A CONCEPTUAL FRAMEWORK DESIGN FOR IMPLEMENTATION OF VEHICLE–TO–GRID (V2G)

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MOTIVATION

- There are growing concerns around the world about energy independence and global warming issues.

- The success of the Toyota Prius – with over 510,000 sold by November 2007 in the US – is a major driver in spearheading the development of battery vehicles (BVs) in the U.S. and Europe.
OUTLINE

- Integration of $BV$s into the electricity grid
  - $BV$s as a load
  - $BV$s as a generation/storage device
  - role of aggregation

- Development of a conceptual framework
OUTLINE

- Major implementational issues
  - design of an incentive program
  - metering and communication/control needs
- Environmental aspects
- Concluding remarks
THE ELECTRICITY GRID

- Not all the MWhs are equal in terms of costs and prices.
- The value of each MWh depends on the time of production/consumption.
- The integration of BVs into the grid can fully exploit the opportunities to:
  - buy when the price is low
  - sell when the price is high
  - provide additional services needed by the grid.
DEMAND AND LMP

Source: NE ISO

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DEMAND AND $LMP$

Source: NE ISO

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DEMAND AND \textit{LMP}

Source: NE ISO

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THE BV AS A "PURE LOAD"
CHARGING THE BVs

Source: Lucy Sanna, “Driving the solution, the plug-in hybrid vehicle,” EPRI journal, Fall 2005

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LEVELING THE LOAD

Source: NE ISO
LEVELING THE LOAD

impacts of the BVs

load

time of day

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Source: PJM
REGULATION SERVICE AND PRICING

Source: PJM

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REGULATION SERVICE AND PRICING

![Graph showing the relationship between demand (MW) and price ($/MW/h) over the course of a day. The graph includes a green line indicating the average price.](image)

Source: PJM

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A basic objective of the system operator is to ensure that the supply – demand equilibrium is maintained around the clock.

Imbalances lead to frequency fluctuations that need to be regulated.

The supply-demand imbalance is checked every 2 to 4 s.
ROLE OF BVs IN FREQUENCY REGULATION

time of day

load/generation

generation

load

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OFF – PEAK REGULATION

- Compliance with the unit commitment schedules becomes difficult during low load conditions that characterize the off – peak periods.
- While, the operator may not wish to turn off units, there may be no choice.
- Wind integration further exacerbates these conditions.
- The regulation prices are, typically, the highest as many units need to reduce their outputs.
PEAK AND OFF–PEAK REGULATION

Source: CAISO

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BVs AND FREQUENCY REGULATION

- Batteries have the ability to both absorb and discharge energy.
- The regulation capacity quantity provided by a battery is relatively small.
- Batteries have very short response times (of the order of ms).
- The frequent switching of batteries may, however, severely impact their life expectancies.

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THE $BV$ AS A “SUPPLY-SIDE RESOURCE”

$s.o.c. \ (\%)$

100

60

6 8 18 24

time of day

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BATTERY ISSUES

- The battery capacity of each $BV$ is small in terms of $kWh$ storage.

- This capacity limitation restricts consequently the "supply-side resource" capability of each $BV$.

- A key requirement for grid integration is the aggregation of $BV$s into a collection with capability to impact the grid.
V2G CONCEPTUAL FRAMEWORK

- Load aggregation
- Resource aggregation
- Explicit representation of uncertainty
- Communications/control layer construction
- Development of incentives
PRINCIPAL PLAYERS IN THE $V2G$ INTEGRATION

- $BV$
- Aggregator
- Aggregated $BV$s
- $ESP$
- $ISO/RTO$
THE INTEGRATION FRAMEWORK

aggregator

load aggregation

resource aggregation

ESP

ISO/RTO

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THE ROLE OF AGGREGATION

- The storage capacity $C$ for a typical $BV$ is in the $1\text{–}30$ kWh range.
- If we consider the total discharge of the full battery over 5 h, the output is in the $0.2\text{–}6$ kW range.
- The aggregator, who gathers together “many” $BV$s to result in a nontrivial aggregated output and load, interfaces with the $ISO/RTO$ on supply-side issues and the $ESP$ on demand-side issues.
FLOWS IN V2G INTEGRATION

- ISO/RTO
- Individual BV owner
- ESP
- Aggregated BVs as a resource
- Aggregated BVs as a load
- Parking facility
- Battery supplier

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V2G CONCEPTUAL FRAMEWORK

aggregated BVs as a resource

ISO/RTO

aggregated BVs as a load

battery supplier A

battery supplier Z

parking facility α

parking facility ζ

all services

$BV$ monitoring data

command

$BV$ aggregation service data

request for $MW$/MWh

$BV$ aggregation load data

command

parking services

batteries

$MWh, MW$
We take into account various sources of uncertainty, including:

- time of arrival
- parking time
- state of charge
- storage of the vehicle
- demand

For the aggregated BVs, we use the Central Limit Theorem ($N > 30$) to justify the representation of the various random variables by normal distributions.
average commute distance is
22 miles = 35 km

Source: Lucy Sanna, “Driving the solution, the plug-in hybrid vehicle,” EPRI journal, Fall 2005
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PARKING LOT UTILIZATION AS A FRACTION OF ITS CAPACITY

fraction

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PARKING LOT UTILIZATION AS A FRACTION OF ITS CAPACITY

fraction

time of day

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PARKING LOT UTILIZATION AS A FRACTION OF ITS CAPACITY
APPROXIMATION OF PARKING UTILIZATION

fraction

normal approximation

time of day

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MODEL OF PARKING UTILIZATION

![Graph showing the utilization of parking spaces over the course of a day. The graph plots fraction of spaces filled against time of day, with a peak around 12-14 hours and a drop-off towards the evening.]

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The role of the s.o.c. is key to the effective management of the aggregated BV integration into the grid.

The output of a battery is a function of its storage capability.
BV's PROVIDE IMPORTANT SERVICE

- The aggregated BV's constitute a very important supply-side resource to the grid

- The presence of the BV's provide the ISO/RTO with considerable flexibility in the scheduling of units

- As a result, the start-up of cycling and peaking units may be delayed or avoided; the availability of reserves is improved and, during off-peak, the need for reserves is reduced
CYCLING UNITS WITHOUT \(V2G\)

Source: NE ISO

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CYCLING UNITS WITH V2G

Source: NE ISO

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AGGREGATED $BV$ POWER/CAPACITY

![Graph showing power output over time of day. The graph peaks around 10 AM.]
Source: PJM
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PERCENTAGE OF BVS PROVIDING THE REGULATION SERVICE

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PROVISION OF LOAD SHAVING SERVICE IN ADDITION TO REGULATION

- The number of BVs providing regulation service remains rather low, with fewer than 10% of the BVs in the aggregation providing service at each point in time.
- We consider the provision of load shaving service in addition to the regulation service.
- We show that the Aggregator can provide 100 MWh of load shaving service at a constant power output between 9:00 and 9:30 a.m for an aggregation of 100,000 BVs.
PERCENTAGE OF BVS PROVIDING LOAD SHAVING AND REGULATION SERVICE

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ENERGY PROVIDED IN ADDITION TO THE REGULATION SERVICE

maximum constant power output for the 9:30 period in addition to the provision of 30-MW regulation service (MW)

size of BV aggregation in thousands

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REGULATION FOR OFF-PEAK CONDITIONS

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REGULATION FOR OFF-PEAK CONDITIONS

![Graph showing regulation (MW) over time of day.](image)

- 10,000 BVs
- 1000
- 500
- 0
- -500
- -1000

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REGULATION FOR OFF-PEAK CONDITIONS

![Graph showing regulation (MW) over time of day with BVs.]
REGULATION FOR OFF-PEAK CONDITIONS

![Graph showing regulation (MW) over time of day for different BVs: 10,000 BVs, 100,000 BVs, and 50,000 BVs. The graph indicates fluctuations in regulation throughout the day.]
REGULATION FOR OFF-PEAK CONDITIONS

![Graph showing regulation vs. time of day with key points at 10,000, 50,000, 100,000, and 500,000 BVs.]
KEY IMPLEMENTATIONAL ISSUES

- Aggregation implementation
- Information layer construction
- Incentive development
- Realization of environmental benefits
V2G COMMUNICATION AND METERING

Aggregator

charging station

distribution grid

ISO/RTO

ZigBee transceiver
ESSENTIAL COMMUNICATION / CONTROL SYSTEM REQUIREMENTS

- Speed: signals need to be sent every 1 to 2 s
- Range: every $BV$ in a parking lot must be on the communication network
- Measurement: metering must be installed to enable payment for services
- Reliability: full utilization of all parked aggregated $BVs$
- Security: $BVs$ may be used to hack the network
ESSENTIAL COMMUNICATION / CONTROL SYSTEM REQUIREMENTS

- **Costs:** each $BV$ has an implanted device and the costs per unit must be low for the large collection of aggregated $BV$s.

- **Extendibility:** the communication layer must allow the integration of additional $BV$s.

- **Interoperability:** a non-restrictive, flexible standard needs to be introduced and implemented.
- ID of each $BV$
- Preferences/constraints of each $BV$
- Parking status of each $BV$
- Storage capability of the $BV$ battery
- The $BV$ battery s.o.c.
- Power flows from $BV$ battery to the grid
- Measured value of metered quantities
THE ROLES OF THE AGGREGATOR

- Development of the parking infrastructure
- Maintenance of the batteries and the network
- Creation of relationships with the BV manufacturers
- Interface with ISO/RTO
VALUE ADDED BY THE AGGREGATOR

- Provides a “package deal” to the aggregated $BV$s in terms of:
  - parking facilities
  - service acquisition and provision
  - charging of $BV$s
  - battery service
- Allows “one-stop shopping” for potential $BV$ participants
- Acts as a provider of environmental benefits for reduced emissions
NET GENERATION BY ENERGY SOURCE UP TO 6/31/2009

- **coal**: 45%
- **natural gas**: 21.4%
- **nuclear**: 20.8%
- **petroleum**: 1.15%
- **hydro**: 7.6%
- **other renewable**: 3.6%
- **other gases**: 0.5%

industry total = 4,115 Twh

Source: Ameren IP
CO₂ EMISSION BY PLANT TYPE
ENERGY CONSUMPTION UNDER MIXED CONDITIONS

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VEHICLE CO\textsubscript{2} EMISSIONS

\begin{center}
\begin{tabular}{c}
\textbf{g/km} \\
\hline
EV France & EV Canada & EV USA & EV Germany & internal combustion \\
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FUTURE WORK

- Improvement of the $BV$ selection for the provision of higher energy and regulation performance

- Design and implementation of a secure and economic communication/control architecture

- Design of an effective incentive program for high $BV$ participation and retention
CONCLUDING REMARKS

- Integration of BVs helps the grid both as loads and as generation sources.
- ESPs and ISO/RTOs will have a new player to do business with.
- Aggregators are key for the implementation of V2G concept to be successful.
- The BV aggregator has the potential for making sizeable benefits.