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ECOBATTEM

(Eco-friendly and Ageing-Aware Energy Management software for Li-ions Battery)

AurorA's Grid
Enabling Ageing-Aware Integration of Battery Storage

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Summary

The ECOBATTEM project has proved that:

1. Low C-rate (below 1C-Rate) and low SoC during micro-cycling have a large impact on ageing mitigation of Li-ion Battery Energy System (BES);
2. A rational management of BES for building application is needed in order to maximize the benefit and extend the lifetime of the BES;
3. Extending the lifetime of BES is essential from a C02 footprint point of view;
4. New business models, such as the leasing one, can involve large deployment of distributed BES and give clear indications to stakeholder in order to define rational subvention of BES;
5. Ageing mitigation via dedicated non-conventional ageing stress test, as well as, ageing-aware energy management seem essential for vehicle to the grid application and second-life battery applications.

Main findings

1. Reducing charging and discharging C-rate in Li-ion cells can mitigate the ageing of the targeted battery up to 95%, while reducing the SoC from 90% down to 50% during micro cycling application (such as primary frequency control) can reduce the ageing of a factor 12.6 (from 300 thousand cycles up to 3.8 million of cycles, experimental findings);
2. The energy management software, integrating dedicated Li-ions ageing model, developed model free and sensor free PV and load consumption forecast, is able to reduce, when it is possible, the C-rate up to 87 %(experimental findings, during 72 days of measurement in the three targeted sites). The associated average ageing reduction and consequent extended lifetime is up to 38.5%.
3. From a C02 foot print point of view, extending the lifetime of the BES up to 38.5%, thanks to an ageing-aware energy management allows for 24% reduction of C02 emission (compared to the same system equipped with a BES without any ageing-aware strategy);
4. The ageing-aware business models showed that adding economic concepts like time value of money (trough leasing) increases the internal rate of returns (IRR) up to 6.14%. The computation for a pooled system enabling multiple revenue streams showed 62.81% of profitable cases with a maximum IRR of 4.91%. Finally, the principle of wealth redistribution leads to IRR bigger than 0% in 29.75% of the scenarios.

Contents

Abbreviations

BES: Battery Energy Storage;

SoC: State of Charge;

SoH: State of Health;

DoD: Deep of Discharge;

V2G: Vehicle to the Grid;

PCR: Primary Control Reserve;

IRR: Internal Rate of Return;

ESR: Equivalent Series Resistance;

EOL: End of Life;

1 Introduction

1.1 Background information and current situation

The recent news about the Nobel Prize of Dr. Goodenough, Dr. Nottingham and Dr. Binghamton deserved the Nobel Prize for Chemistry for their development of Li-ions battery, is a key sign of acknowledgement of the role of Li-ions battery in the energy market.
In fact, they are nowadays deployed to power the portable electronics that we use to communicate, work, study, listen to music and search for knowledge. Li-ions batteries have also enabled the development of long-range electric cars and the storage of energy from renewable sources, such as solar and wind power. This last usage is strictly related to what, on the 25.05.2017 the Swiss Federal Council has decided for, namely to gradually phase out nuclear energy as part of its new energy strategy focused on the increase of energy efficiency and on a large penetration of renewable energy. These two goals are of a major interest for the world-wide community.
As depicted in several references, electricity storage based on Li-ions battery will play a crucial role in enabling next phase of the energy transition [1,2] and in decarbonising key segment of the energy market [3-4].
From a world-wide point of view Adnan Z. Amin, General-Director of International Renewable Energy Agency (IRENA) declared [2] that the role of energy storage based on electrochemical batteries will be crucial for accelerating the renewable energy deployment. Moreover, Michael Breen, CEO of Growing Energy Labs, declares that "the Future of Energy Storage Is Behind the Meter" namely on the customer side. From a national point of view, Benoît Revaz, director of OFEN, declared on March 2016 that the energy consumer will become a prosumer of energy and this involves a change on business model of production and distribution of energy [5].
These three examples rely on these main considerations/forecasted scenario:

i) the exponential penetration of photovoltaic (PV) power plant that happened last decade and on the probability that this integration (rooftop PV) will growth even faster due to the further support of the 2050 energy transition;
ii) world-wide reduction of feed-in tariff;
iii) falling price of Li-ion battery (60% in the last 5 years [2]), moving its usage from niche applications toward broader uses.

Among the different applications of battery energy systems (BES), the most interesting in term of i) world-wide economic impact and ii) revolution of energy sector is the one coupled with rooftop PV [3-4]. As example, in Germany 40% of small-solar PV systems have been installed with BES in the last few years and in Australia, with no financial support in place, more than 7000 small-scale BES were installed in 2016 [6]. These numbers will increase exponentially the incoming years and, by taking into account the future deployment of electric vehicles, IRENA declared there will be a 17-fold growth of battery storage installed capacity world-wide by 2030 (referred to the value of 2017).

The main goals of coupling a rooftop PV plant with a BES are:

i) increase the energy self-consumption and consequently decrease the CO_2 impact of the building;

ii) having a device, the BES, available for a set of ancillary services to be provided to the power-grid (such as peak shaving, voltage control, frequency control, charging of electric vehicle, etc.).

From an electrochemical point of view, these types of usage are characterized by different performances, such as high-pulsed power for short-duration, different charge and discharge cycles, different involved temperature, high-number of cycles with low value of energy (the so-called micro-cycling) and so on. These requirements involve a non-negligible effects on the performance degradation of the battery, namely its ageing. For example a temperature increase of 10 ˚C will reduce the lifetime of a battery by 50% [2], while doubling the charge/discharge current can dramatically reduce the cycling lifetime (4000 cycles at DoD 90% with 0.25 C-rate versus 3000 cycles at DoD 90% with 0.5 C-rate [7]) and an increase of 60% of average state of charge (SOC) can involve higher capacitance fading (increase of 8% in 8 years [7]).
As battery owners and operators looking to maximise the returns from their assets, they have to face off with the challenge of managing degradation of BES. Additionally, the ageing minimization is especially important as single/multi-service batteries have the option of participating in a variety of markets, such as frequency regulation, and each market can have a different risk level according to the asset's load profile and cycling behaviour. Consequently, ageing-cost models of BES have to be built accounting for performance fading associated with these future usages.

From an economic point of view, all the above BES usages request a calculation to estimate the current and future cost of these services for an array of applications and consequently there is the need of a new business model description.
Moreover, there is an incoming need from utility to aggregate distributed BESs in order to create a kind of virtual-plant for providing ancillary services to the grid [8]. Since the BESs can be located in different places, can have different performances, state of health (SoH) and available capacity, it is important to investigate the possibility to deploy, from an ageing-aware point of view, the optimal combination of BSSs.

i) minimizing the performances degradation of the BES for extending its lifetime;
ii) increase the number of cycles and consequently decrease the cost per kWh;
iii) overall indirectly decrease the whole C02 emissions for clean renewable energy deployment.

1.2 Purpose of the project

The pilot project proposal entitled ECOBATTEM Eco-friendly Energy Management for Battery Storage Systems has focused to address the following research questions:

1. *How we can manage the performances degradation of Li-ions BES in order to increase their lifetime, reduce the environmental impact and enable large penetration of renewable energy conversion systems in buildings?*

2. *How is possible to forecast PV production and load consumption of a building with a sensor-less and not-costly equipment?*

3. *Within the 2050 Energy Strategy, it is possible to aggregate distributed BES and settle down the challenges associated with large penetration of renewable energy conversion systems?*

4. *From an utility and battery manufacture point of view, which are the most suitable business models for the promotion of home-Li-ions battery storage systems?*

1.3 Objectives

By taking into account the above listed research questions, we here summarized the obtained results.

1. *How we can manage the performances degradation of Li-ions BES in order to increase their lifetime, reduce the environmental impact and enable large penetration of renewable energy conversion systems in buildings?*

ECOBATTEM Pilot project shown that for BES dedicated to increase the renewable-energy self-consumption, it does not make sense to charge and discharge the targeted battery with the maximum available power. On the other hand, since decreasing the C-rate (both in charge and discharge) can largely mitigate the degradation of the BES (up to 86%) it is important to have an ageing-aware energy management. From an LCA point of view, increasing the BES lifetime is a *sine qua non* condition for mitigating their C02 footprint.

2. *How is possible to forecast PV production and load consumption of a building with a sensor-less and not-costly equipment?*

In the context of the ECOBATTEM pilot project we have developed a forecast technique able to predict and classify (via a machine learning approach) the value of PV production and load consumption at different time steps with an average accuracy ranging from 85-95%. The developed technique does not require any solar irradiance sensor, neither any high-resolution sky camera or any PV/load model of the building. We just need measurements of PV production and load consumption and our algorithm "learns" the behaviour/dynamics of targeted PV and load consumption. It is worth observing that the majority of PV installations are already equipped with power sensors and consequently our forecast technique does not add any additional hardware cost.

3. *Within the 2050 Energy Strategy, it is possible to aggregate distributed BSS and settle down the challenges associated with large penetration of renewable energy conversion systems?*

The proposed EMS is running in a master Rasperry PI and it is able to send optimal ageing-aware set-points to the three targeted batteries connected to the grid (with forecasted usage of these batteries for providing primary frequency control). Of course, the BES having the highest SOH is able to follow the primary frequency control power set point, while if the SOH is not enough (since the equivalent series resistance is high) this goal is not totally achieved.

4. *From an utility and battery manufacture point of view, which are the most suitable business models for the promotion of home-Li-ions battery storage systems?*

ECOBATTEM pilot project focused on original business model description for home storage systems/pool of BES. We observed that the leasing of a BES between an end-prosumers and a local DSO or battery manufacturer is the most profitable win-win business model by only considering the current scope of available revenue stream. Some results show that a market liberalization enabling pooled small-scale installation to provide additional services could widely contribute to the promotion of home-Li-ions BES and enhance the ecosystem profitability.

2 Description of facility

The experimental validations of the proposed eco-friendly energy management software took place in three different sites:

1. **Microgrid at Yverdon les Bains,HEIG-VD.**

In this site a 100kWh/100Kw Li-ions Titanate BES is coupled with a whole distributed PV power plant of 70 kW connected to a local microgrid. Figure 1 illustrates the BES located at HEIG-VD.

2. **Smart-Building at Blue-factory at Fribourg, HEIA-FR.**

In this site a Leclanché Apollion Cube 5 kWh/5kW NMC-G Battery system is coupled with a 6.2 kW peak PV power as well as 5kWp heat-pump.
The listed infrastructure is connected to a living lab environment prosuming energy for currently 80 people in office sector. The infrastructure can be accessed remotely enabling readouts of historical data and/o controllability of the mentioned components.
Figure 2 illustrates the BES located at HEIA-FR.

3. **Smart-Building at Empa Institute (Canton Zurich).**

In this site a Leclanché 100kWh/100 kW NMC-G Battery is coupled with a 80 kW PV peak power.
This BES coupled with PV is connected to a living lab environment prosuming energy for currently 20 people in residential, office, leisure and mobility sector. The infrastructure can be accessed remotely enablingreadouts of historical data and/or controllability of the mentioned components.
Figure 3 illustrates the BES located at EMPA.

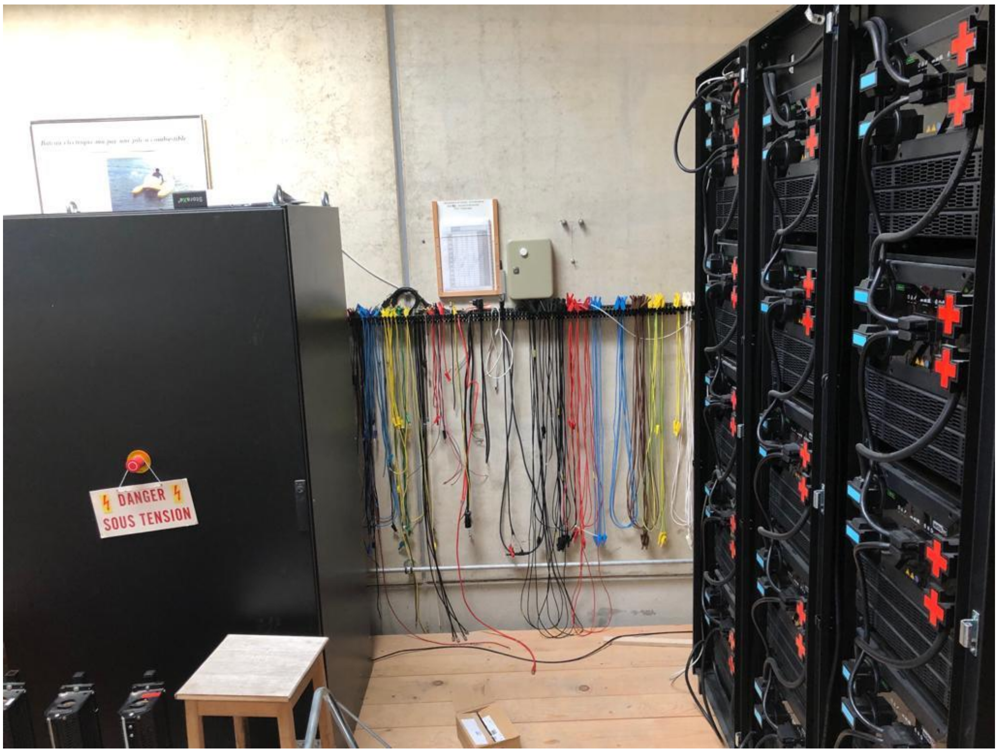


Figure 1: BES at HEIG-VD.

Figure 2: BES at HEIA-FR.

Figure 3: BES at EMPA.

2.1 Starting issues

The measurement infrastructure has been enhanced at the three above sites and some issues have been detected during the experimental phase mainly associated with shut-down of local server and communication protocol issues.
Moreover, for the battery located in the smart-building at Fribourg, some of the Li-ion cells composing the BES are strongly imbalanced (referred to the other cells of the BES). Several times, it happened than even if we reached SoC of 10%, some of them were to 0% and consequently the protection system turn off the inverter. Due to the self-consumption associated with the BMS, the BES continued to be discharged at negative SOC values and in order to fix this problem each time we had to charge, with an external power converter the targeted battery with a very low current (as shown in Figure 4).

Figure 4: low C-rate charging of BES at Fribourg to fix unbalanced cells.

Some problems of unbalanced voltage in the cells happened to the BES located in Yverdon les Bains. As discussed during the presentation of ECOBATTEM project hold on 24th June 2019, we extended the experimental investigation of the proposed EMS, without any additional cost from OFEN side (Aurora's Grid provided the needed HR) for 4 weeks. The Partners of the project as well as Mr. Wirz and Mr. Moser agreed on this matter.

3 Procedures and methodology

3.1 Starting issues

Unfortunately, the BES sizes have been chosen before starting the ECOBATTEM project, and due to the already installed PV plant sizes and the load consumption, it is possible to assume that the BES size were not optimal (in some case oversized and in other undersized). In this respect, even with this challenging conditions, we have been validated our EMS but we had, virtually change the size of the inverter of the BES and the peak power consumption. We here listed the original configuration and the modified one for each site:

- Fribourg, 5.2 kWh, inverter of 6 kW, 6 kW PV peak power, load consumption around 2.5 kW that has been amplified by a factor 2;
- Yverdon les Bains, 100 KWh, inverter of 100 kW (modified to 50 kWh/50 kW), PV peak power of 50 kW et load of 133 Kw (modified to 25 kW);
- Empa, battery of 100 kWh, inverter of 100 kW (modified to 50 kWh/50 kW), PV peak power of 73 kW, load of 85 kW (modified to 55 kW peak).

3.2 Methodology followed for development of the proposed EMS

The methodology followed for developing, testing and fine-tuning the proposed EMS has been the followed:

1) Ageing model enhancement for Li-ion cells;
2) Development of Forecast technique for PV and Load consumption;
3) Deploying real PV and load measurements acquired for more than one year (acquired even before the starting of the ECOBATTEM project) and coupling them with the forecast tool previously developed;

4) Simulating, in an emulated environment with real measurement of PV and load consumption, the installation of a BES, receiving as input the PV forecast and the Load forecast. The output of the EMS was the charging and discharging profile of the BES;
5) Once sufficient results have been obtained in emulations/simulations and while the forecast tool along the ageing model of the battery was improved, we start the experimental validation;
6) Based on the experimental data associated with the real current profile deployed with the 3 targeted BESs we enhance the algorithm (described later on) behind the EMS.
7) We stopped enhancement of the EMS once we achieved the ageing reduction of 38% (computed by using the experimental C-rate reduction and the performed ageing test), since this was the quantitative objective of the project (up to 40%).

3.3 Methodology followed for ageing test characterization

One of the main goals of ECOBATTEM project was the experimental characterization of Li-ion cells under not- conventional operating conditions such as low C-rate and micro cycling. The choice of these two types of test has been detaiedl in the project proposal but we here summarized the mains reasons:

- Low C-rate: this test has been performed since the main claim behind the project was that cycling the BES with a current lower than 1C could significantly reduce the capacity fading;
- Microcyling: this test has been performed since, for ancillary services, such as primary frequency control, the BES should deliver and received high pulsed current with low energy content, the so called micro-cycling.

The End Of Life (EOL) of a cell is the time (or number of reference cycles) after which a cell is not anymore capable to deliver the designed energy, for whatever reason; such parameter is strongly application-dependent, the Li-ion community, both industrial and academic, came up with some conventional definitions of EOL, the most widespread of which is the 80% (sometimes 70%) of initial capacity. Without retracing the history of that, it might be interesting to add two reasons which are related to that particular choice:

- The early graphite-based Li-ion technology did show a capacity fading which was linear down to 80% of initial capacity ([8-9];
- The 80% criterion matches the lifetime definition of other technology coupled with Li-ion, as for example PV plant (that are in the scope of ECOBATTEM project).

Consequently, the number of cycles associated with the above 20% capacity fading have been considered as a benchmark value to compare different chemistries or battery manufacturer. As example TESLA's cell can achieve 400 cycles at DoD 100% with 1 C-rate while other type of cells such the one provide from CATL or Yuasa cell can reach 3000/5000 cycles (in the same operating conditions). These values are not obtained by experimental characterization involving a real ageing of 20%, but based on the electrochemical assumptions that capacity fading in Li-ion cells is linear (if nominal operating conditions are respected, namely no temperature or voltage abusive test). The whole

worldwide battery research community has extrapolated the EOL thank to the capacity fading measured during few hundreds of initial cycles.
The targeted cells of ECOBATTEM project, is the one manufactured by Leclanché SA, with a declared lifetime of 3500 cycles at DoD 100% and 1C-rate. The targeted test in the context of the ECOBATTEM project, were extremely time consuming (as all the battery ageing test). In fact, if we consider the cycling at 0.25 C-rate, one complete cycle requires almost 10 hours namely 10 thousand hours for performing 1000 cycles, namely more than one year. Keeping a test for this long time window, from our scientific point of view and based on the available literature, is not-useful. Consequently, even in the context of ECOBATTEM project, we assumed that:

- the EOL criterion is the number of cycles needed for reaching 80% of the initial capacity, and we extrapolate such a value based on a short (however several months of test) duration of ageing test. Once the “slope” of the capacity fading was detected, we stopped the ageing test.

- The fair comparison between different usages of the targeted cells, already deployed from industrial and academic battery community, has been to directly compare the benchmark value of cycling life associated with the EOL criterion

.
The bench test, shown in Figure 5, has been financed by the Smart Living Lab at HEIA-FR. It is composed by:

• an environmental chamber hosting the targeted cell with operating temperatures in the range -40 °C up to 360 °C. In steady state conditions, the temperature ripple is of ±0.1 °C.
• a power source working in the following V/I ranges 0-80 V, 0-120 A;
• an electronic load working in the following V/I ranges 0-80 V, 0-200 A;
• a control PC using a properly implemented software is developed in the LabView programming environment. This device/program is able to perform the monitoring and control of the whole system;
• a 4 k-type thermocouples with temperature measurement range from 0 up to 250 °C, maximum error of ±0.1 °C are used in our setup.
The electronic load and power supply are characterized by an overall bandwidth spanning from DC to 1 kHz. The cell voltage has to be sampled using an analogue-to-digital converter operating with a resolution of 16 bits with a maximum sampling frequency of 100 kHz. This sampling and monitoring system has to be characterized by a bandwidth from DC to 100 kHz (-3dB) with an overall accuracy of 1.5 mV.

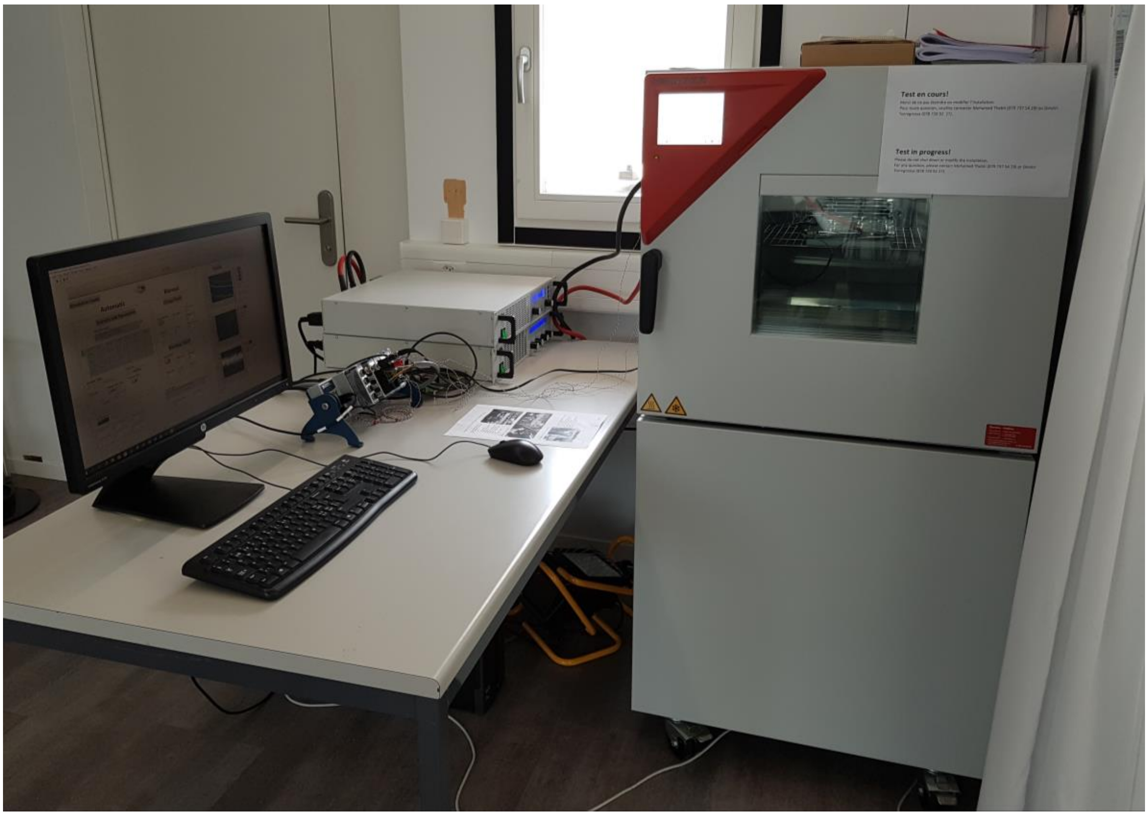


Figure 5: bench test for ageing characterization deployed at HEIA-FR

3.4 Methodology followed for validation of the sensor-less model free PV and Load Forecast

When conceiving the methods used to forecast the power production and load consumption, we wanted to make sure to have algorithms that yield accurate results, but at the same time be feasible to implement on a limited capacity processor and hence inexpensive from a computational and hardware point of view. Moreover, we aimed to have an algorithm that works in "plug-and-play" mode as part of the installed EMS, without the need for human intervention or sensor calibration by a technician.

Supervised learning classification techniques are great in predicting the class of an observation using a set of features. However, they require to be trained on a set of labeled data. This means that in order to integrate such a technique in our EMS, we would need someone to manually label the frames into their true classes. Therefore, this option has been discarded.

Then, we decided to split the process of finding the class into two steps: the first is to estimate the value of the production or consumption, and the second is to map this value to its corresponding class. In the section dedicated to the developed algorithm, we have detailed the method to estimate the

value in the first step. For the second step, we have determined the number of classes for each of the production and consumption, according to the type of action that our EMS will perform in different cases. Our EMS needs to operate in one of 3 production modes, mapped to weather states as: Sunny, cloudy, and mixed. Similarly, the EMS has 7 modes of operation for each of the load consumption classes (*'Very low', 'Low', 'Average low', 'Average', 'Average high', 'High',* and *'Very high'.).* To map a numerical value to a class, we used thresholds which were set dynamically, this guarantees a low computational load on the processor and hence a fast response time for the EMS in real time.
After designing the forecast algorithms, we used recorded data of the production and consumption of one site in Switzerland in Neuchatel (since more than one year of measurement were available) to test and validate the results of the algorithms before we integrate it in the real time EMS.

3.5 Methodology followed for preliminary LCA analysis

Prior to the life cycle assessment of the building coupled with BES and PV, multiple analyses were necessary.
Firstly, the cradle-to-gate life cycle assessment of two Li-ion battery chemistries was performed, the lithium-titanate (LTO) and the lithium nickel manganese cobalt (NMC). To this end, inventories were created with information provided by a manufacturer and with additional data from the available literature.
Secondly, the carbon content of the grid of four countries (France, Germany, Sweden and Switzerland) was modelled in order to improve the accuracy of the electricity use carbon footprint in the analysis. The evolution of the carbon footprint is assessed for an entire year with a time resolution of 1 minute.
Thirdly, the life cycle impact assessment of the building was done for multiple scenarios (these scenario have been suggested by SFOE Committee during revision of ECOBATTEM proposal). These scenarios are a building with electricity supplied:

- only by the grid;
- by the grid and a PV rooftop plant;
- by the grid, a PV rooftop plant and a Li-ion battery.

The CO2 impact of these scenarios was evaluated for a battery of first-life. Finally, an additional use case scenario with Aurora's Grid EMS (EMMA) was performed in order to limit the ageing of the battery and extend its lifetime. Thus, improving the environmental footprint of the system with a better lifetime. One of the strength of the analysis is that the LCA directly includes an electrochemical ageing model. The cradle-to-gate analysis of the batteries included many environmental impacts such as global warming potential (CO2 footprint), fossil depletion, freshwater eutrophication and so on. The cradle-to-grave analysis only considered the CO2 footprint for the sake of simplicity. This LCA analysis highlights that for Switzerland inputs we're able to reduce the CO2 footprint of a building equipped with a BES with an ageing-aware strategy up to 24%.

3.6 Methodology followed for original business model description

During the preliminary discussions about the business model we decided to use the Internal Rate of Return (IRR) computation in order to assess the profitability of a BES investment. The strength of the IRR lies in its easy comparison with key economic metrics such as the Weighted Average Cost of Capital (WACC) and Risk-free rate, commonly used in project profitability assessment. The main idea was then to apply different economic concepts on the principal IRR factors namely, costs and revenues in order to increase the profitability of the BES itself.

The first thing we looked for, it was to reduce the large initial investment of a BES project. We decided to diversify the cost recognition by using a leasing payment. This model offers a way for the end prosumer to increase their profitability through the concept of time value of money.

For the second business model we decided to extend the analysis to the revenues by implementing additional feasible BES services that should arise with a market liberalization such as ancillary services.

Finally, we choose to consider a case that allows an enhanced revenue generation due to the participation of the DSO in the ownership of the BES. This model aims to equally reallocate the costs and revenues of such an investment between the prosumer and the DSO trough a co-ownership of the BES.

3.7 Hierarchic structure of the proposed EMS.

Once the above modifications (associated with the wrong size of BESs) have been performed, our energy management software has been implemented in Python and run on a master Raspberry Pi board, located at Aurora's Grid premises in Lausanne. In order to control the batteries at different sites (HEIA-FR, HEIG-VD and EMPA), our EMS communicates securely using TCP/IP protocol to retrieve data and send commands accordingly:

- for the site in Fribourg (HEIA-FR), the master raspberry pi communicates with a slave raspberry pi board on site, this latter is placed next to the battery inverter and forwards the optimal power setpoint commands directly to it;

- for the site in Yverdons (HEIG-VD), the battery inverter is controlled with a Labview program run on site, and is controlled by the master raspberry pi;

- for the site in Zurich, the raspberry pi communicates the commands to a gateway called OPCUA server which then controls the battery inverter accordingly.

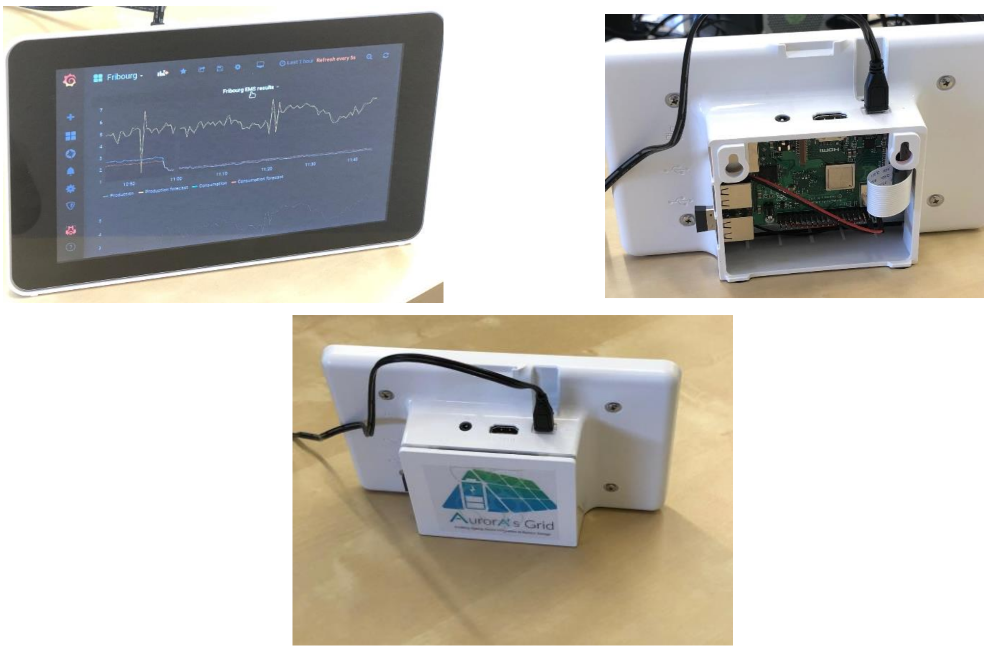


Figure 6: our EMS software, hardware facility.

4 Results and discussion

We have structured the results of ECOBATTEM project on 5 main sub-topics, by highlighting the innovation of each one achieved thanks to the project itself.

4.1 Experimental Ageing Tests, Pulsed Application with micro-cycling

One of the sub-goal of the ECOBATTEM project is the enhancement of knowledge of performances degradation of Li-ions BES in order to increase their lifetime, reduce the environmental impact and enable large penetration of renewable energy conversion systems in smart buildings. In order to achieve this goal not conventional ageing characterizations of Li-ions cells have been planned:

- Experimental characterization of capacity fading and increase of equivalent series resistance during micro cycling, one value of DoD lower than 10% (performed at two different DoD, 0.1 and 1 % at average SOC equal to 90% in one case and 50% in another case).;

- Experimental characterization of capacity fading and increase of equivalent series resistance during cycling test at charge and discharge rate of 0.25C and DoD of 100% (started and completed at early April 2019);

- Experimental characterization of capacity fading and increase of equivalent series resistance during cycling test at charge and discharge rate of 0.25C with DoD of 80% (started in August 2019 and completed at early October 2019).

It is worth noting that the above not conventional types of stress are related to the new incoming usage of BES with modern smart-grid.
The first experimental results are very interesting and encouraging for large deployment of BES for ancillary services and for deployment of software managing the BES and reducing their ageing, since we are proving that i) low C-Rate has a large mitigation ageing impact and ii) high pulsed power typical of ancillary service to the grid has not large impact on the ageing (consequently BES could be deployed for this purpose).
Figure 7 illustrates the capacity fading of Li-ion NMC cell of 43Ah when is cycled at 1C-Rate with a DoD of 1.1%, namely pulsed current of 40 s duration. By observing this figure, it is possible to assume that 3.8 millions of cycles could be performed while the BES is providing ancillary services. Consequently, it is possible to assume that the main ageing stress factor will be the calendar ageing instead of power cycling test.

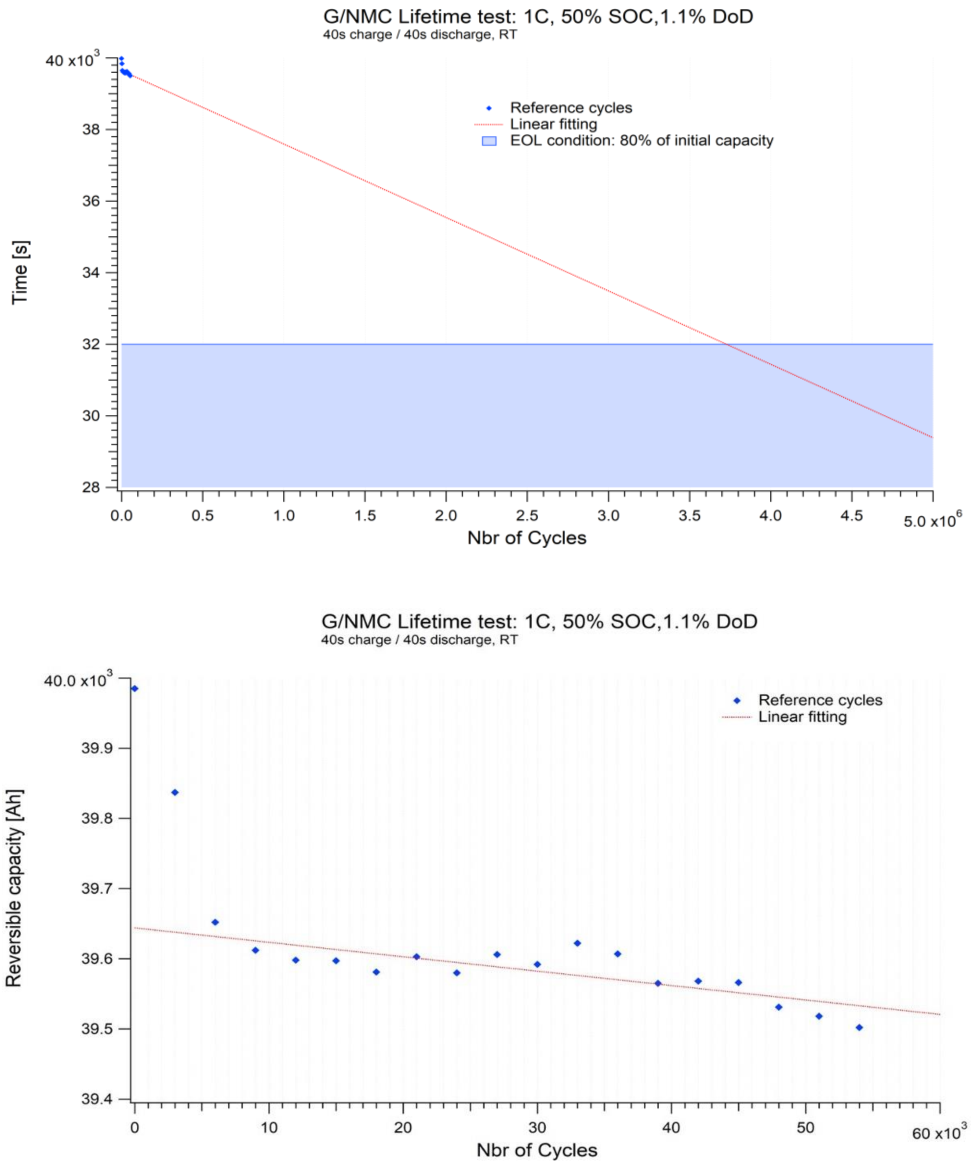


Figure 7: capacity losses of Li-ion NMC cell versus cycles at DoD equal to 1.1% and SOC equal to 50%.

In order to account for the combined calendar ageing during power cycling test, the same ageing test has been performed but with an average SOC equal to 90%. The results are very original and surprising: while keeping the same pulsed current the increase of SOC involves a lifetime drop from 3.8 millions of cycles down to 300 thousand (Figure 8). Consequently, it is extremely important to keep the SOC of the BES as lowest as possible during ancillary services.

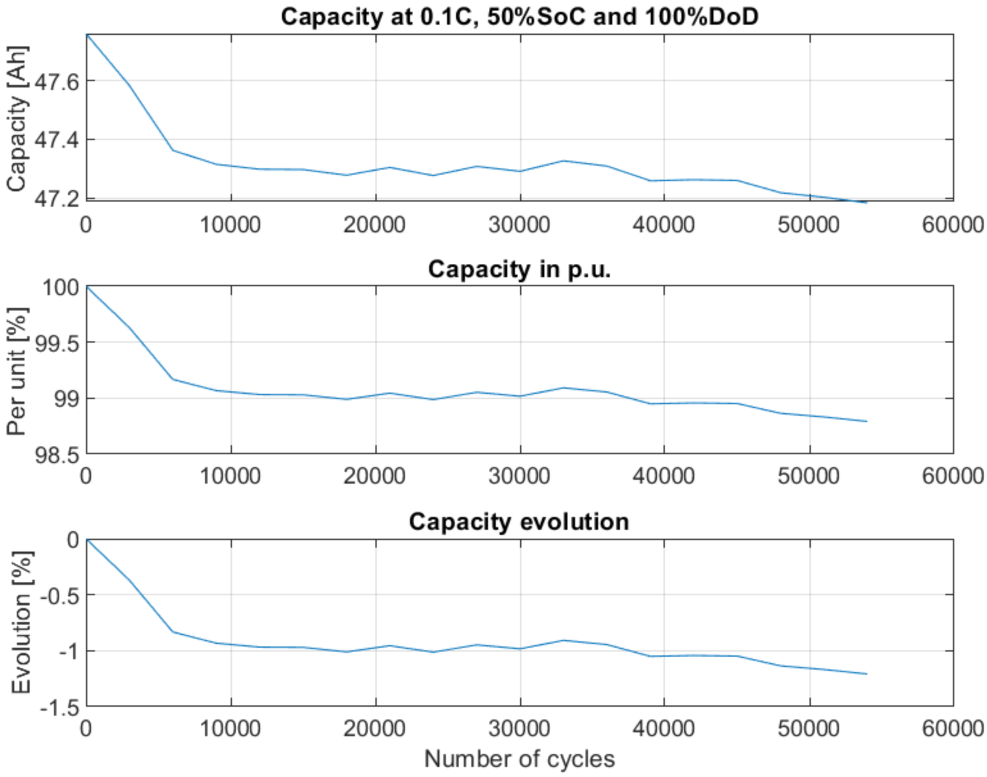
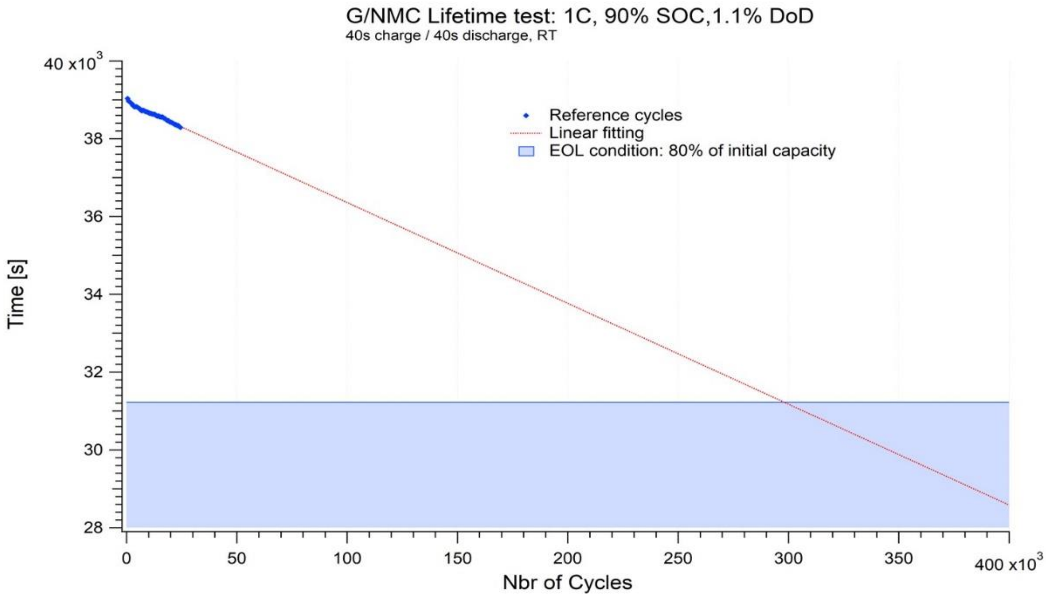


Figure 7 (bis): capacity losses of Li-ion NMC cell versus cycles at DoD equal to 1.1% and SOC equal to 50%.



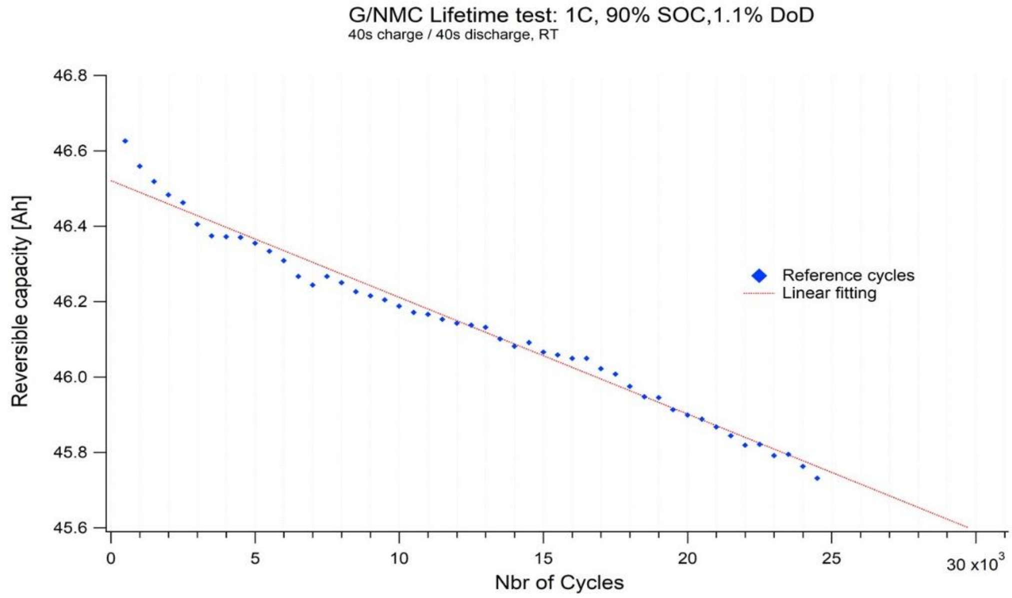


Figure 8: capacity losses of Li-ion NMC cell versus cycles at DoD equal to 1.1% and SOC equal to 90%.

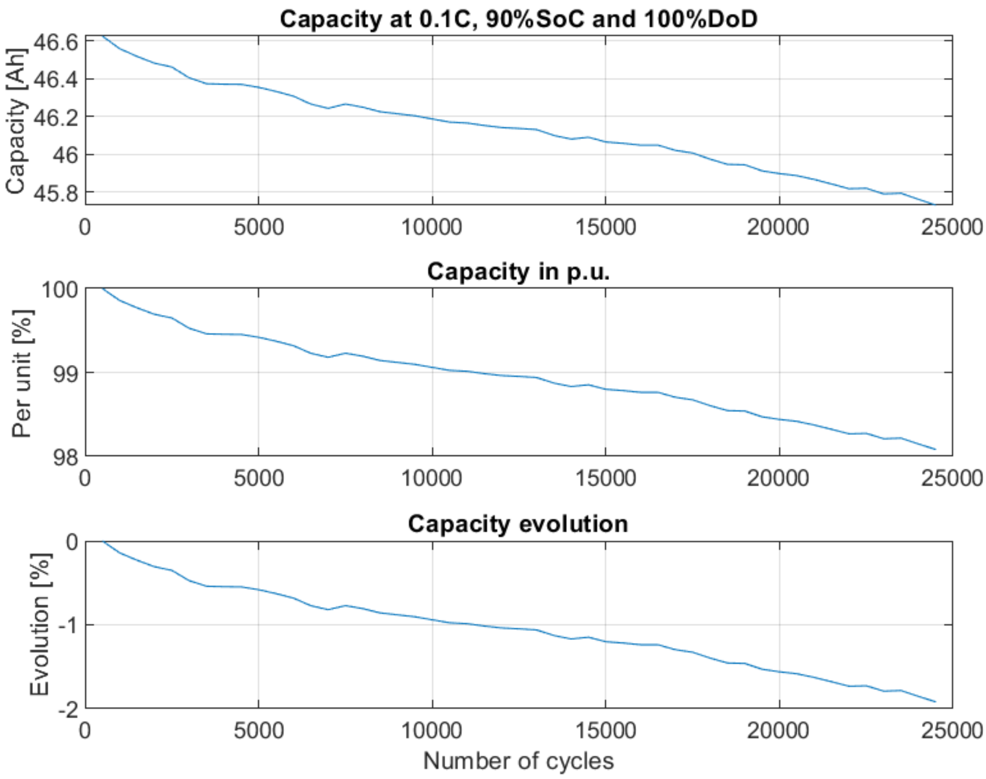


Figure 8 (bis) : capacity losses of Li-ion NMC cell versus cycles at DoD equal to 1.1% and SOC equal to 90%.

4.2 Experimental Ageing Tests, Lowering C-rate

Figure 9 and 10 illustrate the time evolution of the capacity fading of the targeted Li-ion NMC cell versus the number of cycles during an operating condition characterized by a charging and discharging C-Rate equal to 0.25 C and a DoD equal to 100%. From the experimental test, and as expected by Aurora's Grid *as preliminary consideration before submitting the ECOBATTEM project proposal*, reducing the C-Rate current has a non-negligible effect on the mitigation of the ageing of the cells. In fact, without any C-Rate limitation, the owner of the battery could deploy the nominal current for cycling the battery itself (C-Rate equal to 1 and for other application even above). However, the goal of the energy management software developed by Aurora's Grid is to limit the C-Rate at 0.25 C in order to mitigate the capacity fading. From a scientific point of view, the community of researcher working on ageing of Li-ions battery needed this type of information.
More specifically, Figure 9 illustrates:

- The evolution of capacity fading of Li-ion NMC cell when stressed at 1C, DoD 100% at 30 ˚C (the yellow line). This capacity fading is based on data sheet given by the manufacturer.
- The evolution of real measurement of capacity fading (blue line, characterization performed at 0.1C) of the same cell stressed at 0.25 C DoD 100% at 30 ˚C;
- The extrapolated model of the capacity fading (the red line) at 0.25C, DoD 100%.

By observing this figure, it is important to underline that during the first 350 cycles, due to electrochemical phenomena explained in previous publications [10], the capacity of the targeted cell gets higher than the starting value, then the ageing process starts and it is possible to detect the so-called linear trend, from which we can extrapolate and compare the ageing process with the same type of stress at 1C (Figure 10).

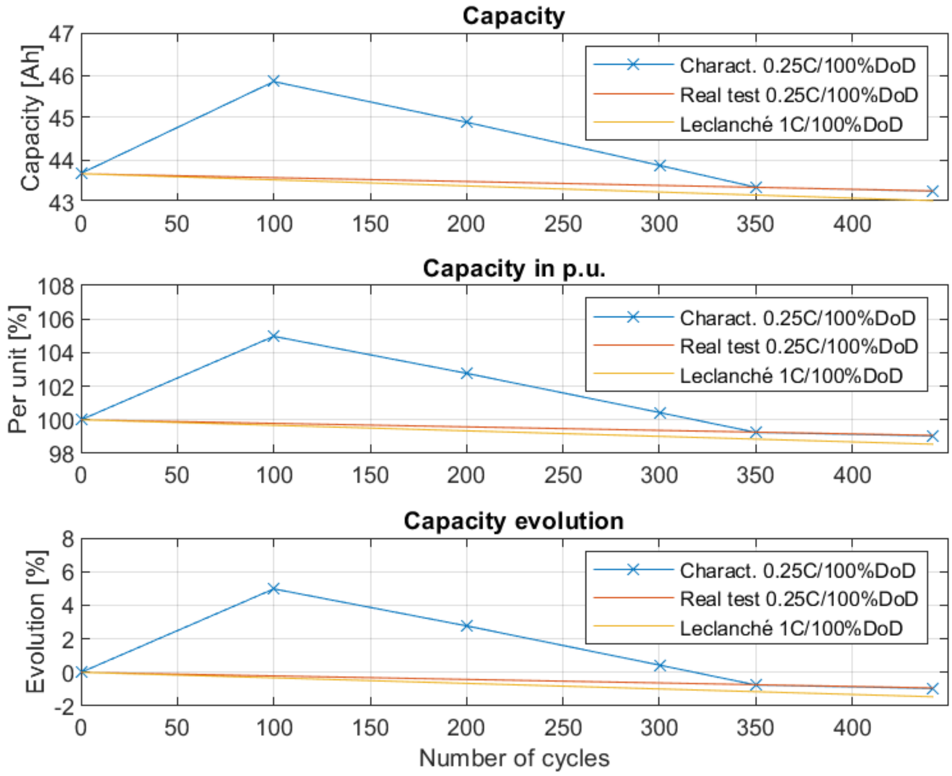


Figure 9: real measurement of capacity losses of Li-ion NMC cell at DoD equal 100% and C-rate equal 1 and 0.25

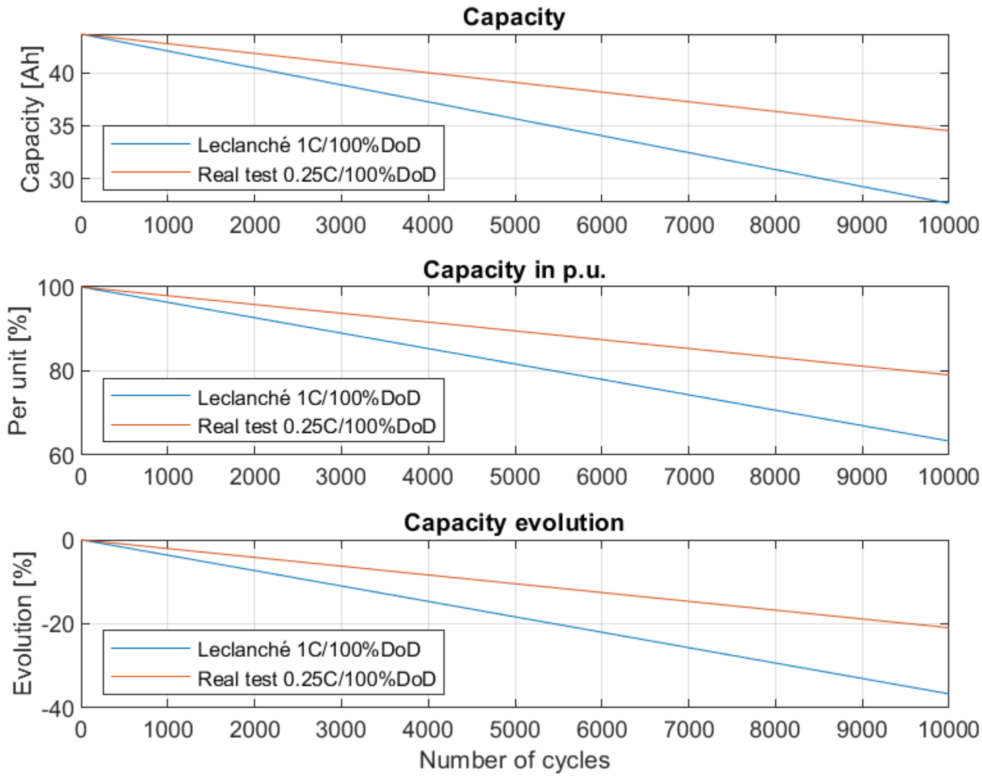


Figure 10: extrapolated mode of capacity losses of Li-ion NMC cell at DoD equal 100% and C-rate equal 1 and 0.25 .

The results of Figure 10 show that after 9800 cycles the cell stressed at 0.25C lost 20% of the initial capacity, while in order to obtain the same capacity loss at 1C rate, only 5500 cycles are required. Consequently, at 0.25 C-rate the lifetime is extended of 4300 cycles that means around 86%.

In the same way, Figure 11 illustrates the time evolution of the capacity fading of the targeted Li-ion NMC cell versus the number of cycles during an operating condition characterized by a charging and discharging C-Rate equal to 0.25 C and a DoD equal to 80%. In the same graph the evolution of capacity fading with 1C rate at DoD 80% is plotted. By observing this figure, it is possible to make the following consideration:

a) the capacity of the cell cycled at 0.25 C, after 400 cycles is still higher than its starting value. Consequently, it is not possible to evaluate the so-called linear trend of the capacity fading.

b) What stated above, relies on the following consideration. Normally, decreasing the DoD from 100% down to 80% involves a mitigation of the ageing process of around 60%. Consequently, since at 0.25 C DoD 100% we started to observe capacity fading after 350 cycles, at DoD =80% we should start to observe capacity fading around 560 cycles.

It is extremely important to underline that with lower C-rate, the internal and surface over temperature of the targeted cell is also lower (power losses depends on the square current). Consequently, with lower C-rate we obtained an additional advantage that will further mitigate the ageing.

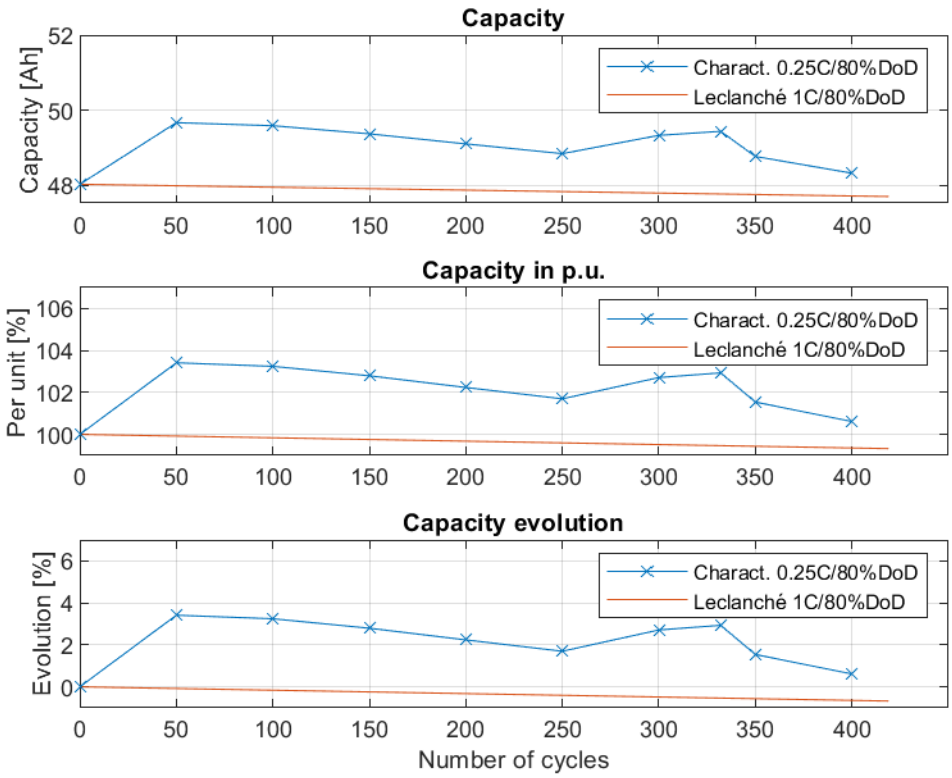


Figure 11: real measurement of capacity losses of Li-ion NMC cell at DoD equal 100% and C-rate equal 1 and 0.25

4.2 Model Free and Sensor Free Forecast of PV production and Load Consumption

Production forecast (machine learning approach)

Preliminary considerations.

To the best of our knowledge, the totality of the PV and Load forecast techniques require i) either complicated PV or load model, ii) either expensive sensor (such as high resolution sky-camera or irradiance sensor) with associated installation cost of these sensors and iii) weather forecast data.

The aim of installing a BES couples with a building equipped with PV is not to forecast the PV production or the load consumption with an accuracy of 99%, but, on the other hand, it is necessary to have an indication (with an accuracy of 85-95%) of both PV and load consumption value, evaluate their time difference and compensate such difference (positive or negative) with the battery energy capacity (it can absorb energy from the PV or inject energy to the building).

From this stand-point, we have developed the first world-wide PV and load forecast capable to predict those values with an accuracy of 80-90% without any sensor and any PV model.

This technique is the core part required by our EMS in order to mitigate the charging and discharging power of the BES and consequently its ageing.

As follow, the description of our algorithm based on a pattern classification machine learning approach (this description is part of a the whole EMS description for which there is a pending patent to be finalized within 23rd November 2019).

Technique description

The aim of the production forecast is to predict the PV power production value in the next time window, this value depends on the solar radiance. We have studied the variations of solar radiance, and found out that the production value is strongly correlated with the last measured points, rather than the historical production data, with the most recent point having the largest weight.

Since the variation in solar radiance is generally gradual, the change in production value over short time windows (30sec up to 15min) is assumed to be linear, and hence can be calculated with high accuracy using a linear combination of the last points. We use this formula to predict the production value:

$$prod(t+1) = prod(t) + \Delta_t * trend$$

where trend = (prod(t-1)+prod(t)) / 2 and $\Delta_t = (t+1) - t$ (=1 with normalized sampling rate)

Using this formula, the result prediction accuracy is >99% on average in all our tests at 30 s, it gets around 90% for 5-15 minutes ahead prediction.

The forecasted production value is then classified into one of three weather classes: Sunny, cloudy, mixed. Consequently, our PV forecast gives also a relative indication of the PV production compared to the maximum value that could reach during a sunny day. This correlation between the maximum PV production during the day and the real-time measurement is performed for each time sample. This correlation, is the most important and original part of the developed EMS, because thanks to this information it is eventually possible to reduce the C-rate applied to the BES: Preliminary to the measurement we know which should be the range value of PV production in order to be classify it in one of the three above sub-classes.

As example, Figure 12 shows the prediction of our PV forecast compared to the real time measurement with a sampling time of 5 minutes.

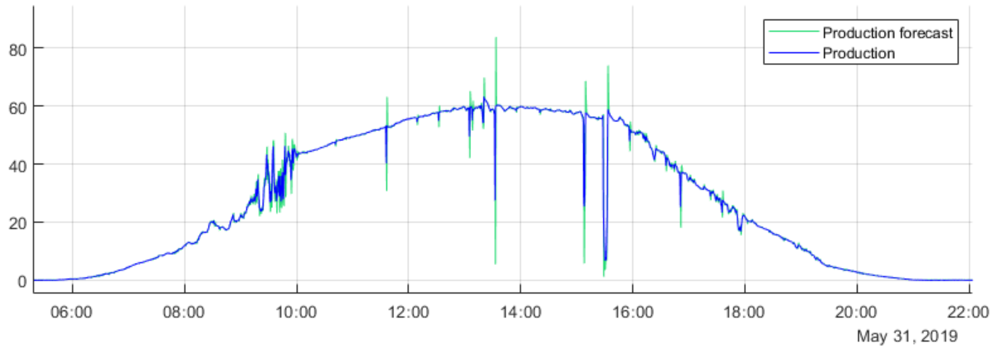


Figure 12: example of PV forecast at Empa facility, May 2019

Figure 13 illustrates as example, the pattern classification (Sunny-S, Cloudy-C, Mixted-M) of the PV forecast for the facility located at EMPA. By observing this figure it is important to highlight that even if the absolute value of the PV power has not been forecasted accurately during the high dynamics, the pattern classification has been accurately forecasted.

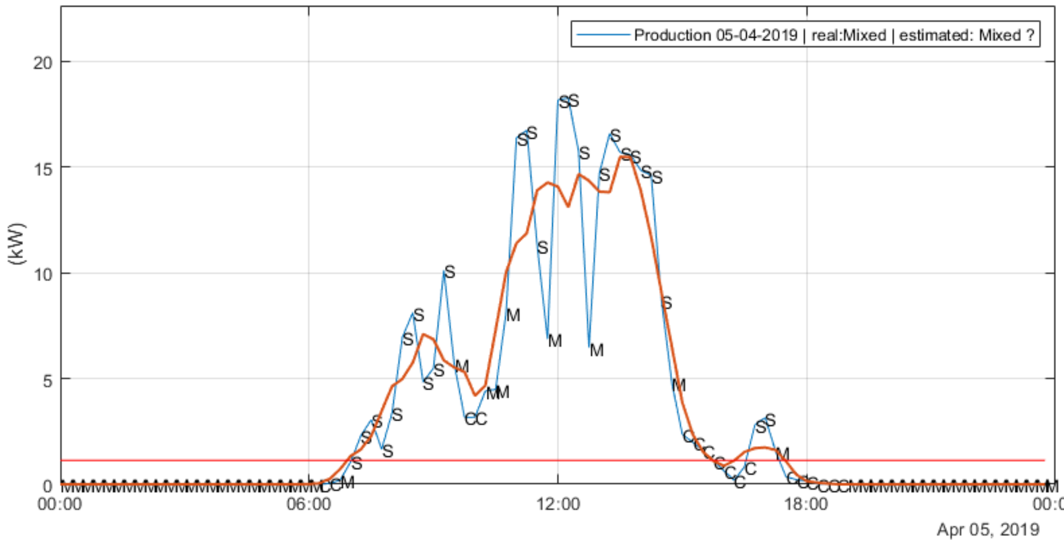


Figure 13: example of real-time pattern classification of PV forecast at Empa facility, April 2019

Consumption forecast:

By following exactly the same methodology developed for the PV forecast, we adapt the same pattern classification technique to the load consumption.

The aim of this forecast is to predict the load consumption value in the next time window given historical consumption data. This value is then classified into one of these classes:

'Very low', 'Low', 'Average low', 'Average', 'Average high', 'High', 'Very high'.

We choose an higher number of classes compared to the PV pattern classification since the variability of the load, incorporating the unpredictability of human behaviors, was higher.

To predict the next consumption value, we use a combination of historical statistics, in addition to the recent measured values:

consumption(t+1) = α * consumption(t) + β * consumption(t-1) + γ * historical_consumption - δ * previous_error

where α = 0.25, β=0.25, γ = 0.5, δ=0.5

previous_error = previous_forecasted_cons - real_cons_value

The historical_consumption is the most challenging step, in fact in order to calculate an exact value, we consider the historical consumption data over the last 14 days, and we differentiate between week days and weekends. Moreover, we split each day into 8 time slices where each slice is of 3 hours duration. We used the so-called sliding time windows. The consumption values are averaged over each time slice and the result is stored as historical_consumption, and used in the above formula.
Our method guarantees the following:

- The change of consumption behavior between weekdays and weekends, is reflected in the calculations;
- The change of consumption behaviors between different day times (morning, afternoon, evening, etc.) is reflected in the calculations;
- Changes in consumption over seasons are taken into account, since the historical data is averaged in a moving window over last 14 days;
- The abrupt changes in the consumption are directly reflected as well;
- The correction factor taking into account the previous error guarantees a convergence towards the correct value.

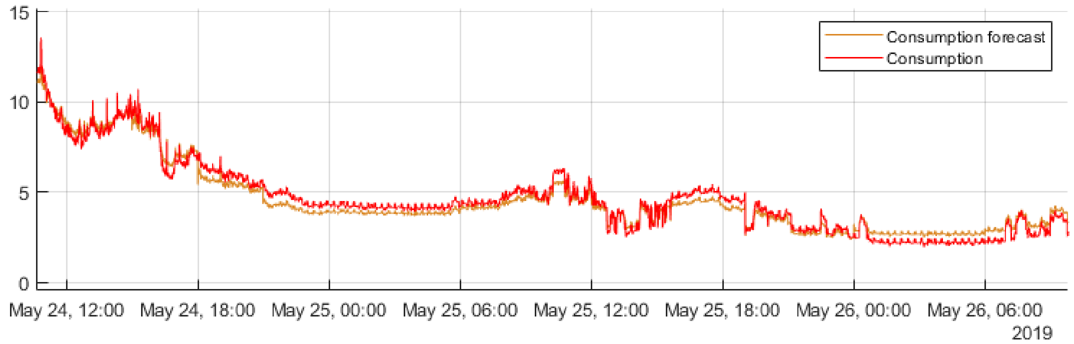


Figure 14: Plot of load consumption values and the corresponding forecast over few days in Yverdons site, sampling time of 5 minutes.

As shown for the PV forecast, Figure 14 illustrates an example of pattern classification of the load consumption at Empa facility.

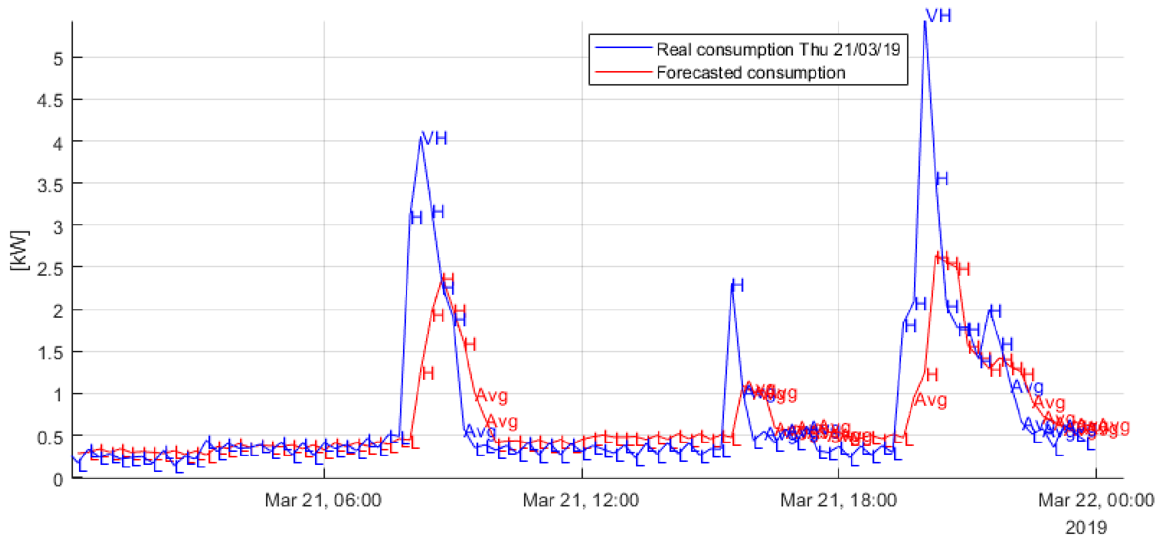


Figure 15: example of real-time pattern classification of load forecast at Empa facility, March 2019

It is important to highlight that a real-time pattern classification of the both PV and Load consumption has been shown during the meeting on the 24th June at HEIG-VD.

4.3 Ageing Aware Energy Management Software

The main idea for illustrating the ageing-aware approach of the developed energy management software could be described by making reference to an installation equipped with PV power plant and a BES with a specific size/chemistry.
Figure 15 illustrates the approach followed by competitors with their energy management software, namely they are charging and discharging the BES with the maximum available power.
Figure 16 illustrates the approach of our EMS. Thanks to our machine learning approach, we are able to forecast the PV production (without any expensive high-resolution sky camera and/or real-time solar irradiance sensor) and load consumption and consequently reduce the charging/discharging current (but with longer time duration) and consequently reduce the ageing of the battery.
We have a pending patent process associated with our algorithm.

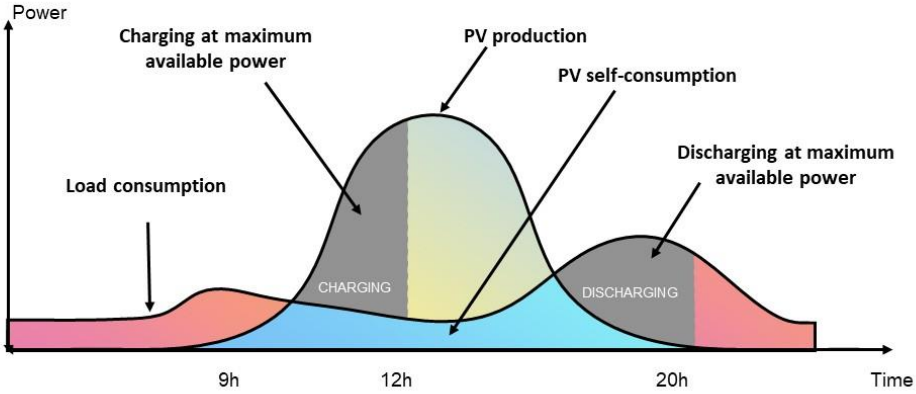


Figure 15: usage of BES without ageing-aware strategy

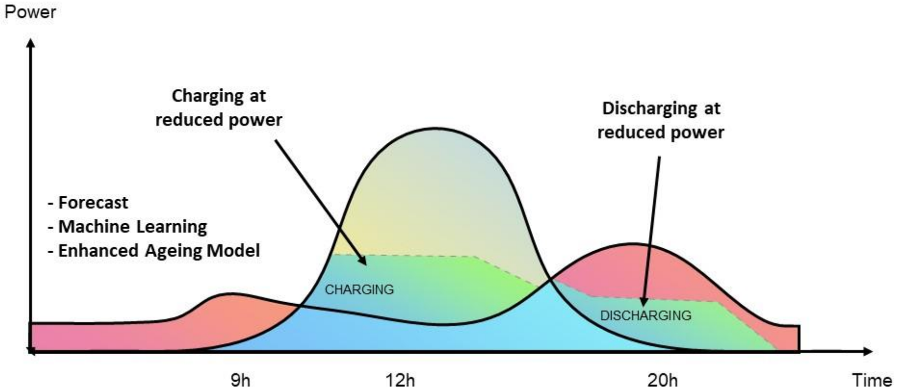


Figure 16: usage of BES with our ageing-aware strategy accounting for meteorological condition/forecast and real usage from the final user.

In this sub-section, once we explained the principle behind our ageing-aware algorithm, we summarized the main results associated with the developed ageing-aware energy management software. All the calculations refer to the simplest case, namely an energy management deploying always the maximum available power (here called "available energy management").

4.3.1 Hierarchic structure and algorithm followed by the Eco-friendly Energy Management Software

As follows the main description of the algorithm followed by the proposed EMS. It is important to highlight that an ongoing patent process will be finalized within 23rd November 2019.

A) First step: the local raspberry PI acquires the PV and Load Measurement (via the local sensor) as long as the SOC from the BMS of the targeted battery;

B) Second step: the PV forecast algorithm integrated into the master raspberry PI computes the forecasted PV production for the next time step (30s-2 minutes or more);

C) Third step: the load consumption forecast algorithm integrated into the master raspberry PI computes the forecasted load consumption for the next time step (30s-2 minutes or more), the same timestep of the PV forecast;

D) The absolute value of the two above forecast along with their relative values (referred to the PV peak plant and the peak load consumption) are processed (kind of machine learning approach). Their absolute difference is also computed and based on these information the EMS is able to compute, from a statistic point of view, if this difference is relatively high or low.

E) Based on the final estimation of the above difference the optimal constant current profile (constant for the whole time step) is evaluated. It will be a charging current if the PV production is higher than the load consumption and a discharging current viceversa

F) Once the type of current profile (charging or discharging) has been established our algorithm will evaluate the value of the constant C-rate to be applied during the next time sample. This value depends also on the information associated to the relative value of PV and Load. As example, a PV production classify as "very high" together with a load consumption classified as" very low" will give a charging current profile with a C-rate very low (namely 0.25C) since statistically speaking during the next timestep this difference between PV and load will be high. Consequently, it does not make sense, from an ageing point of view, to deploy high value of current to charge the battery.

G) At the following time-step the process from point A to F is repeated and consequently we are sure that et each time sample the minimization of the ageing process tool place.

It is important to highlight that if the net power between PV and Load is low, the current profile will not be reduced since we do no take any risk to not charging or discharging the battery for mitigating the ageing process. The ageing process is mitigated only if the available power is considered to be average-high.

4.3.2 Main results on ageing mitigation

Table I summarizes the main results in the three targeted BESs and it highlights the C-rate reduction in charge and discharge phase.

It is important to underline what follows:

1) The average C-rate reduction has been calculated only for the ones with visible ageing-reduction effect;

2) Unfortunately, due to the large amount of raining days in the period March 2019 up to June 2019, it has been difficult to obtain a large amount of day for which the solar irradiance was high, consequently the PV production with high value and consequently having the possibility to mitigate the C-rate during the charging phase (refer to Figure 15);

3) The overall energy balance is the same whenever we deployed our ageing-aware EMS or a available one. This means that the global charged (energy from PV) and discharged (toward the building) energy into/from the BES are the same (without any economic loss). Please refer to Figures 17-19 for a show-case ageing mitigation of our EMS.

4) The effect of current during charging phase is much more important that the one during discharging phase. Consequently, from an electrochemical point of view it is possible to assume the ageing mitigation done by our EMS is much more important.

5) An ageing stress factor that we have not considered in our ageing computation is the temperature. It is worth noting that overtemperature on Li-ion cells depends on two main factors, equivalent series resistance and current. Reducing the C-rate has a double effect: i) mitigate the ageing and consequently the increase of the internal resistance and especially ii) reducing

the current. Based on this consideration the targeted BESs have been operated at a lower temperature.

In Table I, based on our developed Li-ion ageing model and the dedicated experimental ageing test performed thanks to the Ecobattem project, we tried to “translate” the C-rate reduction into the equivalent ageing mitigation/extended lifetime.

Table I: summary of EMS performances

Site	Test days	Days with visible EMS effects	Average C-rate reduction in charge (max)	Average C-rate reduction in discharge (average)	Average C-rate reduction during visible days	Nominal C-rate Reduced C-rate	Extended lifetime Cycle life/years	Extended Lifetime compared to nominal life
HEIA-FR	58	25	22.88% (up to 88%)	9.78% (up to 79%)	34.5%	1.15 C-0.85 C	739 cycles/2	16.4%
EMPA	74	36	22.03% (up to 86%)	2.15% (up to 70%)	53.3%	1 C- 0.47 C	1444 cycles/3.9	32%
HEIG-VD	59	32	22.82% (up to 82%)	0% (battery oversized)	55.4%	1 C-0.45 C	1733 cycles/4.85	38.5%

The extended lifetime (cycles life), has been calculated by the following steps:

a) We evaluated the percentage of days with visible ageing reduction thanks to the EMS effects, referred to the global amount of day.

b) We know that a C-rate reduction from 1C down to 0.25 C involves, for the whole lifetime, additional 4300 cycles.

c) We multiplied this number of extra lifecycle for the C-rate reduction obtained thanks to the developed EMS and then again for the percentage at point a.

d) In this way, we supposed that for the whole life of the BES we kept the same percentage of days with visible effect and the same C-rate average reduction.

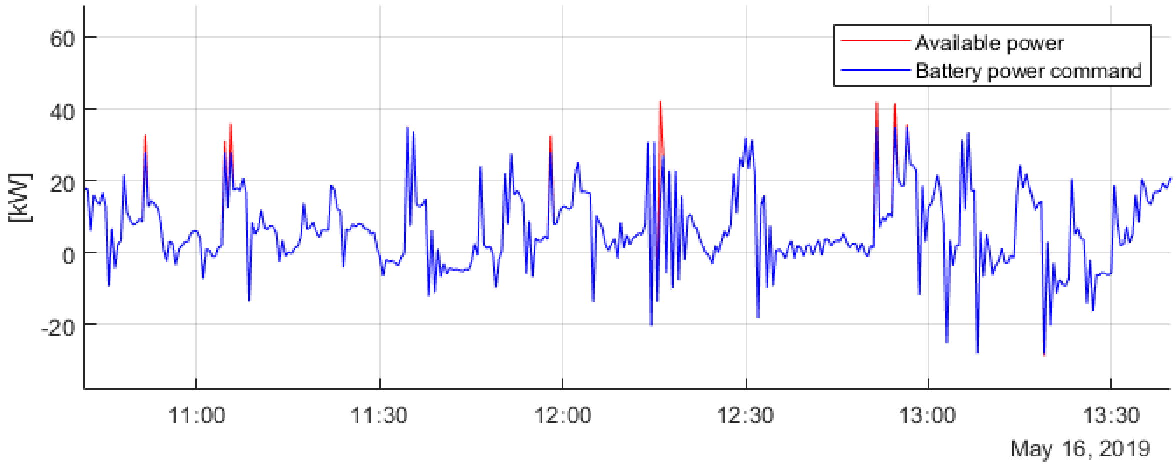


Figure 17: Case where EMS effect is not visible (Zurich battery 100kWh).

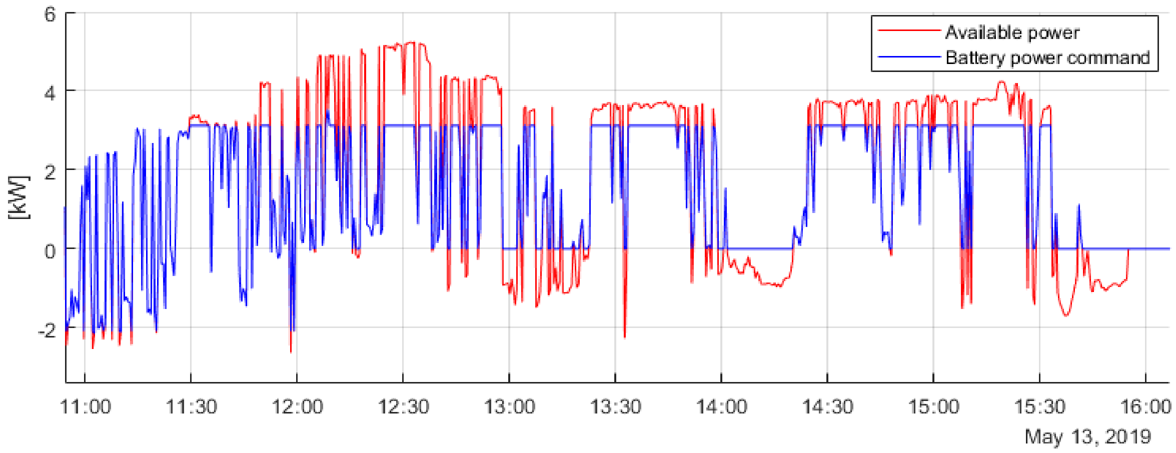


Figure 18: Case where EMS effect is visible (Fribourg battery 5.2kWh)

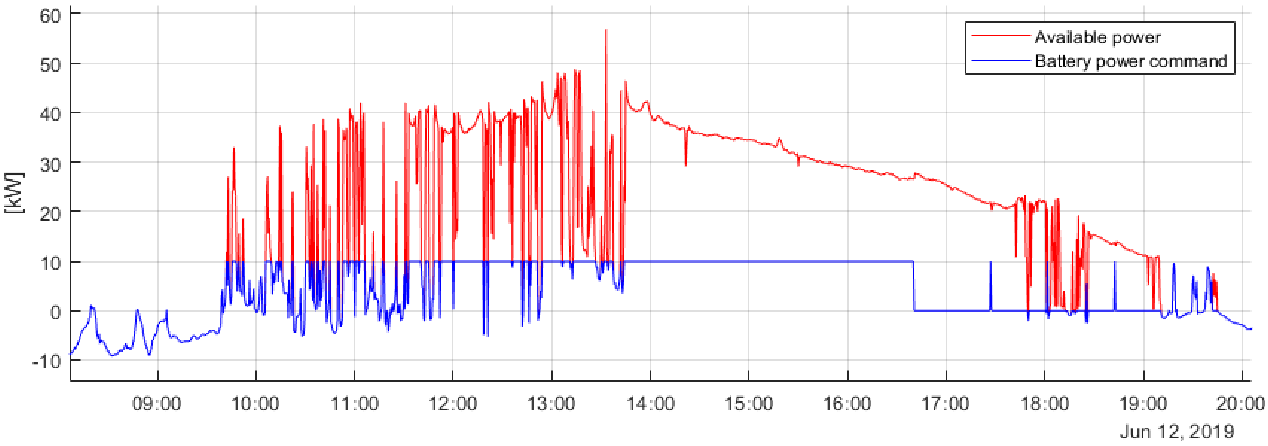


Figure 19: Case where EMS effect is visible (HEIG-VD battery 100kWh/100 kW)

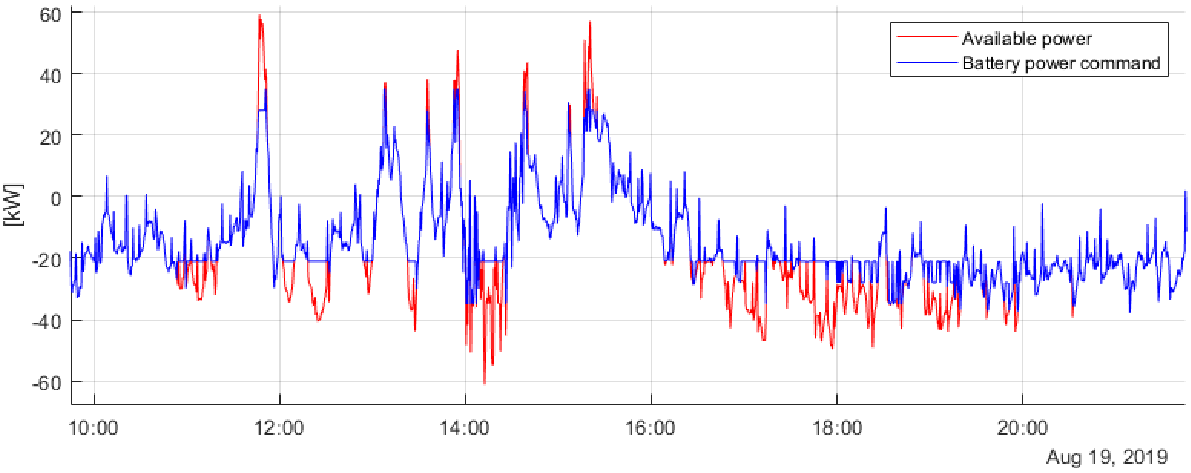


Figure 20: Case where EMS effect is visible (EMPA battery 100kWh/125 kW)

4.3.3 Comparison of the proposed EMS with emulated fixed constraints

We here illustrated a comparison between the performances of the developed and here proposed EMS toward an ageing-aware strategy deploying fixed C-rate limits both in charge and discharge.

In order to perform this comparison, the following key-metrics indicators have been deployed:

1) Renewable self-consumption associated with the targeted strategy;
2) SOH and full equivalent cycles.

The targeted emulated scenario are the following ones:

- No ageing-aware strategy;
- Fixed limit on C-rate and value limits equal to the one obtained dynamically with the developed EMS. Fixed C-rate constraint both in charge and discharge, value of C-rate equal to the average value evaluated, for each targeted site, in paragraph 4.3.2 Table I.

- Fixed limit very low C-rate (extreme case) 0.1C. This value has been chosen to highlight the drawback, from a self-consumption point of view, to deploy very low C-rate (since someone could believe that reducing as lower as possible the C-rate will involve a whole benefit).
- Dynamic C-rate mitigation (thanks to the developed EMS).

By observing Table II it is possible to make the following observations:

1) The proposed EMS gives the best results in term of trade-off between ageing -mitigation and renewable self-consumption
2) A very low C-rate fixed constraints gives the best results for ageing mitigation but it reduces too much the renewable self-consumption
3) The fixed C-rate limit gives very good results in term of ageing mitigation but the renewable self-consumption is slightly affected. It is important to underline this fixed limit changes for each facility and could be established a posteriori thanks to the developed EMS.

Table II: comparisons of EMS performances

Case study	BES	Final SOH	Full equivalent cycles	Discharged renewable energy	Self-consumption
No strategy	EMPA	99.92	17.43	1838 kWh	56.4 %
Fixed limit		99.93	14.72	1818 kWh	56.3%
Very low fixed limit		99.96	7.89	1265 kWh	41 %
Developed EMS		99.93	14.40	1912 kWh	59.75%
No strategy	HEIG-VD	99.90	21.53	1650 kWh	88.2 %
Fixed limit		99.92	16.33	1629 kWh	88.1 %
Very low fixed limit		99.93	14.25	1402 kWh	75.5%
Developed EMS		99.92	17.38	1783 kWh	96%
No strategy	HEIA-FR	99.92	16.77	154 kWh	81.5 %
Fixed limit		99.93	14.93	151 kWh	80%
Very low fixed limit		99.96	8.8	99 kWh	52%
Developed EMS		99.93	14.63	153 kWh	81.3%

4.4 First examples of ancillary services via virtual connected BESs

As planned in WP6, ECOBATTEM project investigates the possibility to provide ancillary services with a virtual power plant composed by the three targeted batteries. The type of service that has been tested is the Primary Control Reserve (PCR) for frequency control. This type of services aims at keeping the frequency of the European power network equal to 50 Hz, by injecting (if the frequency is lower) or absorbing energy from the grid (if the frequency is higher).

In order to preliminary test this type of services, we deployed a real frequency measurement obtained in the following website, sampled every 5 s during one month:

https://clients.rte-france.com/lang/an/visiteurs/vie/vie_frequence.jsp

The by knowing the frequency measurement, for each BES participating to the primary control reserve for frequency regulation, there is a specific power-frequency characteristic. The control power is defined by this function which is defined by ENTSOE's System Operation Guideline (Commission regulation (EU) 2016/631). The function is defined as follows:

$$P_{PCR} = \begin{cases} \pm P_{PCR}^{max}, & |\Delta f| > 0.2\ Hz \\ P_{PCR}^{max} \times \dfrac{\Delta f}{0.2\ Hz}, & 0.01\ Hz < |\Delta f| < 0.2\ Hz \\ 0, & |\Delta f| < 0.01\ Hz \end{cases}$$

The control power is not provided when the frequency is between 49.99 and 50.01 Hz. When the frequency deviation ($|\Delta f|$) is between 0.01 and 0.2 Hz, the control power to provide is linearly proportional to the deviation. For deviations larger than 0.2 Hz, the maximum control power must be supplied (P_{PCR}^{max}). It corresponds to the PCR power accepted for the facility.
By having the frequency, it is therefore easy to express the control power following the above relation.

4.4 Results

Figure 21 illustrates the 2 hours of operation of the three targeted battery with an initial SoC of 50%, the value of SOC for which, based on the experimental ageing characterization runned with pulsed current and described in section 4.1, the ageing of the BES is mitigated. Figure 22 illustrates a 22 minutes operation of the 3 BESs. It is important to highlight that we have deployed the measurement of the frequency described above and we emulated a real time PCR control.
By observing these two figures it is possible to make the following observations:

- The BES located in Zurich (EMPA) as well as the one located at HEIG-VD are able to follow the PCR set reference point without any issue neither in charge neither in discharge.
- The BES located in Fribourg (HEIA-FR), doesn't always follow the PCR set reference point. We believed that this issue is mainly due to the combination of several factors such as: hardware/communication being used, as there are several heterogeneous layers communicating between each other, that does not allow for fast change in the set reference point (sampling time equal to 5 s) and high value of ESR reducing the power that could be extracted or delivered to the BES.

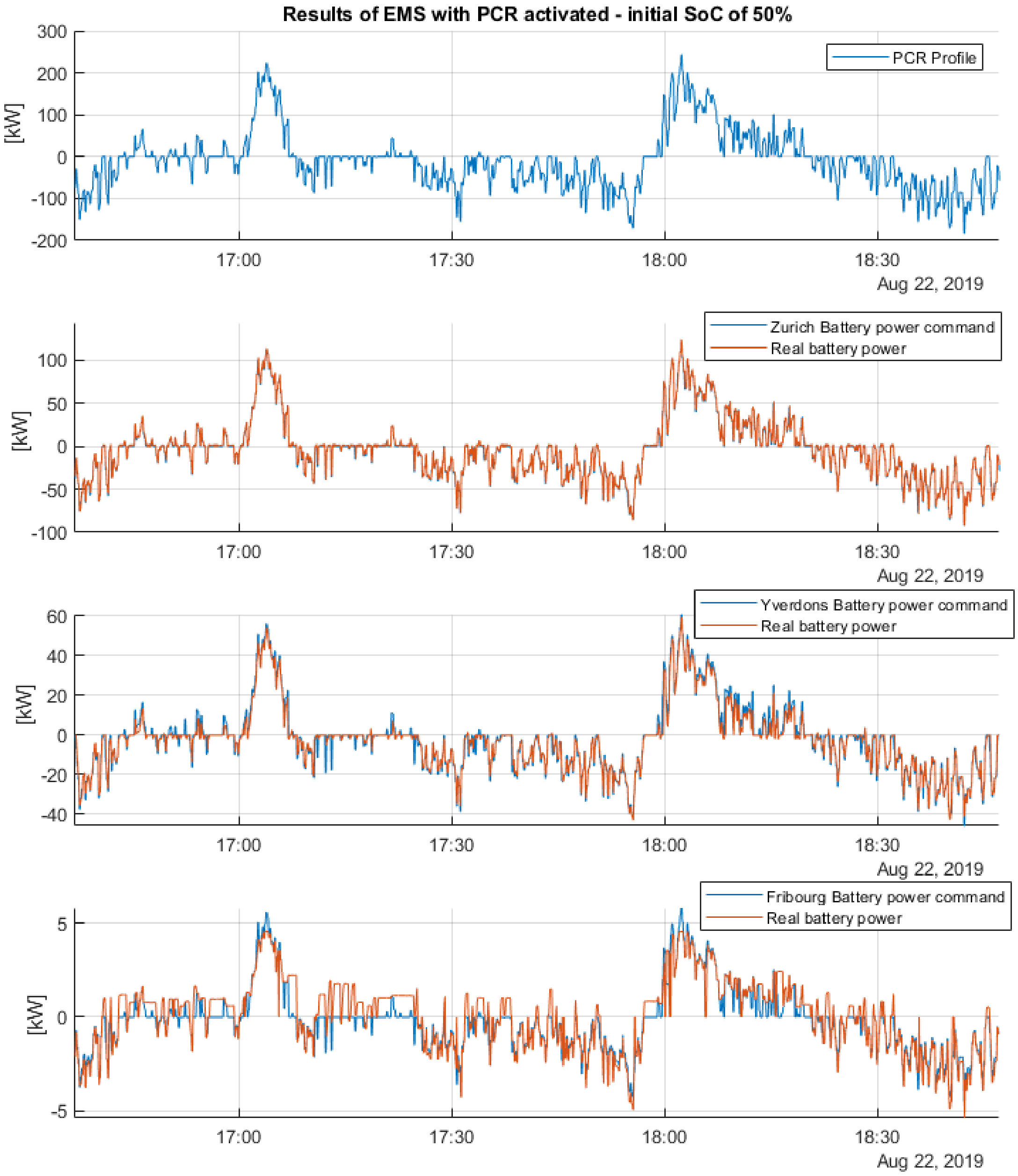


Figure 21: PCR ancillary service provided by the 3 BESs with 50% initial SOC.

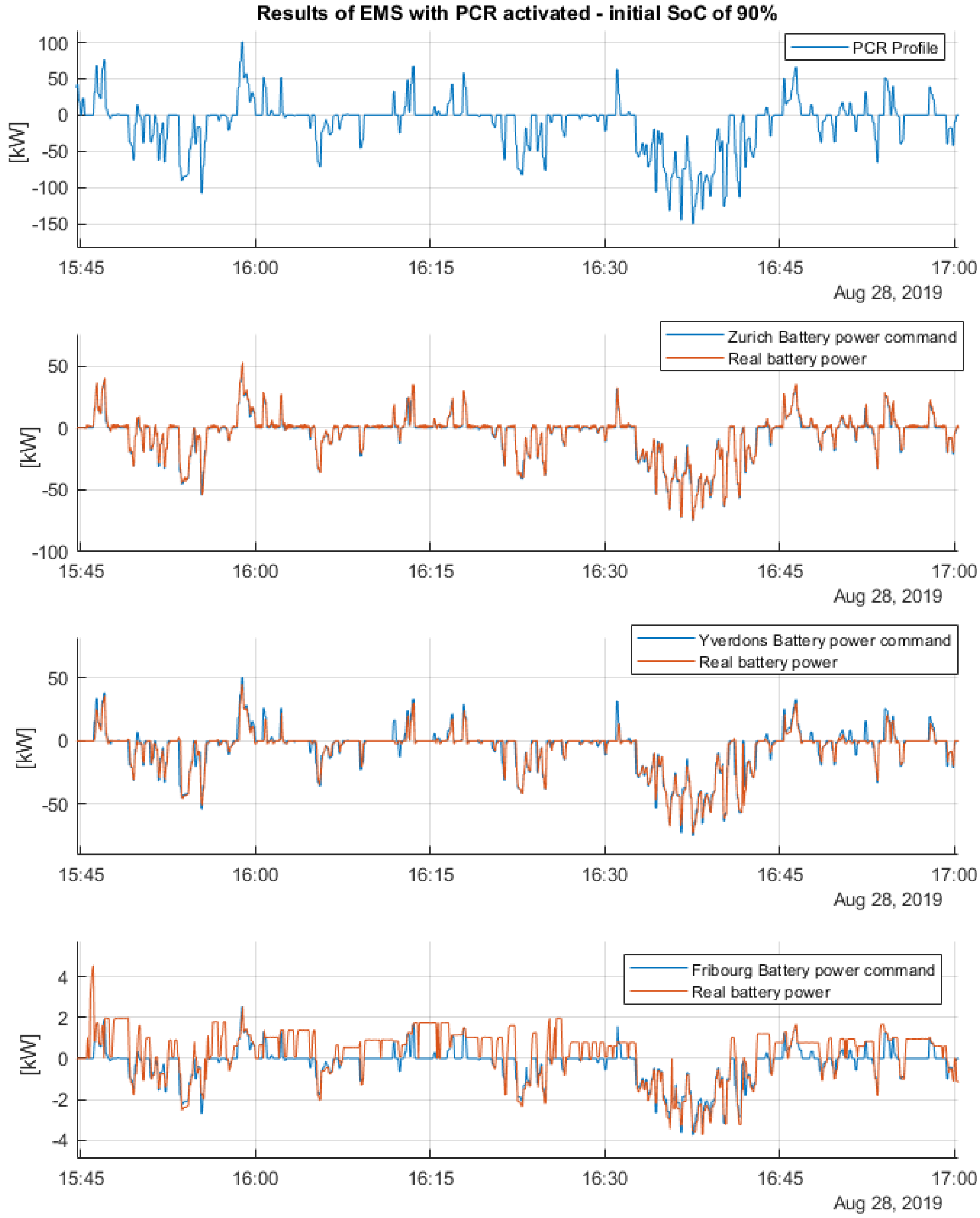


Figure 22: PCR ancillary service provided by the 3 BESs with 90% initial SOC.

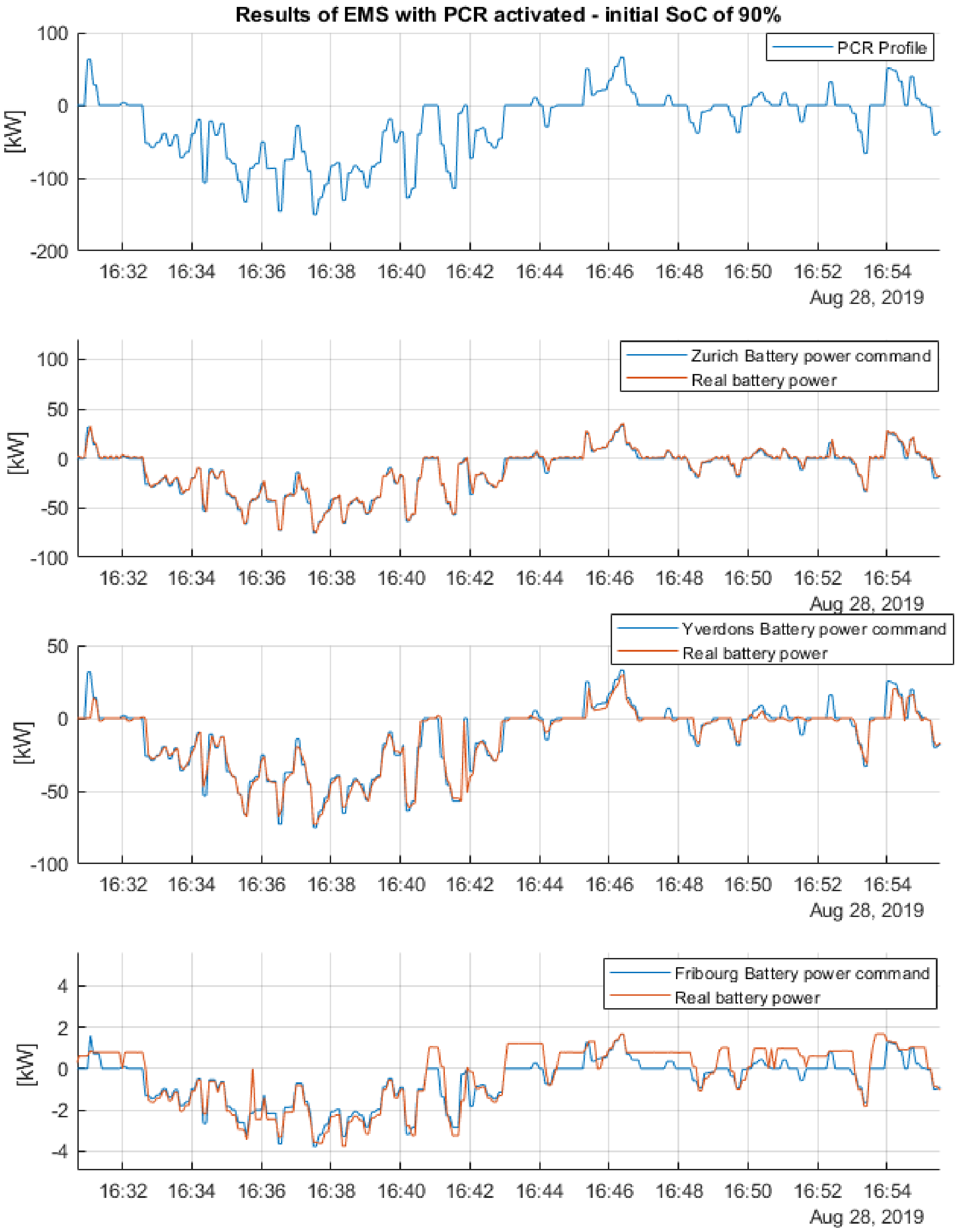


Figure 23: focus on PCR ancillary service provided by the 3 BESs with 90% initial SOC.

4.5 Business Model

In this section we illustrated the Business model description performed for an emulated environment of 45 households composing a pool 45 batteries of 12 kWh (NMC chemistry). For the economic benefit calculations we have emulated the behaviour of our EMS capable to reduce the ageing up to 40% and consequently extend the lifetime of the BES.

Real consumption and production profiles were used. A forecasted BES price of 500 CHF/kWh was used as current high BES prices for small-scale BES are to consequent to provide benefits. To evaluate the economical profitability, the Internal Rate of Return (IRR) was used as the main economical factor. The IRR is computed by using the following formula:

$$\sum_{t=0}^{n} \frac{R(t) - C(t)}{(1 + IRR)^t} = 0$$

With $R(t)$ = Revenues, $C(t)$ = Costs and IRR = Internal Rate of Return (n is equal to 10 if there is no ageing-aware strategy, n is equal 13 if there is an ageing-aware strategy)
Three different kinds $R(t)$ were used for the economical computation:

- **<u>Self-Consumption</u>:**

$$R_{Sc} = Sc * E_P * (r_t - f_t)$$

R_{sc}= Revenue Self-consumption [CHF] S_c = Self-consumption rate

E_p = Energy stored [kWh] r_t = Retail tariff [CHF/kWh] f_t = Feed-In tariff [CHF/kWh]

- **<u>Peak-Shaving:</u>**

$$R_{ps} = \sum_{t=1}^{12} p * P_t$$

p = Peak tariff [CHF/kW] R_{ps} = Revenue Peak-shaving [CHF]

P_r = Exceeded power shaved [kW]

- **<u>Primary Frequency Control (PCR)</u>**

$$R_{PCR} = PCR * P$$

R_{PCR} = Revenue PCR [CHF] PCR = PCR yearly bid [CHF/kW] P = Available Power [kW]

Two kinds of $C(t)$: a fix OPEX of 100 CHF/Year for BES maintenance and unexpected overhead costs and fixed CAPEX of 500 CHF/kWh as the investment cost. Three different business models were analysed for the sake of exploring miscellaneous economical concepts.

4.5.1 Business Model – Leasing

IRR Leasing Battery		Retail - Tarrifs (CHF/kWh)										
		0.2	0.21	0.22	0.23	0.24	0.25	0.26	0.27	0.28	0.29	0.3
Feed - In Tarrifs (CHF/kWh)	0.00	0.56%	1.17%	1.76%	2.34%	2.92%	3.48%	4.03%	4.57%	5.10%	5.62%	6.14%
	0.01	-0.07%	0.56%	1.17%	1.76%	2.34%	2.92%	3.48%	4.03%	4.57%	5.10%	5.62%
	0.02	-0.71%	-0.07%	0.56%	1.17%	1.76%	2.34%	2.92%	3.48%	4.03%	4.57%	5.10%
	0.03	-1.36%	-0.71%	-0.07%	0.56%	1.17%	1.76%	2.34%	2.92%	3.48%	4.03%	4.57%
	0.04	-2.04%	-1.36%	-0.71%	-0.07%	0.56%	1.17%	1.76%	2.34%	2.92%	3.48%	4.03%
	0.05	-2.74%	-2.04%	-1.36%	-0.71%	-0.07%	0.56%	1.17%	1.76%	2.34%	2.92%	3.48%
	0.06	-3.46%	-2.74%	-2.04%	-1.36%	-0.71%	-0.07%	0.56%	1.17%	1.76%	2.34%	2.92%
	0.07	-4.20%	-3.46%	-2.74%	-2.04%	-1.36%	-0.71%	-0.07%	0.56%	1.17%	1.76%	2.34%
	0.08	-4.98%	-4.20%	-3.46%	-2.74%	-2.04%	-1.36%	-0.71%	-0.07%	0.56%	1.17%	1.76%
	0.09	-5.79%	-4.98%	-4.20%	-3.46%	-2.74%	-2.04%	-1.36%	-0.71%	-0.07%	0.56%	1.17%
	0.10	-6.63%	-5.79%	-4.98%	-4.20%	-3.46%	-2.74%	-2.04%	-1.36%	-0.71%	-0.07%	0.56%

Figure 24: IRR Leasing BES

This first business model uses only two revenue streams: self-consumption and passive peak-shaving. The initial investment is redistributed over the BES initial standard lifetime (10 year) as a leasing process with a 1% interest rate. Figure 24 illustrates a sensitivity analysis for different retail and feed-in tariffs that highlight the positive IRR in yellow and green. 54.54% of the IRR are positive and in the best-case scenario the investment can reach an internal rate of return of 6.14%. The fact of redistributing the cost over the lifetime allow the investor to profit from the concept of time value of money and avoid an invasive front payment.

4.5.2 Business Model – Pooling

IRR Buying battery + Ancillary services		Retail - Tarrifs (CHF/kWh)										
		0.2	0.21	0.22	0.23	0.24	0.25	0.26	0.27	0.28	0.29	0.3
Feed - In Tarrifs (CHF/kWh)	0.00	0.70%	1.15%	1.59%	2.03%	2.46%	2.88%	3.30%	3.71%	4.12%	4.52%	4.91%
	0.01	0.24%	0.70%	1.15%	1.59%	2.03%	2.46%	2.88%	3.30%	3.71%	4.12%	4.52%
	0.02	-0.23%	0.24%	0.70%	1.15%	1.59%	2.03%	2.46%	2.88%	3.30%	3.71%	4.12%
	0.03	-0.70%	-0.23%	0.24%	0.70%	1.15%	1.59%	2.03%	2.46%	2.88%	3.30%	3.71%
	0.04	-1.19%	-0.70%	-0.23%	0.24%	0.70%	1.15%	1.59%	2.03%	2.46%	2.88%	3.30%
	0.05	-1.69%	-1.19%	-0.70%	-0.23%	0.24%	0.70%	1.15%	1.59%	2.03%	2.46%	2.88%
	0.06	-2.19%	-1.69%	-1.19%	-0.70%	-0.23%	0.24%	0.70%	1.15%	1.59%	2.03%	2.46%
	0.07	-2.71%	-2.19%	-1.69%	-1.19%	-0.70%	-0.23%	0.24%	0.70%	1.15%	1.59%	2.03%
	0.08	-3.24%	-2.71%	-2.19%	-1.69%	-1.19%	-0.70%	-0.23%	0.24%	0.70%	1.15%	1.59%
	0.09	-3.79%	-3.24%	-2.71%	-2.19%	-1.69%	-1.19%	-0.70%	-0.23%	0.24%	0.70%	1.15%
	0.10	-4.35%	-3.79%	-3.24%	-2.71%	-2.19%	-1.69%	-1.19%	-0.70%	-0.23%	0.24%	0.70%

Figure 25: IRR Pooling Battery

This business model enables a third revenue stream due to the pooling of multiple BES. Due to the satisfied pre-qualification for ancillary services through the pooling of BES, 62.81% of the cases are becoming positive with IRR reaching 4.91%. The addition of a new revenue stream offers the best way to smooth the revenue and reduce the correlation with the future retail and feed-in tariffs as it enables a new fixed revenue stream.

4.5.3 Business Model – Wealth Redistribution

IRR Buying Battery Wealth Redistribution		Retail - Tarrifs (CHF/kWh)										
		0.2	0.21	0.22	0.23	0.24	0.25	0.26	0.27	0.28	0.29	0.3
Feed - In Tarrifs (CHF/kWh)	0.00	-1.00%	-0.60%	-0.20%	0.19%	0.57%	0.95%	1.32%	1.69%	2.05%	2.41%	2.76%
	0.01	-1.41%	-1.00%	-0.60%	-0.20%	0.19%	0.57%	0.95%	1.32%	1.69%	2.05%	2.41%
	0.02	-1.82%	-1.41%	-1.00%	-0.60%	-0.20%	0.19%	0.57%	0.95%	1.32%	1.69%	2.05%
	0.03	-2.25%	-1.82%	-1.41%	-1.00%	-0.60%	-0.20%	0.19%	0.57%	0.95%	1.32%	1.69%
	0.04	-2.68%	-2.25%	-1.82%	-1.41%	-1.00%	-0.60%	-0.20%	0.19%	0.57%	0.95%	1.32%
	0.05	-3.12%	-2.68%	-2.25%	-1.82%	-1.41%	-1.00%	-0.60%	-0.20%	0.19%	0.57%	0.95%
	0.06	-3.57%	-3.12%	-2.68%	-2.25%	-1.82%	-1.41%	-1.00%	-0.60%	-0.20%	0.19%	0.57%
	0.07	-4.03%	-3.57%	-3.12%	-2.68%	-2.25%	-1.82%	-1.41%	-1.00%	-0.60%	-0.20%	0.19%
	0.08	-4.51%	-4.03%	-3.57%	-3.12%	-2.68%	-2.25%	-1.82%	-1.41%	-1.00%	-0.60%	-0.20%
	0.09	-4.99%	-4.51%	-4.03%	-3.57%	-3.12%	-2.68%	-2.25%	-1.82%	-1.41%	-1.00%	-0.60%
	0.10	-5.49%	-4.99%	-4.51%	-4.03%	-3.57%	-3.12%	-2.68%	-2.25%	-1.82%	-1.41%	-1.00%

Figure 26: IRR Wealth Redistribution

Figure 26 illustrates the case of a wealth redistribution between DSO's and prosumers. It' assumed that the system will be prequalified for the provision of ancillary services. The revenue and cost split represent the following percentage, 64.09% for the prosumers (Self-consumption and peak-shaving) and 35.91% for the DSO (ancillary services). This wealth redistribution of costs and revenue enable 29.75% of positive cases for both actors. This last case may be the easiest to implement as it presumes that the DSO is handling the pooling they endure part of the cost and profit form a part of the revenue.

The results of the 3 business cases highlight some interesting findings. The profitability increases in an environment of high retail tariffs and low feed-in tariffs. The more expensive it gets to consume the energy produced by the classical infrastructure the more interesting it become to be independent and self-consume. The ability to distribute the large initial investment over the BES lifetime can drastically increase the expected IRR and finally, by enabling new revenue streams and cost splitting also increase the number of profitable cases.

4.5 LCA

As described in the project proposal, in order to address specific questions raised by the BFE's Committee we performed a LCA computation for multiple configurations with PV rooftop plant and BES. The main activities developed are:

- PV rooftop plant combined with an energy self-consumption without any BES;
- PV rooftop plant combined with an energy self-consumption with not optimal BES size and without the proposed ageing aware EMS;
- PV rooftop plant combined with an energy self-consumption with optimal BES size and with the proposed ageing aware EMS.

We completed the above three analyses. The results are extremely interesting and they support the large deployment of BES. Firstly, a comprehensive LCA of Li-ion NMC graphite cell has been done during a master thesis at Aurora's Grid. More specifically, this work shows that:

- Coupling a battery with a PV, it does not allow for reducing the overall C02 footprint. On the contrary the C02 footprint is increased of 5%.
- Having an ageing-aware energy management allows for extending the lifetime of the BES up to 40% and consequently we reduce the C02 foot print of the BES up to 24%. In this analysis we did not take into account the possibility to postpone the energy self-consumption of the battery during the time window for which the C02 content of the grid-energy is the highest. This will allows for further reduction of the overall C02 footprint of the battery. In anyway, the above LCA results show the importance to have an ageing-aware strategy for BES.

In the Appendix, you will find the whole targeted Master thesis.

5 Conclusions

As follows, a summary of the main findings:

1) Ageing of BES can be largely mitigate by deploying C-rate lower than 1C (the available literature does not account for low C-rate but it claims that only higher C-rate affects the ageing of BES). SoC during pulsed test can increase the lifetime of a factor 12.6, and low C-rate can increase the lifetime up to 86% or even 4300 cycles;
2) Within the context of this project, Aurora’s Grid has developed the first world-wide EMS able to account and mitigate ageing of BES with model-less and sensor-less PV forecast. The experimental validation shown an ageing mitigation ranging from 16% up to 38.5%;
3) C02 footprint of BES can be reduced only if its lifetime is extended, and thanks to the developed EMS we can reduce the C02 footprint up to 24%;
4) Win-to-win business model between DSO and end-prosumer are possible but the end-prosumers needs to extend, as much as possible, the BES lifetime.

6 Outlook and next steps

As follows a list of research needs and pending issues:

1) Further ageing test characterization is needed for distinguish between charging and discharging effect at low C-rate and different DoD; second-life experimental characterisation seems to be the main research topic to be addresses in the next 2 years. For this type of cell, an EMS mitigates its ageing is even more important than for 1-st life cell;
2) Extending the usage of the developed EMS for second-life BES has attracted the interested of an important stakeholder (PSA Groupe the 2-nd European car makers). We do need to adapt and further develop this type of EMS for second-life battery and for multiple type of application (2-nd life container connected to the grid for providing ancillary services);
3) Extending the usage of the developed EMS for V2G application accounting for the ageing of 1-st life battery placed in EV is an extremely important topic.

7 National and international cooperation

Thank to the ECOBATTEM project new collaborations took places between the partners of the project, namely between Leclanché, EMPA and HES-SO.

More specifically, the collaboration between University of Applied Science in Fribourg (HEIA-FR) and University of Applied Science in Yverdon-les-Bains (HEIG-VD) has very well received from the Direction of HES-SO.
The most important international collaboration is related to the project proposal MINERVA (Massive Integration of Electrochemical Energy Storage and Electric Vehicle Applications) for the Eranet-H2020 call and after PDL proposal submitted to BFE.

More specifically, the energy management software under development from Aurora's Grid has attracted several industrial and academic international partners such as: PSA Groupe, OPEL, Technische Universität Berlin and Norwegian University of Science and Technology. All these partners are really interesting to adapt/enhance the software for vehicle to the grid application and for 2-nd life battery.

8 Communication

Aurora's Grid comunicated finalization of EMS software via Linkedin in July 2019. Innovaud supported and shared this communication.

9 Publications

Accepted publication and presentations

D. Torregrossa,EL Niederhäuser, *"Towards a Profitable Third-Life Scenario of Li-Ions Batteries?",* Invited Talk at CCTA IEEE Conference, August 21-24, 201, Copenhagen, Industrial session "Renewable Smart Cities and Buildings" chaired by Pr. Marta Molinas.

E. Mazourenko, P. Herr, EL Niederhaeuser, D. Torregrossa *"Disruptive Business Models Enabling Large Battery Energy System Deployment",* poster presentation Energy Informatics 2019, 8th DACH+ Conference on Energy Informatics, Salzburg, Austria, September 26-27, 2019

D. Vuarnoz, E-L Niederhäuser, D. Torregrossa, D. Gabioud "On the Necessity to Integrate Power Flexibility in Cooling Systems" 2019 3rd International Symposium On Green Energy And Smart Grid (SGESG 2019), Aug. 21-23, 2019|Chongqing,China

Publications to be finalized

M. Thebti, , E-L Niederhäuser, D. Torregrossa, "*Experimental characterization of performances fading of Li-ions NMC cell under not conventional operating conditions*", Journal of Energy Storage.

Patent

A patent application, for “protecting” the developed algorithm has been submitted last 23rd November by Aurora’s Grid and will be finalized within 23rd November 2019.

10 References

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[12] D Torregrossa, M Paolone “Modelling of current and temperature effects on supercapacitors ageing. Part II: State-of-Health assessment”, Journal of Energy Storage 5, 95-101.

11 Appendices

Julien Furrer, Master Thesis on LCA of Li-ions battery for residential applications.

Preliminary patent.

Date: 04-11-2019.

Signature: Dimitri Torregrossa, Founder and CEO of Aurora's Grid