Final report

General information (delete this section)

*Depending of project type, project size and project complexity the **number of pages** in the final report may vary. For smaller **development and demonstration** projects, the final report normally should not be more than 20 pages plus possible relevant appendices. For larger **research, development and demonstration** projects, the final report should not be more than 50 pages.*

The final report will be used for dissemination purposes and the information stated in the final report should be suitable for dissemination. The final report will be published at www.energiteknologi.dk.

*The guidance text (in italic) should be deleted, so the application form **only** contains numbered headings as well as relevant text from the applicant.*

1. Project details

Project title	Cloud BMS, The new generation of intelligent battery management systems
File no.	64017-05167
Name of the funding scheme	EUDP
Project managing company / institution	Lithium Balance
CVR number (central business register)	29391130
Project partners	Lithium Balance, Aalborg University, Blue Ocean Robotics, IVI Fraunhofer
Submission date	07 June 2022

2. Summary

Describe the objectives of the project, the obtained results and how they will be utilized in the future.

The short description should be in two versions:

- *English version*
- *Danish version*

Each version should be brief, no more than 2000 characters (including spaces).

3. Project objectives

- *What was the objective of the project? (English)*

The Cloud Battery Management System (BMS) project developed and demonstrated that the use of big data and artificial intelligence can improve the lifetime and reduce the effective cost of both stationary and non-stationary battery systems. In the project, battery systems were connected to the internet (Internet of Things) and real-life data stored in the 'cloud'. Adaptive battery diagnostics and lifetime estimation models were established from the cloud data by using artificial intelligence algorithms. By processing a large amount of real-life harvested battery data ("big data"), a detailed and quantitative picture showing how different parameters contribute to the degradation of the individual battery was established. In this way, the following unique advantages are realized:

- Battery life could be extended up to 10% by optimizing the utilization patterns to reduce degradation;
- Battery pack capacity and hence cost can be optimized to match the desired lifetime for known operational parameters; depending on the application, the reduction of the battery cost of ownership up to 50% can be achieved;
- The Remaining Useful Lifetime of the battery can be predicted which enables novel business models (2nd life battery usage, enabling the second-hand battery market, extended battery warranty);

This project contributed to the wider use of renewable energy in the energy system as both longer and precisely known battery lifetimes will help in the wider introduction of batteries in:

- Stationary battery energy storage systems (BESS) to form a buffer between the supply and demand of fluctuating energy sources (wind, solar); BESS will be also a source of 'flexibility service' in the grid;
- Vehicles, where batteries will allow (green) electricity to replace fossil-fuel-based oil as an energy source.

The project developed dedicated hardware and software for cloud-based BMS demonstrations and future commercialization. The general advantages of the cloud-based BMS were demonstrated on different battery applications including forklifts, robots, and stationary BESS.

- *Hvad var formålet med projektet? (Dansk)*

Cloud Battery Management System (BMS)-projektet har udviklet og demonstreret, at brugen af big data og kunstig intelligens kan forbedre levetiden og reducere de effektive omkostninger ved både stationære og ikke-stationære batterisystemer. I projektet blev batterisystemer forbundet til internettet (Internet of Things) og virkelige data gemt i 'skyen'. Adaptiv batteridiagnostik og livstidsestimeringsmodeller blev etableret fra skydata ved at bruge kunstige intelligens-algoritmer. Ved at behandle en stor mængde indsamlede batteridata ("big data") blev der etableret et detaljeret og kvantitativt billede der viser, hvordan forskellige parametre bidrager til nedbrydningen af det enkelte batteri. På denne måde opnås følgende unikke fordele:

- Batteriets levetid kan forlænges med op til 10 % ved at optimere brugsmønstrene og derved reducere nedbrydning;
- Batteripakkekapacitet og dermed omkostninger kan optimeres til at matche den ønskede levetid for kendte driftsparametre. Afhængigt af applikationen, kan batteriets ejerskabsomkostninger reduceres med op til 50 %;

- Batteriets resterende brugstid kan forudsiges, hvilket muliggør nye forretningsmodeller. (brug af batterier i såkaldt ”second life” applikationer og aktivere markedet for brugte batterier, samt udvidet batterigaranti);

Dette projekt bidrog til bredere brug af vedvarende energi i energisystemet. Både længere og mere præcist forudbestemte batterilevetider, vil hjælpe til en større udbredelse af batterier i:

- Stationære batterienergilagringssystemer (BESS) til at danne en buffer mellem udbud og efterspørgsel af fluktuerende energikilder (vind, sol); BESS vil også være en kilde til 'fleksibilitetsservice' i nettet;
- Køretøjer, hvor batteriet kan lade (grøn) elektricitet og erstatte fossilt baseret brændstof, som f.eks. olie.

Projektet udviklede dedikeret hardware og software til cloud-baserede BMS-demonstrationer og fremtidig kommercialisering. De generelle fordele ved den skybaserede BMS blev demonstreret på forskellige batteriapplikationer, herunder gaffeltrucks, robotter og stationære BESS.

- *Which energy technology has been developed and demonstrated?*

In the framework of the Cloud BMS project, a few technologies were developed and demonstrated:

- Artificial intelligence-based battery state of health estimation (SoH) and Remaining Useful Life (RUL) prediction that was demonstrated on the Lithium Balance/Xolta BAT-79 commercial battery product. The AI-based algorithm can be utilised when the relevant amount of training battery degradation data is available.
- Use-pattern optimisation algorithm – battery degradation aware energy management to extend the stationary battery lifetime and to lower the cost of battery ownership; The 1.5 years (10% of lifetime extension potential) has been demonstrated using battery degradation aware battery energy management algorithms;
- The new version of the UVD Robot, which has been designed based on feedback from infection prevention specialists to be part of a regular cleaning routine, aims at reducing the spread of infectious diseases, bacteria, and other types of harmful organic micro-organisms and pathogens in the environment. The specific model is the third generation (Model C), which has several new features, that raises a higher level of infection prevention.
  The project demonstrated the potential of 500 days of battery lifetime extension for the robot case (20%). This will lower the cost of robot battery ownership by 7%. The further potential of lowering the cost of ownership is possible with proper robot fleet management (that might help to avoid costly battery replacement).
  Blue Ocean Robotics will utilize future hardware and software (fleet management tool) modifications that will utilize findings from the Cloud BMS project.
- iBMS15 development by Lithium Balance. A new BMS hardware is capable to manage applications up to 60V that was developed for cost optimised mass-production. It includes findings of the Cloud BMS in advanced software algorithms for SoH (state of health) and SoE (state of energy) estimations.

4. Project implementation

- *How did the project evolve?*

  The project evolved according to the project plan, and all the project milestones were achieved from the updated project plan that was submitted and approved by the EUDP in 2018.
  The project had a delayed start due to a lack of appropriate battery degradation data at the beginning of the project (delay in some other commercial and project-related battery commissioning and operation). In consequence, the project extension was requested in 2018 and given by the EUDP.

- *Describe the risks associated with conducting the project.*

  There were a few risks associated with the project. The main was:

  - The difficulties in project management due to many personnel shuffling (both managers and engineering staff) and internal company roadmap modifications throughout the project;
  - The cost of the data storage, transfer, and computation will lower revenues from project developments. In consequence, it is considered to implement the developed solutions on the local (and higher-level) battery Energy Management System (EMS) and/or improve algorithms to lower the cloud computation burden.
  - There is a risk that the battery usage profile optimisation that is based on Cloud BMS findings might not be acceptable in all applications as it might impact the comfort of some customers. So, it is planned to educate customers so they can accept the changed operation profiles by showing the benefit of the Cloud BMS project;

- *Did the project implementation develop as foreseen and according to milestones agreed upon?*

  The project implementation developed as foreseen, and all the milestones were achieved. However, some of the milestones were achieved in a reduced capacity or with different results than initially expected.

  Here is the list of the project deviations:

  Milestone ‘1.1 Cloud BMS operational for 10 forklifts’ -> Data collection has been only performed on 3 forklifts. The considered period did not show too much forklift battery degradation due to very mild usage of the forklifts. However, to meet the main scientific objective of the project, the battery profiles from the field operation of the forklifts were used to perform accelerated aging tests in laboratory conditions. The aging was accelerated by employing elevated temperature and reduction of the periods when the battery is in idling mode. These accelerated tests were designed in such a way, that an expected degradation of 15-20% was achieved during the 14 months of the additional accelerated test.
  Based on the battery degradation results (obtained from laboratory testing), the targeted SoH estimation algorithm was developed. Subsequently, the algorithm was verified using the forklift field data, which was continuously recorded, while the accelerated aging tests were performed in the laboratory. In consequence, the following milestones were added and achieved:

  3.6. Profile development for the accelerated test (based on forklift data)

3.7. Accelerated tests of “forklift batteries” performed

3.8. Development of battery SoH estimation algorithm based on accelerated test

3.9. SoH verification of forklift data

For training the AI-based algorithms, the data (also historical) has been collected from additional Lithium Balance/Xolta stationary battery systems (BESS).In consequence, the following milestones were added and achieved:

1.6. Up to 14 BESS systems in operation and logging data

1.7. Acquiring Battery data from BESS systems implementing reference points.

3.10. Implementing SoH prediction estimation on BESS data

The milestone ‘3.4 Sudden-death algorithms’ was removed from the updated Cloud BMS milestone list due to a lack of appropriate data for sudden battery failure analysis. It was because none of the battery cells failed during different battery systems' operations.

- *Did the project experience problems not expected?*

  Yes. There were a few not expected problems that are listed below:

  - Project management and general human resources-related issues: the project had three project managers: Sune Ebbesen (year 1), Claus Friis Pedersen (year 2), and Maciej Swierczynski (year 3). The project managers were changed as first Sune and later Claus left Lithium Balance. Furthermore, during the project duration, several personal changes in Blue Ocean Robotics and IVI Fraunhofer Institute were present. This resulted in the slower Cloud BMS project progress in the first 1.5 years (frequent onboarding of new people in the project, knowledge, and task transfer). However, all these delays have been made up in the last year.
  - Data availability: the time for the data collection in the cloud (from the battery operation) has started late and it has impacted the accuracy of the AI models (not sufficient data quota for model training). This fact did not impact the model structure, but it impacted the validation phase (it is going to be continued after the project end based on a larger data quota).
  - The COVID-19 and project delays in the first year did not allow for organising the workshop with external stakeholders. In consequence, no additional inputs have been collected in the mid-project development. However, the stakeholder and customer workshop was organised at the end of the project but at this stage, it could not have any impact on the project development. Nevertheless, the inputs from this workshop will be valuable in the future for further improvements of the project outcomes.
  - The findings of the Cloud BMS were supposed to be transferred and demonstrated in WP5 in the new version of the BOR UVD robot. However, due to project delays in the first period, there has not been collected enough robot field data and the redesign and development of the BOR UVD Model C robot did not have the Cloud BMS solution implemented. However, the

impact of the robot usage profile optimisation on the robot battery lifetime was modeled, using the developed Cloud BMS RUL estimation technique. In consequence, the reduction in the robot battery cost of ownership was estimated. This will be validated in detail by BOR after the end of the project (future developments).

5. Project results

- *Was the original objective of the project obtained? If not, explain which obstacles that caused it and which changes that were made to project plan to mitigate the obstacles.*

  Yes. All below mentioned original project objectives were obtained:

  - It was demonstrated that battery life can be extended up to 10% by optimizing the utilization patterns to reduce degradation;
  - It was demonstrated that the battery pack capacity and hence cost can be optimized;
  - The Remaining Useful Lifetime (RUL) of the battery can be more accurately predicted based on AI-based algorithms which enable novel business models (enabling the second-hand battery market) and a more accurate guarantee of battery system lifetime (extended warranty service);

- *Describe the obtained technological results. Did the project produce results not expected?*

  There is a slight deviation in the project regarding the development of BOR's fleet management. As BOR has changed its product development strategy during the project period, fleet management is no longer on its roadmap.

- *Describe the obtained commercial results. Did the project produce results not expected?*

  The commercial results of the project are as follows:

A) Lithium Balance (iBMS15) developed and offered on the market from 2021. A new BMS hardware capable to manage applications up to 60V was developed for cost optimised mass-production. It includes some of the findings of the Cloud BMS in advanced software algorithms for SoH (state of health) and SoE (state of energy) estimations.

B) Xolta (battery-related department of Lithium Balance) – utilization of Cloud BMS algorithms developed for BAT-80 stress battery monitoring (planned to be released beginning of 2023). Furthermore, the more accurate RUL prediction algorithms will be used for offering an extended warranty for Xolta battery products and for better product warranty risk management.
Furthermore, Xolta is planning at the end of 2023 to improve the battery system BAT- 80 operational profiles for some applications to extend the product lifetime.

C) IVI Fraunhofer developed within the framework of the Cloud BMS project:
- the monitoring technology for stationary battery systems
- data compression concepts to lower the cost of data transfer and storage in the cloud

- stress factor-based aging model for RUL estimation & tool for lifetime prediction

D) Blue Ocean Robotics (BOR) developed the UVD robot (Model C). BOR is intending to add part of the Cloud BMS collected knowledge about robot battery degradation into the developed fleet management (not fully decided yet) to improve robot operation and management and lower the cost of battery ownership (avoiding the robot battery replacement during the robot lifetime by extending the lifetime of the battery).

E) Aalborg University is intending to utilize some generated knowledge and scientific findings of the Cloud BMS in the commercially offered every year Industrial course about battery system technology.

- *Target group and added value for users: Who should the solutions/technologies be sold to (target group)? Describe for each solutions/technology if several.*

A) Lithium Balance iBMS: residential battery systems, robot battery systems, 2 & 3 wheelers, low voltage battery applications;
B) Xolta BAT-80: C&I battery systems for housing associations, grid support applications (e.g. frequency, voltage support, etc.), renewable support applications (e.g time shift, energy dispatch), off-grid battery applications, microgrids;
C) IVI Fraunhofer developments: these solutions will be offered to the potential customers: manufacturers of stationary storage systems, and providers of battery monitoring solutions.
D) BOR UVD - The main target group for the robot is healthcare institutions, mainly hospitals. There are various applications in hospitals such as patient rooms, operation rooms, offices, etc.

- *Where and how have the project results been disseminated? Specify which conferences, journals, etc. where the project has been disseminated.*

1. Transfer Learning for Adapting Battery State-of-Health Estimation from Laboratory to Field Operation, Vilsen, S. B. & Stroe, D-I., 2022, (E-pub ahead of print) In: IEEE Access. 15 p., Journal article
2. An auto-regressive model for battery voltage prediction Vilsen, S. B. & Stroe, D-I., 2021, 2021 IEEE Applied Power Electronics Conference and Exposition (APEC). IEEE, p. 2673-2680 8 p. (I E E E Applied Power Electronics Conference and Exposition. Conference Proceedings).

   Battery state-of-health modelling by multiple linear regression, Vilsen, S. B. & Stroe, D-I., 2021, In: Journal of Cleaner Production. 290, 12 p., 125700.

3. A Time-Varying Log-linear Model for Predicting the Resistance of Lithium-ion Batteries, Vilsen, S. B., Sui, X. & Stroe, D-I., 2020, 2020 IEEE 9th International Power Electronics and Motion Control Conference (IPEMC2020-ECCE Asia). IEEE, p. 1659-1666 8 p. 9367839. (2020 IEEE 9th International Power Electronics and Motion Control Conference, IPEMC 2020 ECCE Asia).
4. Log-Linear Model for Predicting the Lithium-ion Battery Age based on Resistance Extraction from Dynamic Aging Profiles, Vilsen, S. B., Kær, S. K. & Stroe, D-I., Nov 2020, In: I E E E Transactions on Industry Applications. 56, 6, p. 6937-6948 12 p., 6.

5. Predicting Lithium-ion Battery Resistance Degradation using a Log-Linear Model, Vilsen, S. B., Kær, S. K. & Stroe, D-I., Sep 2019, Proceedings of 2019 IEEE Energy Conversion Congress and Exposition (ECCE). IEEE Press, p. 1136-1143 8 p. 8912770. (IEEE Energy Conversion Congress and Exposition).
6. Workshop: Cloud- and AI-based battery SoH estimation in various applications

For more information, refer to Appendix.

6. Utilisation of project results

- *Describe how the obtained technological results will be utilised in the future and by whom.*

  The battery operation analysis can help prolong the product battery lifetime, and which product manufacturer can offer a longer warranty and reduce maintenance costs, eventually becoming more competitive in the market.

- *Describe how the obtained commercial results will be utilised in the future and by whom the results will be commercialised.*

  Refer to answers to questions above related to the description of the commercial results utilisation and target customers.

  - *Did the project so far lead to increased turnover, exports, employment and additional private investments? Do the project partners expect that the project results in increased turnover, exports, employment and additional private investments?*

  Lithium Balance/Xolta turnover and employment growth have been substantial during the last three years (3 times more employees). However, only 2 additional employees were designated for Cloud BMS-related work. It is expected that the number of employees, who will continue to work on battery state estimation algorithms, will increase substantially in the next two years. This development will be one of the main cores of competitive battery products in the upcoming years.

  Furthermore, Sensata Technologies invested in Lithium Balance/Xolta by acquiring the company. This gives a lot of opportunities by opening new European and overseas markets.

- *Describe the competitive situation in the market you expect to enter.*
  - *Are there competing solutions on the market? Specify who the main competitors are and describe their solutions.*

  There are currently some competing solutions provided by e.g. Bosch, Panasonic, and Baomas. Bosch combines large volumes of data from vehicle fleets with cloud technology and AI. The self-learning

system makes predictions about the condition of the respective battery and provides condition reports and new operating parameters of the battery.

Panasonic announced will begin offering a new, cloud-based battery management service, known as the UBMC (Universal Battery Management Cloud) service, utilizing a proprietary AI-based technology that incorporates its battery expertise.

Bamomas offers maximisation of the performance of industrial batteries, reduction of operational costs, and improvement of sustainability with a cloud-based battery management system powered by custom-designed sensors, IoT, and machine learning-based analytics.

There are also other solutions focused on advanced battery analytics, (e.g. Twaice), residual battery value estimation, and SoH estimation.

Other companies, (e.g. Irasus, Altelium) offer battery warranty management services to battery system providers.

Moreover, the topic of cloud battery state estimation is gaining closer attention in the last 2 years with several new scientific publications.

Lithium Balance/Xolta is not planning to sell Cloud BMS-developed solutions as a service to battery system providers. The intention is rather to implement advanced battery state estimation and RUL predictions on their products and offer them as turnkey, complete advanced battery systems with unique features for different applications.

- *Describe entry or sales barriers and how these are expected to be overcome.*

  The largest barrier that is expected is related to the proper education of the customers on the long-term benefits of the Cloud BMS solutions on Lithium Balance/ Xolta products. Customers need to understand well the solution and its implication for everyday battery operation. This is expected to be dealt with marketing campaigns that will target differentiation between a standard cheaper and more expensive advanced battery system.
  Another barrier is the much higher competition on the market (compared to 1-2 years ago) and difficulty with clear differentiation between Cloud BMS solutions and competitive solutions. Competitors provide very little details about their solutions, and it is difficult to benchmark.

- *How does the project results contribute to realise energy policy objectives?*

  The Cloud BMS project contributes to optimizing battery usage that prolongs the battery lifetime. This decreases the maintenance cost of the battery and lowers the payback time of the investment (more investors in green solutions). Moreover, the Cloud BMS project facilitate the green transition and open the market for second-hand battery (longer utilisation of battery). Furthermore, it promotes second-hand battery utilisation by defining battery residual value (fewer batteries produces and fewer re-sources used).

- *If Ph.D.'s have been part of the project, it must be described how the results from the project are used in teaching and other dissemination activities.*

  No Ph.D. was trained during the project.

7. Project conclusion and perspective

- *State the conclusions made in the project*

    - Cloud computing can enable AI-based algorithms utilisation for the battery state estimation and RUL prediction. However, these algorithms are implementable when substantial training data is available. The cost of cloud data management undermines some of the benefits of cloud-based algorithms. This should be well managed by performing the cost-benefit analysis for the specific application (it might not make sense for this approach in some applications).
    - There is a high potential for the battery life extension and cost of ownership reduction by employing battery energy management algorithms that are 'battery degradation aware'. The cost of ownership reduction is dependent on the application and is estimated to be between 5% and even up to 50% (in extreme cases when battery replacement in the given product can be avoided due to extended lifetime).
      Modification of the battery usage profile utilisation might bring benefits to the lifetime of the battery but on the other hand, for some applications, it might not be acceptable to the end customers.
    - Reliable battery SoH and RUL are critical for building more trust in batteries amongst customers (especially in the second-hand battery market) and it allows for better warranty risk management for battery system manufacturers.

- *What are the next steps for the developed technology?*

  Lithium Balance will include generated knowledge on the battery state estimation algorithms on iBMS and cBMSver2. However, currently, they are not expected to be cloud-based.

  Xolta is planning to include battery stress factor analysis into its cloud analytic solution. It can provide a better overview of the battery operation for a specific customer and therefore Xolta will be able to give better support to the target customer and better manage the battery system warranty. Xolta is also planning to optimise the energy management of the BAT-80 to extend the battery system lifetime in some of the applications (extended warranty services are expected for some applications in the future).

  BOR is intending to use the knowledge generated during the project for implementing a robot fleet management tool that will extend battery lifetime by managing robot fleet operation profiles.

  AAU intends to improve the SoH estimation algorithm based on the feedback from the project and stakeholder meeting and Xolta is willing to provide test sites. The algorithms will be long-term tested and validated. AAU will also disseminate some of the knowledge generated during the project by conducting updated Industrial/Ph.D. battery energy storage course.

- *Put into perspective how the project results may influence future development*

From the technology point of view, Xolta would like to continue developing the battery analytic tool. On one side Xolta would like to have the opportunity to continue the collaboration with AAU on developing a remaining useful life online model that can update the battery status to Xolta battery operators. Xolta would also like to introduce stress factors to the users, to help them optimize their battery operation and prolong its lifetime. If cloud data management occurs to be too expensive, then Xolta is expecting to perform computation on the battery energy management system computer to minimise the cloud computing cost. From the business point of view, it will be a great breakthrough from the Xolta side to introduce the battery analytic tool to the users and future customers.

It is expected that future Xolta battery systems will be provided with enhanced battery degradation-aware energy management systems that will be focused on battery system extension.

For future products, it is expected that Xolta will be offering extended battery warranty service to the customers based on the estimated battery degradation.

Last but not least, future development is also expected in battery sudden death prediction and to enable the preventive maintenance to minimise/avoid the battery system downtime.

8. Appendices

- Add link to relevant documents, publications, home pages etc.

List of publications:

https://vbn.aau.dk/en/projects/cloud-bms-the-new-generation-of-intelligent-battery-management-sy/publications/

Stakeholder and Customer Workshop:

http://batteriselskab.dk/arrangementer/praesentationer/2021-11-25-workshop-cloud-and-ai-based-battery-soh-estimation-in-various-applications.htm