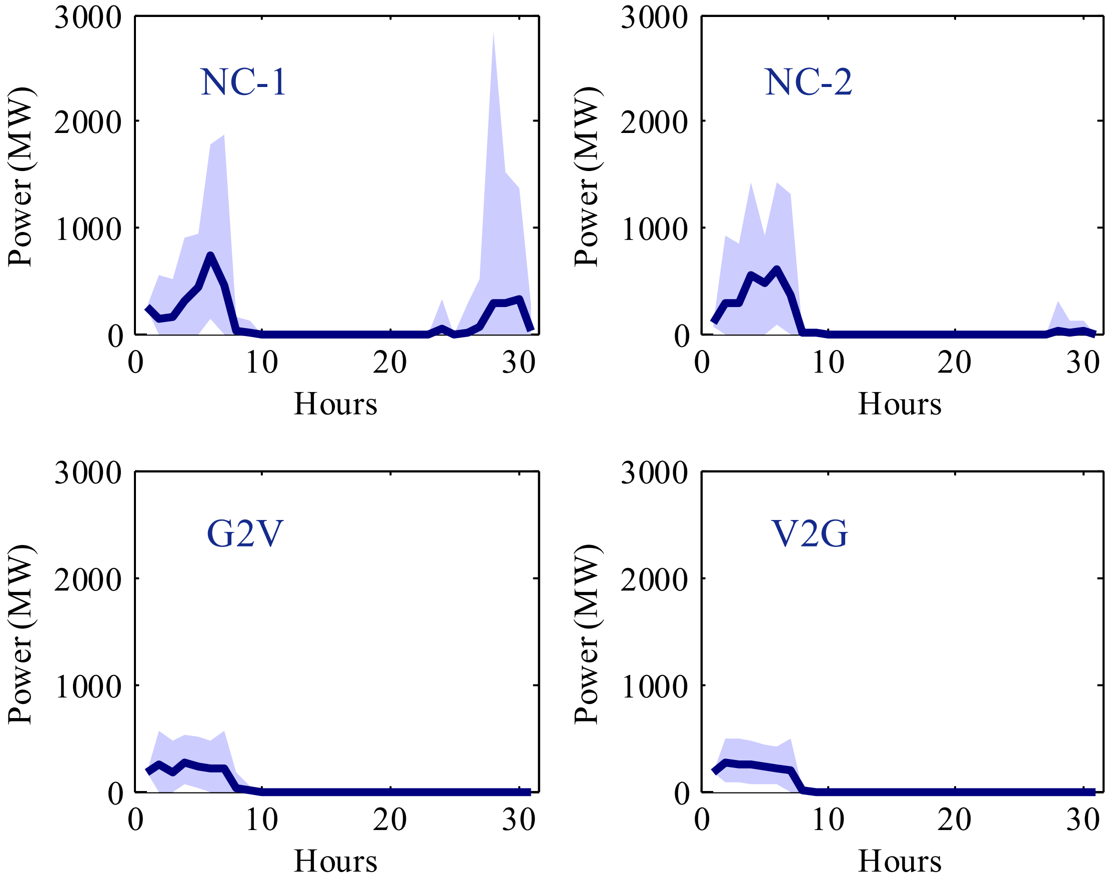
Day-ahead schedule



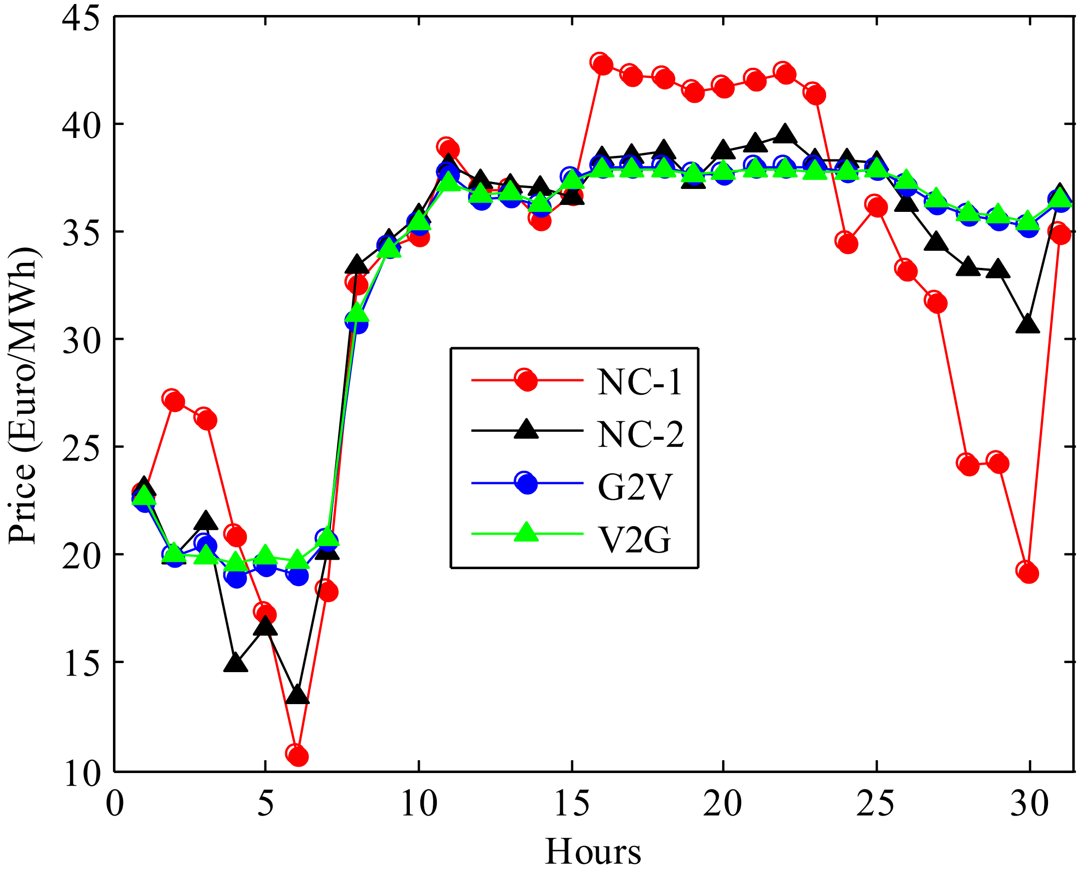
Reserve deployment



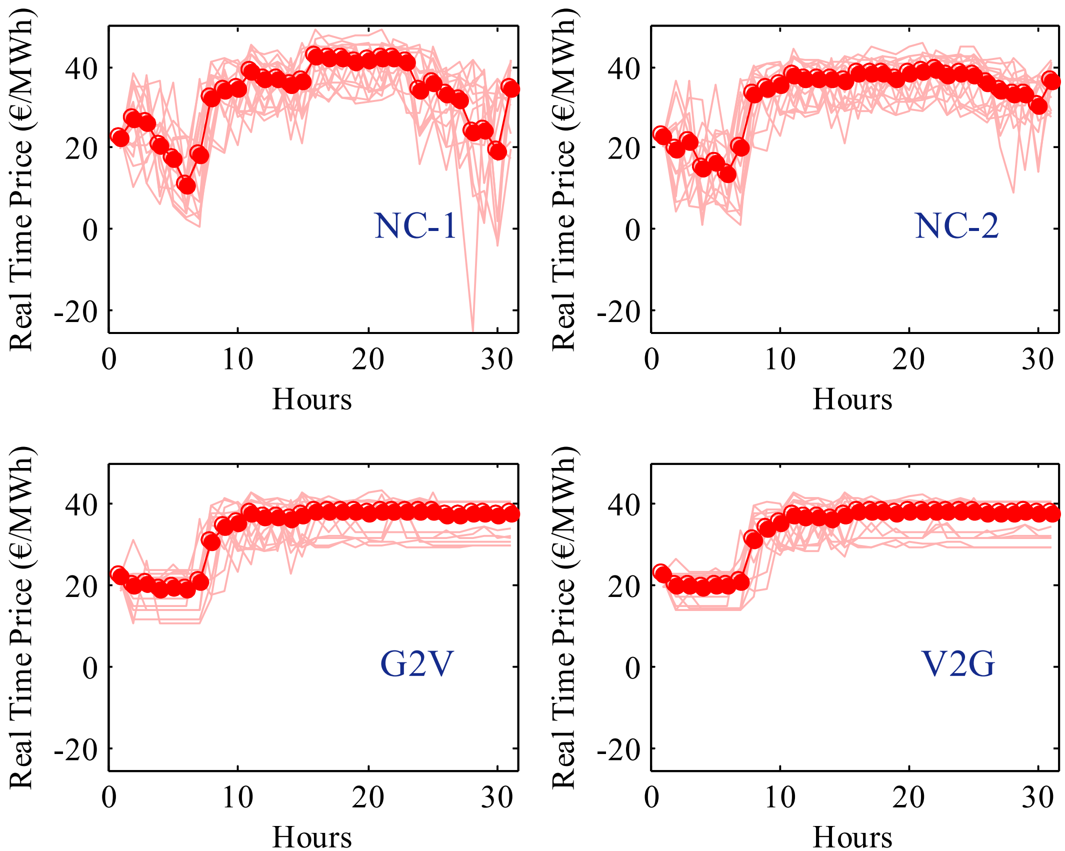
Wind spillage



Day-ahead prices



Real-time prices



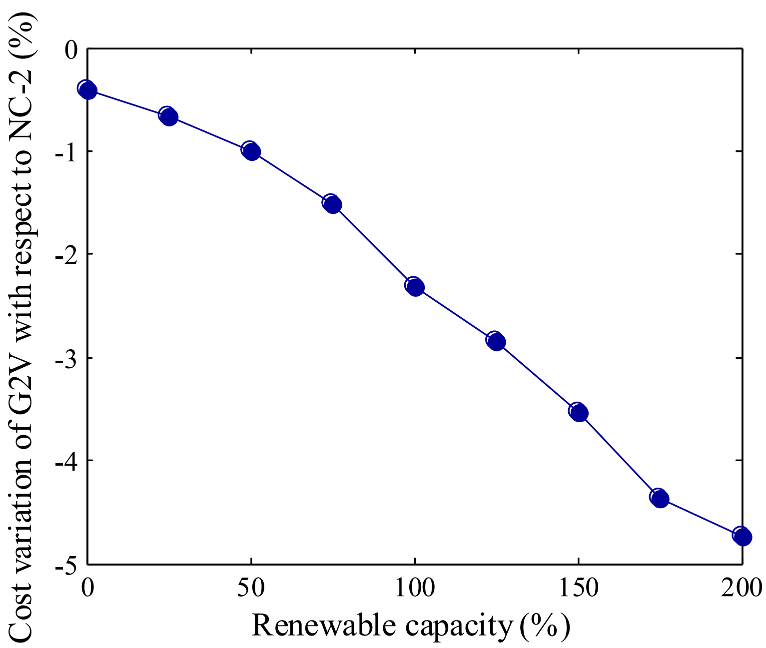
Consumers payments

Expected payment (M€)

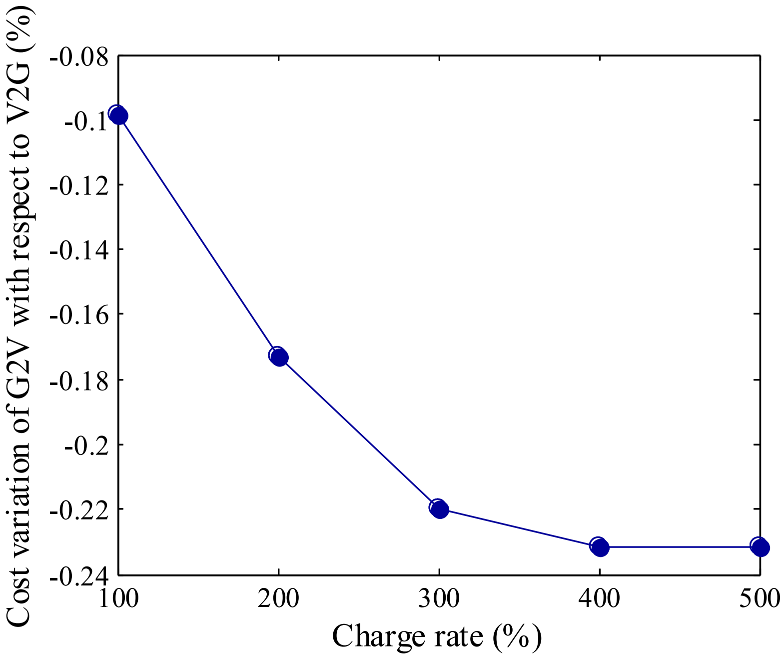
	Non-PEV	NC-1	NC-2	G2V	V2G
Total	27.202	31.613	31.150	31.095	31.123
PEVs	0.000	2.539	2.255	2.214	2.221
Non PEVs	27.202	29.074	28.894	28.881	28.902

Sensitivity analysis

Renewable capacity
(G2V versus NC-2)

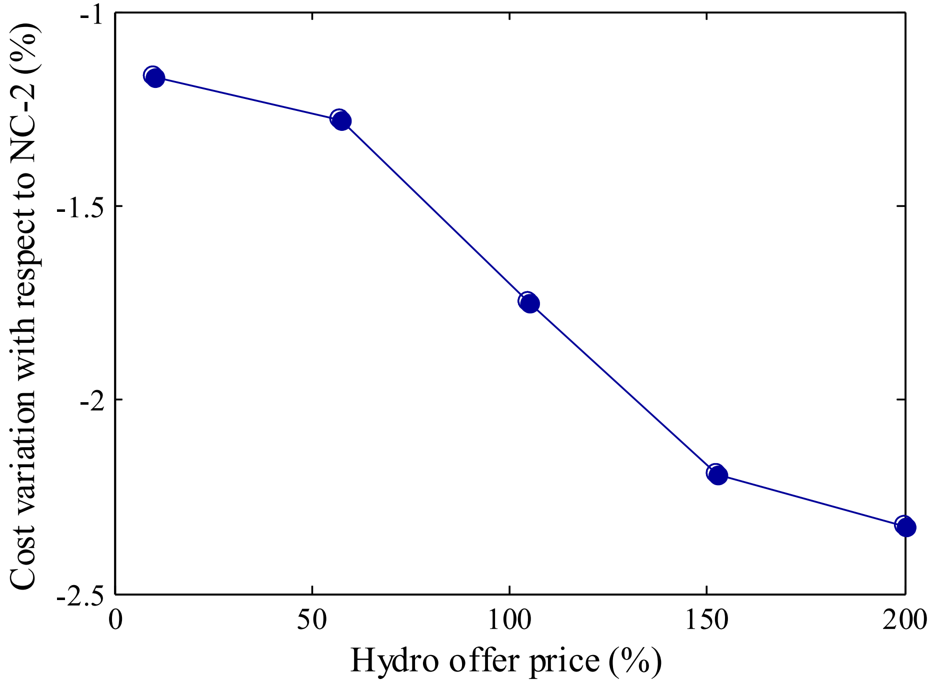


Peak power charge rate
(G2V versus V2G)

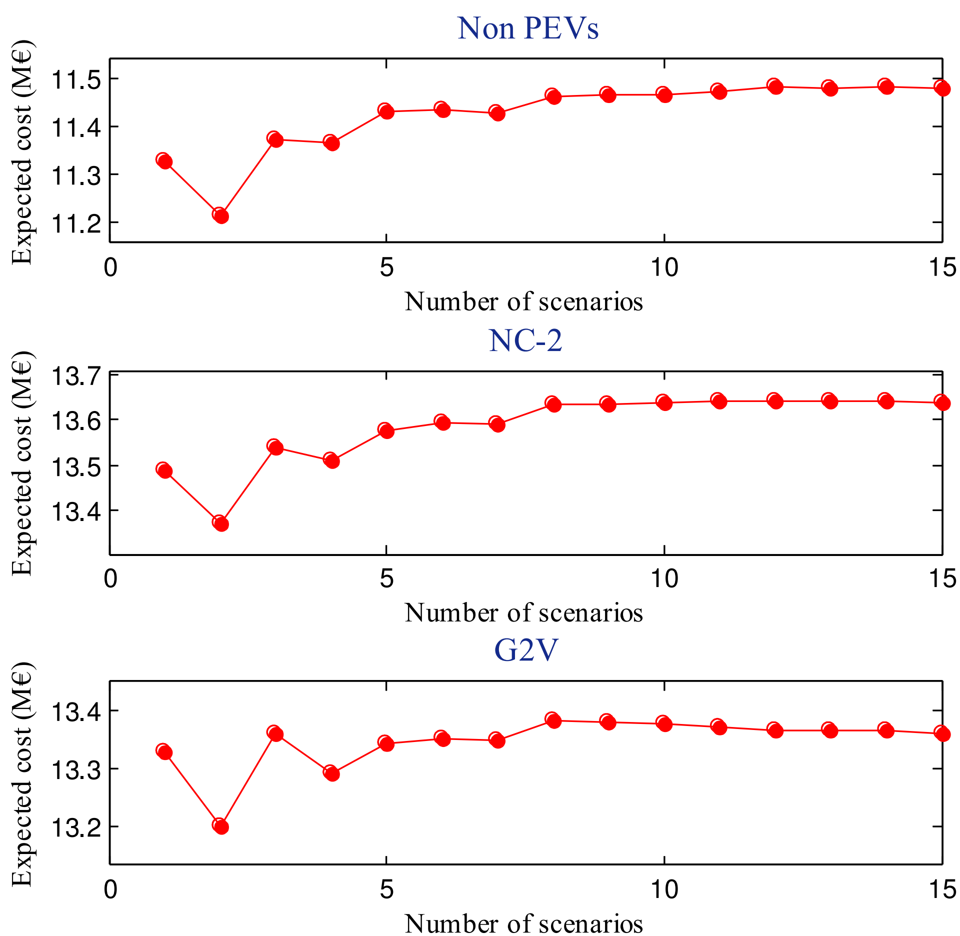


Sensitivity analysis

Hydro offer cost
(G2V versus NC-2)



Number of scenarios



Conclusions

- For the studied day, the coordination between the Independent System Operator and the PEVs:
  - Reduces the expected costs
  - Reduces the wind spillage and the usage of deployed reserves
  - Reduces the difference between peak and valley day-ahead prices
  - Reduces the volatility of real-time prices
  - Is appropriated for those power systems with a significant amount of renewable resources

- The coordination V2G does not outperform G2V significantly

- Solution times are high if coordination is taken into account

Further details

Energy 90 (2015) 827–835

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

ELSEVIER

Operation of renewable-dominated power systems with a significant penetration of plug-in electric vehicles

CrossMark

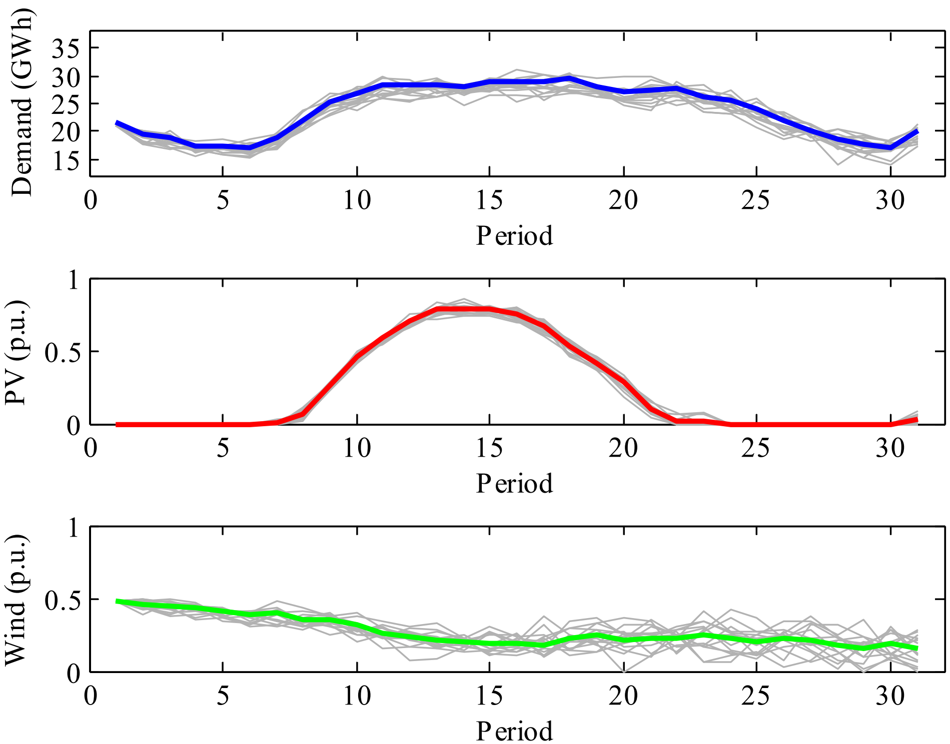
Miguel Carrión [a,*], Rafael Zárate-Miñano [b]

[a] Department of Electrical Engineering, UCLM, Toledo, Spain
[b] Department of Electrical Engineering, UCLM, Almadén, Spain

Thanks very much for your attention!

Input data

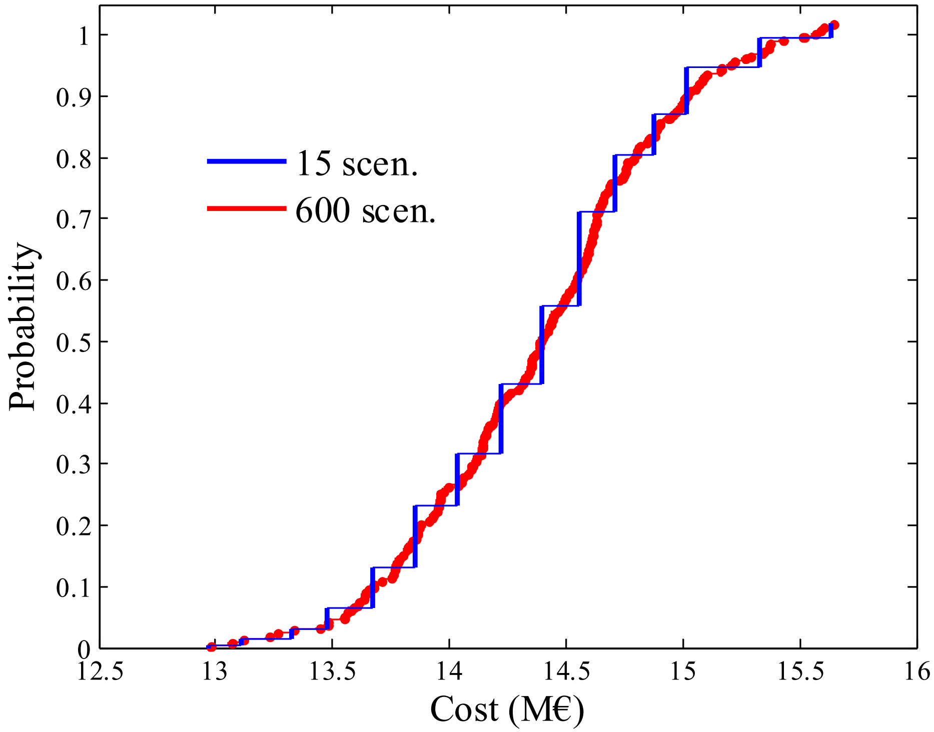
- Uncertainty



- Initial set: 600 (3 x 200) scenarios
- Final set: 15 scenarios (Morales et al., 2009)

Input data

- Initial set of 600 (3 x 200) scenarios
  - Scenario reduction (Morales et al., 2009)



Example for one scenario