RFID-Enabled Modeling and Simulation of Sodium-Ion Batteries for Smart City Energy Systems

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Abstract. The concept of smart cities revolves around integrating advanced technologies to improve urban living standards. Therefore, smart cities require efficient energy systems to satisfy the growing needs for sustainability and resilience. Moreover, Radio Frequency Identification (RFID) technology has emerged as a pivotal enabler in the realization of smart cities. For energy storage applications, sodium-ion batteries (SIBs), with their cost-effectiveness and abundant raw materials, are emerging as a viable alternative to lithium-ion batteries (LIBs). In order to maximize energy storage and management within smart city frameworks, this study investigates the incorporation of RFID technology with SIB mathematical modeling. This paper also explores the diverse applications of RFID in smart cities, highlighting the synergy between RFID and SIB technologies. The preliminary framework for co-simulating SIB parameters with placeholder identifiers proved the possibility to develop a system capable of real-time monitoring and data management of a SIB system with RFID technology. In this study, a Python implementation that models the charge/discharge characteristics of SIBs programmatically using parameters extracted from literature was formulated to monitor battery parameters with RFID simulation. The output file contained battery parameters for each cycle, including RFID tags for traceability.

1 Introduction

The swift growth of urban populations worldwide has significantly strained city infrastructure and resources [1]. Smart cities present a sustainable approach by utilizing advanced technologies to enhance urban management and elevate the quality of life for residents. Among suitable available technologies, RFID technology emerges as an efficient and affordable solution for facilitating real-time data collection, identification, and tracking. RFID technology, which includes tags, readers, and middleware allows for the automatic identification of assets, people, or objects and is well-suited for smart city applications and integration into smart city frameworks because it can function in a variety of environmental conditions and without direct line of sight [2].

In recent years, RFID technology has progressively expanded into numerous new application domains, leveraging its unique advantages [3]. Despite this progress, there remains several areas where the implementation of efficient automatic identification systems would be highly valuable.

Chemical energy is the most viable form of energy storage when considering energy density. Thus, batteries are particularly effective in this regard, as they store chemical energy and convert it into electrical energy with high efficiency and without emitting gases. Consequently, developing rechargeable batteries that are inexpensive, secure, and possess adequate voltage, capacity, and rate capability is very desirable [4]. Currently, LIBs are widely utilized as the primary energy storage solution for high-power battery systems, commonly found in electric vehicles (EVs) and stationary grid-connected energy storage facilities (battery energy storage systems (BESS)).

Furthermore, SIBs are seen to be the most promising addition to the widely used LIBs. This is because the earth's crust has at least a thousand-fold more sodium (Na) than lithium (Li). Furthermore, the physical characteristics, production infrastructure, and performance of both battery types are comparable [5] (see Fig. 1). There are currently few published research on the wireless modeling of complete SIBs. Additionally, developing an accurate and dependable model is crucial for the optimal design of a battery management system (BMS) to ensure the efficient, safe, and long-lasting operation of SIBs.

A BMS typically performs key functions such as temperature monitoring or estimation, cell balancing, state of health (SOH) evaluation, fault detection, thermal management and diagnosis, as well as state of charge (SOC) estimation [6]. Consequently, an effective communication architecture is crucial for facilitating data exchange within the BMS, enabling interaction among internal sensors and controllers, as well as the connectivity with external devices for data storage, display, and external control requires an appropriate communication architecture [7].

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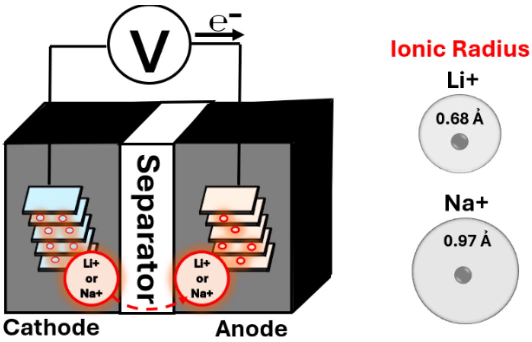

Fig. 1. Cross-sectional diagram of a LIB/SIB with Li-ion and Na-ion ionic radii size.

Beginning with battery cell sensors, the BMS has historically relied on wired and compartmentalized communication between modules. However, adopting the conventional wired connection system with BMS has a number of drawbacks [8]. These include:

i. The cost of assembly since the existing wired BMS systems are expensive. The installation of the tiny, specialized printed circuit board (PCB) both inside and outside of battery cells necessitates extra production stages,

ii. Scalability is a challenge with the present topologies and architecture, as they becoming increasingly complex to maintain. Other negative effects like electromagnetic interference and broken physical connections may also arise from this, and

iii. Placement and spatial considerations since wires add weight and occupy more space. Another level of complexity is added by the positioning of the modules, and sensors. In some cases, the location of battery sensors may be hindered by the usage of physical cables, which would compromise the accuracy and effectiveness of the BMS diagnostic processes [9].

To overcome the constraints of a wired design, transitioning to a wireless approach presents a viable solution. As a potential alternative wireless solution, RFID technology is considered. RFID provides short-range connection and communication capabilities that are well-suited for BMS applications.

To address these limitations, we propose a simulated SIB system architecture leveraging RFID technology, specifically Near-Field Communication (NFC). NFC offers a cost-effective design approach utilizing active or passive readout mechanisms, with the added potential for energy harvesting. This eliminates dependence on primary power sources, enabling more flexible and strategic sensor placement within battery systems. Thus, RFID technologies can enhance energy efficiency and provide enhanced grid capabilities by facilitating real-time monitoring of battery performance and lifespan, among other things [10]. All components of a generic RFID system can be shown in Fig. 2, displaying incorporation of a SIB, applicable in both EVs and BESS.

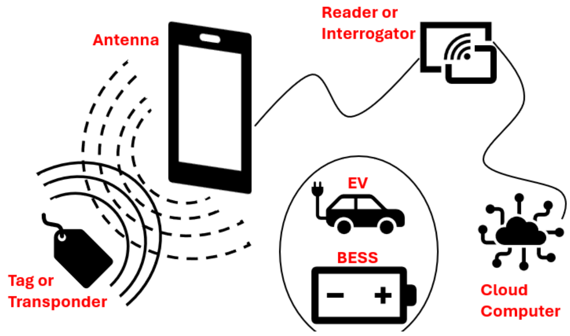

Fig. 2. Schematic diagram of a basic RFID system.

1.1 Research Gaps

Despite significant advancements in both SIB technologies and RFID systems, existing research has largely treated these domains independently. Current literature demonstrates substantial progress in electrochemical battery modeling, BMS, Internet of Things (IoT)-based energy monitoring, and RFID-enabled asset tracking, however, there remains a critical lack of integrated frameworks that combine RFID-enabled telemetry with advanced SIB digital modeling for smart city energy infrastructures.

Currently, existing SIB research focuses primarily on electrochemical material optimization, electrode design, degradation analysis, thermal management, as well as charge-discharge performance, and these studies typically employ physics/model-based or data-driven modeling approaches to investigate battery behaviour under varying operational conditions. Although these approaches improve understanding of battery behaviour, they are generally developed in isolated laboratory environments without incorporating real-time wireless telemetry, distributed sensing, or urban-scale traceability mechanisms required for smart city deployment.

Simultaneously, RFID research has predominantly concentrated on studies limited to supply chain management, inventory tracking, logistics, healthcare monitoring or industrial asset identification. Furthermore, in energy systems, RFID applications have been limited mostly to battery identification, lifecycle tracking, warehouse management and recycling authentication. Thus, very few studies explore RFID as an active sensing and intelligence layer for continuously monitoring electrochemical battery behaviour in operational energy systems. Consequently, there is insufficient research addressing how RFID-generated data can enhance the fidelity, responsiveness, and scalability of battery digital twins within smart city ecosystems.

2 RFID Applications in Smart Cities

In the context of smart cities, RFID is a technology which enables the tracking and monitoring of physical things, whether they are stationary or moving. It gathers both the static and dynamic data of these objects, along with their unique identification numbers for subsequent analysis and processing [11]. The advantages of RFID technology for applications in smart cities are discussed in this study. Uses like:

1. *Public Transportation* - RFID enables contactless smart cards to facilitate easy fare collection and shorten boarding times. Additionally, passengers may receive real-time schedule updates by using RFID tags to track the movement of buses and trains, e.g. the RFID-enabled fare cards used in Singapore's Mass Rapid Transit (MRT) system [12].
2. *Citizen Services* - Access to government offices, public libraries, and leisure facilities may be made easier with RFID-enabled identity cards. Furthermore, hospital medical equipment and other vital assets may be tracked using RFID tags to guarantee their availability when needed.
3. *Smart Parking* - RFID technology can provide smart parking solutions by allowing available spots to be identified in real time. At parking lot entrances and exits, RFID scanners can identify tagged cars and update availability information on electronic signs or mobile applications.
4. *Waste Management* - Waste bins with RFID tags attached can allow bin usage and fill levels to be tracked. Waste management system can use this information to optimize trash truck route planning and guarantee timely collection. This can be particularly important in the application of EVs, where discarded batteries can be transported and tracked for more efficient recycling, ensuring sustainability of these technologies in the long run.
5. *Traffic Management* - Vehicles equipped with passive RFID tags can allow for real-time monitoring and identification, while RFID readers placed at key points offer information for optimizing traffic flow. Electronic Toll Collecting (ETC) and other RFID-enabled toll collecting systems can do away with the need for manned toll booths, which would save time and fuel.

3 SIBs for Smart Cities

Research on SIBs as an alternative electrochemical energy storage technology to LIBs is currently accelerating. These efforts primarily aim to address the need for long-term sustainability and resource availability, additionally, it is also being done for lower production costs, abundant power density, and portability. There are clear benefits to SIBs over their lithium-ion equivalents, such as:

1. Raw material abundance: as Na is more affordable and widely accessible than Li.
2. Scalability: because SIBs are reasonably priced, they may be used in large-scale energy storage systems (ESS).
3. Environmental friendliness: since SIBs employ recyclable and non-toxic materials, which lessen their impact on the environment.

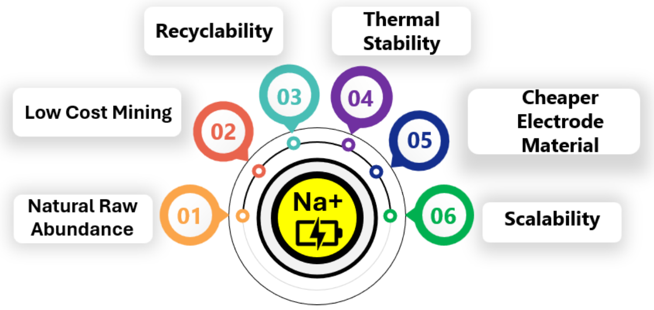

Fig. 3. Advantages of Na over Li for battery application.

Fig. 3 above details some of the advantages that show promise of SIBs to triumph over LIBs. However, regardless of these advantages, issues like reduced cycle life and decreased energy density still need to be resolved [7]. In order to overcome these constraints and maximize the deployment of SIBs in smart cities, precise modeling and real-time performance monitoring are crucial.

In another study [13], we have investigated cutting-edge computational methods that scholars (researchers/academics) and industry participants can utilize to commercialize SIBs and promote sustainable energy solutions for the digital economy. The study demonstrated how material selection, cell design, and system integration may be influenced by Pseudo Two-Dimensional (P2D) modeling, which is based on physical principles and experimental validation. These models will be essential for developing batteries that are safe, affordable, scalable, and ecologically friendly as the digital economy develops.

This study addresses the challenge of integrating RFID-enabled telemetry with SIB modeling to enable scalable, real-time, and intelligent battery monitoring within smart city energy systems. The proposed system consists of simulated RFID-equipped SIB modules capable of continuously transmitting operational parameters such as voltage, current, temperature, and SOC.

4 Role of RFID in SIB Management

The transition to sustainable energy systems is a critical aspect of smart city development. Energy storage solutions, particularly batteries, will play a pivotal role in balancing supply and demand, ensuring grid stability, and supporting the integration of renewable energy. Among emerging technologies, SIBs will gain even more attention for their cost-effectiveness and environmental advantages over LIBs.

Furthermore, the use of wireless technology with BMS is becoming an appealing feature within the academic community, with numerous concepts and designs emerging from both academia and industry. However, these use cases are primarily restricted to intra-module communication. Most system designs continue to depend on wired communication between battery cell sensors and module controllers.

4.1 Real-Time Monitoring

RFID tags embedded within battery modules can transmit critical data to centralized systems. This real-time visibility will enable proactive maintenance and improve battery performance. RFID technology can enable the real-time monitoring of SIB parameters, including (but not limited to):

1. SOC estimation - To determine the battery capacity available for communication and mobility functions.
2. Temperature and voltage levels (thermal dynamics) - To assesses heat dissipation and its influence on battery and network efficiency.
3. SOH estimation and health indicator determination - To evaluate battery aging and its impact on vehicular performance.

4.2 Lifecycle Management

By tracking the lifecycle of individual battery cells, RFID systems can deliver valuable data on degradation rates, usage patterns, and recycling possibilities. This information can significantly support predictive analytics and help extend battery lifespan (prolong battery life).

4.3 IoT Integration

Integrating RFID with IoT platforms will allow data from SIBs to merge with other smart city systems, including energy grids and renewable energy sources. This integration will enable dynamic energy management and load balancing across urban infrastructures.

4.4 Potential Application in Smart Cities

The synergy between RFID technology and SIBs opens new avenues for research and development. According to our knowledge, research on the RFID technology with SIB modeling is nescient and still in its infancy. Thus, this novel work seeks to contribute knowledge for the future direction for this combined application. Some emerging directions for research include:

1. Advanced battery modeling - Incorporating RFID data into machine learning algorithms can improve the accuracy of SIB performance models.
2. Hybrid energy systems - Combining SIBs with other energy storage technologies and leveraging RFID for unified management can enhance overall system efficiency.
3. Standardization - Developing global standards for RFID-enabled battery systems will ensure inter-operability across smart city platforms.
4. Miniaturization of RFID Tags - Reducing the size of RFID components will facilitate their integration into compact battery modules.

Although technical and economic challenges persist, ongoing research and collaboration among stakeholders has the potential to fully realize the capabilities of these technologies. As cities aim to achieve greater sustainability and intelligence, integrating RFID with SIB systems will be instrumental in transforming the landscape of urban energy solutions.

5 Potential Urban Energy Solutions

5.1 Renewable Energy Storage

SIB BESSs (integrated with RFID technology) are capable of storing excess energy produced by renewable sources like wind, hydro and solar power. The incorporation of RFID systems will allow for precise monitoring, ensuring peak battery efficiency while reducing energy loss during both storage and retrieval processes.

5.2 Smart Grid Management

RFID-integrated SIB systems can improve the performance of smart grids by supplying real-time data for efficient energy distribution, facilitating demand-response strategies, and maintaining a steady, stable power supply during peak demand.

5.3 Electric Vehicle Infrastructure

EVs are being used more and more in smart cities in an effort to lower carbon emissions. Thus, SIBs combined with RFID technology can enhance EV charging infrastructure by offering dependable energy storage and delivering real-time updates on the status and availability of charging stations.

5.4 Disaster Resilience

In disaster situations, the use of RFID technology can enable continuous monitoring of battery health and ensuring that the systems remain functional when they are needed most. The RFID-integrated SIB systems can serve as dependable energy sources for essential infrastructure, including hospitals and emergency communication networks.

6 Technical Analysis

6.1 Pre-processing

The mathematical framework comprises a set of linear partial differential equations (PDEs) that govern the conservation of mass and charge across the anode, separator, and cathode regions of the battery cell. Using a Python-based approach with available datasets, we integrated publicly accessible data on battery performance with RFID simulation. In the absence of datasets specifically linked to RFID for SIBs, we simulated RFID data while leveraging existing datasets for battery performance.

To simulate SIBs for RFID applications, experimentally determined SIB parameters were sourced from the literature, where researchers [14, 15] derived these battery parameters through specialized experiments. The extracted parameters utilized in the mathematical modeling process are summarized in Table. 1 below. We used the parameters for the NVPF ($Na_3V_2(PO_4)_2F_3$) cathode and HC (hard carbon) anode, including theoretical capacity, diffusion coefficients, and voltage ranges.

Table 1. Extracted parameters for SIB modeling.

Parameter	Cathode (NVPF)	Anode (HC)	Electrolyte
Material	Sodium Vanadium Phosphate Fluoride (NVPF)	Hard Carbon (HC)	1 M $NaPF_6$ in EC: PC (1:1 weight ratio)
Theoretical Capacity	128 mAh/g	222 mAh/g	-
Mean Particle Radius	0.59 µ	3.48 µ	-
Solid-State Diffusion Coefficient	1.1×10^{-17} to 5.8×10^{-17} m^2/s	3.6×10^{-16} m^2/s	-
Charge Transfer Rate Constant	1.3×10^{-12} $m^{2.5}/mol^{0.5}/s$	5.5×10^{-12} $m^{2.5}/mol^{0.5}/s$	-
Density	3.2 g/cm^3	1.95 g/cm^3	-
Voltage Range	3.0 V to 4.3 V vs Na^+/Na	0.3 mV to 2.0 V vs Na^+/Na	-
Separator Thickness	-	-	25 µ
Separator Porosity	-	-	~55%
Operating Temperature	-	-	25 °C
Energy Density	-	-	-

6.2 Simulation Framework

Herein a Python code that models the charge/discharge characteristics of SIBs using the extracted parameters was implemented. Furthermore, RFID tags were integrated to simulate real-time monitoring of battery performance. The Python script was written to:

- Load the SIB dataset.
- Simulate RFID tags for each battery entry (random RFID tags are generated and assigned to each row of the dataset).
- Integrate RFID data with battery performance parameters.
- Real-time monitoring simulation (a function was created that simulated in real-time the RFID-based battery monitoring, displaying the data for each battery entry sequentially).
- Visualize the data (a function was scripted to create plots that displayed how voltage and capacity changed over battery cycles).

6.3 Python Code

Python integration of parameters into the code:

- *Cycle Life* - The capacity started at an initial value (128 mAh/g) and decreased linearly by 0.02 mAh per cycle. Random noise was added for variability.
- *Voltage* - The voltage started at 3.7 V and declined very slightly per cycle with added noise.
- *Temperature* - Simulated using a sine wave pattern to mimic oscillations (during operation cycles) with some random noise.
- *State of Charge* - Computed as a percentage of the initial capacity.
- *Voltage vs. Capacity Modeling* - Used diffusion coefficients and particle sizes to model voltage profiles at different charge-discharge rates.
- *Charge-Discharge Efficiency* - Simulated the energy losses due to over-potentials using the given charge transfer rate constants.
- *Diffusion-Limited Capacity* - This function was added to estimate the capacity loss due to diffusion (depending on the current density).
- *RFID Integration* - The code attached RFID tags to battery modules to log real-time capacity, voltage, SOC, and temperature based on the above parameters.
- *RFID Simulation* - Each battery cycle generated random RFID tags and logged the battery parameters.

Table. 2 represents the key testing parameters that were used to simulate the performance of SIBs integrated with RFID technology. Where, for example, the voltage vs. capacity modeling made use of diffusion coefficients and particle sizes to model voltage profiles at the specifies charge/discharge rate, and to evaluate the charge/discharge efficiency, we simulated energy losses due to overpotentials using the given charge transfer rate constants. To simulate RFID integration, we virtually attached RFID tags to battery modules to log real-time capacity, SOC, and temperature based on the above parameters.

The simulation ran for of 100 cycles because a short-term test allows for the following; i) quick prototyping and debugging, ii) to observe early trends in performance and degradation and iii) to verify that the model behaves as expected (e.g., capacity decreases, SOC drops) which fits this study's proof of concept (PoC) and experiment objective. Short-term testing is often used to evaluate early-stage degradation or performance under specific conditions, furthermore, for debugging or initial testing fewer cycles (e.g., 100) are sufficient to validate a model.

Table 2. Testing parameters for SIB-RFID modeling.

Category	Value (Unit)
Diffusion Coefficients	NVPF: 5.8×10^{-17} m^2/s HC: 3.6×10^{-16} m^2/s
Particle Radius	NVPF: 0.59 µm HC: 3.48 µm
Current Density	0.1 A/m^2
Cycles	100
Degradation Rate	0.001
Max Current Density	2.96 × 10−06 A/m^2

7 Simulation Results

The RFID tags were added dynamically as a new column. The intended meaning of the simulation was that 100 RFID tags were assigned one per battery module. Where each row in the dataset represents one RFID observation of one battery at one point in time (cycle). Thus, the RFID tags were not changing every cycle. In this paper, the RFID tag is supposed to represent a digital identity attached to a physical sodium-ion battery module. The RFID itself does not measure electrochemistry instead it acts as identity, data carrier, telemetry index, and lifecycle tracker. We added RFID as a new column because RFID is functioning as metadata, and because RFID groups measurements over time.

Real-time monitoring of each battery's RFID and performance data was visualized as battery performance trends (voltage and capacity over cycles). Two plots are obtained: i) the voltage vs. cycles plot and ii) the capacity vs. cycles plot.

Table. 3 represents the obtained simulation results, showing results of the first 5 cycle data entries and also the last 5 data entries, from the 100-cycle simulation run.

Table 3. Results of the SIB-RFID simulation for 100 cycles.

Cycle No.	RFID Tag	Voltage (V)	Capacity (mAh)	Temperature (°C)	State of Charge (%)
1	RFID 942875	3.493	127.872	26.25	99.90
2	RFID 869355	4.059	127.744	26.27	99.80
3	RFID 614091	3.361	127.616	26.09	99.70
4	RFID 935000	4.168	127.488	23.77	99.60
5	RFID 278645	3.069	127.361	25.52	99.50
95	RFID 798521	3.574	116.394	25.77	90.93
96	RFID 766484	3.574	116.277	25.61	90.84
97	RFID 817886	3.459	116.161	24.89	90.75
98	RFID 635508	3.512	116.045	23.12	90.66
99	RFID 683302	3.929	115.929	26.14	90.56
100	RFID 961383	3.678	115.813	24.94	90.47

8 Discussion

From the simulation, two plots were obtained, namely the voltage vs cycles graph which tracked the voltage stability, as well as the capacity vs cycles graph which showed the SIB capacity degradation over the cycle (see Fig. 4). From Table. 3 and Fig. 3, we can clearly observe that the capacity is dynamically decreasing, indicating that the model is simulating capacity degradation correctly over the 100 cycles. In general, the capacity normally fades gradually due to chemical and mechanical changes during cycling. Moreover, the table shows gradual decline in SOC. This reflects real-world applications, when accounting for degradation or discharge of the battery. This results because SOC is modeled using this equation (1):

$$SOC\,(\%) = \left(\frac{Remaining\ Capacity}{Full\ Capacity}\right) x\ 100 \quad (1)$$

Thus, the remaining SOC is updated with each cycle and is always lower than the previous value.

The variability in the voltage model results due to the inconsistency of voltage stability throughout the battery cycle. This oscillation motion was expected, moreover, it correlates with the temperature values observed in this cycle. Temperature and voltage are two parameters which act in-sync, they are directly dependent variables. Although, the voltage and temperature values were variable during cell operation, they remained within limits and still managed to maintain stability in the battery.

For our specific application, NFC presented an ideal solution, providing a secure, robust, and reliable short-range communication interface. Furthermore, the RFID tags randomly generated for each cycle, did not seem to influence the actual battery performance simulation.

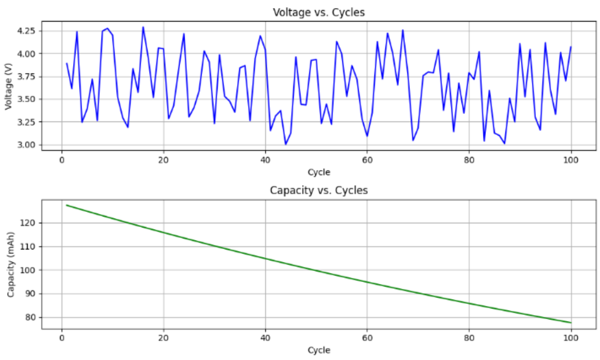

Fig. 4. Voltage-Capacity Cycle Relationship.

9 Limitations to the Current Study

Although the proposed RFID-enabled SIB simulation framework demonstrates the feasibility of integrating RFID telemetry with battery modeling for smart city energy systems, several limitations remain in the current implementation. These limitations arise from simplifications in the electrochemical model, assumptions in the RFID communication layer, computational constraints, and the absence of real-world hardware validation. Understanding these limitations is critical for contextualizing the results and guiding future development toward a more physically accurate and deployment-ready framework. These include:

1. Simplified electrochemical representation - The current simulation employs an empirical degradation model based primarily on linear or semi-linear capacity fade functions. While this approach enables computational efficiency and rapid large-scale simulation, it does not fully capture the complex electrochemical mechanisms occurring inside SIBs. As a result, the simulation may underestimate localized degradation effects and transient electrochemical dynamics.
2. Absence of real RFID hardware constraints - The RFID layer in the simulation assumes idealized communication between RFID tags and readers. In real deployments, RFID systems are affected by several practical constraints, such as signal interference, reader collision and tag collision, and passive RFID power constraints. The simulation currently assumes uninterrupted RFID telemetry availability.
3. Limited thermal modeling fidelity - The thermal model currently uses sinusoidal functions combined with stochastic Gaussian noise to emulate environmental and operational heating effects. Although computationally lightweight, this approach simplifies the thermal behaviour of real SIB systems. Without a coupled electrochemical-thermal solver, the current framework cannot fully predict catastrophic thermal events.
4. Simplified SOC Estimation - The implemented SOC estimation relies on simulated measurement noise and statistical correction mechanisms. While suitable for demonstrating RFID-assisted telemetry concepts, the framework does not yet include advanced estimation algorithms such as the Extended Kalman Filters (EKF), or physics-informed neural networks. Consequently, the simulated SOC accuracy may be overly optimistic compared to practical deployments.
5. No real-time grid interaction modeling - The current simulation focuses primarily on battery-level dynamics and RFID telemetry. However, smart city energy systems involve highly dynamic interactions between renewable energy generation, grid demand fluctuations, EV charging infrastructure, distributed energy resources, and microgrid switching events (if relevant). The simulation does not currently model real-time load dispatch, grid frequency regulation, demand response strategies, renewable intermittency, and bidirectional Vehicle-to-Grid (V2G) energy flow. Therefore, the system-level impacts of RFID-enhanced SIB coordination remain partially unexplored herein.
6. Lack of real experimental validation - A major limitation is the absence of experimental validation using physical SIB hardware and real RFID devices. The framework currently relies on synthetic simulation data generated from assumed operational conditions. While the assumptions are literature-informed, simulation results may diverge from actual battery behaviour. Experimental validation is necessary to confirm the robustness and scalability of the proposed framework.

10 Future Work and Conclusion

In this study, the objective was to develop a solution that replaces the existing expensive and high-maintenance cable architecture (wired-design) with a wireless alternative, while ensuring compatibility with both communication aspects integral to the functionality of the BMS. The results indicated that while the simulation was generating RFID tags and varying voltage and temperature across cycles, the capacity and SOC were steadily declining, as expected. Furthermore, addressing the study's limitations will be essential for transforming RFID-enabled SIB systems from simulated research environments into scalable smart city energy infrastructure.

Research on the wireless modeling of complete SIBs remains unexplored. Furthermore, a BMS must be optimally designed using an accurate and trustworthy model to ensure the long-term, safe, and effective operation of SIBs. Herein we provided a PoC considering integrating RFID technology with SIB modeling as a smart energy solution for smart cities.

Regarding the proposed BMS NFC design, it would be intriguing to delve more into this topic to analyze its hardware and physical attributes. Specifically, future work can consider optimizing the NFC-based BMS communication system involving evaluating factors such as the implementation of a tailored link layer control mechanism, antenna design tailored to the application, and the number of interconnected devices. Additionally, examining alternative high-frequency RFID technologies and comparing their suitability to NFC for the intended BMS applications would provide valuable insights for improving system performance and efficiency.

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