Catch 22: Electric Vehicles and the Required Infrastructure

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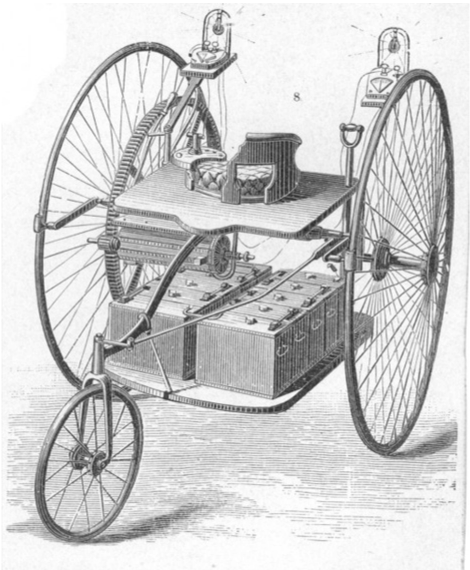
The Beginnings of EVs

- 1828. Hungarian inventor Ányos Jedlik invents one of the first electric motors and constructs a model vehicle that would be supplied by his invention
- 1835. Prof. Sibrandus Stratingh from Groningenand his assistant Christopher Becker construct a small EV supplied by primary batteries
- 1881. William Ayrton and John Perry construct the first usable EV to advertise their other inventions



The Beginnings of EVs

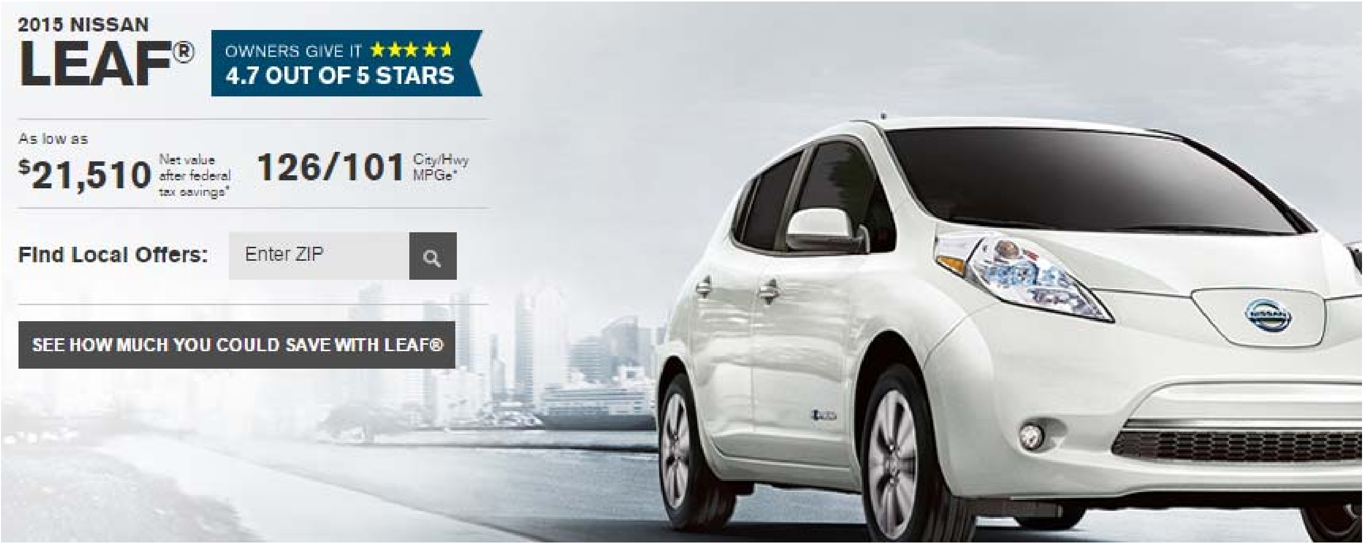
- Already in 1896 a concept of EV battery replacement was proposed
- A delivery vehicle was purchased with no batteries
- The owner would pay a monthly fee and a fee per mile
- This business was on during the period 1910-1924.

Fall and Rise of EV

- Modern fast roads that enable long-distance travel, the development of electric starter of gas-fueled vehicles, and issues with long charging times caused the break of the EV industry
- Years later, oil crisis during the seventies and the eighties spur interest in EVs again
- Since the nineties the people have accepted their responsibility for ecology and the interest in EVs has additionally increased

BEV Today

- These vehicles utilize exclusively the chemical energy stored within their batteries that can be recharged
- The top selling EV today is Nissan Leaf with sales of over 100 000



BEV Today

- The Croatian car industry created two EVs:
  - Loox by Dok-Ing
  - Concept_One bya Rimac Car Company

About the Batteries

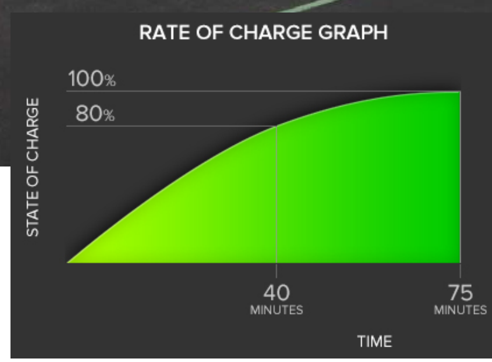
- The most common battery technology is Li-Ion
- The price of a new EV battery is around 10 000 € (500 € /kWh)
- Home chargers (Level I) rated at 1.6 kW require 15 h to fully charge a 24 kWh battery
- Home chargers(Level II) rated at 3.3 kW require 7 h 15 h to fully charge a 24 kWh battery – priced at < 1 000 €

EV Today

- Tesla Motors is the only company that invests in the infrastructure as well
- 338 fast-charging stations

It Can Go Faster

- Model S can be charged at 120 kW



It Can Go Faster

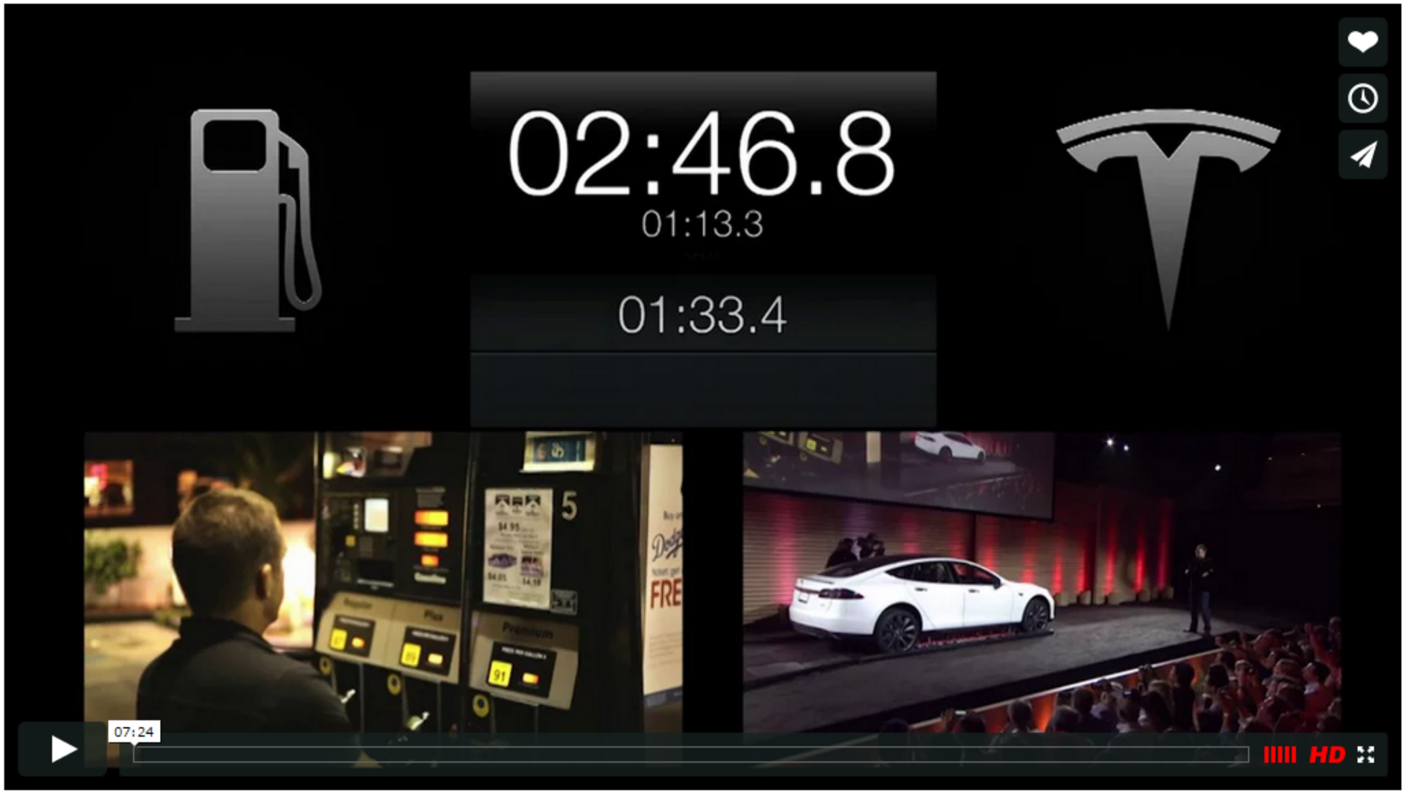
- Model S can be charged at 120 kW

Remaining Issues

- Long charging times, even with Level 2 charges
- Using superchargers is not sustainable with the current power systems, and it is still slower than the current gas stations
- Infrastructure investments needed

(Final) Part of the Solution?

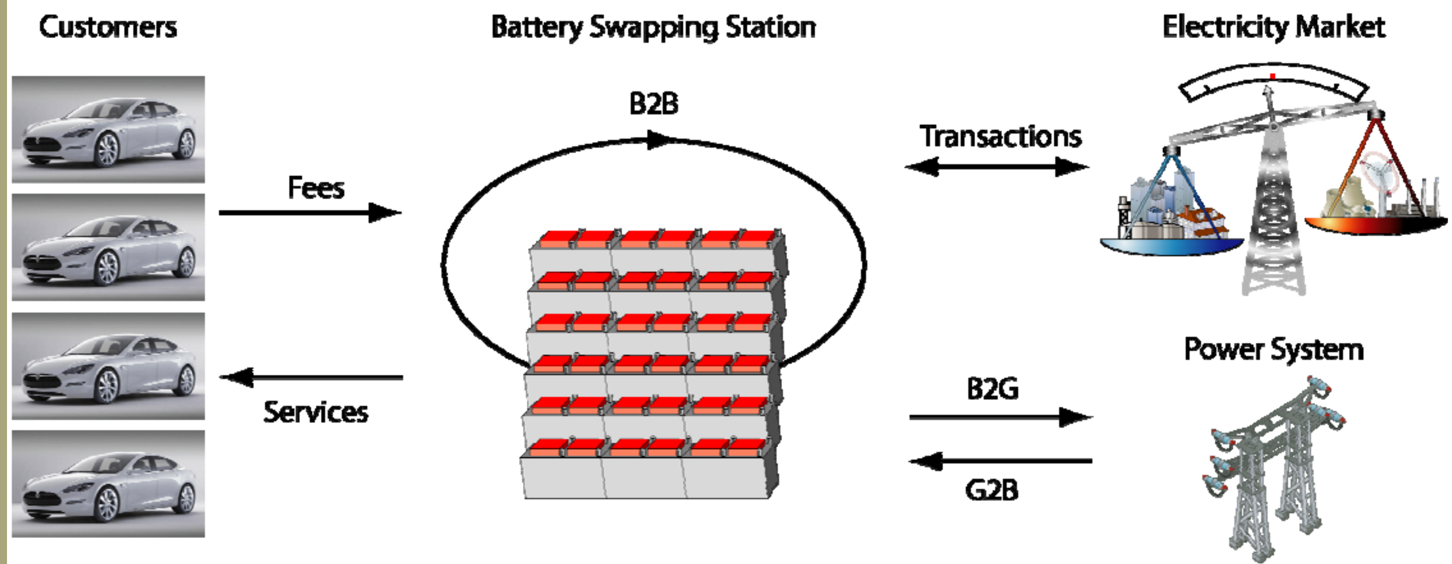
- *Battery Swapping Station* – BSS a profit-seeking business entity resembling a traditional gas station



BSS

- Provides a fully-charged battery to a consumer and receives a depleted battery in return
- Charges consumers a fee for provided services
  - Fee includes cost of labor, battery, and degradation
- Provides services to the power system:
  - Energy arbitrage (i.e. buy low and sell high)
  - Regulation (i.e. maintain power grid stability)
- Eliminates the biggest psychological issue – the *range anxiety*
- The customers lease the batteries – lower investment costs

BSS


Customers
Battery Swapping Station
Electricity Market
B2B
Transactions
Fees
Services
Power System
B2G
G2B

BSS

- **Who are the beneficiaries?**
  - Consumers that own EV(s)
  - Market operator (increased competition in wholesale market)
  - Distribution grid operator
    - Concentrated EV charging at the BSS location instead of sporadic charging by residential consumers (less grid reinforcements)
- **What type of consumers benefit from BSS?**
  - Ones who do not want to invest in EV charging systems
  - Ones who cannot install EV charging systems
  - Ones who do not want to wait for charging
  - Ones who want more freedom with their EVs
  - Ones in an emergency

BSS Business Framework

1) Define and model additional **streams of revenue** obtained from electricity markets

2) Define and model **interactions between the BSS and consumers**

3) Define and model **interactions between the BSS and the power system**

4) Define and model the **uncertainties** (e.g. consumer behavior, market prices, among others)

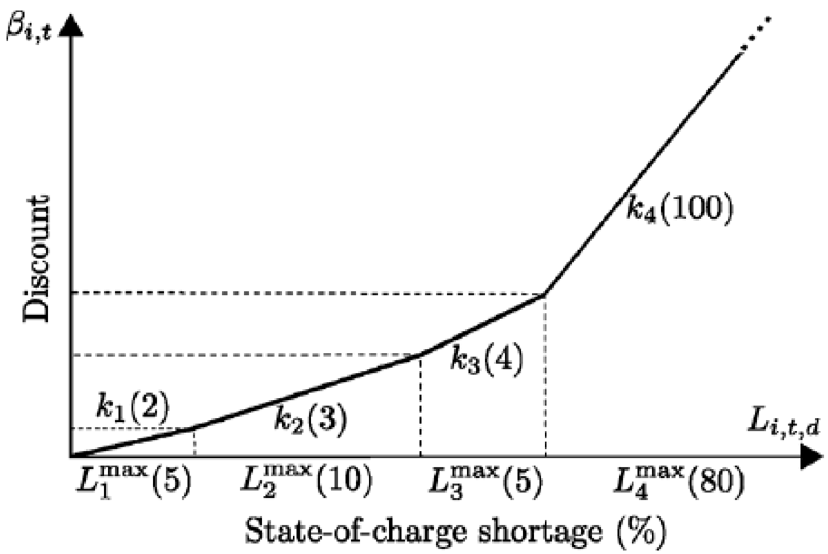
5) Quantification and modelling of the **battery degradation effects**

BSS Business Framework

- The work introduces the concepts of **B2B**, **B2G**, and **G2B** services in the open literature. These are equivalent counterparts to V2V, V2G, and G2V. These services are defined as:
    1) **B2B**: transfer of energy between batteries within a station
    2) **B2G**: injection of energy from batteries to the grid
    3) **G2B**: consumption of energy from the grid to charge batteries
- The model determines optimally *what time of the day* and *how much power* is scheduled for each of these services in order to maximize profits.

Day-Ahead Model

- The decisions are brought based on:
  - SoC of the batteries
  - expected electricity market prices
  - expected dynamics of swapping
- The result are the electricity market purchase/buy bids
- What happens if the BSS does not have fully charged batteries to swap?



Day-Ahead Model

- Objective function:

$$\text{maximize} \quad BSR \sum_{(t\in T)} \sum_{(i\in I)} x_{i,t} - \sum_{(t\in T)} \lambda_t^{\mathrm{DA}} \left(em_t^{\mathrm{buy}} - em_t^{\mathrm{sell}} \right)$$

$$-VoCD \sum_{(t\in T)} \sum_{(g\in G)} bat_{g,t}^{\mathrm{short}} - BSR \sum_{(t\in T)} \sum_{(i\in I)} \beta_{i,t} \quad (1)$$

- Subject to

$$soc_{i,t} = \left(soc_{i,t-1} + bat_{i,t}^{\mathrm{chg}} \eta^{\mathrm{chg}} - \frac{bat_{i,t}^{\mathrm{dsg}}}{\eta^{\mathrm{dsg}}} \right) \cdot (1 - x_{i,t})$$

$$+ SOC_{i,t}^{\mathrm{init}} \cdot x_{i,t} \; \forall i \in I, t \in T \qquad (2)$$

$$soc_{i,t-1} + soc_{i,t}^{\mathrm{short}} \geq BC_g^{\mathrm{max}} \cdot S_{i,g} \cdot x_{i,t} \; \forall i \in I, g \in G, t \in T \qquad (3)$$

$$\sum_{(i\in I)} S_{i,g} \cdot x_{i,t} + bat_{g,t}^{\mathrm{short}} = N_{g,t} \quad \forall g \in G, t \in T \qquad (4)$$

$$em_t^{\mathrm{buy}} - em_t^{\mathrm{sell}} = \sum_{(i\in I)} \left(bat_{i,t}^{\mathrm{chg}} - bat_{i,t}^{\mathrm{dsg}} \right) \quad \forall t \in T \qquad (5)$$

Day-Ahead Model

- Subject to

$$0 \leq bat_{i,t}^{\text{chg}} \leq (1 - x_{i,t}) P_i^{\max} \quad \forall i \in I, t \in T \tag{6}$$

$$0 \leq bat_{i,t}^{\text{dsg}} \leq (1 - x_{i,t}) P_i^{\max} \quad \forall i \in I, t \in T \tag{7}$$

$$\sum_{(g \in G)} BC_g^{\min} \cdot S_{i,g} \leq soc_{i,t} \leq \sum_{(g \in G)} BC_g^{\max} \cdot S_{i,g} \quad \forall i \in I, t \in T \tag{8}$$

$$\sum_{(g \in G)} BC_g^{\min} \cdot S_{i,g} \leq soc_{i,t}^{\text{short}} \leq \sum_{(g \in G)} BC_g^{\max} \cdot S_{i,g} \quad \forall i \in I, t \in T \tag{9}$$

$$bat_{i,t}^{\text{dsg}} \leq P_i^{\max} \cdot a_{i,t} \quad \forall i \in I, t \in T \tag{10}$$

$$bat_{i,t}^{\text{chg}} \leq P_i^{\max} (1 - a_{i,t}) \quad \forall i \in I, t \in T \tag{11}$$

$$em_t^{\text{sell}} \leq M \cdot c_t \quad \forall t \in T \tag{12}$$

$$em_t^{\text{buy}} \leq M (1 - c_t) \quad \forall t \in T \tag{13}$$

$$soc_{i,t=|T|} = SOC_{i,t=0}^{\text{init}} \quad \forall i \in I \tag{14}$$

Day-Ahead Model

- Subject to

$$\frac{soc_{i,t}^{\text{short}}}{\sum_{(g \in G)} S_{i,g} \cdot BC_g} = \sum_{(d \in D)} L_{i,t,d} \;\; \forall i \in I, t \in T \tag{15}$$

$$\beta_{i,t} = \sum_{(d \in D)} k_d \cdot L_{i,t,d} \;\; \forall i \in I, t \in T \tag{16}$$

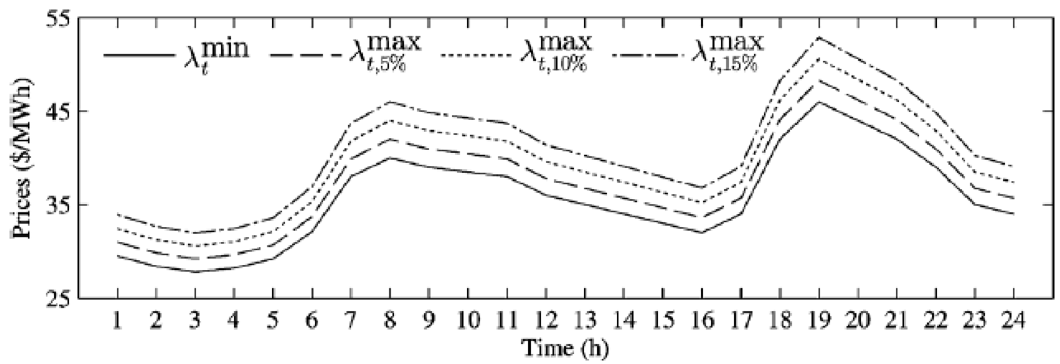
$$0 \leq L_{i,t,d} \leq L_d^{\max} \;\; \forall i \in I, t \in T, d \in D. \tag{17}$$

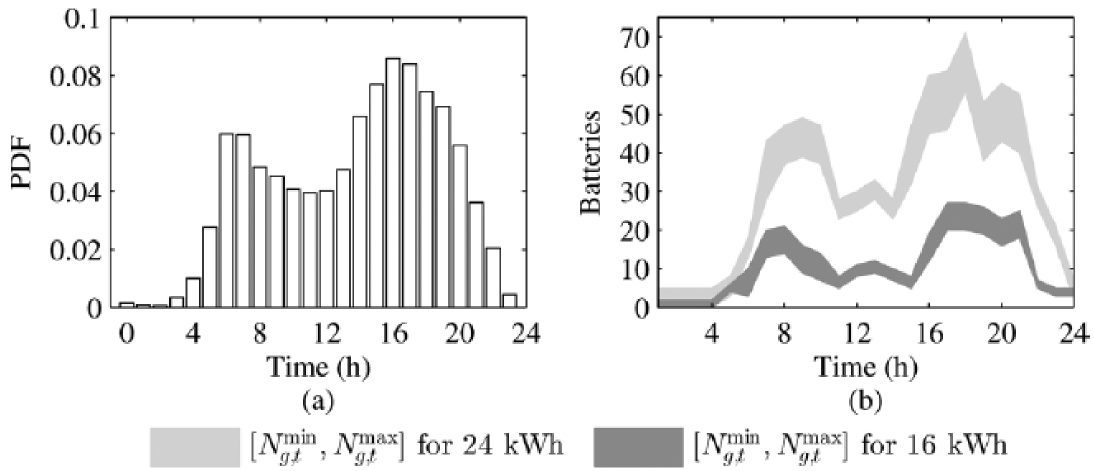
Day-Ahead Model

- This model is not realistic due to the uncertain parameters:
  - battery demand
  - SoC of the incoming batteries
  - electricity market prices

Day-Ahead Model

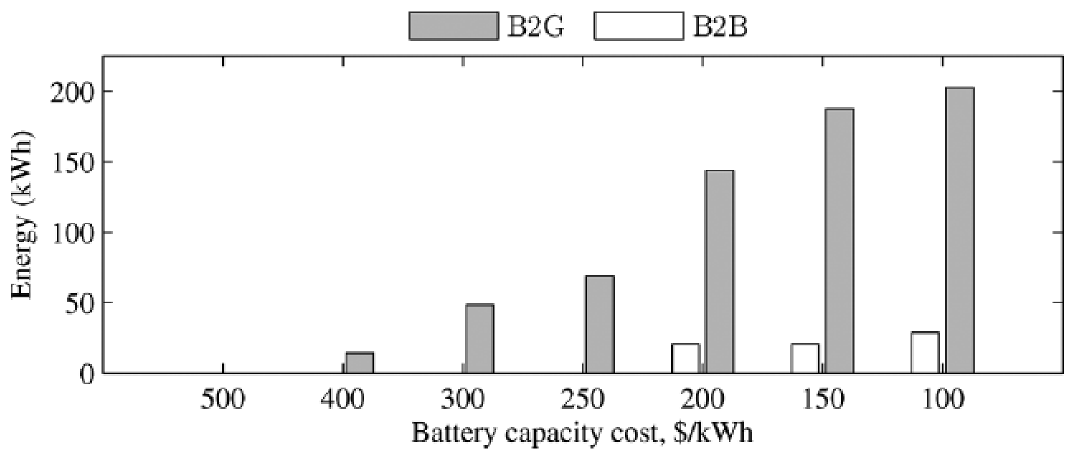
- *Inventory Robust Optimization* and *Multi-Band Robust Optimization*





Test Case

- BSS with 200 batteries with capacity 24 kWh
- We are interested in the degradation effects on the BSS operation – using battery prices 500USD/kWh (from 2012) down to 100 USD/kWh



Test Case

Deterministic vs. Robust solution

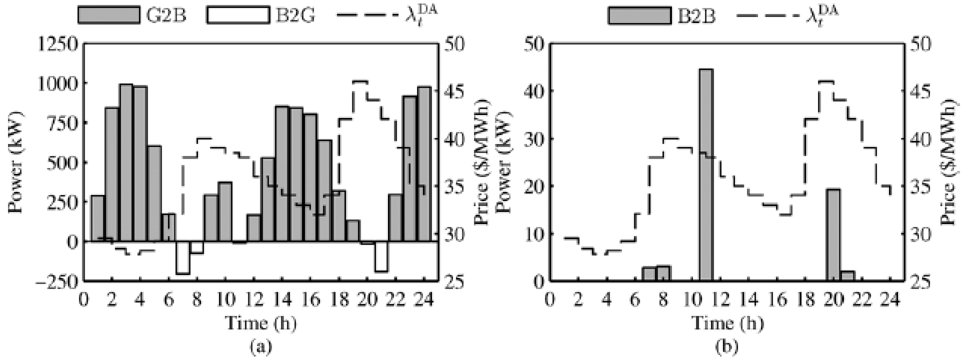


Fig. 10. G2B and B2G (a), and B2B (b) services in the deterministic case.

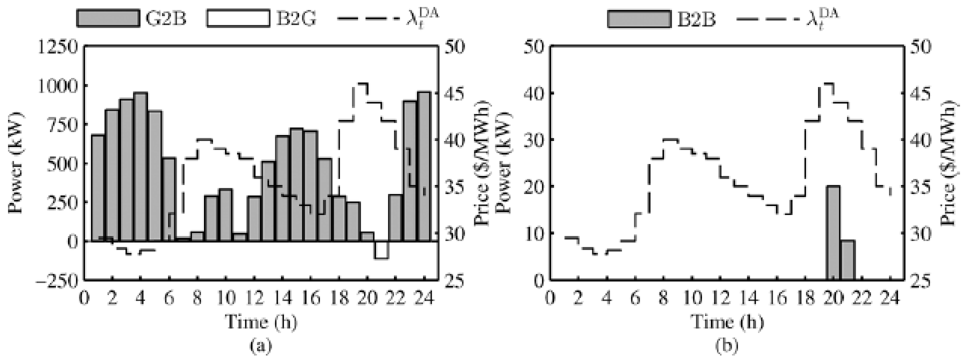


Fig. 11. G2B and B2G (a), and B2B (b) services in the uncertainty case.

Test Case

	Deterministic Solution	Robust Solution
Profit	$55 648	$55 609
Electricity Cost	$323.44	$361.10
Degradation Cost	$28.76	$30.26

Conclusions

- Uncertainty modeling reduces B2G and B2B
- Degradation of batteries should be reduced before B2G and B2B services are to be utilized
- The current battery prices, as well as the degradation effects, are too high in order to support B2G and B2B

The End

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