Final report

1. Project details

Project title	adaptive BATtery diagNOSTIC tools for lifetime assessment of EV batteries
Project identification (program abbrev. and file)	BATNOSTIC Journalnr.: 64015-0611
Name of the programme which has funded the project	EUDP
Project managing company/institution (name and address)	Lithium Balance A/S Hassellunden 13 2765 Smørum
Project partners	Aalborg Universitet (AAU) Teknologisk Institut (DTI) Foreningen for Danske Motorejere (FDM) Applus Danmark A/S (Applus) Lithium Balance A/S (LiBal)
CVR (central business register)	DK29391130 (Lithium Balance A/S)
Date for submission	21/12 2018

2. Short description of project objective and results

2.1 English version

E-mobility is an important asset in the implementation of an effective 100% renewable energy based Danish electric supply by 2035, but the sales of electric vehicles (EVs) disappoint gravely. Doubts on expected battery life makes the investment in an EV uncertain and disables a well-functioning second-hand market. Neither the owner nor a third party can today directly measure the status of a vehicle battery. Currently only the vehicle manufacturer and the authorized dealers can access and interpret the battery data without affecting warranty and often this information is kept secret.

The BATNOSTIC project enables independent automotive professionals to access information on expected remaining EV battery life without infringing the vehicle warranty. Such a service will enforce confidence in EVs, open up a second-hand market, and enable independent auto repair shops and car inspections to offer their services to EV owners.

The BATNOSTIC method has required R&D activities on:

1. A large statistical database to compensate the lack of detailed knowledge on each battery type and the history on each battery. As the database grows the accuracy of the BATNOSTIC method increases.
2. An advanced service to search and extract useful data from the database, then compute the relevant diagnostic information for a particular vehicle.
3. A battery test method and test equipment, that will not void warranties and guaranties on vehicles, using a DC-fast charge connector.

There is no knowledge of any similar methods enabling independent workshops to assess the condition of the EV battery without extensive road testing or by voiding the factory warranty on the car and battery.

The main results for the project are:

1. Suitable test methods researched for good quality of diagnostic results.
2. Diagnostic test equipment developed, manufactured and tested in various locations.
3. Successful EV battery tests with verified export of quality data to the BATNOSTIC database
4. BATNOSTIC test equipment feedback on form, function, user interface and business model, from partners based on involvement in actual tests.
5. Tests and feedback from EV owners in Denmark.

2.2 Dansk version

Elbiler er et vigtigt aktiv i forbindelse med gennemførelsen af en effektiv dansk elforsyning med 100% vedvarende energi i 2035, men salget af elbiler skuffer alvorligt. Tvivl om forventet batterilevetid gør investeringen i en elbil usikker og forhindrer et velfungerende brugtmarked. Hverken ejeren eller en tredjepart kan i dag måle status for en elbils batteri. For nuværende er det kun bilproducenten, og de autoriserede forhandlere der kan få adgang til, og mulighed for at fortolke, batteriets data uden at påvirke garantien. Ofte holdes disse oplysninger hemmelige.

BATNOSTIC projektet gør det muligt for uafhængige fagfolk indenfor bilbranchen at få adgang til information om forventede resterende batterilevetid uden at overtræde garantien. Ydelser som denne vil øge tilliden til elbiler, åbne brugtmarked for elbiler, og gøre det muligt for uafhængige autoværksteder og synshaller at tilbyde deres tjenester til elbilsejere.

BATNOSTIC metoden har krævet forsknings- og udviklingsaktiviteter indenfor:

1. En stor statistisk database for at kompensere for manglende detaljeret viden om hver batteritype og historie for hvert batteri. Nøjagtigheden af metoden stiger i takt med databasens størrelse.
2. En avanceret service til at søge og udtrække brugbare data fra databasen, derefter beregne de relevante informationer omkring batteriets tilstand for det relevante køretøj.
3. Batteri testmetode og testudstyr, som ikke bryder med køretøjets garantier, baseret på adgang via DC hurtigladestik.

Der er ikke kendskab til lignende metoder som gør det muligt for uafhængige autoværksteder og synshaller at beregne tilstanden af elkøretøjets batteri, uden langtrukne testkørsler eller uden at bryde garantien for køretøj og batteri.

Hovedresultaterne for projektet er:

1. Forskning i brugbare testmetoder for resultater af god kvalitet.
2. Testudstyr til diagnosering af batteriets tilstande er udviklet, produceret og testet i flere forskellige lokationer.
3. Succesfulde tests af elkøretøjers batterier med verificeret eksportering af kvalitetsdata til BATNOSTIC databasen.
4. Feedback på BATNOSTIC testudstyr i form af udformning, funktionalitet, brugerinterface og forretningsmodel fra projektets partnere, baseret på aktuelle tests.
5. Test på, og feedback fra brugere af elkøretøjer i Danmark

3. Executive summary

The BATNOSTIC project was initiated to help improve market penetration of electric vehicles. This is sought achieved through better understanding of the state of the used high-voltage battery pack (hereafter referred to as *battery*) in electric vehicles (EVs), as one of the main problems for a potential buyer of an EV is the uncertainty regarding expected range and life-time of the battery. The cost of a battery is estimated to be slightly lower than 50 % of the entire vehicle (https://www.statista.com/statistics/797638/battery-share-of-large-electric-vehicle-cost/), and represents a big unknown factor when buying an EV on the second-hand market or valuating a leased EV. The information on the state of the used battery is only available to the vehicle manufacturer and authorized dealers, and often kept secret. The BATNOSTIC project has found a reliable method to estimate the actual state of the used battery and thus the remaining value both in terms of performance and cost. The method enables independent auto repair shops and car inspections to offer an impartial estimate of the remaining performance of a used EV battery. Something that the project partners have been very keen on with the growing market for EVs.

The method developed during the BATNOSTIC project utilizes novel methods for accessing, measuring, and computing the battery state. These methods are described in detail in the following paragraphs, but the project scope can be broken down in the following steps:

1. Perform accelerated lifetime battery tests on cell level. This was done by purchasing battery cells as spare parts for both the Nissan Leaf (1st generation) and BMW i3 (1st generation). Final data was used as seed data for a remote database.
2. Gain access to the vehicle level battery data through a DC fast-charge port of the EV, this gives direct access to battery voltage and current during charging.
3. Use battery cell data in conjunction with vehicle level battery data to reveal a battery model and state of health estimation method.
4. Establish a remote database that will continue to grow with each new test performed by the BATNOSTIC workshop equipment
5. Develop the BATNOSTIC workshop equipment and establish correct procedures for vehicle tests.

All of this was performed by the project partners and there is no knowledge of any similar methods enabling independent workshops to assess the condition of the EV battery without extensive road testing or by voiding the factory warranty on the car and battery. A close collaboration between project partners has been a key process for the success of the project. The technical group consisting of AAU, DTI and Lithium Balance A/S have held weekly skype-meetings during the project period and thereby pushed the innovation and progression forward with really good test-results as a reward.

The project has been very successful in finding a ground-breaking new EV-battery analysis method for independent parties like auto workshops or vehicle inspection workshops. The project partners have focused on several aspects and technologies, which at the beginning of the project all was at a Technological Readiness Level (TRL) 2-3. Throughout the project there has been researched and developed both new hardware, software, operational procedures, mathematical algorithms combined into a new-to-world product at TRL 5. During the project FDM (Federation of Danish Motorists) has spoken to many members who are reluctant to buy a second-hand EV or have experienced problems with the battery of their EV. Today it is only possible to have the battery checked at the car manufactures dealership and neither independent service providers nor consumer organizations like FDM can give an objective second opinion on the battery state of health. The method and product developed in the BATNOSTIC project is the best (and only) current option to address this issue apart from driving the vehicle strictly disciplined in normal temperature and under homogeneous conditions until the battery is completely empty. This is also confirmed by NAF (Norwegian automotive federation), that has been a valuable provider of market feedback for the BATNOSTIC project.

The method research and feasibility tests are based on more than 200 BATNOSTIC-tests on EV-batteries in lab and workshop environment. Half of the vehicle-measurements serves as initial reference in a large analytic BATNOSTIC-database together with more than 750 charge data for battery cells.
The feedback from workshop professionals have been positive but suggested further improvement in two areas that could be difficult for some workshops: keeping temperature constant at 20°C and reserving space for half a day. Since the market potential for BATNOSTIC test-equipment would increase with less temperature dependent test conditions and shorter test time, a new project has been formed to research a possible temperature compensation for real workshop environment and develop workshop test equipment. New partner Christonik (a SME) wishes to expand their range of test equipment to workshops with a battery tester for electric cars, based on the BATNOSTIC method. They will also seek out sales channels through contacts across Europe and in China and participation in tradeshows in Frankfurt and Shanghai. Lithium Balance (a SME) develops a fast charge interface essential for the BATNOSTIC test equipment. Applus, FDM and NAF will help test the equipment and communicate the results through e.g. FDM's participation in the international cooperation between motoring clubs, FIA as a member of ARC Europe (mobility providers).

4. Project objectives

4.1 Introduction

The BATNOSTIC project aims to provide access for independent automotive professionals to reliable information on expected remaining EV battery life without voiding the warranty on the electric vehicle. Commercial parties can independent of the vehicle manufacturer use this new BATNOSTIC method to assist e.g. owners or buyers of electric vehicles.

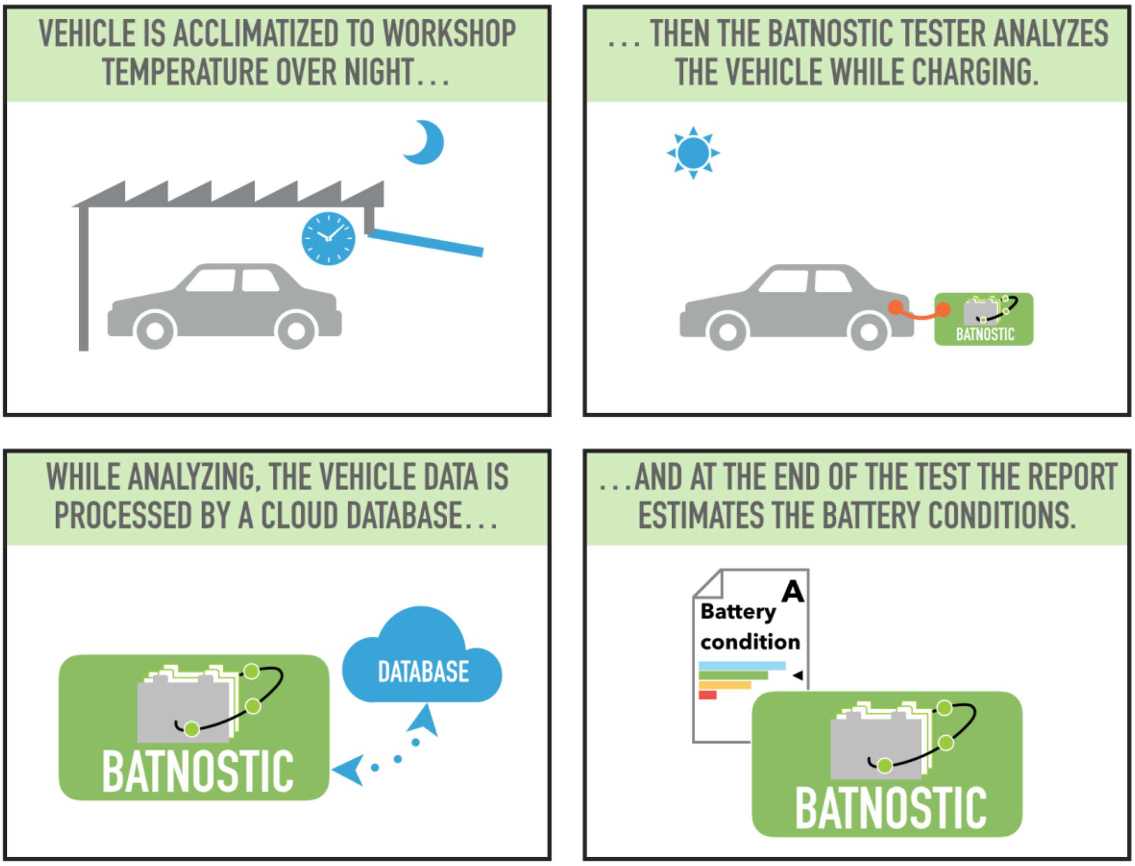
The best method for non-intrusive battery analysis is during DC charging, where there is normally direct access to the battery voltage and battery current via the fast charge connector. By measuring the battery voltage and current, and having the possibility to interrupting and pulsing the charge current, information on battery state and internal resistance can be assessed. A special BATNOSTIC workshop test equipment was developed to measure the battery data during charging, process data and export results to a database.

The most precise assessment of an electric vehicle battery capacity and State of Health (SoH) requires a full discharge cycle and a full charge cycle. To enable a full charge cycle the battery must be empty. Additional to the risk of being stranded away from a charge post, discharging a vehicle completely can be time consuming if it is done by driving. This project has found suitable methods for discharging the EV battery in a controlled but realistic fashion using the vehicles own battery protection to stop the vehicle when the battery is empty.

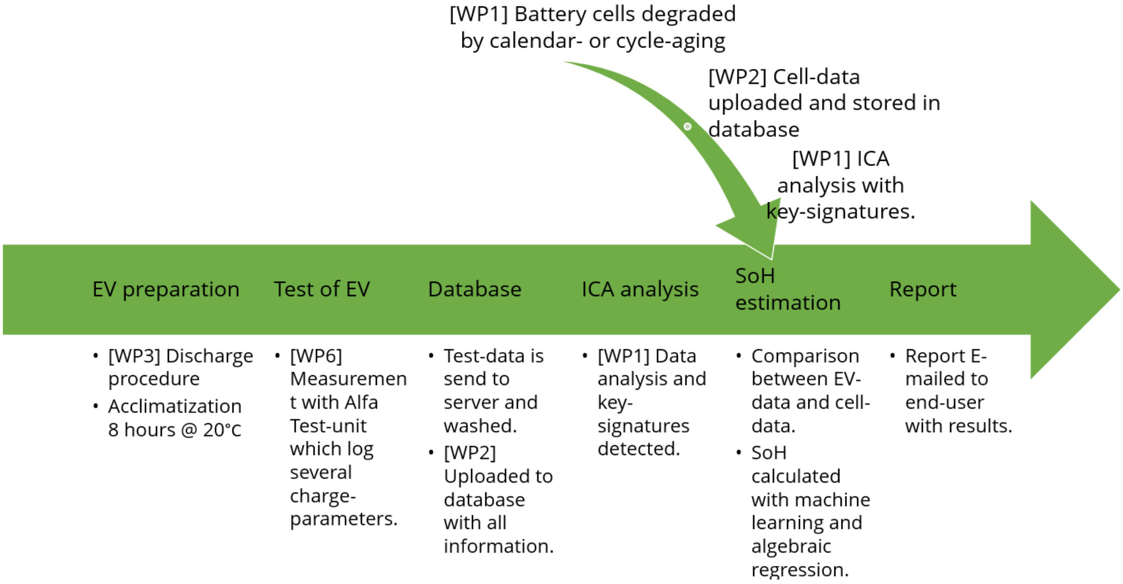
State of health (SoH) is an often-used term for the condition of a battery. There is however no common definition, and no standard for measuring SoH. SoH can depend on very different performance criteria in different applications. In a high-power application internal resistance is of high importance while in EV batteries driving range is important meaning energy content is the key parameter. Degraded battery capacity directly affects the possible driving distance so in this project the SoH refers to energy available for driving relative to the nominal initial energy capacity. However, the initial capacity at Beginning-of-Life (BOL) of a cell might differ just a bit from the nominal printed capacity of the cell, due to small variations in the manufacturing process and electrochemical materials. Mathematical models and algorithms in this project have been calculating SoH with respect to either BOL or nominal capacity depending on availability of the information. This means that a slight offset in the results from different models may appear. Normalizing all models to predict from the same initial capacity might therefore reduce the deviation in the final results. The question of the "correct" initial capacity to use though, is still unsolved, and out of scope of this project.

A novelty in this project is the establishment of an impartial BATNOSTIC database with historical battery data. The data is organized for easy searching e.g. by vehicle identification number and type (VIN), age and mileage. An advanced BATNOSTIC search and voter function compares the actual battery characteristics measured on the target vehicle with the combined stored data of the vehicle type, and seed data from cell level measurements, to estimate the state of the vehicle battery. The search model can estimate uncertainty based on the availability of relevant data.

The BATNOSTIC test procedure as seen from a user is visualized in the figure below:



This section (4. Project objectives) and the next section (5. Project results) contains references to project work packages (WP) and milestones (M). The figure below shows the steps of the complete BATNOSTIC method, from cell test and EV-preparation, to final report with SoH estimation. The WP-number regarding each step is mentioned with the description. The horizontal arrow indicates the steps regarding a test of an electric vehicle, while the diagonal arrow indicates the steps of battery cells tested in laboratory which are used to estimate the SoH of the EV. The test of an EV starts with the discharge procedure and acclimatization to ensure a completely drained battery (within the battery safe-operation-area specified by the EV). After that, a test is started with the Alfa-Test unit, who send the data to the BATNOSTIC server at the end of the test. The BATNOSTIC server stores the data in the database and perform ICA analysis of the data. In the end, the analysed EV data is compared to the analysed cell data, and an estimation of the SoH is calculated and send as an email to the end-user.



4.2 Objectives

4.2.1 AAU

WP1 – Advanced BATNOSTIC battery modelling and state estimation:
The aim is to develop a new combined general-purpose battery model and SoH estimation method suitable for automated lookup in the BATNOSTIC database. Data will be sourced from WP4 and other sources.

4.2.2 TI

WP2 - BATNOSTIC Database:
The aim has been to establish a suitable database with several automatic functions to handle test data. The main function was to receive, wash, process, store and retrieve diagnostic data from remote diagnostic units via secure internet communication. The database must also include data from battery cell tests, as well as a process to automatically compare EV- and cell data. A design-criteria of the database was to enabling fast and easy searching for relevant data and information regarding EVs and test-parameters.

WP3 - Stationary driving discharge test setup:
The aim has been to develop a semi-automatic chassis dynamometer for safe and non-intrusive discharging of EV batteries in the vehicle, as a preparation before each test. Another desire was to log necessary battery data for performance and diagnostic purposes during discharge, as a comparison between charge and discharge analysis.

WP4 - BATNOSTIC seed data acquisition:
The aim has been to collect lots of battery data both from EVs and battery cell tests as a solid base for the analysis modelling in WP1. The more data collected, the more precise the modelling would be. Two different battery chemistries, embracing three different types of electric vehicles, was chosen for the SoH modelling and estimation. The objective included feeding the data of a decent quality to the database in WP2.

WP7 - Lab-tests and field demonstration:
The aim has been to verify the BATNOSTIC concept. The BATNOSTIC Alfa-Test unit has been used to verify the diagnostic concept and demonstrate equipment both in lab environment and workshop environment. The BATNOSTIC Alfa-Test unit was tested and demonstrated in selected workshops with partners as a final verification of equipment handling and usability outside laboratory facilities. The aim was to measure three electric vehicles with known history 3 times by 3 different workshops to assess repeatability and random spread. Reality became a little different, as described in 5.1.2.

4.2.3 LiBal

WP5 - BATNOSTIC Diagnostic components:
The aim is to develop a module for EIS measurements and signal generation to be installed in charger. This includes specification, development, test and implementation of new hardware/software test module(s) for: A) Research suitable EIS measurement method for high precision measurements at high battery voltage. Develop EIS module to measure and assess battery state and faults through the vehicles DC charger interface. B) Research method to inject EIS reference signals into a CHAdeMO and/or Combo compliant DC-charger. After some experiments with EIS on battery pack level at AAU it was concluded that the method would not achieve optimal cost/benefit with the scope of this project (see section 5.1.3 for more information).

WP6 - BATNOSTIC Alfa-Test workshop equipment:

The aim is to develop a workshop tester for SoH estimation based on the BATNOSTIC database described in WP2.

Based on system components from WP5 a workshop diagnostic equipment, suitable for an auto workshop environment is specified and designed. At least one full functional prototype with a CHAdeMO or Combo compatible DC-fast charger is built to enable demonstration. The BATNOSTIC Alfa-Test workshop equipment must have internet access to work with the BATNOSTIC database. In the BATNOSTIC project it will be non-experts who in the end will need information on battery the health condition. A part of this WP is therefore to define which kind of data the end user will demand and in which form.

WP8 - Commercialization and dissemination:

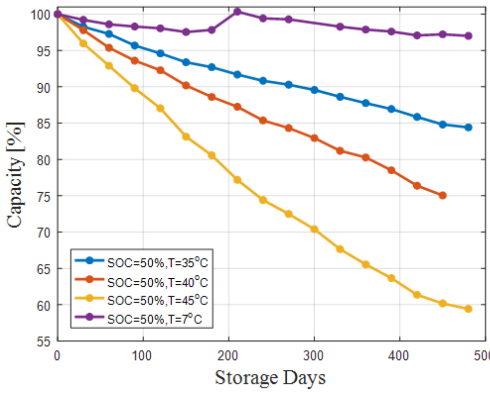
Market potential and business models for both the diagnostic components and web-services based on the database. FDM inform via magazine and other partners via own networks. The concept will be presented at international EV and battery conferences.

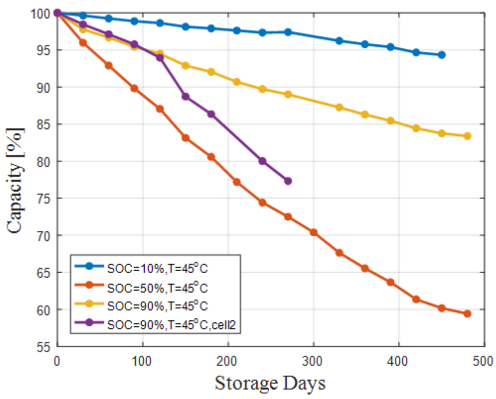
5. Project results and dissemination of results

5.1.1 AAU

WP1 – Advanced BATNOSTIC battery modelling and state estimation:
M3: State-of-the-art report. A literature study was carried out to identify possible SoH estimation methods. It was decided that only the EV battery capacity should be considered as a SoH parameter as the power capability of the battery was assessed to be of less relevance. Based on the literature survey and experience among the consortium members, it was agreed that the Incremental Capacity Analysis (ICA), Pulse Charging and Electrochemical Impedance Spectroscopy (EIS) methods should be considered as potential candidates for SoH estimation.

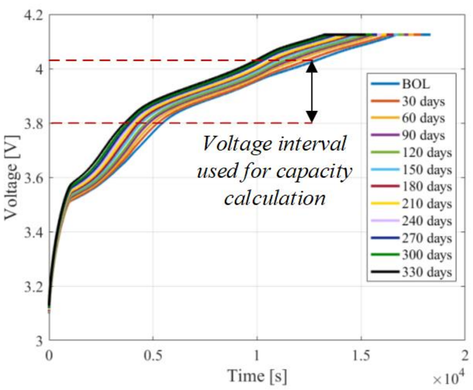
M8: SoH model of selected electric vehicles. Two EV battery types were selected for degradation test and SoH modelling: LMO-based cells for Nissan EVs and NMC-based cells for BMW i3 EV. The cells were exposed both to cycle (at DTI) and calendar (at AAU) aging tests in controlled laboratory environments. The cells were aged considering different temperature, currents (C-rates) and state-of-charge (SoC) levels in order to investigate the influence of the aging conditions. A reference performance test has regular been carried out during the cycle and calendar aging in order to monitor the battery cell characteristics. For example, in the figure below, it can be seen how the capacity of the BMW i3 cells is reducing due to the SoC, temperature and storage days. Surprisingly, it can be observed that for the highest considered aging temperature (i.e., 45°C) the capacity fade at 50 % SoC is worse than for 10 % and 90 %.

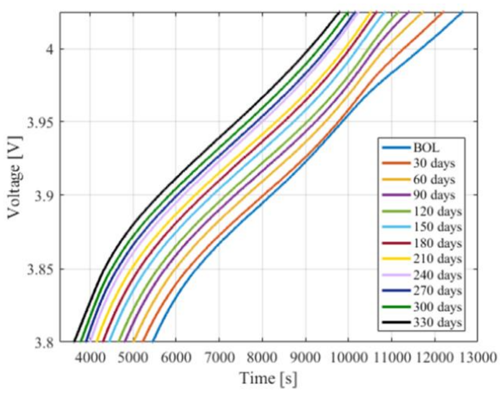




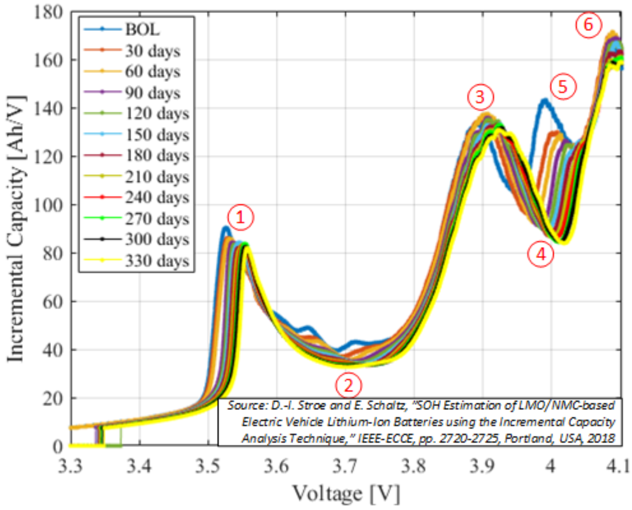
Several SoH models has been investigated:

1. *Inner resistance* from pulse-test. The inner battery resistance can be extracted from the current pulses which were applied during the reference performance test. However, the link between the inner resistance and battery capacity was not strong enough to be considered as SoH method.
2. *Partial Charging Capacity (PCC)*. This method simply monitors the charging capacity in a fixed voltage interval as shown in the figure below *(D.-I. Stroe, V. Knap, E. Schaltz, "State-of-Health Estimation of Lithium-Ion Batteries based on Partial Charging Voltage Profiles," ECS Transactions, vol. 85, no. 13, pp. 379-386, 2018).* It is seen, that as the cell ages, the time interval (and thereby charging capacity) becomes smaller. The relationship between this partial capacity and the full capacity is described by a mathematical equation.



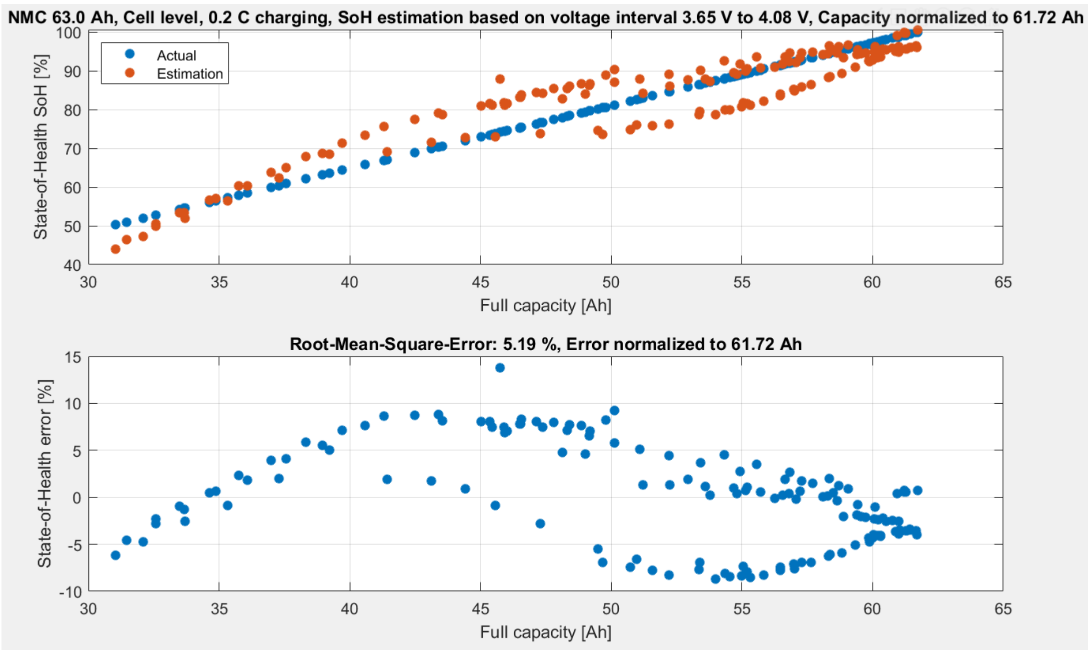


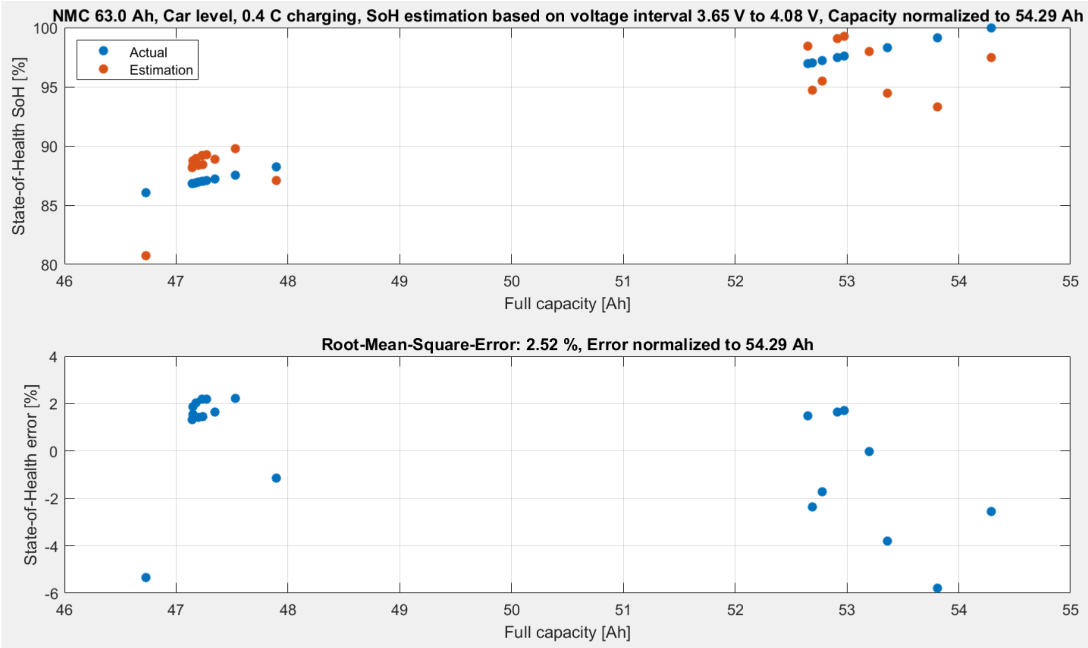
3. *Incremental Capacity Analysis (ICA)*. The Incremental Capacity (IC) is the charging capacity differentiated with respect to the voltage, i.e., IC=dq/dv. By doing so, characteristic peaks and valleys appear as shown in the figure below. It is seen that the location of the peaks and valleys are changing depending on the storage time. A link between the location of the peaks and valleys and the battery capacity has successfully been described by mathematically expressions.



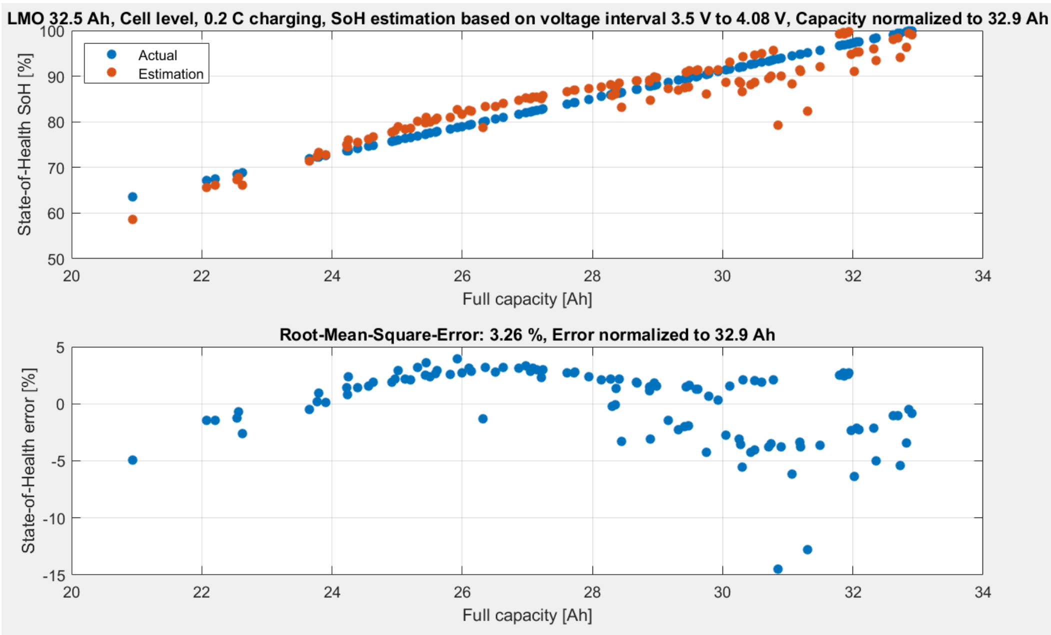
M12: SoH estimation algorithm of selected vehicles based on BATNOSTIC database. SoH estimation based on *PCC* and *ICA methods* have been carried out both on cell level and car level for both BMW i3 and Nissan batteries.

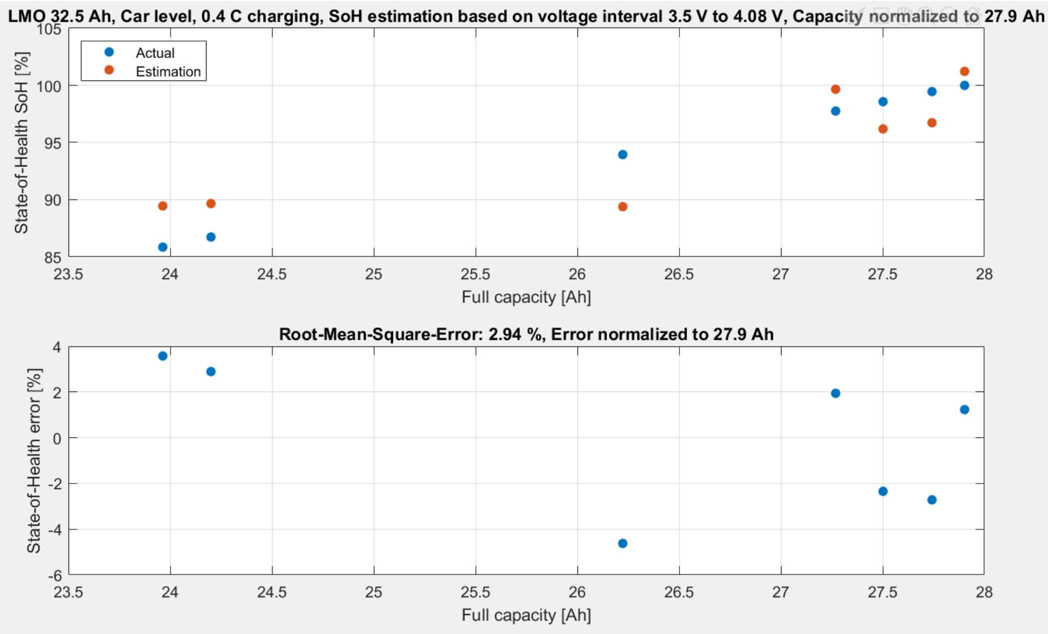
- *PCC* on **BMW i3 batteries**. The estimation error in general become better, the wider voltage interval. However, this on the penalty of longer charging time. In the two figures below the actual and estimated SoH are shown both at cell and car level for the same voltage interval when PCC method is applied on BMW i3 batteries. The SoH error at cell level is below 15 % whereas on car level it's not bigger than 6 %. The root-mean-square-error (RMSE) is also lower on car level than cell level. However, the SoH range is quite limited at car level as the minimum SoH is higher than 85 %. The two results therefore cannot be compared directly at as the error at car level probably will be higher for lower SoH levels.



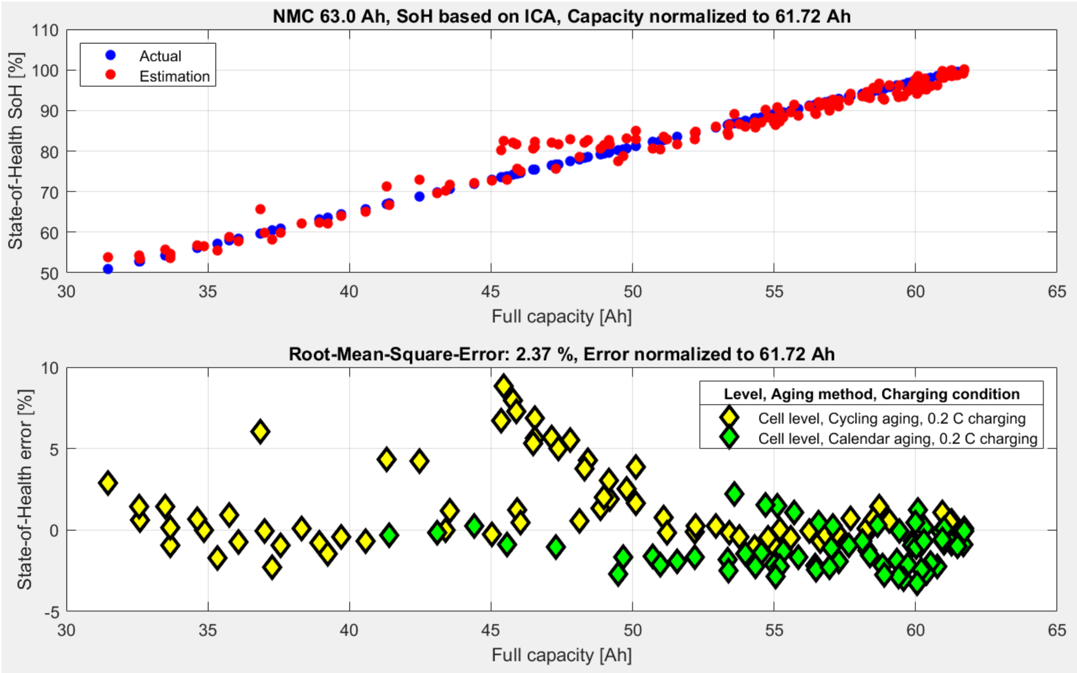


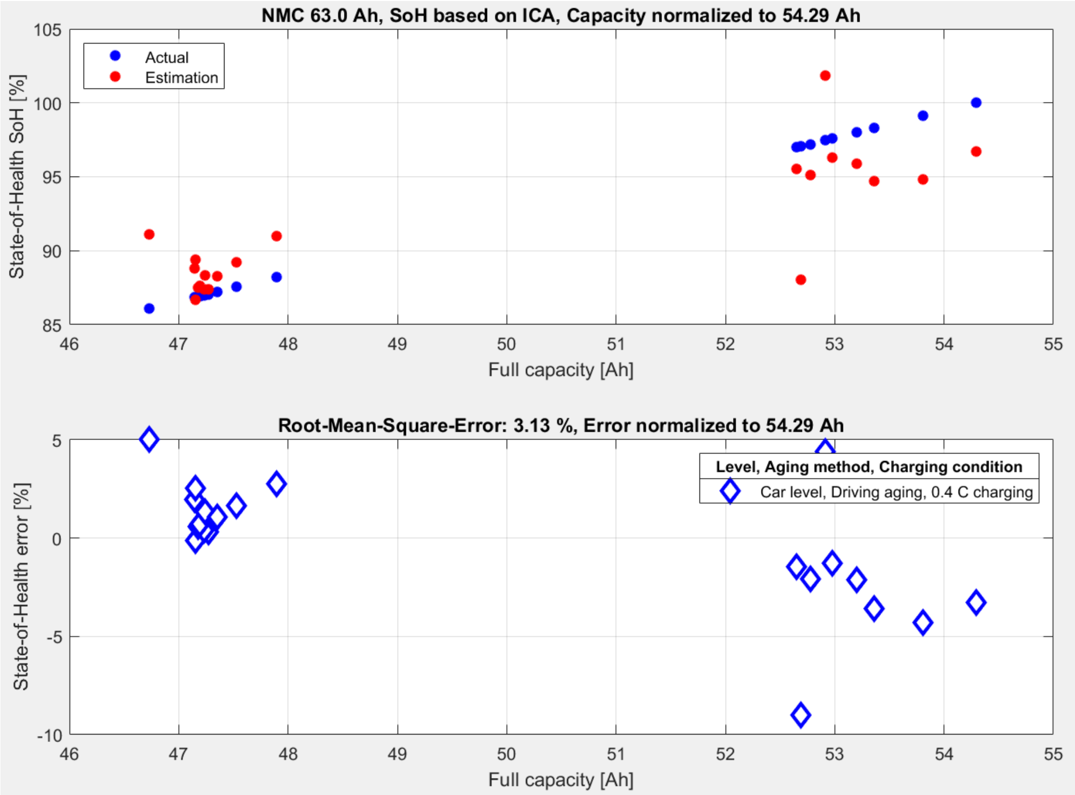
- *PCC* on **Nissan batteries**. In the two figures below the actual and estimated SoH are shown both at cell and car level for the same voltage interval when PCC method is applied on Nissan batteries. The RMSE is relatively low both on cell and car level. Again, as for the BMW i3 car, the SoH range for the Nissan car is relatively small.



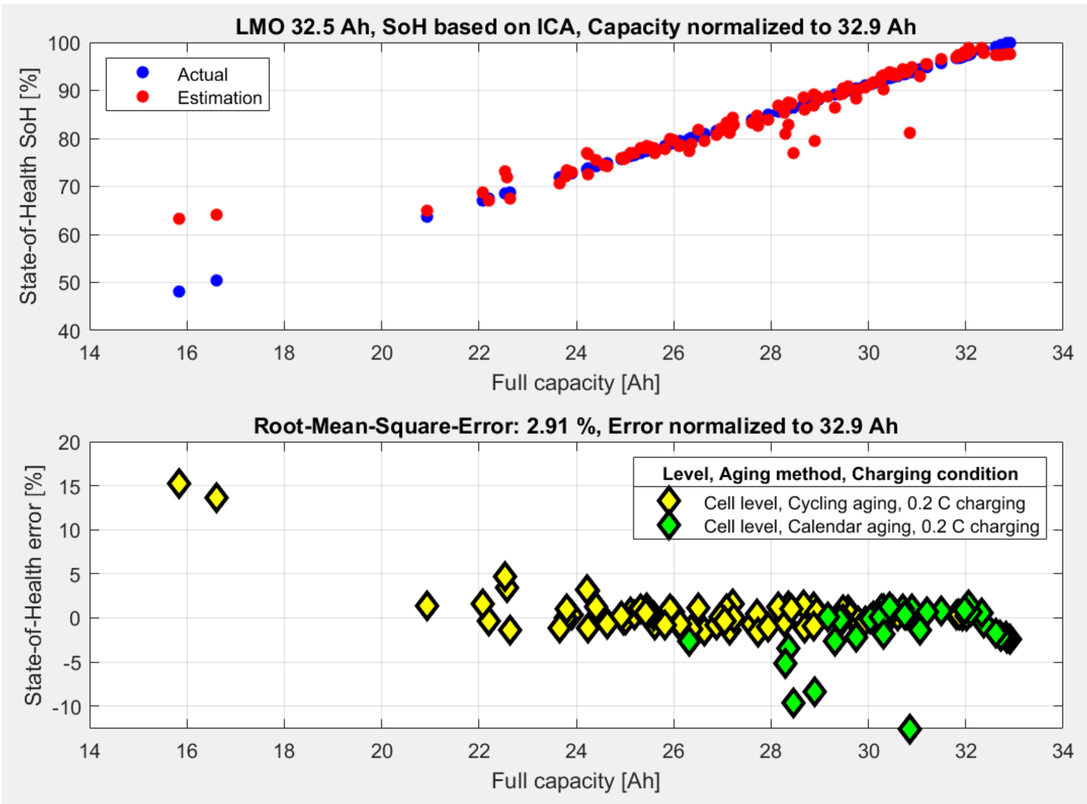


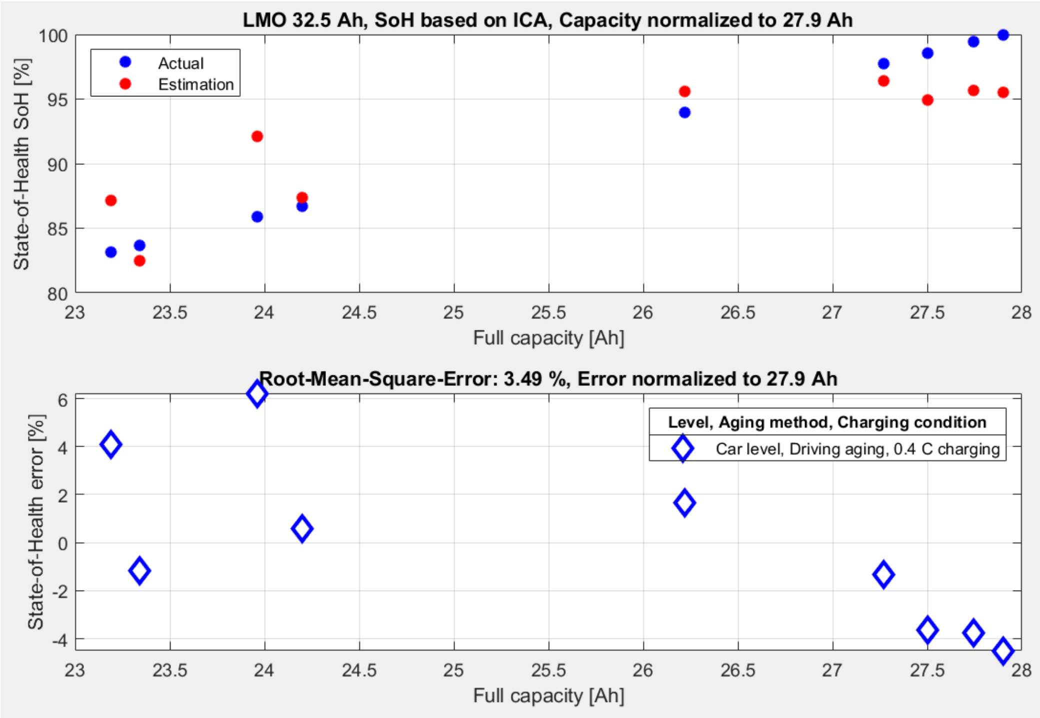
- *ICA* on **BMW i3 batteries**. The same data as above has also been analysed by the ICA method at both cell level and car level for the BMW i3 batteries. The error is below 10 % at both cell and car level. It is noticed that the RMSE at cell level is lower than half in comparison to the PCC method even though they both cover a wide SoH range. On car level the PCC method however indicates a slightly better performance.





- *ICA* on **Nissan batteries**. ICA method has also been applied on cell level and car level for the Nissan batteries. As for the BMW i3 cells, is the performance on cell level better for the ICA method than the PCC method. At car level there isn't any significant difference between the ICA and PCC method.





The PCC and ICA methods have been applied on cell and car level for both BMW i3 and Nissan cells. At cell level, the ICA method provided the lowest error between the estimation and actual SoH for both battery types. At car level, the PCC method shows slightly better performance than for the ICA method for our case. However, the SoH range of the car level data is quite low as it was difficult to find EVs for testing in Denmark. A wider data set on car level is therefore needed in order to assess the real performance of the two methods and to be able to compare with the cell level results. Also, some of the car level data was generated before the final 'BATNOSTIC-procedure' was developed. This could also affect the results. The PCC method is a trade-off between accuracy and speed. The wider voltage interval, the longer charging time. The ICA method has the potential to be faster as only selected peak and valleys needs to be included in the SoH estimation algorithm. This make the ICA method attractive. One of the biggest concerns in the beginning of the project was the influence of the aging condition on the SoH estimation algorithm. The results indicate, that the aging condition doesn't have any significant influence on the SoH estimation algorithm.

5.1.2 TI

WP2 - BATNOSTIC Database:

M4+M13: A relational SQL database was created to store and retrieve information easily for analysis purpose and recalculations on the measured data. The database contains data from both cell tests and vehicle tests. A full-automatic process has been composed to transfer data via a secure internet communication from the test-unit to the BATNOSTIC server at the very end of a vehicle test, where the automatic process continues data handling. Only consistent and valid data can be allowed into the database. In the first step the data is washed, meaning that the data is checked for format errors and valid range. If any errors cannot be corrected the measurement will not be allowed into the database but instead be referred to a manual expert check and process. In the second step the washed data is stored in the database with all necessary information regarding test-date, vehicle- and battery-information and test-unit specifications. In the third step the data is analysed with ICA and a number of different key-signature results are stored in a very consistent way to allow algorithmic analysis and machine learning routines to compare across large arrays of data. New vehicle data is compared to the existing key-signature data-array including key-signature data from comprehensive cell tests. Through different multidimensional analysis methods, the degradation of the battery is calculated. The automatic process ends in an automated voting process selecting the most likely assessment results for the report. A pdf-report with measured and analysed key results is created and sent automatically to the email address entered at the very beginning of a vehicle test. Semi-automatic procedures have been created to store data from further battery cell tests.

The multidimensional analysis used to calculate degradation consist of both algebraic regression and several machine learning models based on the measured EV data and battery cell test data in the database. The algorithms are then used to calculate the degradation of the EV battery. In the report, the degradation is stated as a label (A+, A, B or C) and a calculated uncertainty of the result. The lower the uncertainty, the better. If the uncertainty is too high, the label will automatically result with "C" indicating a new test or measurement must be fulfilled. An example of the generated report is in Annex 8.3.

WP3 - Stationary driving discharge test setup:
M1: An existing DTI dynamometer designed for torque and power versus speed curve measurement over few minutes was modified to load an EV with constant power independent of speed to discharge the battery on well-defined conditions. After tests it was concluded that assessment of battery capacity during rolling discharge on chassis dynamometer was too uncertain for reference analysis. For battery degradation measurement it is important to keep the battery current constant but in the real world it is difficult to manage battery current with a power setting on the dyno. Discharging an EV battery on the dynamometer just to drain energy works well but is time consuming and expensive in operator-hours. The possibility of using a robot driver (actuator operation of speeder and brake) was discussed but dismissed due to the need of massive safety measures that would impede other activities in the same lab. The size of the rollers on the chassis dyno also limit the constant power that can be discharged over longer periods since the tires heat up fast on smaller diameter rollers.
Alternatively, other discharge methods were investigated using the built in A/C system where the battery can be drained stationary until the EV shutdown itself due to completely drained battery. This method does require different methods to simulate a driver present in the vehicle so procedures with check-lists had to be developed for each vehicle type. A mix of the two discharge methods is used throughout the project, where the EV is drained to around 10% SOC at dynamometer or road, then the remaining energy to minimum SOC was drained stationary using the A/C. Operator-friendly discharge-procedures for the relevant EV types has been prepared ready for a product commercialization – these can be used as template for other EV models.

WP4 - BATNOSTIC seed data acquisition:
M6+M9+M11: To establish the SoH models in WP1 a necessary objective has been to degrade battery cells in controlled lab environments to achieve degradation behaviour. Battery cells of both LMO and NMC chemistries has been degraded through cycle- and calendar-aging with a mix of different parameters; Temperature (10°C, 25°C, 35°C & 45°C); Charge-rate (0.5C, 1.0C & 1.5C); State of Charge SOC (10%, 50% & 90%).
One of four test-matrixes with some of the significant results is shown below.

LMO battery cells – cycle test				
Temp.	**Charge-rate**	**Ekv. Cycle**	**Capacity fade**	**Ri rise**
10°C	0.5C	2007	26%	39%
10°C	1.0C	2009	30%	68%
10°C	1.5C	2213	35%	87%
25°C	1.5C	2817	31%	71%
45°C	1.5C	1409	86%	618%

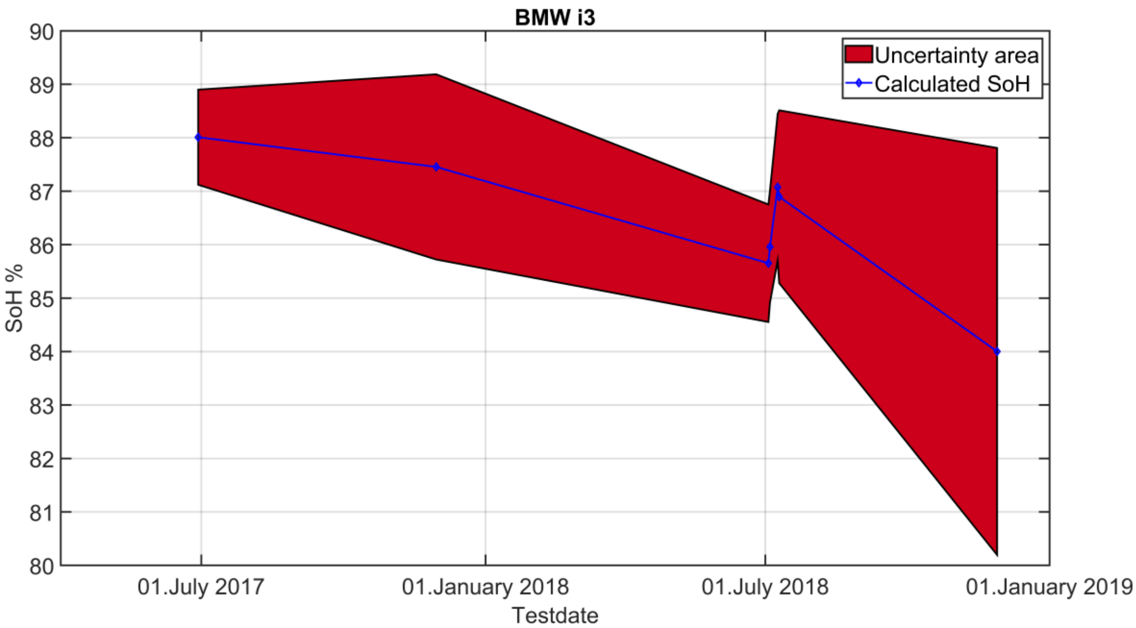
The cells have been degraded up to 86% capacity fade, with up to 3000 equivalent cycles and 400 days of ageing. Through the project, more than 250 Reference Performance Tests (RPT) has been completed to indicate and test the actual SoH during the aging. The RPTs measure both capacity and internal resistance (Ri) in several different ways, resulting in more than 750 capacity measurements and more than 1000 internal resistance measurements, whereas 500 capacity measurements has been uploaded to the BATNOSTIC database in WP2 and used as a base for SoH modelling in WP1.

Throughout the project, around 10 different EVs has been tested with the Alfa-Test unit and data seeded to the BATNOSTIC database. All in all, more than 200 vehicle-tests has been performed to adjust and assess the quality and repeatability of the Alfa-Test unit, the analysis method and the degradation calculation. Half of these EV test has been seeded to the database due to their good and reliable quality. Test-data has also provided the project with an important knowledge of EV battery test-behaviour in different circumstances during changing temperatures, charging C-rates, SOC level etc.

WP7 - Lab-tests and field demonstration:

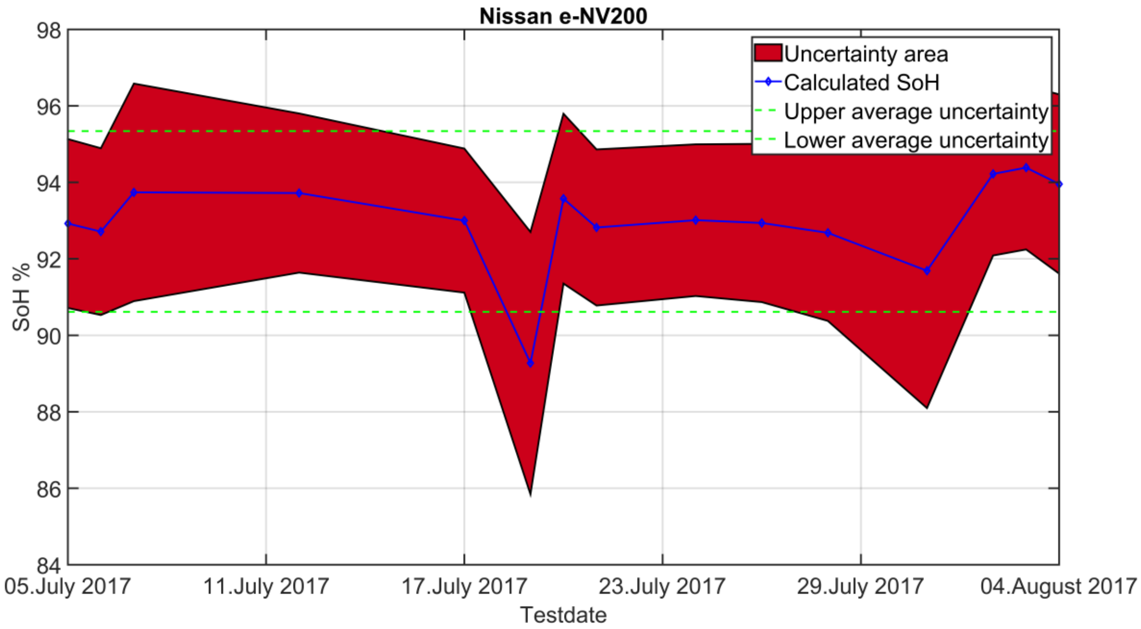
M15: The transportable Alfa-Test unit has at the end of the project been tested at workshops and companies outside lab-facilities. Five different EV models has been successfully tested hence proved the stability of the alfa-prototype. EVs tested during the project are Nissan e-NV200, Nissan Leaf (1st, 2nd & 3rd generation), BMW i3 and Peugeot Ion. A surprisingly problem which arose during the project, was to get access to EVs for test for a period from couple of days to weeks. Therefore, EVs has been rented from rental companies, or borrowed from companies, whenever it was possible. The EVs tested outside lab-facilities was owned by private members of FDM, found via social media. Due to this problem, only one EV has been tested multiple times during projects lifetime.

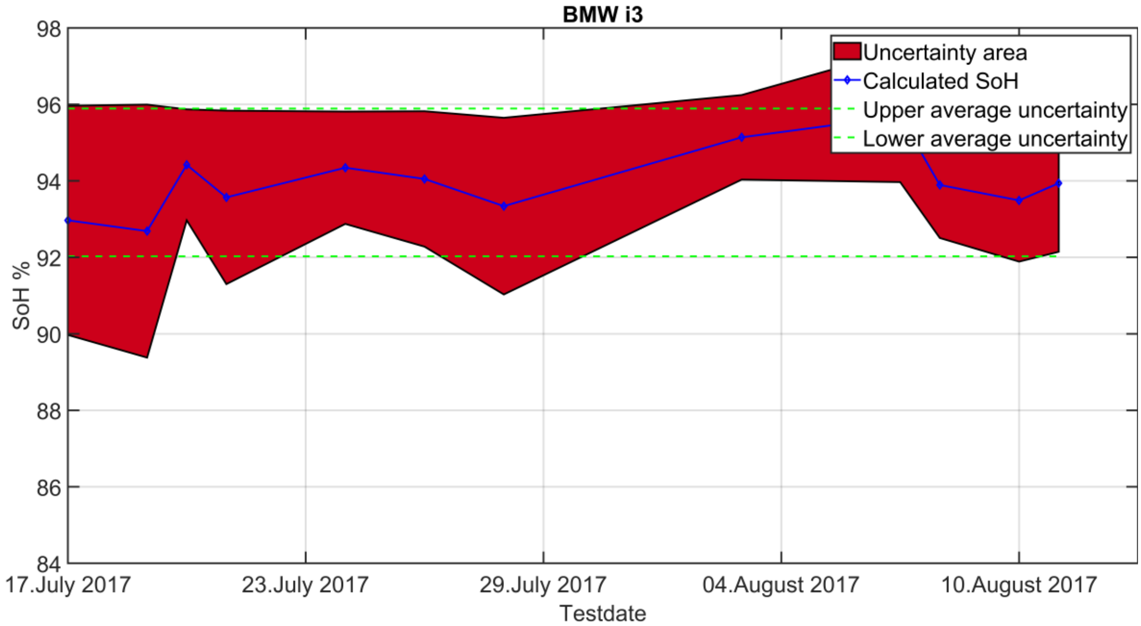
A specific BMW i3 has been tested at least 3 times during the project as a reference vehicle. The vehicle has driven 16605km from the first test to the third test and has a calculated degradation in SoH of 4 percentage-point from SoH = 88% to SoH = 84% as it is seen in the figure below.



The graph shows the tendency of degradation over time, but around July 2018, the repeated test, gets different results. To ensure repeatability and random spread of the analysis method, 2 different EVs (Nissan e-NV200 + another BMW i3) are tested multiple times over short time, where battery degradation is a minimum. The results shown below, indicates a high quality when it comes to repeatability. The calculated SoH fluctuates around 93 – 94 in the two graphs, and the calculated uncertainty is approximately ±3% for the e-NV200 and ±2% for the i3. Due to a resolution in the machine learning algorithms of 2%-point, these results must be accepted at this state of the project, with an expectation of smaller uncertainty area when the resolution gets finer.

The smaller fluctuations may be due to variations in battery temperature or SOC level at test-start. Further research is required to compensate for this.





5.1.3 LiBal

WP5 - BATNOSTIC Diagnostic components:

M2: Full-system EIS method was tested at AAU, but after testing the method on battery packs at AAU, the EIS method was deemed too risky compared to quality of results from completing method. Generation of pure sinus waves on batteries with voltages at or above 400 V require further research in power electronics design. Instead of EIS, DC current pulses where investigated on vehicle level, this method shoved promising results, as the designed and implemented equipment is fully capable of resolving the level of detail needed. Results from accelerated lifetime test on cell level, though, are inconclusive. Most of the data from cell level tests indicates little to no change in internal resistance over more than 1000 cycles. The final decision was to use another method recently highlighted in academic papers. The method is called ICA (incremental capacity analysis) and has previously been used to quantify ageing on cell level data. ICA requires capturing voltage and current at a high resolution and interval.

The diagnostic component was developed specifically for obtaining the relevant data and at the same time being able to control the test sequence using a fast charge unit. The developed component is also able to apply DC pulses for resistance estimation. Full control of the developed component is possible via a custom CAN protocol.

M5: Since ICA and DC pulses was chosen instead of EIS the milestone was modified to incorporate data using the component developed for M2. The component is providing high resolution voltage and current measurements for use by the ICA method and DC pulses. For more information on the ICA method, see section 5.1.1 WP1.

WP6 - BATNOSTIC Alfa-Test workshop equipment:
M7+M10+M14: The workshop equipment is based on two publicly available DC fast-charging standards: CHAdeMO and CCS2/Combo. This selection of fast-charge protocols covers a large group of available electric vehicles on the market in Denmark, the other two known fast-charge standards are 43kW AC (for the Renault Zoe), and Teslas proprietary standards. Tesla does provide an adapter to CHAdeMO, and it is believed that the adapter would work, but this project has not tried that method. For the workshop equipment a commercial DC charger for both CCS/Combo2 and CHAdeMO compliant EV connections was adapted with special software. The workshop equipment consists of the developed component described in WP5, the DC charger with special software, a set of measurement channels for auxiliary voltage and current, and an on-device tablet with secure access to the BATNOSTIC server.

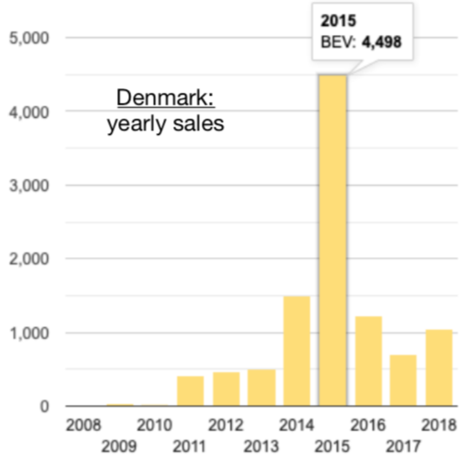
The workshop equipment has been demonstrated in various locations, including:

- Teknologisk Institut, Aarhus
- Lithium Balance A/S, Smørum
- FDM, Roskilde

All locations have provided high quality results and showcased the viability of the design. A set of requirements for non-prototype equipment has also been specified with input from all the project partners. Especially Applus and FDM has provided feedback on workshop requirements, based on their own experiences with various workshop equipment.

WP8 - Commercialization and dissemination:

C1: The market for electric cars in Denmark seemed great in 2014-2015 when the project started but rapidly stagnated in the years after. Now in 2018 it seems that the market is slowly growing again. In Norway the market has almost exploded, and there are more than 160.000 electric cars on the road (see figures below). That market is starting to shift towards a second-hand market as well, bringing the need for evaluating the performance and value of the battery. The BATNOSTIC workshop equipment is the only known alternative to data from the car manufacturers, and *the only* independent evaluation method for assessing the battery. The BATNOSTIC workshop equipment enables independent auto dealers and service providers, who otherwise could not get the same access to the market for servicing and reselling electric cars. Without the BATNOSTIC workshop equipment car manufacturers would effectively prohibit competition and potentially inflating service prices for electric cars.



Analysis of the BATNOSTIC workshop equipment and the accompanying method has been discussed with the Norwegian automotive federation (Norges Automobil-Forbund, NAF) and a Danish component and tool reseller, Christonik. Christonik wishes to expand their range of test equipment to workshops with a battery tester for electric cars. Lithium Balance A/S has in the BATNOSTIC project developed a new component that can control different DC fast charging systems to complement their range of commercial products for batteries and charging in electric vehicles. This controller is central to the new Christonik tester. They, as well as the project partners have provided market feedback for the price-point of the equipment and services. The final price-point that the larger market is willing to pay will be determined in a future project.

C2+C3: Dissemination have been made by AAU at a US conference and three new abstracts are submitted Dec. 2018 for EVER 2019 conference. The scientific content includes methods and findings from the collaborative research and development under this project. Further non-technical dissemination has been presented in DK media, including newspapers and social media (see annex for list). The BATNOSTIC concept has also been demonstrated for three consecutive years at a seminar on energy storage hosted by Teknologisk Institut.

6. Utilization of project results

6.1.1 FDM (Federation of Danish Motorists)

From a consumer perspective the BATNOSTIC project has shown high relevance. It has shown that it is possible to achieve useful information of the state of health of an EVs battery without having access to the CAN bus system of the car or the car manufactures data servers. The battery of an EV is the most important single factor when it comes to the value of the car. The degradation of the battery reduce the range and thereby the usefulness of the car. Combined with the fact that repair or replacement of the battery of an EV is very expensive, knowledge of the state of health of the battery is therefore of great importance for the consumer and the second-hand value chain. During the project FDM has spoken to many members who are reluctant to buy a second-hand EV or has experienced problems with the battery of their EV. Today it is only possible to have the battery checked at the car manufactures dealership and neither independent service providers or consumer organizations as FDM can give a second opinion on the battery state of health. This weaken the consumers' willingness to buy a new as well as a used EV since the second-hand price is very uncertain. All in all, this will slow down the conversion from ICE cars to EV's and thereby delay the greening of the transport sector. FDM has furthermore discussed the issues about getting access to battery data with our colleagues from other European consumer organizations for motorists and received great interest for the project. We will now share the results of the project with our colleagues. This will be done in meetings at the Federation Internationale de l´Automobile (FIA) in January 2019. In the beginning of 2019 FDM are planning to make an afternoon seminar about the project and the findings targeting the EV aftermarket representatives, car leasing companies and other relevant parties.
Further to this FDM will publish an article in the member magazine Motor (+435.000 readers) about the project and the results and we will also upload video from the testing on our website fdm.dk.

6.1.2 Applus

The purpose for Applus to participate in the project was a greener profile, which for a vehicle-controlled company is a big asset.
In addition, it has given Applus an insight into battery maintenance on the electric power plants, which can be used in dialogue with customers, who are just starting to come to the annual technical checks. It is therefore Applus intention to use that knowledge's experience gained through the project for commercial purposes.
The authorities have not yet imposed any requirements on what to check for the annual technical checks in relation to the power line of an electric car, and whether it is to be measured, for example, on the remaining service life of the power plant and disposal system (scrapping). It is Applus opinion that electric cars, are also more likely to fit into the Danish car market, so in the future there will also be a need for and be able to disclose the remaining life of an electric car's power plant when an electric car is purchased on second hand. The residual life of the power plant, will also be part of the "A+ Brugtbilstest" that we are performing in the future, and there are already questions about the residual life of these power plants on electric and hybrid cars from customers, so a tool that can measure on the power plant's condition, regardless of brand, being a big help.

6.1.3 AAU

The results and experience obtained in the BATNOSTIC project has expanded the knowledge of Aalborg University in terms of lifetime characterization and especially in terms of state-of-health estimation of lithium-ion batteries. The combination of laboratory and real-life tests has been very valuable with respect to transferring the theory into real-life applications. The project has strengthened the university's competences within lithium-ion batteries, and we believe that we will be a more attractive partner for other national or international research and development projects related the topics of the BATNOSTIC project.
The BATNOSTIC project has formed the basis of a long thesis (9^{th} and 10^{th} semester) project at AAU. The results are also expected to be included in the annual PhD/Industrial course of AAU on lithium-ion batteries. Furthermore, the results obtained during the project are presented in nine scientific publications (already published or under review).

6.1.4 TI

The results from BATNOSTIC will be utilized by Danish Technological Institute in several ways. The comprehensive research performed in the BATNOSTIC project supplements the current knowledge on electric vehicles and battery SoH estimation within the Danish Technological Institute. DTI will start offering commercial battery reference test on vehicle types that can be analysed with the current BATNOSTIC setup in DTI lab in Aarhus – the reference test at DTI will have a relative high price-level.

The BATNOSTIC methods adds new potentially powerful diagnostic tools to the specialist toolbox also highly interesting in relation to niche applications. The BATNOSTIC methods cannot be applied directly in niche applications but DTI will investigate and assess research needed test feasibility.

The complete remote data acquisition system developed for and verified in the BATNOSTIC project will be reused in other applications requiring field remote data acquisition. The data acquisition system includes a number of developed and proven steps: multi-channel data measurement front-end with high resolution; data format checking, compression; encrypted transmission over public network using cloud service to allow for asynchronous data handling; data acquisition from cloud; data check; storage; decompression and storage into SQL database; multidimensional diagnostic analysis including both machine learning and algebraic regression; voting and selecting best results; generating pdf-report.

DTI is very interested in supporting further development of the BATNOSTIC methods to accept a larger range of vehicle types and to better accommodate the daily routines and temperature conditions at normal workshops. To keep a high diagnostic accuracy on further vehicle types DTI is ready to test battery cells specifically for the BATNOSTIC reference-database and include in the diagnostic software. DTI has the test facilities and routines to test new battery chemistries at cell level and develop test procedures for new models and types of electric vehicles to include these in the BATNOSTIC diagnostic range of supported vehicles.

It will require a massive and focused research effort to develop new enhanced BATNOSTIC test methods that are less temperature dependent with both comprehensive tests at battery cell level and at vehicle level at a range of temperatures.

With the BATNOSTIC results, DTI has an enhanced platform for offering knowledge and test regarding battery-analysis – not only in electric vehicles – but also electrical busses, trucks, boats etc. and thereby help Danish SMVs to increase their market-potential – and maybe become world-leading - in a future with more and more electrical transportation.

6.1.5 LiBal

The methods used in the BATNOSTIC project is expected to be applicable in the battery management systems (BMS) developed by Lithium Balance A/S. The BATNOSTIC methods will be able to improve the diagnostics function of existing and new BMS platforms.

Lithium Balance A/S has also developed the central communication component which is expected to be part of the final product. Sales in the Nordic region would be through a Danish component and tool reseller, Christonik. While sales in the global markets could be handled by Lithium Balance A/S's international distributor network. The knowledge from this project is also used for additional fast-charge functionality components in the product pipeline at Lithium Balance A/S.

7. Project conclusion and perspective

The project is without any doubt a success and a ground-breaking new analysis method for independent parties like auto workshops or vehicle inspection workshops. The project partners have focused on several aspects and technologies, which at the beginning of the project all was at a Technological Readiness Level (TRL) 2-3. Throughout the project there has been researched and developed both new hardware, software and mathematical algorithms and composed a new-to-world product at TRL 5. A huge benefit of the final product is the complete automated process from pressing the start-button at the test-equipment to the final report arrives as an email. The process is very flexible and developed to easily test and add new algorithms, cell data or charger hardware, where the last mentioned is of huge importance if the product is about to reach a commercial market.

The feedback from workshop professionals have been positive but suggested further improvement in two areas that could be difficult for some workshops: keeping temperature constant at 20°C and reserving space for half a day. Since the market potential for BATNOSTIC test-equipment would increase with less temperature dependent test conditions and shorter test time, a new project has been formed to research a possible temperature compensation for real workshop environment and develop workshop test equipment. New partner Christonik, a Danish component and tool reseller which has been involved in the market analysis, wishes to expand their range of test equipment to workshops with a battery tester for electric cars, based on the BATNOSTIC method. Christonik is expected to allocate employees to develop and design and verify the new test equipment and to assign the needed effort for market analyses and marketing of the equipment in the Scandinavian region. They will also seek out sales channels through contacts across Europe and in China and participation in tradeshows in Frankfurt and Shanghai. Lithium Balance A/S has in the BATNOSTIC project developed a new component that can control DC fast charging systems to complement their range of commercial products for batteries and charging in electric vehicles. This controller is central to the new Christonik tester which fits perfectly into Christonik's already existing program of test equipment and the company's knowledge of "taking it to market". Applus, FDM and NAF will help test the equipment and communicate the results through e.g. FDM's participation in the international cooperation between motoring clubs, FIA as a member of ARC Europe (mobility providers).

A great collaboration between project partners has been a key indicator of the project. The technical group consisting of AAU, DTI and Lithium Balance A/S have held weekly skype-meetings during the project period and thereby pushed the innovation and progression forward with really good test-results as a reward.
Throughout the project period feedback from people that have been informed about the BATNOSTIC method agree that there are no known methods that enabling independent workshops to assess the condition of the EV battery without extensive road testing or by voiding the factory warranty on the car and battery.

The project partner FDM is pleased by the future opportunity for neutral test of EV batteries.
"We see BATNOSTIC as a ground-breaking project since independent workshops and vehicle inspection sites can get a tool to perform impartial test of the electric vehicle's battery. We can't necessarily trust the answers we get from the vehicle instrumentation nor the battery assessments from authorised dealers, so the importance of the project is therefore very high." says Torben Lund Kudsk, FDM.
There are no competing products on market. FDM hopes the project can find financing to bring a commercial product on the market within the next few years.

8. Annex

8.1 Links

8.1.1 FDM media

- https://fdm.dk/nyheder/bilist/2018-12-ingen-ved-med-sikkerhed-hvor-slidt-elbilens-batteri-er

8.1.2 EV sales numbers for WP8

- https://www.eafo.eu

8.1.3 Media for WP8

- https://www.teknologisk.dk/projekter/projekt-batnostic/39656
- https://ing.dk/artikel/danmark-paa-vej-med-verdens-foerste-batteritester-elbiler-190580
- https://fdm.dk/nyheder/bilist/2018-11-skal-vi-teste-din-elbils-batteri
- https://stateofgreen.com/en/partners/state-of-green/news/denmark-develops-the-worlds-first-battery-tester-for-electric-cars/

8.2 Disseminations from the project

8.2.1 Conferences:

- Kalogiannis, T; Stroe, D-I; Nyborg, J; Nørregaard, K; Christensen, AE & Schaltz, E 2017, 'Incremental Capacity Analysis of a Lithium-ion Battery Pack for Different Charging Rates' 231st ECS Meeting, New Orleans, LA, United States, 28/05/2017 - 01/06/2017 (poster presentation)
- Stroe, D-I; Knap, V & Schaltz, E 2018, 'State-of-Health Estimation of Lithium-Ion Batteries based on Partial Charging Voltage Profiles' 233rd ECS Meeting, Seattle, WA, United States, 13/05/2018 - 17/05/2018 (poster presentation)
- Stroe, D-I & Schaltz, E 2018, SOH Estimation of LMO/NMC-based Electric Vehicle Lithium-Ion Batteries Using the Incremental Capacity Analysis Technique. in Proceedings of the 2018 IEEE Energy Conversion Congress and Exposition (ECCE). IEEE Press, pp. 2720-2725, IEEE Energy Conversion Congress & Exposition ECCE 2018, Portland, United States, 23/09/2018.

8.2.2 Journals (published):

- Kalogiannis, T; Stroe, D-I; Nyborg, J; Nørregaard, K; Christensen, AE & Schaltz, E 2017, 'Incremental Capacity Analysis of a Lithium-Ion Battery Pack for Different Charging Rates' ECS Transactions, vol. 77, no. 11, pp. 403-412. https://doi.org/10.1149/07711.0403ecst
- Stroe, D-I; Knap, V & Schaltz, E 2018, 'State-of-Health Estimation of Lithium-Ion Batteries based on Partial Charging Voltage Profiles' ECS Transactions, vol. 85, no. 13, pp. 379-386. https://doi.org/10.1149/08513.0379ecst

8.2.3 Journals (under review):

- Stroe, D-I & Schaltz, E, "Lithium-Ion Battery State-of-Health Estimation Using the Incremental Capacity Analysis Technique," IEEE Transactions on Industry Applications (submitted December 2018)

8.2.4 Conference papers (under review)

- Schaltz, E; Stenhøj, L; Nørregaard, K; Christensen, AE; Stroe, D-I, "Incremental Capacity Analysis for Electric Vehicle Battery SoH Estimation," EVER 2019
- Schaltz, E; Nørregaard, K; Johnsen, B; Christensen, AE; Stroe, D-I, "Partial Charging Method for Lithium-Ion Battery SoH Estimation," EVER 2019
- Galiatsatos, AG; Schaltz, E, Stroe, D-I, "Calendar Aging Lifetime Model for NMC-based Lithium-ion Batteries Based on EIS Measurements," EVER 2019

8.2.5 *Presentations without paper*

- Danish Battery Society annual symposium 2017 "Assessing EV battery pack conditions with BATNOSTIC" on March 6th 2017.
- PowerPoint presentation at 4th UNI-SET Energy Clustering Event: "Development of a diagnostic tool for battery state-of-health estimation for electric vehicles" by Erik Schaltz, on March 28th 2017, Imperial College London
- Conference presentation and demo-setup ”Avanceret Energilagring 2017” d. 30/11, 2017, ”Batnostic”
- PowerPoint presentation. Temaaften om batterier hos Miljøstyrelsen: "Levetidsvurdering af batterier til elektrisk køretøjer - et adaptivt batteridiagnostisk værktøj" by Erik Schaltz, on May 9th 2017, Miljøstyrelsen, Copenhagen
- PowerPoint presentation at BG-04 members meeting: "Presentation of the BATNOSTIC-project" by Erik Schaltz, on August 30th 2018, RTX, Nørresundby
- PowerPoint presentation at IDA Arr. 326854 ” Energiteknologisk udviklings- og demonstrationsprogram (EUDP)” on September 18th 2018: ” SafeBESS og BATNOSTIC”. This meeting was setup in cooperation with Energiforum Danmark and DI Energi
- PowerPoint presentation at IDA Energi Arr. 327135: ”Opfølgning på energilagring – forskning og løsninger til at lagre sol og vind” on September 26th 2018: "Battery Energy Storage and Batnostic"
- PowerPoint presentation and demo-setup at ”Avanceret Energilagring 2018” on November 29th 2018. ”BATNOSTIC”

8.3 Example of test report from vehicle test (next page)

BATNOSTIC

Adaptive battery diagnostic tools for lifetime assessment of EV batteries

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BATNOSTIC Report

Vehicle Information

Vehicle-Model: BMW i3 Vehicle-ODO: 44330

Vehicle-VIN: WBY1Z21050VX63881 Test-Date: 28-11-2018

Measured values

Start of test: SoC [%]: 00,0 Battery temperature: 18,0

End of test: SoC [%]: 100,0 Battery temperature: 23,0

Energy charged during test: 17,28 kWh

Calculated 100% Charge capacity[1] kr. 17,28 kWh

Estimated battery data of electric vehicle Li-ion battery

Internal resistance[2] Ri1short: 0,38 Ri2short: 0,00 Ri1long: 0,48 Ri2long: 0,56 Ω

[1] The Charge capacity is typically 10 % higher than available Discharge capacity for the actual battery chemistry. Discharge capacity is the energy actually available for driving.

[2] Internal resistance in the range of 0.2 to 0.4 mohm are usual. If a larger resistance is measured, it could indicate a slightly degraded connection – in such case further diagnosis recommended.

eUDP Energiteknologisk udvikling og demonstration

BATNOSTIC projektet er støttet af programmet for Energiteknologisk udvikling og demonstration

BATNOSTIC

Adaptive battery diagnostic tools for lifetime assessment of EV batteries

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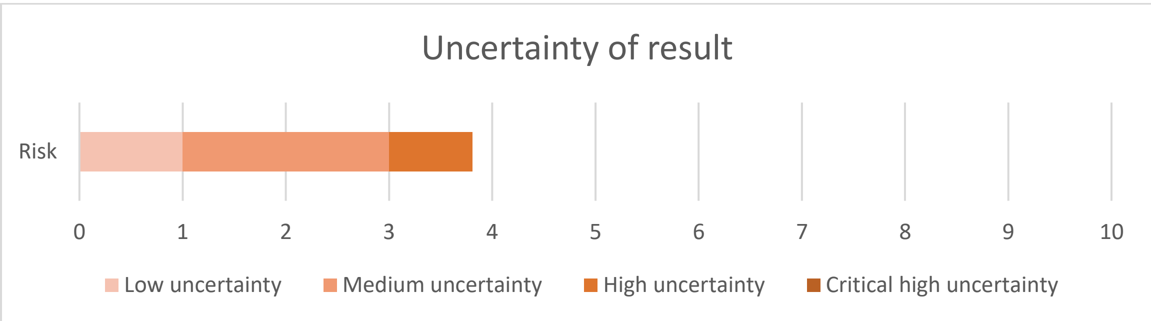
State of Health estimation[3]:



Report Version: R4.1M2.0S4.2D12-12-2018

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[3] Description of State of Health estimation: "A+" is a battery with more than 90% original capacity left. "A" is a battery with 90% - 80% original capacity left. "B" is a battery with less than 80% original capacity left. "C" indicates an unreliable result due a too high uncertainty.

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BATNOSTIC projektet er støttet af programmet for Energiteknologisk udvikling og demonstration