Across Continents Electric Vehicles Services Project: Final Report

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ACES

(Across Continents Electric vehicles Services) Project

Final Report

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1. Project details

Project title	ACES (Across Continents Electric Vehicles Services)
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Name of the programme which has funded the project	System integration
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Project partners	Nissan, Bornholms Energi & Forsyning (BEOF), Nuvve
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Along with authors and reviewers of the final report, the following colleagues (alphabetically listed) participated during the 3.5 years of the project (April 2017 – September 2020) with different levels of involvement. Their contribution to discussions, results and fulfilment of the project objectives is acknowledged.

DTU: Peter Bach Andersen, René Juul Askjær (former), Lisa Calearo, Anne Due, Amaia Gonzalez (guest PhD student), Junjie Hu (former), Marianne Bruntt Jensen, Rikke Høm Jensen, Mattia Marinelli, Anders Bro Pedersen, Alexander M. Prostejovsky (former), Magnus Fich Rabjerg, Kristian Sevdari, Thomas Meier Sørensen, Andreas Thingvad, Chresten Træholt, Antonio Zecchino (former PhD student), Charalampos Ziras.

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3. Short description of project objectives

ACES intended to holistically investigate technical and economic system benefits and impacts by large scale electric vehicles integration in Bornholm, augmented by real usage patterns, grid data and field testing for across continents replicability.

A full scale penetration scenario of EVs in Bornholm was simulated in order to assess how new aggregating functionality can support both technically and economically the successful integration of electric vehicles into the energy system.
It also initiated a small scale pilot project involving 20 publicly and privately owned Nissan vehicles and V2G chargers for proving that EVs can be used for effectively balance the system.

Ultimately, it allowed DTU to tighten the collaboration with a strong industrial partner such as Nissan and further exploit the applied research field of EV integration.

ACES projektets hovedformål var som følger:

Det var ACES projektets mål at gennemføre en holistisk undersøgelse af de tekniske og økonomiske gevinster og udfordringer ved et stort antal elbiler på Bornholm, suppleret af indsamlet elbilsdata, elnetsdata og felttests for at sikre replikabilitet på tværs af systemer og regioner.

Et scenarie med store mænger elbiler på Bornholm bliver simuleret for at kunne identificerer og evaluerer aggregeringsstrategier som kan støtte en teknisk og økonomisk integration af elbiler i elnettet. Projektet også benyttet et mindre pilotprojekt med 20 Nissan elbiler, samt Vehicle-To-Grid (V2G) ladere, for at afdække elbils evne til effektivt at understøtte elnettet.

ACES projektet forberedte et tæt samarbejde mellem DTU og den førende fabrikant af elbiler, Nissan, og fremme den anvendte forskning inden for elbilsintegration.

4. Executive summary

The project investigated techno-economic system benefits of large-scale EVs integration in Bornholm, augmented by real usage patterns, grid data and field-testing for across continents replicability. A full scale penetration scenario of EVs at Bornholm was simulated in order to assess how new aggregating functionalities - both technically and economically - can support a successful integration of EVs into the energy system. The simulation activities were complemented by a pilot project involving publicly and privately owned Nissan vehicles and V2G chargers to prove that EVs could be used to balance the system.

The results cover different areas starting from specification of EV user behaviour in Denmark and Japan in order to quantify realistic loading patterns on the grid: by considering a combination of Japanese charging patterns and Danish driving behaviour, it is derived that a 100% EV penetration would determine an evening peak coincidence factor equal to 40% for a 3.7 kW charge level.

Profitability of service provision is also assessed with particular focus on frequency control, which is market regulated in the Nordic countries. More specifically, primary frequency control is the most valuable at the moment and, it could yield a profit of more than 1000 €/year per EV with a 10 kW bidirectional charger. However, the efficiency of the bidirectional charger, market conditions and price per service could severely reduce the profit. Looking at the distribution level, depending on the specificity of the grid, an interesting revenue stream can also be found for congestion or grid deferral services.

Degradation of the storage is modelled and validated throughout measurements (still ongoing at the time of writing), in order to quantify the amount of degradation that is due to passing of time, driving and usage for grid services. Early results show that the additional wear due to the intense bidirectional power flow during grid provision, such as frequency control, amounts to only few additional percent compared to the natural degradation of the storage. Ratio between power bid in the service and energy capacity, as well as high ambient temperature can have impact the estimated lifetime.

Twenty-one 10 kW bidirectional chargers coupled with Nissan LEAF and e-NV200 along with one 22 kW controllable charger, all located in Bornholm, are used in the demonstration phase. The response characteristics of the vehicles and chargers is firstly assessed in the lab. Afterwards, the system stability is investigated through simulations at the system level, with particular focus on the response time and key characteristics of the power system. Results show that the response time is the critical factor that needs to be addressed in order to ensure a stable service provision in an EV-dominated power system. The specific response time depends on the grid characteristics, but it is reasonably safe to assume that it should be within 1 second, from when the frequency is measured to when the power is deployed.

5. Project objectives and research questions

The project investigated techno-economic system benefits of large-scale electric vehicles (EV) integration in Bornholm, augmented by real usage patterns, grid data and field-testing for across continents replicability. Simulation activities to assess grid impact and battery degradation are complemented by demonstration activities, to prove that EVs can be used to support the energy system.

The key project objectives highlighted in the description of work are listed below:

- Assess the values of EV services in DK, UK and Japan, by using real EV driving and charging data.
- Disseminate V2G applications and best practices in Europe and in Japan.
- Establish tight collaboration with the research area of a large car manufacturer.
- Vehicle manufacturer (such as Nissan) will use the project outcome to improve future vehicle designs in order to make them more "grid proactive".
- Build up on the experience on Bornholm test case and contribute to enrich it.
- Derive guidelines for coordinating system wide services provided locally: Distribution System Operator (DSO) vs Transmission System Operator (TSO).
- Investigate whether EVs can help supporting Bornholm power system.

The main research questions driving the project activities are:

- 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?

The simulation activities were complemented by demonstration activities taking place primarily in Bornholm, but also relying on the hardware in Frederiksberg Forsyning (part of the Parker project).

- EV & chargers in Bornholm (demonstration and degradation measurements):
    - 20 bidirectional commercial chargers (ENEL-Endesa 10 kW)
    - 20 EVs (Nissan LEAF 30 kWh and e-NV200 24 kWh).
    - 1 unidirectional controllable charger (DTU-made 22 kW).

- EV & chargers in Frederiksberg Forsyning (degradation measurements):
    - 10 bidirectional commercial chargers (ENEL-Endesa 10 kW)
    - 10 EVs (Nissan e-NV200 24 kWh).

- EV lab (in Lyngby campus) and SYSLAB (in Risø campus).
- The island of Bornholm with its complete power system

The phases presented in the description of work were fulfilled through development of hardware and simulation results described extensively in Section 6.

6. Project results and dissemination of results

6.1. Driving/charging behaviour

Charging profiles derivation

Due to the low amount of EVs and to the uncertainties related to individual driving behaviour, EV penetration level and different charging power, the uncontrolled charging pattern of EVs is complicated to quantify. On the other hand, system operators have to guarantee stability and security of supply, adapting the grid layout and the operation to the specific network characteristics and components. To operate the grid with large penetrations of EVs, the system operators are interested in forecasting the EV charging load, to estimate impacts and necessities of infrastructure upgrades. In the ACES project we derived a methodology for generating individual EV charging patterns, in order to quantify the realistic loading impact on distribution grid feeders. The methodology is based on historical driving characteristics of private conventional vehicles in Denmark, and home plug-in behaviour of EV users in Japan. The first input is used to define properties, such as the daily driven distance and the expected departure and arrival time, which determine the possible home charging window.

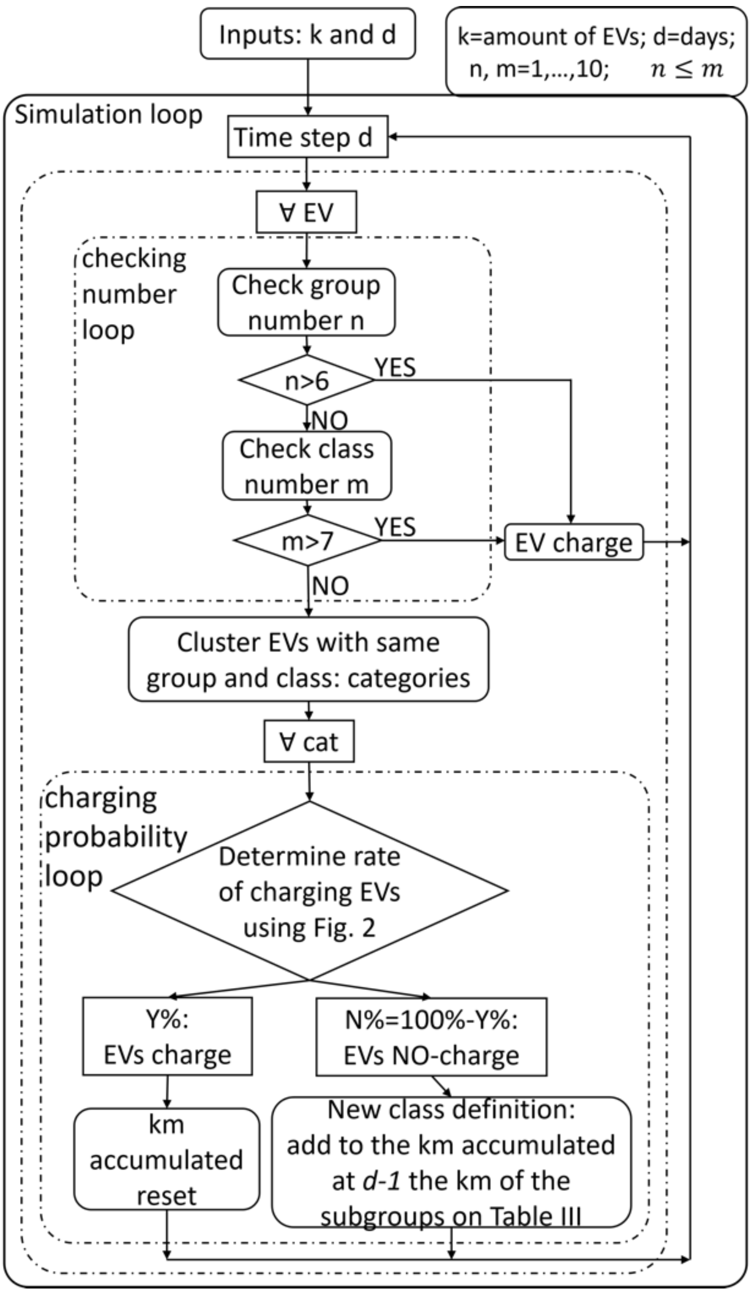
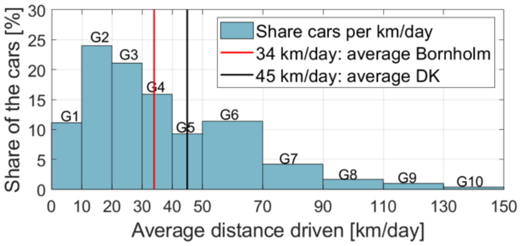


Figure 1. Flow chart describing the derivation process of the charging methods.

Figure 1 shows the flowchart of the model to derive realistic EV charging profiles. The inputs of the model are the number of EVs (k) and the number of days (d) to be simulated. The EVs are initially split into 10 groups and characterized by a group number. The groups are defined by the distance driven per day by the vehicle, as shown in Figure 2.



Class number	accumulated km	Class number	accumulated km
1	$0 < x \leq 10$	6	$50 < x \leq 70$
2	$10 < x \leq 20$	7	$70 < x \leq 90$
3	$20 < x \leq 30$	8	$90 < x \leq 110$
4	$30 < x \leq 40$	9	$110 < x \leq 130$
5	$40 < x \leq 50$	10	$130 < x \leq 150$

Figure 2. Daily average driven distance per share of cars in Bornholm clustered into 10 groups (left plot); Class definition (table on the right).

On day d, the group and the class number of each EV is checked. At the beginning of the simulation all the EVs are considered fully charged (SOC=1 p.u.), meaning that on day 1, the class number of the EV matches the group number. The class number represents the km accumulated by the vehicle at the end of the day since last charging. The EVs, with same group and class number, are clustered into categories (cat).
Using the plug-in probability curves in Figure 3, for each category the rate of charging EVs is evaluated as '%Y', and the distance accumulated by this group is thus reset to 0 (and *SOC=1 p.u.*). The remaining EVs do not charge '%N', so they accumulate kilometres. At the end of the simulation, we know for each considered day and each EV, if that EV is charging or not and which is the plug-in SOC of it. Afterwards, considering the arrival time of cars per each hour of a workday on Bornholm, the EV charging time is distributed throughout the day as shown in Figure 3.

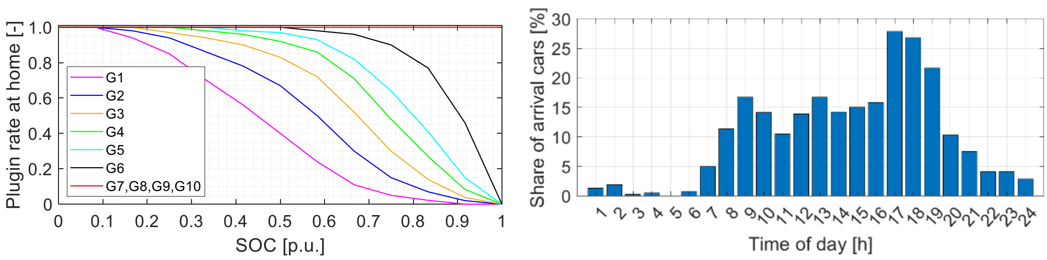


Figure 3. Charging probability (left plot) and share of arrival cars (right plot)

Coincidence factor

The coincidence factor is the maximum amount of EVs, given a certain population size, which will charge simultaneously. Considering a population of 127 households, where each household has a 40 kWh EV, it was found that, because most of the EVs does not charge every day, the simultaneous charging with single-phase chargers (3.7 kW) is never more than 40% EVs, see Figure 4. Even though the energy consumption is the same, when using three-phase chargers (11 kW) the charging power is tripled, but the combined peak only increases to 50%, because the simultaneous charging is reduced to 22%.

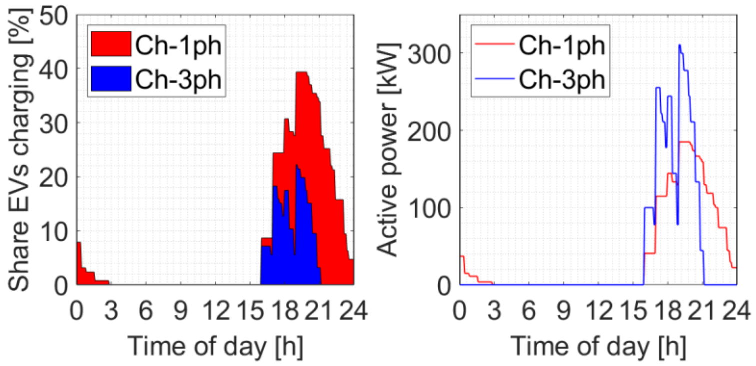


Figure 4. Comparison single-phase and three-phase chargers: on the left the share of EVs charging and on the right the active power during one-day period.

When there are fewer EVs charging on a distribution feeder, it is more likely that most of them will charge at the same time on a given day. Considering different amount of EVs, from 5 to 100, as the most expected value of EVs when considering low voltage distribution feeders, the change in charging power has a significant effect on the coincidence factor, as shown in Figure 5 (left figure). EVs charging with an 11 kW charger overlap less compared to EVs charging with 3.7 kW, because the charge duration is shorter. With 5 EVs the coincidence factor is equal for both 11 and 22 kW, however, for an increasing number of EVs the difference varies between 5 and 10%. When the battery capacity is increased, with the same charging level, the coincidence factor does not change more than 1-2%, see Figure 5 (right figure).

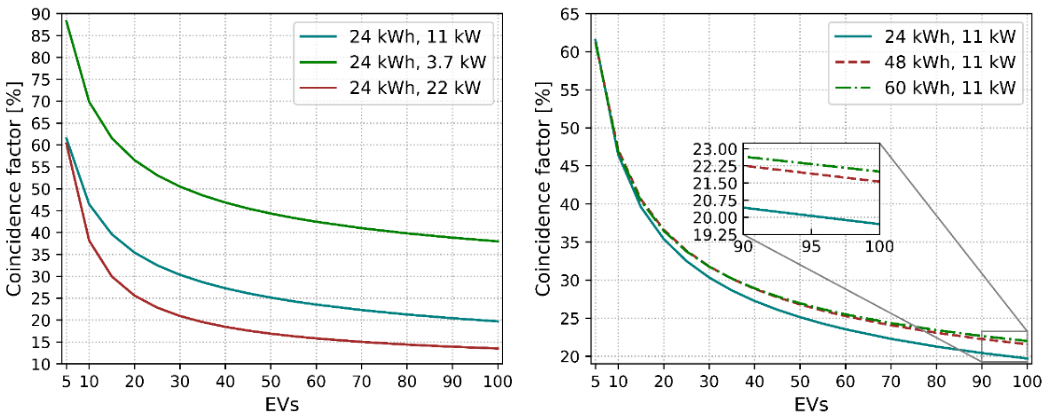


Figure 5. The coincidence factor's sensitivity to a change in charging power (left plot) and sensitivity to a change in battery size and plug-in probability curve (right plot).

By modelling driving behaviors of sets of EVs, we found that the coincidence factor is primarily influenced by the number of vehicles considered, and to a lesser degree by the supported charging power. A higher charging power will result in lower coincidence factors, but higher peak power. By contrast, EV battery size and customer behavior are responsible for smaller variations.

The previous results are based on the derived charging profile methodology, due to lack of available data regarding Danish user charging profiles. Based on internally provided data of 7163 Nissan 24 kWh LEAF in the US, the driving and charging behavior was then investigated. Data were collected from EVs where the owners accepted to share data at the time of purchase, which corresponds to approx. 50% of the sold EVs of the specific model. The driving behavior of the considered US vehicles is similar to the vehicles in Denmark considered in the previous analysis. Indeed the average US driving distance is 17200 km/year equal to 47 km/day, which is a bit higher of the 45 km/day driven in Denmark. Figure 6 shows the share of EVs driving and charging during a work day in 2016, as a representative day. The blue line shows the share of EVs that is driving during the day and the red line shows the share of the EVs that is charging simultaneously. Data analysis showed also that the charging peak is similar for every workday, and that it is lower in the weekend. It can be seen that despite the data being from EVs with only 24 kWh battery capacity, the simultaneous charging peak is only 18%. From the driving curve, the rush hour peak times is identified as 07:00 and 17:30, similar to the Danish ones. Being personal vehicles parked 97.4% of the time, for the EVs this is a huge potential for utilizing the battery capacity during the idle time. The EV is however only available for the grid when the owner plugs it in, which may not happen every day.

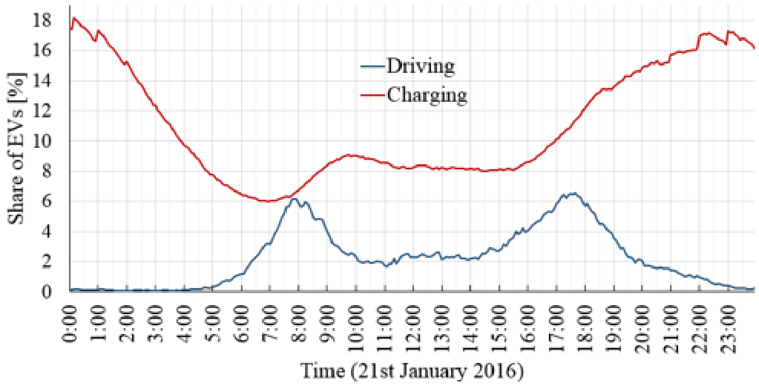


Figure 6. Share of EVs driving and charging during Thursday 21st of January 2016.

Distribution grid impact

The proposed model to derive EV charging load profiles has been applied to a radially run, semi-urban LV grid, based on a real network, located in the Danish town Tejn, Bornholm. The LV grid (Un=400V) is connected to the MV grid (Un=10kV) through a 10/0.4 kV 400 kVA distribution transformer and is supplied by underground cables. The grid consists of 4 feeders, with a total of 127 customers located as shown in Figure 7. The analysed case study represents a typical LV distribution grid in Bornholm, making the results comparable to other distribution grids, at least, in Denmark. On the island there are 985 MV/LV transformers with an average nominal power of 240 kVA. The total peak load of the island is 60 MW so the average peak consumption of each transformer is 61 kW. The ratio between the average peak consumption and the average nominal capacity is 0.25 (61 kW/240 kVA). The ratio in the analysed transformer is 0.46 in the studied week (186 kW as peak, without EVs). The studied grid is therefore significantly more loaded than the average distribution grid on Bornholm.
The analysed scenarios are:

- Base case: current situation of the grid, without EVs, used as benchmark for the system.
- Single-phase chargers [25-100% EVs]: single-phase (3.7 kW) uncontrolled charging with 4 EV penetration levels: 25%, 50%, 75% and 100%.
- Comparison of single- and three- phase chargers [100% EVs]: three-phase (11 kW) uncontrolled charging with 100% EV penetration level.

The base case does not present under-voltage and congestion issues, and the system losses are limited to 2-3% of the total consumption. When including EVs with single-phase chargers, transformer and cable loading increases, see Figure 8. Even though the EVs are equally distributed on the three phases, the single-phase connection and the difference between the charging patterns increase the voltage unbalances in the most critical terminals, loading one phase more than others. The phase-to neutral voltages of the worst terminal are compared in Figure 9 for the end-feeder terminals when 100% EV penetration is implemented.
Differently, when considering 100% EVs with three-phase chargers (11 kW), the charging power is larger (as shown in Figure 4), thus transformer and cables are overloaded for a certain number of hours during the considered week. The most loaded cable is the one that connects the station to terminal 10058, see Figure 9. The system losses are instead reduced compared to the single-phase scenario, due to the more balanced distribution of the EV consumption on the three phases. When the EVs are connected to the system with three-phase chargers, the system is more balanced than with single-phase chargers.

It was concluded that, in the short term with few EVs, the DSO should mainly focus on balancing the grid, because even though the EVs can be equally distributed between the three phases, the difference between the charging behaviour can aggravate the unbalances. In the long run, a larger EV penetration along with the generally growing electricity consumption could cause congestion issues to be the main problem in the distribution grid.

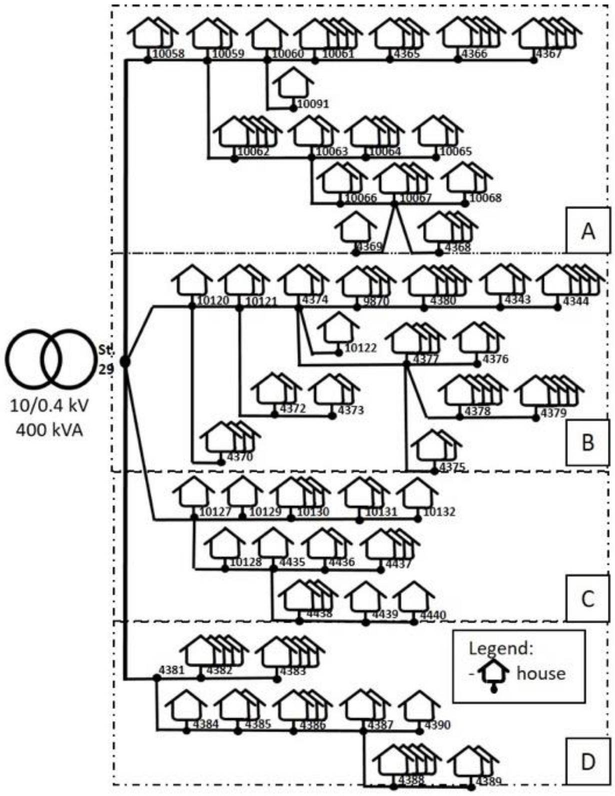


Figure 7. Topology of simulated Tejn LV grid divided in four sub-feeders: A, B, C, D.

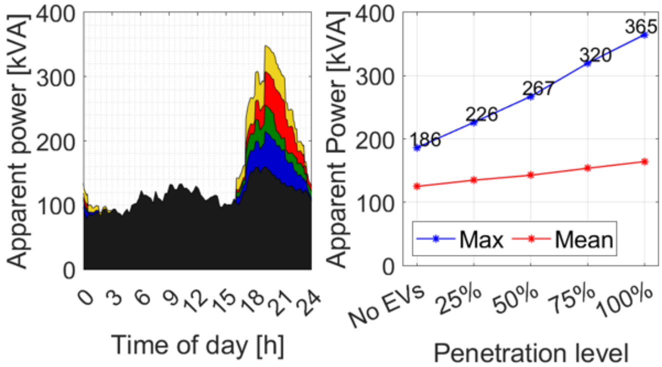


Figure 8. Transformer loading with 0%, 25%, 50%, 75%, 100% EV penetration: left - one-day charging pattern, right - one week max and mean values.

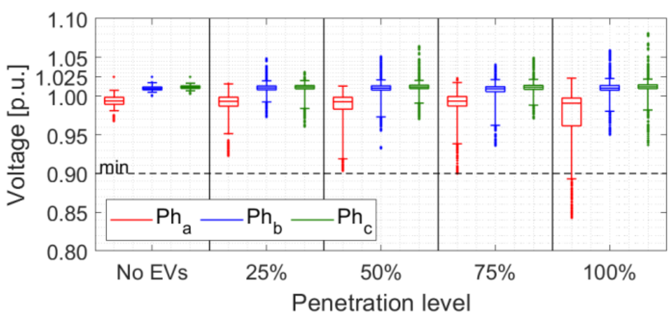


Figure 9. Phase-to-neutral weekly voltages for junction 4379 (end of feeder) in the grid.

Public charger

Large EV penetrations require a developed charging infrastructure, which is a mix of home charging, as considered in the previous analyses, and public chargers. Investments in charging infrastructures are part of a very insecure market, which depends on charging needs, battery capacity, etc., therefore a strategy for developing these infrastructure in an optimal way is needed.

We developed an analysis to estimate the number of public and semi-public charging points that should be set up in Denmark to satisfy the charging needs for 1 million electric cars in 2030. A distinction is made in the analysis between everyday charging and long-distance charging. The former addresses the need for public charging points for the part of the population without the possibility of home charging, focusing on municipalities, car ownership, driving distance and parking conditions. The second addresses the number of charging points for long-distance charging for the whole country, based on the Danes' driving needs.

The analysis is based on the assumption that in 2025 there will be 380,000 EVs and 1 million in 2030. It is the industry's best estimate that EVs (middle class) in 2030 will have an average battery capacity of 80 kWh, average charging power of 100 kW and maximum charging power up to 250 kW. If approx. 40% of the cars in all municipalities were replaced with EVs, the sum of them would be 1 million EVs. Table 1 provides an example of cars, distance driven and parking distribution in three Danish municipalities.

Table 1. Number of cars and percentage of parking places at home, in residential areas and on public roads.

Municipality	Cars per household	km driven per car	% of households with parking in own property	% of households with parking in residential areas	% of households with parking on public roads	Number of vehicles
Copenhagen	0.47	36.5	14%	36%	50%	53,436
Frederiksberg	0.58	31.6	12%	39%	50%	11,802
Lyngby-Taarbæk	0.92	38.2	53%	30%	17%	8,609

It is interesting to observe how large differences there are between municipalities. In general, cities where few people can park at their own house and have their own chargers are also the place with few cars and low distance driven.

In order to evaluate the amount of charging stations, the example of Lyngby-Taarbæk municipality is here provided. The number of EVs in 2030 would be 8608, the average driven distance is 38.17 km/day and the energy consumed per km by an EV is 0.2 kWh/km. The energy needed to charge the group of cars is derived as: 8608 EVs * 38.17 km/EV/day * 0.2 kWh/km = 65,713 kWh/day.

We assumed then that those who have the opportunity to charge on their own property, will have their own home charging stations. Therefore the public chargers should cover the long journeys and the consumption of those who live in apartments or terraced houses/housing associations. This is less challenging for Lyngby-Taarbæk, because in this municipality there are many villas and 53% residents park on their own land. The public charging network therefore only needs to cover 47% of consumption, which corresponds to 30,885 kWh/day.

Considering first charging stations, which deliver up to 22 kW (for example the ones from Eon and Clever), as they are cheaper to install than the fast chargers, we assumed that the charging stations will be running 30% of the time, meaning 7.2 hours per day. Since the cars do not charge at full power all the time, thus an average of 2/3 is delivered, namely 14.6 kW. This means that each charging station can deliver 105 kWh/day. Then we calculated the need for public charging stations in Lyngby-Taarbæk municipality in 2030: 30,885 kWh/105 kWh=294 charging stations.

Secondly, 150 kW charging stations are considered. Delivering on average 2/3 and being used for 15% of the time, they can deliver 360 kWh per day. Fast chargers are used less time during the day, because the charge is shorter thus users may wait for the car to be fully charged. This means that with a purely fast charger, there would be a need of 30885 kWh/360 kWh=86 charging stands. The number of fast chargers is lower, but they are more expensive to set up than the 22 kW ones. In conclusion, the number of charging stations and related investment for covering the energy needs of all Denmark in 2025 and 2030 are displayed in Table 2.

Table 2. Number of fast charging stations

	2025	2030
22 kW	7,566	23,466
50 kW	511	1,585
150 kW, cities	131	405
150 kW, public roads	598	1,889
In total	8,807	27,345
Investment needed (in billion of DKK)	1.1	3.4

6.2. Profitability of services at system and distribution level

Profitability of smart charging electric vehicles in Bornholm

We have analysed a 100% electric vehicle (EV) scenario on the energy system of the island of Bornholm to investigate challenges and opportunities that a realistic system would face when completely shifting to electric transportation. The EVs are subject to different charging strategies in order to assess the impact on the grid, the potential savings on the charging cost and the effects on battery degradation. In contrast to uncontrolled charging, smart charging strategies are designed not only to satisfy the same charging requirements at the EV departure time, but also to maximize the savings on the charging cost and avoid interconnection congestions. Bornholm island is used as a case study because it is a well analysed power system that serves some constraints to the charging schedule, due to the limited capacity of the cable of interconnection with Sweden.

The technical modelling is followed by an economic analysis of the value of smart charging, where Danish prices and taxes are considered. The smart charging strategies, such as demand side management (DSM) and vehicle to grid (V2G) should fulfil the main objective of the analysis: minimizing the overall charging costs while avoiding congestion in the Bornholm-Sweden interconnection cable.

Annual data from generation, consumption and Sweden interconnection energy flow have been considered, while the distribution grid level is out of the scope of the assessment. Figure 10 shows the hourly local generation and the cable flow in the interconnection.

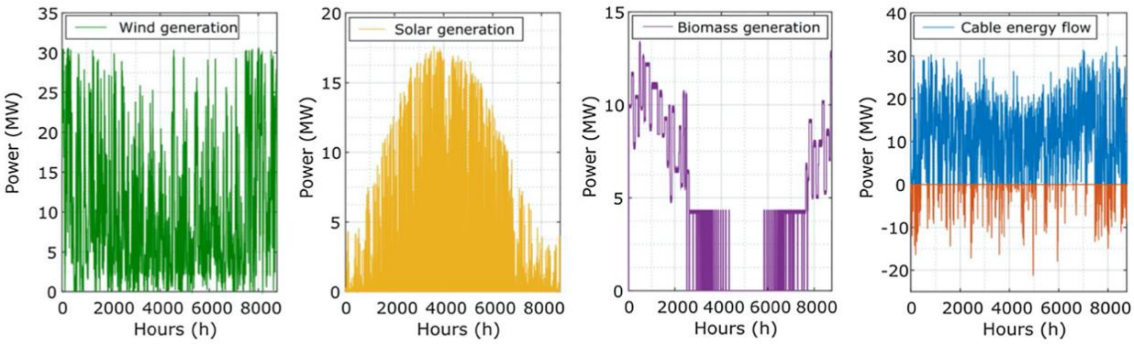


Figure 10. Cable energy flow and local generation data.

The uncontrolled charging profiles (UNC) are derived from the National Danish travel survey and the home plug-in rate at home as described in Section 6.1 and considering that EVs will be charged only at home.

On the days where the owner plugs in the EV for charging, in the uncontrolled charging case EVs start charging immediately. In the DSM strategy the charging is optimized in the hours with the lowest electricity prices, whereas during the V2G strategy charging and discharging are optimized considering the high and low hourly electricity prices, but still ending up at 100% SOC before the plug-out time. By also selling energy the V2G strategy takes advantage of price difference between the individual hours. An example of both strategies is shown in Figure 11.

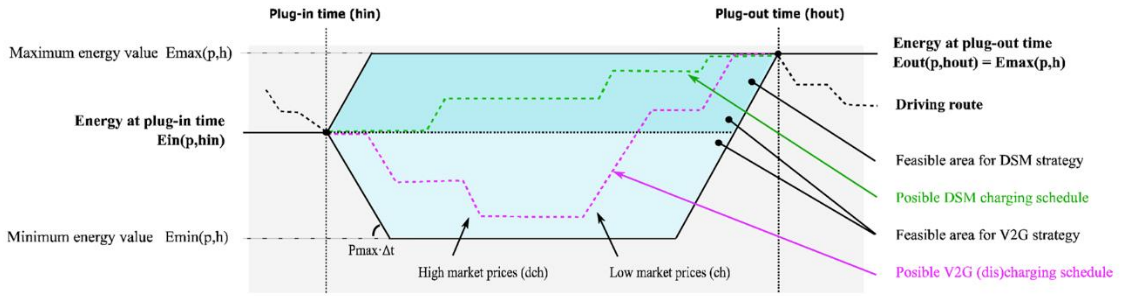


Figure 11. Visual representation of the feasible area of the EV spot market scheduling.

The UNC strategy does not consider the energy flow in the Bornholm-Sweden interconnection cable. The island imports energy from Sweden in the majority of the hours of the year, when the local generation is lower than the local consumption, see Figure 12. Therefore, the major problem is the congestion due to the increase of power flow in the cable in order to charge the EVs. Differently, both the DSM and V2G strategy respect the cable limitation, thanks to the EV charging more spread during the day.

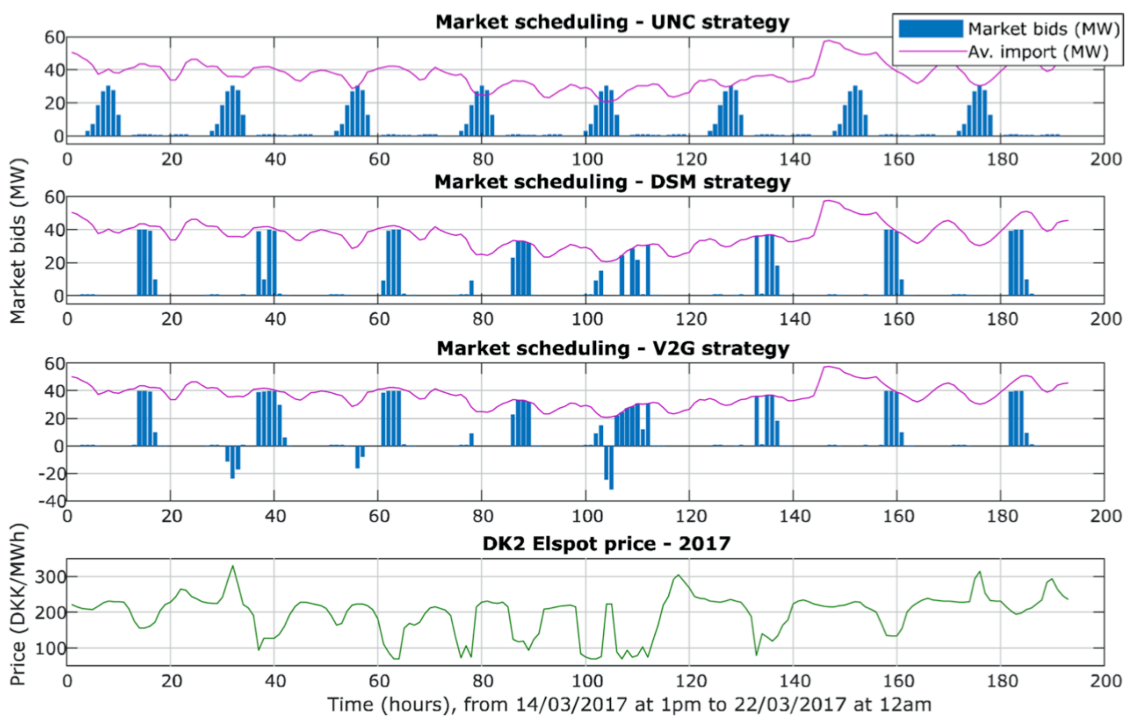


Figure 12. Spot market scheduling for UNC, DSM and V2G strategies for 100% EV penetration level and 1-ph charge.

The average charging costs for all the EV owners can be seen in Table 3. The price for household consumers considers the average electricity price today, including PSO and energy tax. The EV user shows the cost of charging when exempting the PSO and the energy tax. According to the table, considering three-phase charge, average annual charging cost is reduced compared to the single-phase charge, because the high discharging power rate enables to take advantage of the highest price hours to discharge more annual energy.

Smart strategies bring a reduction in annual charging cost of 12%, on top of a reduction in the degradation because of lower average SOC. Moreover, results show a limited benefit in bidirectional charging, because of a marginal increase in savings: V2G is a more demanding operation, which allows discharges, leading to more conversion losses and to higher battery degradation, due to the increase in the number of cycles.
An average EV owner can save 319 DKK per year from using a DMS strategy in comparison to the uncontrolled charging. This only increases to 396 DKK, by using a V2G charger. The overview of the different strategies is compared in Table 3.

Table 3. Comparison of average annual charging cost (DKK/y) under different final prices, charging rates and charging strategies (UNC, DSM or V2G).

Price	Ch. rate	UNC	DSM	V2G
Household consumer	1-ph	6588 (882.8 €/y)	6275	6272
EV user	**1-ph**	**2907 (389 €/y)**	**2570**	**2543**
EV user	3-ph	2885 (386.6 €/y)	2566	2498

Economic value of Distribution grid services

As seen in Section 6.1, if every household has an EV, the required charging could in some situations cause congestion problems of the local distribution grid. Since it is expensive to replace grid components, such as underground cables and low voltage transformers, it may not be convenient to replace them to accommodate a short term power peak. In this regard, to avoid the component replacement, we investigated how an aggregator, controlling the charging power of several EVs, could sell the service of power peak shaving or congestion management to the DSO. Since there is not yet a market, there is not either a monetary remuneration for the EV user support in distribution grids. Thus the economic expenses of the conservative reinforcement solution are used for developing the methodology, which is first derived and afterwards applied to a piece of Danish distribution grid consisting of 127 customers.

Figure 13 shows the two investment strategies. The conservative solution to overloading issues, where the DSO invests in transformer and cables upgrading, is named "economic scenario 1 (ES1)". The proposed approach, where the DSO decides to postpone the components upgrade and adopt the EV support service is named "economic scenario 2 (ES1)". Since all power system components have a limited lifetime, it is not possible to completely avoid installing new components, but the installation can be postponed for x years.

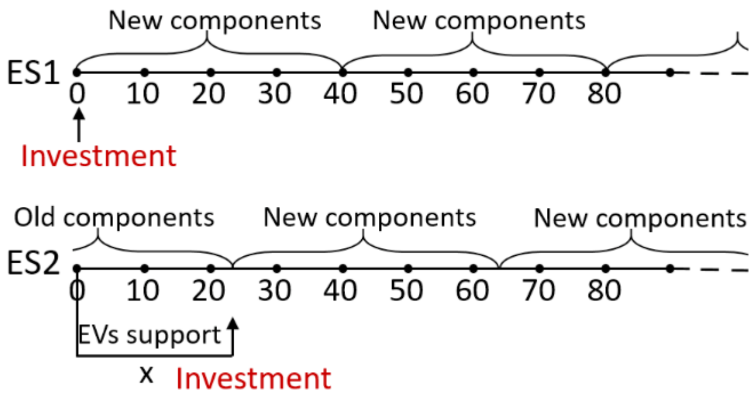


Figure 13. ES1 and ES2 framework comparison.

The techno-economic characterizations of the upgraded transformer and cables, which should be used in ES1, are provided in Table 4 and Table 5. The total investment would be 388718 DKK, which is the sum of the CAPEX of transformer and cables including installation.

Table 4. Parameters and price of the MV/LV transformer for the proposed grid reinforcement solution.

Cable characteristics			
Technology	3PH	Lifetime	40 years
Cross section	240 mm^2	Cost per meter*	653 DKK (88€)
Rated voltage	0.4 kV	CAPEX**	69218 DKK (9273€)
Rated current	400 A (in ground)	*OPEX input*	
Positive Resistance	0.126 Ω/km	O&M Cost Rate	3.50% of CAPEX/year
Positive Reactance	0.069 Ω/km	O&M Cost	2423 DKK/year (325€/year)
Lenght cable *St-10058* Lenght cable *10058-10059*	50 m 56 m	OPEX	2423 DKK/year (325€/year)

Table 5. Parameters and prices of the cable al pex 4x240 mm, for the proposed grid reinforcement solution.

MV/LV Transformer characteristics			
Technology	3PH	Lifetime	40 years
Rated power	630 kVA	CAPEX	319500 DKK (42800€)
Nominal frequency	50 Hz	*OPEX input*	
Rated voltage, HV	10 kV	O&M Cost Rate	3.50% of CAPEX/year
Rated voltage, LV	0.4 kV	O&M Cost	11183 DKK/year (1498€/year)
Connection	Dyn11	OPEX	11183 DKK/year (1498€/year)

The transformer and cables present in Tejn are 40 years old, but still in good conditions, thus it is assumed that the DSO could use them for at least 10 more years. For this reason, the remaining lifetime x is assumed to be of 10 years. Year 0 is considered to be the present year, but assuming 100% EV penetration. Considering the same electric consumption for all the weeks of the 10 years, the money available for the EV support service for 10 years is evaluated using the equation: $M_{EV} = \frac{388718\ DKK}{40\ y} \cdot 10\ y = 97180\ DKK$

By splitting the saved money equally over the ten years, the maximum amount of money that the DSO would save per week in ES2 is 186.9 DKK.

Table 6. ES2: EV support service for three months per year.

ES2	
Money available for 10 years	97180 DKK (13019€)
Money available per 3 months (12 weeks)	9718.0 DKK (1302€)
Money available per week	810 DKK (109€)
Moved energy during one week	393 kWh
Maximum payment per kWh	2.06 DKK (0.276€)

The considered week is a very cold one, representing a conservative scenario, with overloading due to the 100% EV penetration and household consumption. Nevertheless, having limited overloading for just a few hours per week, the DSO would only need to move a small amount of energy to avoid congestion. Furthermore, since the domestic electricity consumption is higher in the winter, the DSO could buy the EV support service for a few months per year for a higher compensation per kWh. By buying the service only for three months the DSO could payback the EV support with up 2.06 DKK per moved kWh.

In the conservative scenario the DSO should invest approx. 388,718 DKK on new upgraded components. With the EV support service the potential available money for the EV support remuneration is evaluated to be 187 DKK/week. Considering a customer with an average EV load consumption, the annual remuneration would be 77 DKK. It is concluded that, if the components are severely overloaded, for the DSO it is more cost effective to invest in components upgrade. Conversely, if the components are barely overloaded or close to their limit, the EV user support can benefit both the DSO and the users.

Economic value of frequency regulation with EVs

EVs can be used for delivering primary frequency control and the revenue can compensate for the costs of driving. The primary frequency control (PFC) service in DK-2 is called Frequency Containment Reserve Normal-operation (FCR-N). FCR-N is a suitable ancillary service for EVs,

because it is compensated per power capacity and the energy requirements are relatively small. This is beneficial for EVs, because they can have a large power capacity and very fast response, but limited energy capacity. However, our investigation showed that the required battery capacity is not negligible, and that more than 3 kWh of capacity is required to be able to deliver 1 kW of FCR-N. This is because the average system frequency can be biased over the hour, which can lead storage units performing FCR-N to become either fully charged or depleted. This is also called the energy content of the frequency.
FCR-N can be provided with series-produced EVs in two ways: by modulating the unidirectional power flow using the on-board 3.7 kW charger, see Figure 14 right; with an external bidirectional charger, see Figure 14 left.

Unidirectional FCR-N can be delivered by any domestic mode 3 charger that is capable of receiving set points via the internet, thus the added hardware cost is limited. The charger informs the EV of the maximum allowed charging current via a PWM signal, and then the EV adjusts the current. The lowest charging value allowed by the IEC 61851 and SAE J1772 standards is 6 A. The maximum capacity, when performing unidirectional FCR-N with a single EV, is obtained by setting the charging baseline to 11 A. In that case, the current can be modulated with ± 5 A in a range of 6–16 A, providing a FCR-N capacity of ± 1.15 kW.
Providing FCR-N with the on-board charger involves low installation cost, because all power conversion occurs inside the EV. The disadvantage is that the service can only be provided until the EV is fully charged. This means that for an average person in Denmark, which drives 45 km per day, 9kWh is the maximum amount of energy. Several series-produced EVs have been found to have an efficiency of the on-board charger of around 90%. Given the daily driving consumption, the efficiency of the charger and a charge cycle with an average of 11 A (2.5 kW), the EV would be fully charged in 4 h. Using an EV with a higher charging power or energy capacity would not increase the revenue, because the limiting factor is the driving energy demand. The average charging time is four hours, which means that in the days where the frequency on average is too high, the EV would charge with higher power and be fully charged sooner. Three hours of service would therefore be a more realistic estimate. Delivering FCR-N from midnight for 3 or 4 hours when the prices are highest, would result in a yearly capacity payment of 390 to 525 DKK.
Providing bidirectional FCR-N lifts this time limitation, as the EV over time is expected to deliver the same amount of energy to the grid as the one received, giving a zero-energy balance. It is therefore only the daily number of grid-connected hours and the power capacity of the power converter that determines the potential capacity payment.

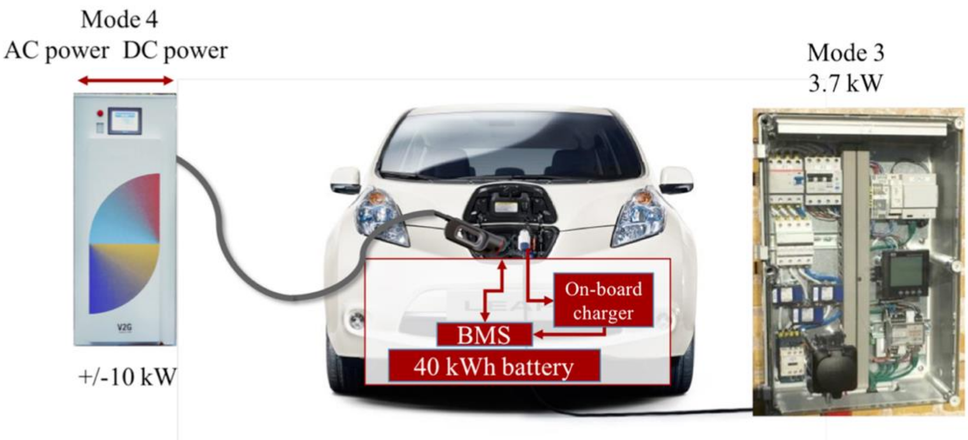


Figure 14. Physical setup – Nissan LEAF with different charging options.

Assuming that the EV is parked from 16:00 in the evening to 07:00 in the morning, it would be available for 15 h to provide grid services. The energy company ENEL has produced a bi-directional charger, seen on the left in Figure 14, with a capacity of ± 10 kW that, via the CHAdeMO DC connection, can be used to perform FNR with all series-produced EVs equipped with CHAdeMO plug. Initiated during the Parker project with the cars in Frederiksberg Forsyning and extended also in Bornholm as part of the ACES project, the commercial

operation of EVs providing FNR in Denmark is tested with the ± 10 kW V2G chargers. The used EVs are the Nissan e-NV200 with a battery capacity of 24 kWh and Nissan LEAF with 30 kWh capacity. Those battery capacities are found to be too small to deliver the service with reasonable security, therefore the simulation study is implemented for 40 kWh EVs.
Considering these conditions, the value of the full power availability of ± 10 kW is 10,462 DKK per year per vehicle. It is found that, even for the 40 kWh EV, the behaviour of the system frequency would cause the EV to be fully charged or depleted in 88% of the days in a year, if full power is committed to the service. This can be seen in Figure 15 where each line shows the evolution of the SOC, when the EV is reacting to a different frequency.

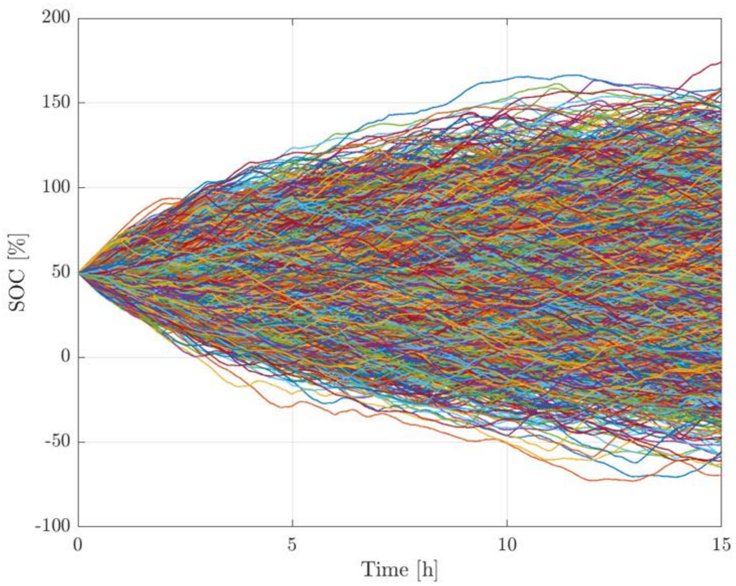


Figure 15. Evolution of SOC, when delivering FCR-N with +/-10 kW regulation capacity. For every line, the 40 kWh-EV is experiencing a different frequency.

To investigate how much FCR-N can be delivered with a 40 kWh EV and a +/-10 kW charger, one year of frequency measurements are analysed. The movement of the EV SOC is described as an optimisation problem that schedules the charging and discharging to deliver as much FCR-N as possible without running out of energy. Real frequency and market data are used for calculating the revenue under the Nordic regulatory framework. Earnings are calculated for the best case where the future energy content is known in advance. The results show that, in order to fulfil the service delivery specifications, a crucial role is played by the bid power compared to the size of the energy storage.
The optimisation problem has found that the maximum power that can be bid for FCR-N is 6.9 kW, such that there is 3.1 kW reserve dedicated for avoiding that the battery is saturated or depleted. Based on one year of system frequency data and the found control parameters, the evolution of the SOC is calculated for every day and it is found to be possible to maintain the SOC in an acceptable region. The resulting SOC is shown in Figure 16.

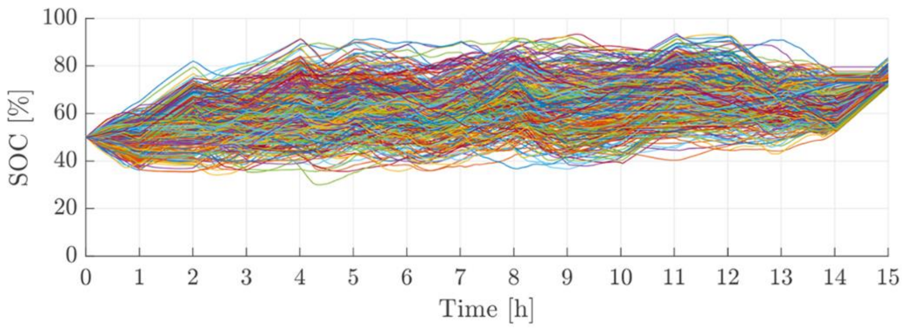


Figure 16. Evolution of SOC every day in a year when including 3.1 kW of reserve.

In the V2G economy, another important role is played by the V2G charger efficiency, which negatively affects the service energy flow. It was found that the used hardware has an efficiency of 90% at full power, but when delivering FCR-N the power is often a fraction of that, which results in an average efficiency of 80% each way and a roundtrip efficiency of 64%. When delivering 6.9 kW of FCR-N for 15 hours, there is an average energy loss of 7 kWh. The absolute amount of energy going through the battery each day amounts to 33 kWh (12.2 MWh/year), which is expected to have an accelerating influence on the battery degradation. Even with the average electricity price for mid-size industry it amounts to 1,560 DKK per year. This cost is subtracted from the yearly FCR-N capacity payment of 8,302 DKK, resulting in a profit of 6,742 DKK.

6.3. Degradation modelling and measurements

One of the main concerns when discussing V2G services is the possible increase of battery degradation. The reduction in energy capacity, described by the state of health (SOH), is an additional cost that has to be accounted when deriving the revenue for delivered grid services. The SOH describes how much the full capacity has decreased relative to the initial capacity, due to irreversible degradation mechanisms. It is defined as the full capacity of the battery at a given time in percent of the initial capacity. However, it is not simple to measure or estimate the SOH of the battery in the EVs. This is because the capacity of batteries employed in EVs cannot be measured online, as they never experience a full charge cycle during normal operation.

The factors influencing battery degradation, measured as capacity fade, can be divided in two: calendar ageing, which is a function of time and temperature, and cycle ageing which is mainly dependent on the number of charge/discharge cycles. Lithium-ion batteries are naturally an unstable structure and will degrade and lose capacity when they age, despite not being used. Like other chemical reactions, the capacity loss occurs mostly in the beginning and then decreases over time, as less of the materials have active interactions. The degradation mechanism occurs faster when there is a high energy density in the battery, which means that it increases with higher SOC and temperature. Especially for EV applications, calendar ageing is the dominating effect because EVs are generally idle more than 90% of the time. Li-ion batteries can be used in vehicular applications until they have lost 20-30% of the initial capacity but can at this point still be used in second-life applications, as stationary storage until 50% of the capacity is lost.

Battery degradation modelling

A collaboration between the partners in the ACES project (Nissan Research Center and DTU) resulted in modelling the effect FCR-N provision on the battery degradation in Denmark. The main dynamics of the battery modelling can be observe in Figure 17.

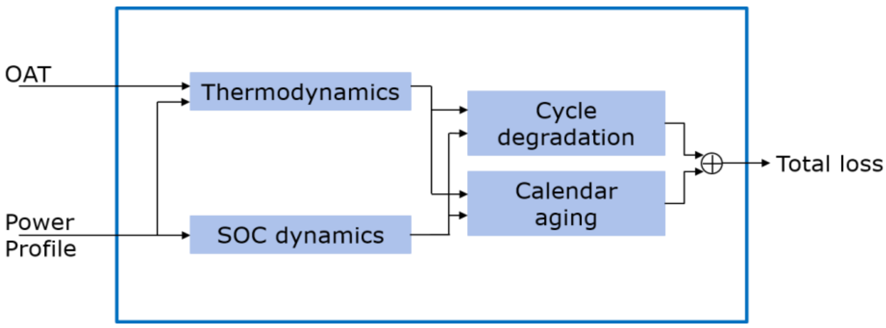


Figure 17. Battery modelling main dynamics.

A representative 24 kWh EV with battery characteristics modelled as Lithium Nickel Manganese Cobalt Oxide batteries is taken as reference. This model is similar to the batteries in the EVs used in Frederiksberg Forsyning (FF) and Bornholm municipality, in the Parker and ACES project respectively. The model is run with a simulation time of 1 second, thereby capturing the effects that the short term power flows have on the battery temperature. Each second the battery temperature, SOC, current going through the battery, and SOH are calculated. The SOH is found from the two components of the capacity loss in percent of the original capacity; calendar ageing (L_{cal}) and cycle degradation (L_{cyc}). The total capacity loss is the sum of the two components and the SOH= 100% − L_{cal} − L_{cyc}.

The modelled EV battery has two main inputs: the outside temperature and the battery power. The outside temperature is one year of measured outside air temperature in Denmark, whereas the battery power considers both driving, Danish average of 40 km/day, and provision of FCR-N with ±10 kW V2G chargers. A representative 14-hour sample of the frequency measured every second in Denmark is in the simulation repeated every day for five years. The frequency sample is used to calculate the power response of the EV according to the requirements from Energinet. It resulted in a daily absolute energy flow of the battery (throughput) of 38.9 kWh.
Table 7 shows calendar, cycle and total degradation of the industrial battery model, both as per year and accumulated values. It can be seen that for this application the calendar ageing is the major factor, but that the contribution decreases with time and mostly occurs in the first year. The capacity loss due to the active usage is lower, but it is increasing as the capacity is decreasing. After five years, the SOH is reduced with 15.73%: two thirds of the capacity loss is due to calendar ageing and one third is due to the charge cycles.

Table 7. Capacity loss due to cycle degradation and calendar ageing as well as the total capacity loss; both per year and accumulated in the first five years of the EV life time.

Year	Cal	Cycle	total	∑Cal	∑Cycle	∑total
1	4.51%	0.81%	5.32%	4.51%	0.81%	5.32%
2	1.97%	0.88%	2.85%	6.48%	1.69%	8.17%
3	1.58%	0.96%	2.54%	8.06%	2.66%	10.72%
4	1.40%	1.05%	2.45%	9.46%	3.71%	13.17%
5	1.37%	1.18%	2.55%	10.83%	4.89%	15.73%

Figure 18 shows how the SOH evolves over time due to the isolated parts and the total degradation. It can be seen that the SOH decreases faster in the summer than in the winter, which is caused by the influence of the outside air temperature.

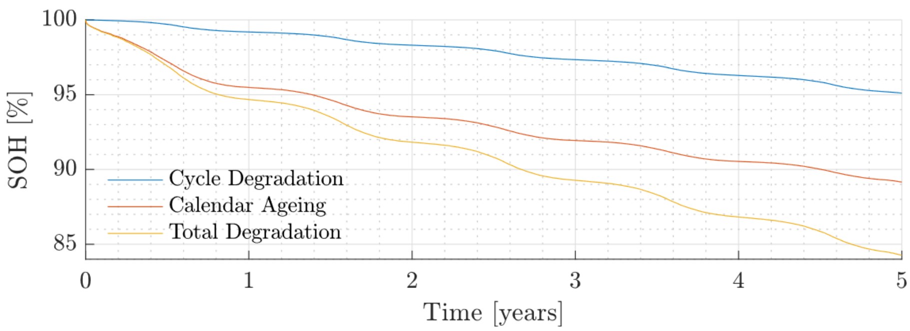


Figure 18. Modelled SOH of a 24 kWh EV, performing FCR-N 14 hours per day.

Similarly to the 24 kWh EV battery, we implemented a 40 kWh battery model tailored for the Lithium Nickel Manganese Cobalt (NMC) Oxide battery, currently used in the Nissan LEAF II generation. The model is firstly derived from the literature and then experimentally validated. The adopted testing procedure consists in characterizing the electrical and thermal battery behaviour and analysing the battery response to power changes, without access to the individual cells. The validation process demonstrates that the model is able to replicate the experimental measurements with errors of maximum 1% for the voltage and the current. Furthermore, the model is complemented with calendar aging and cycle degradation dynamics, which are currently under investigation to be validated on a Nissan LEAF II generation bought in 2018 and only used for LAB testing.

Measured Energy Throughput and losses

As a part of the Parker project, Frederiksberg Forsyning (FF) bought ten Nissan e-NV200 electric vans together with ten V2G chargers. The ten FF EVs were purchased at the same time, registered in Denmark on 07/07/2016 and produced 3 months before.
The EVs are used by FF during the regular working hours and for providing FCR-N the rest of the time. 99% of the days the entire group of vehicles plug in latest at 18:00 and plugged out earliest at 06:30, resulting on a 12:30 hour daily connection period.
In the following, each EV at FF is numbered 1-10 with the prefix FF (FF01, FF02 etc.). Each charger records data for one specific EV and its user. Data from the V2G chargers at FF is logged every second and the analysed period considers 480 days. The data includes the energy capacity of the battery in kWh and the battery voltage and current measured by the charger.
The data collected by the ten V2G chargers at FF has been analysed to find the measured energy throughput of the batteries and the measured amount of energy lost as heat in the chargers. Based on the charger data the average time the charger has had an active power flow for either regular charging or FCR-N is calculated. The active number of hours per day, N_t [hours], is provided in Table 8. The throughput is calculated as the sum of the absolute Ampere or Watt going in and out of the battery. The data is collected for a period of 480 days.

Table 8. Average time duration (N_t), throughput (E_{tp},Ah_{tp}) and average driving distance (N_{Odo}) per day for each of the ten EVs from November 2016 to March 2018 (480 days).

	FF01	FF02	FF03	FF04	FF05	FF06	FF07	FF08	FF09	FF10
N_t	14.2	14.4	12.1	14.6	13.1	13.3	13	9.4	11.2	13.1
A_{tp}	108.3	114.6	93.8	116.7	106.3	112.5	102.1	89.6	85.4	102.1
E_{tp}	39.6	43.8	33.3	43.8	39.6	41.7	39.6	33.3	33.3	37.5
N_{Odo}	9.6	5.8	6.0	7.9	5.6	10.4	5.0	4.1	3.6	8.3

The throughput measured by the charger contains both the flow caused by the FCR-N service and the charging to cover the driving consumption. The throughput during driving is not measured, but it should be estimated and added to get the full throughput of the battery. The driven distance is not measured by the charger, but it has been derived from the vehicle odometer and given as the average distance driven per day, N_{Odo} [km]. The average driving distance for the ten vehicles is 7 km per day. The average throughput of the ten EVs is 41.4 kWh per day, to which the average driving consumption of 4.5 kWh, resulting in a total throughput of 45.9 kWh per day.
Since the second-based charger data measurements are not available for the entire lifetime, the values are compared with data from another source. At the beginning of 2019, a new smart meter was installed from the distribution system operator for billing purposes, which is used to validate the charger measurements. The smart meter was installed the 7th of January 2019 and the values were read the 30th of May 2020, showing the results for all the vehicles for one and a half year. The daily average throughput measured by the billing meter from January 2019 to May 2020 is 45.4 kWh per vehicle per day, which is close to the 41.4 kWh throughput measured by the chargers. The energy consumption for losses and driving is 15.6 kWh per vehicle per day. By subtracting the average driving consumption of 4.5 kWh, the remaining energy for losses is 11.1 kWh per vehicle per day.

Economic cost of degradation

There is an associated cost of the battery degradation as part of the energy capacity is lost. Assuming a battery cost of 180 €/kWh, a 24 kWh EV would cost €4,320. According to the simulation result, there is a 1% capacity loss per year due to the added energy throughput. This is related to the minimum SOH of 50% of a second-life application where the battery has lost all value. The yearly cost of battery degradation due to FCR-N provision is found as 1%/50%·€4,320=€86. The energy consumption for conversion losses is found to be 11.1 kWh per day or 4.1 MWh per year. The average electricity price for mid-sized industrial customers in Denmark is 0.08 €/kWh, which results in a yearly electricity cost of €324. This should be compared with the FCR-N capacity payment of €1100 per year, which still results a profit of 1100 − 324 − 86 =€690.

Considering a 40 kWh EV, the degradation due to FCR is found to be an additional 1–2% to the 7–12% capacity reduction over 5 years. The profitability of the FCR is evaluated considering the frequency measured in DK1, DK2 and Japan. For each case the battery degradation was investigated considering the average SOC equal to 55%, and to 75%, where the higher SOC gives a larger capacity loss due to calendar ageing. The capacity loss is presented in Table 9 as a cost in € over five years at a battery price of 180€/kWh.

Table 9. Cost of driving, cost of driving and Frequency regulation and cost of the combined case minus the cost of driving. For frequency regulation in DK1, DK2 and Japan with average SOC of 55 and 75%.

Mean SOC	**55%**			**75%**		
Country	DK1	DK2	JP	DK1	DK2	JP
$Cost_{BD}^{driv}$ [€/5 y]		876			1314	
$Cost_{BD}^{driv+FR}$ [€/5 y]	968	1081	1019	1418	1565	1438
$Cost_{BD}^{FR}$ [€/5 y]	92	205	143	104	251	124

Battery capacity measurement

To validate our modelling results of the EV battery degradation delivering FCR-N we developed a method for measuring the battery capacity of series produced EVs, via the DC charge port. The SOH of individual li-ion cells is conventionally found by measuring the capacity during full charge and discharge cycles. Generally, the discharge capacity is of interest as it shows how much usable energy the battery contains, but the difference between the two values are only caused by the internal losses, which can be made insignificant by charging with a low C-rate. The li-ion battery of an EV is not accessible during driving so it is not possible to measure the capacity during discharging. The battery is accessible when using an external DC charger as that connects directly to the battery terminals, such that the power can be measured during charging. The power flow of the EV can be seen in Figure 19.

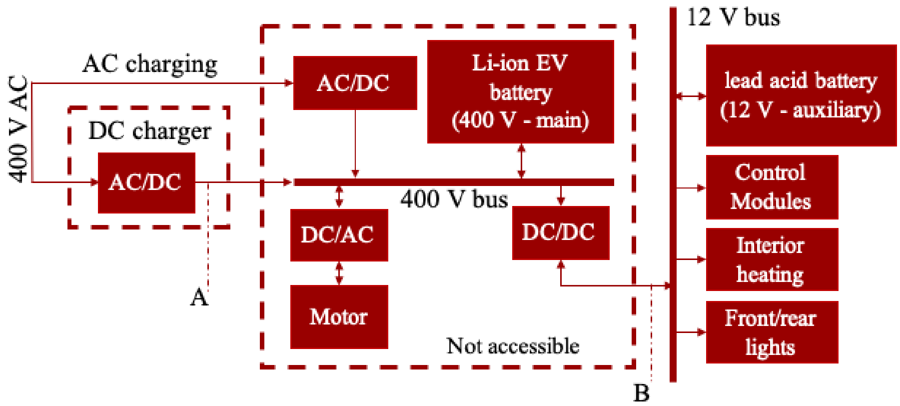


Figure 19. Overview of EV power flows.

When charging with the on-board charger, the battery voltage and current are not accessible for direct measurements, which means that the charged energy can only be measured on the AC side of the converter. This is however not equal to the energy received by the battery, as the on-board charger of several brands have been found to have an efficiency of 90%. It is necessary to use an external charger where the DC voltage and current can be measured directly at the terminals of the battery. The DC voltage and current are measured inside the charger at the charging cable connected to the EV, shown as point A in Figure 19. The BMS has a power consumption during the charging process, which is measured and subtracted from the energy received from the charger, to find the energy capacity of the main battery. All of the auxiliary consumption during charging is on the 12 V bus, where the voltage and current from the main battery is measured at point B in Figure 20. It is assumed that the DC/DC converter supplying the low voltage bus has 100% efficiency, indeed the amount of energy is so low that even 10% loss would be insignificant. The capacity of the battery is derived by the following equation, as the total energy delivered by the charger minus the energy consumed by the auxiliary system during charging:

$$Q_{\text{full}} = \frac{1}{\Delta T}\sum_{k=0}^{N_{\text{test}}}(I_k^{\text{A}} \cdot V_k^{\text{A}} \cdot - I_k^{\text{B}} \cdot V_k^{\text{B}}) \cdot t_s$$

The measurements are done with the equipment described in Figure 20.

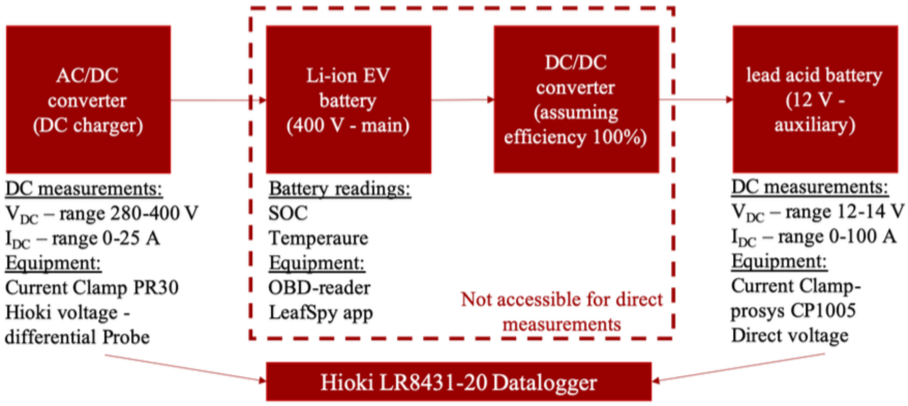


Figure 20. Equipment used for the measurements.

The battery is charged via the external DC charger. In Figure 21 the pack terminal voltage and current measured in point A are shown during a full charge of a 24 kWh Nissan e-NV200. It can be seen that the constant current phase is two hours, followed by one hour of charging with constant voltage.

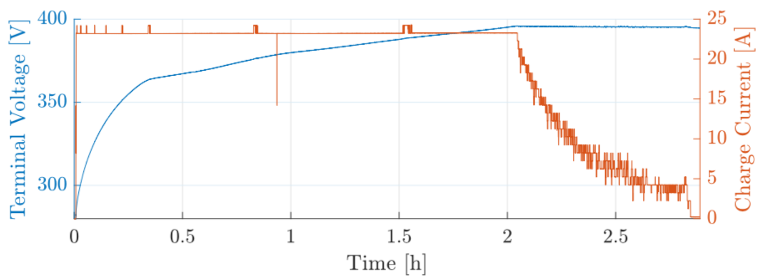


Figure 21. DC voltage and current measured at the EV battery terminals during a full charge of a 24 kWh Nissan e-NV200 EV. Measured at point A (see Figure 19).

Figure 22 shows the power flow from the main to the auxiliary battery during the charge process. The supply from the main to the auxiliary battery is for this EV around 8 A at 14 V, a consumption of approximately 100 W. A higher power flow is observed in the beginning of the charge, as the auxiliary battery initially is recharged to 100% SOC.

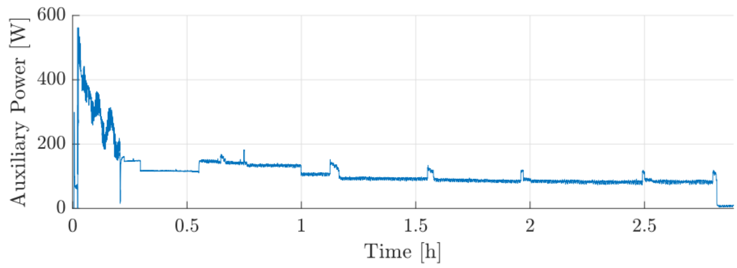


Figure 22. DC power flowing from the main battery to the auxiliary battery during a full charge of a 24 kWh Nissan e-NV200 EV. Measured at point B (see Figure 19).

The auxiliary consumption during a full charge is for a Nissan e-NV200 around 300 Wh, if the initial battery temperature is close to the ambient temperature and the auxiliary battery is close to be fully charged. The capacity measurement method has been tested on Nissan e-NV200 (24 kWh) and Nissan LEAF (24, 30 and 40 kWh). The capacity of all ten FF e-NV200 have been measured over a period of two years and are here presented.

Repeated measurements of new e-NV200 Evalia

As a part of the previous Parker Project, a new Nissan e-NV200 Evalia was used for V2G experiments. The vehicle was registered in Denmark the 28th June 2017 and the capacity was measured one year later on the 28th August 2018. The odometer was only 700 km and the model was only used for few hours for lab experiments. As a completely new EV was not accessible, the usable battery capacity of this model is used as base case for calculating the SOH. The capacity of the Evalia, measured three times over three days, was 22.67, 23.22 and 22.97 kWh. Thus, as conservative number the average capacity of 23 kWh can be considered as Q_{init} for the Nissan 24 kWh generation.

Capacity measurements of the ten FF EVs

The charge capacity of the ten EVs at FF were measured four times over two years: September 2018, June 2019, October 2019 and May 2020. Figure 23 shows for each capacity test the measured SOH plotted against the number of days since the EV production. The line shows the modelled SOH, affected by the total degradation (aging and cycling). The modelled SOH match the trend of the capacity measurements, but for most of the EVs the measured degradation is worse. Discrepancies between the model and the measured values may be caused by different temperatures and SOC levels, and will be further investigated by the authors.

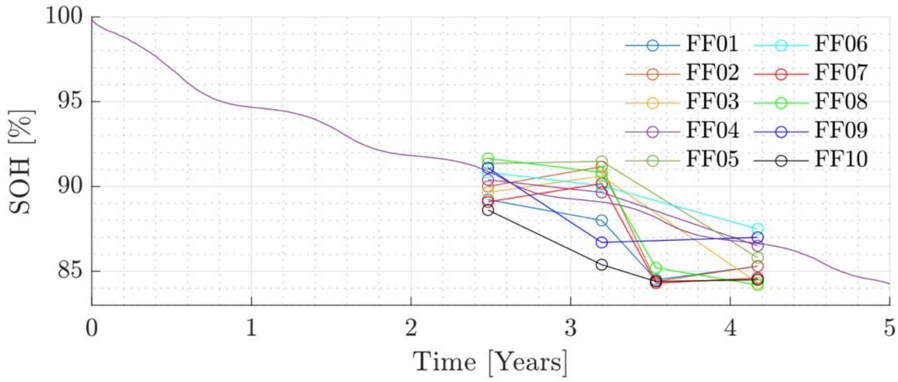


Figure 23. Measured and simulated SOH.

6.4. Unidirectional and bidirectional charger analysis

Bidirectional V2G charger

In order to make the EV flexibility product a tradable asset, appropriate regulations and requirements should be introduced. The establishment of standardized tests for evaluating the charger and EV performance is necessary to categorize the supplied EV flexibility product. So, a deep knowledge of the controlled hardware performance is needed, including the EV charger efficiency for different set-points to assess the accumulated losses during a V2G session. Such insights into the charger's efficiency can guarantee to the charger operator an accurate estimation of the real amount of energy flowing in/out of the battery.

In this respect, we list seven attributes that have been experimentally assessed on unidirectional smart chargers and V2G real hardware.

- Direction: The information if an EV can provide only unidirectional or bidirectional (V2G) power flow.
- Activation time: The period between receiving the set-point and activating the flexibility.

- Ramp-up/ramp-down time: The up/downwards time between activation time and full service provision, and vice versa.
- Accuracy: The difference between the required and the delivered response, e.g., the acceptable response band.
- Precision: The variation of the delivered response for a given set-point.

Figure 24 shows the attributes for an EV flexibility product. Figure 25 shows the required and the provided power of one cycle of an active power test pattern of the 10 kW V2G chargers used at FF. In general, a time shift can be noticed, which here represents the total activation time given the employed remote control setup. Then, one can note the non-perfect linearity in the response to the signal in the continuous portion due to the set-point granularity imposed by protocols and the power electronics in the V2G charger. Finally, the time needed to reach the set-point is utilized for the calculation of the ramping rates, while the measured power at the stable set-point levels allows the calculation of accuracy and precision.

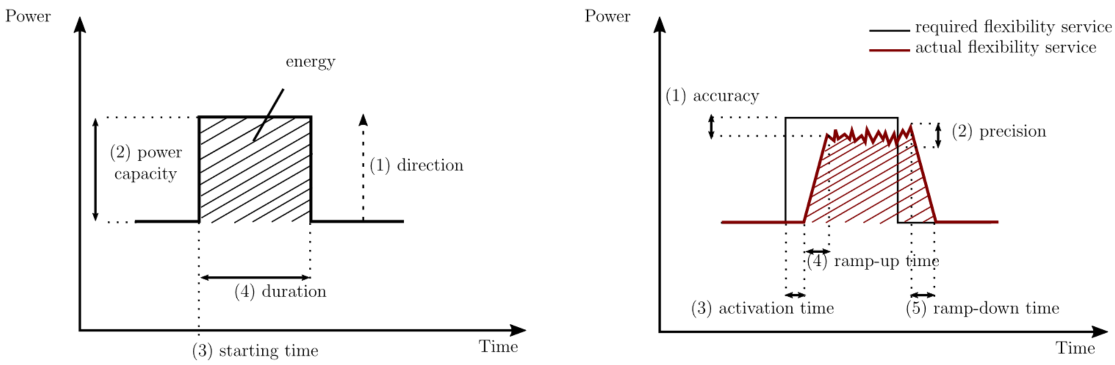


Figure 24 (a) Theoretical and (b) practical attributes of a flexibility service.

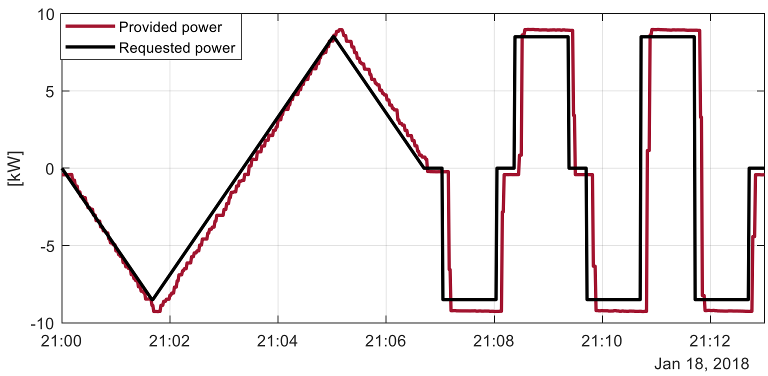


Figure 25. A cycle of the performed remote performance assessment test (positive power implies discharge; negative power implies charge).

Aggregation of bidirectional V2G chargers

Figure 26 shows a sample of the aggregated response from the 20 vehicles in Bornholm following a certain frequency pattern. The average latency between requested and provided power is around 6 seconds and the charger-vehicle pairs are capable of following the desired set-point. However, the effect of such latencies on power system stability should be carefully investigated and potentially update the service specifications for ancillary services provided by demand response. This also emphasizes the necessity to enhance the performance of flexible demand-side units and their control infrastructure. In most cases, commercial chargers are not designed for offering fast frequency control. Their capabilities may need to be adjusted, and the monitoring and control infrastructure further developed, in accordance with the system operator's requirements, especially given the progressive reduction of system inertia, which may require very small delays in the provision of frequency reserves.

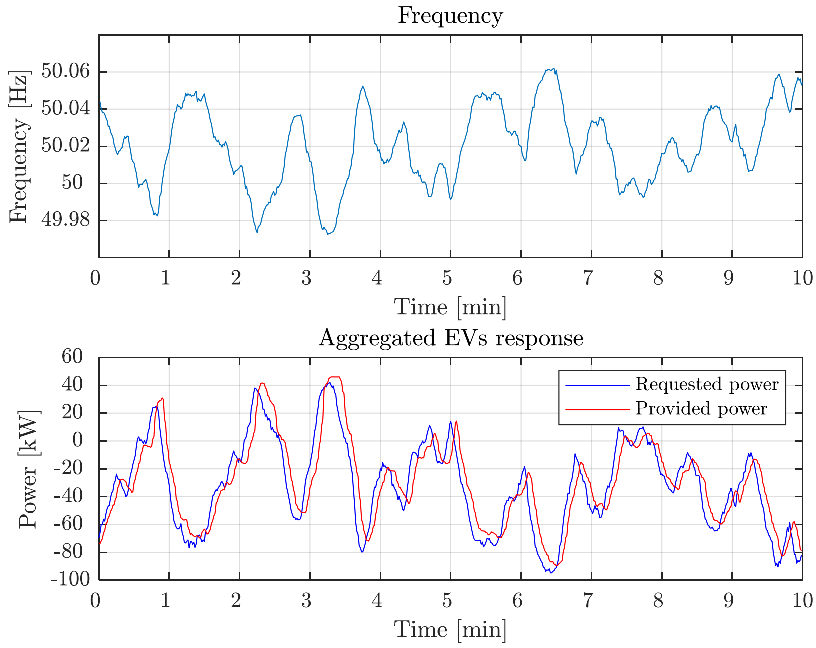


Figure 26. Frequency reserve provision, FCR-N, from 21 electric vehicles located on the island of Bornholm (positive power implies discharge; negative power implies charge).

Unidirectional smart charging

The standard for Electric Vehicle Supply Equipment (EVSE) is the IEC 61851 standard. This standard describes a PWM control signal in the charging cable that sets a limit of the maximum current the connected EV is allowed to charge with. The minimum charging current on each phase is 6 A and the maximum is 80 A, though often limited by the installed equipment to respectively 16, 32 or 63 A. As most EVs will charge with the maximum allowed power, if the internal charger is capable, the PWM signal essentially becomes a control signal for controlling the charging of each EV. Only in the last part of the charging cycle, when the SOC reaches around 80% and above that the EV might draw less power than allowed, as the charging cycle switches from constant current charging to constant voltage charging. This is one of the main drawbacks of using this standard for FCR-N, as the signal sent from the EVSE to the EV is merely a control signal. The signal is seen by the EV as the threshold of charging and one cannot be sure that the connected EV will follow the signal precisely. Another drawback of the standard is that the communication is one-way only. This results in missing information of battery SOC, which makes it difficult to do capacity calculations when moving towards a large-scale setup.

As a part of the ACES project, DTU has developed an EVSE with a built-in computer including mobile communication and measurement hardware. The internal computer has its own distributed control algorithm that is setting the charging limit between 6 and 32 A, according to a frequency measurement received over the internet, such that the connected EV is delivering unidirectional FCR-N. The charger was installed at the hotel Griffen in Rønne on the island of Bornholm, see Figure 27. The hotel customers are allowed to charge at the charger and at the same time they are helping with balancing the Nordic power system. Since Bornholm is occasionally disconnected from the Nordic grid, it is necessary to have an accurate frequency measurement from the island. DTU has developed a frequency meter that every 0.5 s reads the system frequency with 10 mHz accuracy and uploads it to a server such that it can be sent to the charger. The frequency meter is installed at the BEOF main office.

Figure 27. The authors (Mattia, Andreas and Lisa) next to the controllable EVSE developed by DTU and installed at Griffen Hotel, Rønne Bornholm.

A regular guest at Hotel Griffen owning a Tesla model S often connected to the EVSE And Figure 28 shows a snapshot of the frequency, the EVSE current limit and the charging current on three phases. When the current limit is changed, the battery accordingly increases/decreases its consumption with a delay. For increased consumption the delay is 6 s and for decreased consumption the delay is 1 s. The operation of the charger was tested also during an islanded event: the cable connecting the Bornholm island with Sweden was disconnected on the 18th of March 2019 due to maintenance. Figure 29 shows the moment the island was reconnected with the Nordic grid, while an EV was charging and delivering FCR-N. From the figure it can also be seen that the frequency of the Bornholm system is much more volatile than the frequency of the Nordic power system.

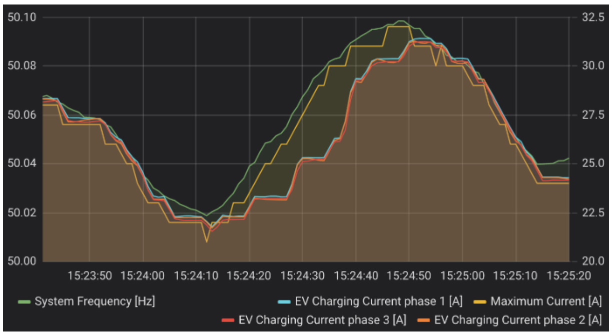


Figure 28. Tesla model S delivering FCR-N while charging at DTU EVSE.

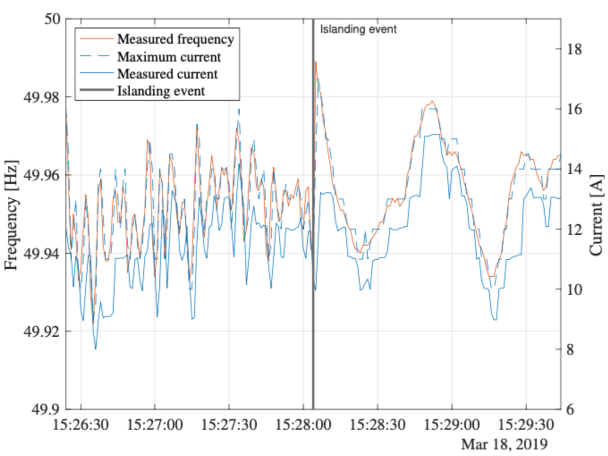


Figure 29. Frequency, Current limit and charging current during and after Bornholm was islanded on 18th of March 2019.

6.5. System stability during islanded event

Power systems mostly rely on controllable generation units to steer the balance between production and variable consumption. This simple, yet effective, principle is challenged by the increase of uncontrollable sources connected to the grid. One of the solutions for low inertia in power systems is fast frequency regulation. Fast frequency regulation fits well storage systems such as EVs together with V2G chargers. The ACES project involves EVs providing ancillary services and flexibility for the power system. Providing ancillary services with tight time requirements, such as FCR-N, can be challenging due to delays caused by sub-optimal hardware, communication latencies and centralized approaches.

As in all dynamic systems, latencies are crucial for stability. In order to assess system performance during normal operation it is necessary to recreate realistic system conditions that would require complete observability of all generating and consuming units with a fine time resolution. While it is nearly impossible to get such information due to the lack of second-based metering in all consumption and generation points, it is fairly simple to get reliable measurements of the electrical frequency. This information can be used to reverse-engineer the balance of the power system and therefore recreate a simulated system, where sensitivity studies can be performed.

Based on the deviation of the grid frequency from 50 Hz it is possible to calculate the difference between the production and consumption that has caused it. The power imbalance that would cause a frequency deviation can be calculated when knowing inertia of the generation connected to the system.

The island of Bornholm is chosen as a case study, because it has a limited cable connection to the rest of the Nordic system and it is capable of operating either synchronized to the larger Nordic system or electrically islanded.

A 45-minute period, while the island was disconnected, on the night of 9th May 2019 was chosen, in order to analyse a situation with only one generator connected to the system. During that hour there was 19 EVs connected with bidirectional chargers delivering FCR-N and a certain amount of uncontrollable and wind production. Load and wind, which form the non-controllable part, are only known as average values over the selected time period.

The system inertia is equal to the generator, called Block 5 (B5). This unit, together with the aggregation of EVs, are the only units providing frequency control. B5 is a steam turbine power plant fuelled with oil and used solely during islanded operation.

Aggregated EVs model

The aggregated EVs model is derived from experimental work previously carried out on similar equipment installed in our laboratory. The model consists of a series of four blocks: a transport delay, a droop characteristic in the form of a look-up table, a ramp limiter and a gain to account for the number of EVs involved. The EV power has a discrete step size due to the fact that each charger can be controlled with a current granularity of 1 A on the DC side. Considering an average DC voltage of 400 V on the EV side, this corresponds to changes of approx. 400 W per charger. An aggregation of 19 chargers, each with rating of 9.2 kW, determines a reserve of 0.175 MW (discretized in steps of 7.6 kW).

The reserve is fully deployed once frequency is below 49.9 Hz (discharging) or above 50.1 Hz (charging), according to the requirements set by the grid operator. In Figure 30 it can be seen how the 19 aggregated EVs provide regulating reserve, which is approximately 10% of that provided by B5. The simulated values are calculated based on the frequency input and the aggregated EVs model, while the historic values are measured during the islanded event.

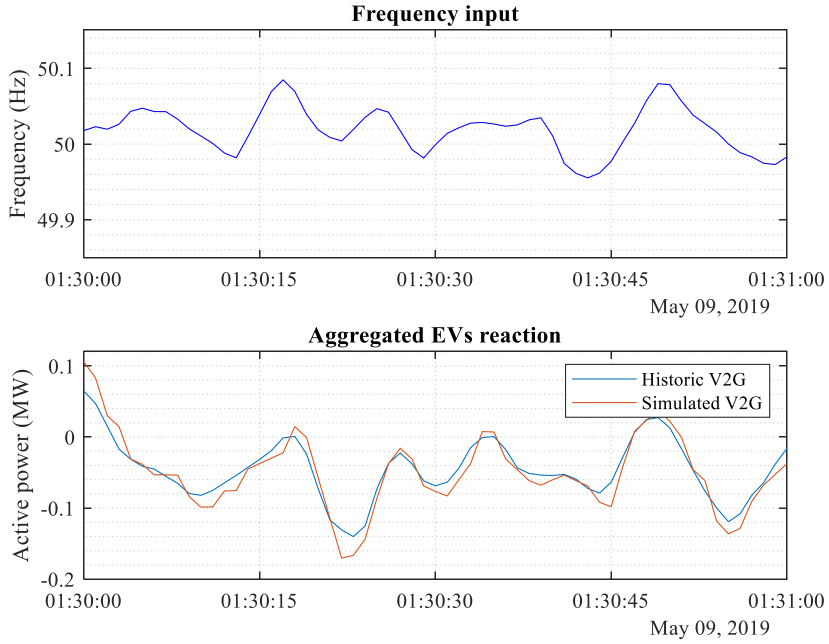


Figure 30. Frequency input (first plot) for 1 minute and corresponding aggregated EVs power (second plot). Positive power implies discharge; negative power implies charge.

Stability analysis of normal operation

Figure 31 shows the results for a 1-minute period. Each scenario has the system residuals as input, reported in the first plot and calculated based on the historical frequency.

- Scenario 1: The benchmark case is the "No EVs scenario" where only B5 offers FCR-N.
- Scenario 2: The historic scenario is where 19 EVs and B5 offer FCR-N.
- Scenario 3: The 50 EVs scenario is where 50 EVs and B5 offer FCR-N. The Aggregated EVs are simulated with 6, 1, and 0.5 second delays from measuring the frequency deviation to changing the power output.

When the EVs have a 6 second delay, it can be seen that employing a higher number of EVs destabilizes the frequency. The oscillations of the frequency are larger in the 6 second delay scenario compared to the 1 and 0.5 second scenarios. Practically, with 0.5 second latency, 19 EVs give a smoother frequency compared to 50 EVs. This kind of response is in line with the behaviour of any dynamic system subject to an increasing proportional gain. In Table 10 it is clear the MAE is increasing with the number of EVs delivering FCR-N with 6 s delay, while it is decreasing when the delay is lowered.

Table 10. Stability analysis of normal operation. Standard deviation and mean absolute error for the different scenarios.

SCENARIO	DELAY [SEC]	RR_{EV} [MW]	RR_{B5} [MW]	STD [MHZ]	MAE [MHZ]
1	-	-	1.667	38.0	30.8
2	6	0.175	1.667	38.4	31.1
3.1	6	0.460	1.667	108.9	93.3
3.2	1	0.460	1.667	28.8	24.0
3.3	0.5	0.460	1.667	24.3	20.4

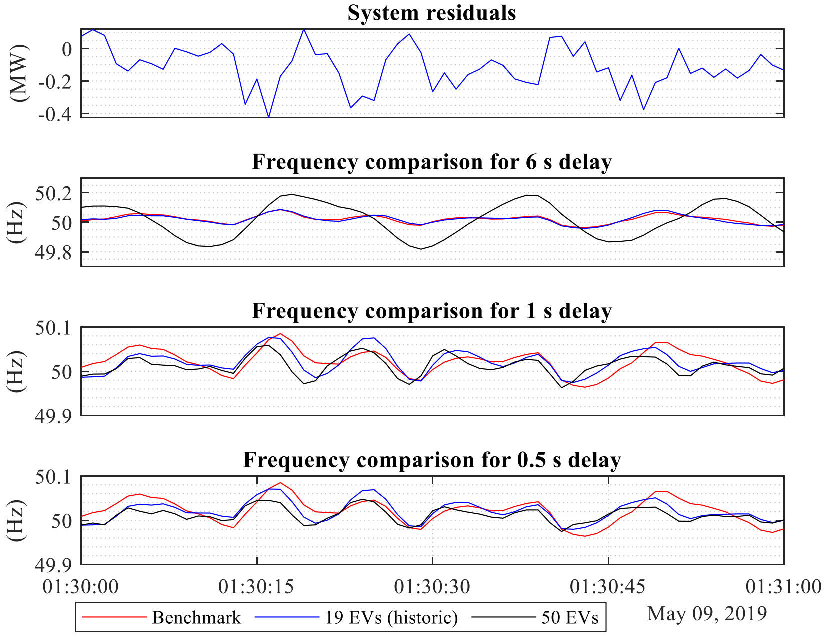


Figure 31. System residuals (first plot); resulting system frequency (second plot) with 6 second delay; resulting system frequency (third plot) with 1 second delay for the 19 and 50 EVs scenarios; resulting system frequency (fourth plot) with 0.5 second delay for the 19 and 50 EV scenarios.

Stability analysis of normal operation with a disturbance

The scenarios are now investigated with the addition of a disturbance in the system. A temporary 1-MW wind generation loss event is included, corresponding to a 5% step with reference to the magnitude of the load. The generation event is only added for 30 seconds. As it can be seen in the upper plot of Figure 32, the system residuals incorporate the 1 MW deviation which is part of the non-controllable generation. The lower plot shows the resulting frequency in selected scenarios.

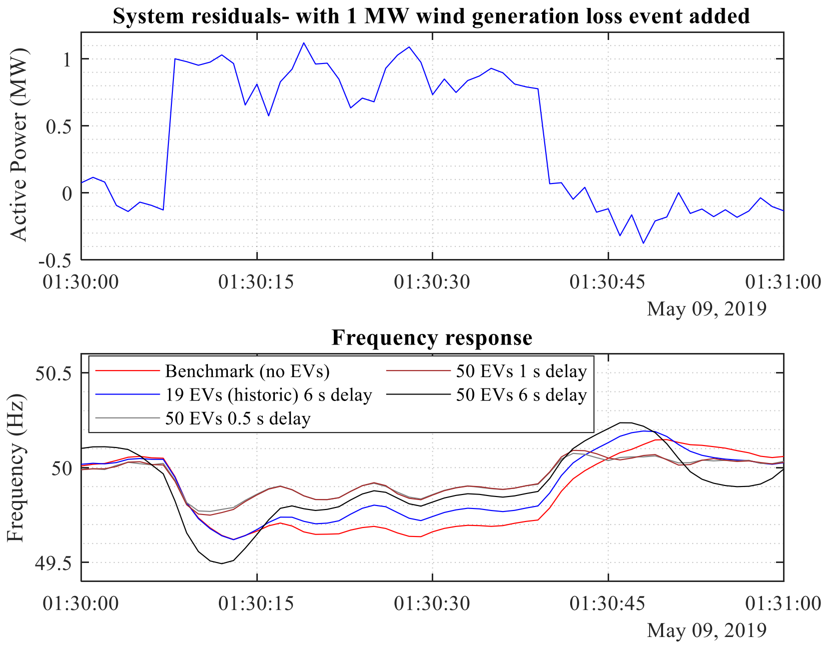


Figure 32. System residuals, with 1 MW event for 30 seconds added (first-plot); system frequency (second plot) with no-EVs scenario, historic (19 EVs) scenario with 6 second and 1 second delay for the 19 and 50 EVs scenarios.

Table 11 shows that for the 1 and 0.5 second delay scenarios, EVs are beneficial to the power system by improving the frequency rate of change (RoCof) and minimum temporary frequency (nadir) (also shown in the first 15 seconds of the second plot of Figure 32). The scenario with 19 EVs and 6 second latency, although not improving RoCoF and nadir, is contributing to a faster recovery of the frequency deviation. This leads us to conclude that, even with such latency, EVs are still beneficial when contributing to the system balance via a threshold-based approach, rather than with a traditional droop-based approach, in case of a large contingency.

Table 11. Stability analysis of normal operation with disturbance. Standard deviation and mean absolute error for the different scenarios.

SCENARIO	DELAY [SEC]	RR_{EV} [MW]	RR_{B5} [MW]	STD [MHZ]	MAE [MHZ]
1	-	-	1.667	51.6	36.3
2	6	0.175	1.667	48.8	34.3
3.1	6	0.460	1.667	111.9	94.7
3.2	1	0.460	1.667	34.1	26.0
3.3	0.5	0.460	1.667	29.9	22.5

Sensitivity analysis on the system stability

During the time period of this investigation, it is known that the primary reserve available for the control operator is 1.842 MW (1.667 MW from the steam generator and 0.175 from the EVs). We intend to investigate the change of the ratio between generator and EVs, while maintaining the same amount of FCR-N: when increasing the numbers of EVs we reduce the reserve from B5 (by increasing its droop gain).
We assess the system's behaviour by analysing different ramp limits for the thermal generator, as reported in Figure 33. In all cases the ramp limits of EVs are kept constant. We simulated the chargers with one second delay.
Figure 33 (left plot) shows that for faster ramping generation, the improvements of MAE are smaller when increasing the percentage of EVs. MAE is the mean absolute error, which in this case is the mean deviation from 50 Hz. The results are obtained with an increasing number of EVs (5% at the time) and constant system inertia. In all ramping cases, it can be said that 30% reserve share from EVs is the upper limit before the system performance starts deteriorating. Figure 33 (right plot) describes the case when ramping of CGU is kept constant, but inertia and EVs reserve share is changing. It is clear that a reduction in system inertia is progressively making the response of EVs less effective, even if their overall response time is only 1 second. Therefore, the smaller the system inertia, the smaller the amount of EVs that can be accepted before system performance starts to deteriorate.

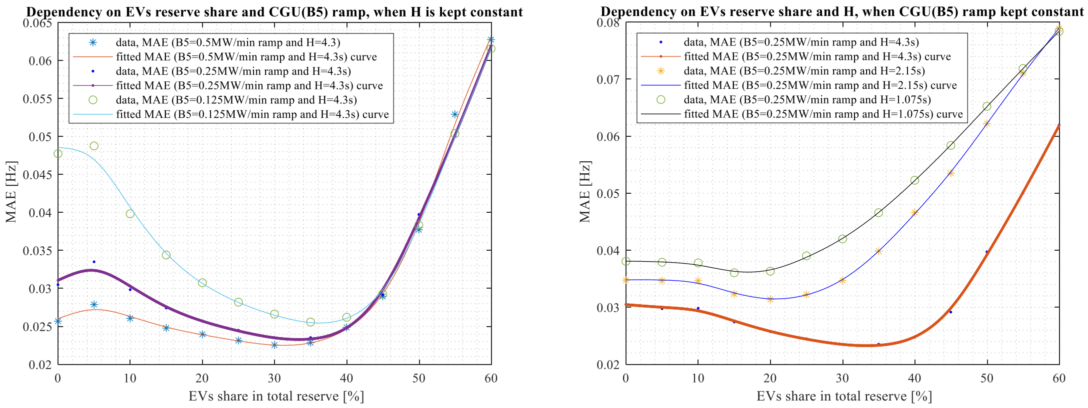


Figure 33. Stability analysis keeping the same H for the system, but changing the ramp limit for CGU (B5) (left plot) and keeping the same ramp limit for CGU, but changing the inertia (H) of the system (right plot) while increasing the reserve share from EVs.

7. Utilization of project results

The project efforts amounted to a total of 130 equivalent person-month (30+ people involved) over 3.5 years (April 2017 – September 2020). The overall budget was 10 MDKK (approx. 1.4 M€), of which 5.5 MDKK with public support from EUDP.

Project results were collected in 29 academic peer-reviewed publications of which:

- 15 journal papers (5 currently under review),
- 14 international conference papers,
- 4 publicly available frequency data-set.

Several of the listed publications were done in collaboration with Danish and EU projects such as: CAR (www.sbcar.eu); Insulae (http://insulae-h2020.eu/); Parker (https://parker-project.com/); Ecogrid 2 (http://ecogrid.dk/); Energylab Nordhavn (http://www.energylabnordhavn.com/); ACDC (https://www.acdc-bornholm.eu/)

For DTU: the ACES project supported one PhD study (to be completed in 2021) and co-funded two PhD studies (one completed in 2019 and one to be completed in 2022). The remaining PhD studies co-funding were provided by a Nordic 5 Tech scholarship and the EU projects CAR and Insulae. The ACES projected also supported ten master students, who contributed to the project activities through the results of their final theses. Besides supporting PhD and master students, the ACES project allowed DTU to strengthen its leading position in the research field of grid integration of electric vehicles.

For Nissan: the project allowed Nissan to verify the impact and opportunity of vehicle grid integration based on quantified result to define future EV business model. The ACES project also supported Nissan to gain insights about modeling of energy system. Nissan will utilize the knowledge to investigate the opportunity of vehicle grid integration worldwide. Result of the project had proven that charging control will be mandatory with high penetration of EVs in future.

For BEOF: the project provided valued insights of system stability and grid impact that e.g. asset management can benefit from. Our Bornholm Simulation model comprising the complete energy system has been upgraded with EV technology enabling us to investigate various scenarios of interest in the future. Studies of deploying EVs in a distribution grid combined with real plug in data underpinned a lower coincidence factor than generally seen, which can be used by the DSO to assess grid capacity for EVs and presumably postpone reinforcement. Insights gained about centralized aggregation and control of EV charging is an optimal starting point for the new R&D project ACDC.

For Nuvve: the ACES project has proven that EVs are capable to optimally perform frequency market regulation services under certain conditions. Nuvve might use these outcomes in order to support the business use case development and further commercialize the V2G technology worldwide. Nuvve will use the degradation results as baseline research for comparisons with other projects, to include the cost of degradation in the internal business analyses and to update the business use cases on frequency control market services. Nuvve will include the important findings in our participation in the regulatory field, in working with the energy industry and in other R&D projects.

8. Project conclusion and perspective

The project key results can be summed up in the three macro-areas.

1. Driving behaviour, coincidence factor for distribution grids and public chargers

- 100% EV penetration causes a (domestic) coincidence factor equal to 40% for a 3.7 kW charge level (22% for 11 kW).
- The coincidence factor may increase considerably if the EVs charging behaviour is synchronized by Time of Use or other factors (price/CO_2 signals).
- The average distribution grid in DK would be able to handle 50% of EVs, though safety margins are reduced (problems may arise if EVs are not equally distributed on the phases).
- 1 million EVs in DK needs ~27000 public chargers (22-150 kW) with 3.4 billion DKK (450 million €) investment.

2. System and local services profitability and battery degradation

- Bidding into the frequency market can be very remunerative, up to 8250 DKK/y (1100 €/y), but the need for extra equipment (V2G charger), cost of losses and need to fulfil bid requirements can reduce the profit.
- Unidirectional modulation for frequency requires less hardware but revenue is limited, 450 DKK/y (60 €/y).
- Potential revenue by speculating on the energy market is very limited given the current variability of prices: up to 336 DKK/y (45 €/y) by using 3.7 kW bidirectional charging.
- Additional wear due to the intense bidirectional power flow during frequency control amounts to only few additional percent compared to the natural degradation.

3. Chargers analysis and system stability assessment

- EVs are capable of providing fast frequency control and contributing to the system stability, as long as certain conditions are fulfilled, primarily response time, which should be below 1 second.
- The 1-second response time is identified as a target requirement, and this is supported by the new version of the Danish grid code for stationary storage.
- Considering the control characteristics analysed, a share of 30% EVs in the total regulating reserve is seen as maximum limit given system inertia and ramping limits of conventional units.
- The current dynamic of EVs providing frequency control is not suitable in stabilizing the system if the number of EVs increases. However, benefits can be observed if EVs are subject to a threshold-based activation.

While the ACES project certainly put firm conclusions to several areas, it left new areas in need for further investigations:

- Large-scale demonstration with thousands of controllable chargers providing flexibility services to the system.
- New system architectures that ensure effective control of the chargers while leaving room for autonomous operation whenever necessary.
- Synergies between stationary storage systems and fast charging stations in order to prevent additional burden to the distribution grid.
- Quantification of the flexibility based on Danish charging behaviour.
- Assessment of conflicting operating modes for chargers such as pursuing lower coincidence factor on the system and maximizing usage of wind power at the system level.

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