Reducing the impact of EV charging on the electric grid
Who am I?

- Jesús Fraile-Ardanuy
- Associate Professor at Technical University of Madrid
- Main research lines:
  - Renewable energies
  - Control system applications
  - Integration of EVs on the grid
Who is my audience?
Outline

- Fundamentals of electric grid
- Fundamentals of electric vehicles
- Electricity markets and EVs
- Analyzing and reducing the impact of EV charging on the electric grid (DATASIM results)
- Summary
Why electricity is held in low esteem?

- Because it is always there.
- Because it is cheap.
- Because we always ignore it unless...

... The lights go out!
Blackouts!

<table>
<thead>
<tr>
<th>Location</th>
<th>Million people affected</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>India</td>
<td>670</td>
<td>30-31 Jul 2012</td>
</tr>
<tr>
<td>Indonesia</td>
<td>100</td>
<td>18 Ago 05</td>
</tr>
<tr>
<td>Brazil</td>
<td>97</td>
<td>11 Mar 99</td>
</tr>
<tr>
<td>Brazil, Paraguay</td>
<td>87</td>
<td>10-11 Nov 2009</td>
</tr>
<tr>
<td>USA, Canada</td>
<td>55</td>
<td>14-15 Ago 2003</td>
</tr>
<tr>
<td>Italy, Switzerland, Austria, Slovenia, Croatia</td>
<td>55</td>
<td>28 Sep 03</td>
</tr>
<tr>
<td>USA, Canada</td>
<td>30</td>
<td>09 Nov 65</td>
</tr>
</tbody>
</table>

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India Blackout

- 670 million people were without electricity.
- Roughly equivalent to the entire population of Europe.
Electric grid fundamentals

1st part
Understanding power systems

Generation

Transmission and distribution network

Consumers

Thermal power plant
Hydro power plant
Wind Energy

System Operator (SO) control center
Transmission Substation
Distribution network
Industrial Customers (Medium or High Voltage)

Residential Customers (Low Voltage)
Distribution substation

Energy flows in one direction, from generation to consumer

Source: REE.es
Understanding electric generation

Hydroelectric power generation

Power transmission cables
Transformer
Power house
Generator
Turbine
Penstock
Downstream outlet
Dam
Sluice gates
Storage reservoir

Source: Environment Canada
Understanding electric generation
Understanding electric generation
Understanding electric generator

Electric Power

Mechanical Power

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POLITECNICA
Transmission stations

Electric Generation (10-20 kV)
Step up transformer

Transmission substations

Transmission (L>200 km) V ≥220 kV

Source: REE.es
Transmission substations

Source: REE.es
Transmission substations

- Transformers are essential in making large-scale power transfer feasible over long distances.
Voltage ratings used in Belgium

- 380 kV
- 220 kV
- 110 kV
- 10 kV
- 0.4 kV
- 150 kV
- 50 kV
- 10 kV
- 0.4 kV
- 10 kV
- 0.4 kV
No storage capacity in the grid

Grid operators need to balance power supply and demand at all times

Source: REE.es  15/07/2014
Generation is continuously adapting to cover the variable demand.

Source: http://www.vreg.be
Different types of power plants are running during the day, covering the electric demand.

In order to promote renewable energies, the demand is first met from renewable sources.

Source: www.unendlich-viel-energie.de/
Problems with intermittent renewable energy

- Sometimes, disconnection of renewable energies are needed during low demand periods.

If Generation > Demand → Wind generators are disconnected

Renewable energy is lost (spilled wind energy) in this case, because it is not possible to store large amount of electrical energy during low demand periods.

Source: REE.es
Balancing solutions

- New network interconnections
- Energy management:
  - Demand response
- Energy storage
- Electric vehicles
Balancing solutions-New transmission lines

- **New electricity highways** (transmission network)
  - A fully interconnected EU electricity market
  - Developing the huge renewables potential
    - **North Europe**: off-shore wind farms, tidal farms
    - **South Europe and Africa**: PV and thermosolar plants
Balancing solutions-DSM

- **Energy management** *(demand side management)*
  - Process of managing energy consumption to optimise available and planned resources for power generation.

- DSM incorporates all activities that influence customer use of electricity and results in the reduction of the electricity demand, which are mutually beneficial to the customers and the utility.
Balancing solutions-DSM

- **Energy management** (DSM main techniques)
  - **Direct DSM:**
    - Load limiters
    - Direct load control
  - **Indirect DSM:**
    - Time of use price
Balancing solutions-DSM

- **Peak Shaving.** Reduction of customer loads during peak demand periods. This can delay the need for additional generation capacity. Peak clipping can be achieved by direct control of customers’ appliances.

**Conservation.** Reduction in consumption by consumers. There is net reduction in both demand and total energy consumption. Strategic conservation can be implemented by motivating customers to use more energy-efficient appliances.

**Load Shifting.** Shifting loads from on-peak to off-peak periods. The net effect is a decrease in peak demand, but not change in total energy consumption.
Balancing solutions-Storage

Recovering stored energy during the peaks, avoids the connection of the most expensive power plants!
# Balancing solutions - Storage

## Classification of electrical energy storage

<table>
<thead>
<tr>
<th>Mechanical</th>
<th>Electrochemical</th>
<th>Electrical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pump storage power plant</td>
<td>Accumulators lead/NiCd/NiMH/Li-ion</td>
<td>Double layer capacitors</td>
</tr>
<tr>
<td>Compressed air storage power plant</td>
<td>HT accumulators NaS/NaNiCl</td>
<td>Superconducting coils (SMES)</td>
</tr>
<tr>
<td>Lift storage power plant</td>
<td>Flow batteries redox flow/hybrid flow</td>
<td></td>
</tr>
<tr>
<td>Fly wheel</td>
<td>Hydrogen/reg.fuel cell</td>
<td></td>
</tr>
</tbody>
</table>

*Source: Fraunhofer ISE*
Balancing solutions

- **Pumped hydro**: At the times when enough power is available, water is pumped to and upper reservoir. When the electric energy is expensive, the water is fall down driving the generator, producing energy.
CAES: At times when enough power is available, compressed air is injected into caverns. The pressure in such a storage facility can reach 100 bars. When the air escapes, it drives a generator via a turbine to produce electricity.
Balancing solutions - Storage

- **Flywheels**: A flywheel is a rotating mechanical device that is used to store **rotational energy**.

- Flywheels have a significant moment of inertia. The amount of energy stored in a flywheel is proportional to the square of its rotational speed.
Balancing solutions-Batteries

- Different types of electrochemical batteries

Redex Batteries

Solar Panels
Balancing solutions-batteries

Distributed storage capacity
Balancing solutions-efficiency in storage

<table>
<thead>
<tr>
<th>Energy Conversion Process</th>
<th>Storage</th>
<th>Discharge</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pump storage hydro power station</td>
<td>84-88</td>
<td>86-91</td>
<td>72-80</td>
</tr>
<tr>
<td>Compressed air energy storage (adiabatic)</td>
<td>77-81</td>
<td>81-86</td>
<td>62-70</td>
</tr>
<tr>
<td>Lead batteries</td>
<td>80-88</td>
<td>81-90</td>
<td>65-79</td>
</tr>
<tr>
<td>Li ion batteries</td>
<td></td>
<td></td>
<td>90-95</td>
</tr>
<tr>
<td>Redox flow battery</td>
<td>84-90</td>
<td>83-89</td>
<td>70-80</td>
</tr>
<tr>
<td>Hydrogen, electrolysis, fuel cell</td>
<td>59-66</td>
<td>35-65</td>
<td>21-43</td>
</tr>
</tbody>
</table>

Source: IFEU – Institut für Energie- und Umweltforschung Heidelberg GmbH
sponsored by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU)
A system model change is needed

- **Actual electrical grid**
  - Demand is not flexible
  - Generation is adapted continuously
  - No storage

- **Future electrical grid**
  - Demand will be flexible
  - Generation won’t be managed due to its intermittence

**Key elements**
1. STORAGE at different levels
2. Active Demand Management (ADM)
3. Communication infrastructure

*Source: IEA.org*
What is a smart grid?

- The Smart Grid is a **bi-directional electric and communication network** that improves the reliability, security, and efficiency of the electric system for small to large-scale generation, transmission, distribution, and storage.
Electric vehicle fundamentals

2nd part
Electric vehicles

First IDEA
Electric vehicles

- EV were clean and easier to use (compared to ICE one)
- Lower maintenance and available infrastructure (no fuel station was available)
- Motors had high power-to-weight ratio.
- Main drawback:
  - Limited range.

Source: [www.istc.illinois.edu/about/](http://www.istc.illinois.edu/about/)
Hybrid Electric Vehicles
Hybrid electric vehicles

- 1900 Porsche hybrid
- HEV can deliver energy for long time
- Retain the ease-of-use advantages of EV

Source: www.istc.illinois.edu/about/
Why did gasoline cars win?

- Ford made cars affordable (model T)
- Gasoline was a waste product of oil refining
- ICE cars were improving continuously while the EV technology were not (overtake in 1920s).

Source: [www.istc.illinois.edu/about/](http://www.istc.illinois.edu/about/)
Revival

- Energy crisis 1970s-1980s
- Advance in power electronics (80s-90s)
- Advance in battery technology (NiMH and Li-ion battery).
- California Zero Emission Vehicle (ZEV) Mandate
  - Requires 2% of the state's vehicles to have no emissions by 1998 and 10% by 2003.

Source: www.istc.illinois.edu/about/
Who kill the EV?

Who Killed the Electric Car? is a 2006 documentary film that explores the creation, limited commercialization, and subsequent destruction of the General Motors EV1.
Nowadays

- Environmental problems
- EU 20-20-20 targets:
  - Reduction EU greenhouse gas emission by 20% below 1990 levels
  - 20% of renewable energy sources
  - 20% reduction of primary energy

Oil supply problems
- Demand increased (China and India)
- Lack of cheap oil
EVs solution

- Energy efficiency
- Cleaner vehicles
- Emission can be avoided of moved to a power plant where large-scale control is possible
- Quieter vehicles (important to reduce stress in the cities!)
- Can help the electric grid!

Source: www.istc.illinois.edu/about/
Hybrid Electric Vehicles

- ICE + Electric motor-generator
- Small battery, gets recharged from regenerative breaking; very limited all-electric range (2-3 km)
- No plug
- Different drivetrain configurations
  - Series: ICE turns generator which charges battery which runs electric motor
  - Parallel: ICE and electric motor both run the car simultaneously
  - Mix
EV classification

- HEV

- Battery
- Fuel Tank
- Power Electronics

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EVs classification

- **Plug in hybrid Electric Vehicles**
  - ICE+Electric motor-generator
  - Larger battery; gets charged by plugging
  - Limited all-electric range (25 km)
E-REV: Extended Range Electric Vehicle

- A PHEV with a bigger battery for driving ranges of 60-100 km using only the battery (all-electric driving); after which the gas engine starts.
EVs classification

- **BEV: Battery Electric Vehicles**
  - Pure electric vehicles; only has an electric drivetrain
  - Range: Leaf (170 km), Tesla (>300 km), i-Miev (150 km)
  - When you’re out of battery, you don’t have any option. You need to recharge it!
EVs classification

- HEV
- PHEV
- E-REV
- BEV
Battery configuration

Composition of Battery Pack for the i-MiEV

Cell (LEV50) → Module (LEV50-4) → Battery pack

Composition of battery pack
Consists of 88 lithium-ion 50Ah×14.8V cells (8-cell modules×10, 4-cell modules×2) made by Lithium Energy Japan
Voltage: 330V
Storage capacity: 16kWh

EV performance
- Driving range on a single charge: 180km
- Quick charge: 0→80% in 30 minutes

Vehicle exterior

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Understanding the recharge process

**Times for recharging and power levels:**

<table>
<thead>
<tr>
<th>Charging time</th>
<th>Power supply</th>
<th>Voltage</th>
<th>Max. current</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 – 8 hours</td>
<td>Single phase – 3.3 kW</td>
<td>230 VAC</td>
<td>16 A</td>
</tr>
<tr>
<td>2 – 3 hours</td>
<td>Three phase – 10 kW</td>
<td>400 VAC</td>
<td>16 A</td>
</tr>
<tr>
<td>3 – 4 hours</td>
<td>Single phase – 7kW</td>
<td>230 VAC</td>
<td>32 A</td>
</tr>
<tr>
<td>20 – 30 minutes</td>
<td>Three phase – 43 kW</td>
<td>400 VAC</td>
<td>63 A</td>
</tr>
<tr>
<td>20 – 30 minutes</td>
<td>Continue – 50 kW</td>
<td>400 – 500 VDC</td>
<td>100– 125 A</td>
</tr>
<tr>
<td>1 – 2 hours</td>
<td>Three phase – 24 kW</td>
<td>400 VAC</td>
<td>32 A</td>
</tr>
</tbody>
</table>

Understanding the recharge process

- **Recharge modes:**
  - **Mode 1.** Household socket and extension cord
  - **Mode 2.** Domestic socket and cable with a protection device
  - **Mode 3.** Specific socket on a dedicated circuit
  - **Mode 4.** Direct current (DC) connection for fast recharging

Understanding the recharge process

Charging sockets:

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Type 1</th>
<th>Type 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase</td>
<td>Single-phase</td>
<td>Single-phase 3-phase</td>
</tr>
<tr>
<td>Current</td>
<td>32 A</td>
<td>70 A (single-63A)</td>
</tr>
<tr>
<td>Voltage</td>
<td>250 V</td>
<td>500 V</td>
</tr>
<tr>
<td>No. of prongs</td>
<td>5</td>
<td>7</td>
</tr>
</tbody>
</table>

What is an EV.. When driving?

- It must perform as a motor vehicle
- It must meet all safety standards
- It must meet driver expectations for mobility and performance

Source: The Grid - Integrated EV by Willet Kempton
What is an EV.. When Plugged in?

- A load
- A smart load
- A distributed storage resource
EVs and their interaction with the power system

- EV is a **new energy consumer**, increasing the **total electricity consumption** and, more important, the **peak demand**.
- No controlled charging

**Effects:**
- Need to connect peak power plants
- Higher electricity prices
- Grid constraints
EVs and their interaction with the power system

- EVs can be also a **smart load**, defferring in a voluntary way their need for electricity.
- Its consumption can be controlled to charge when the marginal **cost of production is lowest**.
EVs and their interaction with the power system (Vehicle 2 grid)

- In longer term, EVs can be used as distributed **storage devices**, feeding back the electricity stored in their batteries.

- This can help to reduce electricity system costs, providing:
  - Regulation services.
  - Spinning reserves.
  - Peak-shaving capacity.

There are still several technical, practical and economic barriers.
Special bidirectional chargers are needed to charge the battery and also deliver power from vehicle to grid.
Some numbers to understand V2G

- **Assuming:**
  - US cars are used 1 hour/day and parked 23 h/day.
  - Battery 24 kWh.
    - Daily travel: 30 km
    - Real consumption (Nissan Leaf): 6.43 km/kWh
    - Storage unused: 19 kWh

- **Power connection:**
  - US 10 -20 kW
  - Europe 3.6-6 kW

How much power are in cars?

<table>
<thead>
<tr>
<th></th>
<th>Denmark</th>
<th>UK</th>
<th>USA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light Vehicles</td>
<td>1.9</td>
<td>28.5</td>
<td>191</td>
</tr>
<tr>
<td>(10^6)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vehicle GW (@15 kW each)</td>
<td>29</td>
<td>427</td>
<td>2,865</td>
</tr>
<tr>
<td>Avg. Electric Load (GW)</td>
<td>3.6</td>
<td>40</td>
<td>417</td>
</tr>
</tbody>
</table>

Total Generation capacity USA: ~1000 GW
Total Generation capacity vehicles: ~ 3,000 GW
6x average load!
EVs aggregators

- The impact of a single EV on the power grid is negligible
- An aggregator need to emerge, where many EVs are pooled as a one unit.
Electricity markets

3rd part
Electricity markets

- Electricity can be treated as a commodity that can be separated from transmission as a service and it can be bought, sold and traded in a special market, named electricity market.

- Producers submit supply bids and traders and larger consumers submit hourly demand bids for the 24 hours of the following day during the trading session.

- The financial market operator combines the production and consumption bids for each hour and finds the marginal price and volume.
Electricity market-Day ahead

- gen 1
- gen 2
- gen 3
- Ret 1
- Ret 2
- Ret 3

Final Price

Price €/MWh

Supply BIDS

Demand BIDS

EV 1
EV 2
EV 3

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EV Aggregator

EV 1
EV 2
EV 3

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EV Aggregator
Vehicle as other generation plant

100 EVs = 1 MW
VIRTUAL POWER PLANT concept

Source: www.cie.org.tw
EV Aggregators

- **Load aggregators** are not a new actor in the electricity market.
- They buy electrical energy in the market representing several customers.
- **EV aggregators** are more advanced:
  - They can offer more services.
  - They can offer more technical flexibility.
  - The need to collect a large amount of information about drivers' behaviour and electricity prices.
Ancillary services are used to avoid short-term imbalances in electricity markets by dispatching resources within seconds or minutes.

Different services:

- **Spinning reserve**: Extra online generation
  - Meet system failures (loss of a transmission line, generator)
  - 20 times a year, 10 min-1 hour duration

- **Regulation**: Online generation to ensure steady system frequency
  - 400 times a day, few minutes duration

Source: Vehicle-to-Grid: Integrating Electric Drive Vehicles with the Power Grid
Electricity Market-Ancillary Services

- In both markets (spinning reserves and regulation reserve) the EV aggregator could present bids for having available:
  - **Capacity** (€/MW)
  - Additional payments for **energy sold** to the network (€/MWh)
Regulation Ancillary service

- Regulation is the continuous matching of supply with demand.
  - Generation > Demand, **system frequency** ↑
  - Generation < Demand, **system frequency** ↓
- Power plants provide regulation today, but they have *slow response*.
- Grid operator controls in real time the output of the power plant

*Source: Vehicle-to-Grid: Integrating Electric Drive Vehicles with the Power Grid*
Regulation Ancillary service

- EVs could regulate the frequency error by sourcing or sinking power according to grid operator real time commands

- 50,000 to **100,000 connected EVs could perform all of California’s regulation** - with faster response than power plants

- Battery state of charge would be maintained above a driver-selected minimum level
  - **Regulation doesn’t require net energy** - just energy back and forth at the right time

Source: Vehicle-to-Grid: Integrating Electric Drive Vehicles with the Power Grid
Regulation Ancillary Service

Frequency Variation

Error signal
Regulation Ancillary Services using EVs
V2G help to reduce costs

- With V2G applications, generates two value streams:
  - **Transportation**
    - Drivers pays for use of battery for driving.
  - **Grid support**
    - Utilities pay for ancillary services
    - Generators pay for buffering PV and wind
    - Load pay for peak shaving
V2G Key aspects

- **Aggregation**
  - Thousands of cars
  - One entity to the grid (aggregator)

- **Communication and control**
  - Grid to aggregator to car
  - Car to aggregator and car to driver

- **Forecast**
  - Arrival/departure times, connection duration, trip duration, electricity prices
Prof. Willett Kempton’s pioneering work in V2G makes UDel the nexus of the Grid on Wheels Project - a business/academic collaboration.

Source: Electric Vehicles: Assets on the Grid
Grid on Wheels participate in PJM’s hour-ahead *reg-up* and *reg-down* markets.

**PJM:**
- 164,000 MW peak
- 60 mil population
- 214,000 sq mi
V2G Real Applications

- University of Delaware (Prof. W. Kempton)

EV Grid supply 15 MINI EV modified for V2G and J1772, to operate in fleet service and provide grid regulation as part of Grid on Wheels.
Information needed by the EV aggregator

**PERSONAL INFO**
- ID
- Minimum SoC when the car is disconnected

**TEMPORAL INFO**
- Departure time instant
- Arrival time instant

**OTHER INFO**
- Total capacity of the battery
- Connection power
- Other restriction for the battery (maximum charging rate)
- Electricity prices

**SPATIAL INFO**
- Traveled distance
- Connection location
- Transmission node location
Why mobility information is important for EV and SG?

- In order to present bids for buying and selling energy (and earn money!), **EV aggregator must reduce the uncertainty** in:
  - Electricity market prices
  - EV owner’s behaviour and preferences

- The aggregator **must associate the bid to a transmission network node**, therefore it must produce this **forecasts by each network node**
Thanks for your attention!