Potential, opportunities and benefits of electric vehicles as frequency regulation resources

Mevludin Glavic, University of Liege, Belgium
Fernando L. Alvarado, University of Wisconsin-Madison, USA
November 18th, 2016

Introduction

Any imbalance between electric power supply and demand results in power system frequency deviations from its nominal value. Frequency regulation is one of the most important services that regional system operators perform to ensure reliable system operation. Traditional power supply sources such as generators are usually automatically modulated to help balance generation and demand by adjusting their output based in part on system frequency. As a result of the decreased inertia of the system caused by decommissioning of traditional power plants and the increase in the penetration of renewable energy sources, the increased use of demand side controls for the purpose of frequency regulation is receiving increased attention. Demand control can provide fast response to any imbalance. This opens up the possibility for Electric Vehicles (EVs) to be used as frequency regulation grid resources. This write-up discusses the potential, opportunities and benefit of doing so.

Potential

A major potential of Electric Vehicles (EVs) as grid resources arises from their ability to respond to supply-demand imbalances, and to help provide fast frequency regulation if they are aggregated in sufficient numbers capable of having an effective system-wide impact. EVs can also provide other services that are required at the transmission level (ISOs, RTOs or TSOs) and distribution level (DSOs) [1]. Table 1 summarizes some of the grid services that can be provided by EVs.

Table 1. Potential grid services that can be provided by EVs [1]

Function	Description	Grid service	
		Transmission level	Distribution level
Traditional demand response	Charging down, on/off	Day-ahead resource, spinning reserve	Grid upgrade deferral, demand charge mitigation
Advanced demand response	Charging down/up, on/off	Day-ahead resource, spinning reserve, **frequency regulation**, one-way energy storage	Grid upgrade deferral, demand charge mitigation, energy arbitrage
Vehicle-to-Grid (V2G)	Charging and discharging energy to grid	Day-ahead resource, spinning reserve, **frequency regulation**, two-way energy storage	Grid upgrade deferral, power quality, demand charge mitigation, energy arbitrage
Battery second life	Used EVs batteries as energy storage	Day-ahead resource, spinning reserve, **frequency regulation**, two-way energy storage	Grid upgrade deferral, power quality, demand charge mitigation, energy arbitrage

EV response can be in the one second time range. This makes them able to respond to power supply-demand imbalances, either by responding directly to changes in frequency (as would be the case for smaller island systems) or to respond to Area Control Error (ACE) signals for large interconnected systems.

Opportunities

Opportunities for EVs as grid resource for frequency control are based on the following two observations:

1. FERC orders no. 755 [2] (Frequency Regulation Compensation in the Organized Wholesale Power Markets) and 784 [3] (Third-Party Provision of Ancillary Services; Accounting and Financial Reporting for New Electric Storage Technologies) all promote performance-based compensation for frequency regulation [4].
2. The integration of demand control for frequency regulation purposes is an ongoing activity in several European systems [5,6].

The above opportunities are further supported by the fact that supply-demand imbalances and system frequency deviations (deviations above and below defined limit from the nominal frequency) occur often and are increasing in duration as well frequency. Figure 1 displays frequency deviations (+/- 75 mHz around the nominal 50 Hz) in Continental Europe for the period 2001-2011. Both the total cumulative time as well as the number of events with higher frequency deviations is increasing.

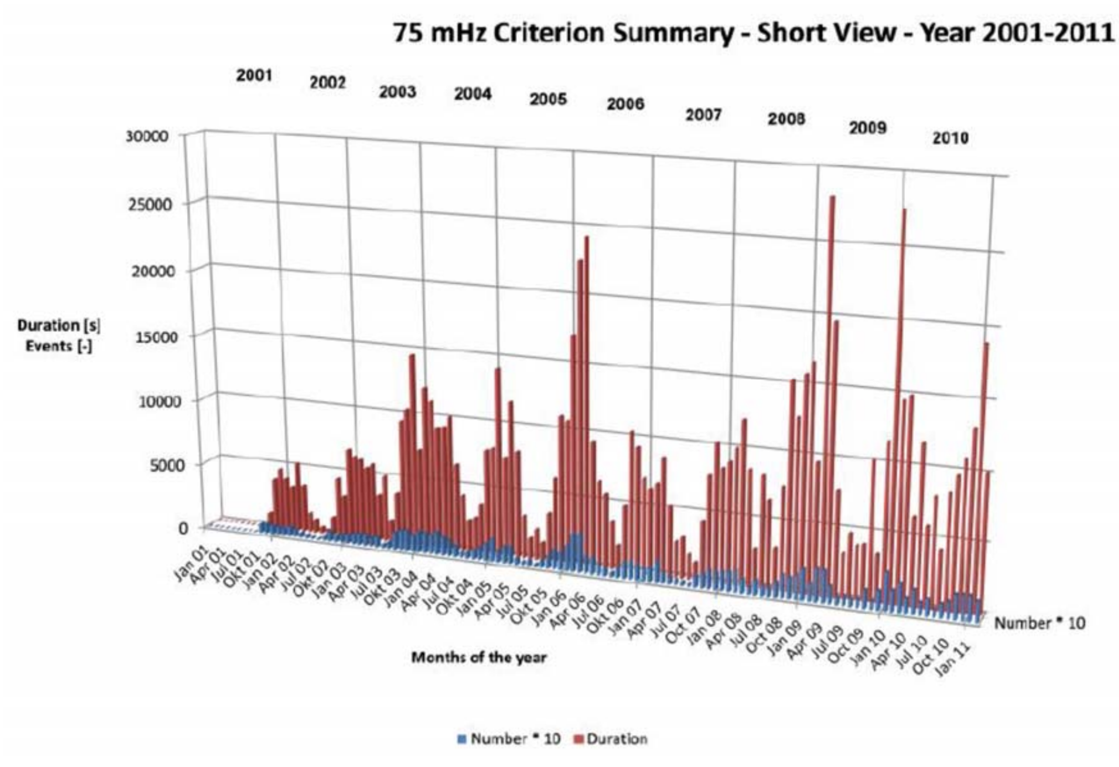

Figure 1: Frequency deviations in Continental Europe (2001-2011, adopted from [7])

Another example comes from a smaller island power system. The frequency deviation statistics for the island and county of Hawaii as reported by Hawai'I Electric Light (HELCO) is shown in Figure 2 with additional information given in Table 2. Other similar monthly charts and tables illustrate that frequency deviations have been growing over time.

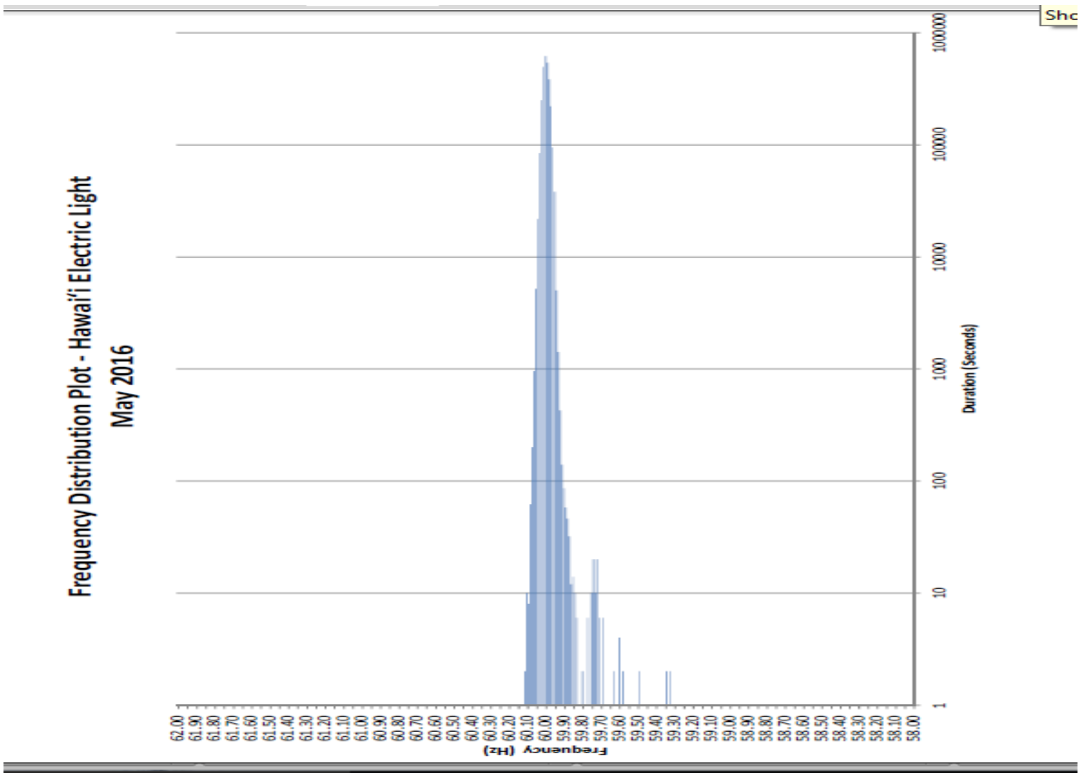

Figure 2: Frequency Distribution Plot, Hawaiian Electric, May 2016

Table 2: HELCO Frequency Excursion Statistics, May 2016

Frequency	<59.95 Hz	>60.05 Hz
Number of Excursions	5109	705
Maximum duration (sec)	126	40
Maximum deviation (Hz)	56.551	60.106
Total duration of Excursions (sec)	24642	2834

Opportunities also stem from the projected growth in EVs. Even with today's EV numbers it is possible to have a sufficient impact on frequency regulation through aggregation. Table 3 summarizes some of the figures for Vermont, California, Hawai'i, UK, and Continental Europe.

Table 3: Current and projected number of EVs

Year	Vermont [8]	California [9]	Hawai'i (all islands) [10]	UK [5]	Continental Europe [11]
2015	1,046	184,657	4,073	9,934	500,000
2020	~15,694	1,500,000	~37,000	550,000	3,300,000
2023	23,000	2,211,000	~64,000	1,200,000	~14,500,000
2030	143,000	~5,200,000	~161,000	3,300,000	50,000,000

~ based on incomplete data (data for Hawai'i beyond 2015 is for Oahu only).

The cost and energy density of batteries for EV's have been steadily improving. This trend is expected to continue. According to [12] by 2022 battery cost are expected to be around $100 per kWh while volumetric energy density is expected to increase to 400 Wh/L.
Aggregation of EVs is a pre-requisite for effective participation in regulation markets. For most regions, a minimum resource size of 1 MW is required for participation in this market. Table 4 summarizes aggregation requirements based on [8] but revised to consider more realistic conditions in terms of EVs availability, state of charge (SOC), etc.

Table 4: Number of vehicles needed to attain minimum resource size

Vehicle	Connection level	Power level (kW)	# of EVs (full capacity available) [8]	**# of EVs (1/3 capacity available)**	**# of EVs (1/3 capacity available and keeping 25%-90% SOC)**	**# of EVs (1/3 capacity available and using only 20% of range)**
Average EVs 2014	Level 1	1.4	715	**2,145**	**3,300**	**10,725**
Average EVs 2014	Level 2	3.6	278	**834**	**1,284**	**4,170**
Higher power EVs	Level 2	6.6	152	**456**	**702**	**2,280**
Retrofit with fast chargers	Level 2	15.0	67	**201**	**310**	**1,005**
Large EVs with fast chargers	Fast charging	60.0	17	**51**	**79**	**255**

In [8] it was assumed that the full capacity of each EV is available at all times. This is not realistic. We provide figures assuming that only a third of the capacity is available, that keeping a battery in an optimal state of charge band is required, and that using only a band of 20% of the battery capacity for regulation is permitted (see columns 5, 6 and 7 of Table 4).

Even with the number of EVs available today it is possible to reach the minimum required number of EVs for effective fast frequency response for many systems. For island power systems (such as Hawaii), the minimum resource size should be considerably lower than 1 MW. Thus the needed number of EVs aggregation is much lower. In PJM the minimum resource size for frequency regulation is 100 kW, thus the numbers of EVs needed for aggregation in PJM is 10 times smaller than the values given in Table 4.

Benefits

In order to quantify the benefits, we provide figures (technical and financial) using publicly available data based on recent studies [5,8,13]. Several regions in the USA have already implemented FERC order no. 755. The manner of implementation varies from one region to another. Some of the regions have implemented fast frequency response as "pay for performance." Table 5 summarizes the practices of several regions in terms of financial figures for the year of 2014. Some of them have implemented fast frequency regulation in order to comply with the terms of FERC order [13].

Table 5: Fast regulation schemes in the USA

Region	Fast regulation scheme	Requirement	Weighted average regulation market price, 2015 ($/MWh)
PJM [13,14]	RegD	Minimum energy capacity for 1 MW fast regulation reserve: 0.25 MWh	31.92
ISO-NE [13,15]	Energy-neutral	Minimum energy capacity for 1 MW fast regulation reserve: 0.25 MWh	25.28
CAISO [13,16]	Pay for performance	Minimum energy capacity for 1 MW fast regulation reserve: 1 MWh -	~15 (2016, jumped from 4.4 in 2015)
MISO [13,17]	AGC-enhancement	Minimum energy capacity for 1 MW fast regulation reserve: 1 MWh	7.49
SPP [18]	AGC-enhancement	Minimum energy capacity for 1 MW fast regulation reserve: 1 MWh	9.11
ERCOT* [19,20]	FFR1	- full MW response within 30 cycles (half a second) after frequency meets or drops below a threshold (59.8 Hz), -duration 10 minutes, -recovery time 15 minutes.	10.87**
	FFR2	-full response within 30 cycles after frequency meets or drops below a threshold (59.7 Hz), -duration 10 minutes, -recovery time 180 minutes.	
National Grid (UK) [5]	None	minimum 10 MW response (likely to change in the near future)	13.08
RTE (France) [21]	None	minimum 10 MW response (likely to change in the near future)	19.8

* not subject to FERC

** computed for the 2013 based on 13 week payments for fast response (Feb. 25 – May 24).

The concept of "effective MW" offers the possibility of higher valuation for fast-responding resources (simply stated, 1 MW of a resource can be equivalent to 2.5 MW when used as a fast-acting resource).

The size of the total regulation market is likely to increase as a result of the increased penetration of renewable energy sources (wind and photovoltaics). PJM provides a "RegD" signal for fast response resources. This signal corresponds to a high-pass filtered ACE. ISO-NE provides an energy-neutral continuous signal for fast response resources that is identical to the "RegD" signal of PJM (it also provides another fast regulation signal "energy-neutral trinary" for on-off type of regulation resources that also could be of interest when thinking about possible uses of EVs). Four more U.S. regions have implement FERC order 755: CAISO, MISO, NYISO, and SPP. MISO and SPP implement a fast regulation signal known as "AGC-enhancement" intended for use by fast responding generation units. CAISO implements FERC order 755 through a pay for performance scheme. The monthly regulation performance accuracy calculation is adjusted using a weighted average of 15 minute interval instructed regulation performance as the weighting factor.

ERCOT (Texas), although not subject to FERC regulations, is in process of creating a fast regulation service market through a pilot project for fast responding regulation service [20]. Two fast frequency response (FFR) services are envisioned based on the system frequency thresholds as indicated in Table 5.

We expect that eventually all control regions will implement the FERC order and provide a signal for fast frequency response not limited to conventional generation units. This will open up the possibility of using EVs for frequency regulation in most regions of the USA.

Illustrations

We assess the revenue and benefit for one car in regions that currently implement FERC order no. 755. We assume that we have home charged electric cars that, when plugged in, can give 10 KWh of regulation (aggregated with other cars to provide the service) per day. Each car is assumed available for 250 days. This gives a total regulation available from an average car of 2.5 MWh. We also assume that the operational (maintenance, communication, data processing) and business overhead costs (operation of demand side platform, staff, marketing, sales) are $10. These costs are deducted from the revenue to get net benefits. The likely net yearly benefit per car is given in Figure 3.

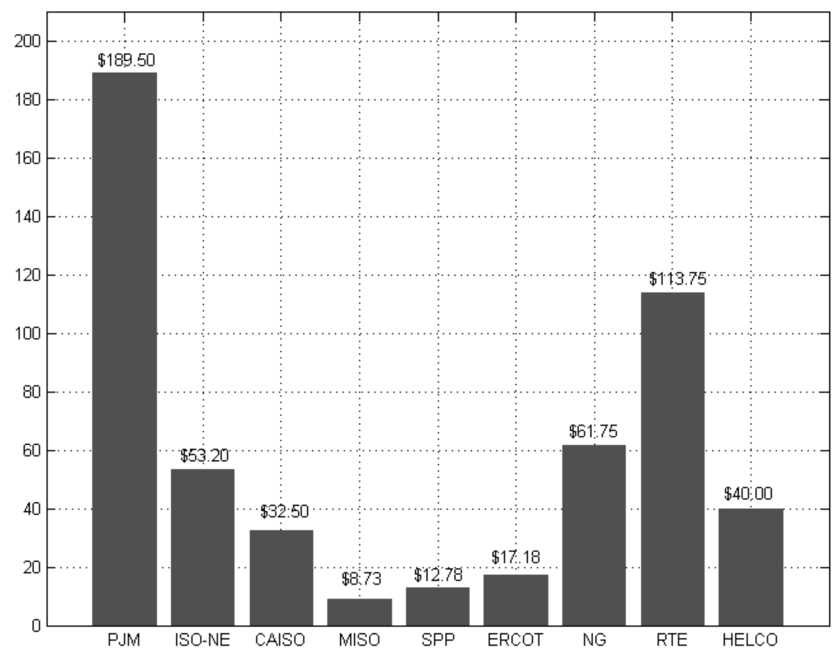

Figure 3: Net yearly benefit for a car (home charging)

The results in Figure 3 for CAISO, MISO and SPP (where currently only generators participate) assume that EVs participate under same conditions. For National Grid (NG) and RTE the concept of “effective MW” (as in PJM) is assumed. In RTE, participation in frequency control was opened to consumers and aggregators, as an experiment, on 1 July 2014 [20]. For ERCOT we use date for the provision for fast regulation service payments over 13 weeks in 2013 [20]. For HELCO the net yearly benefit is computed assuming EV will participate in fast frequency regulation for frequency excursions below 59.9 and above 60.1 Hz (number of such an events is calculated as being approximately 500 taking into account that an EV is available for

250 days and being paid as fast demand response ($10.00 for 80 events) [22]. The number of events is approximately computed assuming the number of events for each month over the whole year will be the same as observed in May 2016 (see Figure 2 and Table 2).

In another example, we assess the projected potential and total revenue for EVs in several regions for 2020 and 2030. The results are presented in Table 6 and are produced assuming projected EV uptake, primary frequency response requirements and low frequency response from EVs as in the National Grid of UK given in [5] for all the regions except for ISO-NE where the uptake is considered to be at the rate of Vermont and RTE where the uptake is considered to be at the rate of Continental Europe (see Table 3).

Table 6: Projected potential and revenue of EVs for fast regulation

Region	EVs regulation potential (% of total)				Yearly revenue (total, million $)			
	2023 (full capacity available)	2023 (1/3 capacity available and keeping 25%-90% SOC)	2030 (full capacity available)	2030 (1/3 capacity available and keeping 25%-90% SOC)	2023 (full capacity available	2023 (1/3 capacity available and keeping 25%-90% SOC)	2030 (full capacity available)	2030 (1/3 capacity available and keeping 25%-90% SOC)
PJM	19.64	4.26	80.05	17.34	74.30	16.10	314.41	68.12
ISO-NE	100	21.66	100	21.66	62.23	13.50	62.23	13.50
CAISO*	39.29	8.51	100	21.66	65.22	14.13	103.69	22.47
MISO*	34.38	7.45	100	21.66	28.54	6.18	59.25	12.84
SPP*	39.29	8.51	100	21.66	39.61	8.58	62.97	13.64
ERCOT**	15.25	3.30	62.16	13.47	25.32	5.49	103.20	22.36
HELCO~	100	68.64	100	100	0.154	0.154	0.39	0.39
National Grid***	12.50	2.71	52.00	11.27	18.32	3.97	86.33	18.70
RTE***	24.08	5.22	98.14	21.26	39.98	8.66	162.94	35.30

*currently only generators participate and EVs assumed to participate under same conditions
**special provision for fast regulation service assumed and computed based on the payment over 13 weeks in 2013 (Feb. 25 – May 24) [20]
***the concept of "effective MW" assumed
~EVs for Hawai'i island only (6% of the Hawaii total, see Table 3 [23]), and assuming a need of 4 MW of regulation reserve.

Greater revenues and benefits are observed in regions where a special provision for fast regulation service is in place (as in PJM and assumed for ERCOT, NG and RTE) and island power system where frequency excursions happen more often. All the computations are performed assuming unidirectional (V1G) charging. Bi-directional charging (V2G) is not considered here. In general, V2G can generate more revenues and benefits (according to [5] approximately two times more than unidirectional). Some reasons why unidirectional charging is considered at this time are discussed in the next section.

A similar study was conducted in Switzerland for the year of 2035 within the THELMA project [6]. This study suggest EVs could provide up to 73% of the needed frequency regulation reserves by 2035.

Discussion

To complete the picture about benefits of using an EVs for fast frequency regulation, some other considerations should be taken into account. The two most important ones are:

1. Possible need for initial investment in hardware and communications infrastructure, and
2. Impact on the lifetime of the batteries.

Most EVs charge points today are not designed with the control, instrumentation and communication capabilities for providing fast frequency response. Fortunately, there are no technical barriers to adapt standard chargers. Additional hardware costs to meet specifications suited for fast frequency response are estimated to be around $13.08 (standard or off-the-shelf hardware can be used) [5].

According to [24,25], impact on battery lifetime is not considerable for unidirectional charging (V1G or V2G-half, where V2G-half means that chargers capable of bi-directional charging used as "load-only"). Battery lifetime is mostly impacted by the number of charge-discharge cycles and depth of discharge. A detailed analysis would be needed before deciding whether to participate in V2G fast frequency regulation. A possible solution would be to use shallow charge-discharge.

With the decrease in the price of batteries the battery life decrease problem will become of lesser significance. According to [24] "Unidirectional EV frequency regulation is of practical interest as EV owners may not allow the discharging of their EVs because of the negative impact of frequent discharging on the lifetime of batteries. Moreover, EV manufacturers may not honor the warranty for EV batteries, if the battery is frequently discharged to provide frequency regulation service." Moreover, we believe that even small impact on the battery lifetime with unidirectional charging could be further reduced if a range (rather than on/off) of charging level is used and simple control strategy in the form:

- If the frequency (or AGC derived signal) is within acceptable range set charge current to normal.
- If the frequency (or AGC derived signal) is below a threshold decrease rate of charge.
- If the frequency (or AGC derived signal) is above a threshold increase the rate of charge.

It is the utility, not the EVs owners, that most directly benefit from EVs participation in fast frequency regulation. The major benefits include: decrease in required frequency regulation reserves from traditional resources. Generators, before implementing FERC order no. 755 PJM procured an annual average amount of regulation of 884 MW per hour. After the order implementation in 2103 PJM procured an average of 575 MW per hour from generators, or a 35% decrease in the amount needed to balance the grid. The benefit is not only a decrease in the rate of change of the frequency but also a generally smoother system response to imbalances.

Conclusions

In conclusion, the use of EVs as frequency regulation resources can benefit both utilities and the owners of the EVs. In some regions, EVs alone will be able to provide the majority of the frequency regulation needs of a system. If properly compensated for the service, owners of the EVs can benefit between $9 dollars up to approximately $190 per year in compensation after all expenses are taken into consideration. This compensation can take the form of explicit payments or it can be implemented as part of special tariff structures for EVs.

References:

1. M. Baumhefner, R. Hwang, P. Bull, "Driving Out Pollution: How Utilities Can Accelerate the Market for Electric Vehicles," National Resource Defense Council (NRDC) report, June 2016.
2. FERC Order No. 755, "Frequency Regulation Compensation in the Organized Wholesale Power Markets," FERC, October 2011.
3. FERC Order No. 784, "Third-Party Provision of Ancillary Services; Accounting and Financial Reporting for New Electric Storage Technologies," FERC, July 2013.
4. A. D. Papalexopoulos and P. E. Andrianesis, "Performance-based pricing of frequency regulation in electricity markets," *IEEE Trans. Power Syst.*, vol. 29, no. 1, pp. 441–449, Jan. 2014.
5. Element Energy, "Frequency Sensitive Electric Vehicle and Heat Pump Power Consumption: Final report for National Grid," Element Energy Limited, July 2015.
6. THELMA project (Switzerland), "TecHnology-centered ELectric Mobility Assessment," available online: http://www.thelma-emobility.net/
7. Eurelectric, "Deterministic frequency deviations – root causes and proposals for potential solutions," Eurelectric – Electricity for Europe, December 2011.
8. S. Morse, K. Glitman, "Electric vehicles as grid resources in ISO-NE and Vermont," Vermont Energy Investment Corporation Transportation Efficiency Group, May 2014.
9. "Early Plug-in Electric Vehicle Sales: Trends, Forecasts, and Determinants," UCLA Luskin School of Public Affairs, 2012.
10. K. McKenzie, "The State of Electrical Vehicles in Hawaii," Electric Vehicles Transportation Center, March 2015.
11. "Electric Vehicles in Europe: gearing up for a new phase," McKinsey&Company, 2015.
12. European Parliament, "Energy Storage: Which Market Design and Regulatory Incentives are Needed?" EP Directorate-General for Internal Policies, 2015.
13. B. Xu, Y. Dvorkin, D. S. Kirschen, C. A. Silva-Monroy, J-P. Watson, "A comparison of policies on the participation of storage in U.S frequency regulation markets," available online: https://arxiv.org/pdf/1602.0442, February 2016.
14. "PJM State of the Market – 2015," available online: http://www.monitoringanalytics.com/reports/PJM_State_of_the_Market/2015.shtml
15. "2015 Annual Market Report – ISO New England," available online: https://www.iso-ne.com/static-assets/documents/.../2015_imm_amr_final_5_25_2016.pdf
16. "2016 First Quarter Report – Market Issues and Performance," available online: https://caiso.com/market/Pages/MarketMonitoring/MarketIssuesPerfomanceReports/Default.aspx
17. "2015 State of the Market Report for the MISO Electricity Markets," available online: https://www.potomaceconomics.com/uploads/midwest_reports/2015_SOM_Main_Body_Final_Rev.pdf
18. "State of the Market Report – Fall 2015, Southwest Power Pool," available online: https://www.spp.org/documents/34155/qsom_2015fall.pdf
19. "2015 State of the Market Report for ERCOT Wholesale Electricity Market," available online: https://www.potomaceconomics.com/uploads/ercot_documents/2015_ERCOT_State_of_the_Market_Report.pdf
20. Available online: http://www.ercot.com/mktrules/pilots/frrs
21. Available online: http://clients.rte-france.com/lang/an/clients_producteurs/services_clients/services_systeme.jsp
22. Hawaii Electric, Maui Electric, Hawai'i Electric Light, available online: https://www.hawaiianelectric.com/save-energy-and-money/demand-response/benefits

23. K. McKenzie, “The State of Electric Vehicles In Hawaii,” Hawaii Natural Energy Institute, March 2015.
24. E. Sortomme, M. A. El-Sharkawy, “Optimal Charging Strategies for Unidirectional Vehicle-to-Grid,” IEEE Transactions on Smart Grid, vol. 2, no. 1, pp. 131-138, March 2011.
25. E. Yao, V. W. S. Wong, R. Schober, “Robust Frequency Regulation Capacity Scheduling Algorithm for Electric Vehicles,” IEEE Transactions on Smart Grid, In Press, 2016.