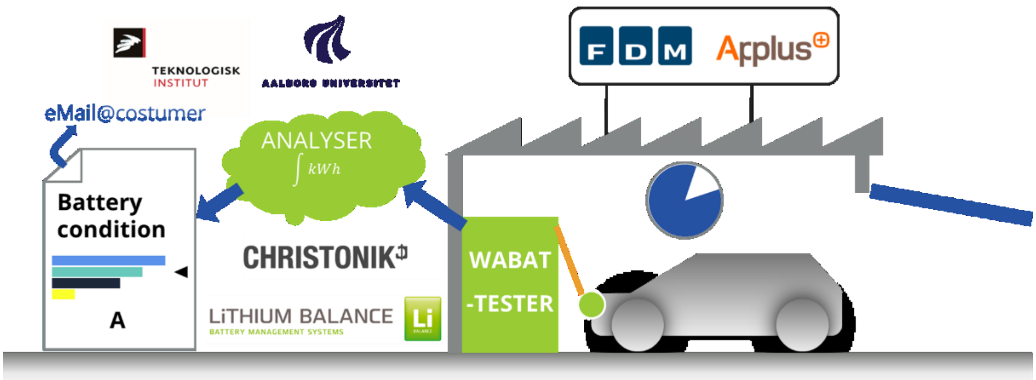
Final report

1. Project details

Project title	EUDP 2019-I WABAT - “Workshop Automated BAttery Tester"
File no.	64019-0056
Name of the funding scheme	Energiteknologisk Udviklings- og Demonstrations Program (EUDP), Teknologiområde: Systemintegration
Project managing company / institution	Lithium Balance A/S, Hassellunden 13, 2765 Smørum
CVR number (central business register)	29 39 11 30
Project partners	Teknologisk Institut, CVR-nr. 56 97 61 16 Aalborg Universitet, Institut for Energiteknik, CVR-nr. 29 10 23 84 Christonik ApS, CVR.nr. 19 75 42 43 FDM (Forenede Danske Motorejere), CVR.nr. 10 37 67 18 Applus Danmark A/S, CVR.nr. 28 31 27 25
Submission date	23 April 2024

WABAT EV-battery diagnosis



2. Summary

WABAT – Workshop Automated BAttery Tester.

2.1 Summary (English)

The WABAT-project has successfully resulted in a Workshop Automated BAttery Tester for battery diagnosis on electrical vehicles (EV) ready for commercialisation with a new temperature tolerant diagnostic algorithm and with test methods suited for EV-workshops. The diagnosis is performed through the DC-charge plug on the EV and is based on an enhanced version of the unique method from the Batnostic EUDP-project (EUDP no. 64015-0611). It seems currently to be the only independent battery assessment method based on actual test where other battery tests are based on data obtained through the car producer.

A healthy second-hand EV market is essential to reach the full transition for electric transportation as requested by the government. Customers must have trust in the electric vehicle technology and also the used second-hand vehicles. The potential buyer of a second-hand EV wants to know that a used car is worth its price in terms of remaining life and operational range. The project has developed new innovative products that contribute to a trustworthy second-hand EV market and the product are ready for market commercialisation. The project has included extensive research and experimental investigation into vehicle batteries, DC-charge control and Vehicle-to-grid (V2G) technologies, that may spinoff knowledge into future national Smart-Grid aspects.

The four main activities of the project have been:

1. A temperature compensated diagnostic algorithm for battery assessment researched from extensive battery measurements at cell and vehicle level.
2. A method to cost effective drain energy from electric vehicles prior to WABAT test researched with focus on Vehicle2X technology.
3. A new digital control unit produced by Lithium Balance has been adapted to serve as frontend in the WABAT test boxes for CHAdeMO and CCS including ability to manage V2G operation.
4. Combining all the above with previous Batnostic knowledge into a new workshop test box to go between a DC fast charger and DC-fast charge connector on an EV. Demonstrated with different EVs and chargers in lab and field test.

All partners have electric car-related activities. Beside the two knowledge institutions, two SME-partners sell components and services to the automotive sector. Two project partners have car inspection activities and represent different customer groups and markets: FDM represents some 30 million of international (incl. Danish) consumers through FIA and has also presented WABAT to UNECE working groups. Applus+ also represents global focus, working with cars in 11 countries. The customer representatives confirm an increasing need for new diagnostic tools for the workshops as electric cars begin to displace conventional cars. The customer-representatives has actively participated in field testing and evaluation of equipment and confirm the relevance of such an independent test product in the market.

The market potential for the WABAT testing equipment is considered to be very large. It is assessed that there are more than 80 million second-hand sales per year in Europe alone so just a small share needing test will require lots of test equipment.

The project was finished to the scheduled 3 years in spite of numerous unforeseen issues including covid-19. The project has moved the current knowledge and research in battery temperature and V2X technologies from TRL 2 to TRL 5/6, and the hardware development of Lithium Balance's control unit and Christonik's WABAT test equipment from TRL 4-5 to 8.

2.2 Summary (Danish)

WABAT-projektet har med succes resulteret i en workshop automatiseret BAttery Tester til batteridiagnose på elektriske køretøjer (EV) klar til kommercialisering med en ny temperaturtolerant diagnostisk algoritme og med testmetoder, der passer til elbil værksteder. Diagnosen udføres via DC-ladestikket på elbilen og er baseret på en forbedret version af den unikke metode fra Batnostic EUDP-projektet (EUDP nr. 64015-0611). Denne ser i øjeblikket ud til at være den eneste uafhængige batterivurderingsmetode baseret på faktisk test, hvor andre batteritest er baseret på data indhentet via bilproducenten.

Et sundt brugtvognsmarked for elbiler er afgørende for at nå den fulde overgang til elektrisk transport som ønsket af regeringen. Kunderne skal have tillid til elbilteknologien og brugte elbiler. Den potentielle køber af en brugt elbil ønsker at vide, at bilen og batteriet er prisen værd med hensyn til restlevetid og driftsrækkevidde. Projektet har udviklet nye innovative produkter, der bidrager til et troværdigt brugt EV-marked, og produktet er klar til markedskommercialisering. Projektet har udført omfattende forskning og eksperimentelle undersøgelser af køretøjsbatterier, DC-opladningskontrol og Vehicle-to-grid (V2G) teknologier, der kan give viden videre til fremtidige nationale Smart-Grid aktiviteter.

Projektets fire hovedaktiviteter har været:

1. En temperaturkompenseret diagnostisk algoritme til batterivurdering undersøgt ud fra omfattende batterimålinger på celle- og køretøjsniveau.
2. En metode til omkostningseffektiv dræning af energi fra elektriske køretøjer forud for WABAT-test med fokus på Vehicle2X-teknologi.
3. En ny digital styreenhed produceret af Lithium Balance er blevet tilpasset så den kan fungere som frontend i WABAT-testboksene til CHAdeMO og CCS, herunder evne til at styre V2G-drift.
4. Kombination af alt det ovenstående med tidligere Batnostic-viden i en ny værkstedstestboks der indsættes mellem en DC-hurtigoplader og DC-hurtigopladningsstik på en EV. Demonstreret med forskellige elbiler og opladere i laboratorie- og felttest.

Alle partnere har elbilrelaterede aktiviteter. Ved siden af de to vidensinstitutioner sælger to SMV-partnere komponenter og tjenester til bilindustrien. To projektpartnere har bilsynsaktiviteter og repræsenterer forskellige kundegrupper og markeder: FDM repræsenterer omkring 30 millioner internationale (inkl. danske) forbrugere gennem FIA og har også præsenteret WABAT for UNECE-arbejdsgrupper. Applus+ repræsenterer også globalt fokus og arbejder med biler i 11 lande. Kunderepræsentanterne bekræfter et stigende behov for nye diagnostiske værktøjer til værkstederne, da elbiler begynder at fortrænge konventionelle biler. Kunderepræsentanterne har deltaget aktivt i feltprøvning og evaluering af udstyr og bekræfter relevansen af et sådant uafhængigt testprodukt på markedet.

Markedspotentialet for WABAT-testudstyret anses for at være meget stort. Det vurderes, at mere end 80 millioner brugte biler sælges om året alene i Europa, så er der en lille andel, der har brug for test, vil det kræve mange testudstyr.

Projektet blev afsluttet indenfor de planlagte 3 år på trods af mange uforudsete problemer, herunder covid-19. Projektet har flyttet den nuværende viden og forskning inden for batteritemperatur og V2X-teknologier fra TRL 2 til TRL 5/6, og hardwareudviklingen af Lithium Balances styreenhed og Christoniks WABAT testudstyr fra TRL 4-5 til 8.

3. Project objectives

3.1 Project objectives

Building on the highly successive Batnostic project (EUDP no. 64015-0611) this project has worked within 4 areas:

1. Research by Aalborg University (AAU) and Danish Technological Institute (DTI) for a temperature compensated algorithm on battery capacity measurement based on extensive battery measurements at cell and vehicle level.
2. A method to cost effective drain energy from electric vehicles prior to WABAT test researched with main focus on Vehicle2X technology was successful for CHAdeMO but CCS fast charge system does not yet allow V2G.
3. A new digital control unit produced by Lithium Balance has been adapted to serve as frontend in the WABAT test boxes for CHAdeMO and CCS including ability to manage V2G operation.
4. Combining all the above with previous Batnostic knowledge into a new workshop test box to go between a DC fast charger and DC-fast charge connector on an EV.

Climate goals or a reduced fossil fuel dependence or emission restrictions in towns or new superior electric technology or maybe just competitive cost are all drivers for the global transition towards electrification of transportation. Denmark has set a goal of 1 million green vehicles (electric, plug-in hybrid and hydrogen vehicles) ~40% of the fleet in 2030. The last years increase in EV sale suggests that the ambitious number may be reached by pure battery EVs alone. But a couple of serious incidents or a public perception of poor EV resale prices can slow down or even stop EV-sales again. The 2030-target requires a sound market for used EVs (Electric Vehicles). For each new car registered in Denmark 2,5 cars are re-registered to a new owner (second hand cars). In average each car has 3.5 owners and the complete fleet age is 8.4 years. The price of an used EV depends primarily on the price-level for new EVs and the capacity and condition of the battery. Car workshops have no equipment for physically testing the battery capacity and condition. The only information available on EV-batteries via diagnostic testers are today the information the OEM provide. In reality all new electric cars are already fully connected to the OEM's dataserver. Currently most OEMs allow (or tolerate) access to battery data. FDM warns that OEM in the future may start restricting third party access to battery data.

The main goal of this project has been to design, construct and test an electric car workshop feasible WABAT battery test equipment. Battery performance and capacity measurement is extremely sensitive to temperature. The WABAT project has improved the test method to allow for vehicle test in a much wider temperature range +17,5°C to 30°C. Previous method required constant temperature for 11 to 12 hours. To measure the available capacity, the EV battery is drained to the minimal SoC (State of Charge) the vehicle allows before the special Batnostic fast charge is initiated.

The market potential for both the WABAT testing equipment, the V2X/DC-charge control unit and the Batnostic server operation is considered to be very large. Isolated, WABAT support from the automobile clubs ADAC, ÔAMTC, TCS, ANWB, NAF and FDM represent close to 30 million members which can be an important stepping stone for deployment of the WABAT concept on the European market. There are 260.000.000 cars in Europe now and all markets expect to become fossil free before 2050. More than 10% of the fleet may be electric within 10 years. In average cars are 8 years old and sold as used 2.5 times. If just 5% of the used sales use an independent battery assessment the European market is more than 400.000 battery tests per year. This will require > 4000 WABAT units within 10 years assuming less than 100 tests per year per WABAT unit in average.

WABAT equipment are one of the tools that can build more trust in second hand electrical cars and therefore contribute to more transparent and trust-worthy second-hand markets. In this way WABAT are also important for the energy system and it is expected that the advanced knowledge researched in the WABAT project will enable spin-of technology for battery condition testing in niche applications like e.g. busses and forklifts.

3.2 Energy technology developed and demonstrated

The WABAT-project relates to the System integration and storage strategy, having a huge focus in developing measurement methods for EVs and batteries, for the benefit of multiple Danish actors. It is supporting the sector coupling between electric energy and transportation, by enabling better transparency of battery health creating more confidence in second-hand battery vehicles and indirectly encouraging better use of the of electric batteries.

The degradation of a Li-Ion battery is caused by many different parameters like e.g. different driving behaviour, charge-conditions, climate conditions etc. in combination with efficiency of thermal management and BMS. It is not sufficient to use the distance driven as an indicator of the battery health condition. With the EVs battery charge being used as grid flexibility or even being used as energy storage facilities via a future Vehicle to Grid context, the EVs may be as much a measure for the grid as a challenge for increasing renewable energy share in the electric grid. The WABAT diagnostic-unit can provide credible assessment of extra wear on batteries due to e.g. grid-services.

The WABAT project address a very important issue for the EV owners and potential second-hand buyers: The health condition of the battery. The battery aging due to driving is already an issue for second hand buyer. However, if the battery is used as part of a Smart Grid during parking with energy fluctuating in and out, then the battery lifetime will be further reduced. The distance driven by an EV can be an indicator of the battery capacity but not necessarily the battery health condition. By developing a tool, which can reduce the uncertainty, the WABAT project provides a contribution to a higher penetration of highly energy efficient EVs in the transportation system thus supporting the Energy Efficiency strategy.

3.2.1 Technology developed – hardware and software.

The WABAT project used the facilities and competencies of the partners to build test hardware and develop an algorithm based on new research. The temperature dependence of batteries is a major challenge when working with batteries and have hence been a main topic for the research. DTI even established a lab with temperature-controlled garage specifically for reference testing EVs in the WABAT-project. An example of the developed WABAT test-equipment can be seen Figure 1 under lab-measurements on an electric car in well-defined temperature conditions. The WABAT test equipment is used between the EV and the DC-charger.

Figure 1 Temperature controlled garage for EV-test established at DTI specifically for performing WABAT EV test under consistent conditions. The tall cabinet at the end of the garage is a CHAdeMO V2G charger 10kW on temporary loan from NUVVE. The vehicle in the garage is a Nissan Leaf 62kWh, that has been tested at regular intervals throughout the project period. In the right picture the WABAT CHAdeMO box is used for test.

Two test equipment have been built by Christonik for different DC-charge standards: The CHAdeMO box is slightly simpler since the charger communication is CAN-bus based; The box for CCS is more complex due to the use of Power Line Communication (PLC) for charge control. Like the WABAT CHAdeMO box, the WABAT CCS box consist of the same principal layout with contactors, PSU, frontend and gateway, but two specialized CCS frontends is added. See Figure 2 for reference.

The WABAT frontend measures the charge voltage and current, auxiliary car battery voltage and current, and temperatures. The measurements are sent to the gateway using a CAN bus. The frontend board is produced by Lithium Balance. The WABAT frontend PCB is based on a new BMS system but adapted especially for the WABAT project in both hardware and software.

The purpose of the two CCS-frontends is to translate the high-level CCS PLC-communication to another format compatible with the WABAT frontend and gateway. They are connected to the car and charger, respectively, and the software of each board is different to reflect the connection.

The gateway receives the measurement from the WABAT frontend and controls the manipulation of charge current if applicable. The collected data is sent to a central database via WiFi-connection to the internet.

The gateway is produced by DTI and handles the test cycle and communication-link to a cloud based data analysis and user interface It receives charging parameters from a GUI website and sends the measured voltages, currents, and relevant charge information to the database and website. During the charge it also manipulates the charge current to achieve the desired charge pattern. An SD-card is used for storing for the measured values locally as a backup. This means the WABAT gateway can function without internet after a charge has been started.

Detailed information on the interoperability of the different hardware and software parts are not described here due to the commercialization process at Christonik.

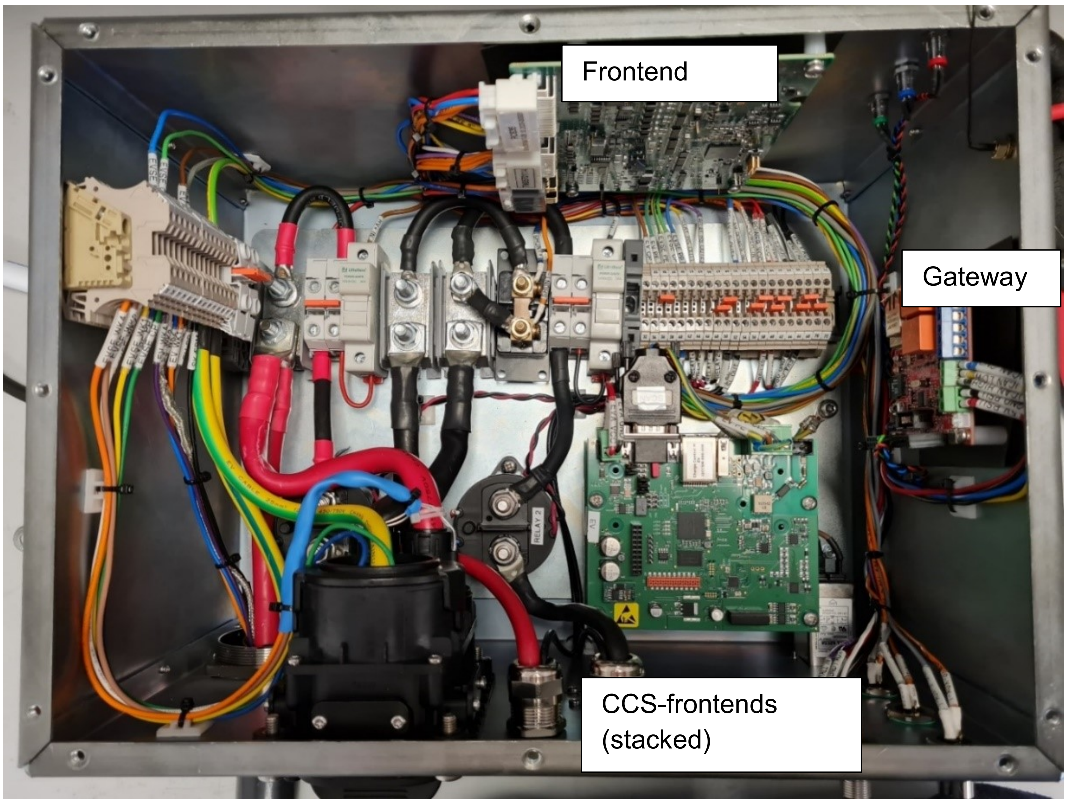


Figure 2 WABAT CCS Box opened without protective covers. The routing of the heavy cable dimensions gives practical handling constraints and high voltage constrains cable and components placement.

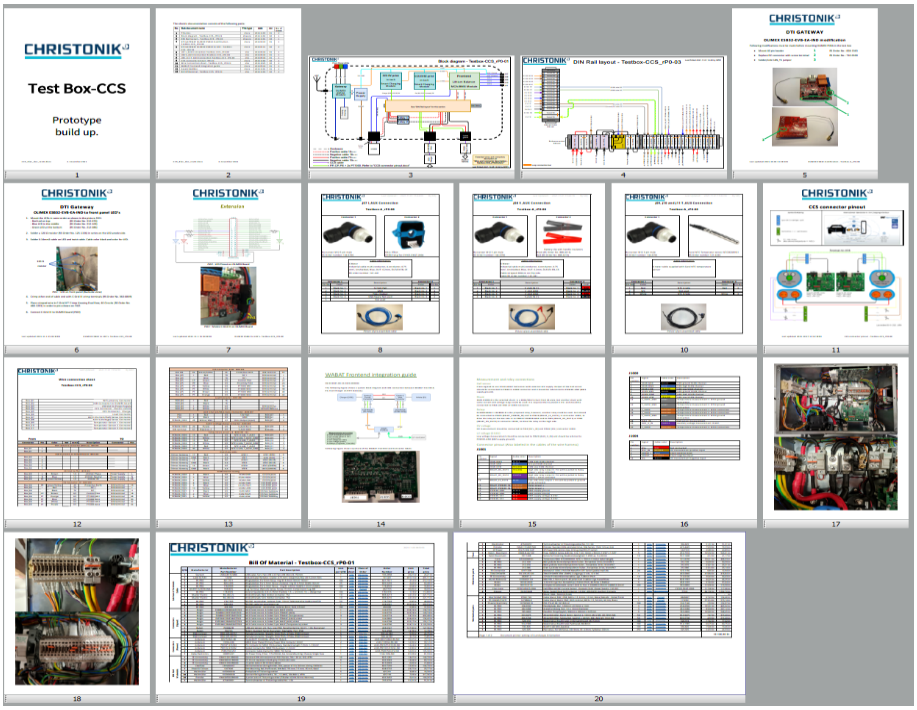


Figure 3 Illustration of Parts-list and assembly documentation for CCS box

3.2.2 Technology developed – Research and diagnostic algorithm.

Please see 5.2 for detailed information om research activities and other related activities.

4. Project implementation

4.1 How did the project evolve?

Though the output of the WABAT project is quite successful with a battery-tester ready for commercialization, the execution of the project has not evolved quite as expected in most of the workpackages. In WP0 – project management – the first months required a lot of meeting activities to discuss and agree on the cooperation agreement between all partners. In the project aiming for a final output at a rather high TRL, ensuring all rights and interests of all partners had strong focus. The time and work spent in the beginning has proven beneficial towards the end of the project, where the management of Christonik, AAU and DTI have negotiated an agreement for commercialisation of the WABAT results.

The number of unforeseen issues that needed to be handled to keep the project on track has been extreme - some of the experienced issues and unforeseen mitigating plan-changes are listed below:

1. The EV-types defined as preferred targets due to foreseen market potential after project end was VW ID., Tesla and new Nissan Leaf (for back-wards reference to BATNOSTIC-project data). But…
    - 1.1. The new VW ID.x kept being delayed and information regarding battery cell types were unreliable and cells were unavailable for test.
    - 1.2. TESLA battery cells only available through import of reclaimed battery packs from damages vehicles – without history of use. After surveying several internet fora for rumours and speculation on cell chemistry used by TESLA, commercially available Panasonic cells believed to be fairly similar to resent Tesla EV-battery types was purchased on the internet by AAU.
    - 1.3. Nissan do not sell the battery cells used in their vehicles, but battery modules intended for stationary storage was believed to be identical to the Leaf chemistry.
        - 1.3.1. First two modules received (each module with 8 cells) turned out to be from different batches and in different mechanical modules – those were returned.
        - 1.3.2. Second couple of modules turned out to have nearly 10% less capacity than expected – there were speculation that the modules might have been stored at elevated temperatures at some stage.
        - 1.3.3. A third couple of modules were ordered and received and the capacity turned out to be only slightly better and still lower than expected. AAU and DTI discussed the issues at some length. Extra multiple tests at both DTI and AAU was setup on several battery-cells to ensure that the capacity loss was not caused by handling or methods after receiving the cells. Some cells were tested at both locations to verify consistency. The extra tests were only indirectly useful for the project results, as it was essential to establish credibility for the tests to be conducted in the project before starting. Eventually it was agreed to start the cell testing with the available cells avoid further delays in the project.
2. Testing of battery cells was delayed and took more time due to
    - 2.1. AAU test labs were completely sealed off for several weeks due to Covid-19 close-down. After limited access to labs was granted again, there were no lab-technicians available to help – many were sent home for extended periods.
    - 2.2. DTI lab work was slightly delayed due to covid-close-down.
    - 2.3. DTI cell test equipment broke down and could not receive service due to on-going covid travel restrictions. DTI attempted temporary in-house repairs to get test going again.
    - 2.4. Cell test time were longer than anticipated due to academic request for data to a deeper end of life capacity
3. Many months into the project, market analysis made Christonik realise that the test equipment should not be part of a DC-charger as planned but rather be a separate test box that can be fitted between an existing charger and any EV. This changed the design-task from mechanical adaptation of a DC-charger with some

communication components to design of an electronic measurements and control box to handle 60 A at 400 to 800 V-DC and charge interface.

3.1. Christonik did not initially have the knowledge in-house to develop and produce the electric parts of the test equipment. They had to depend heavily on support from Lithium Balance and DTI for a long period. A year before project finish, Christonik recruited an electronics and software design engineer with main focus on WABAT, so they are now fully qualified to drive the development on after project finish.

3.2. Lithium Balance investigated possibilities and found, that they had a product suitable to be adapted for measuring frontend in the testbox but needed to find new staff to work on hardware modification, CCS- protocol and new SW build for the frontend. Finding and training qualified staff for such specialist areas takes many months.

4. Any battery testing is very temperature sensitive, so EV testing must take place in temperature-controlled environment. DTI had planned to build a mobile temperature controlled garage but realised that the equipment needed to control temperature was to bulky and complex for a trailer-solution. Instead, a stationary temperature-controlled garage was installed, dedicated to WABAT EV-testing.
5. V2G technology for discharging vehicles was not implemented.

5.1. VW claimed that the ID. would have V2G capability, but the function was not yet released by project finish in 2022. Even though V2G has been demonstrated on prototype vehicles, no commercially sold CCS vehicles has allowed or claimed ability to do V2G. The commercial risk of experimenting with V2G on CCS vehicles has been assessed too high for the project.

5.2. V2G with CHAdeMO was possible.

5.2.1. A V2G DC-charger was kindly on a free loan from NUVVE, but the charger failed frequently due to an internal hardware issue and eventually NUVVE gave up and scrapped the unit.

5.2.2. Testing V2G discharge was then being tested with the WABAT CHAdeMO testbox until the DTI lab-equipment serving as load short circuited due to a semiconductor failure – this failure caused the battery fuse in the rented Nissan Leaf to fail – the car had to be towed to a Nissan repair shop for repair under insurance. (Practical V2G testing stopped after this event).

6. Lack of V2G discharge function meant that discharging of EVs to near empty before WABAT test had to be done by driving (very labour intensive) or discharge by the HVAC in the vehicle, which can easily take more than a day. This meant that any testing (e.g. consecutive testing on the same vehicle at different temperatures) takes days and require more manual handling than anticipated and planned for.
7. Building of WABAT testboxes was delayed by shortages in the supply lines – due to covid-19, blocked Suez-channel and a heated components market not only delaying semiconductors but all kind of materials.

7.1. The CHAdeMO testbox prototype was built first and the few unavailable parts could in most cases be substituted by other similar on-stock components. It did cost a few hours research.

7.2. The CCS-testbox prototype awaited initial testing of CHAdeMO prototype, so the build started a couple of months later. The component supply situation had deteriorated in the meantime and many parts on the partslist had suddenly many month leadtime and had to be substituted to other parts apparently available within reasonable time. Several parts needed to be substituted more than once. The CCS testbox prototype was ready for testing nearly half a year later than planned.

7.3. Due to the huge delay of hardware components for the WABAT CCS tester, the fieldtest periods in WP5 was reduced from 2 to 1 fieldtest in the end of the project. The one fieldtest was highly efficient and demonstrated that the WABAT tester was able to perform the test-charge on 14 different EV's from 2 different DC-chargers. Feasibility of the CCS testbox was also tested on a 300kW fastcharger from Siemens and a VW ID.4 – it worked most times but with some random stability issues – will require a targeted engineering effort for a commercial product.

8. The CCS-hardware specialist stopped working with Lithium Balance a year before the end of the project and before finishing the CCS interface for the WABAT CCS testbox.

8.1. It would take Lithium Balance several months to find a new HW-engineer and then building the needed special knowledge for the CCS charge protocol again. To avoid too much delay in the project, DTI had to take over the finishing of the control software for the CSS testbox.
8.2. Even though the CCS protocol hardware were expected to be close to ready when DTI took over, it turned out that a major redesign of the control setup and a few CCS interface driver-updates were needed together with a new unforeseen software structure in the gateway, to handle the complex CCS-handshake.
9. Organisational changes during the project
9.1. The first WABAT project manager left Lithium Balance halfway through the project due to a takeover. The next Project manager left Lithium Balance a year later, and Lithium Balance had severe problems finding a suitable person willing to take over the formal WABAT project manager role until the project end.
9.1.1. DTI has kept the coordination going within the project throughout most of the project and thus mitigated periods without active project management from lithium Balance.
9.1.2. The Lithium Balance project financial management has suffered from the lack of project management – payments of support to partners has been delayed significantly.
9.2. There have been some budget adjustments in the projects
9.2.1. As AAU got the chance to assign a PhD student to WABAT project after project start, so their budget was adjusted to accommodate this within the original budget.
9.2.2. Travel has been restricted and the way the test equipment has been implemented has required less expenses which has been converted to hours for the SME-partners and the knowledge institutions.
9.2.3. Lithium Balance got some of budget from Christonik to help develop CCS-interface.
9.2.4. To mitigate foreseen delay DTI received budget from Christonik and Lithium balance to help finish CCS-interface implementation

4.2 Risks associated with conducting the project.

Three major technical risks were identified prior to the start of the project and to different degree all risks have been recognised and addressed in the project together with organisational, covid-19 and supply challenges:

Risk 1: Competing product is launched either from OEM or third-part companies. A certified EV-battery test is offered to the public by WABAT partner FDM just prior to closing of the project: FDM has shared information on their prior research for a feasible battery test with the WABAT project – The test method is based on OBD-dongle access to OEM information in the vehicle, and can therefore not be considered a fully independent test, and can only be used if the OEM provide access to battery data. FDM still supports development of a truly independent test method.

Risk 2: Temperature compensating battery capacity measurement is inaccurate. It has turned out to be very difficult to assess the temperature inside the EV-battery from the outside of the vehicle. The reference temperature readings for tested EVs had significant deviations as the charging heated up the battery. Extra temperature testing on different vehicles has been conducted in an attempt to establish a relation between external measured and internal measured temperatures. To mitigate uncertain external temperature reading extra vehicle testing at +17.5°C was added late in the project. Combined with the detailed cell testing it has fortunately been possible to develop algorithms suitable for temperatures between +17.5°C and 30°C

Risk 3: Vehicle-2-X method will not allow a complete drain of the battery. V2G has been a difficult challenge. No V2G-protocol has been released for CCS before the end of the project. Even though V2G has been demonstrated on prototype vehicles, no commercially sold CCS vehicles has allowed or claimed ability to do

V2G in accordance with an available standard. The commercial risk of experimenting with V2G on CCS vehicles has been assessed too high for the project. Some testing has been performed on CHAdeMO until the DTI lab-equipment serving as load short circuited due to a semiconductor failure – this failure caused the battery fuse in the rented Nissan Leaf to fail. The practical V2G research was halted after this event due to cost-risk issue but it was seen that V2G in some vehicles can discharge down to approx. 30%, after which either driving or HVAC must be used to discharge to below 10% SoC.

4.3 Actual project implementation vs. foreseen

The list of unforeseen issues in section 4.1 speaks for itself. Keeping the project fairly on-track throughout so many adjustments has required focus which has been possible only via frequent virtual coordination meetings. There have been very few physical meetings in the project period due to covid-19 restrictions. For most of the project period AAU and DTI have had virtual status-follow up meetings. For periods with intense development there has been weekly or bi-weekly virtual status meetings with DTI, Lithium Balance and Christonik also.

The project duration was kept within 3 years as planned. Apart from dissemination of the results, business analysis and commercialization are not part of the project and has taken place outside the project budget.

4.4 Experienced challenges not expected

The knowledge institutions have more than fully used their assigned hours in the project to mitigate unforeseen challenges. Substantial extra testing has been needed at both cell and vehicle level. First issue was acquiring relevant battery-cells. The project planned for battery cells matching VW ID., Tesla and new Nissan Leaf. VW battery cells couldn’t be found. Commercially available Panasonic cells believed to be similar to resent Tesla EV-battery types and some Nissan battery modules intended for stationary storage but believed to be identical to the Leaf chemistry.

5. Project results

5.1 Original main objectives of the project were obtained

The project has developed new innovative products that contribute to a trustworthy second-hand EV market and the product are ready for market commercialisation. The results of the project will be integrated in a new commercial product to be introduced to the automotive marked in Denmark and Scandinavia within a year from project finish.

The project has included extensive research and experimental investigation into vehicle batteries, DC-charge control, and Vehicle-to-grid (V2G) technologies, to enable a product that can be used to diagnose an EV battery health in most workshop environments and that may likely spinoff knowledge into future national Smart-Grid aspects.

The four main activities of the project, have been:

1. A temperature compensated diagnostic algorithm for battery assessment researched from extensive battery measurements at cell and vehicle level.
2. A method to cost effective drain energy from electric vehicles prior to WABAT test researched with focus on Vehicle2X technology.
3. A new digital control unit produced by Lithium Balance has been adapted to serve as frontend in the WABAT test boxes for CHAdeMO and CCS including ability to manage V2G operation.
4. Combining all the above with previous Batnostic knowledge into a new workshop test box to go between a DC fast charger and DC-fast charge connector on an EV. Demonstrated with different EVs and chargers in lab and field test.

All the activities have been concluded successfully. The V2G draining of battery power on CCS could not be completed as planned because the automotive industry delayed release of CCS-vehicles with the feature enabled. Draining the battery sufficiently before testing is essential to measure the specific signatures of the battery-health. To mitigate the hourly cost of discharging the battery by driving, other less operator-intensive methods were developed for lab-testing.

The project was finished within the scheduled 3 years in spite of numerous unforeseen issues including covid-19.

The current knowledge and research in battery temperature and V2X technologies within AAU and DTI has been elevated from TRL 2 to TRL 5/6. The hardware development of Lithium Balance's control unit and Christonik's WABAT test equipment elevated the from TRL 4-5 to 8.

5.2 Obtained technological results.

5.2.1 Obtained research results

To develop state-of-health (SoH) algorithms for the WABAT-tool, laboratory tests have been carried out on several lithium-ion battery cells. The chosen cells are of NMC (Nickel-Manganese-Cobalt) and NCA (Nickel-Cobalt-Aluminium) types. The NMC-cell are of the same type as of the Nissan Leaf (62 kWh) electric vehicle. Thereby, results obtained at the cell level can be compared to results obtained at the car level. The NCA-type was chosen as this chemistry also are used in Tesla electric vehicles. It should be noted that the selected NCA is not the exact same type as used in Tesla electric vehicles. The specification of the cells can be seen in Table 1.

Battery type	**NMC**	**NCA**
Nominal capacity, Q_{nom}	57.5 Ah	4.0 Ah
Maximum charging voltage	4.2 V	4.2 V
Minimum discharge voltage	2.6 V	2.5 V
Cut-off charging current	2.875 A (C/20)	0.08 A (C/50)
Discharge rate	0.3 C	2 C
Charge rate	1 C	0.5 C
Temperature	25ºC	25ºC

Table 1: Battery cell specifications.

Cell aging

The NMC and NCA battery cells have been exposed to calendar aging (in AAU lab) and cycle aging (at DTI lab) to generate data for SoH modelling. The conditions of the cells during the aging tests can be seen in Table 2 and Table 3.

Temperature\SOC	**10 %**	**50 %**	**90 %**
5ºC			x
25ºC			x
35ºC	x	x	x
45ºC		x	x

Table 2: Test matrix for calendar aging.

Temperature\Charge rate	**0.5 C**	**1.0 C**	**1.5 C**
10ºC	X		
25ºC	X X		
35ºC	X X		

Table 3: Test matrix cycle aging.

Cell Reference Performance Tests

To monitor the evolution of the capacity degradation, reference performance tests (RPTs) were performed on a regular basis for each of the cells. The conditions of the RPTs can be seen in Table 4.

Temperature\Charge rate	**0.2 C**	**0.5 C**	**0.87 C**
10ºC	X	X	X
25ºC	X	X	X
35ºC	X	X	X

Table 4: Battery cell conditions applied for reference performance tests.

Cell degradation results

The degradation evolution of the cells has been monitored at the RPT conditions as stated above. In Figure 4, the relative remaining capacity is shown for the 25ºC\0.2 C condition. It is noticed that the remaining capacity becomes smaller due to storage time and number of cycles. It is also noticed that a high storage temperature and high storage state-of-charge level result in faster degradation as expected. Remarkable, the cells have a huge capacity drop after a certain number of cycles. This is especially seen for the NMC cells.

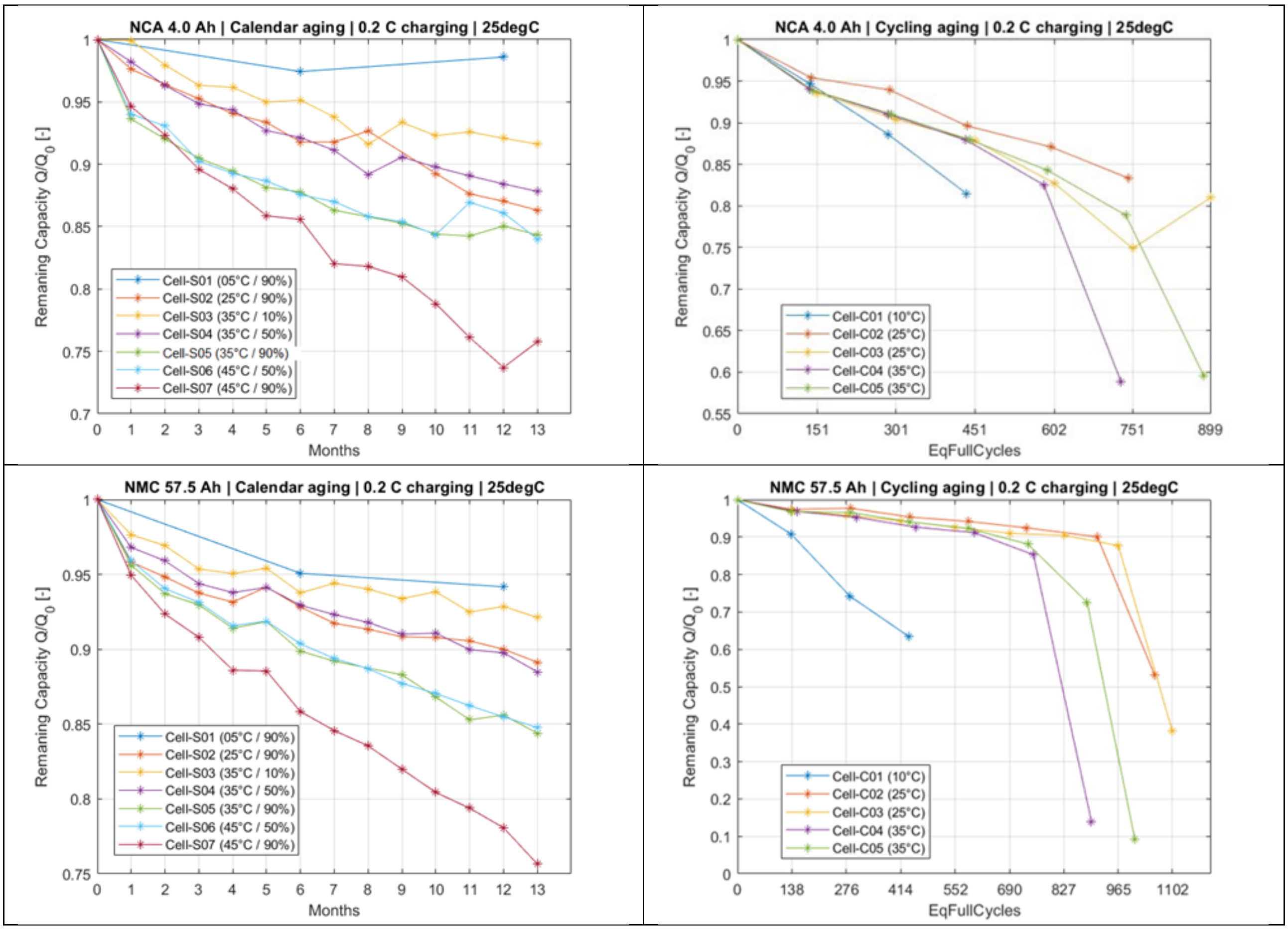


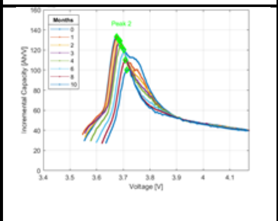
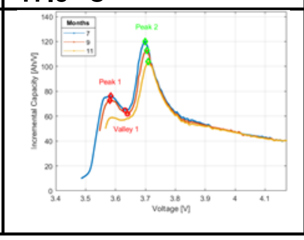
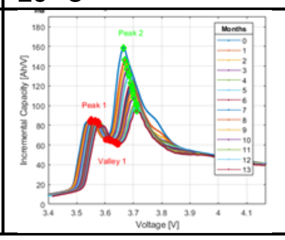
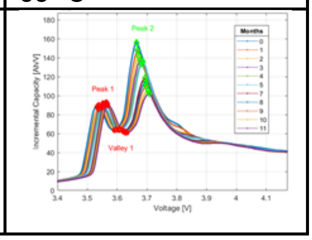
Figure 4 Relative remaining capacity of NCA (top) and NMC (bottom) battery cells exposed to calendar aging (left) and cycle aging (right) at different temperatures and state-of-charge levels.

Cell Incremental Capacity Analysis

The method for state-of-health estimation is based on the incremental capacity (ICA) technique. The incremental capacity (IC) value is calculated as the derivative of the capacity with respect to the voltage, i.e.

$$IC = \frac{dq}{dv}\left[\frac{Ah}{V}\right]$$

The IC curves for a single cell exposed to calendar aging are seen in Figure 5. The IC curves consist of several peaks and valleys. Peak 2 (highlighted with green markers) turn out to be the feature point which shows the most robust trend regarding the aging of the cells, and this has therefore been chosen as the main input parameter of the SoH modelling and estimation.

	10 °C	17.5 °C	25 °C	35 °C
0.2 C				

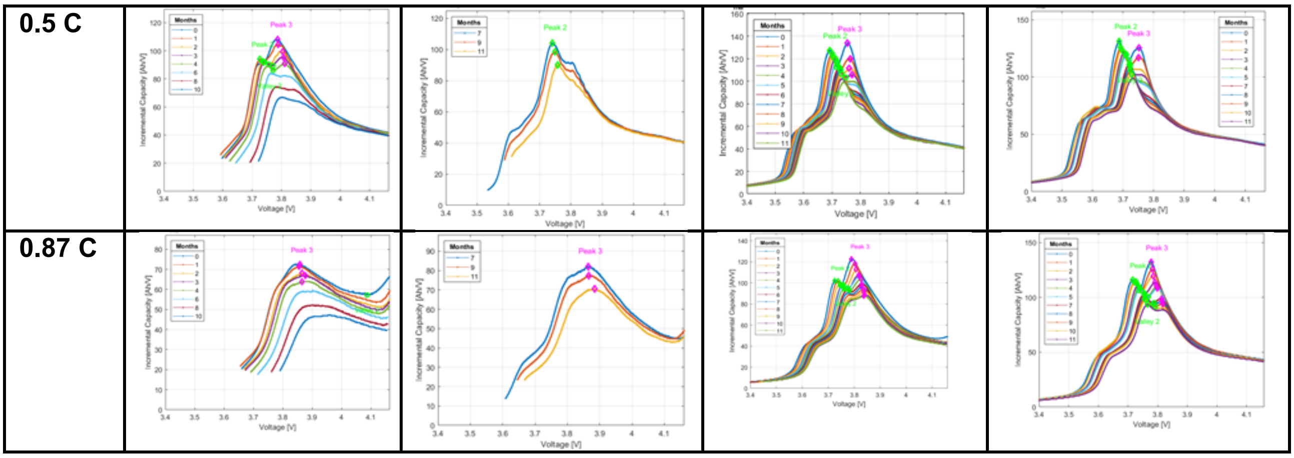


Figure 5 Incremental capacity of a cell exposed to calendar aging (45ºC \ 90 % SOC) applied at different C-rates and temperatures.

Vehicle Incremental Capacity Analysis

Test of two Nissan Leaf (62 kWh) electric vehicles has also been performed as these vehicles have similar battery type as used for cell testing. The IC values of these two vehicles can be seen in Figure 6 and Figure 7. The results are scaled to cell level to be able to compare with the cell aging results. It is noticed that the curves have similar behaviour as for cell level.

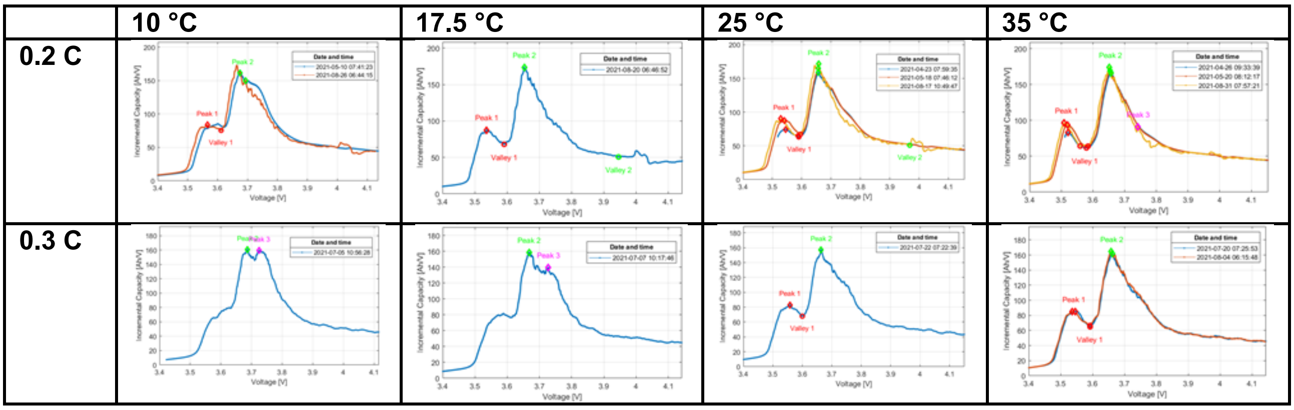


Figure 6 Vehicle 1: Incremental capacity analysis of Nissan Leaf (62 kWh) electric vehicle applied at different C-rates and temperatures.

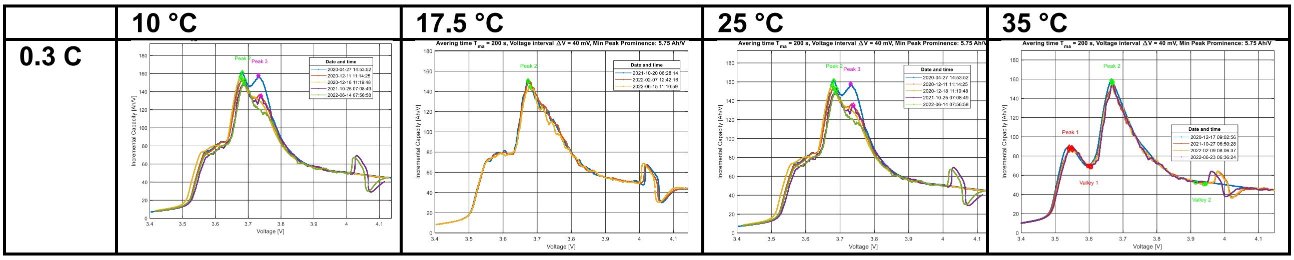


Figure 7 Vehicle 2: Incremental capacity analysis of Nissan Leaf (62 kWh) electric vehicle applied at different C-rates and temperatures.

The Vehicle 2 Nissan Leaf has been tested over the longest duration for approx. two years, i.e., April 2020 until June 2022. Some battery degradation is therefore expected. Unlike in the laboratory, the minimum and maximum vehicle battery voltage levels cannot be external controlled as the car determines this. Therefore, to be able to compare the capacity evolution at cell and car level, a window capacity has been defined. The window capacity is simply the charged ampere-hour throughput between a chosen low voltage level and high voltage level, i.e. $q_{window} = q(V_{low}{:}V_{high})$.

In Figure 8, the full charging capacity and energy are shown for the Vehicle 2's battery being completely drained. The window capacity and milage are shown as well. The first measurement is done after approx. 2200 km and the last measurement after approx. 48200 km. It is noticed that the vehicle experiences a capacity fade of approx. 8 % during the test period, i.e., 4 % per year or 1.7% per 10 tkm.

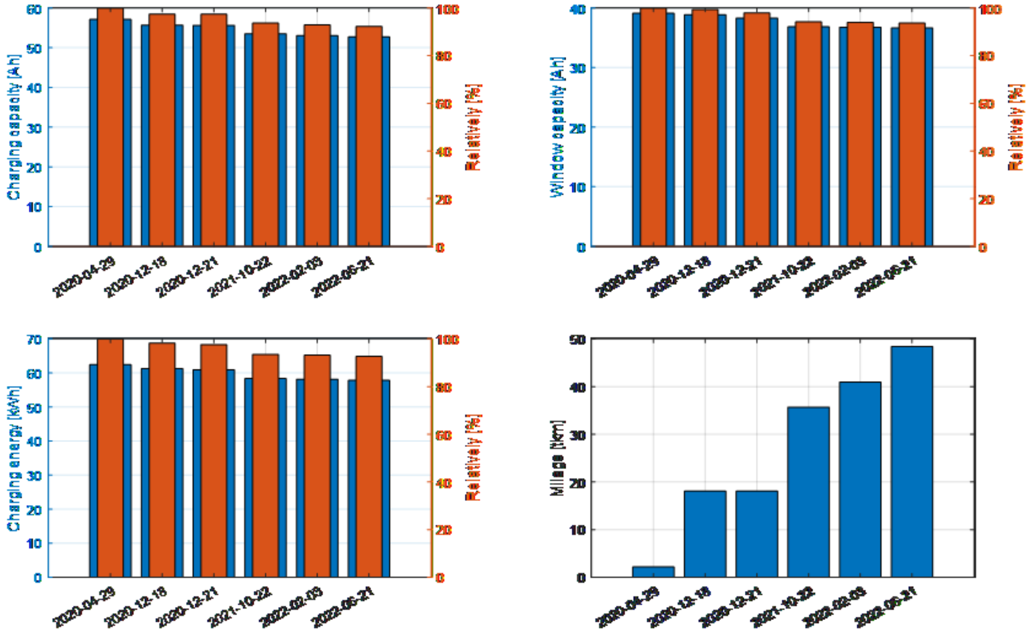


Figure 8 Evolution of basic performance indicators for the Vehicle 2 Nissan Leaf (62 kWh) car. The charging is performed at 25◦C at 0.3C rate from a completely drained battery.

State-of-health modelling

In Figure 9the window capacity is shown as a function of the IC values of Peak 2 for different temperatures. It is seen that a linear relationship exists. The figures include both data from calendar and cycle aging at cell level and vehicle level. Some of the results at car level (driving aging) is however performed at 0.3 C. Therefore, some deviation from the trend line is seen.

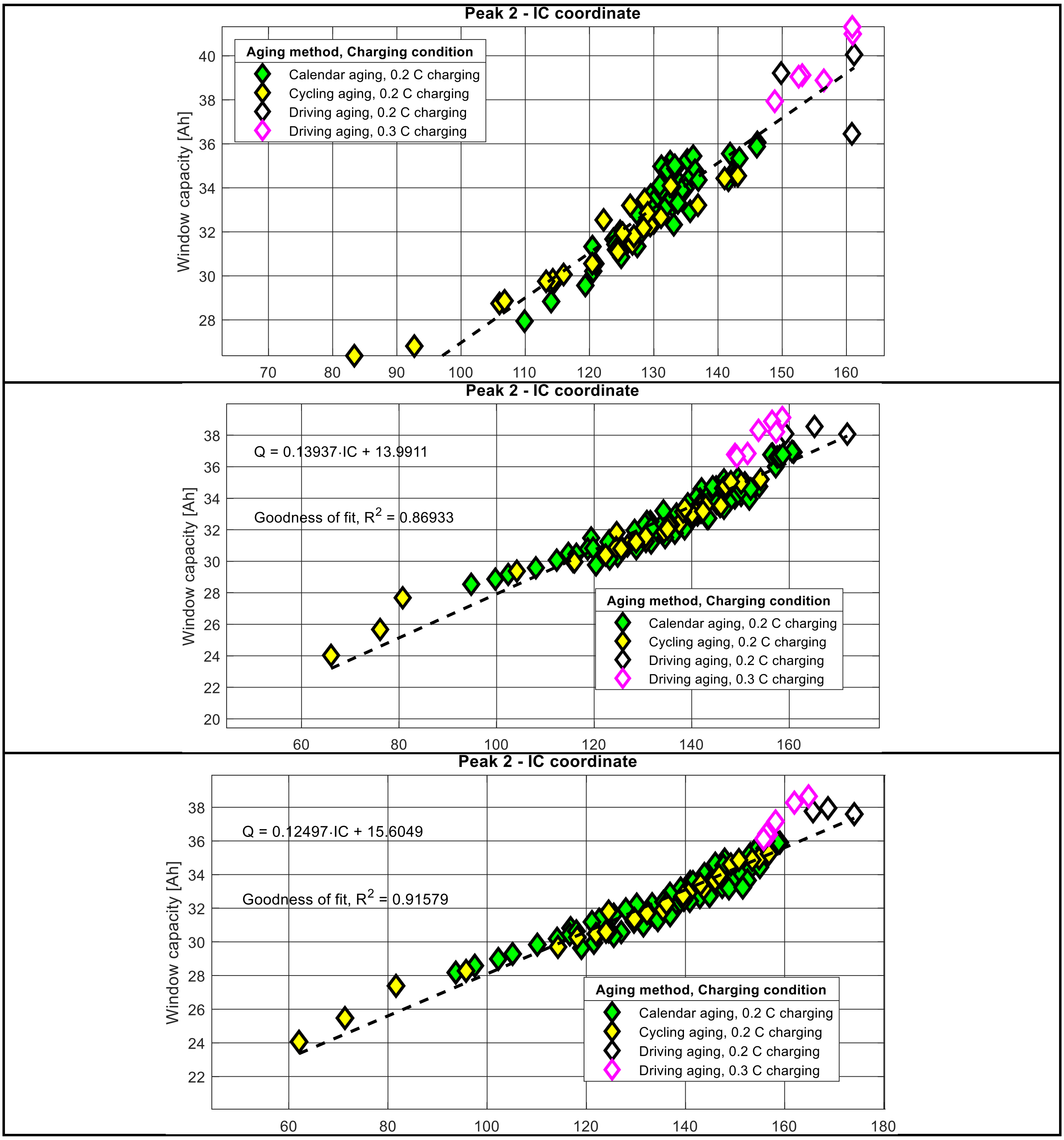
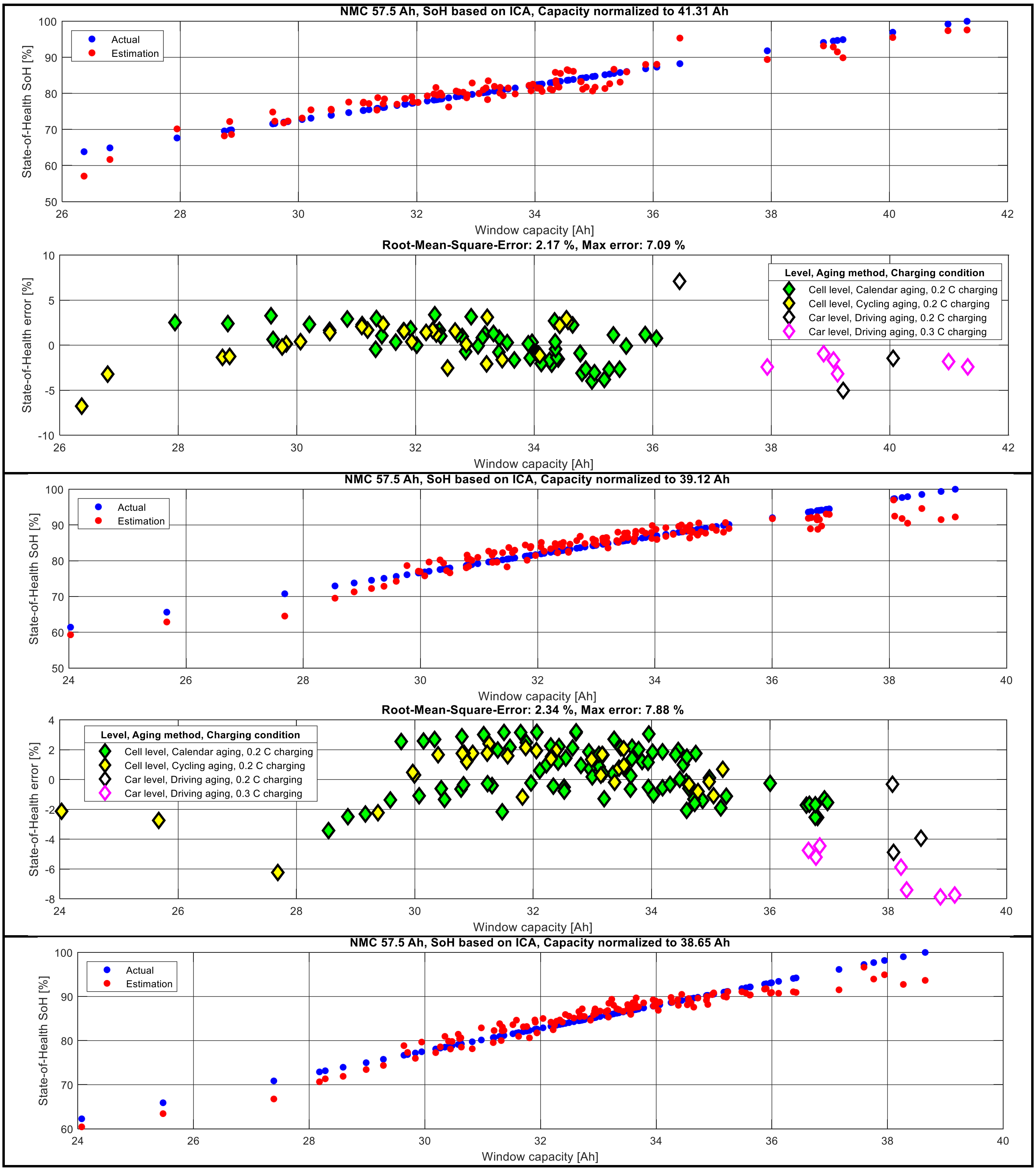


Figure 9 Capacity modelling for 0.2C charging at 10ºC (top), 25ºC (middle), and 35ºC (bottom).

State-of-health estimation

The window capacity (and thereby the state-of-health) can be estimated from the IC value of Peak 2 by a simple 1st order polynomial as shown in Figure 9. In Figure 10 the results of the SoH estimation for three different temperatures can be seen. The root-mean-square-error (RMSE) and maximum errors are provided as well. The RMSE are in general low for all three temperatures, but the maximum error can be as high as almost 8 % for a few cases.


NMC 57.5 Ah, SoH based on ICA, Capacity normalized to 41.31 Ah
State-of-Health SoH [%]
Actual
Estimation
Window capacity [Ah]
Root-Mean-Square-Error: 2.17 %, Max error: 7.09 %
State-of-Health error [%]
Level, Aging method, Charging condition
Cell level, Calendar aging, 0.2 C charging
Cell level, Cycling aging, 0.2 C charging
Car level, Driving aging, 0.2 C charging
Car level, Driving aging, 0.3 C charging
Window capacity [Ah]
NMC 57.5 Ah, SoH based on ICA, Capacity normalized to 39.12 Ah
State-of-Health SoH [%]
Actual
Estimation
Window capacity [Ah]
Root-Mean-Square-Error: 2.34 %, Max error: 7.88 %
State-of-Health error [%]
Level, Aging method, Charging condition
Cell level, Calendar aging, 0.2 C charging
Cell level, Cycling aging, 0.2 C charging
Car level, Driving aging, 0.2 C charging
Car level, Driving aging, 0.3 C charging
Window capacity [Ah]
NMC 57.5 Ah, SoH based on ICA, Capacity normalized to 38.65 Ah
State-of-Health SoH [%]
Actual
Estimation
Window capacity [Ah]

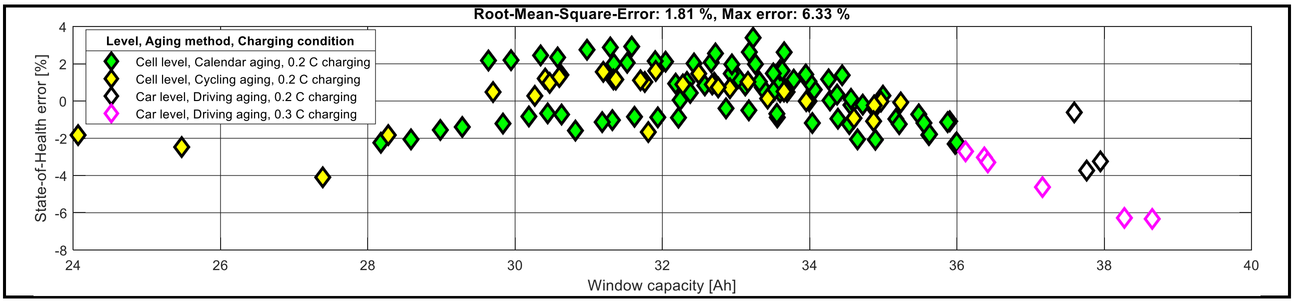


Figure 10 State-of-health estimation at 10ºC (top), 25ºC (middle), and 35ºC (bottom).

Temperature influence

As show in Figure 9, there is a good trend between the IC values of Peak 2 and the actual capacity for different temperatures. However, from a user perspective, it might be more relevant to refer the state-of-health to one specific temperature, e.g. at 25ºC. In Figure 11the 25ºC capacity is shown for IC values of Peak 2 obtained at different temperatures, i.e. the IC calculation is performed at the temperature shown in the legend, but the capacity measurement is performed at 25ºC. It is seen that the 10ºC results are rather scattered whereas the results of the other temperatures are more on a straight line. This means that the variation in capacity for one specific IC value is higher at 10ºC than for the other temperatures.

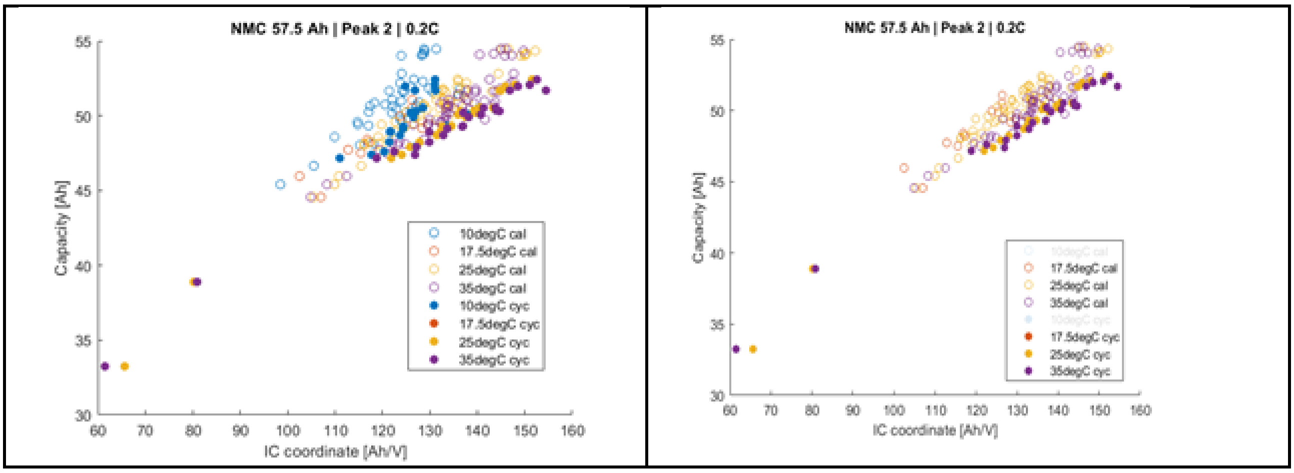


Figure 11 Cell level capacities at 25ºC shown for different Peak 2 IC values at different temperature levels. Right figure: 10ºC results removed.

The capacity at high temperatures is very similar, and it turned out that the vehicle battery temperature increases quite a lot during charging as shown in Figure 12.

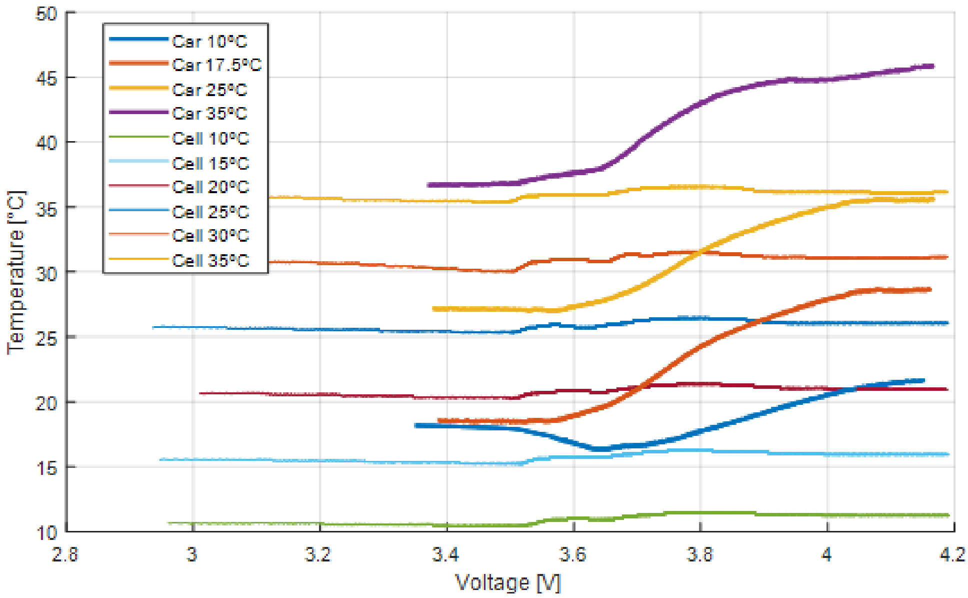


Figure 12 Temperature evolution during charging at cell level and car level at different initial temperature values.

As shown in Figure 4, the degradation was much faster when the cycle aging was performed at 10ºC than at 25ºC or 35ºC. This could indicate that low temperature operation of Nissan Leaf (62 kWh) is not a realistic operation condition, which should be avoided.

For the reasons mentioned above, it was decided to investigate the SoH sensitivity due to the temperature influence.

Temp.\errors	RMSE	Max E	Temp.\errors	RMSE	Max E
10ºC	4.04%	12.45%	**10ºC**	4.60%	13.17%
17.5ºC	1.27%	2.49%	**17.5ºC**	1.47%	2.96%
25ºC	2.02%	7.49%	**25ºC**	1.99%	7.26%
35ºC	1.94%	4.89%	**35ºC**	1.50%	4.32%

Table 5: SoH sensitivity analysis due to temperature influence. Root-mean-square-error (RMSE) and maximum error (E) shown for different temperatures based on 25ºC SoH model (left) and 35ºC SoH model (right) with IC Peak 2 as input at the specified temperature.

In Table 5, it is seen that for 10ºC, both the RMSE and maximum error are quite high, but from 17.5ºC and above, the errors are lower. This indicates that the 25ºC or 35ºC SoH models could be used for SoH estimation if the temperature is 17.5ºC or above. Thus, it can be concluded that including temperature information, in the range 17.5ºC - 35ºC at cell level, will not improve significantly the SoH estimation accuracy.

State-of-health estimation based on vehicle data alone

It turned out that the EV battery temperature was increasing significantly during charging. This is opposite in the laboratory where the cell temperature can be controlled to the desired value. For this reason, it is challenging to compare cell level data with car level data directly. However, since one of the cars used in the WABAT-project has been tested regularly over a period of approx. two years, and the battery has experienced a capacity drop of 8 % (as shown in Figure 8), it was decided to develop a SoH model of that car purely based on the car level data without including cell level data. The model uses the actual temperature to estimate the capacity referred to 25ºC. In Figure 13, the results can be seen. It is noticed that the errors are quite low even though tests were performed from 10ºC initial temperature to 35ºC initial temperature. In the figure, state-of-health is defined for two cases: with respect to 1) the full charging capacity and 2) the window capacity.

Even though the test included data for a limited test period (two years/48000 km), and the battery degradation was relatively low also (approx. 8 % full charging capacity), the results indicate, that it is possible to develop state-of-health models based on car data only without relying on cell level data obtained from laboratory tests.

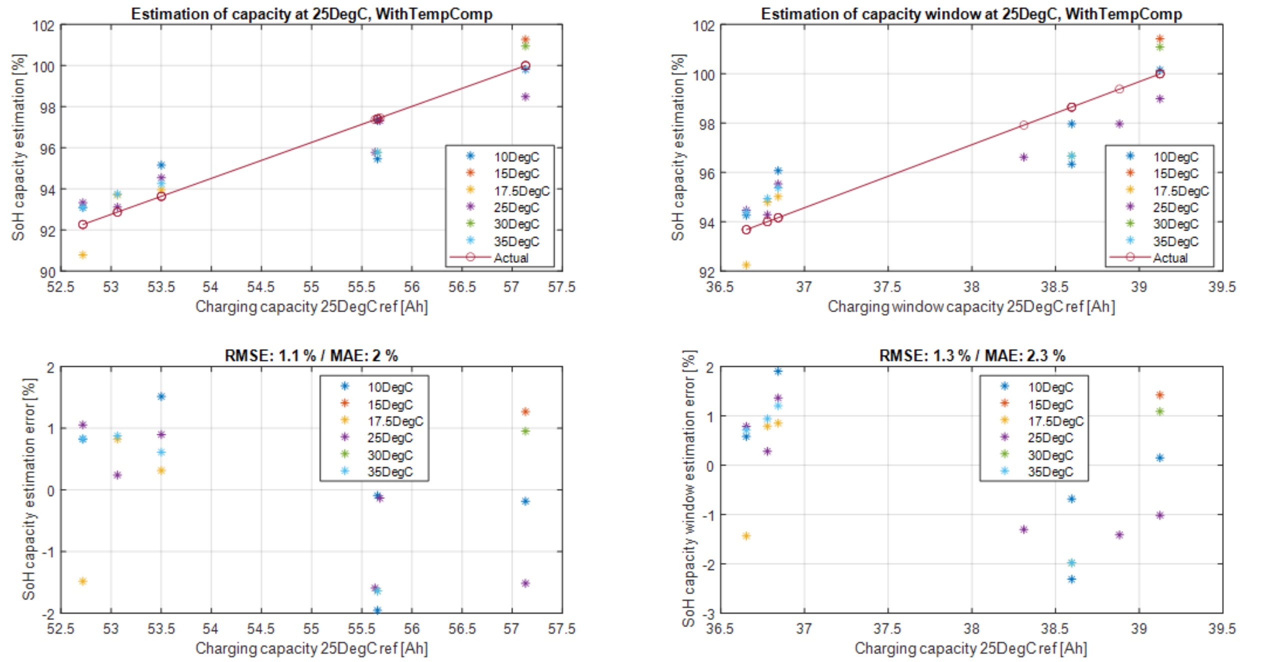


Figure 13 State-of-health estimation (top) and error (bottom) of 25ºC full charging capacity (left) and 25ºC charging window capacity (right). Car: Nissan Leaf (62 kWh).

Transferability to other battery and vehicle types

During the WABAT-project, it was possible to compare results obtained at both cell level and car level only for the NMC-based 57.5 Ah battery cell, which is used in Nissan Leaf (62 kWh). To investigate whether the developed ICA-based SOH estimation model can be transferred to other battery types as well, measurements have been performed at other cars also. Therefore, during May-June 2022, the following cars have been tested:

- Tesla Model 3 (NCA battery type)
- Peugout e-208 (NMC battery type)
- VW ID.4 (NMC battery type)
- Mini Cooper SE (NMC battery type)
- Kia e-niro (NMC battery type)
- VW e-golf (NMC battery type)
- Hyundai Ionic (NMC battery type)

In Figure 14, the IC cures are shown for six different NMC-based electric vehicles. It is seen that they all have a Peak 2 present in the interval 3.6 V to 3.7 V, but the IC values are different. The initial voltage levels are also quite different. This could influence the detection of Peak 2 for those cars with a high minimum allowed voltage level.

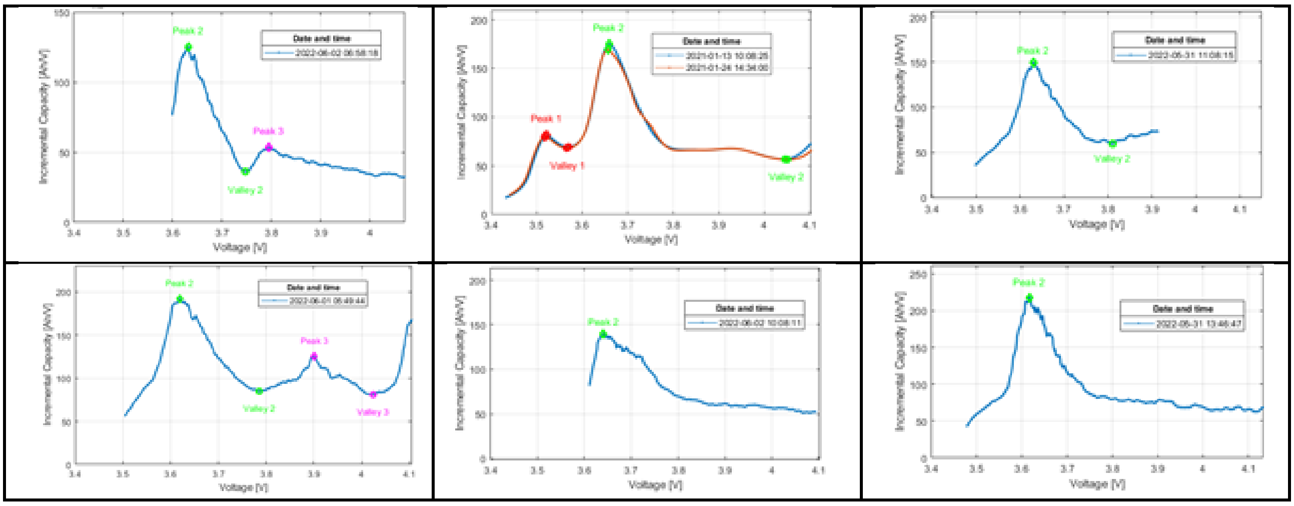


Figure 14 IC curves of different NMC-based electric vehicles. Left Upper: VW e-golf. Left Lower: Mini Cooper SE. Middle Upper: Kia e-niro. Middle Lower: Hyundai Ioniq. Right Upper: Peugeot e-208. Right Lower: VW ID.4.

In Figure 15, the IC curves of the tested 4.0 Ah NCA battery cell and the result of testing a Tesla Model 3 (also NCA based battery) can be seen. It is noticed that the IC curve of the Tesla Model 3 have similar behavior to the 4.0 Ah cell used for laboratory testing. This indicates that the ICA method also could be developed for Tesla NCA-based vehicles.

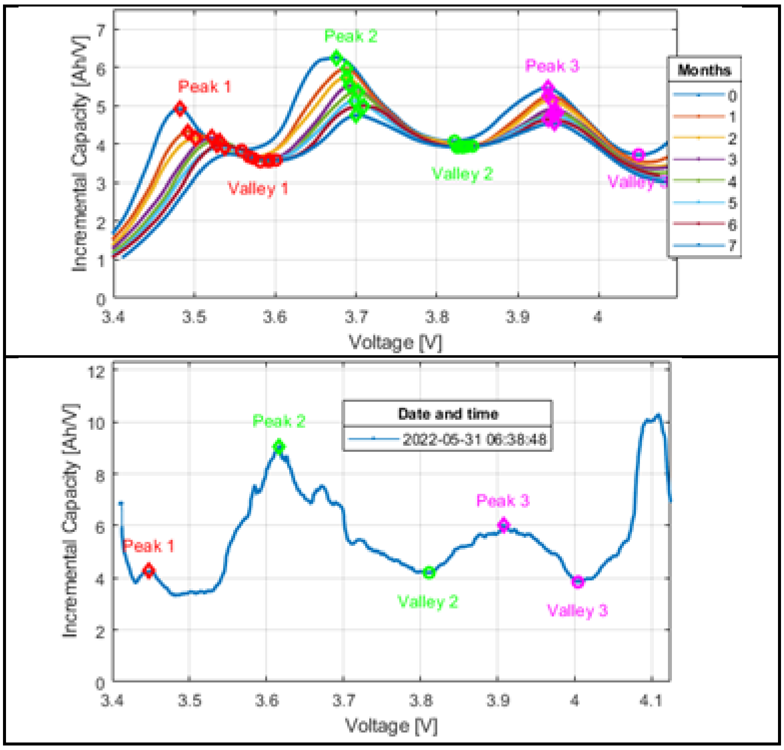


Figure 15 IC curves of NCA based batteries. Top: 4.0 Ah battery cell used for laboratory cell testing. Bottom: Tesla Model 3.

Use of V2G technology to drain an EV battery

To ensure access to the essential key signatures in the low voltage range of the battery, the SoC must be fairly low before measurement. For test on individual cells it is not an issue to drain to minimum voltage limit. In an electric vehicle the Battery Management System (BMS) will protect the battery against operation outside the defined safe and minimum degradation operational window. An EV will always protect itself from over discharge, so in principle you can just drive the car till it stops to drain the battery, but this is a very unpractical method to use inside a workshop before a test. Driving an EV for hours to drain the battery is also fairly labor-intensive and expensive. Therefore, we are looking for alternative ways of draining the traction battery enough to allow a diagnostic DC-charge with the WABAT test equipment. The preferred way would be to drain the energy from the battery using V2G technology, where the battery energy can be either fed back into the grid, dumped into a resistive load, or used locally in the workshop. CHAdeMO has allowed for V2G for several years. In the WABAT project DTI demonstrated that power could be drained from the battery in a CHAdeMO vehicle and into a resistive load by manipulating the CHAdeMO control signals similar to a V2G charger. Unfortunately, all future EVs will have CCS charge interface. The CCS communication and handshake is much more complex and there is no described standard for handling V2G on CCS. Several car manufacturers have demonstrated V2G on prototype vehicles but serial built commercial vehicles only starts becoming available as the project close. It was deemed too commercially risky to attempt V2G on a newer CCS vehicle under warranty. Therefor the research into V2G technology for CCS has been desktop study only but including planning of the telegrams to manipulate.

When direct discharge via a V2G is not available the next method is using the vehicles air conditioning unit. The heating in an EV comes from the traction battery, so by cooling down the vehicle, opening the windows, turning up the temperature target set point the heater will drain the battery. The draining takes longer time but can be done with minimal operator involvement. It is important to always connect a heavy-duty DC-supply to the auxiliary battery before starting any funny business with an EV because the auxiliary battery will drain very fast when the traction battery is empty. It is also necessary to develop procedures for tricking the vehicle into staining active until the traction battery is drained enough. This procedure for draining the battery on an electric vehicle via HVAC is different from car to car and is therefore a part of the competitive knowledge base for a test service. Some vehicles can be drained faster using cooling instead of heating.

Using the HVAC for battery drain was used throughout the WABAT project.

5.2.2 Obtained Hardware results

Please see section 3.2 for description of the developed hardware in the project.

5.3 Obtained commercial results.

The main commercial result of the project is clearly that a project results will be carried over into a commercial product and service immediately after the project is concluded.

Christonik will be carrying the project results into a daughter company named NEQ ApS. This company will be dedicated to commercializing the project results in Denmark, Norway, and Sweden to start and later most of Europe.

The product will be placed at third-party workshops to do test on the Scandinavian EV fleet. The workshop doesn’t pay for the hardware, but pay a fee for every test report, that they sell to their costumer. This way the collaboration between NEQ and the workshop is more a partnership with a mutual interest in more test than a regular costumer-supplier relationship. It also eases the start-up cost of the workshop by not charging the hardware.

NEQ has acquired the first 6 costumers that awaits a finished product and 15-20 more has shown interest.

Please see chapter 6 for details of the commercial results.

5.4 Solutions target group and added value.

Different technological solutions have been investigated in the project with different levels of results.

5.4.1 Diagnostic algorithm solution

Added value target: Christonik.

The solution enables independent third-party on-site workshop diagnostic test of EV-battery in combination with a dedicated test equipment and DC-fastcharger.

5.4.2 Test equipment for diagnostic test with existing charger

Added value target: companies in need of independent third party on-site workshop diagnostic test of EV-batteries (e.g. independent car repairshops and and car test bodies).

All partners already have electric car-related activities. Two of the project partners represent different customer groups and markets: FDM represents Danish car inspection institutions and close to 30 million international (incl. Danish) consumers through FIA affiliation. FIA has shown keen interest in the WABAT project and has frequently been updated on progress. FDM has in the framework of FIA presented WABAT to UNECE working groups (IWG) in the discussions on new definitions and addition to regulation. New requirements set-out in new UN GTR on battery durability. State of Certified Energy (SOCE) and the State of Certified Range (SOCR - GNCAP test procedure on driving range - car labelling Directive' (Directive 1999/94/EC). FDM also works with periodic inspection regulation PTI (UNECE (Periodical Technical Inspections) and the access to data, emissions etc. Applus+ also represents global focus, working with cars in 11 countries. The customer representatives confirm an increasing need for new diagnostic tools for the workshops as electric cars begin to displace conventional cars. The customer-representatives has actively participated in field testing and evaluation of equipment.

The market potential for the WABAT testing equipment is considered to be very large. There are 260.000.000 cars in Europe and all markets expect to become fossil free before 2050. In average cars are 8 years old and sold as used 2.5 times which average over 80 million used car sales per year. If 2% of the used sales need an independent battery assessment, the European market it is more than 1.600.000 diagnostic battery tests per year. Political targets are high regarding electrification of the passenger car fleet by 2030. More than 25% seems likely since actual annual BEV sales-share in Northwest Europe (incl. France, Germany and UK) were already well above 10% in 2020 according to World Economic Forum and is expected to keep growing year by year. When 25% of the fleet is EVs, it will require more than 4000 WABAT assuming an average of 100 tests per year per WABAT unit in average.

A future with only EVs on the road is a nightmare scenario for independent workshops if diagnostic data is only available via OEM information, since history shows OEM reluctance to open for third party repairs. Third party workshops business with EVs could in worst case be limited to changing tires and air filters and the odd renovation of brakes and traffic damages. The WABAT tester doubles as multi-standard DC fast charger and battery test equipment for EVs with DC fast charge interface. This can open for more EV related business at third party workshops e.g. by offering independent battery assessment to the costumers.

5.4.3 Frontend measurement board

Added value target: Christonik is the first target for the product but the project has verified that a dedicated application software can adapt the product to other functionalities.

New application-layer enables a new product based on an existing ISO 26262 automotive qualified BMS circuit board. The BMS-board standard functions provide measurement interface for the high voltage and high current side as well as several temperatures and voltage inputs, relay control outputs and three CAN-bus channels. A dedicated application layer software allows implementation of a dedicated ‘man-in-the-middle’ manipulation of CHAdeMO CAN-bus handshake to control the needed special charge profile for WABAT-test.

5.4.4 Gateway and CCS PLC-interface

Added value target: Christonik is the target for the actual application of an industrial standard development board with application specific firmware. The broad range of built-in communication capabilities of the development board enable the diverse gateway functionality. DTI has trough structured software development combined with open source libraries realised a functional demonstration, that can be used by Christonik for further development of a commercial product.

See section 3.2.1 for further description of the gateway and CCS-frontends.

5.4.5 Reference database for EV-test

For collection of measured data from vehicle testing in lab and in the field a database adapted directly from the Batnostic-project was implemented on a secured server at DTI. Also diagnostic assessment runs from the same server with direct access to the database. The communication between database and gateway in the test equipment is password protected, and only data from already accepted identified units are accepted.

5.5 Project relevant disseminated

Year-month	Dissemination activity	
2022	Barragán-Moreno, A.; Schaltz, E.; Gismero, A.; Stroe, D.-I. Capacity State-of-Health Estimation of Electric Vehicle Batteries Using Machine Learning and Impedance Measurements. Electronics 2022, 11, 1414. https://doi.org/10.3390/electronics11091414	
2022 mar	Alejandro Gismero; Kjeld Nørregaard; Bjarne Johnsen; Lasse Stenhøj; Daniel-Ioan Stroe; Erik Schaltz. Electric Vehicle Battery State of Health Estimation Using Incremental Capacity Analysis Corresponding. Submitted March 2022 to the Journal of Energy Storage.	
2022	A third paper regarding incremental analysis of the anode and cathodes (half cells) is under preparation. Working title: Influence of polarization in the Incremental Capacity Analysis for the State of Health estimation of lithium batteries	
2022	PhD thesis by Alejandro Gismero in preparation. Working title: ‘Battery State Estimation Methods for Electric Vehicles under Real Temperature Conditions’	
2021-dec	Presentation of WABAT project at “Avanceret Energilagring” conference held at Danish Technological Institute, Aarhus.	
2021-sep	Part of the presentation ’Levetidkarakterisering- og modellering og state-of-health estimering af lithium-ion batterier’ given to ‘Batterigruppen 2004’ (BG-04) in relation to their visit at AAU September 2021	
2021	FTZ conference – Odense	
2021-2022	Relevant costumer meetings	

2022	Article in Motormagasinet	

6. Utilisation of project results

6.1 Utilisation of obtained technological results

The results of this project regarding the hardware and software prototype, as well as the algorithm and the knowledge behind it will be used in a commercial setting after the project driven, maintained and further developed by Christonik. It will be used as a consumer service by third-party workshops, to create certainty and transparency within the used EV market as well as new EVs.

With EVs the SoH of the battery will be very influential on the value of the car as a whole, given a replacement of the battery might financially prevent the buyer from making the deal. The SoH is predicted to be used much like the odometer to judge the condition and value of a car. It will not replace the odometer, but coexist as the odometer doesn't tell the whole story when it comes to EVs.

A measurement with financial consequences is important that it's an unbiased and impartial measurement. The outcome of this project can truly claim to be fully unbiased and impartial.

The plan for the commercial future of the product will be setup in partnerships. Partnerships between Christonik and specialized EV workshops. Christonik will provide hardware and software platform for the partners to provide as a service for the consumers. The paystructure will be pay-per-use for the partner, with a decrease per single use as the overall amount of uses per year goes up. This paystructure encourages more sales and effort towards using the equipment compared to regular one-time payment experience shows.

Through experiences from WABAT, FDM gained insight into the high-voltage technology and were therefore able to compare data from the OEM, our own new data from studies on the Renault Fluence car, which could determine that the battery's capacity no longer met the minimum warranty limit. Our test results meant that our member with our documentation got a brand-new battery in his electric car, paid for by the warranty. The case set a precedent for future battery warranty cases for Renault.[1]

6.2 Utilisation of obtained commercial results

During the project Christonik hired an engineer to manage and develop the technical side of the project, both within the project as well as after project. It is expected that Christonik will need 2 or more specialists to fully operationalize the technology. Some of the development is also expected to be outsourced.

[1] https://fdm.dk/nyheder/bilist/2021-02-de-sagde-elbilens-batteri-var-fit-men-det-var-fladt

WABAT will most likely exist in a daughter company of Christonik not to associate HVAC expertise with battery tests. Christonik expect to hit 20% of market potential in the Nordic countries. This will lead to an increased turnover as the daughter company is owned by Christonik.

When the product of the future business based on this project will become mature enough to pull market interest, private investments will be explored to secure funding for end development and operationalization.

6.3 Competitive market situation

Aviloo is an OBD-II port dongle that retrieves the data from the onboard computer system on the vehicle. This in terms means that it measures with the vehicles own hardware and software. Which makes it biased and that could mean tampered results. Not necessarily, but possibly. It works by charging the car to 100%, then configuring the dongle to the test car. When the car is ready the dongle is inserted in the ODB-II port and the test starts. The car will now need to be discharged to below 10% and the test is completed. All in all, this takes several days. For a workshop the time aspect is of utmost importance. Even though the mechanic isn't driving the car during the discharge phase, it still takes a lot more time to perform this test for the workshops.

The Aviloo dongle is on the market already which gives them a head start compared to WABAT, but the impartial aspect of the WABAT equipment might gain a valuable market share.

TÜV does battery tests, some for standardization and some for characterization and performance. TÜV and TWAICE does an indepth tests of batteries for consumer EVs starting 2022 in Germany. They have a strong branding as TÜV is a trusted standardization and testing firm in Germany.

Mastery of technology

Entry barriers for the WABAT system would include to finish an operational user interface. The user interface for the prototype would need a more efficient way of handling a multitude of costumers and devices.

The WABAT system also needs a lot more reference data to become a functional system. For that reason, a lot of tests on new and old cars would need to be conducted to raise the certainty level of the test results.

The hardware design in the prototype does contain some choices of hardware that inhibit further production without some redesign as some measurement circuitry is discontinued. Before the WABAT box can be mass produced further hardware development both for optimization and compliance is needed.

Legal

In order to market the product in EU it would need a CE marking. This implies going through a number of tests to ensure safety and non-interfering behavior.

Capital costs

Before market entry there will be multiple costs

- Operationalization of the product including hardware and software and development there of
- Optimization of components
- Marketing initiatives
- Hiring 2 or mere engineers to support the early stages of customer support, maintenance and development

With the business model proposed for the future of WABAT it would take a considerable capital to engage with many partners as the partners won't have to pay for the hardware upfront, but as they perform tests, the hardware pays for itself. The exact amount will vary with the optimization development

6.4 Project contribution to energy policy objectives

The project contributes to energy policy objectives regarding faster transition of electric transportation and the sector coupling for electric grid and transportation. With a reliable second-hand market for used EV's, the transition towards electric transportation will increase. The WABAT test-equipment will be a crucial part of the impartial test and reliability of the second-hand market. Knowledge gain in battery degradation and V2G technologies, will enable for new projects and market potentials in other areas with batteries as an important asset e.g. electric busses, trucks, trains, ferries and grid connected battery electric storage systems (BESS).

6.5 Ph.D. contribution to results, teaching and dissemination activities.

The WABAT-project is partly financing a PhD project carried out by Alejandro Gismero. Some of the results obtained in the WABAT-project will therefore be presented in the PhD thesis of Alejandro and the belonging papers.

The WABAT-project is a successor of the BATNOSTIC-project (EUDP project no. 64015-0611). The results of the BATNOSTIC-project have been used for the PhD course 'Lithium-Ion batteries Fundamentals, Modelling & State Estimation' at AAU. In addition, AAU lab data has also been shared with guest PhD students and master thesis students who has used the data as part of their project. It is therefore also expected that the WABAT results also will be used as part of future PhD courses and that AAU lab data will be shared with future PhD guest and master thesis students who will use the data as part of their project.

7. Project conclusion and perspective

7.1 Conclusions made in the project.

The main prospective of the projects has been to develop an EV tester suitable for workshop environment on top of the learnings from former EUDP project "BATNOSTIC". A new WABAT tester is ready for commercialization after demonstration with several EVs in a field-test and with different chargers. An diagnostic estimation algorithm has be proposed. This main prospective is at the end of this project definitely a great success for Christonik as the main partner to bring the tool the last step forward to the market in northern Europe.

To perform diagnostic measurement the battery must be drained first. A preferred cost effective method to drain an EV without driving it empty is discharge through the DC-charge port using V2G technology. The CCS-protocol which are the future main DC-fast charge communication protocol of all EVs in Europe was announced for start of the project but not actually released for V2X during the project. The automated drain procedure has therefore been implemented using the HVAC system in the EV instead. It requires more car specific setup and preparation and may take slightly longer but is just as cost-effective as no full-time operator is needed.

With the installation of a climate chamber for EVs at TI, Aarhus, it has been possible to map, model and implement a more complex SoH estimation algorithm in the WABAT setup. This has contributed to expand the temperature range a WABAT diagnostic charge can be performed in without temperature preconditioning. The developed algorithm is accurate within +17,5°C to +30°C range, which is a major improvement from the +20°C target needed for the previous Batnostic project.

Another great conclusion from this project is, that it seems that this test method still is the only method in the market that is 100% impartial and independent from the OEMs. Multiple new 3rd party test-equipment has been tested at both FDM and Applus workshops, but all these methods seems to estimate the SoH of the EV battery from the on-board computer inside the EV. Christonik does then still have the chance of being first into the market for independent workshops. This has potential to become a great story for Danish development of test-equipment for a growing EV-industry.

Conclusions on the commercialization is that there is still some work to do. A significant conversion of code and an integrated server setup for the algorithms is needed for upgrading to a commercial business setup. This was to be expected so the project has delivered to the original hope for possible commercialization.

7.2 Next steps for the developed technology?

The WABAT tester built in this project is workshop-ready and could be a part of daily test-routines on any workshops as-is. But as it always is during product development, multiple design- and technology solutions are being discovered for further improvement and optimisation of the product. Therefore, the intention from Christonik's side, is to design and build a new iteration of the WABAT tester, which then has to be tested and approved from relevant standards before starting a mass-production that can be brought to the European market. Estimated time-to-market is approx. 1 year from project finish.

7.3 Influence on future development perspective

The WABAT diagnostic test method assume that all electric cars of the same brand and model are built similar. The research knowledge developed in the WABAT project suggests that the diagnostic method can maybe be adopted for use on both non-standard batteries either stationary or for mobile applications. It could be very relevant to have methods to assess the state of health for e.g. electric busses. Further research would be needed though to find descriptive methods to handle e.g. more parallel battery strings typical for an electric bus.

There seems to be interesting perspectives in V2X technology in relation to both smart energy and battery diagnostic methods if this can be accessed directly on all CCS-vehicles.

8. Appendices

- Barragán-Moreno, A.; Schaltz, E.; Gismero, A.; Stroe, D.-I. Capacity State-of-Health Estimation of Electric Vehicle Batteries Using Machine Learning and Impedance Measurements. *Electronics* **2022**, *11*, 1414. https://doi.org/10.3390/electronics11091414
- GNCAP test procedure on driving range - UN GTR on battery durability - https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32021R0392&rid=1 - input in connection with Euro7 /CO2 post target –
- https://www.fiaregion1.com/fia/policy/environment/ note that knowledge in WABAT is shared internationally, and contributed to various changes in the regulations/type approvals etc. An important topic such as the battery directive, and type approval 2018/858 here, the electric car was not really included as an electric powertrain was not envisaged and thus no real type approval requirements for electric cars. We have continuously prioritized this work, which is why WABAT has and is still very relevant.