Technical Report on Lithium-Ion Batteries: Transportation, Storage, and Inspection Standards

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List of Abbreviations

Lithium-ion batteries	LiBs	End-of-Life	EoL
Lithium Nickel Manganese Oxide	NMC	State of Charge	SoC
Lithium Nickel Cobalt Aluminum Oxide	NCA	Extended Producer Responsibility	EPR
Lithium Iron Phosphate	LFP	Packaging	P
Electric Vehicles	EV	Large Packaging	LP
Energy Storage Systems	ESS	Packaging Group	PG
Standards Operation Procedures	SOPs	Radio Frequency Identification	RFID
United Nations	UN	Hazardous Materials Regulations	HMR
European Union	EU	Pipeline and Hazardous Materials Safety Administration	PHMSA
U.S. Code of Federal Regulations (CFR)	CFR	Cargo Aircraft Only	CAO
International Air Transport Association	IATA	Damaged, Defective, or Recalled	DDR
International Maritime Dangerous Goods Code	IMDG	Dangerous Goods Regulations	DGR
National Fire Protection Agency	NFPA	Lithium Battery Shipping Regulations	LBSR
U.S. Environment Protection Agency	EPA	Thermal Runway	TR
Society of Automotive Engineers	SAE	Packaging Instruction	PI
International Fire Code	IFC	Open Circuit Voltage	OCV
Jordanian Ministry of Environment	MoEnv	Voltage	V
State of Health	SoH	Time Weighted Average	TWA
The European Agreement concerning the International Carriage of Dangerous Goods by	ADR/RID	Lower Explosive Limit	LEL

Road and the International Statutory Order on the Conveyance of Dangerous Goods by Rail			
Voltage Direct Current	VDC	Photoacoustic Ionization	PID
Hydrogen Fluoride	HF	Metal Oxide	MOX
Carbon Monoxide	CO	Resistive Temperature Device	RTD
Particulates Matter	PM	Negative Temperature Coefficient	NTC
Very Early Smoke Detection	VESDA	Lower Flammable Limit	LFL
Carbon Dioxide	CO_2	High Voltage	HV
Non-Dispersive Infrared	NDR	Remaining Useful Life	RUL
American Conference of Governmental Industrial Hygienists	ACGIH	Depth of Discharge	DoD
Ambere-hour	Ah	Energy Management System	EMS
Battery Management System	BMS	Electrochemical Model	EM
Original Equipment Manufacturer	OEM	Equivalent Circuit Model	ECM
Lithium Iron Phosphate	LFP	Proportion Integration	PI
Internal Short Circuit	ISC	Solid Electrolyte Interface	SEI
Electrochemical Impedance Spectroscopy	EIS	positive temperature coefficient	PTC
End-of-First Life	EoFL	Domestic Lithium-ion Battery Energy Storage System	DLIBESS
Constant Current	CC	Personal Protection Equipment	PPE
Constant Current-Constant Voltage	CC-CV	Closed Current Voltage	CCV

Overview

Overview

Lithium-ion batteries (LiBs) are key technology to store energy and the most popular rechargeable batteries nowadays, where they are available in various sizes, capacities, and chemistries such as Lithium Nickel Manganese Oxide (NMC), Lithium Nickel Cobalt Aluminum Oxide (NCA), and Lithium Iron Phosphate (LFP) [1]; moreover, they are used in various applications such as smartphones, laptops, electronics, electric vehicles (EV), and energy storage systems (ESS). However, according to the United Nations (UN) model regulation, LiBs are considered hazardous waste, class 9, due to the chemical composition of electrodes (cathode and anode), and due to the lack of disposal or 2nd-life application strategies that lead to stockpiling and environmental issues. LiBs consist of anode, cathode, electrolyte, separator, and collectors, such shown in Figure 1.

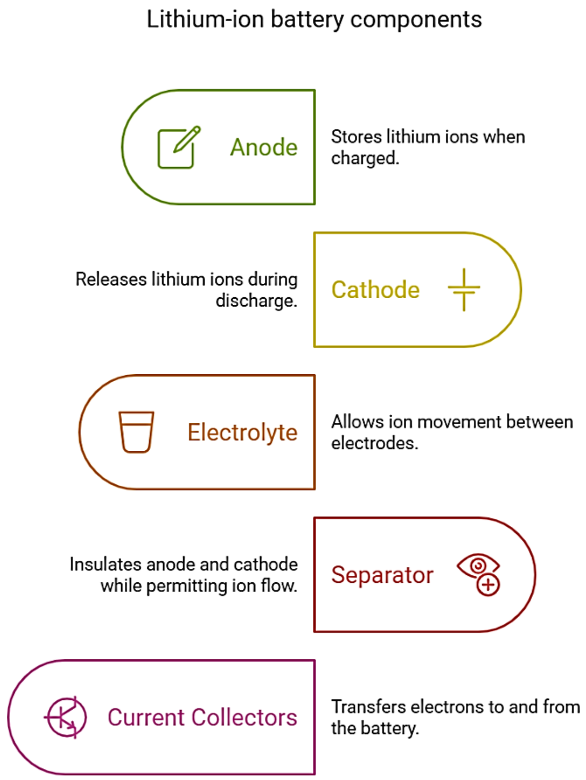


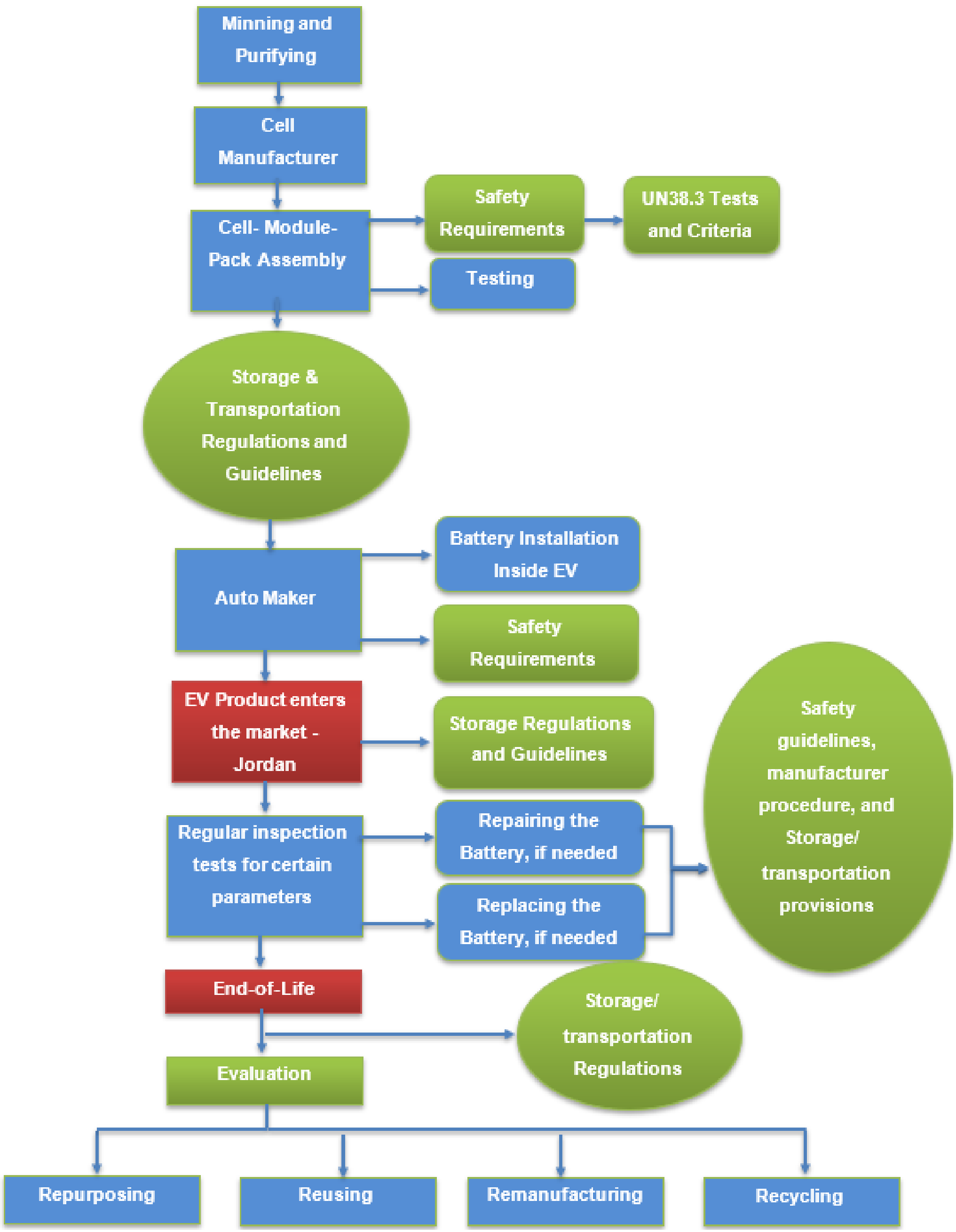
Figure 1: LiB internal components

This work elaborates on the importance of having proper packaging, labeling, transportation, storage, and inspection regulations, Standards Operating Procedures (SOPs), and guidelines for LiBs, according to their classification as hazardous materials (class 9), to mitigate their risks that would harmfully affect both the environment and human life. The research is divided into two parts, the first part focuses on both international and national regulations and guidelines relevant to packaging, labeling, transportation, and storage that have been enacted from the United Nations for Economic Commission of Europe (UNECE), European Union (EU), U.S. Code of Federal Regulations (CFR), International Air Transport Association (IATA), International Maritime Dangerous Goods Code (IMDG), National Fire Protection Agency (NFPA), U.S. Environment Protection Agency (EPA), Society of Automotive Engineers (SAE) Standards, International Fire Code (IFC), Vermont Agency for Natural Resources, and the Jordanian Ministry of Environment (MoEnv), where the international entities followed the UN recommendations regarding packaging and labeling. Whereas the second part focuses on the 2nd-life of the battery, whether reusing or repurposing. Inspection is a crucial stage, where multiple factors such as State of Health (SoH), internal resistance, energy efficiency, and degradation rate play a significant role in determining the best 2nd-life application of LiBs to reduce waste as much as possible. The main stakeholders concerned in this work are MoEnv, Civil Defense, official automotive agencies, workshops, logistic companies, Swaqa landfill, and testing laboratories/ R&D centers, where the abovementioned stakeholders lack the SOPs and best practices to deal with LiBs and any accident related to them. Therefore, the main objective of this work is to highlight the international SOPs and regulations relevant to LiBs and reflect them on the national level to guide the concerned authorities and provide them with the proper knowledge, to proactively prevent risks, and actions necessary to handle any accident in order to protect environment and human beings, and be well-prepared for the next stage of LiBs life chain such as repurposing, reuse, remanufacturing, and recycling.

EV LiBs Life Cycle Path

EV LiBs Life Cycle Path

The flowchart below illustrates the general life cycle of LiBs and what is required at each node from guidelines, policies, and regulations aspects. Nodes that contain storage, transportation, or inspection processes, certain guidelines and regulations must be considered. **For Jordan**, there is no mining, cells manufacturing, or battery pack assembly; therefore, EV LiBs start their life cycle when they enter the market installed in the EV, where inspection tests, repairing or replacing the battery, and battery End-of-Life (EoL) processes need to be standardized and following certain instructions and regulations to ensure the safe operation, and foster circularity.



Definitions

Definitions

There are different terms that should be clarified relating to this document to have a full understanding of the legal framework, such as policies, regulations, procedures, standards, and guidelines, as shown in Figure 2. **Regulations**, which are rules that have the effect of law and are considered as restrictions that are imposed by the authority to regulate any process, then **policies** come out at the first level after regulations, which are a set of principles and rules that prohibit, mandate, and specify attitudes that deal with certain issues, and they are adopted by the government, companies, or groups. After policies, **standards** come out to specify what is required, and how to implement policies; they are most probably technical. **Procedures** are detailed guidance on how to implement policies and standards. However, **guidelines** are additional recommendations and practices to implement the policies.

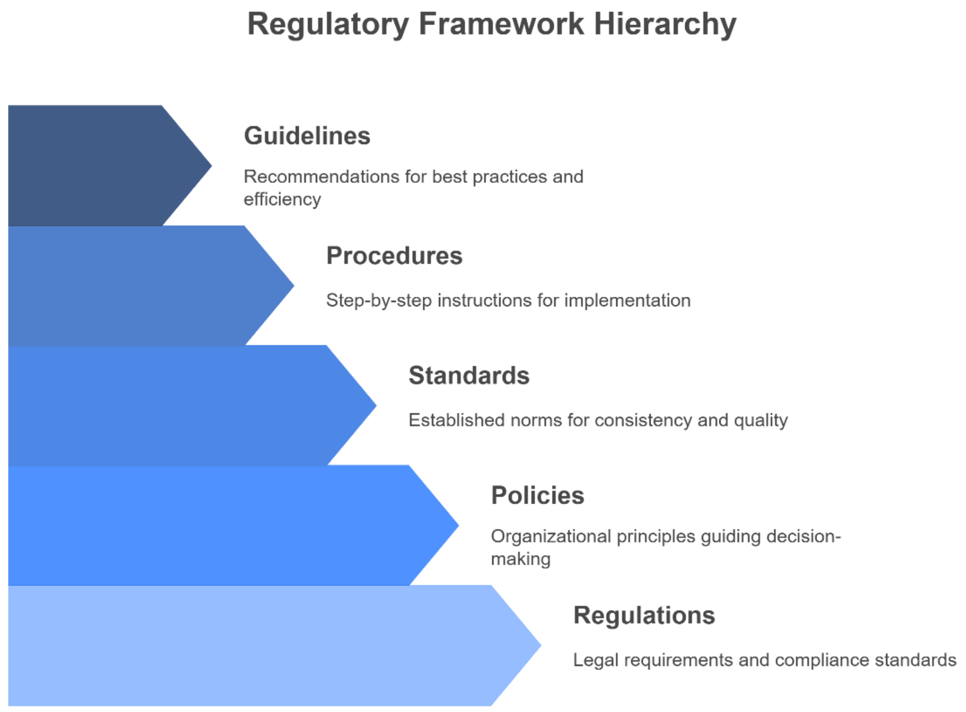


Figure 2: Regulatory Framework

Status Quo in Jordan

Status Quo in Jordan

Since 2015, 163,000 EVs have entered Jordan [2]. Considering that the average lifespan of EV batteries is from 10-20 years before they need to be replaced [3]. it is critical that when reaching the first EoL, the government has clear strategies and instructions that mitigate the potential hazards of EV battery waste, such as stockpiling and environmental risks. Moreover, there is a lack of control and monitoring systems for the disposal process. For example, Swaqa Landfill, the hazardous waste landfill for Jordan, only 2 EV batteries. Moreover, at SWAGA there is no activity logging or registration process for the entered batteries. As shown in the battery's life cycle path, it's mandatory to have guidelines and provisions that ensure safe handling and management for EV batteries at different nodes within their life cycle. Hence, Jordan needs to establish procedures and instructions for inspecting batteries to determine the best second-life applications. Additionally, there is a need for regulations and guidelines to ensure the safe transport and storage of batteries. Nonetheless, the Jordanian MoEnv has issued instructions to manage, and handle spent lead-acid, hybrid, and EV batteries in general "Article13/A"; the instructions focus on transportation, storage, and storage facility requirements, but don't cover all practices and specifications to ensure the safe management of spent batteries and don't specify the type of batteries, whether LiBs, or other types. Regarding the storage instructions, the following points are noted:

- It is mentioned that ventilation and fire suppression systems are required, but without any technical requirements and without mentioning the importance of detection systems
- There are no packaging and labeling requirements and specifications listed
- The maximum altitude for stockpiling the batteries is specified to be 2 meters, which is not mentioned in the international guidelines and best practices.
- There is no limitation on the amount of accumulated energy capacity in one place.
- It is mentioned that the battery's electrical energy shall be discharged, but the State of Charge (SoC) isn't limited.
- It's mentioned that the surface shall be non-conductive and fire-resistant, but the fire barriers and their specifications are not mentioned in the instructions.
- It's important to have an inert filling material such as sand or vermiculite between batteries.

Regarding transportation, the following points are noted:

- The instructions include road transportation only without mentioning other modes of transportation (aerial and maritime).
- There is no inspection for the battery status before transporting it.
- The instructions don't include required actions/SOPs in emergency situations
- Packaging specifications of batteries aren't mentioned.
- The amount/weight of transported LiBs isn't specified.

Finally, the local instructions don't mention any inspection, evaluation, or assessment criteria and requirements, which are crucial to determine the battery status, the best approach of transportation and storage, and the most appropriate 2nd application relevant to spent batteries.

Methodology

Methodology

Figure 3: Adopted research methodology

As shown in Figure 3, national SOPs, instructions, and guidelines related to LiBs management, storage, and transportation have been reviewed; it has been found that there is only one instruction document that highlights the transportation of spent batteries in general, and managing, handling, storing and collecting of spent EV batteries, which has been enacted from the Jordanian MoEnv. Then, a broad international research, focusing on the most pioneering entities, associations, and private companies in managing and handling EV batteries, such as the UNECE, IATA, EU, EPA, NFPA, Vermont Agency, IMDG, and SAE has been conducted, as shown in Table 1. As the international regulations, guidelines, and SOPs are wide and have some contradictions, a gap analysis has been conducted to adopt the most common practices and compare them with the national document in order to have comprehensive instructions draft and policy paper that covers the safety aspects of EV batteries as much as possible. During research, multiple interviews were conducted with the abovementioned entities and other European companies, such as the Vermont Agency and MoEnv, and site visits for Swaqa Landfill, which is a governmental collection center, to gather more information, enhance our research, and benefit from their experience in inspecting and assessing spent LiBs in order to use them further in other applications. At the final stage, this comprehensive document was drafted to inform the local authorities about the best international practices and guidelines. However, **UNECE** guidelines for packaging and labeling are general and suit both transportation and storage processes; therefore, the international entities have adopted UNECE guidelines and considered it as a reference for packing and labeling. Therefore, a separate section in this document will be allocated for UNECE guidelines for packaging and labeling as a crucial and common step before transporting and storing LiBs, then both sections, transportation and storage, will be discussed.

Table 1: International reports, standards, regulations, and guidelines

Type	Name	Description
Recommended Practices/Guidelines	SAE | Recommended Practices for Shipping Transport and Handling of Automotive-Type Battery System-Lithium Ion	Providing a basis from which to determine the relevant regulations to consult when preparing a battery for shipment; moreover, providing recommendations that can be implemented during the development of the battery to be used by qualified users to determine the transportability of a battery.
	SAE | Best Practices for Storage of Lithium-ion Batteries	providing harmonized recommendations regarding facility storage and warehousing requirements to serve as common practice to enable operational safety across several industry functions. Moreover, aiding in mitigating risk for the storage of lithium-ion cells, traction batteries, and battery systems.
	EPA | Guidance on the Safe Storage of Lithium-ion Batteries at Waste Handling Facilities	Storage, transport, and collection guidelines for waste LiBs and emergency response
	Massachusetts Institute of Technology | Lithium-ion Battery Safety Guidance	Storage best practices for LiBs regardless of their size and capacity
Regulations/Provisions	UNECE | Recommendations on Transport of Dangerous Goods, Model Regulations	General provisions for packing and labeling dangerous goods such as LiBs (Class 9) to be well prepared and safe for transportation
	ADR | Agreement Concerning the International Carriage of Dangerous Goods by Road	The agreement enacts general provisions relevant to transporting dangerous goods by road; it's consistent with the "United Nations for Economic Commission of Europe Recommendations on Transport of Dangerous Goods, Model Regulations"
	IATA | Transport of Lithium Metal and Lithium Ion Batteries	It's a guide document based on the provisions of the IATA Dangerous Goods Regulations that clarifies the restrictions and prohibitions of transporting LiBs by air.
	PHMSA | Lithium Battery Guide For Shippers	It's a guidance document to transport lithium batteries for all modes of transportation; it's complied with Hazardous Materials Regulations HMR as part of the U.S. Code of Regulations (CFR).
	IMDG | Transport Regulations for Sea Transport	Special provisions to regulate sea transportation for LiBs
	IFC 2024, Chapter 12 | Electrical Energy Storage	The provisions of IFC 2024 comply to NFPA standards, where the main focus is on

	Systems	the storage of Electrical Energy Systems and limiting the amount of energy stored in one place.
	EU Regulations 2023/1542 | Concerning Batteries and Waste Batteries	Regulations concerning EoL batteries and reducing waste by applying Extended Producer Responsibility (EPR)
Standards	NFPA Standard 855, Chapter 14 | Storage of Used Lithium Metal or Lithium-ion Batteries	Providing minimum requirements for mitigating the hazards associated with lithium batteries
Reports/Articles	Vermont Agency of Natural Resources | Hybrid and EV Batteries Environmental Fact Sheet	Management practices to ensure the safe storage inside the facilities
	Procedure for Assessing the Sustainability of Battery Second Life Applications	Framework for battery assessment and technical viability solutions for 2nd life applications
	Newcastle University Office of Product Safety & Standards | A Study on the Safety of Second Life Batteries in Battery Energy Systems	The report focuses on gateway testing to assess batteries and use them adequately in their 2nd-life
	State of Charge estimation techniques of EV LiBs | Determination of Lithium-Ion Battery Capacity for Practical Applications	Definitions of EV batteries’ parameters such as energy, efficiency, capacity, and internal resistance. Moreover, estimation techniques for the parameters
	GAIA | EV Battery Repurposing and 2nd-life	Assessing SoH, evaluating viability, and deciding a proper configuration for EV batteries to be repurposed
	GIZ | Reuse Handbook of LiBs- Ghanian Context	The report focuses on reusing LiBs in general for various sizes and capacities; moreover, it touches the safety requirements and evaluating procedure to reuses LiBs

UNECE Recommendations Relevant to Packaging and Labeling

UNECE Recommendations Relevant to Packaging and Labeling[A]

This section elaborates on the UNECE guidelines of packing and labeling lithium-ion cells and batteries, where it's divided into 3 sub-sections depending on the size of the stored package as shown in Figure 4.

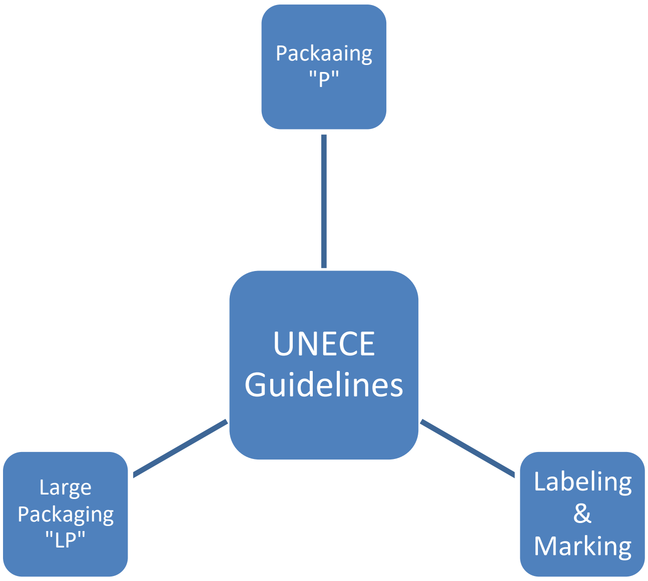


Figure 4: UNECE main sections

The first 2 sub-sections contain different types of packaging according to the battery status, such as damaged/defective, normal, low production/prototype, and disposal/recycling. The 3rd sub-section focuses on labeling and marking recommendations. However, due to severity of LiBs, good quality packaging should be used to mitigate the effect of perilous goods,, such as packaging and large packaging that are strong enough to withstand shocks and loading; and designed to prevent any loss of content, that may occur due to the vibrations, change in temperature, pressure, and humidity, during transportation and transshipment between cargo transport units and warehouses. Packaging that is in direct contact with dangerous goods shall not be affected or weakened by the goods, shall not cause any perilous effect or reaction with the dangerous goods, and shall not allow permeation of the dangerous goods that may cause danger during transportation; therefore, proper inner coating or treatment shall

A: Reference [4]

be provided to packages.All Inner packaging, especially that is made of plastic, glass, porcelain, stoneware, or any material that could be easily broken or punctured, shall be packed in strong outer packaging with suitable cushioning material in a way that prevents any leakage or damage. Furthermore, outer packaging shall be tested with different types of inner packaging, the following variations in inner packaging are allowed without any further testing of the package:

- The inner package is equivalent in size to or smaller than the tested one provided:
    - The inner packaging is similar to the tested packages (Shape- round, rectangular, etc.).
    - The construction material of the inner packaging offers resistance to impact and stacking forces equal to or greater than that of the tested packages.
    - Inner packaging has the same or smaller openings, and the closure is of a similar design (screw cap, friction lid, etc.).
    - Sufficient additional cushioning material is provided to take up the void spaces and prevent movement of the inner packaging.

Due to the danger of the concerned goods, it’s prohibited to pack dangerous goods, that may react with each other and cause combustion, flame, toxic gases, or formation of unstable substances in the same outer package. In addition, packages should have a venting device to avoid any danger that may be caused by the gases emitted from the LiBs, where high concentrations of H_2 and CO are indicators of thermal runaway (TR), except for air transportation, venting devices are not permitted. Empty packaging, normal packages, and large packages that have contained dangerous goods, shall be treated in the same manner as the filled packaging, unless adequate procedures have been taken to nullify any danger. Regarding the period of use of plastic drums and jerricans, normal packages, and large packages with plastic inner receptacles, and any other approved packaging, that are used to transport dangerous goods, it’s limited to 5 years from the date of manufacture of the receptacles, unless a shorter period is prescribed by the manufacturer due to the nature of transported goods. After that period, packaging may be reconditioned, remanufactured, or repaired. However, UNECE has classified packages according to their kind, material, and category into codes and limited their maximum capacity as shown in Table 2:

Table 2: Packages classification

Kind	Material	Category	Code	Maximum capacity [L]/net mass [kg]	Classification
(1) Drums	(A) Steel	Non-removable head	1A1	450/400	Not mentioned for LiBs
		Removable head	1A2		Normal, damaged/defective, liable to rapidly disassemble, disposal/recycling, low production/prototype cells/batteries
	(B) Aluminum	Non-removable head	1B1	450/400	Not mentioned for LiBs
		Removable head	1B2		Normal, damaged/defective, liable to rapidly disassemble, disposal/recycling, low production/prototype cells/batteries
	(D) Plywood	N/A	1D	250/400	Normal, damaged/defective, liable to rapidly disassemble, disposal/recycling, low production/prototype cells/batteries
	(G) Fiber	N/A	1G	450/400	
	(H) Plastic	Non-removable head	1H1	450/400	Not mentioned for LiBs
		Removable head	1H2		Normal, damaged/defective, liable to rapidly disassemble, disposal/recycling, low production/prototype cells/batteries
	(N) Metal, other than steel and aluminum	Non-removable head	1N1	450/400	Not mentioned for LiBs
		Removable head	1N2		Normal, damaged/defective, disposal/recycling, low production/prototype cells/batteries
(3) Jerricans	(A) Steel	Non-removable head	3A1	60/120	Not mentioned for LiBs
		Removable head	3A2		Normal, damaged/defective, disposal/recycling, low production/prototype cells/batteries
	(B) Aluminum	Non-removable head	3B1		Not mentioned for LiBs
		Removable head	3B2		Normal, damaged/defective, disposal/recycling, low production/prototype cells/batteries
	(H) Plastics	Non-removable head	3H1	60/120	Not mentioned for LiBs

		Removable head	3H2		Normal, damaged/defective, disposal/recycling, low production/prototype cells/batteries
(4) Boxes	(A) Steel	N/A	4A	400	Normal, damaged/defective, disposal/recycling, low production/prototype cells/batteries
	(B) Aluminum	N/A	4B	400	
	(C) Natural Wood	Ordinary	4C1	400 kg	
		With sift-proof walls	4C2		
	(D) Plywood	N/A	4D	400 kg	
	(F) Reconstituted wood	N/A	4F		
	(G) fiberboard	N/A	4G		
	(H) Plastics	Expanded	4H1	60	
		Solid	4H2	400	
	(N) Metal, other than steel or aluminum		4N	400	
(5) Bags	(H) Woven plastics	Without inner liner or coating	5H1	50	Not mentioned for LiBs
		Sift-proof	5H2		Not mentioned for LiBs
		Water resistant	5H3		Not mentioned for LiBs
	(H) Plastic film	N/A	5H4		Not mentioned for LiBs
	(L) Textile	Without inner liner or coating	5L1		Not mentioned for LiBs
		Sift-proof	5L2		Not mentioned for LiBs
		Water resistant	5L3		Not mentioned for LiBs
	(M) Paper	Multiwall	5M1		Not mentioned for LiBs
		Multiwall, water resistant	5M2		Not mentioned for LiBs

(6) Composite packaging	(H) Plastics receptacle	In steel drum	6HA1	250/400	Not mentioned for LiBs
		In steel crate or box	6HA2	60/75	Not mentioned for LiBs
		In aluminum drum	6HB1	250/400	Not mentioned for LiBs
		In aluminum crate or box	6HB2	60/75	Not mentioned for LiBs
		In wooden box	6HC	60/75	Not mentioned for LiBs
		In plywood drum	6HD1	250/400	Not mentioned for LiBs
		In plywood box	6HD2	60/75	Not mentioned for LiBs
		In fiber drum	6HG1	250/400	Not mentioned for LiBs
		In fiberboard box	6HG2	60/75	Not mentioned for LiBs
		In plastics drum	6HH1	250/400	Not mentioned for LiBs
		In solid plastic box	6HH2	60/75	Not mentioned for LiBs
	(P) Glass, porcelain or stoneware receptacle	In steel drum	6PA1	60/75	Not mentioned for LiBs
		In steel crate or box	6PA2		Not mentioned for LiBs
		In aluminum drum	6PB1		Not mentioned for LiBs
		In aluminum crate or box	6PB2		Not mentioned for LiBs
		In wooden box	6PC		Not mentioned for LiBs
		In plywood drum	6PD1		Not mentioned for LiBs
		In wickerwork hamper	6PD2		Not mentioned for LiBs
		In fiber drum	6PG1		Not mentioned for LiBs
		In fiberboard box	6PG2		Not mentioned for LiBs
		In expanded plastic packaging	6PH1	N/A	Not mentioned for LiBs
		In solid plastic packaging	6PH2	N/A	Not mentioned for LiBs

UNECE has categorized Li batteries/cells into stand-alone "UN3480" and packed with/contained in equipment "3481". However, packagings are also classified into 3 groups based on the level of toxicity, flammability, and any other hazardous properties: Packaging group (PG) | for high danger materials, PG || for medium dangerousness, and PG ||| for low dangerousness; however, Li batteries/cells are included in PG ||. Figure 5, Figure 6, and Figure 7, and Figure 8 illustrate some of UN packaging types and labels.

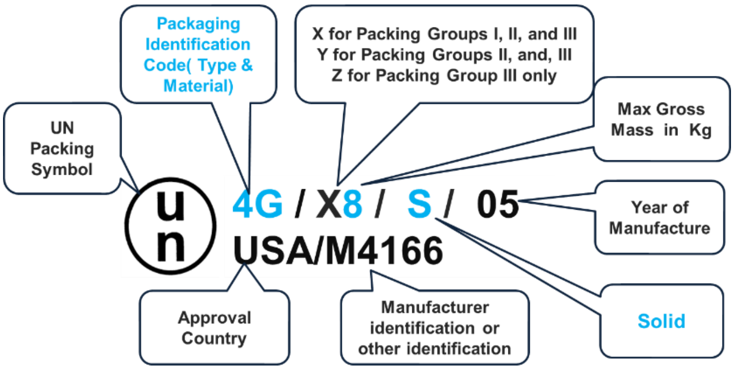


Figure 5: UN packaging specification mark [5]

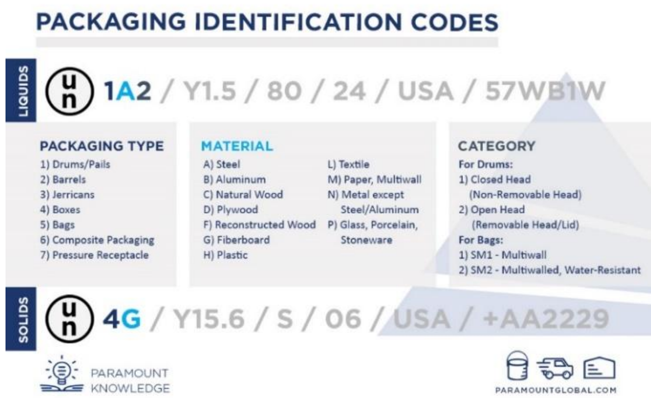


Figure 6: Packaging identification code [6]

Figure 7: UN approved 4A steel box [7]

Figure 8: UN approved 4C1 wooden box [7]

6.1 Packaging "P"

6.1.1 Normal cells and batteries "P903"

1) **Stand-alone cells and batteries shall adhere to the following measures:**
   - Packaging shall be drums (1A2, 1B2, 1N2, 1H2, 1D, 1G), boxes (4A, 4B, 4N, 4C1, 4C2, 4D, 4F, 4G. 4H1, 4H2); or jerricans (3A2, 3B2, 3H2)*

*: Clarified in Table 2

- A non-combustible and electrically non-conductive cushioning material shall be used to minimize the effect of vibrations and shocks and to prevent movement of the cells or batteries within the package that may cause damage during transport
- Packaging shall conform to the PG ||

2) Stand-alone cell or battery with a gross mass of 12 kg or more:

In addition to the abovementioned measure, a stand-alone cell or battery with a gross mass of 12 kg or more shall employ a strong impact-resistant outer casing that shall meet the following:

- Strong outer packaging; or protective enclosures (fully enclosed, wooden slatted crates, or pallets)
- Terminals shall not support the weight of other elements

3) Cells and batteries packed with equipment:

shall follow the stand-alone packaging requirements and then be packed with the equipment.

4) Cells and batteries contained in equipment:

The outer package shall be strong and impact-resistant to prevent any unintentional activation and movement. However, Radio Frequency Identification (RFID) tags, watches, and temperature loggers, which don't pose any risks of generating the evolution of heat, may be transported in strong outer packaging provided these devices meet the electromagnetic radiation standards that don't interfere with the aircraft system when they are active. In addition, large equipment may be transported unpacked or on pallets when the cells and batteries are provided with adequate protection by the equipment.

Note: 2 and 4 packages may exceed a net mass of 400 kg.

Damaged/defective cells and batteries "P908"

The following recommendations are applied for defective/damaged stand-alone and packed with/contained in equipment Li cells and batteries:

- Packaging shall be drums (1A2, 1B2, 1N2, 1H2, 1D, 1G), boxes (4A, 4B, 4N, 4C1, 4C2, 4D, 4F, 4G. 4H1, 4H2); or jerricans (3A2, 3B2, 3H2)*
- Packaging shall conform to the PG || performance level

*: Clarified in Table 2

- Each damaged and defective cell or battery or equipment containing them shall be individually packed in an inner package and placed inside an outer package; however, the inner or the outer package shall be leak-proof and provided with absorbent material to prevent any electrolyte leakage
- Each inner package shall be surrounded by adequate non-combustible and electrically non-conductive thermal insulation material to protect against any dangerous evolution of heat
- Sealed packaging shall be fitted with venting devices
- Non-combustible and electrically non-conductive cushioning material shall be provided to prevent any movement and damage during transport.

Note: A cell or battery with a net mass of more than 30 kg shall be limited to one cell or battery per outer packaging.

Disposal/recycling cells and batteries “P909”

1) Stand-alone lithium-ion cells and batteries shall be packed with the following requirements:
    - Packaging shall be drums (1A2, 1B2, 1N2, 1H2, 1D, 1G), boxes (4A, 4B, 4N, 4C1, 4C2, 4D, 4F, 4G. 4H1, 4H2); or jerricans (3A2, 3B2, 3H2)*
    - Packaging shall conform to the PG || performance level
    - Metal packaging shall be fitted with an electrically non-conductive lining material of adequate strength for the intended use, such as plastic.
2) Stand-alone small lithium-ion cells and batteries (cells equal to or less than 20Wh and batteries equal to or less than 100Wh) may be packed in a strong outer packaging up to 30 kg gross mass and metal packaging shall be fitted with an electrically non-conductive lining material with adequate strength such as plastic.
3) Same packaging measures of the normal lithium-ion cells and batteries contained in equipment may be adopted for disposal and recycling.
4) For Lithium-ion cells and batteries with a gross mass of 12 kg or more, a strong, impact-resistant outer casing, or outer packaging constructed of adequate material and strength shall be employed.
5) Additional requirements; It’s crucial to prevent short circuits and heat evolution by:
    - Protecting battery terminals.

*: Clarified in Table 2

- Inner packaging to prevent contact between cells/batteries.
- Utilizing electrically non-conductive and non-combustible cushioning materials.

Note: Packaging 3 and 4 may exceed a net mass of 400 kg.

Low production runs/prototypes of cells/batteries "P910"

Pre-production prototype lithium cells or batteries that are transported for testing purposes and low production runs of not more than 100 cells or batteries don't meet the testing requirement of UN38.3 shall meet the following:

- Packaging shall be drums (1A2, 1B2, 1N2, 1H2, 1D, 1G), boxes (4A, 4B, 4N, 4C1, 4C2, 4D, 4F, 4G. 4H1, 4H2); or jerricans (3A2, 3B2, 3H2)*
- Packaging shall conform to the PG || performance level.
- The design of the abovementioned outer package shall be tested; in addition, the gross mass of the package shall not exceed the gross mass for which the design type has been tested.
- Each cell or battery shall be packed individually in an inner packaging that is surrounded by non-combustible and electrically non-conductive insulation material and then placed in an outer package.
- A non-combustible and electrically non-conductive cushioning material may be used to avoid shifting and movement of the batteries that may cause vibrations and shocks.
- A cell or battery with a net mass of more than 30 kg shall be limited to one cell or battery per outer package.
- Prototype or low production runs cells and batteries that are contained in equipment shall be packed in a way that prevents unintentional activation.
- The equipment or the batteries may be shipped unpackaged under limited conditions, such as the equipment and the battery shall be strong enough to withstand the shocks and loadings, the equipment or the battery shall be fixed in crates or pallets, and conditions from the competent authority.
- Equipment or batteries/cells may be transported unpacked or on pallets when the cells and/or batteries have strong outer case or provided with adequate protection by the equipment.

*: Clarified in Table 2

- Short circuits shall be avoided by protecting the terminals, preventing contact inside the inner package, and using proper cushioning materials.

Note: Packages may exceed a net mass of 400 kg.

Rapidly disassemble damaged/defective cells/batteries "P911"

Damaged or defective lithium cells and batteries that are liable to rapidly disassemble, dangerously react, or produce a flame or toxic gases under normal conditions of transport shall meet the following instructions:

- Packaging of cells, batteries, and equipment containing them shall be drums (1A2, 1B2, 1N2, 1H2, 1D, 1G), boxes (4A, 4B, 4N, 4C1, 4C2, 4D, 4F, 4G. 4H1, 4H2); or jerricans (3A2, 3B2, 3H2)*
- Packaging shall meet PG | (Highly dangerous).
- The packaging shall be capable of meeting any above-mentioned hazards.
    - The outside surface packaging temperature shall not have a temperature of more than 100 °C. A momentary spike in temperature of 200 °C is acceptable.
    - No flame shall occur outside the package.
    - The structural safety of the packaging shall be maintained.
    - No projectiles shall occur outside the package.
    - The packaging shall have a system to manage the gases, such as air circulation, filter system, etc.

*: Clarified in Table 2

- The inner and outer packaging shall maintain their integrity when dry ice or liquid nitrogen is used as a coolant.
- Packaging performance shall be verified by a test as specified by the competent authority:
    - The verification report shall contain cell or battery name, cell or battery number, mass, type, energy content, test data, and packaging identification.
    - The assessment shall be done under a quality management system, where the traceability of test results and reference data shall be used.
    - A list of prospective hazards in case of thermal runaway, rapid disassembly, toxic gases, dangerous reactions, etc., and preventive procedures shall be cleared.
    - A list of mitigating protections shall be provided; in addition, a list of technical characteristics and drawings shall be used to support the assessment.
    - SoC shall be provided in the assessment; however, if it's not known, the highest possible SoC according to use conditions shall be adopted.
    - The surrounding conditions in which the packaging may be used and transported shall be cleared.
    - In case of multiple batteries or equipment containing batteries, the maximum number of batteries and items of equipment, the maximum allowed energy content of the batteries, protections, and separation inside the package shall be provided.

Large Packaging "LP"

Note: "50" indicates rigid large packaging; "51" indicates flexible large packaging.

Large cells and batteries "LP903"

These cells and batteries, which have a gross mass of more than 500 g and 12 kg respectively, shall be packed in large rigid packaging, conforming to the PG ||, made of steel (50A), aluminum (50B), metal other than steel or aluminum (50N), rigid plastics

(50H), natural wood (50C), plywood (50D), reconstituted wood (50F), or rigid fiberboard (50G). However, stand-alone cells and batteries, and those contained in equipment shall be protected from short circuits and separated by dividers or placed in trays to prevent any expected damage that may occur by:

- Movement within the large packaging.
- Contact with other cells, batteries, or equipment.
- Any load that is held above the batteries, cells, or equipment.

Single damaged battery/single item containing damaged cells/batteries "LP904"

These types of cells and batteries shall also be packed in large rigid packaging made of steel (50A), aluminum (50B), metal other than steel or aluminum (50N), rigid plastics (50H), natural wood (50C), or plywood (50D), conforming to the PG ||. In addition, large packaging shall meet the following:

- Each damaged battery or item of equipment that contains damaged cells or batteries shall be equipped individually in an inner packaging and then in outer packaging; the inner or the outer packaging shall be leak-proof.
- The inner packaging shall be surrounded by non-combustible, electrically non-conductive, and absorbent insulation material.
- Sealed packages shall be provided with a venting device.
- A non-combustible and electrically non-conductive cushioning material shall be provided to avoid damage that may occur due to vibrations and shocks.

Prototypes and low production runs of cells/batteries "LP905"

Pre-production prototype lithium cells or batteries that are transported for testing purposes and low production runs of not more than 100 cells or batteries with a net weight of more than 400 kg shall be packed in large packaging.

1) **Single Battery**

For a single battery, rigid large packaging made of steel (50A), aluminum (50B), metal other than steel or aluminum (50N), rigid plastics (50H), natural wood (50C), plywood (50D), reconstituted wood (50F), or rigid fiberboard (50G), conforming to the PG ||, shall meet the following:

- The design of the above outer packages shall be tested; in addition, the gross mass of the package shall not exceed the gross mass for which the design type has been tested.
- Each battery shall be packed individually in an inner packaging that is surrounded by non-combustible and electrically non-conductive insulation material and then placed in an outer package.
- A non-combustible and electrically non-conductive cushioning material may be used to avoid shifting and movement of the batteries that may cause vibrations and shocks.

2) Single item of equipment

For a single item of equipment containing cells or batteries, rigid large packaging made of steel (50A), aluminum (50B), metal other than steel or aluminum (50N), rigid plastics (50H), natural wood (50C), plywood (50D), reconstituted wood (50F), or rigid fiberboard (50G), conforming to the PG ||, shall meet the following:

- The design of the above outer packages shall be tested; in addition, the gross mass of the package shall not exceed the gross mass for which the design type has been tested.
- The equipment shall be packed in such a manner that prevents unintentional activation during transport.
- A non-combustible and electrically non-conductive cushioning material may be used to avoid shifting and movement of the batteries that may cause vibrations and shocks.

Rapidly disassemble damaged batteries “LP906”

Damaged or defective batteries that are liable to rapidly disassemble, dangerously react, produce a flame or a dangerous evolution of heat or toxic, corrosive, or flammable gases under normal conditions of transport and have a net weight greater than 400 kg shall be packed in large rigid packaging of steel (50A), aluminum (50B), metal other than steel or aluminum (50N), rigid plastics (50H), plywood (50D), or rigid fiberboard (50G) conforming to the PG |. The large packaging shall meet the following requirements in order to treat any of the mentioned hazards:

- The outside surface packaging temperature shall not have a temperature of more than 100 °C. A momentary spike in temperature of 200 °C is acceptable.
- No flame shall occur outside the package.
- The structural safety of the packaging shall be maintained.
- No projectiles shall occur outside the package.
- The packaging shall have a system to manage the gases, such as air circulation, a filter system, etc.
- The inner and outer packaging shall maintain their integrity when dry ice or liquid nitrogen is used as a coolant.
- Packaging performance shall be verified by a test as specified by the competent authority:
  - The verification report shall contain cell or battery name, cell or battery number, mass, type, energy content, test data, and large packaging identification.
  - The assessment shall be done under a quality management system, where the traceability of test results and reference data shall be used.
  - A list of prospective hazards in case of thermal runaway, rapid disassembly, toxic gases, dangerous reactions, etc., and preventive procedures shall be cleared.
  - A list of mitigating protections shall be provided; in addition, a list of technical characteristics and drawings shall be used to support the assessment.
  - SoC shall be provided in the assessment; however, if it's not known, the highest possible SoC according to use conditions shall be adopted.
  - The surrounding conditions in which the packaging may be used and transported shall be cleared.
  - In case of multiple batteries or equipment containing batteries, the maximum number of batteries and items of equipment, the maximum allowed energy content of the batteries, protections, and separation inside the package shall be provided

UN Labeling and Marking Recommendations

The UN number of each package shall be marked on the outside package, where the mark shall be at least 12 mm high, except for packages of 30 kg maximum net mass, where the mark shall be at least 6 mm in height. In case of unpackaged equipment, such as batteries or cells contained in equipment, the mark shall be placed on the equipment or on its handling device. The UN mark shall be visible, legible, able to withstand open weather exposures without any reduction in effectiveness, be displayed on a background of contrasting colour, and shall not be located with other marks that may reduce its effectiveness.

1) **Lithium-ion batteries**

Packages that contain stand-alone LiBs (UN3480) or contained in or packed with equipment (UN3481) or unpacked lithium batteries; and the lithium batteries have a Watt-hour rating of 100Wh or less shall be marked with a minimum of 100 mm wide, 100 mm high rectangular mark, and with a minimum of 5 mm hatched edge containing an image of group of batteries above the UN number as shown in Figure 9.

Figure 9: UN labels for lithium-ion batteries [8]

LiBs that have a Watt-hour rating of more than 100Wh shall be labeled, where the upper half shall only contain 7 vertical stripes, and the lower half shall contain the symbol of the group of batteries with an underlined class number.

2) **Overpacks**

When packagings are overpacked, the overpack shall contain all the required marks and labels of the package; in addition, it shall be marked with “OVERPACK” with at least 12 mm height as shown in Figure 10.

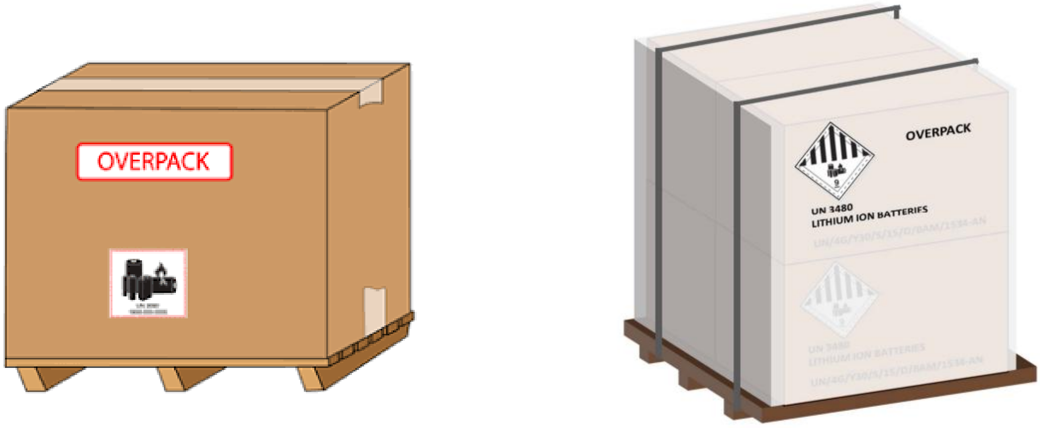


Figure 10: Overpack packaging [9]

3) Empty packaging

Any package that contained dangerous goods, except class 7 goods, shall be identified, marked, labeled, and placarded for those dangerous goods, unless the packaging has been cleaned or purged from vapours or refilled with a non-dangerous substance to nullify any hazards. However, packaging that has been used to transport Class 7 goods (Radioactive material) shall be decontaminated below the level of 0.4 Bq/cm^2 for beta, gamma emitters, and low toxicity alpha emitters, and 0.04 Bq/cm^2 for all other alpha emitters.

Transportation of LiBs

Transportation of LiBs

After discussing packaging and labeling guidelines in the previous section, where packaging is a crucial action to be taken before transporting batteries, a comprehensive overview of transportation provisions from multiple entities and test criteria from the UN is discussed in this section. Figure 11 shows the concerned entities in transportation regulatory frameworks.

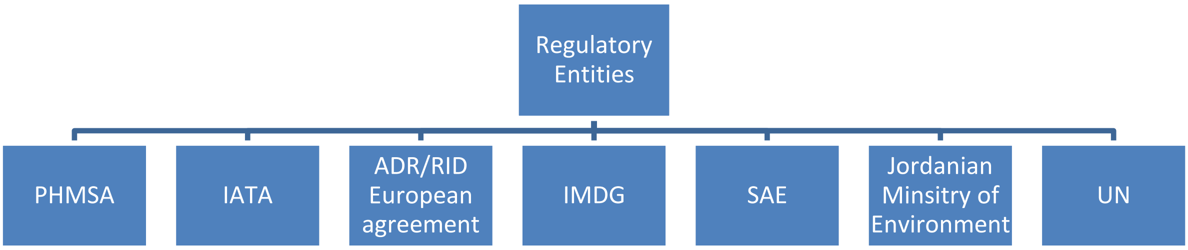


Figure 11: Transportation regulatory entities

7.1 Pipeline and Hazardous Material Safety Administration (PHMSA)[B]

The Hazardous Material Regulations (§ 172.101) described lithium cells and batteries depending on their chemistry and packaging. Lithium-metal batteries are primary (non-rechargeable) batteries that have a higher energy density and lifespan than LiBs, and their anode is made up of pure lithium metal, unlike LiBs, whose anode is made up of graphite. The descriptions are as follows:

- Stand-alone
  - UN3480, Lithium-ion
  - UN3090, Lithium metal
- Contained in/Packed with equipment
  - UN3481, Lithium-ion
  - UN3091, Lithium metal

B: Reference [10]

- Vehicles-the package or shipment contains a vehicle powered by lithium batteries
    - UN3171, powered vehicle

Based on Hazardous Materials Regulations (HMR); 49 CFR parts 171-180, the Pipeline and Hazardous Materials Safety Administration (PHMSA) enacted some shipping regulations as follows:

7.1.1 Guide 01: Stand-alone fully regulated cells/batteries (UN3480)

To have safe shipping for lithium-ion cells that exceed 20Wh and batteries greater than 100Wh, the following instructions must be adhered to:

- Having proper packaging with specific requirements, such as protecting terminals against short circuiting.
- The inner package mustn't contain metallic and conductive materials.
- Packed well to prevent any damage that may be caused due to shifting within the outer package.

However, the outer packages must meet the UNECE specifications and follow the instructions of the manufacturer, where lithium batteries or cells with a mass of 12 kg or more with a strong impact-resistant outer casing must be:

- Packed in strong outer packaging, such as crates.
- Approved by the associate administrator of air transport.
- The shipment must have hazard communication signs, such as a Class 9 lithium battery label, UN ID number UN3480, Shipping name mark 'lithium-ion battery', consignor and consignee details, and emergency response information.
- Shipping employees must be subjected to hazmat training; and both hazardous material shipping paper and emergency response information must be provided.

Due to the severity of lithium-ion cells and batteries, some air restrictions have been adopted to maintain the safety of passengers, the environment, and the facility:

- These shipments are prohibited from being transported as cargo on passenger aircraft;

- Damaged lithium-ion cells and batteries, lithium-ion cells and batteries that have SoC of more than 30%, and packages that weigh more than 35 kg net quantity are also forbidden from air transport.
- Lithium-ion cells and batteries mustn't be packed with hazardous materials from Class 1 (explosive), and Class 3 (flammable gases).

Guide 02: Stand-alone smaller lithium-ion cells/batteries (UN3480)

Regarding cells equal to or less than 20Wh and batteries equal to or less than 100Wh for air shipment, and cells between 20 and 60 Wh; and batteries between 100 and 300Wh for highway and rail shipment only, they undergo the same packaging requirement of the fully regulated cells and batteries from protection against short-circuiting, placing in non-metallic and non-conductive materials, and prevent shifting that may cause damage within the outer package. However, an additional test is required here regarding the outer package, where each outer package has to withstand a 1.2-meter drop test without any damage to cells and batteries, without shifting that may cause contact between batteries, and without causing leakage to the batteries and cells' contents. The package shall not exceed 30 kg gross weight. There are some requirements related to hazard communication; the outer package must have:

- Labels and information, such as a lithium battery mark that includes UN ID number 3480 and a telephone number for additional information; the mark has to be in a hatched edging rectangle or square with:
    - 100mm wide and 100mm high.
    - 100mm wide and 70mm high for smaller packages.
- "OVERPACK" label if the package is overpacked.
- These shipments are forbidden for transport aboard passenger aircraft, so a cargo aircraft only (CAO) label must be on the outer package.
- Shipments across highway and rail, the text marking "LITHIUM BATTERIES-FORBIDDEN FOR TRANSPORT ABOARD AIRCRAFT AND VESSEL is required. According to PHMSA, cells and batteries not exceeding 60 Wh and 300 Wh respectively are also considered small in road and rail transportation; therefore, they could be transported not as fully regulated (UN label, class 9 label, hazmat shipping papers, and package marking are not required).

Air transport has some restrictions regarding the smaller cells and batteries:

- These packages are prohibited from being transported as cargo on passenger aircraft.
- Damaged cells and batteries; as well, cells and batteries that exceed 30% SoC are also forbidden from air transport.
- Only one package of lithium-ion cells and batteries may be placed in an overpack, and the overpack mustn't include hazardous materials from Class 1 (explosive) and Class 3 (flammable solids).
- A shipper may not ship more than one package in any single consignment.
- and each package has to undergo to the following limits shown in Table 3:

Table 3: Small cells/batteries packaging limits

Contents	Lithium-ion cells and batteries with a rating not more 2.7 Wh	Lithium-ion cells with a rating between 2.7 Wh and 20 Wh	Lithium-ion batteries with a rating between 2.7 Wh and 100 Wh
Max. number of cells/batteries per package	No Limit	8 cells	2 batteries
Max. net quantity (mass) per package	2.5Kg	N/A	N/A

Note: Hazmat employees are not subjected to training, no hazardous material shipping paper, no emergency response information is required.

Guide 03: Fully regulated cells/batteries contained in/packed with equipment (UN3481)

Packages that contain cells and batteries contained in or packed with equipment are subjected to some similar requirements as mentioned in the previous sections, in which cells and batteries have to be protected against short-circuiting, prevented from shifting, and packed in non-metallic and non-conductive materials. However, for cells and batteries packed with equipment, the inner package must be separated from contact with electrically conductive equipment; and for lithium cells and batteries contained in equipment, the outer package must be constructed of suitable materials and proper design, unless the cells and batteries are well protected by the equipment itself. In addition, the equipment must be protected from accidental activation. Some hazard communication labels and signs are required for the packages, such as:

- Class 9 lithium battery label.
- CAO label if shipped by air and the net weight exceeds 5 kg.
- UN ID number 3481.

- shipping mark “Lithium ion batteries packed with equipment” or “Lithium ion batteries contained in equipment”.
- consignor and consignee details.
- and cargo aircraft packages mustn’t exceed 35 Kg net weight.

Note: DOT Hazmat employee training, hazardous material shipping paper, and emergency response information are required.
Note: if the package contains both LiBs packed with and contained in equipment, the proper shipping name is “Lithium Ion Batteries Packed with Equipment.

Guide 04: Smaller cells/batteries contained in/packed with equipment (UN3481)

Same provision of guide 02 and guide 03; moreover, the outer package must have Lithium Battery mark, except when the package contains button batteries installed in equipment, or when the package contains no more than four lithium-ion cells or two lithium-ion batteries contained in equipment, or when there are no more than two packages in a consignment. Additional air restrictions, the number of batteries in each package is limited to the minimum required number to power the equipment; plus 2 spare sets

Guide 09: Battery-powered vehicle (UN3171)

LiBs that are contained in vehicles, engines, or mechanical equipment are excepted from guides 02 and 03, therefore some requirements must be followed:

- Have to be securely fastened in the battery holder and protected from short-circuiting.
- There is an exception for prototype or low-production LiBs that are contained in vehicles that are transported by highway, rail, or vessel, which these batteries have to pass the UN38.3 tests.
- In addition, if the vehicle can be shipped in multiple positions other than an upright position, it must be secured in rigid outer packaging.

Note: Any damaged, defective, recalled batteries must follow the HMR (49 CFR Parts 171-180) related to Damaged, Defective, or Recalled (DDR) lithium batteries.

Guide 10: Cargo Transport Unit (UN3536)

Relating to the cargo transport unit, lithium batteries must pass the UN38.3 tests and contain systems to prevent overcharge and over-discharge between batteries; lithium batteries must be packed to prevent short circuits, shifting, and unintended activation. Safety is also one of the crucial requirements for transporting lithium batteries; therefore, fire extinguishing systems and air conditioning systems must be secured to or installed in the cargo transport unit. The cargo transport unit must have a label that indicates the hazardous material it contains, such as marking a placard that contains the class of lithium-ion (class 9) or the UN ID number, and the placard must be marked on 2 opposite sides.

The International Air Transport Association (IATA)[C]

Based on the provisions of the 65th edition (2024) of the IATA Dangerous Goods Regulations (DGR) and IATA Lithium Battery Shipping Regulations (LBSR) 11th edition; IATA has enacted some regulations for shipping LiBs by air. Consequently, lithium-ion cells and batteries must be shipped at a SoC not exceeding 30% of their rated capacity, any cell or battery that exceeds 30% must have permission from the state of origin and the state of the operator. According to the UN Manual of Tests and Criteria, subsection 38.3, manufacturers and distributors of cells, batteries, and equipment powered by them that are manufactured after 30 June 2003 must have the following test summary shown in Figure 12.

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Lithium cell or battery test summary in accordance with sub-section 38.3 of Manual of Tests and Criteria

The following information shall be provided in this test summary:

(a) Name of cell, battery, or product manufacturer, as applicable;

(b) Cell, battery, or product manufacturer's contact information to include address, phone number, email address and website for more information;

(c) Name of the test laboratory to include address, phone number, email address and website for more information;

(d) A unique test report identification number;

(e) Date of test report;

(f) Description of cell or battery to include at a minimum:

- **(i)** Lithium ion or lithium metal cell or battery;
- **(ii)** Mass;
- **(iii)** Watt-hour rating, or lithium content;
- **(iv)** Physical description of the cell/battery; and
- **(v)** Model numbers.

(g) List of tests conducted and results (i.e., pass/fail);

(h) Reference to assembled battery testing requirements, if applicable (i.e. 38.3.3 (f) and 38.3.3 (g));

(i) Reference to the revised edition of the Manual of Tests and Criteria used and to amendments thereto, if any; and

(j) Name and title of responsible person as an indication of the validity of information provided.

Figure 12: LiB test summary [11]

Note: UN3481 and UN3171 have no regulations relating to their SoC at the time this document has been published.

Note: "PI" indicates Packaging Instruction, "|" indicates Fully Regulated, and "||" indicates Small.

Cells/batteries limited to a maximum of 30% SoC (PI 965)

With respect to lithium-ion cells less than or equal to 20 Wh and LiBs less than or equal to 100 Wh, there is no maximum quantity, but there are some limitations on the weight, which the net weight is limited up to 10 Kg by CAO, but it is prohibited from being shipped with Pax. On the other hand, cells of more than 20 Wh and batteries of more than 100 Wh have a limited net weight of 35 Kg per package, and they are prohibited from passenger transport.

Cells/batteries packed with equipment (PI 966 | & ||)

From January 1st to December 31st of 2025, PI 966 (| & ||) should have a maximum of 30% SoC of their rated capacity to be packed with equipment. From the 1st of January 2026, PI 966 section | which may exceed 30% SoC of its rated capacity, must have the approval of the state of origin and the state of the operator. However, any cell or battery of PI 966 section || that exceeds 2.7 Wh must be packed and shipped at a SoC that does not exceed 30% of its rated capacity unless it has approval from the state of origin and the state of the operator. In addition, lithium batteries less than or equal to 100 Wh must have a net weight of 5 Kg for both passenger and CAO packages; however, packages of cells more than 20 Wh and batteries more than 100 Wh have a limited net weight of 35 kg. Furthermore, the maximum quantity of cells and batteries must be the required quantity for operation plus 2 sets for replacement, regardless of the Watt-hour rating.

Cells/batteries contained in equipment (PI 967 | & ||)

To minimize the risk of the lithium-ion cells and batteries contained in equipment, they must be shipped at a SoC not exceeding 30% or with an indicated battery capacity not exceeding 25% (spent battery). In addition, lithium cells that are less than or equal to 20 Wh and batteries that are less than or equal to 100 Wh must have a net weight of 5 kg for both passenger and CAO packages. On the other hand, the net weight of cells is more than 20 Wh, and batteries of more than 100 Wh are 35 kg.

Vehicles powered by LiBs (PI 952)

From the 1st of January 2025, battery-powered vehicles UN3171 will be categorized into vehicles powered by lithium-ion (UN3556), lithium metal batteries (UN3557), and sodium-ion batteries (UN3558); anyway, these vehicles may still be shipped as Battery Powered Vehicles (UN3171) until the end of the transition period, 31st of March 2025. However, starting from January 1st, 2025, the battery(ies) of the transported vehicles must have a SoC 30% as a maximum, or indicated battery capacity not exceeding 25%. Furthermore, starting from January 1st, 2026, transported vehicles that are powered by batteries that exceed 100 Wh and a SoC of 30% of their rated capacity must have approval from the state of origin and the state of the operator. Regarding the Watt-hour rating, any lithium-ion battery that has been manufactured after the 31st of December 2011 with a Watt-hour rating in excess of 100 Wh, and LiBs that are manufactured after the 1st of January 2009 with a Watt-hour rating not exceeding 100 Wh must be marked with its Watt-hour rating on the outside case.

Safe Packaging

According to IATA, it's crucial to prevent any accident that may occur during shipping LiBs; therefore, packed batteries or cells must be separated from each other and from any conductive materials or devices in an enclosed, non-conductive inner packaging (such as plastic bags) to prevent any short-circuit which may occur due to terminals contact, as shown in Figure 13, and the exposed terminal must be protected by non-conductive tape. However, the outer package of PI 965 and PI 966 must be rigid to prevent the batteries or cells from shifting, PI 966 section || must pass the 1.2 m drop test, and PI 965 IB section (small cells/batteries) must withstand a 3-meter stack test for a period of 24 hours, where the shipper may prepare a package containing the battery tendered for transport, then places a weight equivalent to the weight of similar packages.nHowever, stand-alone LiBs (PI 965 IA & IB) mustn't be packed with dangerous goods Class 1 (explosives) and Class 3 (flammable liquids). As we know, LiBs must pass the UN38.3 test, except for the prototypes that are transported for testing or a low-production run. Regarding DDR lithium batteries, they are prohibited from being shipped by air. Regarding PI 967, the equipment must be packaged well in a way to prevent access to activation switches, switch caps, or temperature-sensitive circuit breakers that may cause unintentional activation.

Figure 13: Packaging & cushioning material [11]

Shipping Mark

For fully regulated stand-alone lithium batteries, both Class 9 and CAO labels are required; for small stand-alone batteries, Class 9, CAO, and UN labels are required. For batteries packed with/contained in equipment, it depends on the Watt-hour rating, where fully regulated batteries require a Class 9 label and small batteries require a UN label. However, the border of the UN mark, shown in Figure 14must be a red diagonal hatched border with a minimum width of 5 mm; in addition, the mark has to be in the form of a square or rectangle with a minimum dimension of 100 mm wide x 70 mm high. In addition, the PI 965 shipment's mark must contain the name and address of the consignor and consignee and the net weight.

Figure 14: CAO and Lithium-ion battery labels required in airline transportation [11]

However, the lithium battery mark is not required for the consignment of two PI967 || packages or less, and each package contains no more than 4 cells or 2 batteries contained in the equipment.

ADR/RID, European Union Agreement(D)

The European Agreement concerning the International Carriage of Dangerous Goods by Road and the International Statutory Order on the Conveyance of Dangerous Goods by Rail have enacted regulations for transporting LiBs by road and rail, following the recommendations of the UNECE; however, ADR and RID have categorized lithium-ion cells and batteries according to their Watt-hour rating.

Shipment of small cells and batteries

ADR and RID have not specified a maximum quantity of UN3480 and UN3481, but they have limited the gross weight per packaging to 30 Kg for stand-alone cells not more than 20 Wh and batteries not more than 100 Wh. However, stand-alone and packed with equipment, lithium-ion cells and batteries must be packed in an inner packaging that prevents short circuits and any damage to the battery; and outer packaging that prevents the batteries from shifting (1.2 m drop test passed). Regarding the lithium-ion cells and batteries contained in equipment, the equipment is considered an inner package, but the outer package must be rigid; protection against unintentional activation and short circuits must be considered. ADR and RID have also specified the labels' dimensions of the packages shown in Figure 15; for stand-alone, packed with equipment, and contained in equipment; only for equipment that contains more than 2 batteries and consignments that are more than 2 packages, the minimum dimensions are 120 mm x 110 mm for normal packages and 100 mm x 70 mm for small ones; however, the label isn't applicable for equipment that contains 2 batteries or less, or consignment that is no more of 2 packages. In addition, UN38.3 tests must be performed on the LiBs, and they must pass the tests.

Figure 15: Packaging and labels required in road transport for small cells/ batteries [12,13]

Shipment of fully regulated cells and batteries

D: Reference [12]

Lithium-ion cells and batteries with higher Watt-hour ratings, more than 20 Wh and 100 Wh, respectively, are riskier; therefore, more regulations and different labels will be adopted. According to ADR 1.1.3.6, the maximum lithium content weight per transport unit of UN3480 and UN3481 is 333 kg; any extra weight requires additional requirements to the carrier; regarding packaging; in addition to the regulations, which are mentioned above, cells or batteries with gross weight more than 12 Kg must be packed in a strong, impact-resistant outer casing with a protective enclosure, such as crates or pallets for both UN3480 and UN3481; in addition, the package must be UN approved (PG ||). Bigger packages require bigger labels; consequently, the label of ADR is 10 cm x 10 cm, containing the UN ID number and the Class of the dangerous goods, which is 9 as shown in Figure 16In addition, the container has its placard with a minimum dimension of 25 cm x 25 cm. Transporting such hazardous goods with high Watt-hour rating requires transport documents, such as UN ID number, UN ID name, class (9), (X) number of packages, packaging type (crates, pallets,..etc), weight, and consignor and consignee address. In addition, UN38.3 tests must be performed on the LiBs, and they must pass the tests.

Figure 16: Packaging and labeling for cells/batteries exceeds 20 Wh and 100 Wh [12,13]

Shipment of Lithium-ion battery prototypes

Prototypes are batteries that are not tested according to UN 38.3, due to a small production series of a maximum of 100 batteries and testing reasons only. However, Figure 17 shows that the packaging of these prototypes must be UN approved (PG ||), each battery shall be packed individually in an inner packaging (plastic bag), a non-

Figure 17: Packaging examples of prototypes cells/batteries [12,13]

combustible, non-conductive thermal insulation material inner package, and the package must be secured against shifting. As regards a 100 mm x 100 mm UN 3480 label must be marked additional information, such as consignor and consignee details, UN 3480 LITHIUM ION BATTERIES, 9, battery weight, packaging type, and number of packages, must be marked.

Shipment of damaged/defective batteries

LiBs that are identified as being defective, leaked, vented, that cannot be diagnosed before carriage, or that have sustained physical or mechanical damage are considered non-critical 7, which means there is no danger during transport. These batteries undergo several regulations regarding packaging, marking, and weight limit; they must be packed separately in leakproof inner packaging to prevent the release of electrolytes, must be secured against shifting, sealed packages must be fitted with a venting device, must be packed with non-combustible (rockwool, glass wool, vermiculite) and non-conductive material, must be packed in an absorbent material to absorb leaking electrolyte from leakage batteries, and must be protected from short circuits. In addition, the maximum net weight limit is 30 kg. On the other hand, batteries that may cause danger during transport, “Critical-7”, are batteries that are liable to rapidly disassemble, dangerously react, produce flame, or emit toxic flammable gases. Regarding that, some special packaging regulations must be met, in which the package must be capable of meeting any danger that has been mentioned above; in addition, the package must be tested and approved by the competent authority. However, both ‘Cirtical-7’ and ‘non-Critical-7’ must have a label of UN ID number with a description of the battery status, UN 3480/3481, Damaged/ Defective LiB; and other transport documents that include “Transport in accordance with special provisions 376”; the information of the shipper, consignee, battery weight, packaging type, and number of packages must be provided.

Shipment of Batteries for disposal/recycling

For LiBs less than or equal to 100 Wh or batteries contained in equipment, UN-approved packaging is not required, and the weight is limited to 30 Kg; however, for batteries greater than 100 Wh, the UN PG II is required. However, the battery terminal must be protected, the inner package must prevent contact between batteries, and a non-conductive and non-combustible cushioning material must fill the empty space between the batteries; the package must be suitable and constructed from adequate material in order to prevent short-circuiting and dangerous evolution of heat. As regards marking, the label of "UN 3480 LITHIUM ION BATTERIES FOR DISPOSAL/RECYCLING" must be marked; as well, documents of the shipment must be available, the documents that clarify the shipper's and consignee's details, class, UN ID number, battery weight, packaging type, and number of packages.

Instructions for dealing with emergencies during transportation

The ADR has adopted safety instructions in case of accidents and emergencies that may occur during transporting LiBs, where the members of the vehicle crew shall take the following actions:

- Stop the engine and isolate the battery by activating the master switch, where available.
- Avoid sources of ignition, such as smoking or activating electrical equipment.
- Inform the concerned parties, such as civil defense.
- Place the warning signs and put on the warning vest.
- Keep the transport documents always available for responders to know what they are dealing with.
- Avoid inhalation of fumes, smoke, dust, or vapors by staying up wind; and avoid touching any spillage.
- Use fire extinguishers to put out any small/initial fire in tires, brakes, or the engine.
- Use on-board equipment to prevent any leakages into the aquatic environment or the sewage system.
- Move away from the vicinity of the accident.
- Remove any contaminated clothing and use contaminated protective equipment.

Each transport unit shall contain the following safety equipment:

- A wheel chock of a size suited to the maximum mass of the vehicle and to the diameter of the wheel.
- 2 self-standing warning signs.
- A warning vest.
- Portable lighting apparatus.
- A pair of protective gloves.
- Eye protection.

- A shovel, drain seal, and collecting container.

International Maritime Dangerous Goods Code (IMDG)[(E)]

Following the UNECE recommendations, lithium batteries may be transported by sea if they meet the following provisions that are enacted by IMDG:

- Each cell or battery must pass UN38.3 tests and criteria unless they are manufactured before 1 July 2003. UN38.3 doesn't apply to production runs that consist of not more than 100 cells and batteries and to prototypes that are being transported for testing.
- Each cell or battery shall incorporate a safety venting device or be designed to preclude rupture during transportation.
- Each cell or battery shall be secured from external short-circuits.
- Each battery containing a cell or a series of cells that are connected in parallel shall be secured from reversed current flow.
- Cells and batteries shall be manufactured under a quality management programme that includes:
    - An organizational structure description.
    - Responsibility of personnel about design and product quality.
    - Relevant inspection and test, QC, QA, and instruction of the process operation that would be used.
    - Process controls that are used during manufacturing to prevent and detect internal short-circuit failure.
    - Test data, inspection reports, and calibration certificates.
    - Training programs for the personnel.
    - Procedures to ensure that the final product is safe and not damaged.
- Lithium-ion cells with a Watt-hour rating of not more than 20 Wh; and batteries with a Watt-hour rating of not more than 100 Wh; the battery shall be marked with the Wh rating on the outer case unless they are manufactured before 1 January 2009.
- Cells and batteries shall be packed in an inner package that encloses the cell or battery and precludes short circuits or any contact with a conductive material; the outer package shall also be durable. However, Cells and batteries installed in equipment are excluded.

E: Reference [14]

- Cells and batteries that are installed in the equipment shall be packed in a strong outer package that prevents unintentional activation and any damage to the battery; this requirement doesn’t apply to devices that don’t generate the evolution of heat and devices that are intentionally activated.
- Each package shall be marked with an appropriate LiB mark. Packages that contain no more than 4 cells or 2 batteries are installed in equipment, and there are no more than 2 packages, and equipment that contains only button cell batteries are exempted from the package mark.
- The outer package that contains batteries installed in equipment shall withstand a 1.2-meter UN 38.3 without any shifting or content leakage occurring.
- Cells and batteries shall be shipped at a SoC not more than 30%, except when they are installed in equipment.

Note: Cells and batteries are not subjected to other provisions if they meet the above-mentioned provisions.

Damaged or defective batteries shall be marked with the “DAMAGED/DEFECTIVE LITHIUM ION BATTERIES" label. However, batteries that are disassembled, dangerously react, or produce a flame or toxic emissions shall not be transported except under conditions specified by the authority. In addition, batteries that are being transported for recycling or disposal shall be marked with “LITHIUM BATTERIES FOR DISPOSAL" or "LITHIUM BATTERIES FOR RECYCLING" and packaging instructions of UN P903, P908, P909, P910, LP903, LP904.

SAE Recommended Practices for Shipping, Transport, and Handling of Batteries(F)

This chapter discusses a set of practices and regulatory requirements to prepare LiBs for shipment/transport. The first step of shipment should be determining whether the battery is used, new, or remanufactured; the flowcharts in Figure 18 and Figure 19 below describe how these regulatory requirements are presented

F: Reference [15]

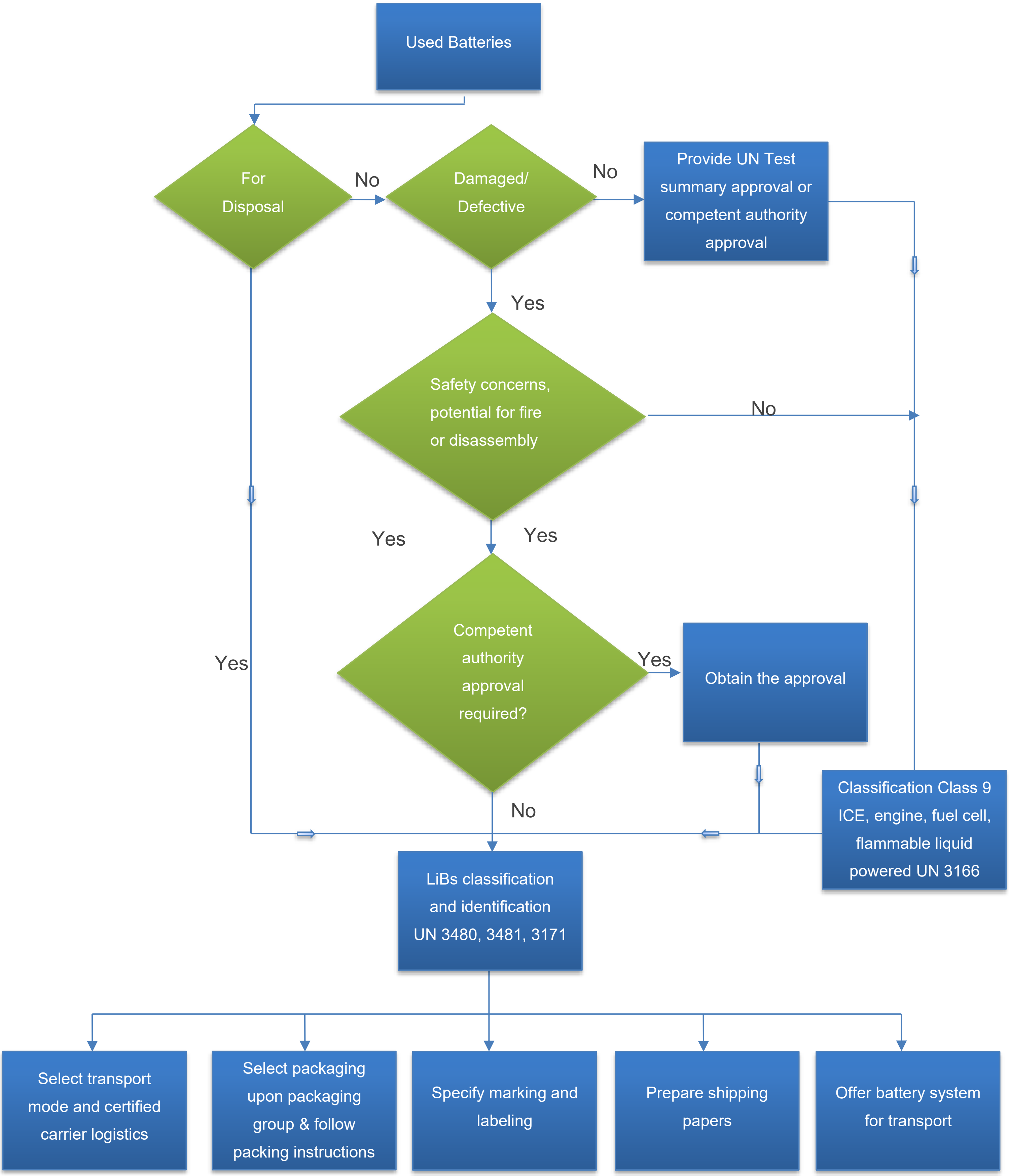


Figure 18: SAE regulatory requirements for shipping used LiBs

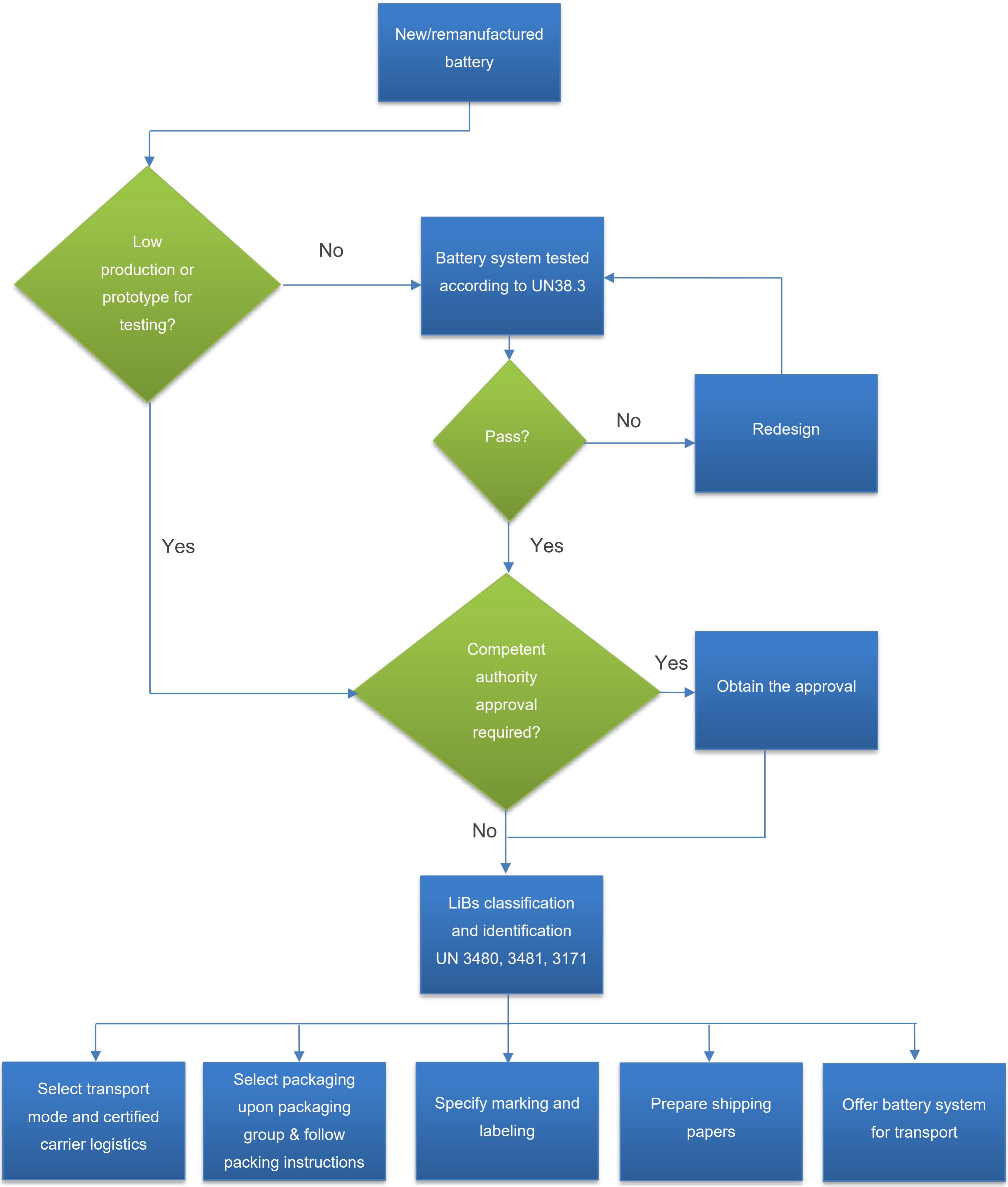


Figure 19: SAE regulatory requirements for shipping new LiBs

For damaged or defective cells and batteries, an assessment shall be carried out including the following safety criteria from the technical expert or manufacturer:

- Severe hazards, such as gas, fire, or electrolyte leaking.
- The use or misuse of the cell or battery.
- Signs of physical damage, such as deformation to the casing or colors on the casing.
- External or internal short circuit protection, such as voltage or isolation measures.
- The condition of the cell or battery safety features.
- Damage to any internal safety components, such as the battery management system.

Battery inspection before it’s being shipped is crucial when there is a reason to suspect that a battery/cell may be damaged, e.g., after a vehicle accident, manufacturer recall, or abnormal handling; therefore, the required actions will be taken.

Active emissions

The inspection is about noticing visible evidence of active emissions, e.g., smoke, venting, flames, sparks, electrical arcs, or abnormal odors different than electrolyte, which has a sweet odor. If active emissions exist, notify the appropriate emergency team.

Explosion, disassembly, or fire

It’s about looking for burned components, deformed plastic cases, peeling or blistering of paint, grey or black residue, melted seals, metallic splatters such as copper or aluminum, and abnormal odor such as burnt odor. If one of the abovementioned symptoms exists, follow the instructions in the “Damaged/Defective Battery Packaging preparation” section.

Leakage

There are some symptoms of electrolyte or internal liquids leakage, e.g., sweet ether-type odor emission, wet areas, salt crystal residue, signs of discoloration, signs of gelatinous residue, or coolant of the internal cooling system. If one of these signs exists, follow the instructions in the “Damaged/Defective Battery Packaging preparation" section.

Rupture

The existence of an opening in the case where internal components are exposed and a liquid may enter. If rupture is detected, follow the instructions in the "Optional Techniques Requiring Special Tools and/or Training" section.

Shock

Determination if the battery has experienced any damage or shock during shipping or use, where shock sensors may be used in the battery or shipping crates to record any shock levels, if the shock levels exceed UN38.3 T4 test levels, the instructions of the "Optional Techniques Requiring Special Tools and/or Training" section shall be applied.

Mechanical integrity

The mechanical integrity of the battery could be identified by abnormal noise while moving the battery; external wiring or electrical connections damaged, such as:

- Dents, punctures, scratches, or corrosion; or physical damage,
- Deformation to the battery or cell casing, or bulging.

If the mechanical integrity is suspect, follow instructions in the "Optional Techniques Requiring Special Tools and/or Training" section.

Current interrupt devices

The inspection is for the fuses. If current interrupt devices are functional and activated, such as a blown fuse, this may cause a short circuit; therefore, follow the "Optional Techniques Requiring Special Tools and/or Training" section.

Temperature

The temperature inspection, which determines if the battery is still generating heat after removal from use, can be performed by a non-contact infrared meter. However, the environmental conditions, such as wind, solar, etc., shall not affect the battery temperature. For batteries above ambient temperature, a sequence of temperature measures shall be performed at different locations around the system; the sequence shall be repeated at least two times, with at least one hour between each sequence. If temperature isn't decreasing towards ambient; therefore, the battery isn't stable, and the emergency response team shall be informed. Whereas, for batteries below ambient temperature, the sequence of temperature measurements, at the same procedure of batteries above ambient, can be performed when the system's temperature is near the ambient temperature. Elevated temperatures above the ambient require the notification of the emergency response team.

Optional techniques requiring special tools/training

To determine the extent of damage, whether it's about rupture, shock, mechanical integrity, or current interruption devices, special training and/or tools are required. In addition to the abovementioned inspections, open circuit voltage (OCV) and isolation are critical inspections that require special tools and training. To perform the OCV inspection test, the contactors have to be closed, and terminals have to be well-protected with non-conductive, non-combustible material; if the contactors are opened, then no voltage should be present. For the isolation inspection of high-voltage batteries (have orange-colored cables/connectors), batteries shall maintain high voltage to ground isolation of no less than 100 n/V.

Damaged/defective battery packaging preparation

To split the battery potential in half, reduce battery pack voltage, and divide potential energy of the battery pack to reduce the hazards during transportation; manual disconnects or serviceable fuses, if equipped, shall be removed. Additional requirements, such as the existence of non-conductive, non-combustible, absorbent cushioning material in the package, are crucial for extra safety criteria. The inner package may also be surrounded by a plastic liner such as flame-retardant bag; However, only one battery may be placed in each outer package during transportation, and the package shall be marked with a damaged/defective LiB label.

The Jordanian Ministry of Environment[G]

The Jordanian MoEnv has enacted some instructions relevant to managing and trading spent lead-acid and hybrid & electric vehicle batteries locally. Due to the hazard of hybrid & electric vehicle battery during transportation and risks that may occur;

G: Reference [16]

- Plastic separators must be held between batteries.
- The transporter must have a license from the ministry.
- The truck must have warning signs.
- Safety equipment must be provided within the truck.
- Packaging of the batteries must prevent shifting and prevent collisions.
- It's also prohibited to transport hazardous materials with the batteries.
- As well, the transporters must be well trained to handle any emergencies.

UN38.3 Test Criteria(H)

Lithium-ion cells and batteries of different classifications UN3480 and UN3481 must be subjected to UN38.3 tests before being shipped. A change in one of the following factors may change the required test:

- Any change in the nominal Wh rating of the battery by 20% or more; and an increase in the voltage by 20% or more.
- A change in the material of the anode, the cathode, the separator, or the electrolyte.
- A change in the protective devices, such as hardware or software.
- A change in safety design in cells or batteries, such as a venting valve.
- A change in the number of component cells.
- A change in the connection mode of the component cells.

Test procedure

1) **Test T.1: Altitude Simulation**
   - The test aims to simulate the air transport of cells and batteries under low-pressure conditions.
   - Cells and batteries must be stored for at least 6 hours at a pressure of 11.6 kPa and an ambient temperature (20 ± 5 °C).
   - Cells and batteries mustn't have any leakage, venting, disassembly, rupture, or fire, and the open circuit voltage after testing mustn't be less than 90% of their voltage.

H: Reference [17]

- The voltage requirement isn't applicable for cells and batteries at fully discharged; therefore, the cells and batteries are considered passed the test.

2) **Test T.2: Thermal Test**
    - This test ensures that the cells and batteries are sealed well, and the internal electrical connections are safe by exposing them to rapid and extreme temperature changes.
    - Cells and batteries must be stored at a test temperature of 72 ± 2 °C for 6 hours, then a rapid change in test temperature to -40 ± 2 °C with a maximum of 30 minutes time interval between the extreme test temperatures.
    - This procedure must be repeated 10 times; after that, the cells and batteries have to be stored for 24 hours at an ambient temperature of 20 ± 5 °C.
    - For large cells and batteries, the exposure to the test temperature must be at least 12 hours.
    - Cells and batteries are considered passed if there is no leakage, no venting, no disassembly, no rupture, or no fire, and the open circuit voltage after testing is not less than 90% of the rated voltage. The voltage criterion doesn't apply to cells and batteries at fully discharged states.

3) **Test T.3: Vibration**
    - A pre-vibration test must be conducted to make sure that there is no leakage, venting, fire, or rupture on the cells and batteries during transportation.
    - The vibration test must be a sinusoidal waveform with a logarithmic sweep starting from 7 Hz to 200 Hz and then back again to 7 Hz, traversed in 15 minutes.
    - This cycle shall be repeated 12 times for a total of 3 hours for each of three mutually perpendicular mounting positions of the cell.
    - One of the directions of the vibration must be perpendicular to the terminal face.
    - The logarithmic frequency sweep differs depending on the gross mass of the cells and batteries, small batteries, and large batteries.
    - For cells and small batteries (less than 12 Kg)
        - The frequency sweep is from 7 Hz a peak acceleration of 1 g_n is maintained until 18 Hz is reached.
        - then the amplitude is maintained at 0,8 mm (1.6 mm total excursion) and the frequency increases until a peak acceleration of 8 g_n occurs (approximately 50 Hz);

- then a peak acceleration of 8 g_n is maintained until the frequency is increased to 200 Hz.

- For cells and large batteries (more than 12 Kg)
  - the frequency sweep is from 7 Hz, a peak acceleration of 1 g_n is maintained until 18 Hz is reached;
  - then the amplitude is maintained at 0,8 mm (1.6 mm total excursion) and the frequency increases until a peak acceleration of 2 g_n occurs (approximately 25 Hz);
  - and then a peak acceleration of 2 g_n is maintained until the frequency is increased to 200 Hz.
- In addition to the requirements mentioned in the first paragraph, the open circuit voltage for cells and batteries mustn't be less than 90% in their third perpendicular mounting position to pass the voltage criterion.

4) **Test T.4: Shock**

- A pre-test must be conducted to ensure the robustness of cells and batteries during transportation and prevent any dangerous risks from leakage, venting, disassembly, fire, and rupture.
- The shock test states that each cell has to be subjected to a half-sine shock of peak acceleration of 150 g_n and pulse duration of 6 milliseconds.
- Large cells may be subjected to a half-sine shock of peak acceleration of 50 g_n and pulse duration of 12 milliseconds.
- Each battery is subjected to a half-sine shock of peak acceleration depending on its mass.
- Pulse duration shall be 6 milliseconds for small batteries and 11 milliseconds for large batteries, as shown in Figure 20

Battery	Minimum peak acceleration	Pulse duration
Small batteries	150 g_n or result of formula $\text{Acceleration}(g_n) = \sqrt{\left(\frac{100850}{\text{mass}^a}\right)}$ whichever is smaller	6 ms
Large batteries	50 g_n or result of formula $\text{Acceleration}(g_n) = \sqrt{\left(\frac{30000}{\text{mass}^a}\right)}$ whichever is smaller	11 ms

a Mass is expressed in kilograms

Figure 20: T.4 Shock of small and large batteries [17]

- Each cell or battery must be subjected to 3 shocks in the positive direction and 3 shocks in the negative direction in each of three perpendicular mounting positions of the cells or batteries for a total of 18 shocks.
- The open circuit voltage of each cell or battery after the test must be no less than 90% of its voltage to pass the test.

5) Test T.5: External Short Circuit

- This test aims to simulate the external short circuit of the cells and batteries to make sure that they are safe to be transported without showing any risks, such as disassembly, fire, or rupture.
- The test must be conducted at least at an ambient temperature.
- The cell or battery shall be heated for a period of time until the cell or battery external case reaches 57 ± 4 °C; the period of time depends on the size of the cell or battery and should be assessed.
- If the assessment isn't feasible, the period shall be 6 hours for small cells and batteries and 12 hours for large cells and batteries.
- After reaching the specified temperature, the cell or battery shall be subjected to one short circuit condition, and the total external resistance shall be less than 0.1 ohm.
- The temperature of the external case will increase in the presence of the short circuit condition, then it will cool down.
- The short circuit condition shall be continued for at least one hour after the small cell or battery case temperature returns to 57 ± 4 °C.
- For large cells and batteries, the short circuit condition remains until the case temperature decreases by half of the maximum observed temperature during the test.
- The external case temperature mustn't exceed 170 °C; in addition, no rupture, no fire, and no disassembly must occur during the test and within 6 hours after the test.

6) Test T.6: Impact/Crush

- This test is performed on cells, and it's done at the manufacturing level.

7) Test T.7: Overcharge

- This test aims to assess the ability of rechargeable batteries or single-cell batteries to withstand overcharge conditions.
- The charge current must be twice the manufacturer's recommended maximum continuous charge current, but the minimum voltage of the test shall be less

than two times the maximum charge voltage of the battery or 22 V when the recommended charge voltage is not more than 18 V.

- When the recommended charge voltage is more than 18 V; thus, the minimum voltage of the test shall be 1.2 times the maximum charge voltage.
- The test must be performed at ambient temperature and for 24 hours.
- The rechargeable battery mustn't show any fire or disassembly during the test within 7 days after the test to be considered passed.

8) **Test T.8: Forces Discharge**
    - This test aims to evaluate the ability of primary and rechargeable cells to withstand a forced discharge condition.
    - The test shall be performed at ambient temperature by connecting the cells in series with a 12 Voltage Direct Current (VDC) power supply at an initial current equal to the maximum recommended discharge current.
    - To specify the discharge current, a resistive load with a specific size and rating must be connected in series with the cells, and the time interval (hours) of the forced discharge of each cell can be calculated by dividing the rated capacity of the cell (Ah) on the initial test current (A).
    - No fire and no disassembly during the test within 7 days after the test; therefore, the cells could be considered passed.
9) **Instructions related to the quantity and condition of the cells and batteries** that must be taken when the rechargeable cells and batteries are being tested under the T.1 to T.8 tests:
    - T.1 to T.5 tests of rechargeable batteries must include the following quantity and conditions:
        - Testing 5 cells at the 1st cycle, in fully charged states, then 5 cells after 25 cycles ending in fully charged states.
        - Testing 4 small batteries at the 1st cycle in fully charged states, then 4 batteries after 25 cycles ending in fully charged states.
        - Testing 2 large batteries at the 1st cycle in fully charged states, then 2 batteries after 25 cycles ending in fully charged states.

Note: A small battery is a LiB with a gross mass of not more than 12 Kg.

- Testing rechargeable cells and component cells of rechargeable batteries under the T.6 test must also include the following quantities and conditions:
    - Testing 5 cells at the 1st cycle where the SoC is 50% of the rated capacity, then 5 cells after 25 cycles, ending at a SoC of 50% of the rated capacity.

- Testing of rechargeable batteries or single-cell batteries under the T.7 test shall include the following quantities and conditions:
    - Testing 4 small batteries at the 1st cycle in fully charged states, then 4 batteries 25 cycles ending in fully charged states.
    - Testing 2 large batteries at the 1st cycle in fully charged states, then 2 batteries after 25 cycles ending in fully charged states.

Note: Batteries or single-cell batteries without overcharge protection, that are designed to be used as a component in equipment that affords protection, aren't subjected to this test.

- Testing rechargeable cells and component cells under the T.8 test shall include the following quantities and conditions:
    - 10 cells at 1st cycle and 10 cells after 25 cycles ending in fully discharged states.
    - 10 component cells at 1st and 10 cells after 25 cycles ending in fully discharged states.
- Testing a battery assembly, either contains aggregate lithium content of all anodes, fully charged states, not more than 500 g, or has a Watt-hour rating of not more than 6200 Wh, which the battery is assembled from batteries that have passed all applicable test, one assembled battery in a fully charged state shall be tested under tests T.3, T.4, T.5, and T.7.
- When connecting all battery modules electrically to form a battery pack, the modules must pass the required tests; however, if the aggregate lithium content of all anodes, which are in fully charged states, is more than 500 g, or in case the LiB has a Watt-hour rating more than 6200 Wh, the assembled battery doesn't have to be tested if the assembled battery of a type that has been verified as preventing overcharge, short circuits, and over-discharge between batteries.

Managing, Handling, and Storing LiBs

Managing, Handling, and Storing LiBs

Many hazards may occur during storing and managing spent LiBs, such as short-circuit, physical damage and shock, thermal abuse (external heating), water ingress (moisture), long-term storage (decomposition), and the hazards that may affect the environment. EPA, MIT, NFPA, and SAE have enacted proper guidelines and standards for managing and storing waste LiBs to avoid their hazards as discussed in this section; in addition, the Jordanian ministry of environment has issued instructions regarding storing LiBs and their storage facility.

8.1 Environmental Protection Agency[I]

To collect portable LiBs waste such as batteries of smartphones, electronic tools, laptops, etc., it's recommended that distributors use plastic boxes or drums, keep them in a suitable place, and then bring them back to the civic amenity sites, taking into consideration the following specifications:

- Cold and dry place that is located away from sources of heat and moisture.
- Out of direct sunlight, which shall be covered and weatherproof.
- Segregated from other combustible materials.
- Out of reach of children.
- Outside of building access/escape routes.

However, waste LiBs containers shall be subjected to routine inspection and supervision. In addition, leaking batteries mustn't be accepted or deposited with other batteries, and batteries' terminals shall be taped with non-conductive material to avoid short circuits. Civic amenity sites that collect waste LiBs are recommended to adhere to the following measures to manage waste LiBs:

- Risk assessment- appropriate control measures shall be applied to manage the site.
- Adequate signage to the designated place of LiBs waste, segregated from other waste, and a labeling guide for waste holders. Also, a non-metallic tape is recommended to be available at the site.
- A designated place shall exist for damaged and leaked LiBs.

EPA has also recommended some measures to maintain the safety of the facility

I: Reference [18]

and employees:

- Training shall be conducted for all employees to identify the risks of waste LiBs, segregate waste according to their kind, and inspect batteries' bulging, hissing, and smoking.
- Damaged batteries and those for the SoC aren't known; specific protocols must be applied.
- Batteries must be removed without being touched with a non-conductive shovel.
- Batteries shall be quarantined in a designated area and packed with absorbent, non-flammable material like sand and vermiculite in Figure 21.

Figure 21: Inert filling material (sand and vermiculite) [18]

- It's not allowed to accumulate batteries in significant quantities.

However, non-conforming, damaged, and leaking batteries must be placed in a quarantine area following specific measures, such as:

- Cool and dry, away from sources of heat and moisture.
- Out of direct sunlight and covered.
- Not subjected to extreme heat (above 50 °C) and extreme cold (below 10°C).
- Well-ventilated.
- Bunded area and impermeable surface.
- Subjected to routine supervision.
- Secure and safe from vandalism.
- Segregated from combustible materials.
- Light shall be adequate to identify the waste.

- Appropriate signage and floor markings.
- Inert filling material shall be placed around the damaged or leaking battery to reduce the risk of short-circuit, help conduct heat away, and starve any heated battery from oxygen and fuel.

In addition, EPA has noted practice measures for the storage of waste LiBs in containers:

- The terminals and the exposed wires of waste LiBs must be tapped.
- Batteries and trailing wires can be wrapped and sealed in clear plastic.
- The package must be suitable and protect the batteries from being damaged during storage or transit.
- Containers must be fit for storage, always closed, and filled to the approved capacity.
- Steel containers or drums must be provided with a pressure relief device and spark filter on the lid; the steel drum shall be surrounded by vermiculite.

Massachusetts Institute of Technology(J)

According to MIT, some instructions should be followed to maintain optimal LiBs performance, reduce the risk of fire and explosion, and store the batteries safely:

- Batteries that are not used for more than 3 days must be stored to avoid damage and any unsafe conditions.
- It’s recommended to use fireproof safety bags or containers.
- Terminals must be protected.
- Batteries shall be removed from the device before storing it.
- It’s recommended to reserve a designated area for LiBs away from other batteries and goods, that is a dry and well-ventilated area at room temperature or lower. It’s also recommended not to store the batteries at a temperature close to their manufacturer's upper and lower ranges.
- Batteries shall not be stored in a refrigerator, where it may cause internal condensation when it’s brought to room temperature.
- The area shall be free from any material that may catch fire, such as wood, tables, carpet, textiles, and gasoline.
- Class ABC and CO_2 fire extinguishers shall be available in the storage area.
- It’s recommended to place a fire detector in the storage area.
- Avoid the contact between batteries and conductive materials.

J: Reference [19]

- Avoid heat and moisture sources, especially when the batteries are fully charged.
- Inspect the batteries routinely for any signs of damage before use.
- Adhere to electrical protection standards to avoid electrical hazards, especially for HV batteries above 60 V.
- Avoid mixing new and old batteries or mixing different types of batteries.
- Promptly disconnect the battery, during operation or charging, if any hazardous signs occur such as heat, smell, abnormal behavior, or bulging.
- Working Area:
  - Surface shall be non-conductive and non-combustible; cover the surface with insulation material if the surface is conductive.
  - Ambient temperature should not exceed 60 °C; the best working ambient temperatures are between 15 °C to 35°C.

U.S. National Fire Protection Association[K]

According to U.S **NFPA**, collection areas of wasted lithium batteries shall comply with the following instructions:

- Individual containers shall not exceed 0.21 m^3 in size each, with an aggregate limit of 0.42 m^3.
- Battery collection containers must be separated from each other and from combustible materials by a minimum of 0.9 m of open space.
- Battery collection containers shall be located at a minimum of 1.5 m far away from the exit of the room or space.
- The container shall be approved to store lithium batteries; it shall be open-top and non-combustible.
- Batteries collection containers shall be spaced a minimum of 3 m apart from any combustible material.

After collecting wasted lithium batteries, they must be stored in an indoor proper place, room, prefabricated portable building or container, metal drums, or outdoor area. Regarding indoor areas, the following measures must be applied:

- Each room, space, or prefabricated building and container shall be separated from other spaces by fire barriers and horizontal assemblies with a 2-hr fire resistance rating. Fire barriers are vertical building elements such as walls and shafting closures, where horizontal assemblies are surface, ceiling, and roofs.

K: Reference [20]

- Spaces, rooms, or prefabricated buildings directly containing wasted batteries or containers/metal drums that contain wasted batteries shall be provided with a fire alarm system with an aspirating smoke detector system, and an automatic sprinkler system.
- Vermiculite must be used to separate batteries that are stored in metal drums.
- Area that contains metal drums or approved containers for transportation must not exceed 61 m^2 and must be separated by a minimum of 3 m from other battery storage areas.

When supports and walls aren't obstructed more than one side or more than 25% of the perimeter of the storage area and the structure is noncombustible construction and doesn't exceed 334.5 m^2 this may be considered an outdoor storage location for lithium batteries, and they shall comply with the following:

- Each pile size shall be limited to 83.6 m^2 and separated from other piles by 3 meters.
- Outdoor piles shall be located a minimum of 6.1 m away from lot lines, public ways, buildings, hazardous materials, and other storage.
- Weather protection should be provided.
- Fire alarm system activated by a radiant-energy detection system if the aggregated area is greater than 37.1 m^2.

However, the following areas are exempted from the abovementioned measures:

- Areas where new or refurbished batteries are installed or packed for use in devices, equipment or vehicles.
- Areas where batteries are staged along the assembly lines during the manufacturing process.Areas where new or refurbished batteries have no more than 300 Watt-hour rating.
- Areas within a facility that operates within the procedure of limiting the SoC to 30% or less.

EU Regulation “Directive 2006/66/EC”(L)

Regarding EoL, LiBs have been restricted from landfilling and require a 50% recycling rate. Still, this legislation was designed according to the market-dominant batteries, lead-acid, and cadmium. Regarding the battery market change, in October

L: Reference [21]

2020, the EC suggested repealing Directive 2006/66/EC and replacing it with amendments to Regulation No 2019/1020 to reduce the burden of LiBs. The proposed EU regulation contains several measures related to batteries EoL, including:

- EPR to properly manage the EoL process and attain both the collection and recycling targets.
- Postpone EPR when batteries are repurposed in 2nd life applications.
- A reporting system of EV and industrial batteries; in addition, attain EoL collection rates of 65% in 2025 and 70% in 2030.
- The recycling process shall meet the minimum material recovery rates during each recycling process for Cobalt, Nickel, Lithium, and Copper.

8.5 SAE Practices for Storage of LiBs(M)

Due to the hazards of LiBs, such as chemical energy, electrical energy, electrolyte release, propagation, and emissions, it’s important to adopt safety practices for the storage of large quantities of LiBs to mitigate the potential risks associated with LiBs.

8.5.1 Chemical energy

LiBs chemical energy has some concerns and safety risks, these concerns include thermal runaway, generation of heat, and production of open flame. The chemical energy hazards may be mitigated by the following strategies:

- **Containment**: It’s obtained via packaging, facility structure, and/or limiting the amount of energy for a given space.
- **SoC**: Low SoC reduces the possibility of a thermal runaway and the risk of propagation between cells; it’s recommended to store the batteries at a SoC not exceeding 30%.
- **Storage Temperature**: The lower the temperature, the less reactive the cell chemistry will be, and a higher internal temperature rise will be required to reach the temperature of cathode decomposition.
- **Detection**: Utilizing early detection sensors, such as CO, H_2, heat, smoke, and Volatile Organic Compounds (VOC), for a faster deployment of fire suppression technologies.

M: Reference [22]

Electrical Energy

Due to the high voltage of automotive batteries, which are above 60 VDC, electric shock, internal/external short circuit, or arc flash may occur. External short circuits can occur due to mishandling, improper design, or improper packaging and cause thermal runaway, arc flash, or heat generation. According to SAE standards, the following practices shall be adopted to mitigate the potential risks:

- **Physical Containment**: The containment is via packaging or battery enclosure/casing itself to avoid high voltage exposure and short circuits. Components of battery packs such as modules or cells don't have casing or enclosure like the pack; therefore, packaging is important to avoid exposure to high voltages.
- **Battery Size**: Adopting common design practice will minimize the voltage exposure for battery pack components to be less than 60 VDC, where lower voltage and energy contained in these serviceable components cause less hazard if a short circuit occurs.
- **Battery Terminal Protection**: It's crucial to protect battery terminals to avoid any contact with conductive materials and short circuits. Protection can be accomplished by recessed terminals, finger proof design, isolated battery enclosure, or packaging.
- **SoC**: State of charge shall not exceed 30% to reduce the possibility of a thermal runaway.
- **High Voltage Identification**: Labels and signage shall be utilized to inform personnel and emergency responders about the high voltage storage areas. In addition, battery packs shall be also labeled with ISO high voltage warning icon or any similar icon dictated by regulations.

Electrolyte Release

Lithium-ion electrolytes contain organic solvents, lithium salt, and additives, where the concern is that the organic solvents are flammable and some of the components of the electrolyte have a low flashpoint; low flashpoint components may cause a fire if they encounter a surface that is at a temperature above their flashpoint during the electrolyte leakage. On the other hand, the presence of lithium hexafluorophosphate (LiPF6) salt in the electrolyte generates hydrofluoric acid during the life of the cells, and the hydrofluoric acid becomes hydrogen fluoride (HF) gas when it's released into the environment; the HF can corrode other metals and burn human skin. The following mitigation strategies may be deployed to avoid the risk of electrolyte release:

- **Physical Containment**: The strategy aims to collect and isolate electrolytes from electrical sources and exposure to humans, where packaging and facility structure are key factors for the strategy. Packaging may contain absorbent material or trough for trapping any leaked electrolyte or fluids.
- **Detection**: Sensors that may detect any change in the environment due to lithium-ion electrolyte leakage, that contains Carbon Oxide (CO) and H_2, are crucial to dealing with any potential fire.
- **Runoff Controls**: trenching or absorbent socks may be used along the perimeter to contain any leakage.

Note: Flashpoint is the minimum temperature at which the liquid gives off vapor to form an ignitable mixture with the air near the surface of the liquid.

Propagation

TR events can cause heat and flame due to several factors such as chemistry, spacing between cell batteries, SoC, and internal subsystem design. However, TR may propagate via radiation, convection, or conduction. In order to mitigate the risks and concerns of propagation, the following strategies may be adopted:

- **Physical Containment**: this strategy is obtained by packaging or facility structure to limit the propagation of fire or heat. In order to isolate the source of heat from other combustibles, an appropriate distance, limiting the number of sources of energy for a given space, and physical barriers are used, where the physical barriers are described by their fire resistance time.
- **Battery Design**: The design of the battery itself can reduce the possibility of or prevent TR propagation, where batteries that contain demonstrated control of thermal propagation may replace the need for physical containment.
- **SoC**: as recommended, SoC shall not exceed 30%.
- **Fire Suppression systems/Automatic Sprinkler System**: fire suppression can be achieved either by human response or automatic systems; the feature of automatic systems is that they don't require any interaction from individuals; therefore, they are preferred.

- **Detection**: utilizing sensors that can detect any change in the environment due to smoke or heat.

Emissions

LiBs pose toxic, flammable, and explosive concerns that can occur due to cell failure. Toxic gases such as HF may be present; in addition, particulate matter (PM) of different sizes, $PM_{2.5}$, less than 100 nanometers in size, and greater than 2.5 micrometers, may also be emitted from battery fires. Flammable gases (H_2, methane, propane, and ethylene) can also be released. Trapped gases in enclosed spaces with high concentrations may cause explosive conditions; the following mitigating strategies shall be applied to ensure the safety of personnel, environment, and facilities:

- **Containment**: an emissions management and control process shall be applied to avoid flammable and toxic concentrations; fire suppression strategies may also be effective in controlling emissions. However, in order to calculate the flammable, explosive, and toxic concentrations, the potential volume and mass of emissions and constituents shall be known; in addition, the management processes shall include these calculations in the design and may include ventilation, infiltration, and scrubbing.
- **Detection**: Usage of emissions, heat, and pressure sensors.

Fire suppression technologies

As an initial step, defining the goal of suppression activity, the types, volumes, and chemical composition of the stored batteries are crucial. Due to the risk of fire propagation and battery re-ignition, some strategies should be considered for battery suppression before adopting the technologies, such as fire circumstances, surrounding environment flame elimination, and cooling impact. Suppression types and technologies are clarified in Figure 22 below:

Suppressant Type	Suppression Technology	Flame Elimination	Fast Acting	Cooling Effect	Inhalation/ Asphyxiation Hazard/ Concern
Water	Water jet	✓	✓	✓	
	Water spray/sprinkler	✓	✓	✓	
	Water + surfactants	✓	✓	✓	
	Water mist	✓	✓	✓	
	Deluge	✓	✓	✓	
	Submersion	✓	✓	✓	
Compressed gasses	Carbon dioxide (CO_2)	✓	✓		
	Nitrogen (N)	✓	✓		✓
	Argon	✓	✓		✓
	Halon 1301	✓	✓		
Liquefied compressed gasses	Halon 1211	✓	✓		
Dry chemical/media	Dry chemical	✓			✓
	Copper powder	✓			✓
	Sand	✓			
	Purple K	✓			
Foam	Aqueous film foaming foam (AFFF)	✓			

Figure 22: Fire suppression technologies [22]

1) Water

It's considered an excellent cooling medium to prevent thermal propagation, but it may form toxic and combustible emissions such as HF and H_2 when it reacts with the electrolyte. There are multiple suppression technologies:

- **Water jet**: provides cooling and inhibits re-ignition by applying a stream of water directly to burning materials.
- **Water spray/sprinkler**: fine water droplets surrounded by air, which is non-conductive, that have enough momentum to penetrate the fire and cool surfaces; as well as expanding energy through vaporization to cool the air.
- **Water surfactants**: surfactants can improve the efficacy of water extinguishment.
- **Water mist**: it's a range of droplets with a size under 1000 μm, these droplets have a larger surface area to volume ratio; therefore, they have a greater heat energy absorption from hot air, but they have less penetration to fire plume than the larger droplets; thus, less cooling to the burning material.
- **Water deluge**: releasing a large volume of water into an area.
- **Water submersion**: submersing the battery in water, either by flooding the battery enclosure itself, or flooding the area around the battery. Before

removing the battery from the water, it must be confirmed that heat generation has ceased, there is no possibility for re-ignition, and proper measures have been taken to safely remove the battery and dispose of it.

2) Foam Extinguishants

The foam extinguisher shown in Figure 23 may not be the most effective approach for fire extinguishment of LiBs, due to its working principle, where it separates the air and the fire source to extinguish the fire, but LiBs' cathode is an internal source of oxygen; therefore, the foam won't be very effective.

Figure 23: Foam extinguisher [23]

3) Powder/Dry Powder Extinguishants

The powder extinguishants shown in Figure 24 is also not very effective in fire extinguishment for LiBs, where it doesn't provide cooling and re-ignition may occur. Powder extinguishants work by chemically interrupting the fire reaction and it may cause breathing problems.

Figure 24: Powder/dry extinguisher [24]

4) Compressed Gases

The same status of powder extinguishants, where compressed gases can create breathing problems, and they don't provide significant cooling for LiBs. Compressed gases work by displacing oxygen, and LiBs have an internal source of oxygen, which is the cathode.

5) Halon-Based Extinguishants

Halon works by chemically disrupting the combustion reactions; in addition, halon doesn't provide cooling and it's a global warming agent; therefore, it's not recommended to use halons agents for LiBs.

Environmental monitoring and detection technologies

On another aspect, it's crucial to monitor the batteries and detect any potential risk at the storage facility using technologies that can provide early notice of cell venting. LiBs failure may be accompanied by overt signs and symptoms such as flame, vapor, smoke, or heat; however, large batteries may be stored in containers, boxes, or crates and don't show any gas release signs.

1) Flammable Gas Release

Lithium-ion cells contain flammable gases and particulates that may cause an explosion in case of cell venting; the flammable gases include hydrogen, methane, ethane, ethyl methyl carbonate, dimethyl carbonate, methyl formate, and carbon monoxide. The flashpoint of these gases is very low and can combust in the presence of oxygen and a flame source of a temperature lower than -20 °C. The autoignition temperature, which is the temperature that a material spontaneously ignites in a normal atmosphere without any external source of ignition, ranges between 450 °C for ethylene and 585 °C for hydrogen; and the venting cell can generate temperatures as high as 1000 °C; therefore, the presence of appropriate concentrations of flammable gases and oxygen can lead to an autoignition when the cell vents.

2) Hazardous Gas Release

In addition to flammable gas releases, cell venting releases such as hydrogen fluoride, ethylene carbonate, diethyl carbonate, and diethoxy ethane, which are hazardous to humans.

3) Carbon Dioxide Release

Gas release contains substantial amounts of carbon dioxide, where concentrations between 1000 and 4000 ppm can be lethal for humans within 10 minutes of exposure time. In general, carbon dioxide tends to inhibit the combustion of flammable gases, but vent gases may readily ignite if gases or particulates above the autoignition temperature encounter sufficient oxygen.

4) Detection of Venting Gases

Venting Gases can be detected by using sensors for automated monitoring and handheld devices for inspections. Regarding standard smoke detectors, they are biased to carbonaceous soot particles, which are not generally released in early venting stages, specifically at lower SoC or SoH cells. Generally, the early gas release is about a plume of condensate formed from the electrolyte material, but the problem is the detection threshold of the smoke detectors, which may not recognize a vapor plume until it contains sufficient amounts of carbon particles. The following technologies can improve venting gas detection:

- **Very Early Smoke Detection (VESDA):** It's a continuous air drawing into the pipe network, where dust and dirt are removed from the air sample at the first stage, and then the sample goes through a smoke detection chamber and is exposed to a laser light source; the light will scatter if smoke is present. The second stage is about providing clean air to the detector to keep it free from contamination; in order to extend the detector's life and minimize alarms' disturbance. In contrast, VESDA is not able to detect flammable gases before combustion. Figure 25 shows one of the VESDA types.

Figure 25: VESDA Smoke Detector [25]

- **Carbon Dioxide (CO_2) Sensors**: the most used CO_2 detectors are Non-Dispersive Infrared (NDR) technology, which monitor and detect CO_2 based on the absorption of infrared light at a specific wavelength; which is 4.26 μm for CO_2 as the most commonly used; this wavelength isn't absorbed by any other found gases; therefore, cross-sensitivities, moisture, and humidity possibilities are reduced. CO_2 concentrations in open air spaces range between 400 to 1000 ppm; however, the American Conference of Governmental Industrial Hygienists (ACGIH) recommends adopting a CO_2 threshold limit value of 5000 ppm for 8-

hour Time Weighted Average (TWA) and a ceiling exposure limit of 30000 ppm for a 10-minute period, where 40000 ppm is considered hazard on life and health. A single cell can generate concentrations of CO_2 in excess of 20000 ppm. Figure 26 shows one of the carbon dioxide sensor types.

Figure 26: Carbon dioxide sensor [26]

- **CO Sensor**: CO is colorless, tasteless, odorless, and toxic; therefore, it's crucial to have such a high-quality sensor for detection. Figure 27 shows one of the most commonly used CO sensors, which is an electrochemical sensor that utilizes a fuel cell to generate current when CO is present, it's accurate and has low power consumption. However, the permissible exposure limit for CO is 50 ppm over an 8-hour period.

Figure 27: Carbon monoxide sensor [27]

- **Hydrogen Sensors**: the Lower Explosive Limit (LEL) of hydrogen is 40,000 ppm. If the concentration exceeds that limit in the presence of a flame source, sufficient oxygen, and thermal energy (temperature above 585 °C), hydrogen will combust. The single Li cell vent can release 16,000 ppm and above in a confined space. Due to the high thermal conductivity of hydrogen, the sensors rely on thermal conductivity technology to detect H_2; in addition, helium is used to test the functionality of hydrogen sensors. Figure 28 shows one of its types.

Figure 28: Hydrogen sensor [28]

- **Hydrocarbon sensors**: multiple technologies exist to detect hydrocarbon release resulting from cell vent or electrolyte leakage, such as pellistor, photoacoustic ionization detectors (PID), and metal oxide (MOX) devices. These technologies are available as part of a handheld gas sensor device, and they are infrequently used in automatic detection systems due to their short life and cross-sensitivity with other hydrocarbons.
- **HF Sensors**: HF gas exists as a colorless gas, fuming liquid, or dissolved in water (hydrofluoric acid). The permissible exposure limit of HF is 3 ppm for 8 hours. Concentrations more than that would irritate, burning, and damage the mucus membrane in the lungs and eyes. Figure 29 shows one of these sensors, which are available in handheld devices, not in automated monitoring systems.

Figure 29: hydrogen fluoride sensor [29]

- **Thermal-Infrared Sensors**: bolometers and thermopiles are examples of thermal imaging systems that sense variations in radiant energy. They can be used in both automated systems and handheld devices; in addition, they are highly accurate and have a fast response time. They are used for electronic devices such as batteries, where they sense the released infrared energy of 5–15-micron wavelength. The automated thermal imaging system poses some programming challenges due to the necessity of identifying specific targets to observe and ignoring other signals to avoid any confounding from other reflective surfaces. Figure 30 shows one of the infrared sensors.

Figure 30: Thermal-infrared Sensor [30]

- **Thermal Sensors-Thermocouple, Resistive Temperature Devices (RTD), Negative Temperature Coefficient (NTC)**: these sensors work well in automated monitoring systems to detect general events, but for TR events that may occur to a single cell within a battery pack, it’s difficult to rely on them to monitor a large battery array. In addition, the sensor location and the outside package may influence response characteristics.

LiBs storage system recommendations

Storage systems are crucial to contain and control any LiBs failure, whereas the system at a minimum shall be able to deal with fire, heat propagation, electrical shock hazards, electrolyte leakage, hazardous emissions, pressure, and runoff from failure events.

1) Storage System Considerations

To identify a proper storage system, it’s important to identify what is being stored, including battery chemistry, SoC, SoH, product state, storage duration, and physical properties (size, shape, volume, mass, rated energy). In addition, knowing the storage location, including environment (indoor/outdoor, temperature), building characteristics (fire suppression and venting systems, dedicated storage rooms), other existing materials (flammable, toxic), and occupant densities. the quantity of stored batteries, and how they shall be stored.

2) Storage System Failure Controls

In order to mitigate LiBs risks and hazards during handling and storage, containment shall be considered as the first strategy. The containment strategy (barriers, storage containers, packaging) shall include a time frame to allow adequate time for emergency responders to arrive; IFC has adopted a 3-hour fire rating for general storage of LiBs. For barriers, understanding the room's resistance to fire, how much time barriers will delay a failure event, and proper spacing to prevent fire from propagating shall be considered. Regarding storage containers, they should be designed for detection, fire suppression, emission management, and mitigating risks. Packaging shall demonstrate the ability to control fire, pressure, and emissions. Detection, including inspection, is critical for mitigating LiBs risks, where the technologies used are mentioned in previous sections. Fire suppression strategy can be employed by passive and active methods, where the passive method employs specialized materials as heat barriers to contain and control a battery fire and some materials can expand upon exposure to high heat to prevent fire propagation. While the active method relies on the arrival of emergency responders to the location upon the signal of the detection system. According to the hazards of emissions and runoff on personnel, environment, and facility, it's important to consider emissions management and runoff strategies in the storage system design. A lot of emissions and leakages are toxic and could cause different health problems for personnel, as well as explosions when they are pressured in a confined space or encounter other materials; therefore, containers with proper ventilation, space ventilation, catch basins, reservoirs, and sewage systems shall also be considered in the design.

Summary

The hazards and risks that may occur during the storage of LiBs, and the mitigation strategies are demonstrated in the Table 4:

Table 4: Hazards, risks, and mitigation strategies of LiBs storage

Hazards	Risks	Mitigation Strategies
Chemical Energy	Thermal	Containment by packaging, or facility structure

	Heat generation	SoC
	Flame	Storage temperature & detection sensors
Electrical Energy	High voltage above 60 VDC	Physical containment by packaging
	Electrical shock	HV identification using labels and marks
	Short circuits	Battery terminal protection
	Arc flash	SoC
Electrolyte Release	Flammability	Physical containment
	Low flashpoint	Detection sensors
	Toxic gases	Runoff controls
Propagation	TR, heat, and flame propagation	Physical containment
		SoC
		Automatic fire suppression systems
		Detection sensors
Emissions	Toxic and flammable gases	Containment
	Trapped gases in confined space	Detection sensors

To adopt fire suppression technology, it's important to determine prior to the battery type, volume, and chemical composition to choose the most adequate technology. Table 5 includes some of the fire suppression technologies:

Table 5: Fire suppression technologies

Technology	Extra information
Water	Water Jet
	Water Spray/Sprinkler
	Water Surfactants
	Water mist
	Water Deluge/submersion
Foam Extinguishants	Not effective (cathode has an external source of o_2)
Powder/dry powder Extinguishants	Not effective (breathing problems)
Compressed Gases	Not effective (breathing problems)

However, flammable gases and CO_2 releases may cause hazards during storage; therefore, detection technologies are critical to avoid any potential risks. The detection technologies are mentioned in Table 6

Table 6: Detection technologies

Technology	Information
VESDA	Proactive detection by drawing air continuously to a pipe network
CO_2 Sensors	NDR technology is used at a specific wavelength
CO Sensors	Electrochemical sensors that have fuel cells to detect CO
Hydrogen Sensors	Thermal conductivity technology is used to detect H_2
Hydrocarbon sensors	Pellistor, PIDs, and MOX devices are examples of hydrocarbon sensors. They are only used in handheld gas sensors
HF Sensors	Used in handheld devices, and it's crucial due to the danger of HF on humans
Thermal-infrared Sensors	Bolometers and thermopiles are used for detection; they are highly accurate and have a fast response time
Thermal Sensors (Thermocouple)	RTD and NTC are used in automated monitoring systems to detect general events, but not effective for TR.

It's recommended to know what is being stored (battery type, size, etc.), and where is it stored (environment conditions, building characteristics, occupant density, etc.).

International Fire Code[(N)]

Scope: ESS having capacities exceeding the values shown in Figure 31.

TECHNOLOGY	ENERGY CAPACITY[a]
Capacitor ESS	3 kWh
Flow batteries[b]	20 kWh
Lead-acid batteries, all types	70 kWh[c]
Lithium-ion batteries	20 kWh
Nickel-cadmium (Ni-Cd), nickel metal hydride (Ni-MH) and nickel zinc (Ni-Zn) batteries	70 kWh
Nonelectrochemical ESS[d]	70 kWh
Other battery technologies	10 kWh
Other electrochemical ESS technologies	3 kWh
Sodium nickel chloride batteries	70 kWh
Zinc manganese dioxide batteries ($Zn-MnO_2$)	70 kWh

Figure 31: EES capacities [31]

1) Size and Separation

N: Reference [31]

According to IFC, the maximum allowable accumulated lithium-ion storage systems in one place is 600 kWh. The systems shall be segregated into groups, each of which shall not exceed 50 kWh and shall be separated by a minimum of 914 mm from the other groups and from the wall.

2) Elevation

Lithium-ion storage systems shall not be located in a floor that exceeds a height of 22860 mm above the lowest level of fire department vehicle access. In addition, the floor shall not be located below the lowest level of exit discharge.

3) Fire Suppression Systems

For the systems that don't exceed 50 kWh, the automatic sprinkler system shall be designed with a minimum of 1.14 L/min based over the area of the room or 232 m^2, whichever is smaller.

4) Maximum Enclosure Size

Outdoor walk-in units which store EES, shall not exceed 16154 mm x 2438 mm x 2896 mm.

5) Egress Separation

Energy storage systems that are located outdoors shall be separated by at least 3048 mm far away from any means of egress.

6) Ventilation based on Lower Flammable Limit (LFL)

This system limits the maximum concentration of flammable gases to 25% of the LFL of the total storage volume.

7) Ventilation based on exhaust rate

Mechanical exhaust ventilation shall be provided at a rate not less than 5.1 L/sec/m^2 of floor area of the storage room. The ventilation shall remain on until the flammable gas detected is less than 25% of the LFL.

8) Gas Detection System

The system should be designed to activate the ventilation system when the level of flammable gases in the room exceeds 25% of the LFL. The gas detection system shall be provided with a minimum of 2 hours of standby power.

Vermont Agency of Natural Resources[O]

Regarding EV LiBs that have high voltages ranging from 100 to 600 volts, the

O: Reference [32 & 33]

following management practices ensure the safety of storage facility, employees, and environment:

1- Safety training for employees related to disassembly, handling, and removal of battery.
2- Battery terminals isolation.
3- Check the battery status (damaged, defective, or normal).
4- Storage facilities shall be climate controlled and well ventilated.
5- Storage area shall be separated from other combustible materials and occupied spaces.
6- DDR batteries shall be stored in a quarantine area different from non-DDR batteries.
7- Storage facilities shall be equipped with adequate fire detection and suppression systems.
8- Regular thermal and visual inspections shall be applied.
9- Never stockpile spent batteries.
10- Damaged or swollen batteries shall be stored in a closed watertight storage container (5-gallon plastic pin such as polyethylene) with fire containment materials such as sand and vermiculite.
11- Safety equipment shall always be available (goggles, gloves, aprons).
12- Class D fire extinguishers are highly recommended for extra safety with LiBs.
13- Always separate batteries by type (status).
14- Store batteries upright on an impervious surface.

RIVIAN[(P)]

Rivian Automotive has adopted certain guidelines for storing and handling High Voltage (HV) batteries:

- PPE shall be worn before handling HV batteries.
- Damaged batteries shall not be charged.
- Standalone HV batteries shall not be stored at temperatures below -40°C and over 60°C.
- Never charge or discharge standalone HV batteries at temperatures below -20°C and above 45°C.
- HV batteries shall be stored at a SoC between 30% and 50%, where the recommended transportation SoC is 30%.
- HV battery packs shall not be stacked over each other without crates, where a maximum of 2 packs could be stacked.

P: Reference [34]

- HV battery packs shall be stored away from other flammable materials, structures, and packs; at least 15 meters away.
- Ventilation is necessary for HV packs.

The Jordanian Ministry of Environment(R)

On the national level, MoEnv is responsible for managing and regulating hazardous waste such as lithium-ion batteries. According to the instructions for 2023, the following must be followed regarding storage and facility requirements:

- Designated space to discharge the electrical energy of stored batteries.
- Storage shall be in closed areas.
- Storage facility surface shall be non-conductive and fire resistant.
- Storage with fire distinguisher, ventilation, and emergency.
- The facility shall be dry, well-ventilated, and have a maximum ambient temperature of 35 °C.
- Spent batteries shall not be directed to heat, flammable, water, and humidity sources.
- Spent batteries shall not be collected directly on the surface.
- The rubber insulator shall be placed under the batteries.
- Placing insulation materials containing sand or silica such as vermiculite between the batteries.
- Batteries' height shall not exceed 2 meters.
- Using rubber gloves for cracked batteries.

R: Reference [16]

2^{nd} Life of LiBs

2^{nd} Life of LiBs

This section covers different inclusive aspects regarding the 2^{nd} Life of LiBs from inspecting and testing several parameters of LiBs to reusing and repurposing them in various applications. Through that cycle, battery assessment & evaluation, and assessing the technical viability of the 2^{nd}-life application are crucial as shown in Figure 32.

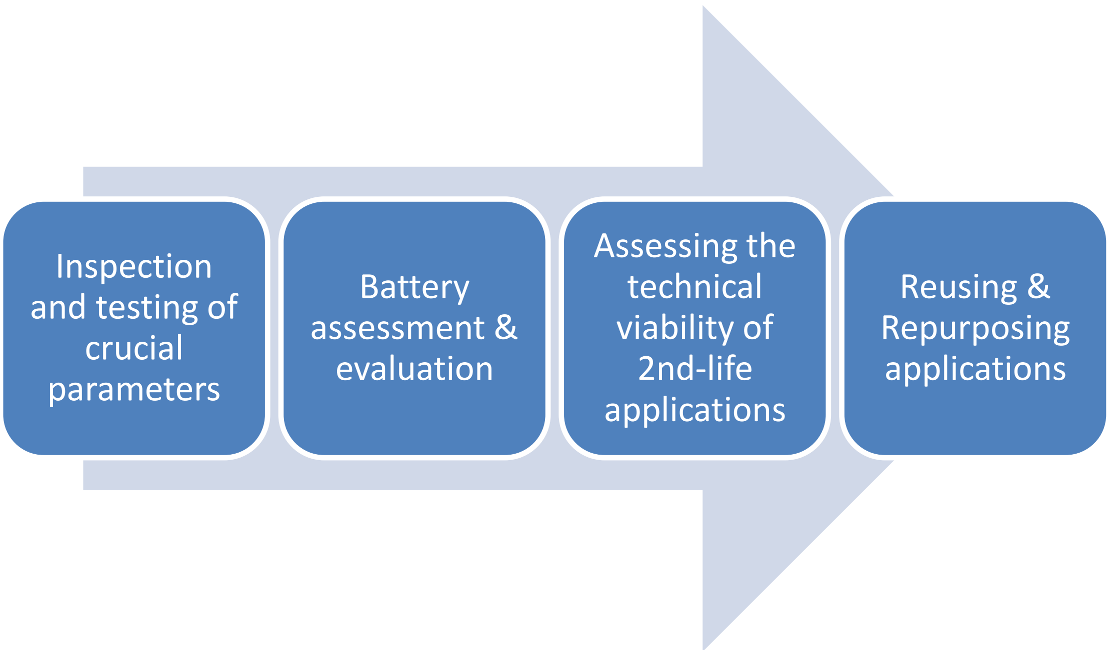


Figure 32: LiBs 2^{nd}-life cycle

9.1 Framework for battery assessment[Q]

A clear framework for battery assessment, shown in Figure 33. During and after its 1st life could aid in the decision-making process, where each 2^{nd}-life application has its market size, revenue potential, size requirements, and duty cycle; the battery state at EoL shall match these 2^{nd}-application factors. The battery assessment comprises 3 stages: battery state evaluation (degradation conditions such as energy, power, and external wear), technical viability of different solutions (requirements, and economic evaluation.

Q: Reference [35]

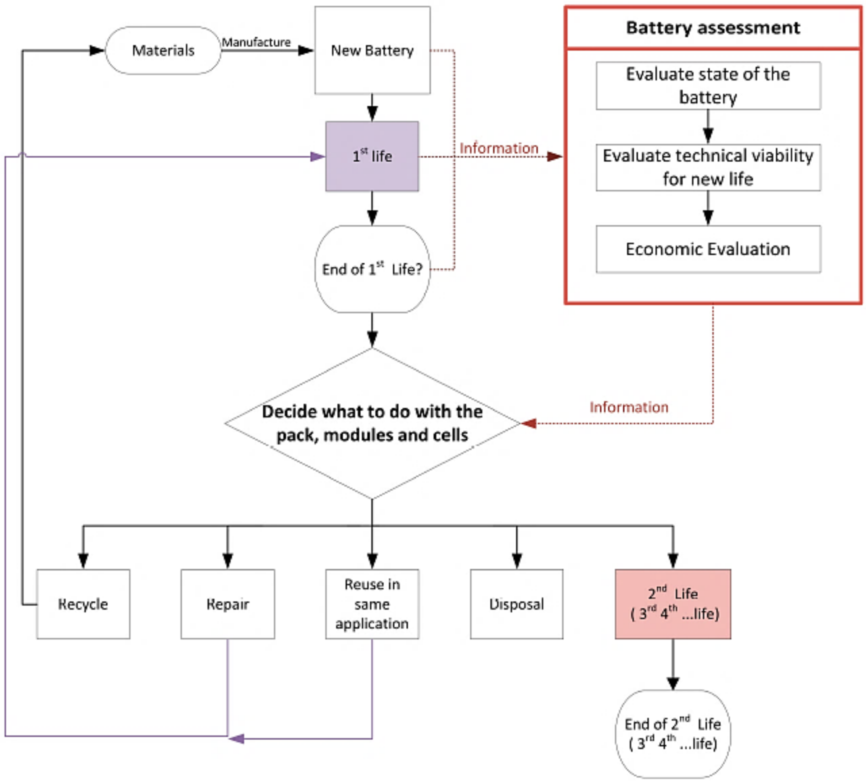


Figure 33: Battery assessment framework [35]

9.1.1 Battery state evaluation

This stage can begin before the battery reaches its EoL, where the first step is to collect important information from cell manufacturer and pack manufacturer/assembler including cell format, chemistry, operating voltage and current, number of cells, number of modules, design, capacity, and expected number of cycles. The second step is to obtain data that helps in calculating the Remaining Useful Life (RUL) in the possible application; it includes two categories:

1) Continual estimation of battery health

There are main factors that aid in calculating battery health during the first life of the battery such as distance driven, battery age, ambient temperature, Depth of Discharge (DoD), and battery charging and discharging rates, or the direct calculations of the SoH depending on the algorithms.

2) Testing the battery pack

At the end of the 2^{nd}life of the battery, internal resistance and capacity tests are being performed and may take 2 days to assess the battery; the tests may be carried out at the pack level, module level, or cell level.

Technical viability of different solutions

The aim of this stage is to meet the different requirements of the 2nd-life applications with the adequate battery configurations as shown in Figure 34. The most discussed 2nd-life applications are peak shifting, grid services, renewables integration, support EV charging stations, and time-shifting (energy arbitrage).

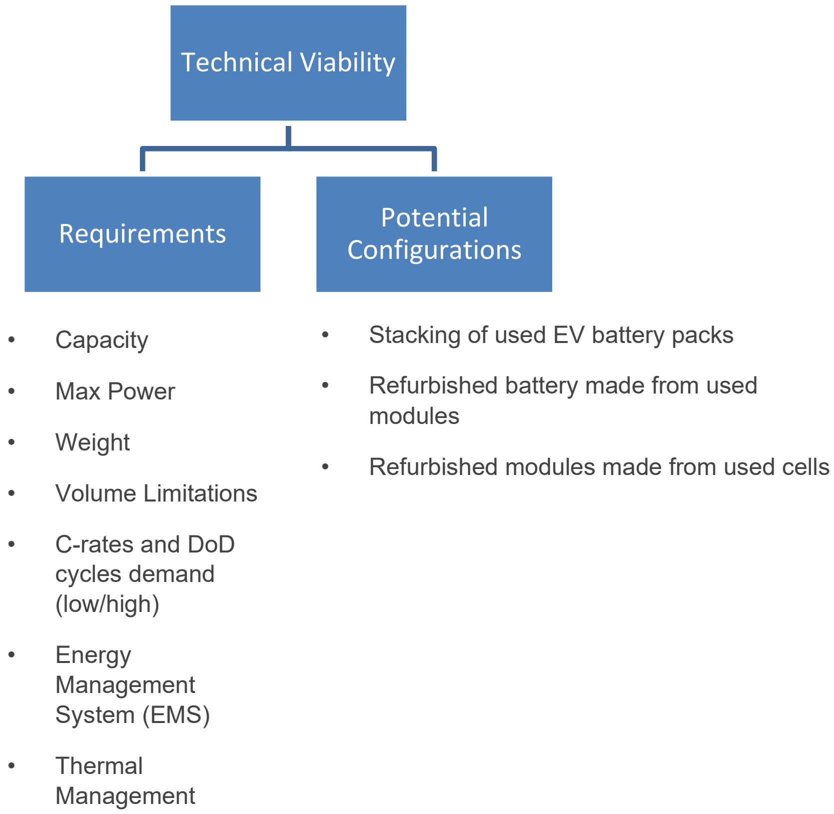


Figure 34: Technical viability-requirements & configurations

1) Requirements

Each application requires different battery configurations and characteristics; therefore, the following requirements shall be analyzed.

- **Capacity**: There are key factors that limit the maximum energy storage capacity that each application needs such as maximum investment, energy demand, regulations, consumer needs, economics (feasibility) considering the future degradation.
- **Max Power**: Each application requires certain power and can hold certain max power; therefore, the maximum C-rate the battery can deliver shall be

compatible with the application; however, lithium batteries' C-rate typically varies from 0.5C to 5C.

Note: C-rate is the ratio between the device's maximum current draw and the battery's rated capacity in ampere-hour (Ah).

Weight: As discussed before, each application requires a certain capacity; therefore, it's sometimes required to add extra cells to reach the desired capacity, which means extra weight. Some applications such as stationary may not be affected by the weight and some like the mobility applications may be affected; more weight means more power consumption and less range for vehicles.

- **Volume Limitations**: Some applications are limited by a specific design and volume of the battery, such as mobility applications and small electronic devices. For stationary applications, volume isn't considered as a primary limitation.
- **EMS**: EMS is responsible for managing and controlling the energy flow in the installation of different components; it depends on the adopted algorithm, where some algorithms are responsible for optimizing the revenue of the system and some for improving the life of the system's elements. EMS is different from Battery Management System (BMS); BMS is responsible for ensuring the safe operation of the battery. Therefore, a new EMS has to be implemented depending on the new application.
- **Thermal management**: It's important to manage the temperature of the batteries using different thermal systems that comply with ambient temperature and working conditions such as liquid refrigeration or forced air, where the battery's degradation will be reduced. Moreover, it's important to consider the economics side; reusing the old thermal system, purchasing a new one, or not using any thermal system (performance reduction shall be considered).

2) Potential Configuration

Table 7 shows some potential configurations for LiBs.

Table 7: Technical viability configurations

Configurations	Features	Challenges
Stacking Battery Packs	• Modules distribution doesn't affect the performance • Temperature can be controlled by the internal heating and cooling of the packs • No need for disassembly or redesign steps; therefore, less cost and complexity. • Waste reduction and enhance the circular economy • Less risk of failure, due to less manipulation with the battery components	• No Original Equipment Manufacturer (OEM) warranty • Performance is affected by the worst cell/module • Additional costs for shape adjustments and thermal management system modifications • Complexity of repair and periodic maintenance for the internal components • Unexpected current flows between the battery packs when they are connected in parallel • Additional cost for DC/DC power converters when connecting packs in parallel • BMS modification if it's not able to communicate with the power converters
Refurbished battery made from used modules	• Better performance, due to selecting the best modules to form a pack • More flexibility in dimensions • New BMS is designed for the new application and can communicate with power converters • Simpler to be repaired	• Module performance is affected by the worst cell • Modification of the thermal management system • Complexity of repairing and period maintenance for source components • Packs shall be designed in a modular way • Additional costs for replacing discarded components from the pack • Additional costs for disassembly, exterior assessment, performance assessment, and new battery pack integration
Refurbished modules made from used cells	• Better performance, only good cells will be used • More flexible design (size and shape); therefore, could be used in more applications	• Higher cost for disassembling to cell level • Difficult to disassemble the pack without damaging the cells • More waste generation, a lot of components may not be used in the new pack • High cost of re-assembly, new BMS, internal components such as busbars, outer case, and sensors • Some applications require certain shape of cells (prismatic or cylindrical)

Inspection and performance testing

The effect of aging and unknown stress/abuse

Degradation processes have two effects on the battery, which are capacity fading and increased internal resistance; both effects have consequences on energy, power, and efficiency. In addition, degradation causes ageing, which has two types: [36]

- Irreversible: permanent ageing.
- Reversible: pre-ageing conditions generate and vanish; moreover, preventing irreversible ageing is possible by recovering initial conditions of the battery, such as using longer resting time at appropriate temperatures. The pre-ageing conditions happen due to low temperatures or high current rates.

Ageing occurs at the cell level, where Lithium Iron Phosphate (LFP) cells of LiBs degrade slowly, even up to 50% SoH but NMC cells deteriorate rapidly after 70%-80% SoH. The time at which degradation or deterioration occurs is referred to as the Knee, which means that the battery reached its end of life. Other purposes include structural damage of the cathode, which may accelerate aging. The location of modules recovered from an EV battery pack plays a crucial role in their SoH; this may be obvious in accelerated aging.[37].

1) Calendar aging and cycling at the normal current

Calendar aging may reduce the battery's stability, where structural changes take place and affect the degradation process. With a decrease in SoH, higher inhomogeneity of lithium in the anode and a reduction of the graphitization of the anode occur; this causes anode fragmentation, resistance increase and joule heating [37].

2) Loss of lithium inventory during aging

When the flux of lithium ions to the anode is insufficient during charging to match the charging current, due to low solvent viscosity, low ion diffusion coefficients at low temperatures that require low charging C-rates, the lithium ions will be reduced to the metal, this is called lithium metal plating [37].

Gateway testing of 2nd life battery(S)

1) State of Health, State of Safety and Remaining Useful Life

S: Reference [37]

To determine the battery's destination (reuse, re-purposing, remanufacturing), gateway testing is essential to inspect any battery, module, or cell damage to ensure that it's safe for a 2nd life application; in addition, to analyzing the data stored in BMS which is considered crucial in determining RUL of the battery. The gateway assessment, as shown in Figure 35, may include, but is not limited to the following:

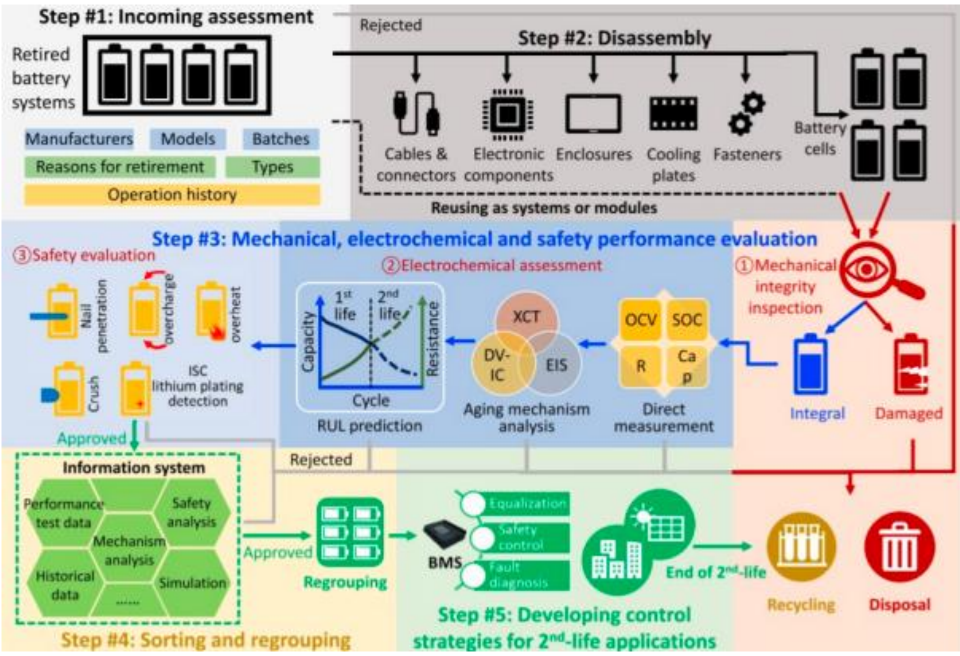
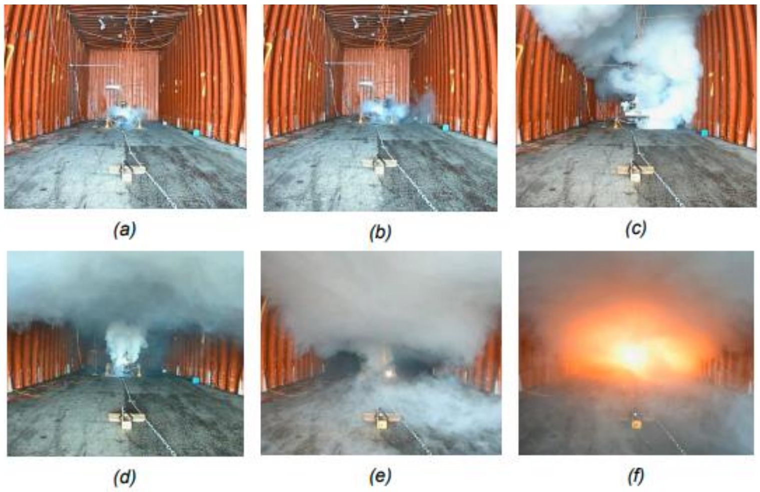


Figure 35: UK gateway assessment [37]

- Assess the battery system or modules; if rejected, take it to disposal or recycling.
- If the battery system or modules are accepted, there are 2 options:
  - Disassembly into cables, electronic components, cooling plates, and cell level.
  - Take it as a whole system or modules.
- Mechanical, electrochemical, and safety evaluations
  - Mechanical integrity inspection, whether damaged or integral.
  - If damaged, take it for recycling or disposal.
  - If integral, apply direct measurements (SoC, OCV, R, Capacity), aging mechanisms analysis (XCT, Electrochemical Impedance Spectroscopy (EIS), DVIC), RUL prediction (Cycle vs Resistance diagram), and safety evaluation (nail penetration as shown in Figure 36, overcharge, overheat, crush, Internal Short Circuit (ISC), lithium plate detection). If the results are rejected, take them to disposal or recycling.



A single 1.67kWh EV module was penetrated by a nail at 40% SoC. (a) Nail penetration, (b) less than one second later pouch cell(s) burst ejecting black cathode particles, (c) 17 s after penetration, (d) 56 s and (e) 79 s after penetration and evolution of second, heavier than air vapour, and (f) 87 s after penetration and module self-ignites, consuming vapour cloud and drawing it back. The experiment was conducted in a standard 76.8 m^3 sea container.

Figure 36: Penetration test [37]

- Build an information system that includes historical data, safety analysis, mechanism analysis, simulation, performance test data of the cells; if approved, regroup the cells; else take it to disposal or recycling.
- Add the BMS that includes equalization, safety control, and fault analysis.
- The new battery system is ready for its 2^{nd} life application.

2) UKESL Approach to Gateway Testing

UKESL produced a workflow to train factory workers on a series of pass/fail gateway tests using the Nissan Leaf EV Battery as a working model. At the pack level, the following tests and inspections shall be applied to assess the state of the battery pack:

- Visual inspection for any damage or corrosion.
- Pressure test.
- BMS test.
- The characterization test focuses on internal resistance and SoH.
- Power test to check the ability to charge and discharge.

If the pack fails any test, it should be opened and examined to see if there is any possibility of repair before re-testing it again. After re-testing, if the pack still fails in any test, we shall look at the module level and apply EIS, which is a technique that measures internal resistance and charge transfer resistance, to assess the modules. Failed modules of EIS tests within 3 minutes shall be sent to materials recovery, and passed modules can be used in further applications.

3) EV Recycling Approach to Gateway Testing

EVRC is a recycling company that takes EoFL EV packs and uses them in remanufacturing LiBESS for variety of applications such as constructions and marine, but second life domestic LIBESS are excluded. EVRC applies the following procedure:

- Creation of a safe work system.
- Disassembly of EV pack.
- Visual inspection for the modules.
- Current/voltage tests.
- Modules internal resistance measurements using DC methodologies.
- SoH determination using power and capacitance measurement.
- Insulation and isolation for the modules.
- Pressure tests, if necessary.
- BMS replacement by an appropriate system; retaining or revising original BMS could be dangerous.

4) UL 1974 Standard

It's a manufacturing process standard, where the factory of manufacturing or repurposing shall be certified under this standard in U.S and Canada, not the batteries themselves. The assessment of End-of-First Life (EoFL) pack shall include the following:

- Visual inspection.
- Information on the pack such as withdrawal reason, length, and nature of storage and handling history.
- SoH using BMS data
    - Average, extreme, and out of specification values of current, voltage, and temperature.
    - Total times or number of instances at extremes or out of specification.
    - Total number of charges and discharges.
    - Total times or numbers under charge or under discharge.
    - Total number or type of error messages.

After assessing BMS data, if there are no concerns and reasons to take the pack for material recovery, the next stage of assessment shall be performing battery pack tests, including:

- OCV

- HV isolation check
- Capacity
- Internal resistance
- Check for BMS controls and protection components (if intended to be re-used)
- Discharge/charge cycle test whilst monitoring temperature, voltage, and current
- Self-discharge

If the tests are passed, disassembly to the smallest unit required for repurposing shall be applied, which is typically module level, and modules will be subjected to the same tests; however, it's recommended to place modules in the same grade and use them in the same repurposed battery to achieve balance. The cells, which are assembled into the repurposed battery, should be of the same model and from the same original manufacturer.

EV battery's functional parameters

1) Energy

It's the first measure to compare the performance of different batteries, it's calculated using the equation *(1(1)***Error! Reference source not found.**.

Energy $$E\ (Wh) = Voltage_{average}(V) * C_{discharge}(Ah) \quad (1)$$

$V_{average}$: average voltage during discharging, it's obtained by integrating the discharge voltage overtime and dividing by discharging duration.

$C_{discharge}$: Discharging capacity.

Energy density may also be calculated as whether gravimetric (W/kg) or volumetric (Wh/L) energy density, excluding the terminals. Energy is used to define the battery size and the driving range [36].

2) Capacity

The total number of ampere-hours can be withdrawn from a fully charged battery under certain conditions. There are multiple ways to assess the capacity: constant current (CC) cycling, constant current-constant voltage (CC-CV), and constant power methods. In the CC cycling method, the temperature and the current, between the voltage limits, have to be constant during the charging/discharging cycles, where the testing temperature at each time may vary to simulate the real-life operation; the temperature management system during the EV operations is most probably limited to around 30-35 °C to have the optimal performance and lifetime, but during parking, the thermal management system is inactive. The battery may be exposed to a wider temperature range, which affects its lifetime and self-discharge. However, the charging and discharging C-rates during the assessment shall match the C-rates of the intended application to have realistic data [35]. The available capacity depends on four factors: operational conditions, environmental conditions, age, and SoH. The capacity at a certain cycle (m) could be calculated using equation (2)**Error! Reference source not found.**:

Capacity

$$Q_m = \frac{SoH * Q_n}{100\%} \tag{2}$$

Where Q_n is the nominal capacity of the battery and Q_m is the capacity of the battery at cycle number m [38]. High-Capacity EV battery testers and Charge-Discharge-Cyclers specialize in testing and evaluating the battery packs. These equipment simulate the real-life driving conditions and perform charge-discharge cycles, capacity tests, aging tests, thermal tests, and safety tests.

3) Power and Internal Resistance

This test determines dynamic power capability at different SoC in ranges between 90% and 20%, different discharging currents depending on the intended application's C-rate, and different temperatures. The maximum deliverable power is defined as the power at which the drawn current depresses the battery's open circuit voltage to 2/3 of its initial value. **Error! Reference source not found.** (3) shows the general equation of power [36].

Peak power

$$P_{peak} = V_{ocv} X\, I_{peak} \tag{3}$$

4) Storage and Charge Retention

This parameter focuses on self-discharge when the battery system isn't in use, and some of the ageing factors that affect this parameter are temperature, SoC level when it's not in use, and end of charge voltage, where the higher these factors, the higher the degradation of the battery. Therefore, it's recommended to perform the test at the most challenging SoC and leave the battery at OCV. Two scenarios would be related to this test, the first one when the battery system isn't in use during parking and the auxiliary systems consume energy; the second one when the battery system is shipped and the terminals are disconnected, meaning that no energy is consumed. However, ISO, IEC, and SAE aren't addressing calendar life ageing during the full duration of the battery life; they only address the ageing during the storage period (not in use period) [36].

5) Energy Efficiency

It's the ratio between net energy delivered by a battery during a discharge test to the total energy required to restore the initial SoC by a standard charge [36]. Battery energy efficiency can be calculated either as round-trip, which implies charging and discharging over the same SoC range, or as one-way [35]; as shown in equations (4), (5), and (6) below:

Cyclic Efficiency

$$\eta_{cycle\ (round\ trip)} = \eta_{ch\ (one-way)} * \eta_{dis\ (one-way)} = \frac{E_{\ discharged}}{E_{charged}} X100\% = \frac{P_{discharged}}{P_{charged}} X100\% \text{ [39]} \quad (4)$$

Energy Integral

$$E = \int_0^t U(t)\, I(t)\, dt \text{ [39]} \quad (5)$$

Cyclic Efficiency Integral

$$\eta_{cycle} = \frac{\int_0^{t_d} U_d\, I_d\, dt}{\int_0^{t_c} U_c\, I_c\, dt} \text{ [36]} \quad (6)$$

Where P (voltage * current) could be determined by experimental measurements using multimeter across the terminals [36], U_d, I_d, U_c, I_c are discharge and charge voltage and current, respectively, and t_d and t_c are discharge and charge time [40]. However, one-way efficiencies, charging or discharging efficiency, may be assumed to be equal and defined as the square root of round-trip efficiency. In practical life, one-way efficiency depends on operating and ambient conditions and can be calculated by three methods: [40]

- Heat loss measurement.

- OCV characteristics vs. SoC.
- Voltage/current measurements.

OCV characteristics can be determined by subjecting the batteries to a full CC-CV cycle at low C-rates and then take the average of the measured charging and discharging Closed Circuit Voltage (CCV). Therefore, one-way charging/discharging energy efficiency can be defined as shown in equations *(*7) and *(*8) [41]:

Charging Efficiency

$$\eta_{Ch} = \frac{\int_0^{t_c} U_{OCV}(t)\, I_c(t)\, dt}{E_{ch}} = \frac{E_{batt}}{E_{ch}} \qquad (7)$$

Discharging Efficiency

$$\eta_{dis} = \frac{E_{dis}}{\int_0^{t_{dis}} U_{OCV}(t)\, I_{dis}(t)\, dt} = \frac{E_{dis}}{E_{batt}} \qquad (8)$$

Figure 37 shows the U_{OCV} is determined from the OCV characteristics as explained above, E_{batt} is a theoretical value that can't be determined from measurements.

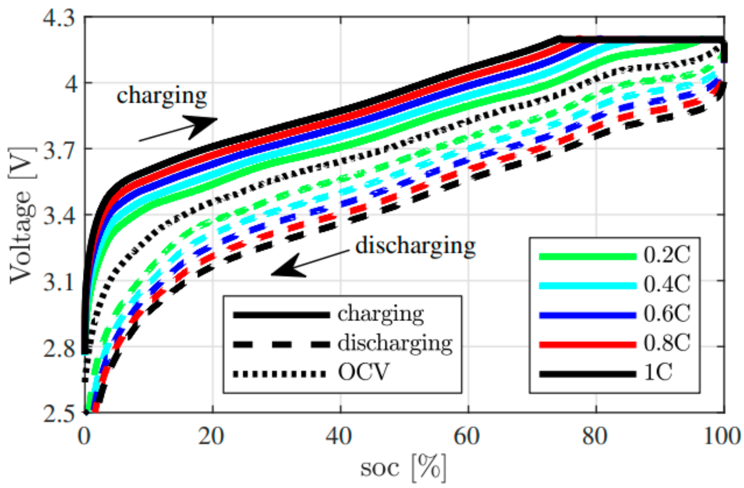


Figure 37: Voltage and SoC characteristics during charging and discharging [41]

Figure 38 represents OCV characteristics and voltages during CC-CV cycles for a Litihum Nickel Manganese Cobalt (NMC) cell. During charging, there is no voltage drop, which implies that internal resistance doesn't consume any current/electrons (irreversible process/-ve current), it increases the voltage; therefore, higher C-rates give higher voltage even more than the OCV. The internal resistance varies during charging and discharging and depends on the storage temperature and the overall use of the battery.

C-rate \ En. eff.	η^{ch}	η^{dis}	$\eta^{ch} \cdot \eta^{dis}$	η^{cycle}	$\Delta\eta$
0.2C	0.98	0.98	0.95	0.95	0.13%
0.4C	0.97	0.96	0.93	0.93	0.11%
0.6C	0.96	0.95	0.91	0.91	0.05%
0.8C	0.95	0.94	0.89	0.89	0.05%
1.0C	0.94	0.92	0.87	0.87	0.08%

Figure 38: Efficiencies and C-rate [41]

Lower C-rate during charging implies lower charging current and voltage; therefore, E_{ch} is lower, and the charging efficiency is higher. During discharge, a lower C-rate means lower discharging current and a higher voltage (lower voltage drop caused by the IR); thus, higher E_{dis} and higher discharging efficiency.

6) SoC

SoC is the ratio between real remaining capacity and the maximum capacity, it's also essential for safe vehicular operation. There are a lot of methods to estimate the SoC such as, ampere-hour integral method, model-based estimation method, OCV method, coulomb counting method, and the data driven method.

- Ampere-Hour Integral Method/Coulomb Counting Method

Equation *(9)* shows the parameters of estimating SoC, which are the initial SoC, coulomb efficiency, current measurement errors of battery current from disturbances such as temperature and noise battery load current, and the maximum available capacity after the aging and operating conditions (nominal capacity) to be known; thus, it's less reliable to be adopted [39].

SoC Estimation (coulomb method)

$$z_k = z_0 - \frac{\int_{t_0}^{t_k} \eta \, I_L(t) dt}{Q} \tag{9}$$

Z denotes SoC, η denotes coulomb efficiency, I_L denotes load current of battery, and Q denotes maximum available capacity [38].

- Model-Based Estimation Method

There are three models to estimate or infer the SoC, which are Electrochemical

Model (EM), Equivalent Circuit Model (ECM), and EIM. Moreover, there are a lot of nonlinear state algorithms to estimate the internal state of batteries such as Kalman filter, Luenberger observer, and proportion integration (PI) observer.

- OCV Method

This method is straight and accurate but requires a lot of rest time to attain equilibrium between stages; the rest time is affected by the nearby surroundings [39]. Figure 39 shows the procedure of estimating the SoC.

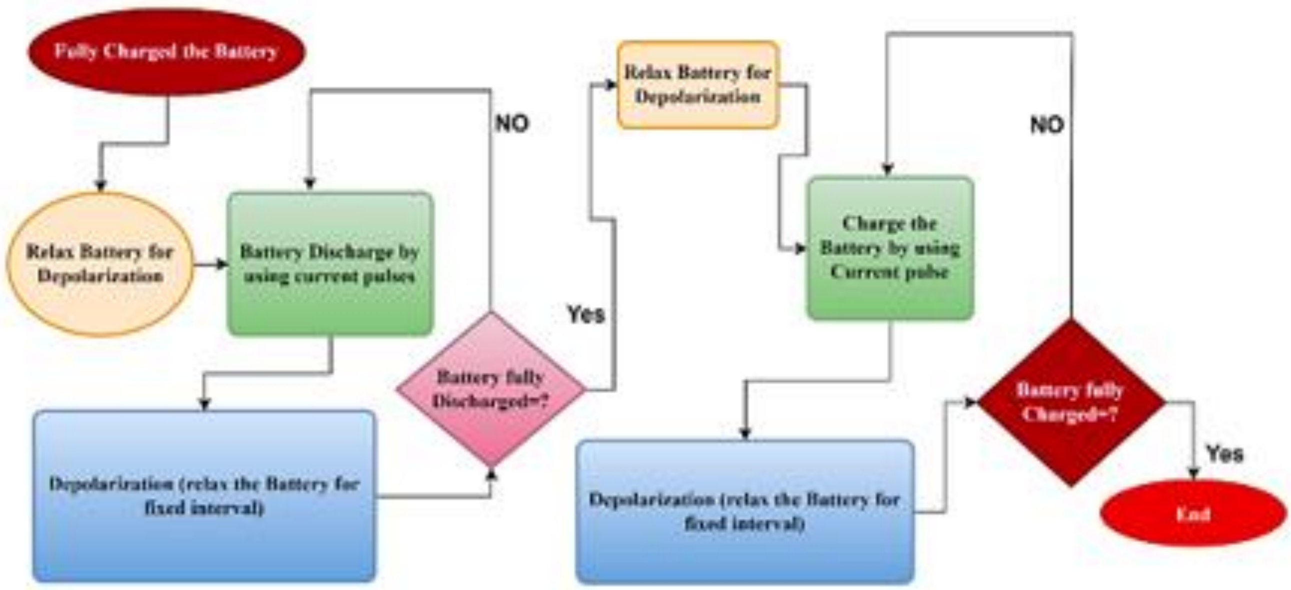


Figure 39: SoC estimation procedure [42]

OCV-SoC characterization data could be obtained in a laboratory using a scientific grade **battery cycler (8-cell battery cycler made by Arbin) and an environmental chamber made by Cincinnati Subzero);** and different models, such as linear, non-linear, hybrid, and tabular models. The straight-line form is the simplest form of the linear OCV model but not accurate at very low (0-30%) and very high (80-100%) rates, due to its dependency only on two parameters. To collect the data of OCV characterization, the following procedure should be followed [43]:

a) Use a high precision battery cycler that has low measurement noise and an environmental chamber to collect data
b) Fully charge at room temperature, either by using CC, or CV method. When the charging current falls below C/N (i_c < C/N), then terminate the CV charging.
c) Put the battery in a fixed environment/temperature, so the OCV characterization could be performed precisely.

d) Discharge the battery slowly, i_d=C/N rate, until the terminal voltage reaches v=OCV_{min}. The total discharge time is denoted as T_d.

e) Charge back the battery slowly, i_c=C/N rate, until the terminal voltage reaches v=OCV_{max}. The total charge time is denoted as T_c.

Note: C/N is the nominal capacity divided by 1/the number accompanying the C-rate, which is "N".

Note: K_d is the number of samples collected during discharging, K_d= N*sampling time. K_d may vary depending on the available capacity, regardless of the labeled capacity.

Note: The discharge/charge capacity is defined as $Q_{d/c}=i_{d/c}*T_{d/c}$, where T is the discharging/charging time and defined as $T_d = \Delta * k_d$, $T_c = \Delta * (k_c - k_d)$, and Δ is the sample time, and 60 seconds would be sufficient to model the OCV.

f) The measured voltage across the terminals and the current through the battery is denoted as shown in equations *(*10) and *(11)*:

Voltage across Terminals

$$z_v(k) = v(k) + n_v(k) \tag{10}$$

$$z_i(k) = i(k) + n_i(k) \tag{11}$$

Where $v(k)$ and $i(k)$ are the true values k is the time, n_v and n_i are voltage and current measurement noise that is assumed to be zero-mean white with standard deviation (s.d) σ_v and σ_i, respectively. After substituting, the measured voltage across terminals can be calculated using equation (*12*):

Final Equation of Voltage Across Terminals

$$z_v(k) = V_o(s(k)) + z_i(k) * R_{eff} + n(k) \tag{12}$$

Note: The zero-mean white noise is a random signal characterized by having a mean value of zero and uncorrelated across time, where the noise is the values that fluctuate randomly and rapidly around the mean, and zero-mean denotes as the average signal over time is zero.

The effective resistance $R_{eff} = R_{int} + R_h$, R_h is the hysteresis resistance, $n(k)$ is the noise term, and $V_o(s(k))$ denotes OCV. The goal is to estimate the parameters that define OCV $V_o(s(k))$.

Note: $n(k)=n_v(k)-n_i(k)*R_{int}$

g) Define the SoC, denoted as S, at a given time K

- Using Coulomb counting method, equation *(*13):

SoC using Coulomb Counting Method

$$s(k+1) = s(k) + \frac{\Delta_k * i(k)}{3600Q} \qquad (13)$$

Where $\Delta_k = \Delta$ is the time difference between two measurements in seconds, i(k) is the current in amperes, and Q is the battery capacity in Ah,

$$Q = \begin{cases} Q_d, & i(k) \leq 0 \\ Q_c, & i(k) > 0 \end{cases}$$

but the approach's cons are initial SoC error, current measurement errors, current integration error, timing oscillator error, and uncertainty in Q.

LiB safety systems(S)

There are four key systems in LiBs that should be safe before using the battery in their 2nd life applications.

1) Solid Electrolyte Interface (SEI)

SEI is the first safety system in the cell; it is formed during the first charge. SEI prevents thermal runaway from occurring, and it prevents the reduction of the organic carbonates employed in the electrolyte when the LiB is fully charged.

2) Physical Safety System

The physical and chemical safety systems are designed to cut either internal ionic circuits (movement of lithium-ions) or external electronic circuits (movement of electrons). Safety vents, thermal fuses such as temperature cut-off circuitry, positive temperature coefficient (PTC) thermistors, and shut-down separators are examples of physical safety systems inside the cell.

3) **Chemical Additives**

They are crucial to facilitating SEI formation, improving SEI structure, enhancing

S: Reference [37]

the thermal stability of LiPF, and improving the conductivity, viscosity, and wettability of the solvent. Chemical additives form 5% of the solvent; they also reduce solvent flammability, provide overcharge protection, and terminate battery operation during abuse conditions.

4) BMS

BMS is considered a safety system at the battery level, it prevents overcharge and discharge, gives high temperature alarms, and prevents cell imbalance (cells with lower SoH). However, selecting cells or modules with similar SoH is critical in reusing, remanufacturing, and repurposing batteries. BMS has to be modified or replaced according to the application, if the modules or battery is intended to be repurposed. For LiBs, the voltage measurement of each cell is crucial to have a reliable operation, where voltage failure may cause overcharge or over-discharge in certain cells; but the disassembly to cell level after the EoFL is too expensive and in some cases not applicable, hence module level would be enough.

Installation and maintenance[S]

After determining the destination of the LiB after its EoFL, it's crucial to take into consideration the safe installation. For Domestic Lithium-ion Battery Energy Storage System (DLIBESS), it's important to consider a safe unconfined location with good ventilation and detection systems; where roof voids provide an effective means of spreading fire to rooms beneath and adjacent houses; DLIBESS in a loft or cupboard on an upper floor could provide unknown hazard to the fire and rescue services; and DLIBESS under stairs could be an obstacle for emergency egress. Warning signage that indicates the danger of the installed EES such as HV signage (above 60 V) and a mark of "A battery pack is installed". In addition, regular maintenance or Building Management System is a good practice to ensure the safe operation of DLIBESS.

Repurposing[T]

The repurposing process of LiBs requires four steps, which are assessing the SoH, evaluating the battery's viability for a 2nd-life, deciding on a configuration, and reassembling the battery pack in the new configuration. Due to the current EV battery's design, which doesn't support the repurposing, it's crucial to disassemble the battery to apply the required performance tests and procedures that ensure a safe and viable

S: Reference [37]

T: Reference [44]

2^{nd}-life battery.

Assessing the SoH

To ensure that the EV battery is viable for repurposing, assessing battery's SoH, and charging and discharging rates is important, but due to the difficulty of accessing repurposing companies to this information from the BMS, it could be done by a cycling process, which includes testing the capacity and internal resistance. The cycling process takes up to 2 days and requires trained technicians to monitor a full charge and discharge of the battery. However, each battery manufacturer has adopted certain guidelines and procedures for discharging the battery safely. In order to discharge the battery, the SoH, capacity, SoC, allowed voltage, and current range must be known to discharge the battery.

Evaluating battery viability for a 2^{nd}-life

There are key characteristics, such as battery capacity, max power, weight, volume, energy management system, thermal management, and possible battery configuration, that play crucial roles in determining a battery's viability for repurposing. However, a higher battery capacity requires more cells to be installed, leading to higher weight; the importance of weight depends on the 2^{nd} life application; the extra weight wouldn't be an obstacle for stationary products.

Deciding on a configuration

1) Battery pack stacking

It's about connecting battery packs in parallel to create the final 2^{nd}-life battery, packs shall have the same characteristics, where the performance of the 2^{nd}-life battery will be affected by the worst-performing modules and cells; in addition, a power converter may be necessary to manage unexpected current flows between batteries. This configuration suits grid services that require a large battery capacity.

2) Refurbishing Battery Modules

First of all, the battery pack is disassembled into modules, and then the modules of the same characteristics are assembled into a new battery pack with a modification on the thermal management system. In addition, repairing the modules is simpler than the whole battery pack.

3) **Refurbishing Battery Cells**

Disassembling to the cell level would give additional advantages of selecting the best and most effective cells to rebuild the modules and battery system; in addition, regarding the size, it gives a lot of flexibility on the configuration, which makes it useful for small electronic devices.

Reassembling the battery pack in the new configuration

The 2nd application of used batteries may require more than one battery pack; therefore, using different batteries in ages, state of degradation, design, and models is challenging, where different batteries should work in sequence, so older batteries don't slow down the entire system; regarding to that, software and controller monitors for all batteries' variables during charging and discharging cycles shall be connected with the system to ensure efficient energy yields.

Reusing(U)

In this scenario, the battery is reused directly in the same equipment/device which it was extracted from, unless the battery can't be reused, so it has to be dismantled into cells/modules, and the cells/modules could be used in different applications.

Safety requirements

Safety standards such as OHSAS 18001 or ISO 45001 shall be implemented at the workplace and SOPs for LiBs shall be defined. Some general requirements such as wearing protective clothes and equipment, using proper tools, reporting any accident, being well trained to use the tools and fire extinguishers.

1) **Overheating, Venting and Leaking Cells/Batteries**

Electrical shorting, rapid discharging, overcharging, manufacturer defects, mechanical damage, and many other causes may cause an increase in the internal temperature and pressure faster than the dissipation rate; thus, overheating occurs. As a result, the adjacent cells may be overheated; therefore, if the cells don't return to

U: Reference [45]

the room temperature, they may vent, catch fire, or explode; therefore, using a chamber in this situation is recommended. Venting may be indicated by hearing sounds like puffs and clicks. However, if venting, overheating, or leaking occurs, apply the following procedure:

- Disconnect the charger if the cells/battery are under charging.
- If a cell/battery is venting/smoking
  - Evacuate the area.
  - Put on fire-proof gloves and a gas mask.
  - Put the cell/battery inside a metal or hard plastic barrel with 3% saltwater solution.
  - Label the barrel with hazardous waste and put outside.
  - After 48 hours dispose of the cell/battery and the contaminated water following the local regulations.
- If the cell/battery leaks
  - don't touch or approach it until it reaches the room temperature.
  - Check its temperature using a remote device, if it's not existed, don't handle the cell/battery for a period of at least 24 hours.
  - After reaching the room temperature, label it with hazardous waste and dispose of it.

2) Exploded Cell

Explosions happen due to overheating or mechanical damage; they release white smoke that may affect the personnel's health; thus, it's recommended to adhere with the following procedure:

- Evacuate the area.
- Activate the ventilation system until the cell is being removed from the area and no residual smoke/odour is detected.
- Put the cell/battery in a chemically inert cushioning material such as sand/vermiculite, then label it as a hazardous waste and dispose of it.

3) LiBs Fire

As a result of thermal runaway or increased temperature, the battery may start venting flammable vapors that may cause fire. Adhere to the following procedure for small scale fire:

- Evacuate the area and close the entrance.
- Activate the fire alarm.

- Use fire extinguishers like ABC (dry powder), Carbon dioxide (CO_2), foam (non-combustible), sand, or sodium bicarbonate may be effective.
- Pour water to eliminate any possibility of the battery reigniting and affect any adjacent batteries; 1-5 liters may be enough depending on the battery size.
- When the situation is under control, put the cell/battery in a chemically inert cushioning material such as sand/vermiculite, then label it as a hazardous waste and dispose of it.

For large scale fire that involves furnishing and structural buildings:

- Evacuate the area.
- Activate fire alarm, and don't try to extinguish the fire using a portable fire extinguisher.
- Call the emergency.

4) Electrolyte exposure

Each battery type has its own electrolyte composition, but the first aid procedure is the same for the electrolyte exposure:

- Eyes: flush eyes with water for at least 15 minutes forcibly while holding the eyelid apart.
- Remove the contaminated garments.
- Skin: flush with cool water or get under the shower for at least 15 minutes.
- Inhalation: move to fresh air.

Inspection Procedure

- Visual inspection for any signs of swelling, fire, mechanical damage.
- Electrical inspection for the OCV and the connector integrity.
    - If the battery has a deep discharge rate, charge it with low current.
    - If the voltage is 0V, battery shall be sent to cell extraction.
    - If the voltage is within the nominal operating voltage, continue to assess the battery's health.
- Diagnose the SoH:
    - Discharge the battery in constant discharge current of 1 C-rate or 0.5 C-rate.
    - Perform a constant current-constant voltage charging at 1 C-rate or 0.5 C-rate current.

  - Discharge the battery with 1 C-rate or 0.5 C-rate current and record how many Ahs have been extracted from the battery.
  - If the SoH is 70% or more, the battery can be reused in the same application, if less, the cells shall be extracted and re-used in another application.

If the cells are required to be extracted from the battery, adhere to the following procedure:

- Discharge the battery to a safe operating voltage.
- Manual extraction
  - Open the case
  - Remove the cell pack from the battery
  - Remove the BMS
  - Remove the busbars
- Sort the cells depending on the 2nd life application
  - DIY grade diagnostics, using 1kHz impedance measurement devices and battery charger-testers (not accurate and enough to diagnose the cell performance).
  - Laboratory level diagnostics, using EIS measurement device that does sequential impedance measurement at multiple frequencies; and cell cyclers that measure the capacity at high accuracy. It's expensive and slow, where each cell may take 2-20 minutes for EIS and 6 hours for capacity measurement using cyclers.
  - Fast diagnostics using fast impedance and sorting (FITS) equipment that simulate EIS measurements and use special machine learning algorithms for analyzing SoH, but it's expensive.
- Table 8 shows potential 2nd-life applications, their SoH requirements and the required impedance.

Table 8: 2nd-life application and their SoH technical requirements

2nd life application	SoH Requirements	Impedance
Same application	>90% <5% variation for multicell batteries	Variation within 5 mΩ or +-5%, whichever is smaller
Energy Storage System	>70% <5% variation within battery	Variation within 5 mΩ or +-5%, whichever is smaller
Power bank	>60% <5% variation within battery	Variation within 5 mΩ or +-5%, whichever is smaller

2nd life battery pack for less power-consuming equipment	>50% <5% variation within battery	Not important for single cell batteries, variation within 5 mΩ or +-5%, whichever is smaller for multicell batteries

Summary

Summary

On the international level, the UN has enacted guidelines relevant to packaging, which have a crucial role within both transportation and storage processes; the guidelines classify LiBs according to their status into normal, damaged, disposal & recycling, prototypes, and damaged that is liable to rapidly disassemble; and classify the packaging into packaging “P” and large packaging “LP” according to the stored item’s size and weight; moreover, packaging is also classified into PG (PG |, PG ||, and PG |||) according to the toxicity and flammability of the stored item, which PG | is considered the most dangerous; however, lithium-ion is considered PG | and PG || depending on their status. The material of the packaging for LiBs could be steel, aluminum, plywood, fiber, plastic, or metal other than steel and aluminum. Moreover, the UNECE has adopted certain labels and marks for LiBs, where stand-alone batteries have a UN3480 label and are packed with/contained in equipment have a UN3481 label. Regarding **transportation**, the U.S. CFR and PHMSA have adopted the UNECE packaging and labelling guidelines and their classifications that are relevant to lithium-ion batteries and enacted their own regulations and instructions for safe air and road transportation. The instructions classified the cells and batteries into small, equal to or less than 20 Wh for cells and 100 Wh for batteries, and fully regulated, greater than 20 Wh for cells and 100 Wh for batteries, for air transportation; however, for highway transportation, cells between 20 Wh and 60 Wh and batteries between 100 Wh and 300 Wh are considered small. In addition, the instructions limited the SoC of the batteries/cells to 30% maximum for safety purposes and focused on the importance of not existing any metallic conductive materials and other hazardous materials inside the package, and on protecting the terminals. However, IATA has focused on the same topics regarding the SoC, terminal protection, and non-conductive metallic material inside the package. Regarding highway and road transportation, the ADR/RID EU agreement has enacted provisions that ensure safe transportation for normal, damaged, small, and prototypes of LiBs, where the maximum lithium content weight per transport unit is 333 kg and a non-combustible, non-conductive cushioning material such as vermiculite shall be inside the package of damaged batteries to handle any situation such as leakage. Moreover, it’s important to have the related documents approved during transportation, such as packaging weight, type, and number of packages. SAE has recommended some practices and assessments for shipping transport and handling LiBs. The assessment is divided into two categories, used and new batteries; moreover, the assessments follow the UN guidelines and classifications, and focus on assessing any signs of damage, rupture, emissions, and the mechanical integrity of batteries. Regarding **managing and storing** LiBs, SAE, MIT, EPA, Vermont Agency, NFPA, and IFC have issued reports, standards, and best practices to have safe and doable storage. Where IFC limited the stored capacity of LiBs in one place to 600 kWh; NFPA has put specified some measure such as having a 2-hr fire resistance barrier between the storage spaces/rooms; MIT specified that the storge room surface shall be non-conductive and non-combustible to deal with any leakage; EPA mentioned that damaged batteries shall be quarantined in certain places that are cool, dry, and well-ventilated; moreover, the batteries shall be surrounded by an inert filling materials such as vermiculite and the terminals shall be protected. Vermont Agency of Natural Resources has put management practices to ensure the safety of employees, the facility, and the environment. Last but not least, SAE Standard has focused on the best practices to mitigate hazards and risks of lithium-ion batteries relevant to chemical and electrical energy, electrolyte release, propagation, and emissions, where the practices limited SoC, storage temperature, and specified adequate detection systems such as sensors, and fire suppression technologies such as water, foam, and powder, to exist at the storage area. As regards **inspection** of LiBs, there are still no clear standards, guidelines, and regulations for evaluating and inspecting them, where it's important in determining the 2nd-life application for them to foster circularity. A research group has adopted a battery assessment to evaluate the state of the battery, technical viability, and economic potential. Moreover, the U.K. government has adopted a gateway testing approach to determine the best destination for the battery, where the testing approach includes visual inspection, then mechanical, electrochemical, and safety evaluation, then evaluating the BMS to suit the 2nd application. However, this report includes the most important parameters to be evaluated and inspected, such as energy, SoH, internal resistance, and energy efficiency, where these parameters play a crucial role in determining the most appropriate application for the spent batteries. Moreover, it touches repurposing and reusing scenarios of lithium-ion batteries in general. On the other hand, **the Jordanian MoEnv** has issued instructions to manage and handle spent lead-acid, hybrid, and EV batteries in general; the instructions focus on transportation, storage, and storage facility requirements, but they have some gaps comparing with the international best practices and regulations. The instructions don't mention detailed specifications and requirements regarding packaging, labeling, storage facility infrastructure, and transportation. Therefore, it's recommended that the MoEnv follow the international practices and regulations mentioned in this report that align with Jordanian capabilities and vision. The **recommended practices**, including but not limited to the following:

- **Storage**
    - Adopt UN regulations relevant to packaging and labeling.
    - Conduct battery status assessment to implement proper storage.
    - Protect terminals
    - Ensure that the storage area is dry, cold (15-25 °C), well-ventilated, and away from temperature and humidity sources.
    - Fire extinguishers, detection and alert systems are crucial to be available in the storage facility.
    - Spaces shall be separated by fire barriers of 2-hour fire resistance.
    - Crates shall be used in case of stockpiling/storing HV batteries above each other.
    - Ensure that the stored batteries have a maximum of 30% SoC.
    - Never stack more than two HV batteries.
    - Storage area shall be segregated away from other combustible materials.
    - Limit the stored energy to a maximum of 600 kWh of lithium-ion batteries in one place.
    - Damaged/defective batteries shall be quarantined.
- **Transportation**
    - Adopt UN regulations relevant to packaging and labeling.
    - Conduct battery status assessment to implement proper transportation.
    - Personnel shall be well-trained to deal with any emergency.
    - Packages shall be secured from shifting and movement.
    - Inner packages shall be filled with inert filling material such as vermiculite.
    - Packages shall be tested and leak-proof.
    - Batteries at the same package shall be separated by dividers.
    - Each road transport unit of batteries more than 100 Wh shall have a maximum of 333 kg of lithium content.
    - Terminals shall be protected.
    - Batteries shall have a maximum of 25% SoC for air transport.
- **End of Life Inspection**
    - Define main parameters to be assessed and inspected to determine the most appropriate 2nd-life application for batteries.
    - Workshops should have a license to inspect lithium-ion batteries.
    - PPEs should be used while inspecting batteries.

- Implement the gateway testing for inspecting batteries, where it starts with a visual inspection, then a mechanical, electrochemical and safety evaluation, then finally a BMS evaluation to be compatible with the 2^{nd} application.
- The 2^{nd}-life application's configuration and requirements shall be determined proactively.

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