Electric Vehicles and Their Impact on Trustworthy Power Grid Informatics

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Outline

• Motivation
• Challenges of EVs
  – EV Problems discussed at IEVC’14
    • Wireless charging
    • Electrification of roads
    • EV Batteries
    • Standards
• Impact on Power Grid Informatics caused by EVs
• Conclusions
Motivation (Why EVs?)

Beijing pollution

New York Pollution

Paris pollution

LA Pollution vs Cheyenne
Motivation

- Increasing popularity of Electric Vehicles (EVs)
- Limitation: access to public charging facilities.

Chart 1.1: Total EV Charging Station Unit Sales by Region, World Markets: 2011-2017

(Source: Pike Research)

Stakeholders

Energy Providers: Distribution and Generation Infrastructure of Electricity

National Policy Makers

Road Infrastructure Providers

Urban City Transport Planners, Logistics, ...: Planning Electrification Infrastructure

EV Makers: Cars, Trucks, Busses, Motorcycles, Trains

IT Organizations: IT Infrastructure
Players in USA

• Car Companies:
  – Toyota (USA Division)
  – Ford Motor Company (crowd-sourced energy)

• IT/Telecom Companies:
  – Qualcomm (wireless charging for EV and PHEV)
  – Cisco (network infrastructure and connectivity associated with electrical charging)
  – IBM Software Group (Automotive 2015 Project)

• Universities:
  – Ohio State University (Major Center on EVs and Transportation – Three Land Speed Record Electric Cars)
  – University of California, Davis (Batteries)
  – University of Michigan (wireless charging)
  – Clemson University (Major Center on Transportation - Urban Mobility Systems)
  – Oregon State University (EV power electronics)
  – University of Colorado at Boulder (EV power electronics)
  – USC (power grid and EV)
  – Virginia Tech (power grid and EV)
  – New York University (wireless charging)

• National Labs:
  – Oak Ridge National Laboratory

• Service Companies
  – Transportation Power Solutions (division in RES – Renewable Engineering Systems)
CHALLENGES OF ELECTRIC VEHICLES
Challenges of EVs

• Electric mobility Beyond 2020!!
  – Eco-friendliness, safety, comfort, efficiency
• EV Charging
  – Charging Stations
  – Static Wireless Charging
  – Dynamic Wireless Charging
• Electrification of Road Infrastructure
• Design of Electric Vehicles themselves
  – Battery (size, weight, temperature, capacity)
  – Speeds of EV – 1 and 2 speed vehicle optimal for passenger cars, trucks may need 3 speeds (higher gears)
• Standards
EV Charging - Charging Stations (1)

- In USA by 2020 first stage of major EV deployment in form of **Hybrid Plug-in Electric Vehicles (PEV)**
- Volvo anticipates huge Hybrid EV technology revenue increase
- Pike Research forecasts by 2017
  - 1.5 M of charging stations
  - 5.1 M PEVs in USA
  - EV supply equipment (EVSE) drops by 37% (Gartner)

- Car Metrics to consider
  - BMWi3 car
    - 12.9KW per 100 km
    - acceleration time 0-100km/h takes 7.2 seconds
    - Number of speeds: 1 speed (corresponds to 1 gear)
    - Number of miles per battery

Charging Stations (2)

- Challenge: Who installs charging stations?
  - Case study in Brussels:
    - On public land (e.g., public parking space) only utility company can install charging stations; utility charges for electricity
    - Parking company 3rd party should only charge for space
      - But often parking company charges for parking space and usage of charging station; user pays twice
    - On private land (e.g., private garage) 3rd party company installs charging station and charges for electricity
Charging Stations (3)

• Challenge: More PHEV than charging stations
  – Do we establish reservation system?
  – What will happen to other drivers?
  – Is inductive charging the solution?
EV Charging - Static Wireless Charging (1)
Static Wireless Charging (2)

• First paper about wireless charging by **Tesla 1908 !!**
• Technology: ICET – Inductive Contactless Energy Transfer
• Challenges: weak coupling factor, lower efficiency, high magnetizing
• **Solution:** bidirectional inductive contactless energy transfer (CET)
• CET systems used for
  – Sensor actuators (microwatt power range)
  – EVs (hundreds kilowatts)
• Current efficiency of ICET
  – 80-95% for 10-40cm distance
Static Wireless Charging (3)

• Challenge: People are concerned regarding safety
  – Electric power is transferred through air
  – Tests are going on at ORNL

• Challenge: Long Charging
EV Charging - Dynamic Wireless Charging (1)
Dynamic Wireless Charging (2)

• Technology: Dynamic Wireless Power Transfer (D-WPT)
• Solutions:
  – By ORNL – first vehicle that does D-WPT
    • They work with
      – Evatran LLC
      – CU-ICAR – Clemson University International Center for Automotive Research
      – Toyota Motor Co.
    • They demonstrated
      – dynamic WPT and validated 6.6 KW capable wireless power transfer apparatus at 85% efficiency
      – Complete integration design and vehicular integration
Dynamic Wireless Charging (3)

• Solutions:
  • Italy: FABRIC project
    – 200m test track, 20m long coils, 20KW
  • France: Qualcomm, Vedecom
    – 100m test track, 85 KHz, > 20KW
Dynamic Wireless Charging (4)

• Challenge: Impact on EV speed
  – if we have 2 m long coils of 20 KW, one needs to go slowly at 36 km/h
  – If one goes at 108km/h, one has only 200ms charging time

• Challenge: Impact on Power Grid
  – Simulation study by FABRIC project:
    • If one considers average 10 EV/km/lane over 1 hour with 500 simulated EVs with max capacity 30 EV/km/lane, then one can achieve 2-8 MW load demand
    • We will need energy storage system if demand fluctuation which will be the case
    • Energy storage systems can minimize demand variability
      – Overall peak load reduction will be less expensive
    • Load shaping and shaving is needed!!!
Dynamic Wireless Charging (5)

• Further Challenges:
  – Communication latency
  – Infrastructure issues for Power grid distribution
  – Coil sequencing

• Electric roads may need solar panels next to the road to provide electricity
Dynamic Wireless Charging (6)

• Pros:
  – Smaller battery
  – Cheaper EV
  – Extended driving range
  – Extended battery lifetime
  – Energy efficiency
  – Comfort
  – Increased mobility
  – No visual pollution

• Cons
  – Expensive infrastructure
Electrification of Road Infrastructure (1)

- ORNL is conducting **dynamic roadway projections**
  - Estimate cost and impacts for **electric roadway** given
    - Current vehicle information from supporting lab data
    - Current electric vehicles
  - Estimate cost and impact for electrified roadway given
    - 40 miles per hour vehicular speed
    - Charging pads with 11 KW for small vehicle to keep it charged
- First Results of Projections for Atlanta
  - If we consider 25-30KW, estimated 30% lane coverage, it would cost $2.8M per Mile of electrified road per lane
Electrification of Road Infrastructure (2)

- **Roadmap of electrification**
  - 0% electrified roadways for EV cars in 2020
    - By 2020 smart eVehicle (Hybrid)
    - By 2022 50% increase of PHEVs in Europe (forecast)
    - By 2025 integrated system (information cloud + driver commands + vehicle sensory data = integrated energy management)
  - Building business cases towards 2050
    - 4 US Metro Areas
      - LA - Long Beach
      - San Francisco-Oakland
      - San Diego Area
      - Atlanta Area
    - Base case of 100 KW and 30KW WPT
  - Bus (and trucks) lanes will be first go towards electrification
    - stable routes
  - Trains are already electric
Electrification of Road Infrastructure (3)

• Challenges:
  – Cost of dynamic WPT on vehicle
    • What is the impact of WPT on vehicle (size of battery)?
  – How do we pay for road electrification?
    • Road use cases – toll roads, taxes
  – Where do we place charging pads?
    • Case study – I-75 South Atlanta
Electrification of Road Infrastructure (4)

- Challenges for Wireless Charging:
  - Road material for on-the-road charging
  - How do we deal with water, snow, sand, ice, clay, etc on roads?
    - There is loss when roads are wet. We need different material to minimize loss even in wet conditions.
  - How do we deal with structural integrity of road?
    - Roads can crack, have rutting problems
    - We need device to test roads for structural integrity.

Source: KTH Smart Road Infrastructure Project
EV Battery

• Challenge: Size of battery
  – If we have charging stations, we need larger batteries
  – If we have charging pads (WPT), we would need smaller batteries
    • Desirable 1.6 KW batteries or even 1.5 KW
• Impact of WPT on Battery Size
  – We will need coils spaced close to each other
  – We will need to have sensors on coils, to enable coils to be energized and controlled with speed,
    – Sensors would know how fast you go and energize accordingly
  – With sensors, one starts with first coil and then the next will be fired up dynamically
    • Energy savings since coils will not be needed to be on constantly
EV Battery (2)

• Challenge: Cost of Battery
  – Cost target of $250 per KWh is unlikely to happen by 2020
    • According to Dr. Bernarsch, CEO Virtual Vehicle Research Center
  – However, overall prices are going down
    • TESLA-S2 battery price is going down

• Challenge: Energy and Thermal Management in EV
  – With intelligent and Integrated energy and Thermal management in EV we can increase driving range
Standards (1)

- **SAE J2954 Standard – Wireless Charging**
  - Combining DSRC/RFID Wireless Charging J2954 Communications Subgroup
    - In Vehicle Navigation
    - Electric charging stations
    - Vehicle diagnostic and performance
    - Charging and ePayment solutions
  - DSRC 5.9 GHz ~300m range
- **IEC 61851 Standard - EV Conductive Charging System**
  - IEC 61851-24: digital communication between EV charging station and electric vehicle for control of charging
Standards (2)

• Joint Project between ISO and IEC – dedicated to interoperability and safety in wireless magnetic interaction vehicle interaction
  – ISO TC22/SC21 and IEC TC 69
  – ISO 19363 – Magnetic field wireless power transfer – interoperability and safety requirement
  – IEC JPT 61980 – electric vehicle wireless power transfer (WPT) system
  • Specific requirements for communication between EV and infrastructure with respect to WPT systems
  – ISO/IEC 15118 – road vehicle to grid communication interface (all network protocol stack layers defined)
• All standards at this point provide safety requirements and protection against electrification
  NO protection against cyber-attacks yet
Summary of Challenges of EV Systems

• Challenge: Cost
  – Number of EVs must go up
  – Charging technologies must improve
  – Weight and size of batteries must go down
  – Cost of electrification
  – Standardization is necessary

• Other challenges not discussed in this talk but very much of interest to EV Car Manufacturers:
  – Automated vehicle driving
  – Connected vehicles
IMPACT ON POWER GRID INFORMATICS
What is Power Grid Informatics?

• **Power Grid Informatics** is the science of cyber-information about power grid. It studies the structure, algorithms, behavior, and interactions of power grid physical systems and artificial cyber systems (cyber-physical systems) which store, process, access and communicate information. The field considers the interaction between human power grid/utility operator and/or stakeholder and power grid information systems alongside the construction of computer interfaces.

• **Trustworthy Power Grid Informatics** encompasses the study of systems that represent, process and communicate digital information in real-time, reliable, secure and private manner (availability, integrity, confidentiality, privacy).
Cyber-Physical Components

- **Road:**
  - **Sensors** on/in the roads (coils) in case of dynamic wireless charging, signaling, other road functions
  - **Road Side Units (RSU)** next to the road for capturing, processing and communicating wirelessly sensory information (cell towers, wireless access and processing points)

- **EV Car:**
  - **Mobile smart meter** to measure charging levels and usage levels
  - **Other sensors** monitoring other functions of car services

- **Power Grid Utility:**
  - **Cloud computing and storage** to store and process all the sensory information and provide power grid services

- **Road Services and 3rd Party Services:**
  - **Cloud computing and storage** to store, process and share related contextual information offered in conjunction with power grid services
Impact on Power Grid Informatics – Processing

- **Challenge: Provide IT Services** in Power Grid Informatics for EVs
  - Represent and Process Information via Algorithms towards
    - Accurate range estimation
    - Navigation
      - Cooperative IT system allows for robust traveling via re-routing
    - Assignment of charging stations
    - Placement of charging stations and charging pads

- **Challenge: Enable Seamless Information Integration** related to Power Grid Infrastructure, Trustworthy IT Infrastructure, EV Design, and Road Infrastructure (with wireless charging)
  - Large number of sensors (EV, road, power grid, people)
  - Different information representation
  - Different communication technologies
  - Different digital and energy storage capabilities
  - Mobility issues
  - Different security and privacy capabilities and demands
Impact on Power Grid Informatics - Processing

- Challenges for Business Models: Big Data
  - Cost-benefit analysis
  - Environmental life-cycle assessment
- Challenges for Charging Concepts: Real-Time
  - Vehicle authorization
  - Charging profile negotiation
  - Monitoring of power transfer while EV is over pads
  - Billing and payment
  - Coordination of WPT hardware with information control transmission
Impact on Power Grid Informatics – Processing

• Intelligent Power Management inside EV
  – In PHEV, we have auxiliary electrified system (air supply system, power steering, entertainment system)
  – Multi-physical system, auxiliary energy buffers, local constraints, controlled by real-time CPS control system

• Solution: Game Theory Approach:
  – Energy suppliers vs energy consumers in PHEV
  – Energy suppliers: Engine, electric motor, battery
  – Energy consumers: auxiliary system
  – Game-Theory guides decisions when each player scheduled its activation and deactivation on a prediction horizon
Impact on Power Grid Informatics - Access

- Make available power grid information with high integrity to ensure:
  - Power service continuity
  - Flexibility and extendibility,
  - Monitoring of demand growth
  - Electrical efficiency
  - Operational efficiency
  - Power quality

- **Deal with large power fluctuation** due to power transfer design, effect of traffic conditions
  - Deal with Variable number of vehicles in lanes in case of WPT

- **Solution:**
  - Platooning of vehicles might reduce peak load demand via coordinated power transfer
  - Adequate lane design must happen
  - Energy storage and traffic control will help
Impact on Power Grid Informatics - Communication

• **Vehicle-to-Grid Communication**

• **Challenges:**
  – Real-time Digital Communication of Status/Control Information
    • Availability and integrity of information
  – Real-time Authentication
    • Identification, authorization, authentication, verification
  – Location Privacy
Solution for Roaming Service Model

- **EV**
  - subscribes to the utility
  - makes monthly payment to the utility

- **Utility**
  - manages subscribing EV’s information
  - bills the EV monthly

- **Pad Owner**
  - installs charging pads
  - provides dynamic charging service
  - may receive energy from some other utility
One Possible Solution: Key Management and Authentication Protocol Overview

Utility

Pad Owner

Li, Nahrstedt, Smartgridcom’14
Problem: Find optimal locations for charging facilities to serve the most traffic flows. Constraint: budget.

Link information:
- Length in unit
- Traffic flow in veh/hr
Approximation Solution

We follow steps:

1. Pick candidate paths to assign only charging pads.
2. Make rest of the nodes candidate sites to assign charging stations. Note: pads and stations cannot overlap.
3. Optimize which path(s) to assign charging pads and which node(s) to assign charging stations.

To locate:
- 1 charging pad
- 1 charging station
Conclusion

- This community plans for 2050
  - Tremendous engineering and scientific problems need to be solved until 2050
    - Wireless charging, new materials, heterogeneity, ...
- EVs, Power Grid, Roads are all becoming cyber-physical systems
- Information will be acquired, stored and processed leading to
  - Big Data problems (volume, velocity, variety, value, visualization...)
  - Information Representation and Integration problems (many stakeholders)
- Information will be communicated in trustworthy manner leading to
  - Security and privacy problems (access control, authentication, ..)
  - Information Reachability problems due to mobility
  - Heterogeneous communication problems (latency, losses, ...)
  - Integrated social, vehicular and road network problems
OPTIMAL PLACEMENT OF CHARGING STATIONS AND DYNAMIC WIRELESS CHARGING PADS

(CHANG, LI, NAHRSTEDT)
Objective

• Charging facilities:
  – Charging station
  – Dynamic Wireless Charging pad

• Find optimal locations for charging pad and station
  – Intersection/node: station
  – Road/link: pad
Goal: find optimal locations for charging facilities to serve the most traffic flows. Constraint: budget.

Link information:
- Length in unit
- Traffic flow in veh/hr
Flow Refueling Location Model (FRLM)

• Proposed by M. Kuby in 2005

• Major features:
  
  — Assume vehicles travel on pre-planned routes.
  
  — Consider EV driving range
  
  — Allow EVs to refuel multiple times while driving
A candidate combination is a set of candidate locations (nodes & links).

- Candidate combination 1: \{A, C, D\}
- Candidate combination 2: \{B, AD\}
An eligible combination of an OD pair is a candidate combination which could ensure an EV to complete a round trip from O to D.

State of Charge (SOC). E.g. 6 unit.

Candidate combination: \{B, AD\}
- \{B, AD\} is an eligible combination of Flow AB.
- \{B, AD\} is not an eligible combination of Flow AC.
Challenge

- # combinations = \( \binom{4}{1} \times \binom{5}{1} \) 1 station, 1 pad

- # combinations = \( \binom{4}{2} \times \binom{5}{1} \) 2 station, 1 pad

- # combinations = \( \binom{4}{3} \times \binom{5}{1} \) 3 station, 1 pad

...
Approximation Solution

- We follow steps:
  1. Pick candidate paths to assign only charging pads.
  2. Make rest of the nodes candidate sites to assign charging stations. Note: pads and stations cannot overlap.
  3. Determine which path(s) to assign charging pads and which node(s) to assign charging stations.

To locate:
- 1 charging pad
- 1 charging station
Sample Network

Goal:

To locate: 1 Charging station, 1 Charging pad

On: 1 Candidate link $p_3$, 2 Candidate nodes $p_1$, $p_2$
Coefficient matrix

\[ a_{hp} \]

<table>
<thead>
<tr>
<th>Candidate location</th>
<th>( p_1 )</th>
<th>( p_2 )</th>
<th>( p_3 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( h_1 )</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>( h_2 )</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>( h_3 )</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

\[ b_{qh} \]

<table>
<thead>
<tr>
<th>Combination</th>
<th>( h_1 )</th>
<th>( h_2 )</th>
<th>( h_3 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( q_1 )</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>( q_2 )</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>( q_3 )</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>( q_4 )</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>( q_5 )</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Combination 1 (\( h_1 \)) 170veh/hr
Combination 2 (\( h_2 \)) 280veh/hr
Combination 3 (\( h_3 \)) 190veh/hr
Optimization problem formulation

\[
\text{maximize } Z = \sum_{q} f_q^T x_q \\
\text{s.t. } \sum_{h \in H} b_{qh} v_h \geq x_q, \forall q \in Q \\
\quad a_{hp} y_p \geq v_h, \forall h \in H, \forall p \in P \\
\quad \sum_{p \in P} y_p = c, \\
\quad y_{pn} + y_{pr} \leq 1, \forall p_n \in p_r, \forall p_n \in P, \forall p_r \in P \\
\quad x_q, y_p, v_h \in \{0, 1\}, \forall q, \forall h, \forall p
\]

- Maximize the flows being refueled
- A flow is captured if at least one eligible combination is open
- A combination is open if all facilities required by the combination are open
- Fix the number of charging facilities to locate
- No overlap of stations and pads
- Binary variables
Evaluation

Find optimal locations for 3 charging facilities

**TOP FLOWS OF THE NINE NODE NETWORK**

<table>
<thead>
<tr>
<th>Flow ID</th>
<th>O</th>
<th>D</th>
<th>Distance</th>
<th>Path</th>
<th>Volume (veh/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>4</td>
<td>8</td>
<td>5</td>
<td>4 → 8</td>
<td>1197</td>
</tr>
<tr>
<td>22</td>
<td>4</td>
<td>5</td>
<td>3</td>
<td>4 → 5</td>
<td>1092.5</td>
</tr>
<tr>
<td>10</td>
<td>2</td>
<td>4</td>
<td>4</td>
<td>2 → 4</td>
<td>1068.8</td>
</tr>
<tr>
<td>24</td>
<td>4</td>
<td>7</td>
<td>5</td>
<td>4 → 7</td>
<td>1026</td>
</tr>
<tr>
<td>34</td>
<td>7</td>
<td>8</td>
<td>3</td>
<td>7 → 8</td>
<td>756</td>
</tr>
</tbody>
</table>
Facility Allocation

Charged Traffic flows

<table>
<thead>
<tr>
<th>Flow ID</th>
<th>O</th>
<th>D</th>
<th>Distance</th>
<th>Path</th>
<th>Volume (veh/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>2</td>
<td>4</td>
<td>4</td>
<td>2 → 4</td>
<td>1068.8</td>
</tr>
<tr>
<td>11</td>
<td>2</td>
<td>5</td>
<td>7</td>
<td>2 → 4 → 5</td>
<td>147.86</td>
</tr>
<tr>
<td>13</td>
<td>2</td>
<td>7</td>
<td>9</td>
<td>2 → 4 → 7</td>
<td>180</td>
</tr>
<tr>
<td>22</td>
<td>4</td>
<td>5</td>
<td>3</td>
<td>4 → 5</td>
<td>1092.5</td>
</tr>
<tr>
<td>24</td>
<td>4</td>
<td>7</td>
<td>5</td>
<td>4 → 7</td>
<td>1026</td>
</tr>
</tbody>
</table>

Charged Traffic flows with different combinations

<table>
<thead>
<tr>
<th># pad</th>
<th># station</th>
<th>Configuration</th>
<th>Volume (veh/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>0</td>
<td>Link 4, Link 5, Link 10</td>
<td>3515.1</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>Link 4, Link 5, Node 1</td>
<td>2309.1</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>Node 1, Node 2, Link 5</td>
<td>2726.9</td>
</tr>
<tr>
<td>0</td>
<td>3</td>
<td>Node 1, Node 2, Node 4</td>
<td>1692.2</td>
</tr>
</tbody>
</table>
Charging time required

Nissan Leaf

Node 2 ➔ Node 7, 252 mile.
Speed limit 70 mile/hr.
Requires 3.6 hours to complete the trip.

Charging station: 24 hrs of charging.
Charging pad: does not need to stop for charging.
Summary

- Goal: final optimal locations for charging facilities including **charging stations** and **charging pads**.

- Extended the FRLM model.

- Locating charging pads:
  - Serve more traffic flow
  - Save charging time
Topic Slide

• Main Point
  – Sub-point
    • next point
      – and yet another point
        » oh ... and don’t forget this important point!!