Economics and battery degradation from V2G services

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Outline

• About me and my research team

• Research on EV integration

• Profitability of services at system and distribution level

• The control of frequency with EVs…

• …and consequences in term of degradation. Modelling and measurements.

• Conclusions
About me

**Academic positions**
- Associate professor @ DTU since 02/2017 in the [DER group](#)
- Postdoc and researcher @ DTU between 09/2012 and 02/2017
- Postdoc @ University of Genova between 03/2011 and 08/2012

**Degrees**
- PhD in power systems (03/2011) from the University of Genova
- MSc in Electrical Engineering (10/2007) from the University of Genova (Italy)

**Research areas**
1. DER modelling and experimental validation with particular focus on EVs
2. Architecture of future low-inertia power systems with high share of DER
3. Control and operation of hybrid plants including wind, photovoltaic and storage
4. Multi-energy systems with focus on synergies between domains

- [Google scholar](#) and [Scopus](#) pages. And my DTU page [here](#)
- Didactic material from my course is also available on [YouTube](#) and on my personal [site](#).
About my team 1/2

• Tatiana Gabderakhmanova, postdoc working in the INSULAE project
  – Postdoc project: Islanded energy systems

• Andreas Thingvad, PhD student working in the ACES project
  – PhD project: Enhancing the role of electric vehicles for a proactive integration in global power systems
  – PhD project to be concluded in June 2021

• Lisa Calearo, PhD student working in the ACES, CAR & INSULAE projects
  – PhD project: Large-scale integration of distributed energy resources in islanded power systems considering user needs
  – PhD project to be concluded in July 2022

• Jan Engelhardt, PhD student working in the INSULAE project
  – PhD project: Coordinated control of stationary storage systems and electric vehicles fast charging in AC grid embedded DC microgrids. PhD project to be concluded in November 2022
About my team 2/2

• Jan Martin Zepter, PhD student working in the INSULAE project
  – PhD project: Synergies of Multi-Energy Systems in the Provision of Flexibility to Islanded Electricity Networks
  – PhD project to be concluded in November 2022

• Kristian Sevdari, research assistant working in the ACDC project
  – PhD project (to start in December 2020): Control and clustering of autonomous electric vehicle chargers
  – PhD project to be concluded in November 2023

• Mirko Ledro, research assistant working in the INSULAE project

• 1 PhD scholarship in Electric Vehicles Clustering Methods for Distribution Grid Services and Planning (working in the ACDC and FUSE projects)
Why research projects on Electric Vehicles grid integration? Need and opportunity

- Daily electricity consumption in DK: 93 GWh
- Additional energy loading due to EVs: 9 GWh (1 million EVs)
- 1 million EVs (60 kWh each) → 60 GWh equivalent storage
The ACES project
Across Continents Electric vehicles Services

Budget: 10 MDKK (=1.4 M€)
Public grant (EUDP): 55%
Equivalent person-months: 130 over 3.5y (04/17-09/20)
Public chargers and EVs used in the demo:
20 Nissan Leaf and env-200

Distribution Feeder in Rønne
- LV grid: 400 V
- 10/0.4 kV 400 kVA distribution transformer
- 4 subfeeders: 110 known load consumptions
- **8 10 kW DC chargers**
- Common district heating
ACES project – most relevant research questions

• Can a large set of EVs contribute to balance power systems without inducing local grid issues?

• Given a certain population, how many EVs will charge altogether?

• How do specific driving patterns and EV energy capacity affect the control method when providing grid services?

• How much does battery degradation affect service profitability?
AC & DC charging options for EVs

- Possible charging/V2G options:
  - 10 – 50 kW DC via external charger bidirectional control
  - 3.7 - 11 - 22 kW AC via internal charger unidirectional control
Smart charging: market scheduling on the island of Bornholm

Goal: Minimizing charging cost (spot price based); Avoid interconnection cable congestions

→ 12% average annual charging cost with V2G, and 11% with smart charging

→ V2G vs uncontrolled EV owner savings: ~45€/y

A. González-Garrido, A. Thingvad, H. Gaztañaga, M. Marinelli, "Full-scale electric vehicles penetration in the danish island of Bornholm—Optimal scheduling and battery degradation under driving constraints", J. Energy Storage 23 (2019)
Smart charging: distribution grid service

Goal: Avoid overloading issues (transformer and cables)

- Lowering investment cost (societal benefit)
- Lower EV consumption during overloading hours
- Annual remuneration per customer: ~10 €/y

Conservative solution

Proposed methodology

Primary frequency control

Goal: Potential earnings from primary frequency control regulation

1 year of PFC:
- 40 kWh
- 15 hours
- ±10 kW

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<tbody>
<tr>
<td>Capacity payment</td>
<td>1400 €/y</td>
<td></td>
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<tr>
<td>- Electricity costs*</td>
<td>200 €/y</td>
<td></td>
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<tr>
<td>= Revenue</td>
<td>1200 €/y</td>
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</table>

*industrial electricity prices

On-board charger
BMS
40 kWh battery
What is primary frequency control? (bidirectional vs unidirectional)
Response of unidirectional chargers in Bornholm (installed at Griffen hotel)

- DTU-made charge controller installed in Bornholm.
- EV charged: Tesla model S (average latency 2 s).

Bidirectional Frequency Regulation - V2G

EVS in FF
- 24 kWh
- 14 hours
- ±9.2 kW
Primary frequency control (bidding requirements and revenue implications)

- V2G 14 hours of FCR-N +/-10 kW:
  - Yearly revenue: 1395 EUR/year
  - 88% scenarios violated energy constraints (few minutes)

- V2G 14 hours of FCR-N +/-6.9 kW
  - Yearly revenue: 1118 EUR/year

- Yearly energy loss: 2.6 MWh
  - 0.08 EUR/kWh $\rightarrow$ 208 EUR per year

- Yearly Throughput: 12 MWh
  - Yearly full cycles with 40 kWh battery: 150

Battery lifetime reduction due to PFC – modelling and measurement methods

- Battery modelling and simulations
- Battery capacity measurements
- Battery model validation (ongoing)
Battery lifetime reduction due to PFC – technical modelling approach

Battery modelling – technical perspective

4 dynamics:
- Thévenin equivalent circuit
- Thermal dynamic
- SOC dynamic
- Degradation dynamic

Calendar degradation: SOC, battery temperature and time.
Cycle degradation: battery temperature, capacity and current.

Model input:
- Power
- Outside temperature

Model output:
- Battery degradation: calendar and cycling loss

Calendar ageing vs cycling ageing

The diagram illustrates the thermal dynamics of a battery system, showing the interactions between different components and parameters. The figure on the right presents a graph of Lcyc/PEC (%) vs Battery Temperature (°C), with data points indicating the effect of different temperatures on the cycle efficiency. The graph shows a clear decrease in cycle efficiency as the temperature increases.

The text on the right side of the diagram cites a study by A. Thingvad, L. Calearo, P. B. Andersen, and M. Marinelli, titled "Empirical Capacity Measurements of Electric Vehicles Subject to Battery Degradation from V2G Service," which is under review.
Overall degradation considering driving and frequency regulation (in DK and JP)

Overall degradation considering driving and frequency regulation (in DK and JP)

Frequency regulation considering degradation costs (adding the economic perspective)
Frequency regulation considering degradation costs

- 40 kWh EV, 13 hours @±9.2 kW.

- Degradation costs over 5 y and assuming end of life of battery at SOH 50%

<table>
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<tr>
<th>Mean SOC</th>
<th>55%</th>
<th>75%</th>
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<tbody>
<tr>
<td>Country</td>
<td>DK1</td>
<td>DK2</td>
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<tr>
<td>$Cost_{BD}^{driv}$ [€/5 y]</td>
<td>876</td>
<td></td>
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<tr>
<td>$Cost_{BD}^{driv+FR}$ [€/5 y]</td>
<td>968</td>
<td>1081</td>
</tr>
<tr>
<td>$Cost_{BD}^{FR}$ [€/5 y]</td>
<td>92</td>
<td>205</td>
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Battery capacity measurements

Diagram showing the flow of power from a 400 V AC source through an AC charger, EVSE, AC/DC converter, Li-ion EV battery (400 V - main), followed by DC/AC, DC/DC, and finally leading to the 12 V bus and various components like lead acid battery (12 V - auxiliary), Control Modules, Interior heating, Front/rear lights, and Not accessible components A and B.
Battery capacity measurements

• 40 kWh - 1 Nissan Leaf in the lab (no driving and no frequency control)
• 30 kWh - 2 Nissan Leaf in Bornholm (driving and frequency control)
• 24 kWh - 10+2 Nissan env-200 in Frederiksberg and Bornholm (driving and frequency control)
• Measurements are carried out on 24 kWh EVs offering 9.2 kW of frequency control 14 h/day. The solid line represents the expected degradation predicted by the model.

• Degradation is larger than what calculated in the previous study case, which was based on a 40 kWh (and same 9.2 kW power bid).

A. Thingvad, L. Calearo, P. B. Andersen, M. Marinelli, “Empirical Capacity Measurements of Electric Vehicles Subject to Battery Degradation from V2G Service,” under review
Conclusions

- Profitability from smart charging market based: ~45 €/y
- Profitability from smart charging for distribution grid service: ~10 €/y
- Profitability from primary frequency regulation with V2G (and fulfilling bid requirements): ~900 €/y, but need for extra equipment
- Ratio between power and energy is important factor
- SOC-based control to prevent full charge or discharge
- Additional wear due to frequency regulation amounts to only 1-2-% of the total 7-12% capacity reduction
- Even with low electricity price energy losses are significant but can be expected to decrease with improved efficiency in the chargers
- Degradation from FCR-N is low but should still be taken into account

- More results available in the final event presentations and recording
  - https://youtu.be/W-pd_11svQ
  - https://drive.google.com/drive/folders/1tqGiPKTAjSpm_hoMgp7Kszhb2LZOnyJ
References

• A. González-Garrido, A. Thingvad, H. Gaztañaga, M. Marinelli, “Full-scale electric vehicles penetration in the danish island of Bornholm—Optimal scheduling and battery degradation under driving constraints”, J. Energy Storage 23 (2019).


• L. Calearo, A. Thingvad, M. Marinelli, “Thermo-electrical validation and degradation dynamics of a lumped EV battery model,” Under review.


• A. Thingvad, L. Calearo, P. B. Andersen, M. Marinelli, “Capacity Measurements of Electric Vehicle Battery Degradation from V2G services,” Under review