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SHORT COMMUNICATION

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A generic framework for recycling of battery module for electric vehicle by combining the mechanical and chemical procedures

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Summary
By year 2020, due to enormous growth of production of electric vehicles, it is estimated that approximately 250 000 tons of battery must be disposed or recycled. Till date, the technology to recycle this much amount of batteries in a single year does not exist. Nor, do the methods for recycling are standardized and regulated because of differences in configurations of battery packs. This article conducts a systematic review on research of recycling methods for battery pack used in various stages such as from the dismantling/ disassembly of the battery pack, the detection of the residual energy of the battery, and the recycling/recovery of materials from the battery. The review summarizes basically the 2 main aspects of recycling of battery pack: the mechanical procedure and the chemical recycling. The work describes the existing recycling technology in these 2 aspects and identifies the important research problems in the process of recycling of battery pack such as (1) complexity of dismantling process of battery pack; (2) diversity of connectors used in battery pack; (3) safety of dismantling of battery pack; (4) instability of chemical materials in battery; (5) the chaos of the recycling market; and (6) emerging battery dismantling technologies. One important direction suggested is the automation of battery pack disassembly, which is a main factor towards formulation of generic framework for recycling of battery pack in an efficient manner. Based on these gaps, the present work also proposes a framework for the recycling of battery pack by combining the semi-automation mechanical procedure of battery pack and enhanced chemical recycling of battery for recovery of vital materials. Future work for authors is to work on establishing and validation of proposed framework. The advantages of the proposed framework are compared with that obtained from the existing framework. The proposed framework when used shall result in efficient and effective recycling of battery module and promote greener environment.

KEYWORDS
battery pack, battery pack recycling, chemical recycling, electric vehicle

1 | INTRODUCTION

Governments around the world have given great attention to the research on promoting greener technology such as those of electric vehicles. The trend to replace polluting petrol and diesel cars with new electric vehicles has gathered momentum in the recent years. Figure 1 shows that the global demand for electric vehicles is large and is expanding. Besides, we can see clearly that the market size of China's electric vehicles is also becoming enormous gradually.

For electric vehicles, the battery packs are the most important power source of providing energy to the transmission systems. Therefore, the research of battery pack is important to make the electric vehicles function efficiently.[1-3] Besides, in recent years, the consumption of lithium battery has increased gradually as shown in Figure 2. The growth of the data in this graph shows the increasing demand for electric cars, which is also adapted to the use of electric cars advocated by China.

Significant research on study of failure mechanisms and development of methods (numerical and experimental) for fault diagnosis of batteries has been conducted.

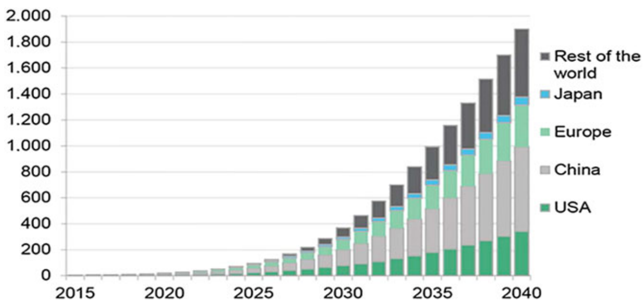

FIGURE 1 Yearly electricity demand from EVs, 2015–2040 (TWh) [Colour figure can be viewed at wileyonlinelibrary.com]

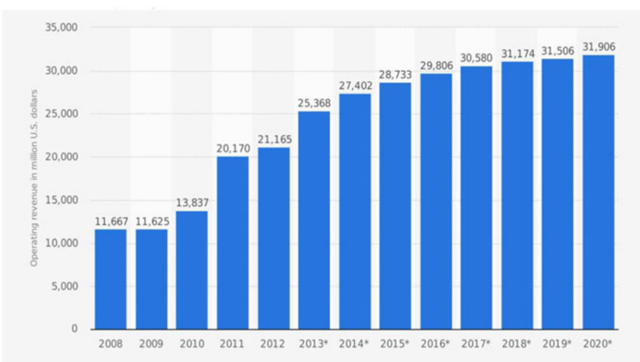

FIGURE 2 Operating revenue of lithium-ion battery manufacture in China from 2008 to 2020 [Colour figure can be viewed at wileyonlinelibrary.com]

Some key researches include the state-of-art studies on the state of health (SOH) estimation of batteries,[4] degradation mechanisms of batteries,[5] failure modes and mechanisms for lead-acid batteries,[6] phase change materials for thermal management of batteries,[7] and progress in development of Vanadium redox flow batteries.[8] However, the studies on recycling of battery module has not received much attention.

As per report,[2,3] without recycling, the battery demand is predicted to outstrip the supply in 2030. Hence, the recycling of the battery pack becomes the focus point. Also, by the year 2020, it is estimated that approximately 250 000 tons of battery must be disposed or recycled. Till this date, the technology to recycle this much amount of batteries in a single year does not exists. Nor, does the methods for recycling are standardized and regulated and followed because of different configurations of battery packs. There is an unanswered question on how to deal with the lithium ion batteries, which often are embedded in hundreds or more in a battery pack. Further, the recovery of materials from the battery is essential to ensure the growth and sustainability of the electrical vehicle market.

In view of the current market demand, the author has conducted a detailed investigation and research on the battery recycling problems.[9,10] Figure 3 illustrates the research problem on recycling of the battery module for electric vehicle. To solve this problem, it is highly desirable to establish a framework that is semi-automated/automated for ensuring the faster and efficient disassembly of battery pack, identification of residual energy of batteries in battery packs and recovery of materials from the batteries.

The objective of the study is to propose a generic framework for recycling of battery module for electric vehicle in an effective and efficient way. This objective is achieved in several phases. In the first phase, a systematic study on research of recycling methods for battery pack used in various stages such as from the dismantling/disassembly of the battery pack, the detection of the residual energy of the battery, and the recycling/recovery of materials is conducted. The study summarizes basically the 2 main procedures used for recycling of battery pack: the mechanical procedure and the chemical recycling. In the second phase, the work discusses the existing recycling technology in these 2 aspects and identifies the important research problems in the process of recycling of battery pack. In the last phase, based on these research directions, the present work proposes a generic framework for the recycling of battery pack by combining the semi-automation mechanical procedure of battery pack and enhanced chemical recycling of battery for recovery of vital materials. The advantages of the

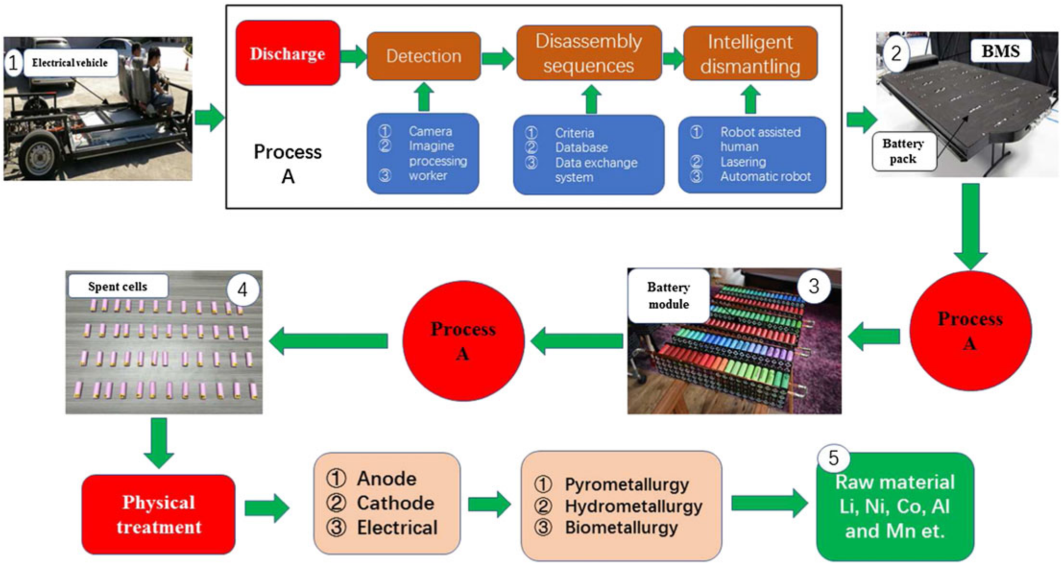

FIGURE 3 Formulation of problem of recycling of battery module for electric vehicle [Colour figure can be viewed at wileyonlinelibrary.com]

proposed framework are then compared qualitatively with that obtained from the existing framework.

2 | RESEARCH ON RECYCLING OF BATTERY

This section describes the research on recycling of battery module which includes 3 major categories: (1) mechanical disassembly methods; (2) chemical materials recycling; and (3) the detection of residual energy. This work summarizes the results and achievements of the past studies on recycling processes, unveils findings and new directions of research, and proposed a novel and generic framework that attempts to solve the current problem on recycling of battery module in an efficient and effective way. Each of the major category used in recycling is discussed as follows.

2.1 | Mechanical disassembly methods

2.1.1 | The disassembly processes

Dismantling is the first step of recycling of battery pack. The disassembly processes are difficult to be operated and are time-consuming because of the complexity of the battery pack in context of shape, size, and heterogeneity of the components used. Thus, there is a need to introduce a kind of automation (may be semi-automatic) in the dismantling of battery module. Figure 4 shows the disassembly processes which include the 3 levels of dismantling procedures[3,11] as follows.

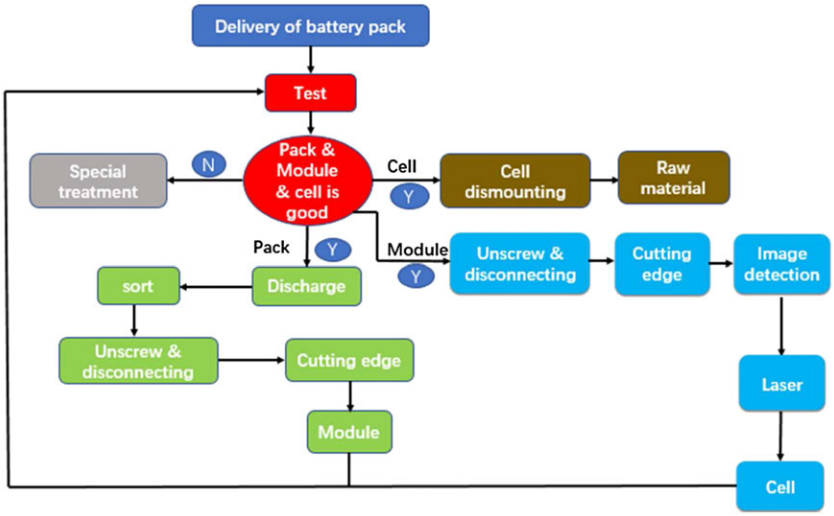

FIGURE 4 The disassembly processes of battery module [Colour figure can be viewed at wileyonlinelibrary.com]

1. Dismantling of battery pack to modules.
2. Dismantling of module to cells.
3. Dismantling cell into single components.

The performance of the batteries is observed during every procedure. The batteries will be discharged if the test performance of the batteries meets the safety standards. The test steps, the discharge process, and the sorting process need to be carried out manually, because there are various unknown changes in the batteries of the battery pack. Besides, the cables and clamping elements are manually cut.[12] The disassembly of module can be done by combining the laser methods with image processing.[13] The following 3 steps are needed for disassembly of battery pack as follows:

2.1.2 | The manual disassembly tools

In this section, the tools of loosening the screws and components are discussed.[14] The most widely used unscrewing tool is the pneumatic tool as shown in Figure 5. The tool can adapt to screws of different specifications. However, the worker needs to find the precise location of the connection which can consume lot of time. Besides, their study illustrates a flexible gripping tool as shown in Figure 6. The device consists of rotatoric drive and linear moveable needles. The gripping processes include 3 steps: generation of new surfaces; handing operation; and loosening of tool and object. The needles can grip the objects easily, regardless of the shape of the objects. One of the gripping is stationary while the other can be moved into the necessary position to grip the battery cell during the disassembly processes. Maybe, it is useful to grip the cell, but it is unnecessary to break the connection between the adapting pieces.

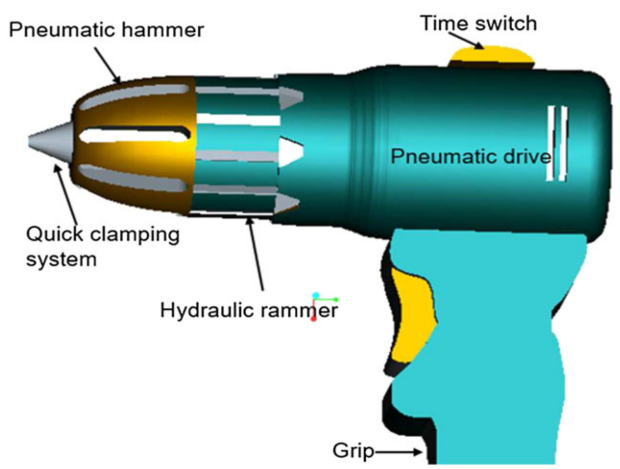

FIGURE 5 The unscrewing tools [Colour figure can be viewed at wileyonlinelibrary.com]

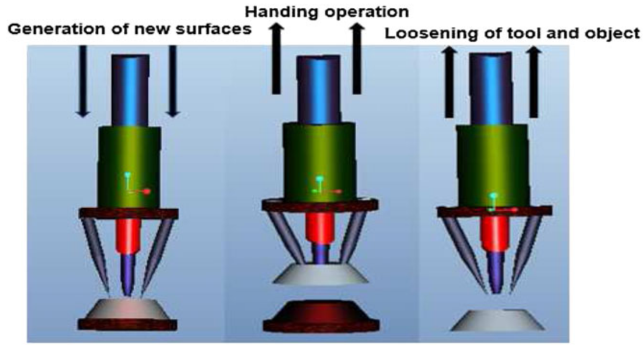

FIGURE 6 The gripper tools [Colour figure can be viewed at wileyonlinelibrary.com]

Study conducted in Peeters and Vanegas[15] summarizes disassembly tools used in electronic equipment. Among the discussed tools, one of the separating tools as shown in Figure 7 can be used for the disassembly of battery pack. This is a tool used for the dismantling of LCD TVs. The tool can be inserted in a design gap and pull apart the housing components. This is the pneumatically actuated semi-automated tool. In authors opinion, such design of a tool can be used for dismantling the power electronics cover and the system cover. Because the covers are big and heavy, the manual disassembly will consume a significant amount of time. Comparatively, this tool costs less dismantling time.

2.1.3 | The semi-automatic disassembly tools

In this section, the semi-automatic disassembly tools used to control the robot to recycle and replace sleeve wrench bits are discussed.[16] Figure 8 shows the hybrid disassembly work station for battery pack. In this work station, both the human and the robot can access the disassembly object and battery. Their study proposed the hybrid system of human and the robot to share a common workspace to minimize system complexity and time.

A robotic tool (Figure 9) consists of a commonly available cordless electric screwdriver, the DC motor, and chuck.[14] The researchers have modified and mounted

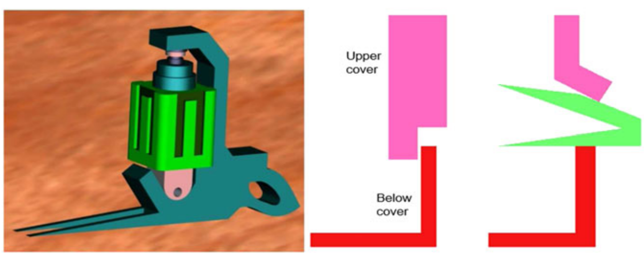

FIGURE 7 Separating tools [Colour figure can be viewed at wileyonlinelibrary.com]

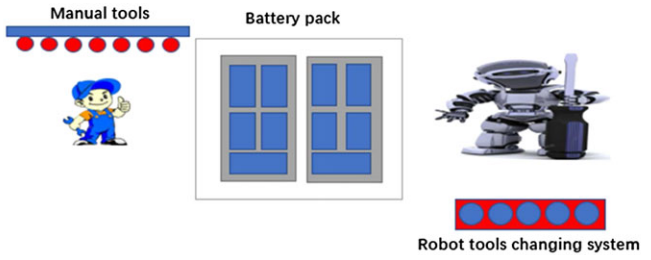

FIGURE 8 The hybrid disassembly work station [Colour figure can be viewed at wileyonlinelibrary.com]

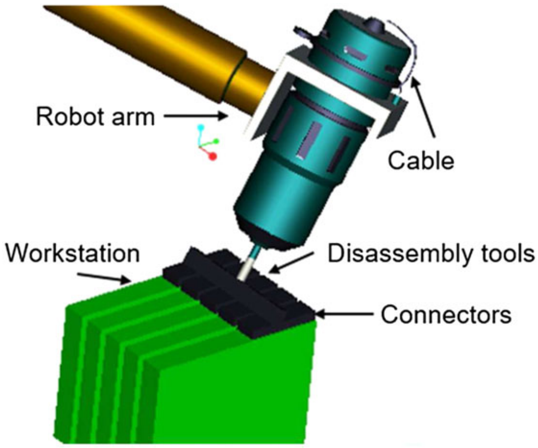

FIGURE 9 Robot flange with electric screwdriver [Colour figure can be viewed at wileyonlinelibrary.com]

the tool. Robot used was the KUKA Lightweight Robot (LWR) which has a 7 degree-of-freedom robot arm with torque sensors in each joint. The location of screws was obtained by the method of camera-based detection.

2.2 | Chemical recycling

Chinese industry[17] made a statement in China's parliament in the year 2016: "Speeding up the recycling of lithium batteries is a matter of urgency, has become a major issue for the development of the new energy vehicle industry.".[18] Therefore, the recycling of lithium batteries is one of the most significant problems. During the process of recycling, the chemical treatment is vital which is the key of the chemical material recycling. The chemical processes used are described as follows:

2.2.1 | Chemical treatment

During the recycling process, the chemical treatment is necessary. The chemical treatment mainly comprises 3 methods[18-28] as follows:

The Toxco[29] presented a method which can apply to all sorts/configurations of lithium batteries. During this process, the materials are cooled in liquid nitrogen before being mechanically shredded and mixed with the water. The main product of this process is lithium hydroxide, and some by-products are obtained.

The Sony[30] uses a higher temperature to recover the cobalt during the process the cells are incinerated. In this, the standard hydro-metallurgical techniques are used to recover the cobalt. The scrubbing system on the incinerator releases the organic components lithium and fluoride which avoids emission problems.

Michael J. Lain[30] illustrates and describes the AEA technology recycling process. The process includes 4 steps: mechanical shredding, electrolyte extraction, electrode dissolution, and cobalt reduction. The process recovers more of the cell raw materials under room temperature.

2.2.2 | Chemical materials recycling

Lithium ion cells contain electrodes, electrolyte, and metal materials such as cobalt, aluminum, copper, and iron. The main composition of components in the cells is shown in Figure 10. There exist many literatures published on the recycling of chemical materials[31-35] from the battery. There are 2 main models for the recycling of batteries as follows.

1. Directional recycling process: Firstly, the cell is obtained by physical disassembling, and then the shell and core are cut. After the pretreatment process of coring, crushing, pyrolysis, leaching, and other pretreatment processes of the core-core, the material of nickel, cobalt, manganese, and lithium is obtained. Using special extraction agent, Li ion can be

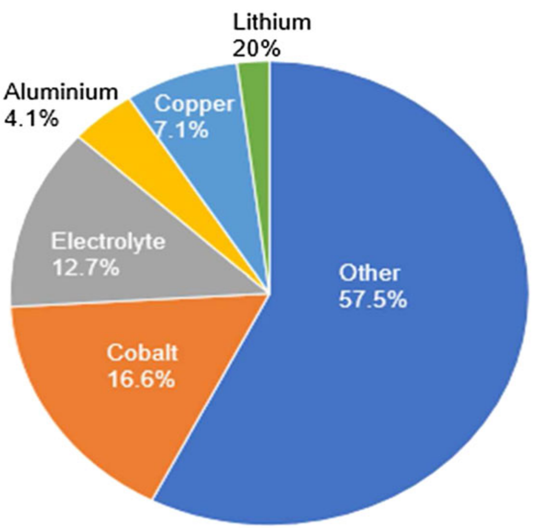

FIGURE 10 Components in a single ICR18650 cell [Colour figure can be viewed at wileyonlinelibrary.com]

extracted. The nickel cobalt manganese acid is obtained by the method of chemical salt and calcining.
2. Power battery material re-synthesis process: Steps involved in this process are mechanical disassembly - crushing separation - treatment - material repair - battery remanufacturing.

In the case of high degree of automation, the waste battery housing is decomposed into electrolyte, diaphragm, copper powder, aluminum powder, positive electrode waste powder, and negative electrode waste powder. Among them, the electrolyte is recovered in the form of mixed solution, the anode material is repaired, and the material can be repaired for the battery.

2.3 | The detection of residual energy

The capacity and cycling performance of lithium battery are higher than those of the lead-acid battery. Therefore, it still has a great recycling value even when it is scrapped. To make full use of the residual energy, it can be applied again to the storage facilities or other low electronic power devices to achieve the maximum utilization of resource.

The detection process[36] is the most important process for the power storage battery, which includes appearance inspection, polarity detection, voltage discrimination, charging and discharge current discrimination, residual energy testing, etc.

It is also necessary to determine the waste power storage batteries before the residual energy detection to make sure the safety is maintained. After determining the types of batteries, the charging and discharging tests are performed according to the characteristics of lithium battery to confirm the residual energy. The specific steps are as follows: the inspection of the appearance - the collection of information - calculation of discharge current.

3 | RESEARCH DIRECTIONS WITH FUTURE ASPECTS

The paper illustrates the research directions with future aspects on the recycling of battery pack (Figure 11). Some of the key findings are as follows.

1. Complexity of dismantling process of battery module

The process of disassembly of battery pack is complex because the battery pack comprises parts of heterogenous nature such as screws, clamps, and non-rigid ones. The battery modules are connected by different joining

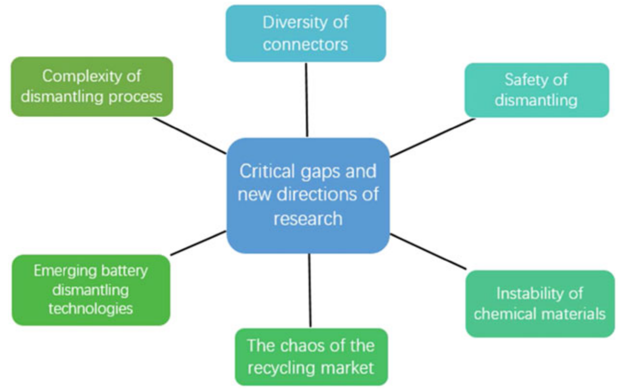

FIGURE 11 Research directions with future aspects [Colour figure can be viewed at wileyonlinelibrary.com]

technologies and different connections which make the dismantling procedure extremely slow and difficult.

2. Diversity of connectors in battery module

The relevant paper[32] presented that there are so many different screw types used for the joints that the amount of time will be spent for changing the tools during the disassembly process. Besides, the locations of connectors are difficult to obtain.

3. Safety of dismantling of battery module

The survey studies[37] described that the battery pack has a risk of getting exploded during the process of disassembling. The main reason is due to the short circuit of the battery pack. Therefore, the care should be taken, and the safety procedure with guidelines and training program should be developed for safer dismantling of pack.

4. Instability of chemical materials

The biggest issues facing the recycling of EV batteries are the inherent chemicals involved. Some of the chemicals in these batteries have toxicity. Besides, materials like cobalt and lithium have a whole set of chemical properties that are tougher to deal. And then, the chemicals are unstable so that they are easy to react.

5. The chaos of the recycling market

It can be stated that the different pack and module design confuses the recycling market. Different connection and standard cause the high cost of the recycling. Therefore, the professional and a generic recycling platform and system must be developed.

6. Emerging battery dismantling technologies

The biggest problem[38] is the dismantling in the process of recycling. However, this process is time-consuming and inaccurate. Therefore, we need to develop many new semi-automatic tools assisting the human worker. In this context, a camera-based detection can be used to make the parts well accessible to obtain the accurate location of screws and components. Besides, there is a need to design a complete dismantling system to make the process of disassembling efficient.

4 | FRAMEWORK FOR RECYCLING OF BATTERY PACK

As per existing literatures,[39-42] the frameworks for recycling are developed with a focus on chemical processes for recycling and recovery of materials from batteries. The frameworks developed in the past studies are summarized and shown in Figure 12. The processes shown in Figure 12 clearly show that the processes involved for mechanical disassembly were of manual nature. The reason could be that in the past decades (relative to the present), the research on battery packs or the electric vehicle has not received much attention as the demand and production of battery packs for electric vehicle were on smaller scale.

Based on the research gaps discussed in Section 3, this paper attempts to propose a standard/generic framework for recycling of a battery module as shown in Figure 13. The proposed framework (Figure 13) includes the exploration of application and development of intelligent methods (laser/camera-based detection) for mechanical disassembly of battery pack and its integration with improved chemical recycling. In our proposed framework, the higher degree of automation and intelligence in the mechanical dismantling process are incorporated as also discussed in the literature.[43-46] Once, the semi-automatic mechanical disassembly system and intelligent database exchange system enters the practical stage, it would not only promote greener environment but also result in reduced recycling cost. To reduce the pollution caused by the waste battery and recycling of the raw

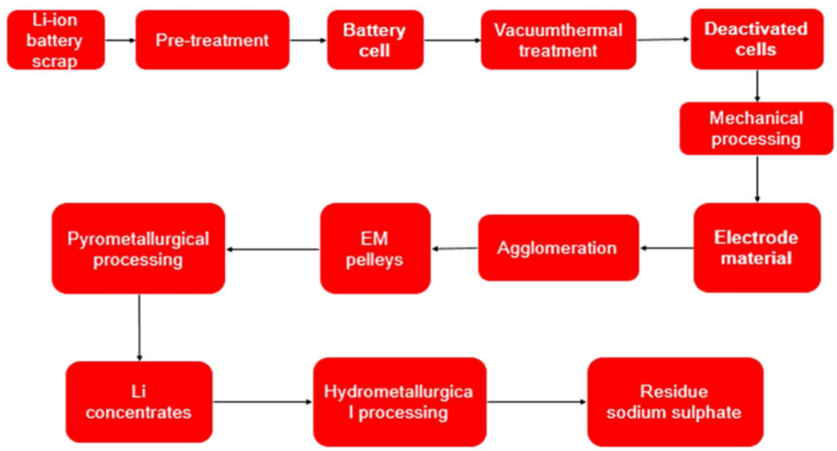

FIGURE 12 Existing framework of recycling procedure of battery module [Colour figure can be viewed at wileyonlinelibrary.com]

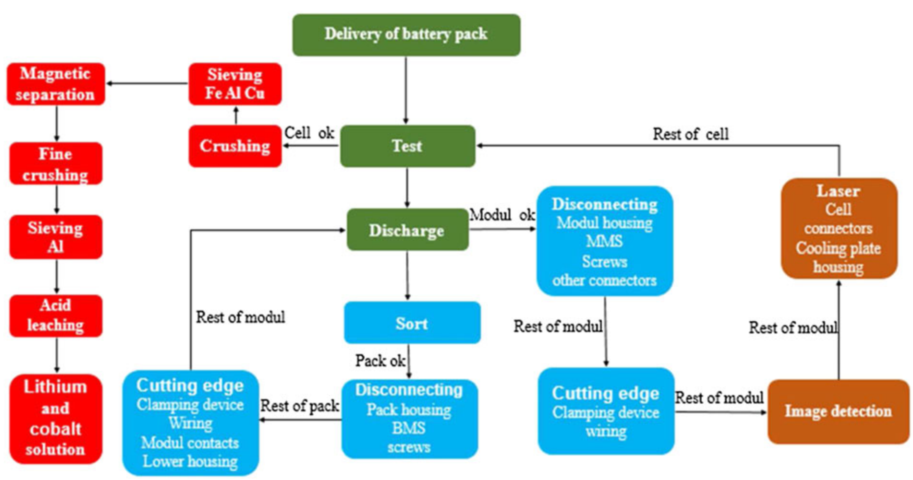

FIGURE 13 Proposed framework of recycling procedure of battery module [Colour figure can be viewed at wileyonlinelibrary.com]

material in an efficient way, the government should put more efforts on the recycling market with a series of polices and regulations. At the same time, the industrial sector should formulate strict industry standards to adjust the chaotic recycling market. This would ensure that the recycled products meet the high-quality standards (quality and environment protection) and thereby accepted for reuse.

5 | CONCLUSIONS

The present studies highlighted the research problem on proposition of a generic framework for recycling of battery module in an efficient and safer way, where the batteries in hundreds or more are embedded. The purpose to conduct this study is based on the facts being reported that by the year 2020, there will be around 250 000 tons of battery that need to be disposed/recycled. It is also known that none of world's largest economies has the facility/technology to recycle this amount of batteries in a year. Authors are thus motivated to work on conducting the review and proposed framework on the existing technologies being used to recycle a battery module used in electric vehicle.

This paper illustrates the current developing status of battery recycling, unveils critical gaps, and lists new research directions. Six identified research directions are as follows: (1) complexity of dismantling process of battery module; (2) diversity of connectors in battery module; (4) safety of dismantling of battery module; (5) instability of chemical materials; (6) the chaos of the recycling market; and (7) emerging battery dismantling technologies. Based on these gaps, the present work also proposes a framework for the recycling of battery pack by combining the semi-automation mechanical procedure of battery pack and enhanced chemical recycling of battery for recovery of vital materials. The advantages of the proposed framework are compared qualitatively with that obtained from the existing framework. The proposed framework includes the exploration of application and development of intelligent methods (laser/camera-based detection) for mechanical disassembly of battery pack and its integration with improved chemical recycling. The existing frameworks for recycling are developed with a focus on chemical processes for recycling and recovery of materials from batteries. The processes involved for mechanical disassembly were of manual nature. The reason could be that in the past decades (relative to the present), the research on battery packs or the electric vehicle has not received much attention as the demand and production of battery packs for electric vehicle were on smaller scale. Further, the sophisticated probabilistic[47,48] and artificial intelligence methods such as neural networks and genetic programming for developing the semi-automatic disassembly procedure for battery pack can be explored.[49-51] Thus, the existing framework when used and validated for recycling of battery module shall result in slower disassembly of packs and consumption of vital time, tools, and manpower.

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