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Safety and Security Impacts on Integrated Use of Li-On Batteries in an Energy Island

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***Abstract*— Batteries are central for Energy Islands as they provide a local energy storage by enabling reduction of the overall environmental footprint of energy consumption and helping to reach a CO2 neutral balance. The role of batteries in the E-LAND project is to locally store green energy, use energy efficiently, and to reduce peak loads with energy storage systems. However, to do this effectively installation and use of battery require considerations with respect to both safety and security. This paper elaborates on the project´s safety and security challenges when the Li-on management system is integrated with other systems.**

***Index Terms*—batteries, energy storage, safety, security.**

I. INTRODUCTION

The continued decarbonization of the energy sector through the use of renewable energy sources provides both opportunities for local energy systems and challenges for existing electricity networks. Mainland regions such as isolated villages, small cities, urban districts or rural areas oftentimes have issues with weak or non-existing grid connections. These areas are known as energy islands. Energy islands are often consuming and producing the total or part of their energy. The goal of the European-funded H2020 project E-LAND [1] is to provide a service bus application enabling energy islands to optimize the management of energy, for both production and consumption. The E-LAND solution is developed to address communities of end-users' needs to reach technology and business challenges on the energy market. This solution includes an optimal scheduler tool that delivers computations for best uses of the loads and optimal discharge of batteries in order to upgrade battery life expectancy and to improve their productivity. This optimal usage of batteries become crucial when considering the scarcity and price of raw materials, as well as for reducing energy consumption and CO2 emission to reach towards sustainable and responsible energy consumption. This paper addresses considerations regarding safety and security requirements when using batteries in energy islands.

II. BACKGROUND

A. The E-LAND Project and Toolbox

E-LAND is a Horizon 2020 EU project to create novel solutions for decarbonized energy islands, comprising stakeholders across industries and countries around the globe [1]. The E-LAND project consist of 14 partners: University of Girona, Schneider Electric, Borg Harbor, GECO Global, Smart Innovation Norway, Intracom SA Telecom Solutions, the Reiner Lemoine Institute, Valahia University of Targoviste, Centre for Resources in Energy Efficiency and Climate Change, the University of St. Gallen, Instrumentación y Componentes INYCOM, BSES Yamuna Power Limited, Auroville Consulting and Institute for Energy Technology (IFE). The main delivery of the E-LAND is the E-LAND toolbox. The concept of the toolbox is a modular set of methodologies and information communications technology (ICT) tools that deliver an optimal energy schedule to minimize the cost of production, consumption of energy for multi energy islands and isolated communities. The modular toolbox can be customized to meet local requirements and expandable to incorporate new tools as new challenges arise.

B. Batteries in E-LAND

The role of batteries in E-LAND is to store green energy locally, use energy efficiently and reduce peak loads with energy storage systems. There is large potential in reduction in energy consumption, assisting in balancing renewable energy sources and thereby significantly reduce CO2 emissions. Batteries play a crucial role in localized energy storage and are thus an important asset when it comes to reducing the overall environmental footprint and eventually CO2 neutral energy

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islands. Amongst electro-chemical storage technologies, the lithium-ion battery is the most common and most promising, and the number of projects and installations using lithium-ion batteries is continuously increasing. The size of a battery storage system can vary significantly from site to site. Within E-LAND, 270 kWh batteries are for example included at the pilot site in Romania.

III. Battery safety

It is commonly known that lithium-ion cells can have safety issues. For example, a large number of battery safety incidents has been reported worldwide over the past years within e.g. battery energy storage systems (e.g. the LG-Chem fire April 2019 in Arizona [2]), transport (e.g. fires in the APU battery of Boeing Dreamliner [3]), electric and hybrid-electric ships, electric vehicles and mobile devices (e.g. recall of the Samsung Galaxy Note 7 model [4]). Consequences of safety incidents in battery storage systems, such as fires, can be catastrophic. A thorough understanding of a battery's properties and behavior, such as battery life, state of health and the corresponding safe operational conditions are vital for the safety of larger energy storage systems, especially for applications in energy islands.

A. Battery Ageing, Degradation and Life

Li-ion battery safety incidents are most often related to the ageing and degradation of the battery cells. While the fact that aging of lithium-ion cells leads to a reduced capacity and cell life is extensively covered in the literature by several research groups [5], the safety effects of ageing are far less studied, with only a handful of empirical studies published [6], [7] and [8]. Ageing and degradation of Li-ion batteries will in many cases contribute to reduced thermal stability which potentially affects the safety performance of the batteries.

A Li-ion battery's calendar and cycle life depend on the specific Li-ion chemistry used in the battery, the battery materials structure and quality (electrodes and electrolyte) and the parameter space for a battery's operating conditions, operating and storage temperature, charge and discharge current rates, maximum and minimum state-of-charge for operation, state-of-charge during no-load operation (storage) and cooling and heating of battery system. Due to the large number of different Li-ion battery chemistries in use and various battery manufacturers, the details of a specific battery's cycle and calendar life are in general not well-known. In some cases, the battery manufacturers provide select datasets, and/or research papers present battery life data for specific battery cells and chemistries. However, these data are often collected at extreme temperatures and/or presented as anonymized battery cells and can thus only give indications of the expected cycle life for a given Li-ion battery chemistry.

B. Lifetime Concerns

Assessing a battery's cycle life is time consuming. Accelerated cycling (i.e., employing higher than operational charge and discharge currents) is often performed to assess the cycle-life of a battery. However, such tests often yield either too optimistic or entirely wrong cycle life predictions because these high currents can frequently be associated with higher internal temperatures. Temperature is recognized as the most important factor for Li-ion battery capacity decay and ageing: both, higher (> 30°C) and lower (< 10°C) temperatures affect the energy and capacity and will reduce the expected battery life. Additionally, charging at low temperatures has been reported to contribute to irreversible loss in capacity through Li-plating and can consequently impose a significant safety hazard through internal short-circuits within the battery cell.

Besides external temperatures, certain operational conditions of a battery can led to undesirable high temperatures: high operational current rates lead to a reduction in voltage and an increase in the dissipated heat in the battery. The higher the current, the more heat will be produced in the battery. If the generated heat is not able to escape the battery cell, it can contribute to local heating effects in the electrode materials which again will contribute to cell degradation. The study in [9] modelled the temperature distribution within a prismatic battery cell based on thermal conductivity data and reported that at high discharge rates (2C, with C heat capacity) the temperature in the battery could increase by 40°C at the end of discharge. This illustrates the importance of thermal control in connection with high current rates and its links to cycle life. Results from testing of selected commercial Li-ion cells at IFE's battery testing laboratory performed as part of the SafeLiLife NFR project (228739, [10]) confirm that the largest influence on a battery's cycle life is the temperature during cycling. Both, high (45°C) and low (5°C) temperatures significantly reduce cycle life compared to cycling at room temperature, i.e., 25°C. A general negative effect on cycle life was also observed on increasing the current rates. Fig. 1 shows an example for the cycle life for a 30+ Ah $LiFePO_4$-based power lithium-ion cell at various temperatures and current rates over the full state of charge window.

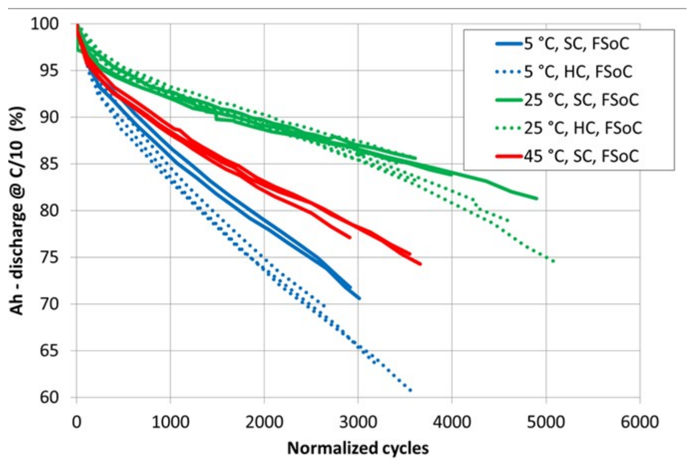

Fig. 1 Cycle life for a selected lithium-ion cell (LiFePO4-based power cell) at several cycle temperatures and current rates in the full state-of-charge window (FSoC). The cycle life was measured as remaining capacity at C/10 discharge current vs normalized cycles.

C. Battery Stability

There are many factors that can make a lithium-ion cell unstable and eventually start a fire. These factors could be e.g., overcharge, overload, heat exposure, external short-circuit, over-discharge (followed by a charge) and internal short-circuit. If the cell/battery system is not able to handle the heat generation caused by these factors, this could evolve into decomposition of the cell material, physical reactions like ventilation, gassing, fire and in rare cases even explosions. Fig. 2 illustrates different factors affecting the stability of a lithium-ion cell (yellow and blue circles) and the potential physical reactions (red figures on the right).

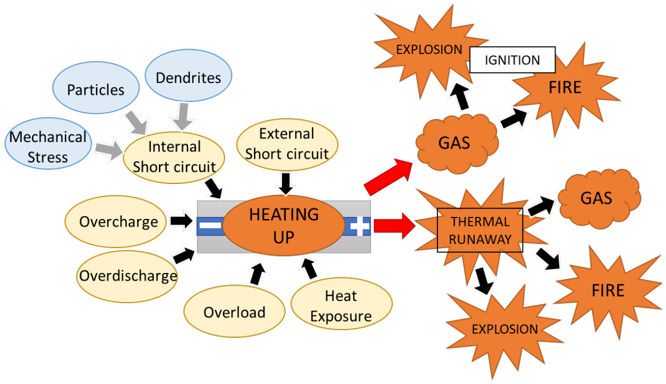

Fig. 2 Overview of different factors that could affect the stability of a lithium-ion cell (yellow circles) and the reaction pattern leading to different physical reactions (red figures) (source: [10]).

An electronic system, the Battery Management System (BMS), can take care handling most of these factors. Consequently, the overall likelihood for a fire in a lithium-ion cell is very low. However, certain factors, such as an internal short-circuit under development, cannot be reliably detected by the BMS or other currently commercially available system. An internal short-circuit could for example arise due to production defects or occur because of cyclic degradation (e.g., mechanical stress or lithium dendrites) of the cell (blue circles shown in Fig. 2). Although the probability of a safety issue (fires and explosions) is very low in general (one in 1 million to one in 10 million), the consequences are catastrophic, and cannot be ignored.

One of the failure mechanisms related to degradation of safety properties of a lithium-ion cell is the development of internal short-circuits. An internal short-circuit is a mechanical connection between the anode and cathode material/current collector inside the lithium-ion cell. When a cell short-circuit internally, the stored electrochemical energy is liberated as heat. If the cell is not able to remove the heat fast enough, a rapid temperature rise could appear at a localized spot in the cell. At temperatures above 190 °C (dependent on the cathode material) cathode materials will decompose and start liberating oxygen. At temperatures above 400°C the autoignition temperature for most of the organic solvents (the electrolyte contains organic solvents) is reached and a fire could eventually start. Even if the short-circuit does not raise the temperature above 400°C, the amount of heat delivered at the short could make the battery material thermally unstable leading to exothermic decomposition of the material. This could eventually force the cell into thermal runaway (minimum 10°C/min heat rate). Therefore, the thermal stability of cathode material is the traditionally way of ranging the effect of an internal short-circuit in lithium-ion cells. An internal short-circuit could release up to 70% of the battery's electrical energy in less than 60 seconds [11]. This indicates that the short-circuit also depends on the cell's energy content (SOC, energy density and size). Fig. 3 shows safety test results for Li-ion cells that were cycled and aged at different temperatures (Fig. 1). Heat rates as a function of temperature for new and cyclic aged lithium-ion cells observed in an accelerated rate calorimeter (ARC). The cell aged at 5°C went into "thermal runaway" at a much lower temperature than the cells cycled at 25°C and 45°C [10].

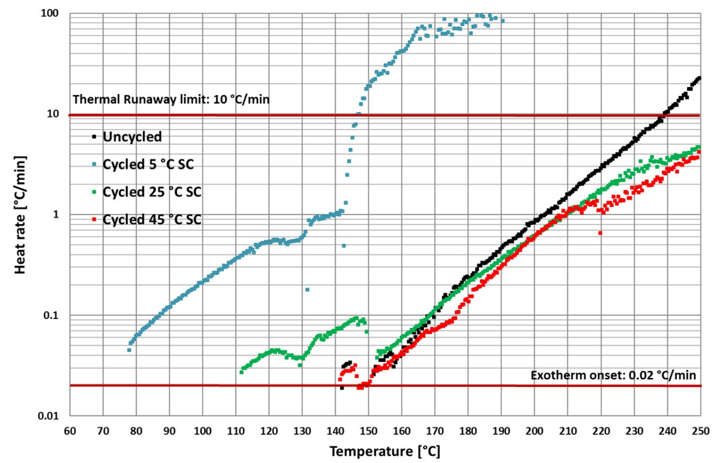

Fig. 3 Results from safety tests of the cycled cells (30+ Ah $LiFePO_4$-based power lithium-ion cell) in Fig. 1. The graph shows that the cell was cycled and aged at 5°C went to "thermal runaway" at a much lower temperature than the other cycled cells for the same Li-ion type and chemistry [10].

In general, the Li-ion cells can handle neither over-charge nor over-discharge. At temperatures above 60°C, the batteries can initiate a self-heating mechanism which eventually can result in both gassing of electrolyte and fire/explosion. Especially when charging at low temperatures, metallic lithium can be formed at one of the electrodes. This can eventually cause an internal short-circuit of the battery, which again could cause a fire in the cell. Safety properties can be significantly different for new and aged cells: for aged cells it can be observed that the "thermal on-set temperature" is often reduced [10]. This can lead to unreliable operation features and increased safety considerations and requirements. This is especially important for cells cycled at low temperatures.

The thermal stability for uncycled cell materials and cells is well-documented, but the effect of cyclic ageing on thermal stability is far less studied. If the thermal stability or physical reaction of the cell changes, it also could change its ability to pass a propagation test. The degradation effects of cyclic ageing of lithium-ion cells are complicated and not fully understood.

IV. SECURITY CONCERNS

A. Exposure of Existing Legacy Operational Infrastructure

In an energy island where both batteries and a smart management system like the E-LAND toolbox are included, there will be communication between the BMS on-site and the management toolbox, often via a secure communication. This communication is a machine-to-machine gateway which permits on-site equipment management from the energy management application cloud platform, with main functions: (1) collect data from the on-site equipment and send it to the toolbox, (2) transmit service orders from the toolbox to the on-site BMS, (3) facilitate on-site equipment maintenance and (4) host local distributed intelligence. Only the BMS communicates directly with the external environment and is the only link between the toolbox and the onsite equipment. This means that only one IP (Internet Protocol) address needs to be configured to have Internet access. The BMS needs to be connected to the internet with a wired network, using the onsite VLAN (Virtual Local Area Network). To expose data and retrieve dispatch commands, the BMS makes an outgoing call using a HTTPS protocol. The communication between various battery systems could for example use Modbus TCP (Transmission Control Protocol) protocol. The BMS is identified as critical asset to enable data and functionality for the integration of a toolbox like the E-LAND toolbox. For each risk identified through conducting risk analysis, mitigation(s) has(have) been proposed, formulated as a high-level detail action, applicable to most of the use cases/technical functions and components of the E-LAND solution, see [12]-[14]. Proposed mitigations include:

- Physical protection of storage device, encoded files or storage area.
- Policy/limitation on what an external e.g., BMS can do of operation and interaction with data application programming interfaces (Application Programming Interface - API).
- Establish network security best practices.
- Authenticate users for all user interface interactions.
- Change default access credentials after installation.
- Enforce limits in hardware so that no setting changes can damage equipment.
- Train personnel on secure networking requirements so that battery owners will understand the impact of bypassing security settings.
- Require approval of next level of management for critical security settings.

B. Asset Hardening and New Integration Requirements

During the risk assessment, [14], we found that hardening of each component and proper configuration management of the assets are important when operating for example batteries. New integration requirements were also identified, such as having a trusted and reliable time synchronization source and logging of both user and system (application) activities.

In our experience we find that custom application event logging is often missing, disabled or poorly configured. Custom logging provides much greater insight than standard infrastructure logging alone. Application logging should be consistent within the application, consistent across the environment and use industry standards where relevant, so the logged event data can be consumed, correlated, analyzed, and managed (OWASP: Open Web Application Security Project, Application Logging).

C. Concerns in a Multi-cloud Environment

National Institute of Standards and Technology (NIST) defines cloud computing as a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources (e.g., networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction [15]. There is a complexity with interoperability between different cloud providers when addressing cyber security issues and maintaining compatibilities and monitoring of resources, e.g., enough storage and maintaining encryption key services. The management systems (like a BMS or a E-LAND toolbox) should enable a secure and seamless data integration and orchestration for advanced tools e.g., forecasting, optimization to external sources of data (e.g., weather forecasts) regardless of where the service is provided. Introducing scenarios where different parts of toolbox services are provided by different vendors in a multi-cloud environment could introduce operational risks that impact the functionality and trust in the applied toolbox. Central components, like an Energy Service Bus, are more exposed with regards to providing a communication layer between applications and therefore more vulnerable to denial-of-service attacks and cloud outage issues. This can be illustrated when cloud providers experience service denial issues causing datacenters to overload on incoming traffic, and thus preventing legitimate users from accessing services on the same networking channels. The result of this resource exhaustion can impact the services developed in the project.

Data privacy concerns in the project account the number of stakeholders, systems and interconnections, and the risk of exposing data through the many API’s is considered high as poorly designed APIs could lead to misuse or data breach [16]. For the project data protection and data privacy has become a shared, but distributed responsibility much in thread with the definition stating that privacy concerns the ability of an individual or group to privately and to selectively share information, only amongst themselves [17]. For the E-LAND project, data privacy concerns relating to GDPR between different third-party cloud providers is a concern and there is a need for control and review of e.g., encryption services and third-party provider's internal controls.

D. Advice for Asset Hardening and Integration Requirement

A common situation for the end users and pilot site owner is the fact that many existing energy systems lack ICT-based interconnections to achieve a cost-efficient integrated local energy system. A good knowledge about existing IT (Information Technology) and OT (Operation Technology) assets- and infrastructure is an important matter for a successful integration. When introducing battery equipment and integrating the toolbox different services in e.g., a multi-cloud environment this tends to be more complicated for the owners to deal with, especially understanding how their asset and information are being exposed and what kind of risks are introduced when integrating the toolbox. The convergence of IT and OT infrastructure is still a challenge that needs to be addressed for better interoperability between these environments. It easy to underestimate the complexity also in existing legacy infrastructures. Organizations have different maturity- and technology-readiness levels that impact their ability to adopt new technologies. It often comes down to how the business is able to align holistic factors on process, technology, and organization to manage their digital transformation. An example of a mitigation recommended is security measure on password and username storage. The E-LAND toolbox extensively relies on components with API interfaces across multiple clouds and infrastructure services that rise the complexity in keeping track of vulnerabilities and impact. Therefore, both proper application (API) hardening against attacks and achieving resilience to compromises in a multi-cloud environment is expected to be more complex to protect and more difficult to operate than in nonconnected battery management system.

V. Conclusions and Recomemndations

As described in section III, operational temperature is one of the most important factors when it comes to battery safety. The ideal temperature for battery operation is at room temperature, while storage at low temperature will prolong the battery life. Both, low and high temperature operation can be harmful to battery life and safety. Reliable temperature control of the battery at system, module and cell level is therefore crucial to ensure safe and efficient operation.

With large volumes of used batteries soon becoming available due to the ever-increasing number of electric cars in use, the re-use (2nd life use) of batteries in energy storage systems is gaining increased attention. By changing the type of application and thus the usage patterns, the battery's life and thereby its value can be extended. Safety considerations for the operation of such 2nd life cells must be adjusted: initial studies [10] indicate a significant increase in thermal instability for aged compared to new uncycled cells, strongly depending on the 1st life operating conditions. As shown in [18], coordinated use of numerous of 2nd life batteries grouped together, for example in a container, can provide a more optimal operation of the batteries and prolong the lifetime of the batteries before they are recycled. However, the behavior of 2nd life cells and the best operating conditions with respect to both, safety and lifetime are not well understood yet. Detailed research on the state-of-health and state-of-safety of 2nd life batteries is required, and very conservative operational conditions are recommended.

Connecting all systems introduce possible threats that should be tempered as they could negatively affect the battery management system and lead to adverse effects on the battery equipment. Therefore, addressing cyber security threats in an energy island is about balancing technical infrastructure and assets risks with business needs and protecting data from unwanted or unintentional information disclosure. This paper discusses some cyber security risks relevant for energy island and presents some recommended mitigations.

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