



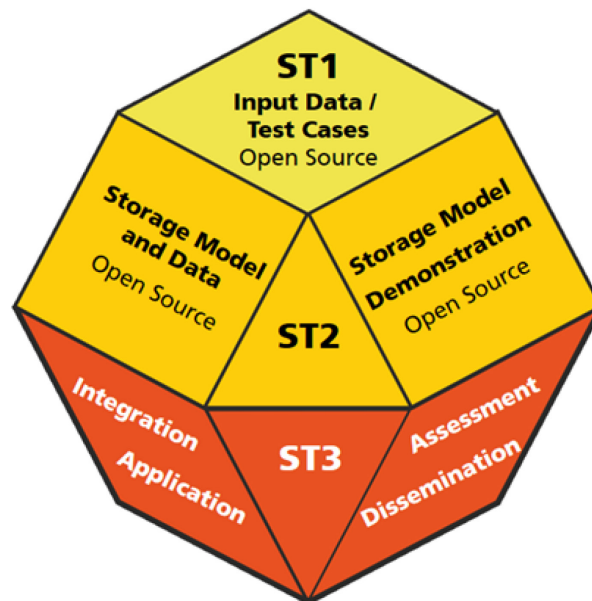
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## IEA ECES Annex 32 Open Sesame

Modelling of energy storages for simulation/  
optimization of energy systems – open-source  
energy storage models

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**IEA ECES 32**  
**»Open Sesame«**



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## Zusammenfassung

Der Übergang zu einer verstärkten Integration von erneuerbaren Energien in das derzeitige Energiesystem geht mit dem Einsatz von Speichersystemen einher. Der IEA Annex 32 zielt darauf ab, die Rolle von Energiespeichersystemen mit Hilfe von geeigneten, wissenschaftlich validierten und quelloffenen Modellen zu bewerten. Der Schweizer Beitrag wird sich auf die Modellierung von elektrochemischen Batterien konzentrieren, wobei der Schwerpunkt auf den für verschiedene Anwendungen erforderlichen Detaillierungsgrad und die damit verbundene Systemanalyse gelegt wird. Open-Sesame Battery ist ein quelloffenes Degradationsmodell, das auf Belastungsfaktoren basiert, die mit der Chemie zusammenhängen und durch experimentelle Tests und Literaturrecherche ermittelt wurden. Das Modell ist in der Lage, die Kapazität und den Leistungsabfall eines Batteriesystems zu berechnen, das einem bekannten Leistungs- und Temperaturprofil ausgesetzt ist.

Repository der Ergebnisse:

Open-sesame Referenzcode: <https://gitlab.ti.bfh.ch/oss/esrec/open-sesame.git>.

Open-sesame GUI (SoXery): [www.tinyurl.com/soxery](http://www.tinyurl.com/soxery).

BatMaestro-Implementierung des Open-Sesame-Codes: <https://github.com/csem/batmaestro>

## Résumé

La transition vers une intégration accrue des énergies renouvelables dans le système énergétique actuel s'accompagne de l'utilisation de systèmes de stockage. L'annexe 32 de l'AIE vise à évaluer le rôle des systèmes de stockage d'énergie à l'aide de modèles appropriés, validés scientifiquement et libres. La contribution suisse se concentrera sur la modélisation des batteries électrochimiques, en mettant l'accent sur les niveaux de détail requis pour les différentes applications, et sur l'analyse des systèmes associés. Open-Sesame Battery est un modèle de dégradation open-source basé sur des facteurs de stress liés à la chimie et obtenus par des essais expérimentaux et des recherches bibliographiques. Le modèle est capable de calculer la perte de capacité et puissance d'un système de batterie soumis à un profil connu de puissance et de température.

Référentiel des résultats:

Code de référence open-sesame: <https://gitlab.ti.bfh.ch/oss/esrec/open-sesame.git>.

Open-sesame GUI (SoXery): [www.tinyurl.com/soxery](http://www.tinyurl.com/soxery).

Implémentation BatMaestro du code open-sesame: <https://github.com/csem/batmaestro>

## Summary

The transition to an increased integration of renewable energies into the current energy system is accompanied by the use of storage systems. IEA Annex 32 aims to assess the role of energy storage systems with the help of suitable, scientifically validated and open-source models. The Swiss contribution will focus on modelling of electrochemical batteries, with a focus on levels of detail required for different applications, and associated system analysis. Open-Sesame Battery is an open-source degradation model based on stress factors that are chemistry related and have been obtained by experimental testing and literature search. The model is able to compute capacity and power fading of a battery system subjected to a know power and temperature profile.

Repository of results:

Open-sesame reference code: <https://gitlab.ti.bfh.ch/oss/esrec/open-sesame.git>.

Open-sesame GUI (SoXery): [www.tinyurl.com/soxery](http://www.tinyurl.com/soxery).

BatMaestro implementation of open-sesame code: <https://github.com/csem/batmaestro>



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## Abbreviations

DoD	Depth of Discharge
G-NMC	Graphite anode and Nickel-Manganese-Cobalt cathode
LFP	Lithium Iron Phosphate
LTO	Lithium Titanate Oxide
SoC	State of Charge
SoH	State of Health
SoR	State of Resistance



# 1 Introduction

## 1.1 Background information and current situation

The energy system is changing due to variable energy production. This requires new and more storage devices to balance demand and production and additionally to increase flexibility. The aim is to always select the best storage systems with the best operation mode to balance the energy system. The challenge is that there are hardly any, scientific proven, source models for energy storage systems, which are an indispensable prerequisite for operation or structural optimisation and for assessing the value of storage systems. The task is to develop a standardised and scientifically proven approach and methodology to assess various storage devices for various applications: grid connected, and grid operated, island grids/ remote areas, industrial sites, and residential areas. The results are generic open-source models and data sets. These scientifically proven models should be used to find answers to current storage questions (technical, economic, and regulatory). The overall aim of this Annex is smart energy conservation and to understand and foster the role of energy storages in the energy system by optimising applications and operation modes and by assessing the benefit to the energy system.

## 1.2 Purpose of the project

The IEA Annex 32 Open Sesame is an initiative to coordinate the development of comprehensive and scientifically validated models for relevant energy storage devices, with a special focus on the adaptation of the model complexity to the targeted application/analysis domain (from building/district to regional/national scale). Together with the provision of storage systems open-source models, the creation of standardized data sets of production/consumption from/for different systems and countries with homogenous and consistent time-space resolution is achieved. These data sets serve as test cases for evaluating and optimizing energy storage utilization and operating strategies.

The consortium led by FhG Umsicht (DE) is composed of over 10 international research partners, from Switzerland CSEM and BFH are part of it.

The annex is in line with other IEA activities as TIMES & MARKAL framework for the long-term economic evaluation of national energy systems, which were co-developed by the PSI team in the frame of IEA ETSAP (Energy Technology Systems Analysis Program). In fact, PSI was the contact point for the cooperation between Annex 32 with IEA ETSAP (Energy Technology Systems Analysis Program).



## 2 Open-Sesame Model

A python-based software and an online tool (named SoXery) has been developed to evaluate the aging in a battery given the usage conditions. The model is based on a semi-empirical model and takes the power and temperature profiles of the battery to calculate the aging that the cell will undergo over a certain period. The output from the model, that is chemistry dependent, includes among others the calendar and cycling aging, the increase in internal resistance as well as an unfulfillment power map. The tool is intended to be used as a first approximation by users to select the most appropriate cell chemistry given a usage profile, or to size their battery according to their applications if certain numbers of years of operation are required.

### 2.1 Equivalent Circuit Model for dynamics behavior simulation

The model consists of two parts: i) dynamics model and ii) degradation model. The dynamics model governs the voltage, internal resistance and soc change during charging and discharging. It is based on a simple equivalent circuit model consisting of a voltage source and a variable resistor, as shown in Figure 1. The equation for the voltage at the terminals of the battery is:

$$V = OCV(SoC) - i * R(SoC, T)$$

Where,

V = voltage at the terminals of the battery

T = temperature

OCV = open circuit voltage of the battery as a function of the SoC

i = current through the battery

R = resistance of the battery as a function of SoC and temperature

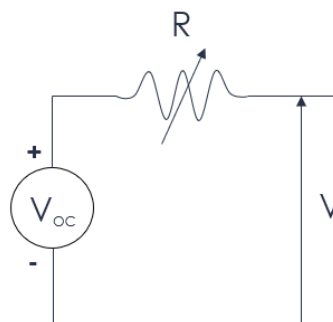


Figure 1: Equivalent circuit model

### 2.2 Chemistry influenced stress factors for battery degradation modelling

#### 2.2.1 Degradation calculation

The simulation of battery ageing is the focus of the Open-Sesame simulation environment. Thanks to the simulation of battery usage profiles, a statement can be made about the expected capacity and power ageing. The performance indicator considered to keep track of the capacity fading is the State of Health (SOH) and the one that monitor the power fading is the increased battery internal resistance, State of Resistance (SOR). The information about the aging can be used to carry out further analyses about the optimum battery size and the total cost of ownership of the battery system for the considered



application. The simulation of battery ageing is based on a semi-empirical model. Instead of simulating physical or chemical processes within the cell, ageing is described using functions that attempt to replicate the results from laboratory measurements. So-called stress factors are defined and used to account the effect of operating conditions on total observed degradation. For example, it is possible to describe the influence of an influencing variable such as the current C-rate on ageing.

At the core of this approach lies a fundamental assumption, that the stress factors are treated as "independent". This foundational concept allows these factors to exert their influence autonomously, acting without mutual interference. Consequently, when multiple stress factors converge under specific conditions, their combined impact is viewed as the product of the individual effects considered in isolation. Open-Sesame also follows the superposition approach. The stress factors are assigned to calendar and cycling ageing. The effective ageing is then calculated from the sum of the calendar and cycling ageing, similarly to the approach followed in [1]. The calendar ageing is always effective, even if the cell is currently undergoing a cycle. With superposition, it is therefore not necessary to differentiate between calendar ageing and cycling ageing in the respective time period. This is an advantage of superposition. There are disadvantages when working out the ageing parameters as this increases the effort involved in testing or data needed: the calendar ageing has to be separated from cycling ageing.

The starting point for calculating ageing is the degradation under standard conditions, representing common operating strategy, i.e. temperature of 25°C, 60% DOD, 1 C-rate, average SOC of 50%. The degradation obtained at this condition, is reported as reference aging and it will correspond to a baseline degradation with no stress factor applied. Degradation under standard conditions can be derived from laboratory tests or, if no measurements are available for a cell, from the data sheet. In Open-Sesame these are the following four parameters:

- Reference calendar ageing ( $\Delta SoH_{Ref_{cal}}$ ) in  $\Delta SoH$  /time [%/sec]
- Reference cyclical ageing ( $\Delta SoH_{Ref_{cyclic}}$ ) in  $\Delta SoH$  /EFC [%/EFC]
- Reference calendar ageing ( $\Delta SoR_{Ref_{cal}}$ ) in  $\Delta SoR$  /time [%/sec]
- Reference cyclical ageing ( $\Delta SoR_{Ref_{cyclic}}$ ) in  $\Delta SoR$  /EFC [%/EFC]

Based on the degradation under standard conditions, the stress factors (SF) and the temporal resolution of the simulation, the calendar ageing for SoH and SoR is calculated per time step ( $t_{resolution}$ ):

$$\begin{aligned} SF_{SoH_{cal}} &= SF_{SoH_{SOC_{cal}}} * SF_{SoH_{T_{cal}}} \\ \Delta SoH_{Degradation_{cal}} &= \Delta SoH_{Ref_{cal}} * SF_{SoH_{cal}} * t_{resolution} \\ SF_{SoR_{cal}} &= SF_{SoR_{SOC_{cal}}} * SF_{SoR_{T_{cal}}} \\ \Delta SoR_{Degradation_{cal}} &= \Delta SoR_{Ref_{cal}} * SF_{SoR_{cal}} * t_{resolution} \end{aligned}$$

The same approach also applies analogously to the calculation of the cyclical ageing of the SoH and SoR caused by a cycle that is scaled in terms of equivalent full cycle. The calculation of the calendar ageing, which was carried out for all time steps, is then summed with the results of the cyclical ageing.

$$\begin{aligned} SF_{SoH_{cyclic}} &= SF_{SoH_{DoD_{cyclic}}} * SF_{SoH_{Crate_{cyclic}}} * SF_{SoH_{AVG_{SOC_{cyclic}}}} * SF_{SoH_{T_{cyclic}}} * CycleEquivalent \\ \Delta SoH_{Degradation_{cyclic}} &= \Delta SoH_{Ref_{cyclic}} * SF_{SoH_{cyclic}} \\ SF_{SoR_{cyclic}} &= SF_{SoR_{DoD_{cyclic}}} * SF_{SoR_{Crate_{cyclic}}} * SF_{SoR_{AVG_{SOC_{cyclic}}}} * SF_{SoR_{T_{cyclic}}} * CycleEquivalent \\ \Delta SoR_{Degradation_{cyclic}} &= \Delta SoR_{Ref_{cyclic}} * SF_{SoR_{cyclic}} \end{aligned}$$



In Open-Sesame, it was determined that the total degradation caused by cyclical ageing is assigned to the last time step of the cycle in each case. This gives the progression of the SoH and SoR a staircase shape:

$$\Delta SoH_{Deg} = \Delta SoH_{Degradation_{cyclic}} + \Delta SoH_{Degradation_{cal}}$$

$$\Delta SoR_{Deg} = \Delta SoR_{Degradation_{cyclic}} + \Delta SoR_{Degradation_{cal}}$$

### 2.2.2 Stress factors definition and calculation

In Open-Sesame, 12 stress factors are used. Six are there to influence the SoH. Another six influence the SoR. The stress factors are used to take current cell conditions (SoC, C-rate, etc.) and other circumstances (cell temperature) into account when analysing degradation. A stress factor can increase (stress factor >1) or decrease (stress factor <1) the reference degradation. If the stress factor is one, the degradation corresponds to the defined reference condition. If the effect of a stress factor on battery ageing is not known, or if the laboratory data is not clear in this regard, the stress factor can be initialised to a constant value of one. The stress factors that are constantly set to one ensure neither increased nor reduced degradation but follow the reference.




As mentioned earlier, the stress factors were compiled from the results of long-term measurements taken in the BFH laboratory and supplemented where necessary with sources from the literature [2]. Despite additions from literature sources, there are stress factors for which the data basis was too small to be able to define stress factors. These were initialised with one as described above. The following table is an overview about which stress factor is implemented in the model for which chemistry among the three most used:

- NMC – Nickel Manganese Cobalt
- LFP – Lithium Iron Phosphate
- LTO – Lithium-titanium-oxide

Table 1. Stress factors overview for three different chemistries.

Stressfactor:	NMC:	LTO:	LFP:
SoH calendaric (Temperature)	✓	✓	✓
SoH calendaric (SoC)	✓	✓	✓
SoH cycling (AVG SOC)	✓	✗	✓ <sub>NMC</sub>
SoH cycling (AVG Temperature)	✓	✓	✓
SoH cycling (DoD)	✓	✓	✓
SoH cycling (C-Rate)	✓	✓	✓
SoR calendaric (Temperature)	✗	✓	✗
SoR calendaric (SoC)	✗	✓	✗
SoR cycling (AVG SOC)	✓	✗	✓ <sub>NMC</sub>
SoR cycling (AVG Temperature)	✗	✓	✓
SoR cycling (DoD)	✓	✗	✓
SoR cycling (C-Rate)	✓	✗	✓



-  Computed stress factor
-  Stress factor was initialized with "1"
-  Stress factor was taken over by a different cell chemistry (NMC)

The relationship between the stress factor and various parameters is established through empirical data. For instance, when considering the impact of temperature on calendar aging, the process is as follows: First, data for calendar aging at different temperatures is gathered, designating one temperature as the reference point (stress factor equal to 1). Next, linear regression models are applied to the capacity loss obtained from each temperature dataset. The slope of each temperature regression model is then normalized to the reference case's slope. These normalized values represent the stress factors corresponding to the various temperatures. Subsequently, these stress factors and their respective temperatures are subjected to regression analysis (in this instance, an exponential regression), enabling the derivation of the dependency of the stress factor on temperature for calendar aging.

In Figure 2 it is possible to find an example of stress factor calculation.

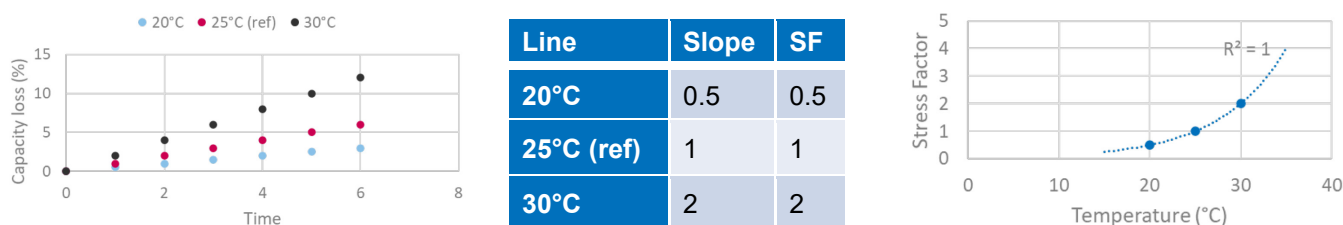


Figure 2. Stress Factor computation example: temperature effect on calendaric degradation

Assumption: the linear regression model applied to the data is mandatory. This means that, even if the effects are not linear and the capacity loss follows a different trend, they will be linearized for the regression model to get only a slope value.

### 2.2.3 Model assumptions

To maintain the model simple and fast to be computed over long-term simulations, other assumptions have been made like: geometric complexities of the cell structure are omitted from the analysis, and no distinctions between energy and power cells configuration for the same chemistry are made. Furthermore, the model assumes a shared behaviour among cells with the same "core" chemistry, such as NMC, LFP, and LTO. This assumption implies that these cells undergo similar degradation effects and are equally influenced by stress factors without differentiating among the different composition changes (NMC111, NMC811 and so on...). While these simplifications contribute to the model's efficiency, they come with the risk of neglecting nuanced variations that may exist due to geometric or functional differences among cells.

## 2.3 Validation

The validation of SoH degradation calculations using Open Sesame has been successfully conducted, focusing on NMC chemistry, and utilizing two distinct datasets coming from two BFH projects. It's important to note that the data used to calculate the stress factors belongs to a battery and a supplier entirely different from those used to validate the model.



To achieve this, an extensive series of simulations were executed. These simulations involved configuring various cell conditions, including reference degradation, voltage range, nominal capacity, nominal energy, resistance factor, and more. The objective was to validate the effects of the stress factors on the total degradation. Notably, among these factors, the only one tuned during the validation activities is the temperature stress factor that was the one having the biggest influence.

During the validation process, the results were rigorously assessed based on the maximum relative error as the designated measure of accuracy. Further enhancing the validation, are the simulations considering different C-rate levels, Depth of Discharge (DoD), and Average State of Charge (SoC) conditions.

$$e_{rel,max} = \left| \frac{x_{exp} - x_{sim}}{x_{exp}} \right|_{max}$$

In the forthcoming phases, the goal is to extend and validate the model for SoR data, encompassing a wider temperature range and the identification of the knee-point. Additionally, efforts will be directed towards validating the model for other battery chemistries, further expanding the scope and applicability of the developed methodology.

1<sup>st</sup> data set validation activities:

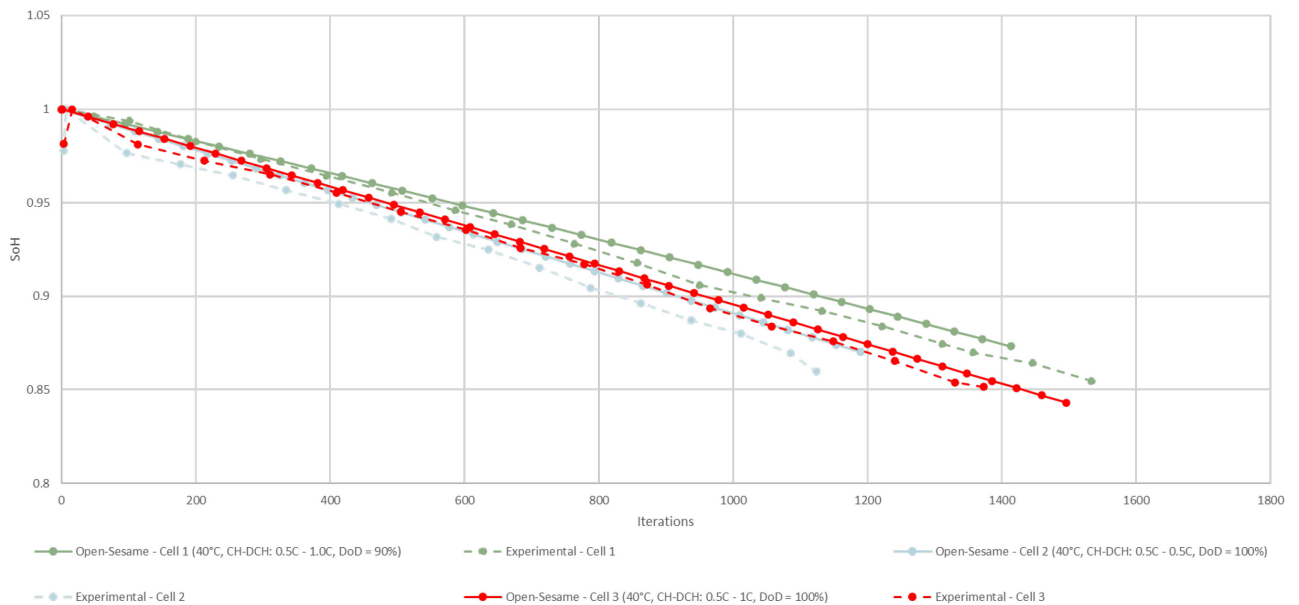


Figure 3: Results comparison at T = 40°C

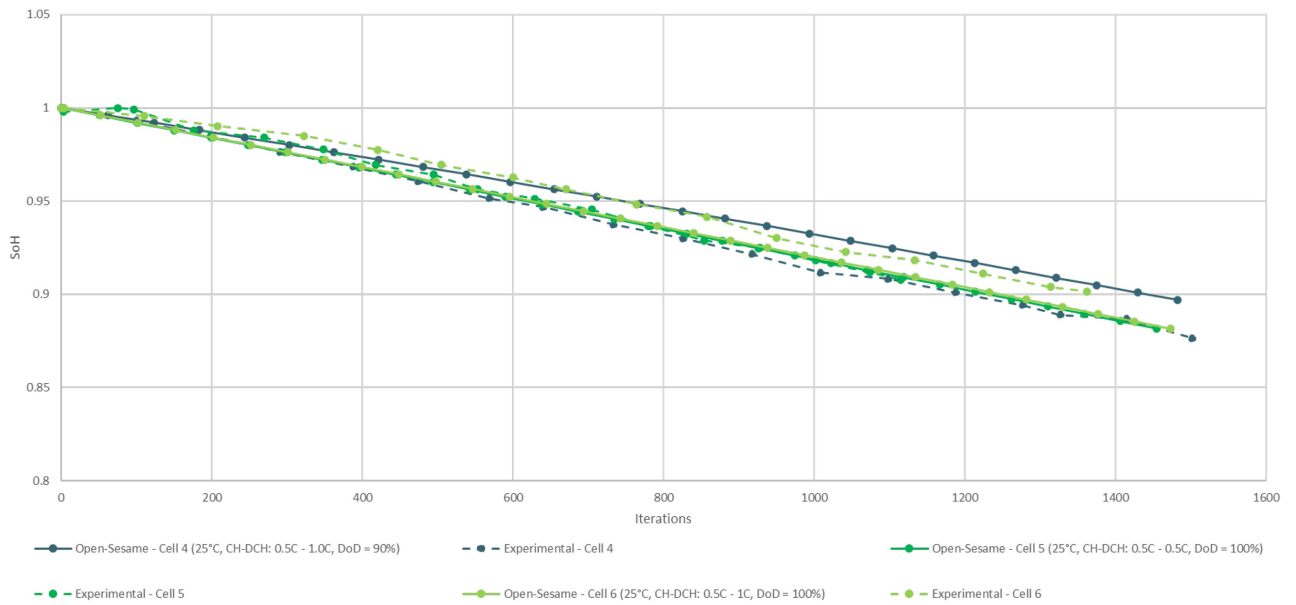


Figure 4: Results comparison at T = 25°C

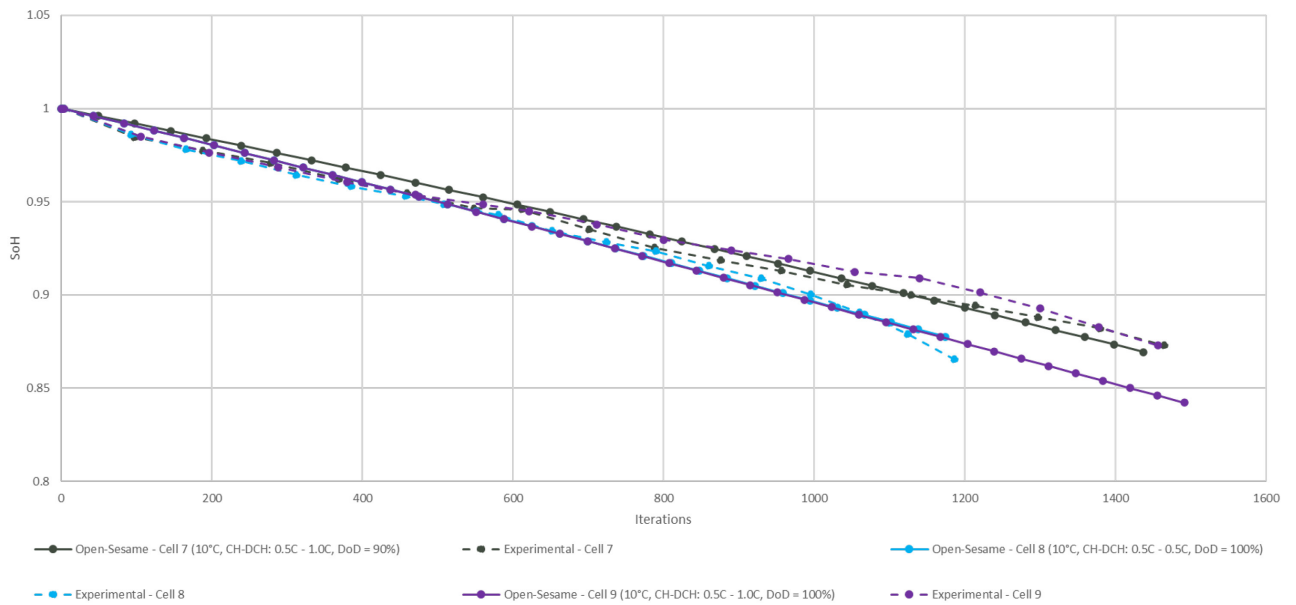


Figure 5: Results comparison at T = 10°C

In Figure 3, Figure 4 and Figure 5, the degradation trends obtained experimentally (dotted lines) are compared to the degradation trends computed by Open Sesame (continuous lines) at three different temperatures, 2 different C-rates and 2 DODs.

The validation process for this dataset involved an iterative tuning approach that successfully optimized the Temperature Stress Factor, minimizing the error between the simulated results and the measured ones. This fine-tuning has significantly improved the model's accuracy in predicting battery degradation. Crucially, the maximum relative error consistently maintained a level below 4% throughout the validation exercises, which spanned diverse scenarios. It is worth highlighting that, without any tuning, the error is



about 10%, depending on the application. This underscores the significant impact of the applied fine-tuning on the model's predictive performance.

This consistent and robust performance serves as a testament to the model's reliability and its capacity to deliver precise predictions across a spectrum of conditions.

2<sup>nd</sup> data set validation activities:

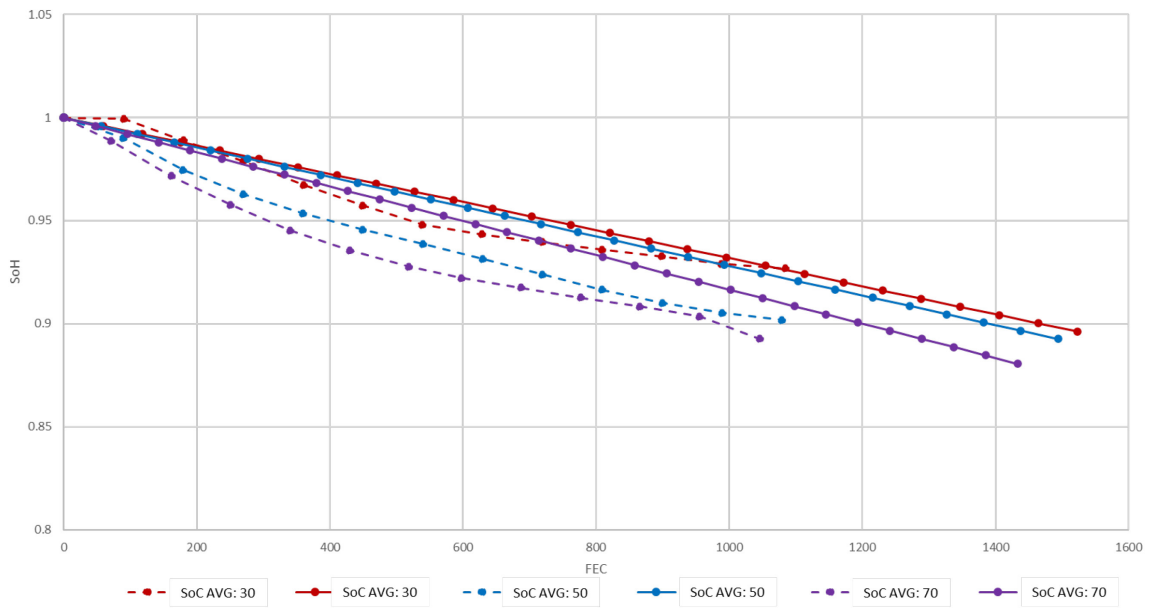


Figure 6: SoC AVG effects ( $T = 45^{\circ}$ , DoD = 60, Crate = 1),

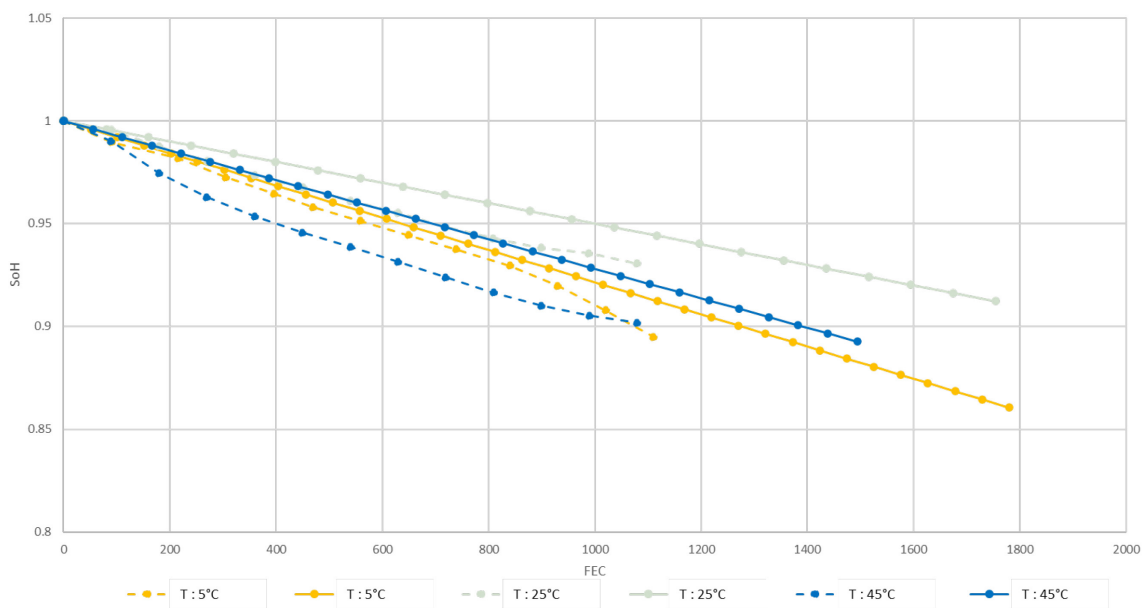


Figure 7: Temperature effects (SoC AVG = 50, DoD = 60, Crate = 1)

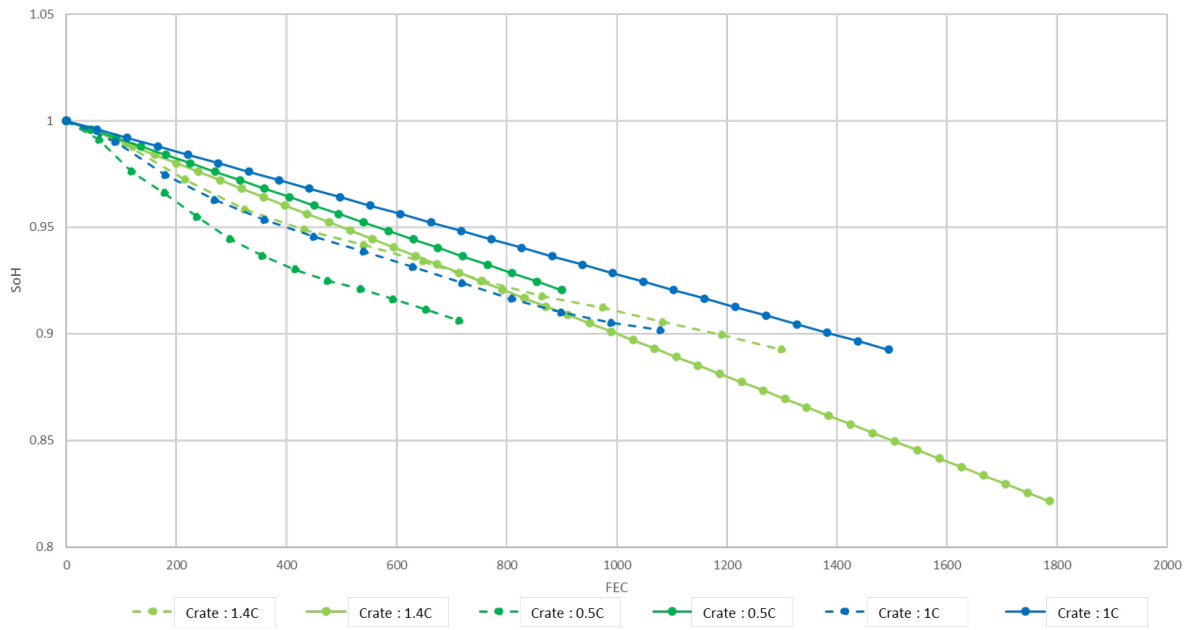


Figure 8: C-rate effects (SoC AVG = 50, DoD = 60, T = 45°)

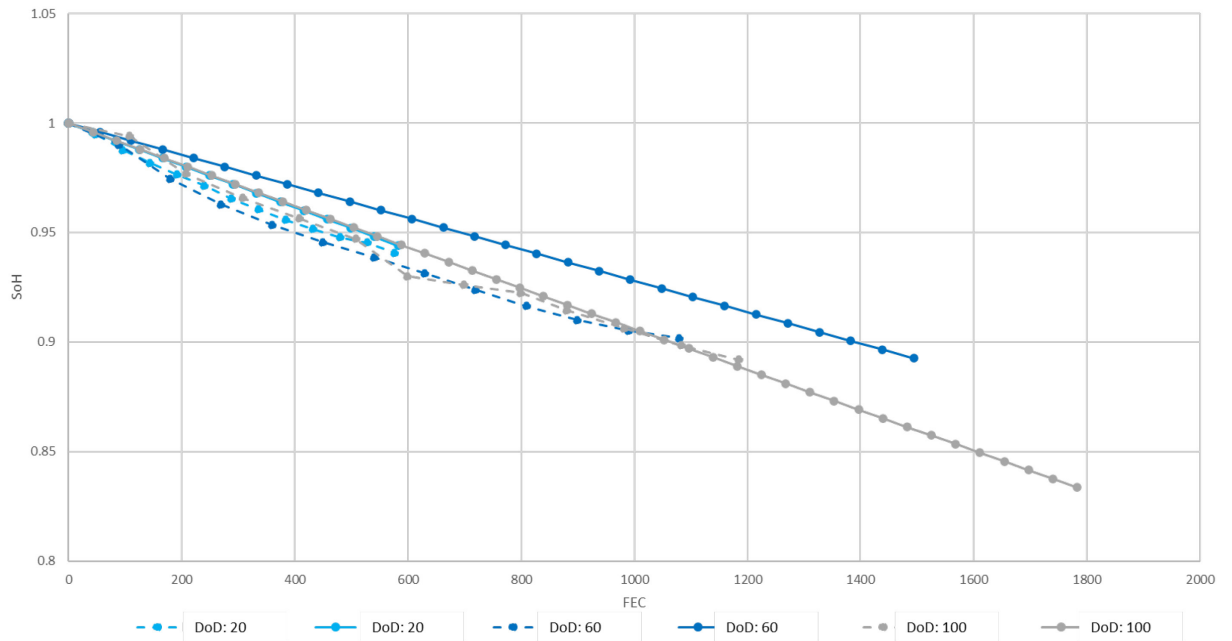


Figure 9: DoD effects (SoC AVG = 50, Crate = 1C, T = 45°)

In conclusion, the results obtained from this study underscore the robustness and accuracy of the developed model for predicting SoH degradation.

In Figure 6, Figure 7, Figure 8 and Figure 9 it is possible to see the model's capability to effectively capture variations in AVG SoC, at different temperatures, different C-rate conditions, and the effects of DoD. Particularly, the maximum relative errors observed throughout the validation process consistently remain lower than 4%, reaffirming the model's reliability.



These findings present a significant step forward in our understanding of battery degradation and have practical implications for battery management and performance. The success of this validation process lays a strong foundation for future work, which includes expanding the model's applicability to various chemistries and capturing nuanced knee-point behaviour.

## 2.4 Model framework

The model has been implemented in a python framework that consider the structure represented in Figure 10.

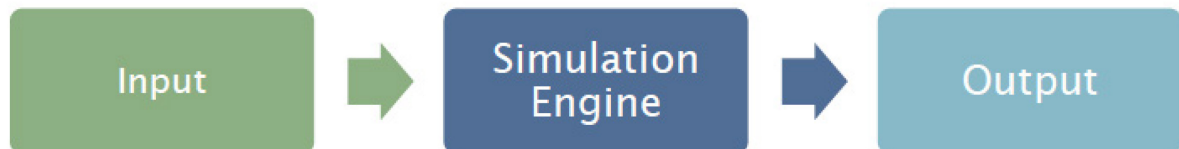


Figure 10. Model structure

### 2.4.1 Data Inputs

Open-Sesame has been built to demand as little information from the user as possible. With this intend in mind, the simulation engine needs two types of input data. The user shall provide a power profile (or a SOC profile) along with a temperature profile. Both profiles should be a time-series and included as a CSV file.

By defining specific parameters on the main python file, the user can customize the simulation model. The input parameters can be classified into three categories:

- Battery parameters (Energy, Chemistry ...)
- Initial conditions (Initial SoC, SoC max ...)
- Simulation settings (Time resolution, iterations ...)

Thanks to the simple design of Open-Sesame, the user only needs to implement parameters that are easily obtainable and often already known. However, the model also uses some basic curves and data that assumes to be similar within the same chemistry type. In Figure 11 and Figure 12, the Open-circuit voltage curve as function of the SOC and the internal resistance (IR) map as a function of Temperature and SOC for a typical NMC cell can be seen.

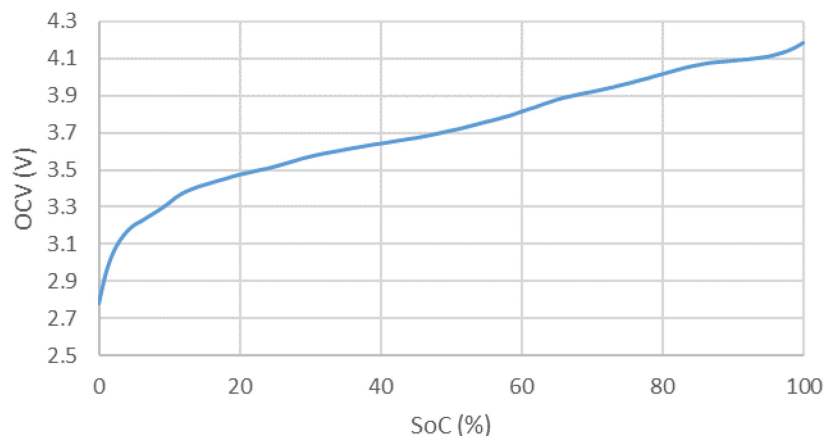


Figure 11: OCV vs SoC graph for an NMC cell

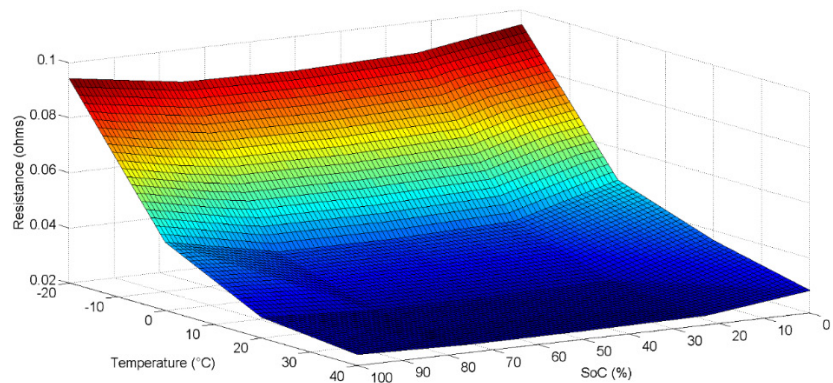


Figure 12: R-SoC-T map for an NMC cell

### 2.4.2 Cycle identification

To perform the cycling degradation analysis, small cycles need to be identified to be able to associate to each of these cycles their contribution to the total degradation. The SoC profile of the battery must be examined with regard to the charging and discharging cycles performed. As part of Open-Sesame, two different approaches were used to detect charge and discharge cycles. Both algorithms require the SoC profile of the battery over a specific period. The overall degradation calculation can only be carried out after the algorithm recognized charge and discharge cycles.

This method can potentially lead to a conflict when selecting the observation period. On one hand, if a long observation period is selected, the degradation from the cycle is only updated at the end of the long observation period. As a result, the subsequent cycles are calculated in the same observation window with the SoH and SoR not being updated. On the other hand, if the observation period selected is too short, there is a risk that discharge cycles are not fully included in the observation period and are therefore incorrectly divided into partial cycles.

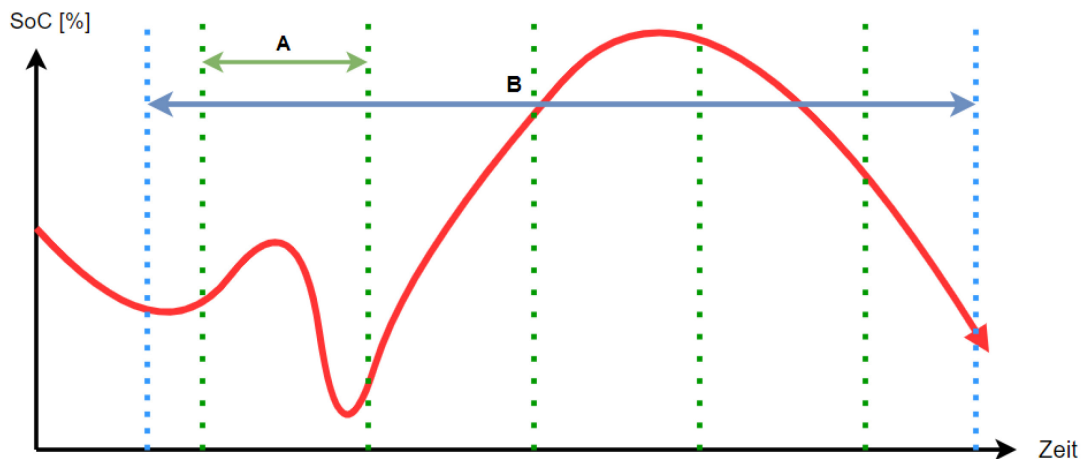


Figure 13: Illustration of the potential cycle identification conflict in selecting the observation period.

Figure 13 shows two different periods A and B, with which the SoC profile can be divided.

A is five times shorter than for B and thus a full discharge cycle is divided into several partial cycles which probably leads to an underestimation of cyclical ageing. Period B however includes the full discharge cycle within the observation period.

In principle, the selection of a too short observation period is assumed to have a more negative effect on the accuracy of the simulation results. The following criterion can be used to set the optimum observation period:



Period under review > 5 \* Discharge cycle time<sub>Longest cycle</sub>

### 2.4.2.1. Rain-Flow Algorithm

The Rainflow counting method is often used for cycle counting in electrochemical energy storage systems thanks to its similarity to mechanical systems. The rainflow algorithm used in Open-Sesame is based on the implementation of the algorithm in Python "rainflow 3.0.1" and in accordance with the ASTM E1049-85 standard [3].

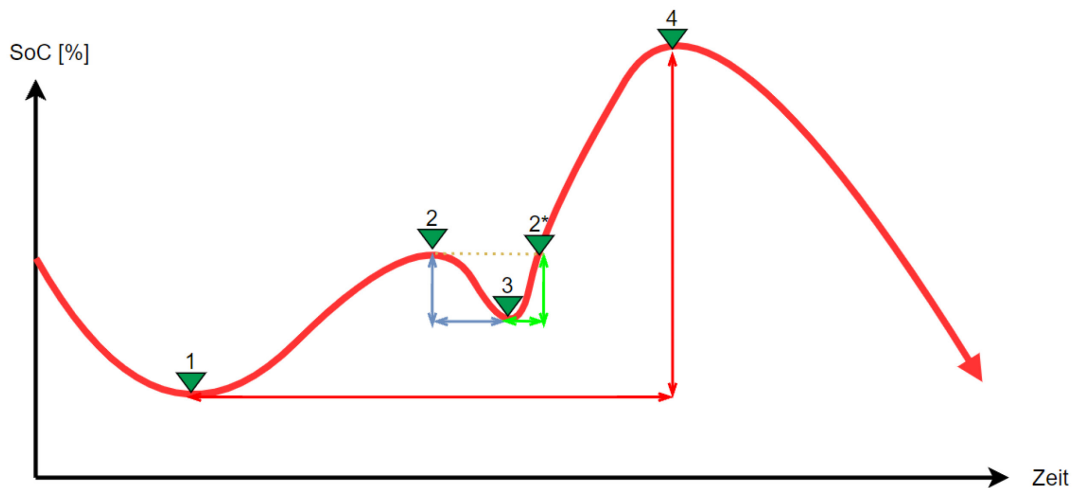


Figure 14: Principle of the Rainflow algorithm. Three half cycles were detected (1-4, 2-3, 3-2\*)

The Rainflow algorithm starts by searching for local maxima and minima in the SoC profile. Once these have been found, full and half cycles are determined between these maxima and minima. The rule is followed that the subsequent maximum must be smaller than the current one for the cycle to end at this point. The same applies to the local minima. In Figure 14, the two sub-cycles 2-3 and 3-2\* are sub-cycles of the much larger half-cycle 1-4. Point 2\* was transposed to the same height as point 2 so that the sub-cycle can be completed.

A modified rainflow algorithm was implemented as part of Open-Sesame. In this model, full cycles found are always divided into two half cycles (charging and discharging cycle). This allows an average C-rate to be assigned to the half-cycles found. This determination of the C-rate would not be trivial for a full cycle, as this consists of a charge cycle and a discharge cycle. The average C-rate was calculated taking into account times without charging:

$$C\ Rate_{half-cycle} = \frac{SoC_{Start} - SoC_{End}}{time_{Start} - time_{End}}$$
$$Ignore\ time\ steps\ when: \frac{d_{SoC}}{dt} = 0$$

This methodology arises from the observation that the SoC profile plateau displays local maxima and minima exclusively at the onset or conclusion of a cycle or sub-cycle. Accordingly, the duration during which these plateaus persist must be omitted when calculating the average C-rate. In the context of battery application, these plateaus commonly appear when the battery undergoes prolonged periods of inactivity following a charging cycle.



The method used to compute the C-rate for half cycle is also used analogously to calculate the average temperature and the average SoC during the half cycle. The DoD of all half cycles results from:

$$DoD_{half-cycle} = abs(SoC_{Start} - SoC_{End})$$

#### 2.4.2.2. Valley-to-Peak Algorithm

Another approach to detecting cycles is the valley-to-peak approach. As with the rainflow algorithm, this approach starts with searching local minima and maxima.

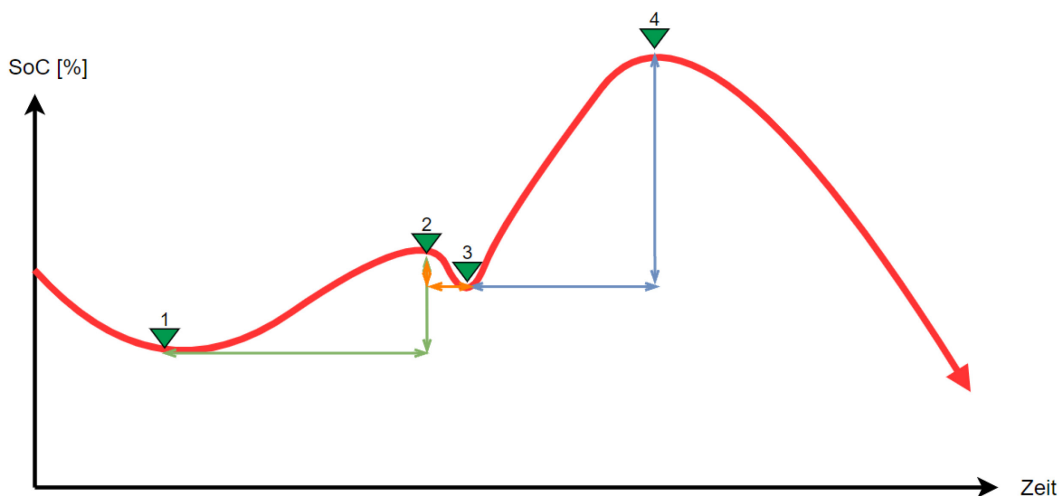


Figure 15: Valley-to-peak algorithm. Three half-cycles were found.

Figure 15 explains how the peak-to-valley algorithm works. A total of two local maxima (2 and 4) and two local minima (1 and 3) were found. In the valley-to-peak algorithm, a half-cycle is defined from a local minimum to the subsequent local maximum and vice versa. The example illustrates the effect of the Valley-to-Peak algorithm. The large half-cycle from point 1-4 is divided into two parts by the small discharge cycle 2-3 (half-cycle 1-2 and half-cycle 3-4). This division results in two partial cycles with half the DoD. In the degradation analysis, the sum of these two cycles has a smaller effect on degradation than the half cycle (1-4) would have. The calculation of the DoD, average C-rate and average temperature is basically the same as for the Rainflow algorithm. As no sub-cycles are detected with this method, these do not have to be taken into account when calculating the average values.

The two algorithms provide the same information. Both can therefore be used in the same simulation environment.

#### 2.4.3 Data Outputs/Model Outputs:

Outputs of the simulation are provided to the user in different manners.

Performances results are provided for each cycle and regroups information such as SoR, SoH, SoC, Vbat etc... Each cycle can be visualized by the user such that he understands all major information at any moment in time.

Cycles results regroups all information related to stress factors variations during the cycle. This means that the user can understand better all impacts of his profile on all stress factors for each cycle.

Finally, degradation results are containing information about the degradation of the battery for every timestep of the simulation. The results are actualized after each cycle performed and are useful to follow the degradation along the entire expected lifetime of the battery.

Figure 16 shows some examples on how the outputs can be displayed.

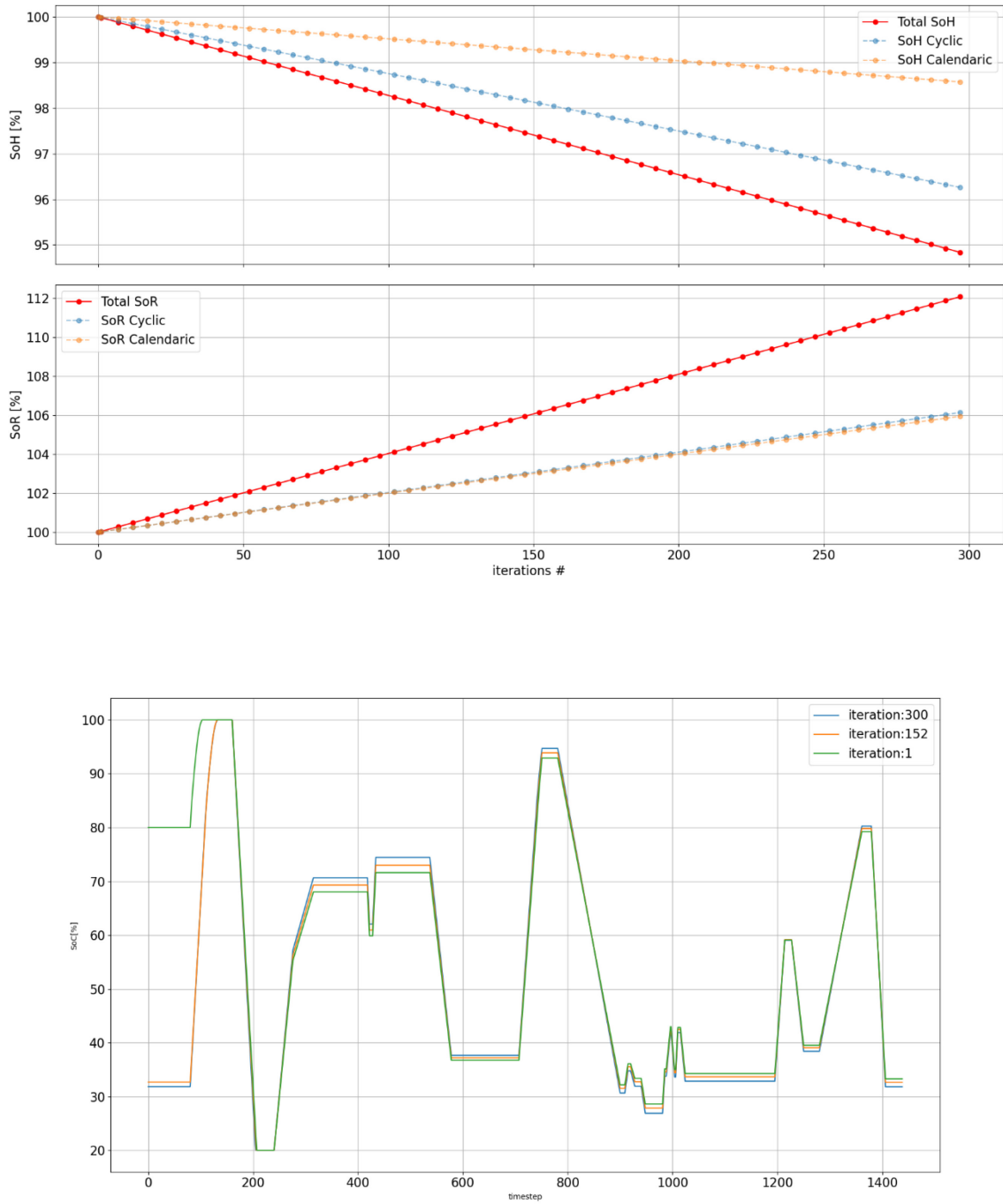


Figure 16. Example of possible outputs that can be visualized.

#### 2.4.4 Github structure

The code repository for the open-sesame model developed can be found on this link: <https://gitlab.ti.bfh.ch/oss/esrec/open-sesame.git>.



The gitlab repository is structured in three different folders:

- doc
- src
- tests

In the doc folder, the pdf user-guide of this project and the relevant documentation can be found to understand the model. The src (source) folder contains all the scripts and data tables useful for the simulation. Finally, the folder tests regroup all testing-scripts, input data and profiles useful for quickly run the model. On the top level of the project-folder the user will find "app-demo.py" and "app-demo\_SoC.py" Scripts. Both are Demo-Scripts on how to define a simulation and run it.

#### 2.4.4.1. Optimal Charging Strategies in Electrified Public Transport - OCSEPT

The acronym OCSEPT (spoken similarly to "accept") represents a software tool for determining optimal charging strategies in electrified public transport. Open-sesame-Battery has been integrated into a tool from ETHZ which aims to optimize the usage of electrified public transport. Open-sesame-Battery is in the center piece as it is used to model the degradation of the battery depending on Real-time operation strategies.

Repository: <https://ocsept.gitlab.io/ocsept/>

Article on the subject [3]: <https://doi.org/10.1016/j.etrans.2022.100196>

#### 2.4.5 Thermal model

Since Open Sesame model does not link an increase in C-rate to an increase of temperature seen by the battery that could eventually increase the relative stress factor, BFH elaborated 2D model to determine the temperature distribution within a pouch and cylindrical cell with a Finite Volume method approach using MATLAB to help creating guidelines for thermal system sizing and improved the definition of the right temperature stress factor to be considered in the aging analysis. The model was successively translated to python to be considered as an extension of the basic Open-Sesame-Battery model, but its validation is still in progress, and it has not been released in the open-source version.

The goal of this model is (i) to understand the thermal behaviour of a cell for different operating profiles and (ii) to be easily linked to the equivalent electric circuit model (ECM) and improve the temperature increase that is expected while operating at high C-rates (improving at the same time the resulting degradation) (iii) to help sizing the battery thermal management system. The model uses the battery's thermal properties, internal resistance, and current to determine the produced heat during operation and allows to visualize a temperature distribution map.

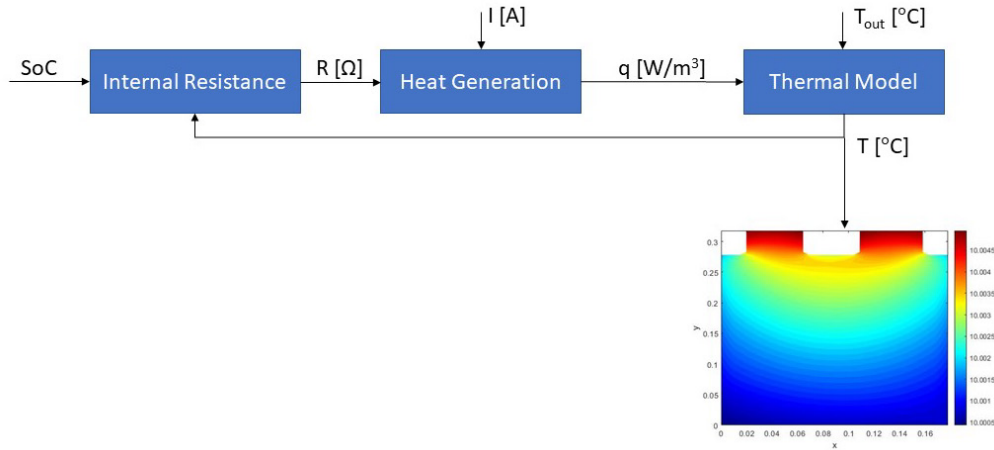


Figure 17. Thermal model flowsheet.

The Thermal model can be described by a transient, diffusive transport equation with a source term according to the following expression:

$$\rho C_p \frac{\partial T}{\partial t} = k_x \frac{\partial^2 T}{\partial x^2} + k_y \frac{\partial^2 T}{\partial y^2} + q$$

Where  $\rho$  refers to density,  $C_p$  to specific heat capacity,  $k$  to the thermal conductivity,  $q$  to heat generation per unit volume and  $T$  to temperature.

Enthalpy is given by,  $h = \rho C_p \Delta T$ , with  $\rho$  and  $C_p$  constant. Thermal conductivity,  $k$ , is also constant.

For a lithium-ion battery, the heat generation is determined by the complex electrochemical reactions occurring during charge and discharge. There are four major components that encompass battery heat generation[4]: reaction heat, ohmic heat, polarization heat and secondary reaction heat.

Through a thermodynamic energy balance on a complete battery cell, Bernardini derived an expression for battery heat generation [5], this expression is most widely used in its simplified form.

$$q = I(U - V) - I \left( T \frac{\partial U}{\partial T} \right) = RI^2 - I \left( T \frac{\partial U}{\partial T} \right)$$

Where  $q$  refers to the total heat generation,  $U$  to the battery open voltage,  $V$  to the battery voltage,  $I$  to the current,  $T$  battery temperature and  $\frac{\partial U}{\partial T}$  is the entropic heat coefficient.

The expression can be further simplified by using the battery internal resistance  $R$ , which can be accurately estimated, whereas the heat related to material phase changes and mixing effects can be neglected due to their negligible influence on the total heat generation.

In large batteries, heat generation from the current collectors can have a significant effect on the overall heat generation and it should be considered [6]. For this model tab heat generation was determined as.



$$q = \rho' \frac{l}{S} I^2$$

Where  $\rho'$  is the material's resistivity ( $\Omega.m$ ),  $S$  is the tabs cross-sectional area and  $l$  Tab length.

The model has been solved with finite volume method and applied to cylindrical and pouch NMC cell subject to a current profile. The temperature estimation has been validated with respect to laboratory measurements, the relative error between model estimation and measured value is always below 15%.

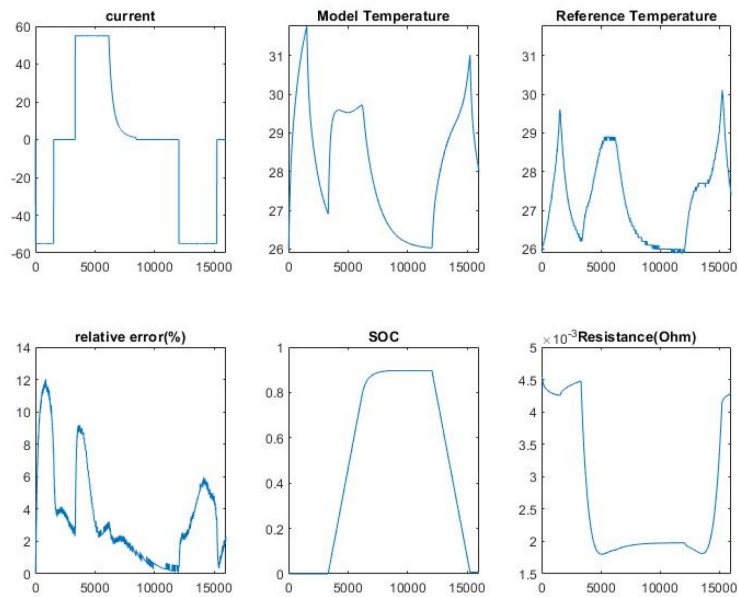


Figure 18. Pouch cell thermal behaviour during charge and discharge. Comparison between Model and Reference (measured) temperature at the middle of the pouch cell.

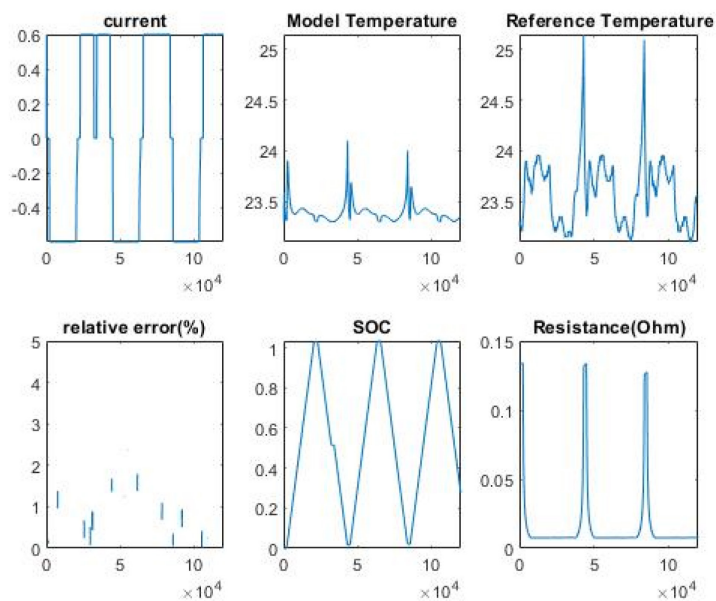


Figure 19. Cylindrical cell thermal behaviour during charge and discharge. Comparison between Model and Reference (measured) temperature at the middle of the cylindrical cell.



In Figure 18 and Figure 19 the model capabilities to estimate temperature increase during charge and discharged has been assessed by comparing the model results with laboratory measurements. The thermal model on single cell level has been simplified from a 2D to a lumped capacitance model [7][8] to assess the thermal need on battery module level. The lumped model is faster to be solved and consider the interaction of closely spaced cells:

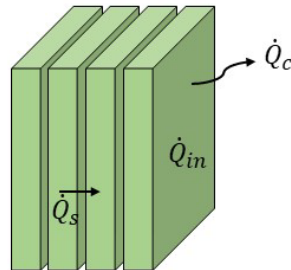


Figure 20. Battery module geometry

$$V\rho C_p \frac{dT}{dt} = -hA(T - T_\infty) + \dot{q}_{in}\rho V + \dot{q}_s A_s \quad (4)$$

- $A_s$  conductive heat transfer area
- $A$  convective heat transfer area
- $T_\infty$  outside Temperature
- $T_0$  previous time-step Temperature

The main goal of the lumped capacitance thermal model is to be able to estimate the temperature along a battery module. In Figure 21 is possible to observe that when 10 cells are in contact with each other the temperature starts increasing and the heat cannot be evacuated easily only by convection.

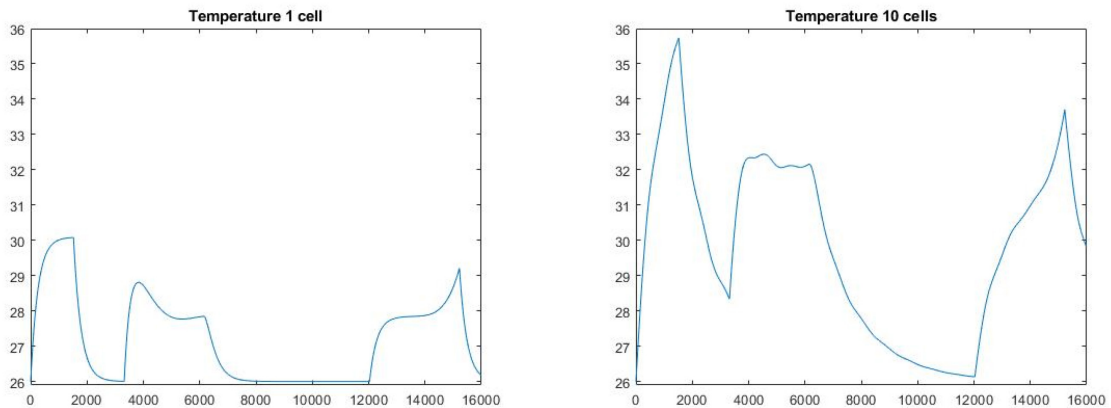


Figure 21. Temperature profile differences between a single cell and a module of 10 cells in series.

As the temperature increase is important to limit the long-term degradation and to assure a safe battery operation, a thermal model that gives indication about temperature distribution and thermal system sizing is of considerable support.



## 3 Application

### 3.1 Graphical User Interface (CSEM)

As anticipated the web interface named SoXery is available online at [tinyurl.com/soxery](http://tinyurl.com/soxery). The user must provide the profile parameters and battery parameters. The first profile parameter is the input profile in the .csv format. This file consists of power and temperature data for the cell at a certain time resolution. In addition to this, the user must also provide this time resolution and time horizon for the simulation. In the battery parameters, the user must provide the size of the battery pack, the cell chemistry and the minimum and maximum SoC allowed during the simulation.

The output of the simulation is displayed in two panels. The first panel displays KPIs such as SoH and SoR and the contributions of calendar and cycle aging in each one of them. It also displays the total number of full equivalent cycles performed by the battery and maximum and minimum currents and temperatures imposed upon the battery. The second panel displays several graphs which depict the trend of certain parameters over the simulated period: SoH, SoR and SoC. For instance, Figure 22 shows the decrease in the SoH for a specific application profile.

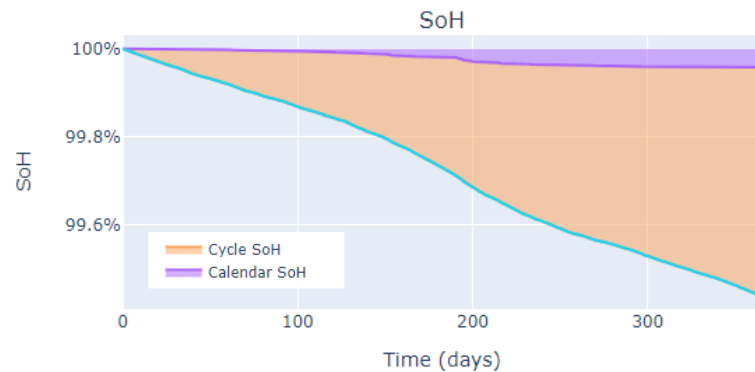


Figure 22. SOH decrease over usage.

A graph showing the input profile is also displayed so that the user may cross check if the input power profile has been applied as provided. Finally, an unfulfillment map is displayed. This map shows whether there were certain times during the simulation where the battery could not provide or absorb the power specified by the user. An example of such a map is shown in Figure 23.

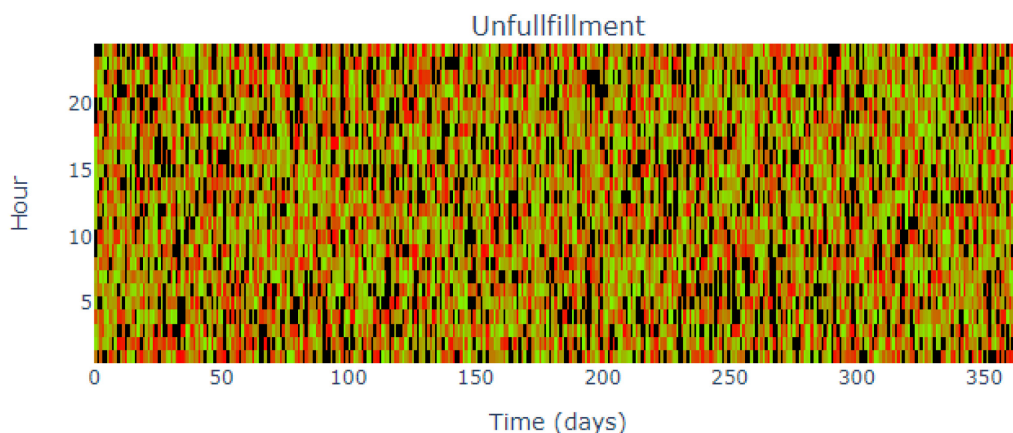


Figure 23. Unfulfillment map.

The green regions on the map show the instances when the battery SoC is away from the set maximum or minimum SoC while the red regions show the instances where it is not. The black regions depict the



times where the input profile could not be followed. The amount of black in the map is an indication to the user that the battery sizing may need to be increased.

## 3.2 BatMaestro

BATMAESTRO is a battery model implementation in Python that includes battery lifetime modeling and that is compatible with mixed-integer linear optimization framework. BATMAESTRO was derived as a modification of the Open-SESAME-Battery.

The code repository for the BatMaestro implementation of open-sesame code can be found on this link: <https://github.com/csem/batmaestro>

## 3.3 eBusPlus

In an electric bus, the battery is the most important, but also the most challenging element for the design and the planning. In particular, it is difficult to record precise performance figures and estimating the service life is difficult. The ageing process is therefore constantly monitored with a measurement campaign and accompanied by experts from BFH.

The knowledge gained is implemented in Open-Sesame-Battery and helps dealing with the architecture of the entire vehicle, which is fully optimized to achieve high performance. Only in this way the maximum potential of the electric drive can be exploited.

In contrast to the "SwissTrolley plus" project, the ageing model is there to be continuously compared with actual measurements on the test vehicle for the duration of the pilot project and, be adapted for error minimization. Based on the laboratory values from the accelerated service life tests the real-time Telemetry data from the vehicle will be used to optimize the service life model the battery is the biggest cost driver for electric buses. It is therefore extremely important to correctly dimension the capacity required for a bus route. On the one hand, it should be as small as possible so that no unnecessary acquisition costs are incurred, and no unused weight is dragged around. On the other hand, it should be large enough so that the repetitive charging and discharging cycles do not extend the capacity range too far. Do not utilize the capacity range too much and cause the battery to age too quickly. Both criteria can be met with the appropriate placement of charging facilities on the bus route or at terminal stops.

# 4 Conclusion

Open-Sesame-Battery model was created as open-source software for battery degradation (capacity and power fading) computation to assess the lifetime of a battery system subjected to a known power and temperature profile. The model framework is built upon several assumptions and simplifications that makes the tool lean and easy to be used over long term simulation at the expense of the model precision. The validation activities have proven that whenever testing data are available, a model tuning is important to keep the maximum relative error below 5%. In case the tuning is not possible, the maximum relative error can be as high as 10%.

Open Sesame Battery model has been distributed over different research groups and Swiss battery players like ETHZ, Hess, SBB.

The model is implemented in a GitLab platform, and it is kept alive to accommodate further improvements coming from a bigger community.



## 5 Publications

- [1] Bhoir, Shubham Sharad. *Aging Modelling of Li-ion Batteries and its Implementation to Evaluate the Impact of V2G Service Provision on the Batteries of EVs*. MS thesis. 2021.
- [2] Bhoir, Shubham, Priscilla Caliandro, and Claudio Brivio. "Impact of V2G service provision on battery life." *Journal of Energy Storage* 44 (2021): 103178.
- [3] Fabio Widmer, Andreas Ritter, Pol Duhr, Christopher H. Onder, Battery lifetime extension through optimal design and control of traction and heating systems in hybrid drivetrains, *eTransportation*, Volume 14, 2022, 100196, ISSN 2590-1168, <https://doi.org/10.1016/j.etrans.2022.100196>.

## 6 References

- [1] B. Xu, A. Oudalov, A. Ulbig, G. Andersson, and D. S. Kirschen, "Modeling of Lithium-Ion Battery Degradation for Cell Life Assessment," *IEEE Trans. Smart Grid*, vol. 9, no. 2, pp. 1131–1140, Mar. 2018, doi: 10.1109/TSG.2016.2578950.
- [2] Maik Naumann, Franz B. Spingler, Andreas Jossen, Analysis and modeling of cycle aging of a commercial LiFePO<sub>4</sub>/graphite cell, *Journal of Power Sources*, Volume 451, 2020, 227666, ISSN 0378-7753, <https://doi.org/10.1016/j.jpowsour.2019.227666>.
- [3] American Society of Testing Materials (ASTM), "Standard practices for cycle counting in fatigue analysis," ASTM E1049-85, West Conshohocken, PA, 2005
- [4] D. C. Wang Zichen, "A comprehensive review on thermal management systems for power lithium-ion batteries," *Renewable and Sustainable Energy Reviews*, p. 139, 2021.
- [5] D. Bernardi, et al "A General Energy Balance for Battery Systems," *Journal of the Electrochemical Society*, Volume 132, p. 5, 1985. DOI 10.1149/1.2113792
- [6] Todd M. Bandhauer et al, "A Critical Review of Thermal Issues in Lithium-Ion Batteries," *Journal of The Electrochemical Society*, pp. 158 (3) R1-R25, 2011.
- [7] A. A. Pesaran, "Battery thermal models for hybrid vehicle simulations," *Journal of Power Sources*, p. 377–382, 2002.
- [8] W. J., "Lumped Thermal Capacity Model," in *Encyclopedia of Thermal Stresses*, Springer, 2014.

## 7 Activities and results

Here below the main research activities carried out in the last years are reported:

1. *Test the model in different projects and, whenever possible, compare the simulation results with the observations of real-life battery applications*

This activity has been the most important for the 2022. The open-sesame battery simulation toolbox has been promoted and used in different use cases:

- Second life application: CSEM has been asked by a Swiss company to run some simulation to determine the battery degradation for future second life adoption.
- Automotive application: CSEM has been asked by a US company to run some simulation to verify the fidelity of their findings on the SoH estimation.



- Electric Bus: BFH is collaborating with HESS and ETHZ for the next generation of fully electrical bus. Open Sesame has been used to:
  - Showcase business cases to BVB and BVZ based on bus line requirements and battery chemistries.
  - Determine optimal design and control of traction and heating systems in hybrid drivetrains having as objective of the optimization the battery lifetime extension [3].
  - Trolley Bus application: Open-Sesame was used in BFH to evaluate the method of electrification of bus lines considering the impact of the charging method on the battery life and the total cost of the system. In particular three charging systems were considered: (i) stationary night charging (ii) stationary opportunity charging and (iii) In Motion Charging (IMC). A paper will be published next year based on this evaluation.
  - Train application: Open-Sesame has been used in BIENE project to assess the great potential from both sustainability and economic side of complete electrification of SBB diesel fleet to battery drive train.
2. *Release the battery simulation toolbox to the external, so that to reach the goal of an open-source modelling framework.*

The simulation toolbox is now fully open source:

- The source code is available here: <https://gitlab.ti.bfh.ch/oss/esrec/open-sesame> and has been updated and maintained regularly. It comprises of a test case and a user guide that explain the software architecture and the input/output of the python code.
  - The web interface named SoXery is available <http://www.tinyurl.com/soxery> or at <https://portal.csem.ch:9260/>, which include also an [user manual](#) and a user feedback form.
3. *Set-up the basis for an optimization framework based on the developed battery simulation toolbox.*

CSEM has investigated the opportunity to integrate the open-sesame battery simulation findings in the CSEM's [NRGMaestro™](#) optimization framework, a toolbox for district energy optimization. This has led to a new connected project: BatMaestro that generated results in form of an open-source optimization code which can be found at this [link](#)