Adaptable equivalent circuit model for electrochemical storage elements as a part of energy system modeling for ZEB

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***Abstract* — In the context of global energy transition, reduction of building energy consumption takes an important role. In order to achieve buildings with yearly net zero energy, integrating energy production such as Building-Integrated Photovoltaic (BIPV) can be a low cost solution. However storage elements become necessary to optimize their functioning in terms of energies exchanges. This paper is focused on electrochemical storage elements; their modeling in order to choose the best one in term of efficiency and lifetime. To simulate their behavior in the context of BIPV, a simple model must be designed to take into account the complexity of the system. A modeling technique for electrochemical storage elements with few parameters is presented in this paper for easy integration in building-scale simulations, which aims to be easily adaptable to new technologies and future evolutions of energy storage elements. The ADREAM building of LAAS-CNRS, a ZEB research platform and demonstrator, provides the necessary experimental data for this work.**

Keywords—Zero energy building; intermittency of PV; electrochemical storage; battery cell modeling; energy system simulation

I. INTRODUCTION

As buildings are responsible for about 40% of the global energy consumption, they represent one of the primary targets of world policies that aim to reduce energy consumptions. The final objective is the achievement of energy savings in the order of 25% by 2030 [1]. The concept of a net Zero Energy Building (ZEB) was defined in the scientific literature by 2006, but it had not been concretely translated into laws and norms, until the National Renewable Energy Laboratory (NREL) proposed some preliminary definitions in 2006 [2]. Recent demonstrations of this concept implied two conditions. The first one was focused on drastic reductions of energy demand for heating and electrical consumption. The second condition was that this type of building produced its own annual renewable energy [3, 4, 5]. Among the different renewable energy sources, such as the solar irradiation, the wind, the biomass, etc., solar energy has a high potential of exploitability due its wide availability.

Technological and structural drawbacks limit the development of this type of buildings. Among them, the reliability of renewable sources is a major issue, as well as the insufficient knowledge of adapting their usage to building integrated systems (limited space, problematic thermal effects, difficulties to forecast the production, high dependency on weather, high costs and system complexity). In 2015, the International Energy Agency edited a report about different energy performance metrics and their evolution between 2000 and 2012 based on two scenarios of consumption and greenhouse emission reduction by 2025 [6]. In these scenarios, ZEB metrics take a significant place and require further investigation in research in order to optimize building energy systems.

Since 1999, demonstrations of Building-Integrated Photovoltaics (BIPV) appear as a ZEB solution [7, 8]. In order to achieve complete autonomy, energy storage elements are to be paired with renewable energy production to respond to energy demands when renewable producible is unavailable. Storage elements must also guaranty high quality of the provided energy by smoothing out peak production and or peak consumption. The difficulty lays in the choice of the best technology of storage elements among multiple solutions. This paper comparatively treats of the electrochemical elements that are the most adapted to this type of application (high intermittence, high usage time, robustness and low cost).

In order to study and design complete ZEB energy systems through simulation; each element of the energy system needs to be modeled individually. The building ADREAM of LAAS-CNRS was designed as a BIPV research platform for the development of ZEB metrics. While other studies treat of energy production models or heat exchange models [9, 10], this paper focuses on a simple modeling methodology usable for multiple electrochemical storage technologies that can be used in the context of ZEB. The objective of this work is to develop models of storage elements with few parameters and a reduced number of experimental tests in order to rapidly characterize new technologies and future evolutions. Finally, this work aims towards the development of a complete model of the energy exchanges in a ZEB.

This paper introduces different electrochemical storage technologies that are adapted to the context of ZEB in section 2. A methodology to develop a simple equivalent circuit model usable for multiple battery technologies is presented in section 3. To validate our approach, a presentation of the ADREAM building which is the subject of a general ZEB energy system modeling is done, and finally, a conclusion and perspectives on modeling of electrochemical storage elements in ZEB are given (section 5).

II. Electrochemical storage technologies adapted for ZEB

Storage of electrical energy is one of the key points for successful renewable energy development. Several different technologies exist nowadays and it is essential to identify the most adapted ones for usage in an energy-optimized building. Determinant factors for comparison [11] are battery lifetime (depending on depth of discharge DOD per cycle), the efficiency of the cells (ratio of charged/discharged energy), their price and their environmental footprint. These storage devices must be able to store as much as possible of the overproduction from renewable sources and must be able to restitute this energy as needed when the production is not sufficient to supply for the buildings consumption. In this case the stored energy is discharged over several hours, meaning specific energy (Wh/kg) is more valuable than specific power.

For our first approach, four technologies of batteries have been selected based on their performance in a building context: Solar Lead acid, Lithium iron-phosphate, Lithium polymer, EDLC supercapacitors and hybrid LIC lithium-supercapacitor.

A. Lead acid batteries

The lead acid battery technology [12] is the oldest rechargeable accumulator technology, existing since 1859. It is very commonly used today and different variations exist for different applications (energy storage, power storage). Even in new optimized elements adapted for solar applications, it presents a low specific energy (33 to 42 Wh/kg). Nevertheless, it can be a good compromise for major stationary energy storage due to its low cost and its robustness to environment temperature.

The AGM (Absorbent Glass Matt) and OPzV (using tubular electrodes) [13] are the most adapted lead-acid technologies for photovoltaic production and especially in energy optimized buildings. The electrolyte is jellified in hermetic sealed battery blocs, minimizing maintenance needs. These specific types of lead acid batteries can have a lifetime of 500 to 1500 cycles at 80% depth of discharge (DOD) against 300 to 600 cycles for other lead acid technologies. Their self-discharge is a slow 3% to 10% per month [12].

B. Lithium iron phosphate batteries

Lithium-ion batteries [14] are industrially produced since the beginning of the 1990's and are the most used storage device today on the electronic consumer market.

Mobile devices generally use mixed cobalt-lithium batteries $LiCoO_2$ for their high energy density. The lithium iron phosphate battery $LiFePO_4$ presents a slightly lower energy density (~90Wh/kg) but a longer lifetime (2500-3000 cycles at 80% DOD) and a better security, which makes it especially adapted for stationary high-energy storage. The price of the $LiFePO_4$ technology is higher than for lead acid batteries but stays competitive due to having the highest lifetime among batteries, meaning less replacing and maintenance costs. It also has a better capacity in fast discharges and deep discharges while maintaining a low self-discharge rate (around 3% per month). Low voltage variation while discharging greatly reduces the complexity of the voltage regulation for this technology. It is therefore one of the best-adapted batteries for inhabited environment when used with a protection system against overvoltage and overcurrent.

C. Lithium-ion Polymer batteries

Lithium Polymer (LiPo) cells use a solid polymer as electrolyte (SPE) such as polyactrylonitrile, polyethylene oxide or polymethyl methacrylate instead of an organic solvent with lithium-salt. The main advantages of this technology are their easy shaping in space and weight and their low self-discharge (~5% per month), making them a good choice for embedded electronics. While they are mainly used in radio controlled equipment (RC modeling), LiPo cells can be used for autonomous mobile homes and have even been used for simple low energy housings for homeless people in the USA as presented in [15].

D. Electrical double-layer capacitors EDLC

EDLC is a technology halfway between batteries and electrolytic capacitors that are able to store more energy than a classical capacitor. The energy can be stored and released at higher power than in a classical capacitor. Double-layer capacitors are not limited by the electrochemical charge transfer kinetics of batteries and can charge and discharge at a much higher rate and with a lifetime of more than 500 000 cycles. Current EDLC with organic electrolytes operate at 2.7V and reach energy densities around 5-8 Wh/kg [16]. The general drawback of EDLC is their high cost in comparison to lead-acid or lithium batteries. However, hybridizing these battery technologies with EDLC supercapacitors can greatly increase their lifetime [17].

E. Lithium supercapacity chemical hybrid LIC

The intermittency of photovoltaic production can be problematic for energy storage. Hybrid systems using lead acid and lithium ion batteries with supercapacitors are largely studied in this domain and tend to improve the smoothing of production or consumption peaks directly related to intermittency [18].

Lithium supercapacitors (LIC) [19] are first designed in 1991 by Kanebo Co based on a patent from 1981. They are new electrochemical hybrid storage devices that have been created to combine principles of lithium-ion batteries and double-layered supercapacitors (EDLC) and then make trades-off of several properties described previously. The main goal of this hybridization is to combine the benefits of each technology in terms of energy density, power density, charge/discharge speed and lifetime. This new hybrid technology is emerging like a potential alternative to electrical hybridization of lithium-ion batteries and EDLC, being used both as energy and power source.

Manufacturers show a very high number of capacitive cycles (>100 000) and a long lifetime, making this technology very interesting for stationary renewable energy structures [19]. Additional studies can be done to verify their daily cycling withstanding in particular in BIPV context. This type of hybrid seems very promising for renewable energy applications. In the Neocampus project [20], the LAAS-CNRS lab, associated to the CIRIMAT lab are studying this type of hybrid storage to test their performance and modeling them in the smart-city context.

III. Simple Equivalent Circuit Model for Electrochemical Storage Elements

For zero energy building applications in particular BIPV buildings, the quantity of storage element needed can be quickly achieved. In order to reduce costs and guarantee a use of these elements during a long time, it is important to select the right storage technologies and design their hybridizations. From energy production to consumption, a system scale simulation is needed. The complexity of this type of applications implies the use of numerous models and an appropriate simulation environment able to process large amounts of data. Following previous studies on PV production [21] a simple equivalent circuit modeling methodology for electrochemical storage elements has been developed. The goal of this modeling method is to be fast and reproducible for every type of electrochemical storage element. The simplicity of the model permits its usage in any type of simulator without compromising simulation speed through the usage of a low number of parameters. The model has to be easily obtainable with a reduced number of experimental tests regardless of technological differences or possible future evolutions, at the cost of reduced precision.

This methodology focuses on the study of a single elementary cell of the desired electrochemical storage element (ESE). Once a single cell's performances are modeled correctly, the results can be extrapolated to the scale of complete battery packs.

The performances of an ESE can be approximated using an equivalent circuit composed of a variable voltage source and a variable resistance as shown in figure 1 [22].

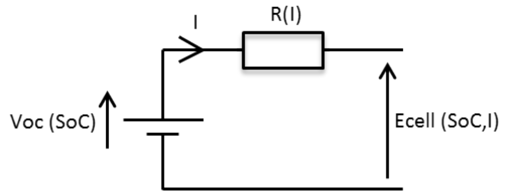

Figure 1: Shematic representation of the Voc(Soc), R(I) equivalent circuit model.

The voltage source Voc represents the open circuit voltage of the cell and can be expressed in function of its state of charge (SoC) defined by equation (2). The series resitance R represents the internal resistance of the cell, which varies with the intensity of the current I. The total voltage Ecell in the cell can be expressed through a simple equation as (1).

$$E_{cell} = V_{oc}(SoC) + R(I) * I_{bat} \quad (1)$$

Where I_{bat} is the charge/discharge current applied to the cell.

The proposed modeling method consists on the choice of a very simple electrical model linked to an easy identification of the parameters Voc(Soc) and R(I) for each electrochemical storage technology as follows.

A. Open circuit voltage Voc

A relation exists between the open circuit voltage Voc and the state of charge of a battery cell, SoC and is the first parameter to be determined for the equivalent circuit model. [23]. In order to determine this relation, an experimental procedure was developed on the battery cycle bench of the ADREAM platform, comprising a battery cycler BCS-815 from Bio-Logic and a thermal enclosure to work at a fixed temperature of 25°C. The cell is charged or discharged at its nominal current rate, 1C, by steps of 50 mAh. After each step, the cell is let to rest until the voltage stabilizes until |dV/dt|< 5mV/h. Ecell is then measured. It can be considered as a point of V_{oc} used to evaluate the corresponding SoC. Charged or discharged Ampere-hour are counted by the BCS-815 cycler and compared to the total capacity of the cell to find SoC through equation (2) for each point of measure.

$$SoC = C_{Ah} / C_{ref} \quad (2)$$

Where C_{Ah} is the current quantity of charge in the battery in Ah.

C_{ref} is the total reference capacity of the cell when it is fully charged in Ah.

Figure 2 shows an example of results of this experimental technique for the 18650 ENIX Energies Lithium phosphate 3.2V, 1500 mAh cell. This test has been conducted at nominal charge current 1C (1.5A), with a regulated temperature of 25°C, applying 50 mAh per step of charge.

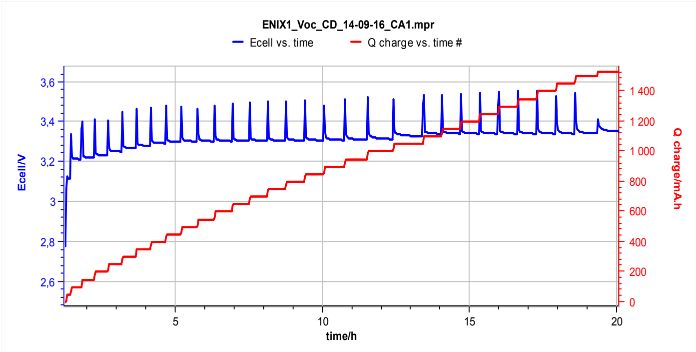

Figure 2: Cell voltage Ecell (V) and Q the quantity of charge of the cell (Ah) in function of time during 50 mAh step charging for 18650 ENIX Lithium phosphate cell.

After a full charge or discharge by steps of 50mAh is achieved, it is possible to trace the Voc = f(SoC) as shown in figure 3.

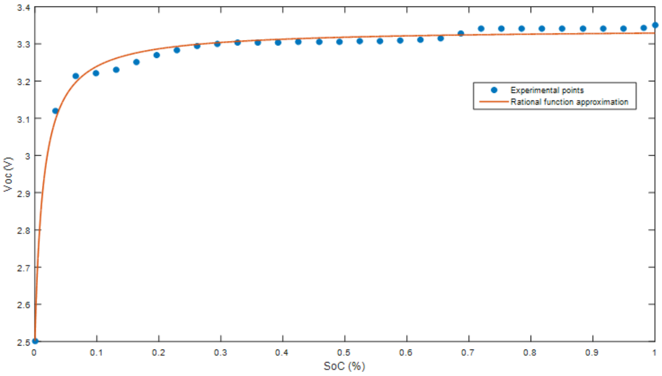

Figure 3: Voc(SoC) and its modeling done by a simple rational function of degree 2 for the 18650 ENIX Lithium phosphate cell.

In this example, a rational function of degree 2 given in equation (3) can describe the relation between Voc and the Soc. In other cases like supercapactors or lead-acid batteries, a polynomial function could be more appropriate.

$$Voc = (p1*SoC^2 + p2*SoC + p3) / (SoC^2 + q1*SoC + q2)$$

$$\begin{aligned} \text{with } p1 &= 3{,}348 \\ p2 &= 0{,}1986 \\ p3 &= 0{,}000122 \\ q1 &= 0{,}06489 \\ q2 &= 0{,}04886 \end{aligned} \qquad (3)$$

The relation between Voc and the SoC of each storage element is represented by a simple voltage source in the equivalent electrical circuit model of figure 2. In order to further complete the model, the internal resistance parameter must be expressed in function of charge/discharge current.

B. *Internal resistance R*

Chemical and thermal loss phenomenon in the battery cell can be expressed as an internal resistance. Thus, this resistance depends on multiple parameters and is therefore non linear. However, for simplifying the modeling approach, the resistance is only expressed as a function of the charge or discharge current applied to the cell. To analyze this dependency between those physical phenomena, a small number of experimental charge/discharge cycles at different currents were done and a measure of the mean resistance was done for each cycle, using the BCS-815. Experimental conditions are constant current during each cycle and constant temperature regulated at 25°C. Once experimental points for the internal resistance are acquired, a relation between R and I can be determined. A logarithmic base is used in order to simplify the equation to a low degree polynomial function.

Figure 4 shows an example of points of equivalent internal resistance measured for a 18650 ENIX Lithium phosphate cell (same cell as in the example of part 3.A) for different charge rates: 1C, 2C, 3C, 0.5C, 0.25C and 0.1C. The points are represented through a logarithmic scale in order to approach it with a polynomial function log(R) = f(log (I)).

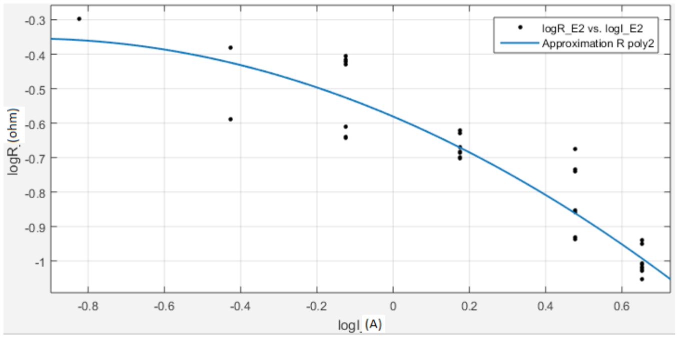

Figure 4: Measures of internal resistance R for different current charge rates and the modeling of R(I) in logarith scales using a degree 2 polynomial for a 18650 ENIX Lithium phosphate cell.

Once a simple relation between the internal resistance R and its charge/discharge current I has been identified, it is introduced as the series resistance in the equivalent circuit battery model.

C. *Complete model*

Once the two parameters Voc and R and their dependencies with respectively SoC and I have been determined for each type of storage element, it is possible to use them in a simple model as the one shown in figure 2. Combining the different dependencies can be done by classical solvers such as matlab in order to obtain a relation between the total cell voltage Ecell, the state of charge SoC and the delivered current I. Figure 5 shows an example of experimental charge of the 18650 ENIX Lithium phosphate cell and the simple modeling obtained in this study.

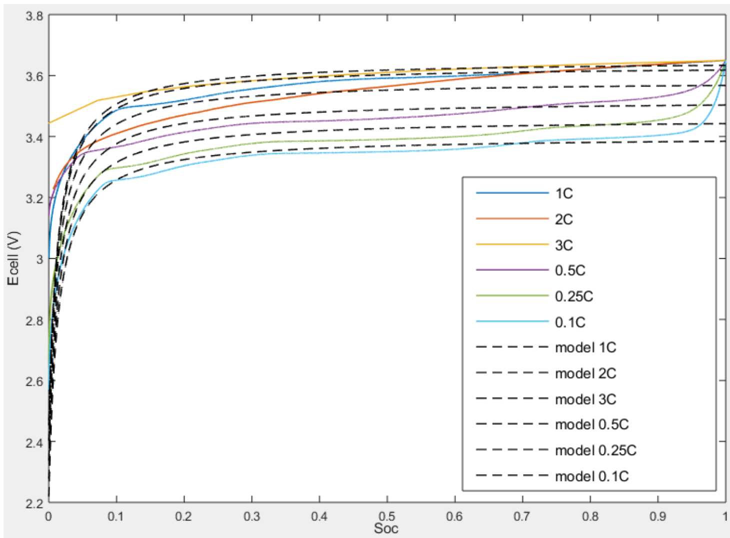

Figure 5: Experimental measures for the charge of the 18650 ENIX Lithium phosphate cell and simulations done with the EC model at different current rates.

When comparing the experimental data with the model data, it can be noticed that the start and end of charge are not very accurately reproduced by the model due to its simplicity, not including capacitive elements, temperature and other non linear elements. The limitations of such a model are clearly visible on this graph. Nevertheless, for the purpose of entire system (building) scale energy simulations it can be sufficient, as most of the usable energy in an electrochemical storage cell is available functioning when the cell is functioning at linear voltage (represented by the mostly linear area between 0.1 and 0.9 of SoC on Figure 6). Statistically, each cell must be considered in a global context of numerous ones in battery pack.

The relative root mean square error (RRMSE) is used to compare the model to the experimental data for each rate of current. Equation (4) gives the expression of RRMSE and results are shown in table 1.

$$RRMSE = \left[\left\{ \frac{\sum_{i=1}^{N} (y_i - x_i)^2}{N} \right\}^{\frac{1}{2}} \right] \Big/ \bar{x} \qquad (4)$$

Table 1: Relative Root Mean Square Error between model and experimental data at different current rates

Charge Rate	I (A)	RRMSE
0.1C	0,15	0,0135
0.25C	0,375	0,0153
0.5C	0,75	0,0222
1C	1,5	0,0196
2C	3	0,0177
3C	4,5	0,0686

The RRMSE is below 10% (0.1) in general, which is a standard goal for this type of model. It is observable that the error is increasing with charging current. This is due to the fact that the model's Voc parameter is determined at nominal current. Higher currents also increase the cell's temperature, which decreases efficiency. The influence of temperature is not studied in this model and needs further investigation.

The developed model is meant to be a part of an energy system model at the scale of a building for research on ZEB. The ADREAM building in LAAS-CNRS provides experimental data and infrastructures for this project.

IV. The ADREAM building

The ADREAM building (French acronym for Embedded reconfigurable Dynamic Autonomous and Mobile Architectures) was inaugurated in 2012 [8]. Comprising a large surface of BIPV systems, it can be used as an experimental platform to validate numerous concepts on Smart Grids, micro-grids, as well as on Ambient Physical Cyber Systems in the context of Smart City development. Figure 6 provides an aerial view of the building ADREAM, showing the totality of its photovoltaic surface.

Figure 6: Aerial view of the ADREAM building

Today, ADREAM is entirely monitored through a large sensor network, which includes a meteorological station. The acquisition of four years of production and consumption data allows the extensive examination of the building's functioning, as well as its ongoing optimization. This process relies on a large amount of data (thermal, electrical, air quality, comfort, lighting, etc.) being stored every day in the platform's database through 6500 sensors.

Recent scientific studies on the building are based on the concept of New Generation Energy Networks. The related domains include power electronics, data processing, security functioning, and automation. The resolution of the associated challenges demands the understanding of the different behaviors of connected systems in an electrical network, such as photovoltaic panels, inverters and storage elements, through complete model elaboration and analysis. Each type of energy source (thermal or electrical) present in the building can be studied through a modular monitoring infrastructure. Additionally, the emulation of different consumption profiles (e.g. lighting, electronic equipment, data servers) coupled to human usages is possible.

Finally, a modeling approach to energy management and optimization for the totality of the systems, integrating all the entities of production, consumption and storage has been initiated. The electrochemical storage element modeling methodology presented in this paper constitutes one part of this general modeling approach. It aims to be used to model the different storage technologies installed in the building and usable for ZEB design.

V. Conclusion and Perspectives

In the context of ZEB research, energy system models are a crucial point for future building design. In order to develop a complete energy system model, each element of the system is modeled separately. A simple, reproducible and accurate modeling approach for electrochemical storage elements has been produced. This methodology aims to be applicable for each electrochemical storage technology usable in ZEB. In addition, the model's parameters Voc and R are determined through a very limited number of experimental steps: a single step by step cycle charge or discharge and a few charge-discharge cycles at different current rates. This modeling technique can be used for rapid determination of an appropriate energy model for new electrochemical storage technologies and to be used in larger-scale system simulation.

The work on the presented modeling methodology forms the basis for uncovering and examining further perspectives. The proposed model can be used to compare general characteristics of different storage elements usable in ZEB. A comparison of the model's accuracy and reproducibility with more complex models such as predictive models and neural network models can be done for additional validation. The impact of cell temperature is another point of improvement to be investigated. In the ZEB context, electrochemical storage elements can also be compared to other thriving storage technologies like hydrogen (H2) in conjunction with fuel cells.

Finally, the model's usage as a subsystem in a complete energy system model for ADREAM constitutes the next step of this work.

AKNOWLEDGEMENTS

This work is done in the Neocampus project context [20] and concerns in particular three laboratories: CIRIMAT, LEPMI and LAAS. The objective is to conceive an LVDC grid based on renewable energy sources and electrochemical storage devices that are adapted to any type of low energy building scenario.

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