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ENERGY REDUCTION IN AUTOMOTIVE PAINT SHOPS A REVIEW OF HYBRID/ELECTRIC VEHICLE BATTERY MANUFACTURING

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ABSTRACT OF THESIS

ENERGY REDUCTION IN AUTOMOTIVE PAINT SHOPS AND A REVIEW OF HYBRID/ELECTRIC VEHICLE BATTERY MANUFACTURING

Automotive industry is facing fundamental challenges due to the rapid depletion of fossil fuels, energy saving and environmental concerns. The need of sustainable energy development has motivated the research of energy reduction and renewable energy sources. Efficient use of energy in vehicle manufacturing is demanded, as well as an alternative energy source to replace gasoline powered engines. In this thesis, we introduce a case study at an automotive paint shop, where the largest amount of energy consumption of an automotive assembly plant takes place. Additionally, we present a summary of recent advances in the area of hybrid and electrical vehicles battery manufacturing, review commonly used battery technologies, their manufacturing processes, and related recycling and environmental issues. Our study shows that energy consumption in paint shops can be reduced substantially by selecting the appropriate repair capacity, reducing the number of repainted jobs and consuming less material and energy. Also, it is seen that considerable effort needs to be devoted to the development of batteries for hybrid and electric vehicles in the near future, which will make this area challenging and research opportunities promising.

KEYWORDS: Sustainable energy, energy reduction in automotive paint shop, renewable energy, hybrid/electric vehicle, battery manufacturing.

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April 20th, 2010

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ENERGY REDUCTION IN AUTOMOTIVE PAINT SHOPS AND A REVIEW OF HYBRID/ELECTRIC VEHICLE BATTERY MANUFACTURING

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RULES FOR THE USE OF THESIS

Name Date

THESIS

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The Graduate School
University of Kentucky
2010

ENERGY REDUCTION IN AUTOMOTIVE PAINT SHOPS A REVIEW OF HYBRID/ELECTRIC VEHICLE BATTERY MANUFACTURING

THESIS

A thesis submitted in partial fulfillment of the requirements
for the degree of Master of Science in Electrical Engineering
in the College of Engineering at the University of Kentucky

By

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Lexington, Kentucky

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Lexington, Kentucky

2010

DEDICATION

This thesis is dedicated to God, for His infinite blessings. To my parents, Hugo and Patricia, my sister Alexandra, and my boyfriend Carlos, my sources of motivation and inspiration.

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INTRODUCTION

Actual increments in energy, fuel consumption and price, and the growing importance of reducing carbon emissions, have imposed to the governments and companies around the world the finding of solutions in order to improve energy and fuel consumption efficiency. The need of developing sustainable and renewable energy sources has led to the analysis of different approaches in various areas, depending on the problems and challenges of countries around the globe. However, priorities, motivations, and policies are different for every country, and so are the solutions proposed for them. The 2007 Report on Energy and Climate Change by the World Energy Council (WEC) states that there is not a single solution that can provide energy to the world, and meet its emission goals at the same time. Given the difference between countries' needs, each one should develop its own strategy to climate change [1].

Worldwide, transportation is one of the areas with the greater contribution to the total greenhouse gas (GHG) emissions. In United States, it produces around the 33% of the total GHG emissions, and accounts for more than 60% of the total petroleum consumption [2, 3]. For this reason, the reduction of fossil fuels consumption is mandatory, and the introduction of alternative fuels and energy storage technologies plays an important role. At the same time, effective reduction of energy usage in the manufacturing process through an adequate production system design will lead to significant energy savings and a considerable reduction in carbon emissions [4, 5].

This chapter presents and introduction to the main concepts related to sustainable energy development strategies focused on energy reduction in vehicle manufacturing sector, and the use of renewable energy sources for hybrid and electric vehicles.

1.1 Sustainable Energy Development

Sustainable development has been defined as “the development that meets the needs of the present without compromising the ability of future generations to meet their own needs” [6, 7]. One of the main factors to achieve a sustainable development within a society is to plan a sustainable energy development. This plan should include an efficient utilization, conservation and supply of energy resources, with long term availability, reasonable cost, and environmental safety, in order to minimize waste of primary resources [6, 8].

Sustainable energy development strategies can be focused on two technological challenges: energy reduction/conservation in the production process, and replacement of fossil fuels by various sources of renewable energy. Energy reduction is associated to the efficient usage of resources in the production processes. It is directly related to the environmentally conscious manufacturing (ECM) concept, which includes planning, developing, and implementing manufacturing processes and technologies that make an efficient use of energy, while minimizing or eliminating waste and reducing scrap [9]. On the other hand, renewable energy has been considered as an important choice in many countries, but less than 15% of primary energy supply in the world is based on renewable energy [10]. According to [1], the most used sources of energy are fossil fuels (88%), electricity from nuclear energy (6%) occupies the second place, and electricity from hydropower, and other sources like solar energy and wind (6%) complete the percentage. The main fossil fuels used are oil (37%), coal (28%) and gas (23%).

1.1.1 Energy and emissions reduction

The deep reduction of energy consumption or energy efficiency in production processes is a major objective in a sustainable energy development plan. The majority of CO_2 emissions associated with manufacturing facilities is related to their energy usage. The adequate design of processes to make an efficient usage of energy and resources, and to recycle, remanufacture or reuse products is the main characteristic of environmental conscious manufacturing (ECM). Implementation of ECM provides safer and cleaner facilities, reduced environmental and health impact, improved product quality, lower product cost, higher productivity, worker protection, and lower future costs for disposal. Energy reduction basically points to minimize waste and resources, and includes products, processes, and technologies that will decrease in-process waste. Thus, some activities that can be implemented in order to achieve energy and emissions reduction include input changes, production process design changes, product reformulation, inventory control and worker training [9].

Companies around the world are encouraged to take the necessary and appropriate steps to identify the production processes where financially attractive improvements can be made to reduce energy use and meet Environmental Protection Agency (EPA) regulations. In recent years, EPA's Office of Transportation and Air Quality (OTAQ) has established new regulations to reduce nitrogen oxide (NOx) emissions from diesel engines, and NOx, total hydrocarbons (THC), and carbon monoxide (CO) from gasoline-fueled vehicles. Even though passenger vehicle emissions levels have decreased, the overall emissions in the automotive industry are very significant [11].

Different actions have been implemented for major automakers like Toyota, Ford and Porsche to contribute to their overall energy reduction process [12, 13]:

- Use of modern digitally controlled heating systems and efficient lighting, energy management and control systems.
- Updated air handling and emissions control in paint process systems.
- Computerized control of air compressors in paint shop applications and pneumatic tools.
- Encapsulation for complete dust protection, which enhances vehicle paint coat while reducing the required amount of conditioned hall air required.
- Use of electrostatic precipitators for paint dust that decrease the emission of solvents and particles to a minimum, exhaust air purifiers, and increased amount of circulated air.
- Optimization of painting process to significantly reduce the footprint and energy use of paint booths, including projects to convert paint fumes into electricity, and use of zirconium oxide pretreatment to inhibit surface corrosion while using less energy.

- Flexible manufacturing to assemble different vehicles on the same production line, using less manufacturing facilities space and optimizing tools utilization.
- Power cuts during extended production shutdown periods.
- Employee training in the sustainable energy development plan, and better practices in manufacturing.

Vehicle production is a heavily energy consuming process. It is reported that 37 automobile assembly plants across the nation have spent about $700 million on energy every year [14]. In automotive assembly plants, painting is the largest energy consumption unit. More than 60% of the total energy is consumed by paint shop, mostly in painting booths and ovens [15]. Thus, reducing energy consumption in paint shops, and in particular, in the painting process, has significant importance. In Chapter 2, a case study to reduce energy usage at an automotive paint shop is presented. It is shown that a suitable repair capacity design can reduce the number of unnecessary repaints, which will also decrease the consumption of total energy and the environmental impact.

1.1.2 Renewable energy for commercial vehicles

Renewable energy technologies produce commercial energy by taking advantage of natural phenomena and resources, and turning them into useful energy forms. Even when not all renewable energy technologies have zero environmental impact, there is a great environmental advantage in their use with respect to the conventional energy sources. Also, most of renewable energy resources are not exhausted, unlike fossil fuels, and favor power system decentralization and local or small application solutions [6]. The most common renewable energy technologies use resources such as water, wind, sea and tide, solar (thermal and photovoltaic energies), geothermal (heat of the Earth's core), and biomass (wood, other combustion products, biogas, biofuels, etc.) [1, 16, 17].

Renewable energy technologies are becoming a good choice to replace conventional energy sources, due to the more and more affordable equipment and conversion systems available in the market. However, renewable resources change independently from demand, and for this reason, it is very important to count on an energy storage mechanism. In order to achieve a significant contribution to sustainable energy use, considerable development of energy storage methods are required [18].

Recently, biofuels are being used for the transportation sector in some countries [1]; they are solid, liquid, or gaseous fuels derived from organic matter. Most biofuels are derived from dead plants or animal excrement. Many countries are using biofuels for transportation, and the most common are ethanol/gasoline blends and biodiesel. Besides biofuels, electric power is acquiring great importance in the development of new technologies for commercial vehicles. Electric vehicles are propelled by an electric motor (or motors) and powered by rechargeable battery packs. New research and development (R&D) in battery technologies for hybrid and electric vehicles are being conducted, and major automakers have launched their proposals to the market with positive results. Nickel-Metal Hydride (NiMH) batteries have been developed for their use in hybrid electrical vehicles (HEVs), with satisfactory results in the global market. Lithium Ion (Li-ion) batteries are being developed for principal automakers and battery manufacturers for their use in next generation HEVs, Plug-in HEVs (PHEVs), and electric vehicles (EVs). At the same time, new battery manufacturing technologies are being used, which impulse new developments in recycling processes and process control.

Additionally to the battery manufacturing, the U.S. Department of Energy (DoE) has established a program to develop supercapacitors, also called electrolytic double-layer capacitors [19]. These have capacitors and batteries characteristics, with the difference that there is no chemical reaction, which increases cycling capacity. The storage of energy in supercapacitors is performed as an electric field between two electrodes. This is the same principle that capacitors use to store energy, except that supercapacitors use an electrolyte ionic conductor instead of an insulating material. Supercapacitors have long cycle life and power density. However, their energy density is lower than the one batteries have, and their energy storage capacity is still low. In addition, cell balancing is needed to improve cell to cell capacity. At the moment, supercapacitors are only considered as power-assist devices, and are used in parallel with another energy storage device. Therefore, the implementation cost is high and the application range is limited [18, 20, 21].

Lately, hydrogen (H_2) is being deeply explored as a fuel for passenger vehicles. It can be used in fuel cells to power electric motors or burned in internal combustion engines (ICEs). By a reverse electrolysis process, hydrogen and oxygen can produce both water and electricity. Unlike batteries, fuel cells generate electrical energy as long as they have fuel supply, therefore they do not have limited cycle life [19]. There are many types of fuel cells, such as: Alkaline fuel cell (AFC), Phosphoric Acid fuel cell (PAFC), Molten Carbonate fuel cell (MCFC), Solid Oxide fuel cell (SOFC), Solid Polymer fuel cell (SPFC), and Direct Methanol fuel cell (DMFC). Basically, the differences between them are the electrolyte used, their operating temperature, their design, and their field of application. Except for DMFCs in which liquid methanol is used directly as the fuel, the other types of fuel cells work with hydrogen. Recent R&D has been focused on the SPFC technology, because PAFC and AFC have not enough power density, and MCFC and SOFC have a very high temperature operation that is not convenient for use in EVs. However, results have not been as expected for implementation in passenger vehicles [18, 19].

As advances in battery technology for HEVs and EVs are the main short-term solution for the fuel consumption of commercial vehicles, concepts related to batteries for hybrid and EVs, their requirements, and the manufacturing processes for the major battery contestants are studied in Chapter 3.

1.2 Summary

Importance of sustainable energy development strategies has been increased in recent years, with the need of minimizing energy emissions and environmental impact of the different economic sectors worldwide. The automotive industry is one of the major contributors of energy consumption and CO_2 emissions to the environment, and most of the emissions associated with their manufacturing facilities are related to their energy usage. Therefore, energy reduction strategies need to be implemented in vehicle manufacturing sector, with focus on the painting process, where the highest energy consumption takes place. At the same time, renewable energy sources need to be implemented in hybrid and electric vehicles; novel battery technologies such as NiMH and Li-ion are the main short-term solution being implemented in commercial vehicles. For this reason, the aim of this document is to present a case study on an automobile paint system to show that a change in process design can reduce energy usage significantly, and to analyze the state-of-the-art of battery manufacturing for hybrid and electric vehicles.

The remaining of the document is organized as follows. In Chapter 2, a case study to reduce energy usage at an automotive paint shop by modifying its repair capacity is presented. In Chapter 3, an introduction to HEVs, PHEVs and EVs, their characteristics and parameters that make them important candidates for the new generation of commercial vehicles is provided, as well as the main concepts necessary to understand battery operation, performance, and energy management. Also, this chapter analyzes battery requirements and development in the last years, reviews manufacturing processes of the main battery technologies considered for HEVs and EVs, their recycling processes and some environmental issues. Finally, Chapter 4 collects main conclusions and some proposals for future work. All proofs are provided in the Appendix.

Chapter 2

ENERGY REDUCTION: A CASE STUDY IN AN AUTOMOTIVE PAINT SHOP

2.1 Introduction

Vehicle manufacturing is a heavily energy consuming process, and painting is the unit with the largest energy consumption. Thus, reducing energy consumption in painting process, has significant importance. Most of the studies on energy improvement focus on process and technology improvement, such as renovation in painting equipment or process. For instance, paper [22] describes a process based cost model for automotive painting. Using such a model, the cost of changing the painting process and using alternative technologies can be estimated. Likewise, [23] introduces typical vehicle painting process and identifies the repetitive painting and curing processes as the huge energy consumers. It also presents energy consumption reduction efforts by reducing the number of processes in painting booths. In addition, paper [24] proposes an equation to model the energy usage as well as the environmental impacts and economic costs of each unit in paint shop, and studies the major energy consuming ones. Recently, reference [14] summarizes the energy use in vehicle assembly process and presents energy efficiency measures for specific process in painting systems. It also provides suggestions to reduce energy consumption, such as reducing air flow in painting booths, and minimizing heat recovery to reduce waste heat, etc.

Clearly such efforts have significant impact on improving energy efficiency in paint shops. They typically require process renovation, new equipment upgrades, and significant investment in advance. Therefore, an alternative approach, which relies on system design and operation, such as reducing energy consumption through efficient production operations would be very valuable. In other words, a method to reduce energy usage through production system design while improving productivity and quality is an area worth for investigation.

Due to the importance of painting operations in vehicle assembly, substantial effort has been devoted to improvement in paint shops. Papers [25] and [26] present analytical models to predict the throughput in paint shops and outline continuous improvement procedures. Such methods have been successfully applied in paint shops. Papers [27] and [28] introduce quality robustness design of repair and rework system in paint shops to improve quality buy rate. Paper [29] describes a case study to investigate the coupling between operation speed and paint quality. However, energy issues are not considered explicitly in these works. Therefore, a study to investigate procedures for energy reduction through production systems analysis is needed.

This chapter presents a case study on paint system design to reduce energy usage at an automotive paint shop. Specifically, it is shown that by designing appropriate repair capacity, a reduction of number of unnecessary repaints can be obtained. It will also result in less consumption of total energy as well as emissions. The remainder of this chapter is structured as follows: Section 2.2 introduces the painting system in an automotive paint shop. The model and problem formulation are presented in Section 2.3. Using such a model, the energy consumption formulas are derived in Section 2.4 and possible energy reductions are studied. Section 2.5 describes a repair capacity redesign project. Finally, Section 2.6 presents a general summary. All proofs can be found in the Appendix.

2.2 Painting System

The automotive painting system typically consists of the following processes: painting (i.e., color coating and baking, including painting booths and ovens), repair (spot repair and panel exchange), rework (where jobs will be resent to painting process again) and inspections, which are immediately after each operation. An illustration of such processes is given in Figure 2.1.

After painting and inspection, a good quality job will be sent to confirmation deck. A defective job will be routed either to repair (for spot repair, such as scratch polishing, dent removal, or for panel exchange) or to rework if the defect is severe, and in this case the whole vehicle will be repainted. Jobs routed to component replacement will be inspected

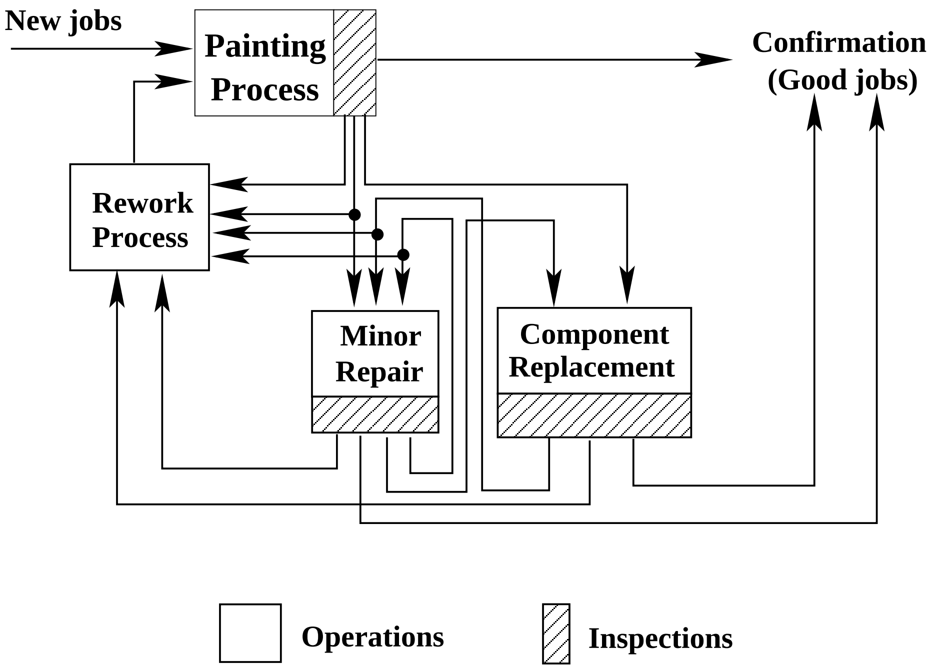

Figure 2.1: Illustration of job flow in painting system

again after finishing the process. The good jobs will be delivered to confirmation, and still defective jobs are routed either to spot repair or to rework. Similarly, spot repair jobs will be sent to confirmation deck if it passes the inspection, back to spot repair again, to component replacement, or to rework, if it is still inferior to quality standard.

Typically, component replacement can be finished quickly, but spot repair may take longer time since all operations are manual and are followed by baking procedures. Therefore, the number of spot repair jobs that can be carried out everyday is limited due to floor space and resource constraints. In addition, upstream of the repair shop, small buffers are usually designed, which again limit the repair capacity. Moreover, the repair facility is typically designed based on a projected or average value of first time quality (i.e., the job ratio to pass painting inspection the first time). However, due to production fluctuation, such a goal cannot be achieved all the time. Therefore, insufficient spot repair capacity will occur and may lead to blockage of the painting process. Such blockage is detrimental since it may result in over-baking of the vehicles, and finally, the scraps. To avoid this blockage, a typical practice in paint shops is to reroute the jobs that only need spot repair to rework, and then repaint them so that the flow in the system will be able to sustain.

Although rerouting jobs may solve the blockage problem, this will lead to unnecessary repaints (i.e, jobs that only need spot repair are routed to repaint), and it also introduces new problems, since it is typical that the repaint quality is significantly lower than first time quality. This is due to additional exposure to dirt. Moreover, unnecessary repaints may interrupt desired sequence so that more frequent color changes may be observed. Again this can increase painting cost and reduce paint quality. Therefore, such rerouting of jobs will lead to a reduction of quality and an increase of repair and repaint jobs. As a result, more jobs will be processed in painting process.

As the painting booths and ovens are the major energy consumption units, and both new and repainted jobs are processed here, reducing the total number of jobs passing the painting process is an effective way to cut off energy usage. This implies that the number of unnecessary repaint jobs should be reduced. To achieve this, designing an appropriate repair capacity is needed. Sections below intend to provide a better design option to ensure a lower number of processed jobs and a reduction in energy consumption.

2.3 Model and Problem Formulation

To model the painting system described above, the following notation is introduced:

n: production capacity, i.e., number of first time painting jobs per day,

$q(t)$: first time quality, i.e., percentage of good jobs after first processing at painting operations in day t,

α_x: probability that a defective job should go to panel exchange after painting process inspection,

α_s: probability that a defective job should go to spot repair after painting process inspection,

α_r: probability that a defective job should go to rework after painting process inspection,

β_{sx}: probability that a job should go to panel exchange after spot repair,

β_{ss}: probability that a job should go to spot repair again after spot repair,

β_{sr}: probability that a job should go to rework after spot repair,

β_{sg}: probability that a job has good quality after spot repair,

β_{xs}: probability that a job should go to spot repair after panel exchange,

β_{xr}: probability that a job should go to rework after panel exchange,

β_{xg}: probability that a job has good quality after panel exchange,

N: spot repair capacity (maximum number of jobs that can be repaired) per day,

c: unit energy cost of painting a vehicle.

The following relationships exist since the total probability is equal to one:

$$\alpha_x + \alpha_r + \alpha_s = 1 \tag{1}$$

$$\beta_{sr} + \beta_{ss} + \beta_{sx} + \beta_{sg} = 1 \tag{2}$$

$$\beta_{xr} + \beta_{xs} + \beta_{xg} = 1 \tag{3}$$

The following assumptions are introduced:

(i) First time quality $q(t)$ is considered as a random variable.

(ii) A job can be reworked or repaired multiple times. No scrapping of jobs is assumed.

> **Remark 1** Typically, there is a limit (e.g., four times) on how many times a vehicle can be repainted. When the rework rate is small, which is the majority of the cases, the probabilities that a job will be repainted or a job has to be scrapped will be very small. Therefore, assumption ii) is acceptable.

(iii) All repainted jobs have same probability of becoming good jobs, independent of the number of times they have been reprocessed.

(iv) All routing probabilities are constant in time. In other words, the probabilities that a defective job should go to panel exchange, spot repair, and rework are kept unchanged whether the job is a first-time processed job or multiple-time reprocessed job.

(v) First-time processed jobs have a higher good job ratio than repainted jobs. Repaint quality, $q_r(t)$, is proportional to first time quality and $q_r(t) = \rho q(t)$, where ρ is a constant $(0 < \rho \leq 1)$.

Let $n_r(t)$, be the number of jobs routed to rework and repaint in day t. Then $n_r(t)$ is a function of the first time quality and spot repair capacity. Thus, the total energy usage in painting in day t is defined as:

$$E(t) \quad = \quad c \cdot (n + n_r(t)). \tag{4}$$

Therefore, the problem to be addressed is formulated as follows: *Under assumptions (i)-(v), develop a method to investigate the energy consumption as a function of spot repair capacity.*

The solution to this problem is presented below.

2.4 Energy Evaluation and Comparison

Consider the paint system shown in the Figure 2.1. Define $\widetilde{n}_s(t)$ as the number of jobs that should be routed to spot repair in day t. Then $\widetilde{n}_s(t)$ may be larger than the jobs actually go through spot repair in day t, which is $n_s(t)$, and $n_s(t)$ equals to $min\{\widetilde{n}_s(t), N\}$. Similarly, let $n_x(t)$ be the number of jobs routed to panel exchange in day t, and $n_g(t)$ the number of good jobs going to confirmation station in day t. Using conservation of flow, the following equations describe the system behavior:

$$\begin{aligned}
n_r(t) \quad &= \quad n[1-q(t)]\alpha_r + n_r(t)[1-\rho q(t)]\alpha_r + n_x(t)\beta_{xr} + \min\{\widetilde{n}_s(t), N\}\beta_{sr} + \\
&\quad\quad \max\{\widetilde{n}_s(t) - N, 0\}, \\
n_x(t) \quad &= \quad n[1-q(t)]\alpha_x + n_r(t)[1-\rho q(t)]\alpha_x + \min\{\widetilde{n}_s(t), N\}\beta_{sx}, \\
\widetilde{n}_s(t) \quad &= \quad n[1-q(t)]\alpha_s + n_r(t)[1-\rho q(t)]\alpha_s + n_x(t)\beta_{xs} + \min\{\widetilde{n}_s(t), N\}\beta_{ss}, \\
n_g(t) \quad &= \quad nq(t) + n_r\rho q(t) + \min\{n_s(t), N\}\beta_{sg} + n_x\beta_{xg}.
\end{aligned}$$

Using the above equations, a closed formula to calculate the total energy to produce n vehicles with good paint quality can be derived.

Theorem 1 *Under assumption (i)-(v), the total energy consumed in day t, $E(t)$, is given by:*

$$E(t) = \begin{cases} cn\frac{1-\alpha_r'[1-\rho q(t)]+\alpha_r'[1-q(t)]}{1-\alpha_r'[1-\rho q(t)]} & \textit{if } N \geq n_s(t), \\ \\ \frac{cn[1-(1-\rho q(t))(1-\alpha_x\beta_{xg})+(1-q(t))(1-\alpha_x\beta_{xg})]}{1-[1-\rho q(t)][1-\alpha_x\beta_{xg}]} - \frac{cN(\beta_{sg}+\beta_{sx}\beta_{xg})}{1-[1-\rho q(t)][1-\alpha_x\beta_{xg}]} & \textit{if } N < n_s(t), \end{cases} \tag{5}$$

where

$$n_s(t) = \frac{n\alpha_s'[1-q(t)]}{1-[1-\rho q(t)]\alpha_r'}, \tag{6}$$

$$\alpha_s' = \frac{\alpha_s+\alpha_x\beta_{xs}}{1-\beta_{ss}-\beta_{sx}\beta_{xs}}, \tag{7}$$

$$\alpha_r' = \alpha_r + \frac{\alpha_s(\beta_{sr}+\beta_{sx}\beta_{xr})}{1-\beta_{ss}-\beta_{sx}\beta_{xs}} + \frac{\alpha_x(\beta_{xr}+\beta_{xs}\beta_{sr}-\beta_{ss}\beta_{xr})}{1-\beta_{ss}-\beta_{sx}\beta_{xs}}. \tag{8}$$

Proof: See the Appendix. ■

Note that in equations (6)-(8), $n_s(t)$ indeed represents the smallest spot repair capacity to accommodate all the jobs that should be spot repaired in day t, and α_s' and α_r' represent the actual probabilities a defective job is routed to spot repair and rework, respectively (where all the defective jobs exiting from panel exchange and spot repair have been taken into account). Clearly, when spot repair and panel exchange have 100% quality rate, i.e., $\beta_{sg} = \beta_{xg} = 1$, we have $\alpha_r' = \alpha_r$ and $\alpha_s' = \alpha_s$.

As explained in Section 2.3, typically $\rho < 1$, then $q_r(t) < q(t)$. When the spot repair capacity is insufficient, the total number of jobs processed by the painting process will be increased by rerouting the jobs that only need spot repair to repaint. This will lead to more energy consumption, more material usage and more emissions as well. Therefore, it is important that the spot repair capacity should be sufficient so that the unnecessary repaints would be minimal.

As one can expect, increasing spot repair capacity leads to a reduction of number of jobs to be processed in painting process and also a decrease of energy usage. When repair capacity N is greater than $n_s(\min\{q(t)\})$, there will be no rerouted jobs. In this case, the energy consumption will be a constant. Therefore, we obtain,

Corollary 1 *Under assumptions (i)-(v), the average energy consumption in painting process, $\overline{E}$, is monotonically non-increasing with respect to N.*

Proof: See the Appendix. ■

In many production system designs, the average value of first time quality, $\overline{q}$, is typically used. Let $E_{\overline{q}}$ be the energy consumption with a constant first time quality $\overline{q}$, and denote $\overline{E}_{q(t)}$ as the expected energy usage with random first time quality $q(t)$. The following relationship is obtained:

Corollary 2 *Under assumptions (i)-(v),*

$$\overline{E}_{q(t)} > E_{\overline{q}}. \tag{9}$$

Proof: See the Appendix. ■

This result indicates that without considering the first time quality variability (by using average first time quality), less processed jobs are predicted, and a smaller energy consumption will be expected. In this case, typically, a smaller spot repair capacity will be selected. However, due to variability, such capacity design may lead to more unnecessary repaints so that more jobs need to be processed and a large energy usage will occur. Therefore, variability in first time quality cannot be ignored.

Assume the first time quality follows a uniform distribution. An analytical expression of $\overline{E}$ can be obtained.

Theorem 2 *Under assumptions (i)-(v), assume $q(t)$ follows a uniform distribution in interval $[q_a, q_b]$, the average energy usage, $\overline{E}$, can be calculated as:*

- *if* $q_s < q_a$,

$$\begin{aligned}\overline{E} &= \frac{cn}{q_b - q_a}\Bigg[\Bigg(\frac{1}{\alpha'_r\rho} - \frac{(\alpha'_r\rho - \alpha'_r)(1-\alpha'_r)}{(\alpha'_r\rho)^2}\Bigg) \\ &\quad \times\Big[\ln(\alpha'_r\rho q_b + 1 - \alpha'_r) - \ln(\alpha'_r\rho q_a + 1 - \alpha'_r)\Big] + \frac{(\alpha'_r\rho - \alpha'_r)}{\alpha'_r\rho}(q_b - q_a)\Bigg], \end{aligned} \tag{10}$$

- *if* $q_a \leq q_s \leq q_b$,

$$\begin{aligned}\overline{E} = {} & \frac{cn}{(q_b - q_a)}\Bigg[\Bigg(\frac{1}{\alpha'_r\rho} - \frac{(\alpha'_r\rho - \alpha'_r)(1-\alpha'_r)}{(\alpha'_r\rho)^2}\Bigg) \times \Big[\ln(\alpha'_r\rho q_b + 1 - \alpha'_r) \\ & - \ln(\alpha'_r\rho q_s + 1 - \alpha'_r)\Big] + \frac{(\alpha'_r\rho - \alpha'_r)}{\alpha'_r\rho}(q_b - q_s)\Bigg] \\ & + \frac{c}{(q_b - q_a)} \times \Bigg[\Bigg(\frac{n}{(\rho - \rho\alpha_x\beta_{xg})} - \frac{n(\alpha_x\beta_{xg} + \rho - \rho\alpha_x\beta_{xg} - 1)}{(\rho - \rho\alpha_x\beta_{xg})^2} \\ & - \frac{N(\beta_{sg} + \beta_{sx}\beta_{xg})}{(\rho - \rho\alpha_x\beta_{xg})}\Bigg) \times \Big[\ln\Big((\rho - \rho\alpha_x\beta_{xg})q_s + \alpha_x\beta_{xg}\Big) \\ & - \ln\Big((\rho - \rho\alpha_x\beta_{xg})q_a + \alpha_x\beta_{xg}\Big)\Big] + \frac{n(\alpha_x\beta_{xg} + \rho - \rho\alpha_x\beta_{xg} - 1)(q_s - q_a)}{\rho - \rho\alpha_x\beta_{xg}}\Bigg], \end{aligned} \tag{11}$$

- *if* $q_s > q_b$,

$$\begin{aligned}\overline{E} &= \frac{c}{q_b - q_a}\Bigg[\Bigg(\frac{n}{(\rho - \rho\alpha_x\beta_{xg})} - \frac{n(\alpha_x\beta_{xg} + \rho - \rho\alpha_x\beta_{xg} - 1)}{(\rho - \rho\alpha_x\beta_{xg})^2} \\ &\quad - \frac{N(\beta_{sg} + \beta_{sx}\beta_{xg})}{(\rho - \rho\alpha_x\beta_{xg})}\Bigg) \times \Big[\ln\Big((\rho - \rho\alpha_x\beta_{xg})q_b + \alpha_x\beta_{xg}\Big) \\ &\quad - \ln\Big((\rho - \rho\alpha_x\beta_{xg})q_a + \alpha_x\beta_{xg}\Big)\Big] \\ &\quad + \frac{n(\alpha_x\beta_{xg} + \rho - \rho\alpha_x\beta_{xg} - 1)(q_b - q_a)}{\rho - \rho\alpha_x\beta_{xg}}\Bigg], \end{aligned} \tag{12}$$

where

$$q_s = \frac{n\alpha'_s - N(1 - \alpha'_r)}{n\alpha'_s + N\rho\alpha'_r}. \tag{13}$$

Proof: See the Appendix. ■

Remark 2 It is shown in [28] that the quality buy rate at painting (i.e., overall quality ratio, including both first time and repainted jobs) is practically insensitive to distribution type of first time quality, but only dependent on mean and coefficient of variation of it. Since energy consumption is proportional to the number of processed jobs and then to the quality buy rate, a similar property will also hold. Thus, for any other distribution of first time quality, as long as mean and coefficient of variation are known, we can find a uniform distribution with same mean and coefficient of variation and use it for energy evaluation.

To illustrate the effect of spot repair capacity design for energy reduction, consider two painting processes following the same uniform distribution for first time quality $q(t)$, but with different spot repair capacities N_1 and N_2. Then the energy consumptions of these two systems, $\overline{E}_1$ and $\overline{E}_2$, can be compared using the results from Theorem 2. Here $n = 1000$ and $\rho = 0.6$. The routing probabilities are defined as follows:

$$\begin{aligned} \alpha_r = 0.2, &\qquad \alpha_s = \alpha_x = 0.4, \\ \beta_{xr} = \beta_{xs} = 0.15, &\qquad \beta_{ss} = \beta_{sx} = \beta_{sr} = 0.1. \end{aligned} \tag{14}$$

Let $N_2 = 50$, and N_1 is changing from 50 to 200. The results are shown in Figure 2.2 for different mean values of first time quality.

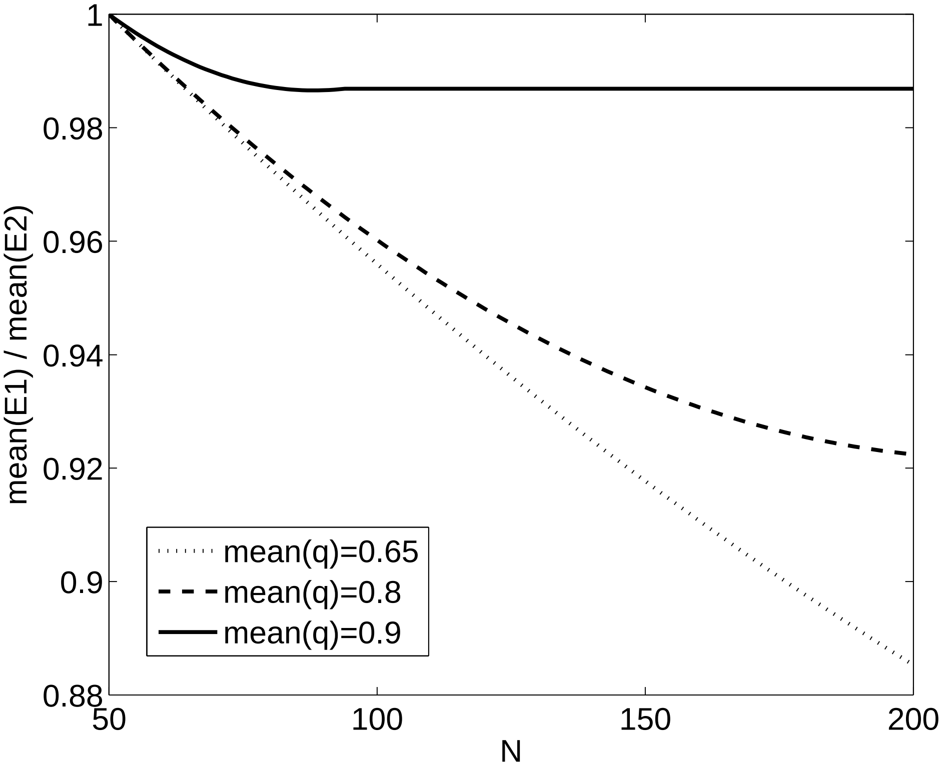

Figure 2.2: Energy consumption: $\overline{E}_1/\overline{E}_2$

It can be seen that the energy usage is monotonically decreasing as a function of spot repair capacity when it is insufficient. When the capacity is large enough so that there is no rerouted jobs, this consumption will be constant. As we have larger spot repair capacity, it is possible to decrease the number of jobs going through the painting process, and therefore, the energy consumption. As one can see, the energy savings that can be obtained are from $2-12\%$ for mean values of $q(t)$ from 0.65 to 0.9. Since a huge amount of energy is consumed in automotive paint shops, in particular in the painting process areas, even a small percentage of reduction is still significant in overall volume.

2.5 Case Study

In this section, a spot repair capacity redesign project at an automotive paint shop is introduced. Consider the paint system shown in Figure 2.1. The routing probabilities are $\alpha_s = 0.5$, $\alpha_x = 0.35$, $\alpha_r = 0.15$, $\beta_{xr} = \beta_{xs} = \beta_{ss} = \beta_{sr} = \beta_{sx} = 0.05$. The daily production volume is $n = 765$, and $\rho = 0.5$. The average first time quality is $\overline{q} = 80\%$ with lower and upper bounds equal to 0.65 and 0.95, respectively. The spot repair capacity is $N = 90$, which is almost sufficient to avoid rerouted jobs if first time quality is constant.

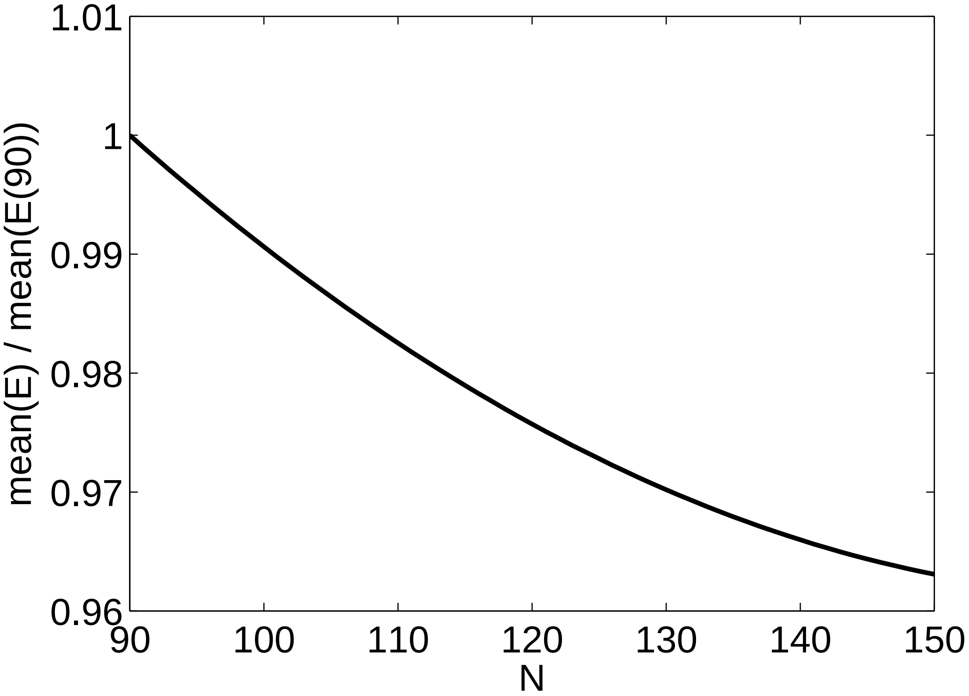

Figure 2.3: Reduction in energy consumption

The goal of this project is to provide recommendations to redesign the spot repair capacity to reduce the number of unnecessary repaints and therefore, to reduce the energy consumption. To accomplish this, the model introduced in Section 2.4 is used. Specifically, the capacity of spot repair is increased from 90 to 150. The results of potential energy reduction are illustrated in Figure 2.3. Clearly, almost a 4% of energy reduction can be obtained. As it was said before, since the painting process consumes the largest amount of energy in automotive assembly plant, such reduction will be significant. For example, more than $700 million were spent by 37 assembly plants per year and 60% of it was in painting, on average more than $11 million were spent in each paint shop. Then, a 4% reduction will result in close to half million dollar in savings in energy per year. In addition, it reduces a considerable amount of material cost by avoiding unnecessary repaints and can finally improve the system throughput. Therefore, even though increasing spot repair capacity will lead to an increase of investment cost and repair workforce, the saving over a long time period on energy and improvement on productivity we can obtain are usually much larger than the cost of increasing repair capacity. In particular, for systems with large volume of production and high-profit products, the long term impact of this improvement will be significant.

2.6 Summary

In this chapter, through a case study at an automotive paint shop, the impact of production system design on energy consumption was investigated. Specifically, it shows that the energy usage of a painting system can be reduced by a better design of the spot repair capacity so that the unnecessary repaints will be smaller. Moreover, it also provides plant engineers and managers a quantitative tool to evaluate energy improvement efforts.

Clearly, such a work will also result in a significant environment benefit due to less emissions are generated. Therefore, the method presented here provides another approach to reach energy efficient and environmentally friendly (EEEF) manufacturing.

Chapter 3

BATTERIES FOR HYBRID AND ELECTRIC VEHICLES

3.1 Introduction

The increasing demand of alternative and sustainable energy sources to replace gasoline powered engines has intrigued the development of battery technologies for hybrid and electric vehicles. This has brought both challenges and opportunities. Not only new battery designs with advanced features are needed, but also a high manufacturing capacity to satisfy the increasing market is required. Different energy storage technologies have been developed and tested in commercial vehicles in order to find an economical solution that provides emissions and fuel reduction without giving up efficiency. Thus, architectures combining an internal combustion engine (ICE), an energy storage device, and an electric motor have been designed to accomplish these goals.

The objective of automotive industry is to reduce fuel consumption, emissions, and manufacturing cost, while enhancing reliability, safety and comfort [30]. The overall power system design, the cranking and starting systems, the load leveling, and the standby power also affect the vehicle's electrical system, and impact the characteristics of the battery. The growing increase in the power-consuming functions for electrical systems also requires the improvement of the battery system and operation conditions [31, 32]. Therefore, the selection of appropriate battery technology for an automotive application has a significant importance. The production of hybrid electric vehicles (HEVs) and electric vehicles (EV) has created a need for higher voltage batteries with long life and increased reliability [33]. To meet these demands, Nickel-Metal Hydride (NiMH) and Lithium Ion (Li-ion) technologies are major contestants. NiMH battery is already commercially used in current HEVs with positive results, while Li-ion batteries are awaited with high expectation. Mature technologies like Lead-acid, and other batteries based on nickel and sodium, have been also studied in previous attempts in the development of HEVs and EVs.

A considerable amount of literature has been found in the design, chemistry, development, and management systems for automotive batteries, but the case is not the same for the manufacturing and recycling processes, and the environmental issues behind the different battery technologies. This chapter aims to review the main characteristics of hybrid, plug-in, and electric vehicles, and the most important parameters of batteries. At the same time, a review of recent advances in automotive battery technologies, their manufacturing processes, the importance of energy management and battery monitoring in the detection of possible performance problems, as well as environmental and recycling issues is presented.

The remainder of this chapter is structured as follows: Section 3.2 presents a comparison between hybrid and electric vehicles, and a review of commonly used architectures. In Section 3.3, the most important battery parameters that define the performance and response of batteries in a given application are explained, as well as the parameters related to energy, battery management and monitoring. Section 3.4 outlines the typical requirements for new hybrid and electric automobile batteries. The development of HEV and EV technology is introduced in Section 3.5. In Sections 3.6-3.9, lead-acid, nickel, lithium and sodium based technologies are described, respectively. Finally, a summary is given in Section 3.10.

3.2 Hybrid, Plug-In Hybrid, And Electric Vehicles

3.2.1 Hybrid electric vehicle (HEV)

A HEV is propelled by combining mechanical power from an ICE, with electrical power from a battery (primary and secondary power source). Normally, the vehicle works most of the time in the engine's maximum efficiency zone, where the output is maintained at an almost constant power level. The secondary power source is an energy storage device, usually a battery or a supercapacitor, that provides auxiliary power and takes advantage of regenerative braking and deceleration energy, which makes HEVs very efficient. The battery starts working when more power than the engine can provide is needed. Based on the percentage of battery use inside the vehicle's design, different levels of hybridization can be distinguished [33]-[37]:

- Micro-HEVs provide automatic engine stop/start operation with regenerative braking, and use conventional 12V battery technology with generator capacity in the range of 2-4 kW. The battery supplies the power demand during the stop phases, where the engine is shut off, to save fuel and reduce noise. Other requirements, like air conditioning, places additional demands to the battery.
- Medium HEVs supply energy for engine starting, idle loads, electrically assisted launch from stop, torque assistance, and charge recuperation during regenerative braking, which in turn provides higher fuel saving benefits. The most important requirement in this type is charge acceptance, and the battery has to work at partial state of charge (PSoC). Typical battery capacities are 4-10 kW, and electrical systems of 42V. The Civic Hybrid, Honda Insight, and GMs Saturn VUE are examples of this category.
- Power-assist or Full HEVs offer energy for engine starting, low-speed acceleration, idle loads, full electric launch, torque assistance, regenerative braking energy capture, and limited electric-only range. Used power is around 50-70 kW. Electric drive and battery typically operate at high voltages above 200V. The Toyota Prius and the Ford Escape hybrid are examples of power-assist HEV.

All of these powertrain hybridization levels increase fuel economy by allowing the engine to shut off while idling and during deceleration. They capture electrical energy through regenerative braking. In all cases, the batteries have the advantage of self-recharging. In general, the full hybrid tends to reach its best mileage in city driving, while the medium hybrid tends to reach its best mileage on the highway [36].

3.2.2 Plug-in hybrid electric vehicle (PHEV)

Plug-In HEVs (PHEVs) provide typical full HEV capability, while at the same time, their batteries can be recharged with electricity from an off-board power source such as a conventional residential AC power outlet. This imposes large energy storage demands on the battery, which are not met by previous HEV designs. The electrical power requirement depends on vehicle weight and is above 70 kW. Important improvements in powertrain configurations are also needed in order to handle the increased thermal management demands [20, 21].

PHEVs can work in two modes: charge depleting (CD) and charge sustaining (CS). When the PHEV is fully charged, it is driven in CD mode, where the vehicle is powered by the energy stored in the battery. Once the SoC reaches its minimum level, the vehicle changes to CS mode, and the fuel engine start driving the vehicle (like a HEV). After fully charged, the range in CD mode (or all electric range-AER) is the distance a PHEV can work electrically with the heat engine off, before the engine turns on for the first time (switched to CS mode). A common notation is used to describe the CD range: PHEV-x, where x means the CD range in miles (i.e. PHEV-10, is a vehicle with CD range of 10 miles) [38, 39].

A PHEV operates like a HEV when the battery is discharged to a certain SoC (depleted). Most HEVs operate in a CS mode around a predefined SoC. During CS operation, the battery has to meet the discharge and regenerative power with available energy around this SoC. The United States Advanced Battery Consortium (USABC) and the FreedomCAR partnership have set battery requirements and targets for CS power-assist HEVs [38].

3.2.3 Electric vehicle (EV)

EV, also called BEV (Battery Electric Vehicle), is a fully electric vehicle with no supplementary fuel engine. The battery must be recharged by plugging it into the electric grid every time the mileage capacity of the battery is exhausted. The main advantages of EVs are their independence of fuel use and their low emissions, which depend on the power source of the utility plant producing the electricity to recharge the EV. A disadvantage of EVs is their limited driving range, which may be several hundred miles, but is still lower than driving demands. Thus, the principal challenge for the EV batteries is to provide a good driving range performance before recharging, comparable to that of the ICE (approximately 300 miles). With recent technologies, recharging the battery pack of an EV can take from four to eight hours, and the need to recharge can occur on the road; therefore, all the road infrastructure must be changed to provide this service, and customers have to adjust their schedules around it. The idea of lacking a back-up system in EVs is a big limitation that implies more technical demands, and drives to the faster development of PHEV and HEV technologies [36, 40].

3.2.4 Parameter comparison

In order to compare the different battery requirements related to every HEV configuration, various parameters are taken into consideration. Table 3.1 shows the common values that characterize each HEV configuration for parameters like power, energy, and voltage, which are useful to select the optimal battery. The energy content and the power performance are the main specifications for the battery design. In addition, calendar life and weight are also important.

Table 3.1: Characteristic parameters of HEV configurations [35, 41, 42]

HEV	Energy(kWh)	Power(kW)	Voltage(V)	Weight(Kg)	Calendar life
Micro	~ 0.025	$2 - 4$	12	< 10	15 years
Medium	< 1	< 10	$12 - 42$	< 20	15 years
Full	< 4	$< 50 - 70$	> 200	< 50	15 years
Plug-in	$5 - 20$	~ 80	> 200	< 50	15 years
BEV	> 15	$40 - 80$	> 300	~ 120	> 5 years

3.2.5 HEV architectures

One important advantage of HEVs is the flexibility to be powered by electricity, a fuel, or both. For this, HEVs have an electric motor and a heat engine which make the vehicle's design more complex. In addition, an electronic control system determines the interaction between the power sources. There are two general categories to arrange the primary and secondary power sources: series and parallel. Figure 3.1 (based on [39]) shows a general architecture for each configuration.

In *series configuration* (also called Range-Extended Electric Vehicle - REEV) a serial drivetrain powers the vehicle using an electric motor and energy from the battery. The output of the heat engine is converted to electrical energy by a generator, and the battery can be charged through it, or through an electrical outlet. In *parallel configuration*, the

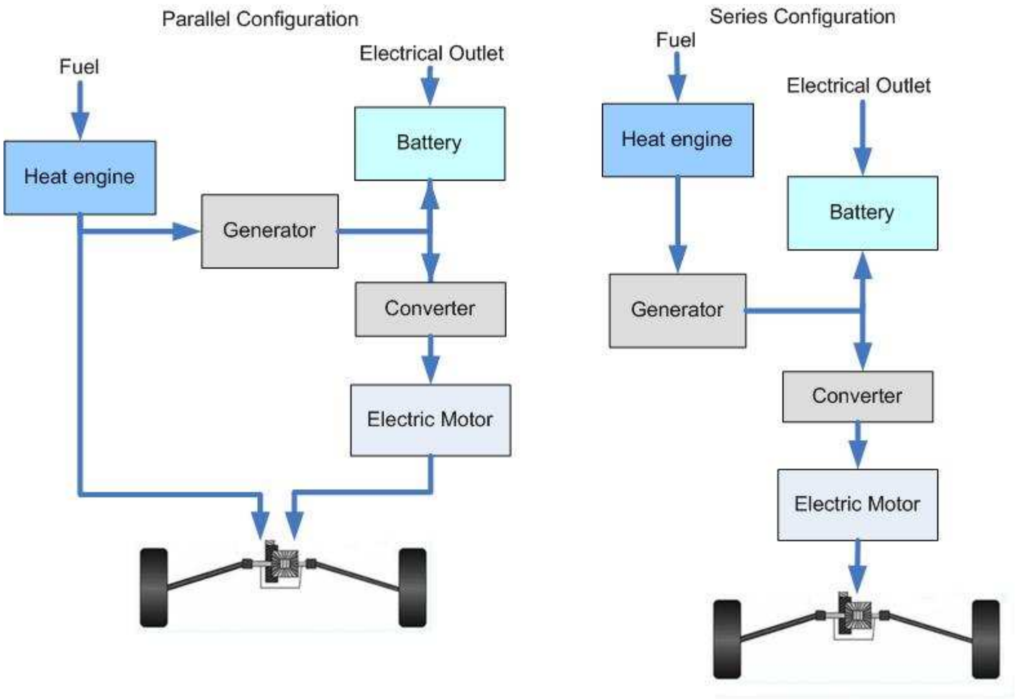

Figure 3.1: HEV parallel and series architectures

primary engine shaft has a direct connection to the drivetrain, providing the opportunity to use electricity and fuel at the same time, or fuel only. In comparison to the series system, the heat engine in the parallel system is larger, with an output around 80kW. The electric motor is smaller, with an output around 30kW, and provides additional power when the demand is higher than the heat engine's capacity can handle at maximum efficiency (in acceleration and hill-climbing). In the series system, it is common that the heat engine has a smaller output, and the battery has a larger one. Toyota is developing the plug-in version of the Prius, using parallel architecture, and General Motors Corporation (GM) is working on the Chevrolet Volt based on series architecture [34, 39].

3.3 Battery Parameters and Energy Management

In this section, the most important parameters for battery design are explained, as well as the main concepts related to battery management and monitoring.

3.3.1 Battery parameters

The discharging/charging behavior of a battery depends on a number of factors like current, voltage, and temperature. This section presents the main parameters that specify the behavior and performance of a battery for hybrid and electrical applications.

Cell and battery voltages

Electric cells have nominal voltages which represents the approximate voltage when the cell is delivering electrical power. In order to provide a required voltage, cells have to be connected in series. The voltage will fall when the battery is in use, and will raise when the battery is being charged. The equivalent circuit of a battery is shown in Figure 3.2 [43]. A general equation to represent this behavior is:

$$V = E - I \cdot R \tag{1}$$

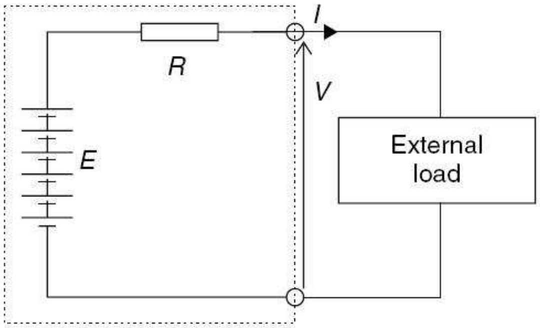

Figure 3.2: Equivalent circuit of a battery with 6 cells [43]

If the current I is zero, the terminal voltage is equal to E, and this is called the open circuit voltage (OCV); this can be used for an approximation of SoC in some systems. However, Lithium batteries have a high initial OCV, that falls by some millivolts and never recovers its initial value. If the battery is being charged, then the voltage will increase by $I{\cdot}R$. Clearly, in electric vehicle batteries the internal resistance must be as low as possible. The closed circuit voltage (CCV), or cell voltage under load depends on the SoC, the current, temperature, lifetime and storage period [43, 44].

Internal resistance

The internal resistance determines the battery's power output, and represents the capability of the battery to handle a specific load. The battery internal direct current (DC) resistance must be low to avoid voltage drop caused by the current demand, which limits the battery's output. This value can change depending upon the way how it is calculated, and the SoC. In most of the battery systems, the internal resistance comprises the ohmic resistance within the electrodes and the electrolyte. Such resistance increases when the conductivity is reduced on the active materials, mainly when the end of discharge is approaching [44].

Battery capacity

The battery capacity is defined as the electrical charge in units of ampere-hour (Ah) that can be extracted from the battery. This is one of the most important parameters that must be considered in battery modeling, because usually changes in capacity are a result of unwanted side reactions inside the cell. Capacity also depends on the time the battery takes for discharge, the current of discharge, the end-of-discharge voltage, and temperature. SoC and the previous storage period also have influence on it. The nominal capacity of a battery is typically specified by the manufacturer [43, 44].

Energy stored

The main purpose of a battery is to store energy. The energy stored in a battery depends on the electrical charge stored and its voltage; thus, it has a variable value. It also depends on the discharge rate and the temperature. Its common measurements are given in watt-hour (Wh) [43, 44].

Available energy

This concept refers to the energy that can be obtained from the batteries as they operate in HEVs, between 25% and 75% SoC. An HEV battery has a capacity around 10% above and below the nominal baseline level of 50% SoC. Thus, what is available is only about one-half of the total battery energy. Therefore, in terms of battery design, it is very important to consider the full battery capacity or energy, and not only the available value [34].

Energy density

In order to compare systems, it is very common to relate a battery energy content with its weight or volume. Energy density is the amount of electrical energy stored per cubic meter of battery volume. It has units of Wh/m^3. If we know this value and the energy stored, it is possible to estimate the required volume (m^3), which has an important impact in the vehicle design [43].

Specific energy

Specific energy is the amount of electrical energy stored for every kilogram of battery mass. It has units of Wh/Kg. With the energy stored in the battery and the specific energy, an estimation of the battery mass can be given. As a reference, a typical value for the specific energy of a lead-acid battery is 25 Wh/kg, while a modern Li-ion battery offers 125 Wh/Kg or more [43, 44].

Specific power

Specific power is the amount of power obtained per kilogram of battery (W/Kg). It can vary, because the power given out by the battery depends upon the load connected to it. However, it is not recommended to operate a battery close to its maximum power for more than a few seconds, because it is going to discharge very fast and the operation will be inefficient. Some batteries have very good specific energy, but with low specific power, which means they store a lot of energy, but can only give it out slowly. Thus, high specific power normally results in lower specific energy because at high power, energy is taken out of a battery quickly, which reduces the available energy [43].

Energy efficiency

Energy efficiency is the ratio between released energy and stored energy. This is a very important parameter, and is very used in electric vehicles to analyze how efficient their use of energy is, which results in the reduction of emissions. Energy efficiency will change considerably with how a battery is used: if it is charged and discharged very fast, energy efficiency decreases in the same proportion. An energy efficiency as high as possible is the desirable result. Therefore, the battery must have limited losses in terms of energy transfer and self-discharge [18, 43].

Duty cycle

In general terms, the battery is operated at a nominal SoC level near 50%, so that it can deal with charge/discharge overcurrents without going into overcharge (above 80% SoC), deep discharge (below 20% SoC), or overdischarge (below 0% SoC). A normal operating window for HEV batteries is between 30-70% SoC, but it can change depending upon the technology used; it is seen that only about half of the capacity is being used. The nominal hybrid operating level is chosen depending on the charge-delivery and charge-acceptance characteristics of the electrochemistry and battery type being used in the vehicle. In design, a level below 50% SoC would be used if a battery is better on discharge than on charge acceptance, but, if it is better in charge acceptance, a level above 50% would be chosen [34].

Battery life

The exact number depends on the deep cycles, the battery type and design, and also on how the battery is used. Over the time, battery performance degrades, including power, energy capacity, and safety. Two types of battery life can be considered: calendar life and deep cycle life. Calendar life is the battery's ability to resist degradation over time, and is independent of how much the battery is used. The USABC, the Massachusetts Institute of Technology (MIT) and the Electric Power Research Institute (EPRI) have set a goal for battery life in 15 years at a temperature of 35 °C. On the other hand, deep cycle life is the number of discharge-recharge cycles the battery can perform. One full deep cycle would be: starting at 90% SoC, ending at 25% SoC, and recharging back to 90% SoC. The USABC's battery goal is 5,000 deep cycles. This goal assumes one complete deep cycle each day, 330 days of the year, for the 15 year life span of the vehicle [39].

Operating voltage limits

U.S. Department of Energy (DOE) and the Partnership for a Next Generation of Vehicles (PNGV) have specified an operating range of 300-400V, which implies an OCV of 350 V at 50% SOC. This allows for a 50V window either way during operation, necessary for compatibility with the control system electronics [34].

Depth of discharge (DoD) and self-discharge

Energy storage is followed for a quick release of energy on demand. The discharge is also called the power transmission rate, and can be a limiting factor that determines the time needed to extract the stored energy without affecting the battery life [18].

Self-discharge is the amount of energy dissipated for the battery over a given amount of time without using it. This is an important factor to determine for how long the battery can be left without recharging. This parameter changes with battery type and temperature [43].

Cycling capacity

Cycling capacity is the number of times the battery can release the energy level required after each recharge [18].

3.3.2 Energy and battery management

Conventionally, the alternator output voltage in electric vehicles systems was chosen to guarantee sufficient recharge of the battery after lighting and engine cranking. In the present, the alternator voltage setpoint is typically modified depending on estimated battery temperature, vehicle acceleration demand, etc. With the introduction of fuel-saving strategies, power supply management, and vehicle electrification, energy and battery management becomes mandatory for HEVs and EVs [45, 46]. The final goal of *energy management* is to guarantee the suitable electrical power supply to a component. If the expected voltage or the available energy under an estimated load is too low, energy balance may be improved by a reduction of energy consumption or by an increment of energy generation. In other words, energy management refers to control of generation, flow, storage, and energy consumption, and it depends almost completely on battery management [45, 47].

The term *battery management* should be used only if an active feedback is given to the battery. Normally, batteries are only passively monitored, and information is provided, but not managed. Common measurements of observable values such as voltage, temperature, and current are provided by the Battery Management Systems (BMS). These values are input data processed during Battery State Detection (BSD). BSD is related to the analysis of non-observable values, or internal parameters and properties that may not be accessible for direct measurement, such as acid gravity, active material utilization, no homogeneities, etc., but that help to determine battery state, performance, and capacity. In addition, battery management covers the control of current and voltage levels, recharge conditions, operational limits with respect to SoC and temperature, temperature management, among others [47].

Battery management is important to analyze the battery state of charge (SoC), state of health (SoH), state of function (SoF), and ensure that the vehicle can be restarted. In the case of back-up batteries, the SoC and SoH are monitored to verify that the battery is always capable of carrying out the required duty cycle in a given moment [48].

Battery management system (BMS)

BMS is a solution to provide accurate information about the battery state, and to ensure two basic functions: improvement of reliability and robustness of the power-supply system, and reduction of fuel utilization and CO_2 emissions, which require higher demands on the battery. BMS consists of a sensor that measures current, voltage and temperature of the battery, and an algorithm that determines characteristic information about the battery state, charging voltages and refresh cycles. BMS' outputs are defined in terms of SoC, SoH and SoF. This information is very important for hybrid and EVs, to perform system-level energy management. However, in recent automotive applications, other parameters like dynamic power delivery and charge acceptance are as important as battery state [46, 49].

Usually, BMS uses an acquisition unit for monitoring battery voltages, currents, temperatures, and other parameters like pressure, and estimating battery status. In addition, electrical, chemical and thermal models are included to determine SoC, SoH, SoF, internal cell temperature, internal resistance, etc. Using these values, the BMS can define the next adequate load limits. Through a Controller Area Network (CAN) interface, these results are communicated to the energy management system to define the load flow between the ICE, the electric drive and the hydraulic braking system, as shown in Figure 3.3. Also, BMS controls the cooling system: it regulates the cooling fan speed if air is used, or the pump delivery in case of a liquid cooling system.

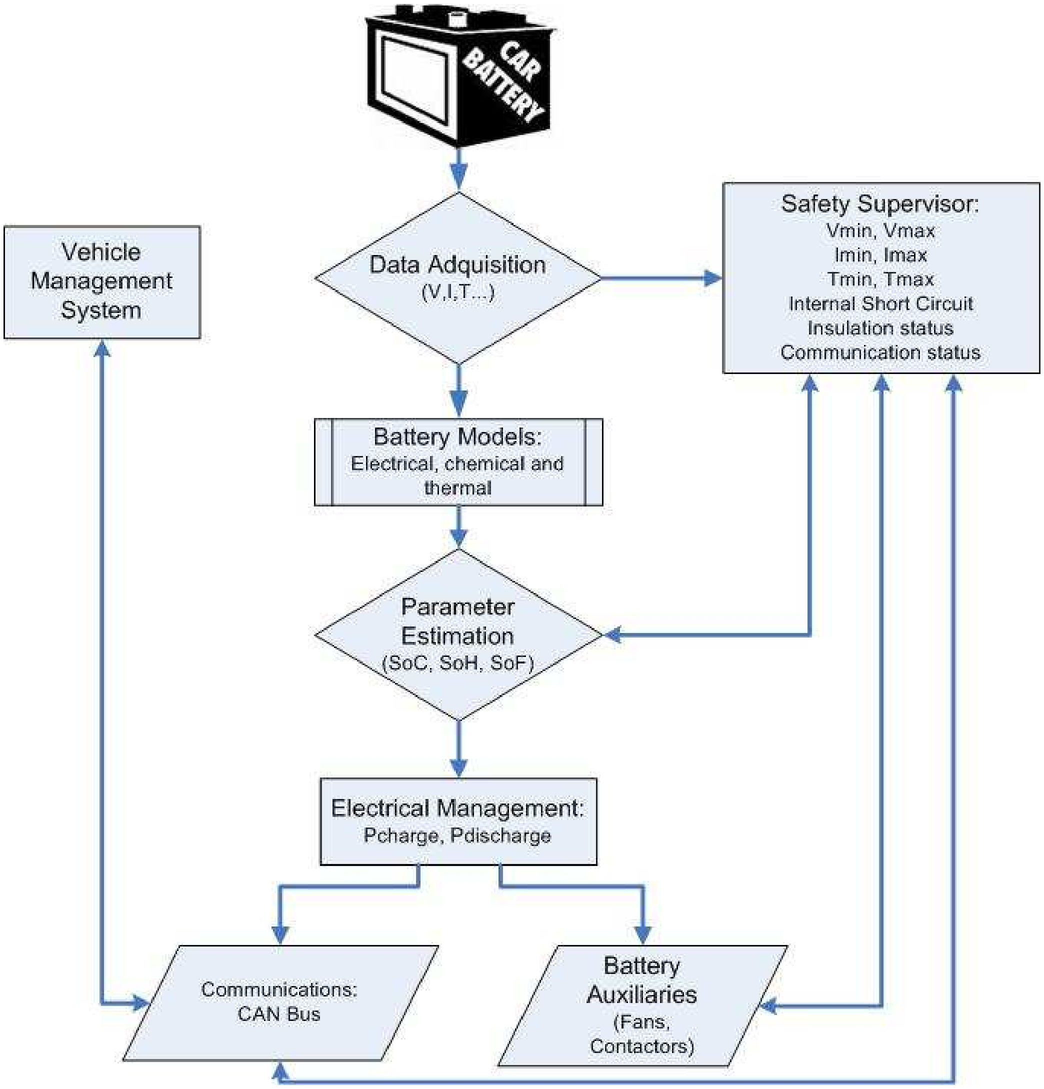

Figure 3.3: Battery Management System flow diagram (based on [42])

Additionally to those functions, BMS is in charge of the battery safety supervision, to ensure that voltages, currents, and temperatures are within appropiate ranges. It also checks insulation state, and if needed, it can operate the contactors to disconnect the battery from the powertrain. Finally, the communication between the vehicle management system and the BMS is supervised, and an emergency disconnection can occur when any problem is detected [42].

Knowledge of the SoC, SoH and SoF permits specific and dynamic battery management. This could include consumption control, switching of quiescent and charging current, warning signs, as well as control information to increase the SoC.

State of charge (SoC) SoC is the percentage of electrical charge actually stored in the battery with respect to the total storage capacity. However, battery manufacturers are interested in the amount of charge they can get instantly from the battery, including the actual status of the battery. SoC is a monotonous state function, which does not change with temperature changes or with time without an electrical current flowing. Therefore, algorithms and mathematical treatments can be applied to SoC values. Many approaches have been made to implement SoC sensors within the batteries, making use of property changes of the electrolyte like specific gravity (SG), conductivity, refraction, vapor pressure, etc. The methodology utilized to measure SoC is based on measuring the equilibrium open circuit voltage (OCV) when the vehicle is not in use. SoC is measured by analyzing the voltage dip on starting, and the voltage response to small fixed load applied every few hours when the vehicle is not operating [31, 45, 48].

With a linear relationship between electrolyte's SG and OCV, SoC can be calculated as:

$$SoC = (OCV_{actual} - OCV_{min})/(OCV_{max} - OCV_{min}), \tag{2}$$

where OCV_{max} and OCV_{min} are equilibrium open circuit voltages at two different SoC values, e.g., 100 and 20%. However, this definition by itself is not very useful, because the OCV can have many variations after a long battery relaxation time. Even if the vehicle is parked, the OCV may need many hours to achieve the equilibrium, and it is not possible to identify if a recharge period occurred just before. In addition, higher battery loads required for HEVs can reduce the measured voltage and give an underestimated OCV value [31, 45].

Based on the SoC value, the depth-of-discharge (DoD), or the fraction of battery capacity that can be used from the battery, can be calculated as [45]:

$$DoD = (1 - SoC). \tag{3}$$

Accurate estimation of SoC is a complex task. Classical methods for SoC estimation include: measurements of the extracted charge, battery internal impedance or resistance, and battery voltage without load. Statistical models, or artificial-intelligence-based models can be also used. However, the best way to provide an accurate result is by using a combination of two or more of these methods [49].

State of health (SoH) SoH describes the battery's degree of degradation. A battery may not be able to fulfill a special specification, but still can have the capacity to complete another. Then, SoH measures the internal resistance, which change with battery life at a given SoC. Therefore, SoH is defined using the power profile which describes the battery's duty cycle. Under the load of this power profile *P(t)* or current profile *I(t)* of duration t_0, the voltage of the battery will show a minimum value, U_{min}. The lowest acceptable voltage under load, U_1, and the lowest voltage of a typical relaxed battery, U_{fresh}, are used to define SoH as follow [31, 45]:

$$SOH = (U_{min} - U_1)/(U_{fresh} - U_1) \tag{4}$$

As one can see, SoH is a monotonous state function that can have different values, each one representing a state of the battery. A relaxed battery is represented by SoH=1, a battery just meeting the threshold has SoH=0, and negative SoH values represent batteries which fail the specified duty. SOH depends on temperature and SoC [31]; if a battery has several duties, all the respective SoH figures can be checked, and the minimum SoH value is used as a general value for the battery [45].

State of function (SoF) In many cases, the battery's SoC or SoH do not help to determine if the battery performs as needed [45]. Therefore, the SoF can be determined by measuring the SoC and SoH in order to monitor battery condition. SoF defines to which degree the battery could currently perform an intended function [48]. In general, SoC and SoH compensate each other with respect to battery performance: a poorer SoC may be acceptable for a relaxed battery with high SoH, or an old battery with lower SoH may complete its duty if it is kept at a higher SoC. In this way, the SoF combines the battery state parameters (SoC, SoH, temperature), and in some cases the short-term previous discharge/recharge history [45]. The SoF is based on state parameters, rather than on reference conditions, as it is the case of the SoH. When a current profile *I(t)* is the relevant duty for evaluation, the voltage response can be used for calculation:

$$SoF = (U_{min} - U_1)/(U_{fresh} - U_1), \tag{5}$$

for actual SoC, SoH and temperature condition. In the case of braking energy recuperation as the target battery property, the amount of charge Q that can be recharged within a certain period of time will give the relevant information:

$$SoF = (Q_{min} - Q_1)/(Q_{fresh} - Q_1), \tag{6}$$

for actual SoC, SoH and temperature condition. For other types of battery duty, the appropriate observable values for SoF determination may be defined as needed [47].

3.3.3 Determination of battery status

In order to guarantee correct functionality of electrically powered components in the vehicle, to keep the battery in its best operational window, and to detect limited battery functionality on time, battery performance must be determined by constantly measuring temperature, SoC and SoH. The correct strategies to define SoC and SoH have to be chosen according to the specific environment, and should include expected operating scenarios and acceptable error tolerances [47]. Additionally, the SoF has been proposed to define the output of an automotive BMS. Each SOF directly sends information to the vehicle-level energy management, regarding to which degree the battery could support specific loads, deliver propulsion power, or accept regenerative (REGEN) charge [46].

In addition, voltage U, temperature T, and current I can be measured directly (observable values) to perform battery monitoring. These values are the input information for battery state detection (BSD) [47]. This term includes the analysis of the state vector P of the battery, and values of internal parameters that may not be accessible for direct measurement. When analyzing the battery status, voltage and current must be evaluated as function of time. Also, additional sensors must be needed to determine temperature and to compensate its influence on battery properties. In [45], some alternatives are evaluated for processing and evaluation of measured data, such as balancing of current flow for tracking of changes of SoC, estimation of a dynamical battery impedance, evaluation of battery voltage at point of zero current, analysis of battery open circuit voltage, and comparisons with characteristic patterns or mathematical models. In fact, no matter what the final design of the vehicle electrical system is, there will be more electrical power needs in future designs. For systems needing a highly-reliable power supply, the battery becomes a main component into the electrical system. Therefore, determination of battery status will be of higher importance in order to keep the battery in a good operational range, to predict its capability, and in multiple battery systems, to control the mutual energy exchange.

3.3.4 Prediction of battery performance

Once the state values are determined, the battery behavior under a possible future load profile can be predicted. A load profile must be predicted using characteristic data or mathematical models, and it is characterized by the current $I(t)$ or the power $P(t)$ needed as a function of time, and by the lowest (or highest) allowable voltage level. The prediction may be made for the short-term, with current battery status, or for medium-term with an estimated future status of the battery [45]. In addition, four different approaches have been defined for the determination of changes in battery characteristics. When all the information is available, these approaches may be combined with a BSD, to gather all the information by [47]:

- monitoring of battery operating history to determine the age and actual status,
- consideration of special events, to improve estimations based on real conditions,

- for different load profiles, direct measurements of battery status for early detection of health conditions,
- for parameters that are not accessible for direct measurements, use of models for estimation of battery state and ageing.

3.3.5 Determination of battery degradation

Determination of battery performance is related to an actual battery status. Degradation means performance under hypothetical reference conditions, such as SoH with respect to a certain load profile. However, SoH describes the actual battery status only. For prediction of the battery degradation and battery lifetime, a special life model is needed. Battery properties such as corrosion, water loss, changes of active material properties, etc., must be analyzed [45].

3.4 Battery Requirements

In vehicles with an internal combustion engine, the energy storage device is the passive starting, lighting, and ignition (SLI) battery, which charge and discharge depending on the energy that is consumed and generated. The battery provides the electric power for cranking the ICE, maintains electrical energy during operation, and supply electrical energy when the engine is off. This energy is recharged from an alternator driven by the internal combustion engine (ICE) [31, 45]. In classic vehicles, SLI batteries are of the Lead-acid type, with 12V nominal voltage and flooded design. An improved technology, the VRLA batteries, have been used in vehicles since late 1980s without been outspread in large numbers [50]. Lately, different battery designs are available, where Nickel and Lithium technologies are in an advanced level of development. Also, vehicle electrical architecture changes are under consideration, and dual voltage, high voltage, and dual battery systems are evaluated to enhance production, distribution, storage, and management of electrical energy in the vehicle [31].

The demand for electric power in vehicles is growing. In particular, using electrical energy for vehicle's propulsion presents important advantages in the attempt to reduce fuel consumption and CO_2 emissions. In addition to electrically controlled and powered systems for steering, braking, and stabilization, new functions have been introduced, such as an improved battery cycling for the ICE's stop/start operation mode, the torque assist/acceleration assist mode, electrical brake energy recovery, and energy management to detect the battery capability to accept charge. These trends are imposing new requirements on the energy storage devices [20, 47]. The new HEV and EV designs have to provide fuel economy, reduced emissions, longer cycle life, safety, comfort, reliability, and availability.

As the technical demands for new automotive batteries increase, as well as the power requirements for electrical systems, a summary of the common battery requirements are identified as follows [21, 31, 32, 34, 45, 46], [51]-[55]:

- High battery capacity and high cycling capability to cover increased energy demands for engine-off and idle periods. The useful battery capacity is only half of the nominal capacity, because it must operate at a SoC close to 50%, to manage charge or discharge and prevent overcharges above 80%, or discharge below 20%.

- High discharge power to hold up new cranking technologies, which require very fast changes in the engine's duty cycle for rapid acceleration or hill-climbing.

- Good recharge capability, for quick response during engine-off and idle periods. Charge acceptance characteristics (specifically at low temperatures) define the charge balance of the power supply system. Contrary to the deep discharge in traditional non-HEV applications, advanced HEV applications will require good charge acceptance in a dynamic discharge/charge operation. This is called dynamic charge acceptance (DCA). Batteries for HEVs and EVs are operated in a partial SoC (PSoC, between 30% and 70%) to provide a higher boost-charge acceptance during regenerative braking.

- Higher power capacity. The demand, that started from less than 500 W in the nineteen sixties, had been increased to more than 2 kW by the year 2000. Considerable increments have been experienced by actual EVs (the Chevrolet Volt pack contains 16 kWh of lithium-ion cells of which 8 kwh are usable).

- Improved automatic stop/start features (particularly for urban traffic) and driving strategies to minimize pollution and energy waste during engine idling [53].
- Changes in electrical network architectures, with the possibility of dual-voltage levels due to the increased loads powered by the electrical system. There are loads that can operate at lower voltages, and others that, because of the high power consumption, must be operated at higher supply voltage. 42V PowerNet has been established, as a solution to fulfil the demands for higher efficiency in the different vehicle functions and components.
- Redundant design and battery management and monitoring to ensure high reliability for cranking and constant energy to safety and relevant components. Additionally, algorithms are refreshed to keep the battery in the appropriate working conditions. These algorithms consider both the SoH and the available vehicle's energy. In this way, possible failures caused by low or high SoC levels can be prevented.
- Battery's reliability depends on cells' reliabilities; therefore, higher voltage batteries (with a larger number of cells) have to maintain more severe reliability goals at the cell level. Because of this, battery manufacturing processes require better process control to meet these higher reliability levels.

These functions may be realized independently or as a combination with each other. Satisfying all these requirements simultaneously and efficiently with respect to technical and cost restrictions is still in progress.

3.5 Development of Battery Technology

Developing high-performance rechargeable batteries for EVs is a challenging task because of the need to fulfil multiple battery requirements: high energy, high power, safety, long life, low cost, resistance, and minimal environmental impact [56]. In recent years, automakers are focusing on battery for HEVs, including 42 volts enhanced power generators/alternators, and integrated starter-generator (ISG) systems. They have developed a set of general battery performance and price goals through the Partnership for a Next Generation of Vehicles (PNGV) and the United States Advanced Battery Consortium (USABC).

The PNGV program leads research and development (R&D) projects with the federal government and the United States Council for Automotive Research (USCAR), formed by Ford Motor Company, Daimler Chrysler Corporation, and GM. The main objective is to improve competitiveness in manufacturing and to implement energy efficient solutions for passenger vehicles [33, 57]. By 2011, PNGV's goal is to reach a continuous production of new passenger vehicles that accomplish an equivalent of 100 miles per gallon with conventional fuels [34]. On the other hand, the U.S. Department of Energy's (DOE) Vehicle Technologies Program (including the FreedomCAR and Fuel Partnership programs) has developed R&D activities to improve the batteries and power electronics of PHEVs while enhancing vehicle efficiency technologies. At the same time, DOE, USABC and U.S. automakers are working in developing advanced batteries for PHEV applications and defining battery requirements. Several laboratories, like Argonne National Laboratory (ANL) and National Renewable Energy Laboratory (NREL) are also conducting analysis to help define different battery requirements [33, 38].

In the last 15 years, many different approaches have been presented by major automakers and other research programs. In 1996, the EV1 from GM was introduced, moving the concept of EV to the commercial market. In September 2000, the RHOLAB project (reliable, highly optimized lead-acid battery) was proposed under the UK Foresight Vehicle Programme with the objective of developing an optimized lead-acid battery solution for HEVs. Real vehicle data was collected from testing the battery pack in the Honda Insight. However, the limited driving range of lead-acid batteries had limited their market acceptability and activated the development of higher-specific energy batteries [58, 59, 60].

NiMH batteries quickly became the technology of choice for the emerging electric vehicle market. Major automotive companies including Daimler Chrysler, Ford, GM, Honda, and Toyota have developed HEVs with NiMH batteries into the market [60]. Toyota introduced Prius, the first commercial HEV, using a 6.25 Ah cylindrical sealed NiMH D-size cell [34]. In 1994, GM joined Ovonic Battery Company (OBC) to impulse NiMH battery technology for electric and hybrid vehicle applications. After this, GM announced that they would introduce the EV1 with NiMH batteries in 1999, with a driving range of up 140 miles on a single charge. They also launched their electric conversion S-10 pick-up truck equipped with GM Ovonic NiMH batteries, offering a range of over 90 miles [60]. Other advances were proposed by Varta, Ovonics and SAFT in 2000, and funded by the U.S. DOE for use in the PNGV Programme [34].

Recently, given the high cost in NiMH technology, as well as the oversized battery packs, battery researchers have turned their interest into Li-ion technology [61]. Li-ion batteries have a higher energy density than any other type batteries. Even though NiMH battery holds about twice the energy per pound of the conventional lead-acid battery, Li-ion cells hold roughly twice as much energy per pound as NiMH batteries do. The ability of Li-ion batteries of carrying relatively high energy makes the development of EV possible. In addition, lithium is the lightest solid element, so it is easily portable, and cheaper than other battery raw materials [59]. To make Li-ion batteries practical for mass-produced EVs, new technologies must be developed to increase the energy storage and fast discharge capability of the batteries. In addition, the battery cycle life must be lengthened to the average vehicle life, and the cost must be kept as low as possible [62].

The Toyota Vitz CVT 4, a car sold only in Japan, was the first production car to use Li-ion batteries. It used a four-cell, 12 Ah Li-ion battery pack to power electric accessories and restart the engine after idle stop [62]. Recently, Tesla Motors, in San Carlos CA, presented the Tesla Roadster, an all-electric sport car that uses 6831 Li-ion cells. They give the car up to 250 miles of range, as well as the acceleration of 0 to 60 miles per hour in less than 4 seconds [62]. But the major developments are just starting. In January 2010, GM launched the first Li-ion battery pack manufacturing plant in the U.S. operated by a major automaker in Brownstown, MI [63, 64]. The raw lithium cells will be delivered from LG Chem's plant in Korea. After the packs are assembled at this facility they are then transported to Detroit-Hamtramack plant where the Volts will be assembled. Production is set to begin in March 2010. The Volt's battery pack is made up of multiple linked battery modules and more than 200 battery cells [63, 64]. LG Chem also plans to begin building a Li-ion cell factory in Michigan beginning later 2010 [52]. To understand the Li-ion's advance in battery size, the batteries from GM's EV1 and Volt can be compared. The EV1 pack used lead-acid cells, and it was almost 8 feet long and weighed 1200 pounds. Volt pack, using Li-ion cells, stores the same 16 KWh in a 5 foot long container weighing 400 pounds [59].

Other battery manufacturers are also increasing their investments in Li-ion technology. A123Systems is planning the construction of new world-class Li-ion battery manufacturing facilities in the U.S., with the first construction location in southeast Michigan. This plant would enable the company to dramatically expand production capacity, with full production volumes designed to supply battery systems for five million HEVs or half million plug-in EVs per year by 2013 [65]. Similar efforts on new lithium battery developments have also been observed from many other manufacturers, in addition to the research that the major automakers themselves are conducting. Once lithium batteries have met energy-storage, power-delivery, durability, and cost goals, a large investment in manufacturing capacity will be needed to produce them [62].

In Sections 3.6 to 3.9, main candidates for energy storage in hybrid and electric vehicles will be surveyed. The battery technologies analyzed are those considered appropriate by manufacturers to provide the required energy, power, cycle life, and other requirements necessary for effective HEV operation. Manufacturing processes are reviewed, along with key factors such as quality control, safety, cost, environmental concerns, and recycling.

3.6 Lead-Acid Technology

The lead-acid battery for classical SLI is a mature technology. The system consists of a lead current collector, lead oxide as the positive active material, spongelike lead as the negative active material, and sulfuric acid as the electrolyte. During discharge, active materials are transformed into lead sulfate. Lead-acid systems have been used in many applications due to their temperature tolerance, low cost, high adaptability, intrinsic safety, and well established recycling process [37, 46, 53, 66]. However, lead-acid batteries face life cycle limitations when operated at a high rate partial SoC (HRPSoC), operation mode of HEV applications [37]. In this, the battery unit will be discharged and charged at higher rates than in conventional automotive applications [67].

In addition, other disadvantages in battery performance, such as short cycle life, low specific energy, low rate of recharge, and environmental issues in the manufacturing process regarding to the use of lead, have been identified. There is also a problem in battery design: the lowest corrosion rates are reached with pure lead grids, but these are restricted to use in small cells. Moreover, to achieve low weight, high utilization of the active materials is required, and this is related to large changes in the volume of the material that limit life cycle. Basically, the limitations of the lead-acid system are caused by its electrochemistry. Failures like corrosion, degradation or creation of lead sulfate in the positive material, short-circuits, and loss of water, are among the common issues found in this technology [53].

Energy restrictions of lead-acid batteries, and the demands to reduce weight and maintenance cost, accelerated the development of VRLA batteries. VRLA batteries are maintenance-free, and power density can be boosted by increasing the surface area of the electrodes. However, this also increases the rate of corrosion and reduces battery life [37]. Some improvements in energy throughput, cycle life, power density and other requirements have been achieved with the introduction of VRLA batteries, using the absorptive glass mat (AGM) design, which uses a glass fiber mat that is impregnated in electrolyte [46, 53].

Other proposals related to the improvement of lead-acid batteries have been developed. Within the framework of the European project bipolar lead-acid power source (BILAPS), a different production option was developed for the bipolar lead-acid battery. The tests show the possibility of operating the bipolar lead-acid battery in a hybrid mode, and the costs of the system are estimated to be much lower than those for NiMH or Li-ion based high-power systems [68]. However, an important challenge is in manufacturing and quality control. The technology required for manufacturing the improved lead-acid battery type is demanding. Parameters like plate thickness, reproducible weight of active material filling, reproducible composition of materials on assembly, quantity of electrolyte filling, and pressure on the electrode plates on assembly, require more development and severe control [53].

3.6.1 Lead-acid batteries

Manufacturing process

The Lead-acid battery production process is basically an eight-stage flow shop as shown in Figure 3.4 [69, 71].

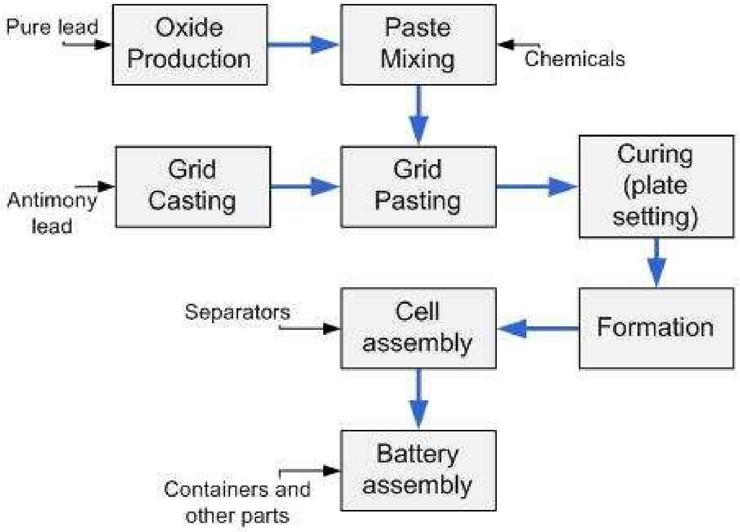

Figure 3.4: Lead-acid battery manufacturing process

Oxide production The lead oxide may be prepared by the battery manufacturer, as in many larger battery manufacturing facilities, or may be purchased from a supplier [70]. The ball-mill and the reaction-pot (or Barton pot) are two manufacturing processes for the preparation of battery oxides. According to [72], ball-mill oxide is the preferred type for ensuring product consistency, and for battery applications in places with different climatic conditions. Oxide produced by the ball-mill process is found to be mechanically less troublesome. Nevertheless, the reaction-pot method is used satisfactorily by many companies for the production of automotive batteries. It is a cheaper process, occupies less space per ton of oxide produced, and implies a lower investment. Oxide is generally stored in bunkers and transferred directly to the batch weighers feeding the paste mixers. Most of the systems are usually fully enclosed to eliminate hazardous manual operations, and to meet environmental standards. A barrel is accepted or rejected based on the average percentage of pure lead, and the homogeneity of the oxide powder in each barrel [71].

Grid casting Battery grids are manufactured by casting or stamping operations. In the casting operation, lead alloy ingots are charged to a melting pot, from which the molten lead flows into molds that form the battery grids. The stamping operation involves cutting or stamping the battery grids from lead sheets. The grids are often casted or stamped in doublets, and splitted apart after they have been either flash dried or cured [70]. Commonly, the grid casting machine is the principal method of producing battery grids. Alternative methods use expanded-metal or continuous-casting techniques. Continuous-casting process can work with both ultra-low antimony and lead-calcium alloys. With the expanded-metal technique, only calcium-lead alloys can be used [72]. The grids must be rigid, free from discontinuities, and have specified weight and thickness. Two types of test are conducted to check the grids strength and ductility. In a destructive test, a grid is bent over a 1 inch diameter steel pipe and the final sample must be free from cracks. A non-destructive test is a visual check for discontinuous parts and weigh of grids. Control of grid weight implies control of its thickness, which increases the battery cost [71].

Paste mixing and grid pasting A mixture of lead oxide powder, water, and sulfuric acid produces a positive paste. The same ingredients in slightly different proportions with the addition of an expander make the negative paste [70, 71]. The method of preparing pastes generally is a batch process, because in a continuous process it is difficult to get pastes within the defined tolerances for the production of high-quality batteries [72]. Control of types and amounts of components is essential; any major deviation in the specified quality and amount of ingredients could produce defective plates. Paste quality is monitored by visual inspection for color, and by density and penetration tests [71].

In the process, the pasting machines force the paste into the spaces of the grids, which are made into plates. At the completion of this process, a chemical reaction starts in the paste and the mass gradually hardens, liberating heat. Needle-shaped crystals of lead sulfate are formed throughout the mass. The amount of paste carried by the grids, the weight and the thickness of the pasted plates must be controlled to ensure high capability of the plate to be charged [70, 71]. Some manufacturers use precut grids before pasting, which improves the shelf life of wet batteries. This development eliminates plate cutting of unformed plates as a separate operation, and removes environmental aspects by reducing the high value scrap associated with plate cutting [72].

Curing (plate setting) For many years, curing has been made by using separate cubicles or by covering pallets of pasted grids with canvas sheets, requiring more than 70 hours. However, due to climatic changes during the year, large variability was detected. Therefore, curing procedures use special ovens having preset humidity and temperature profiles. These systems improve product consistency, quality and work-in-progress (WIP), since the turnaround is reduced to less than 48 hours [70, 72].

Formation In this process, a direct current is applied to the battery terminals to store electrical energy in the form of chemical charges. In this way, the concentration of the sulfuric acid increases and the percentage of lead sulphate decreases. Successful formation is measured by the absence of sulphated plates and cells that are equally charged. The main problems encountered in the formation process are the sulphation, overcharged and undercharged plates [71].

One of the most important manufacturing decisions is whether to make dry-charged or wet-charged products. Although plates using antimonial grid alloy can be made into dry or wet-formed products, those with low-antimony or calcium grids are processed only into wet-formed products. During dry-charge formation, the battery plates are immersed in a dilute sulfuric acid solution; the positive plates are connected to the positive pole of a direct current (DC) source, and the negative plates connected to the negative pole of the DC source. Then, the individual plates may be assembled into elements first and then formed in tanks, or formed as individual plates. In the case of formed elements, these are placed in the battery cases, the positive and negative parts of the elements are connected to the positive and negative terminals of the battery, and the batteries are shipped dry. In turn, the wet-charge formation process is done with the plates in the battery case. After forming, the acid may be dumped, fresh acid is added, and a boost charge is applied to complete the battery [70, 72].

Production of wet-formed batteries implies a reduced number of processes compared to the dry-charged, and therefore, lower levels of waste are generated. Because of the reduced number of processes, the simpler alloy situation, the environmental advantages and lower cost of manufacture, the production of wet-formed batteries is usually preferred [72].

Plate cutting For the production of dry-charged batteries from plates formed as castings, it is still necessary to include a plate-cutting operation prior to battery assembly. As mentioned before, for wet-formed batteries the cutting of unformed plates will be made before pasting [72].

Cell and battery assembly In assembly, a battery cell is formed by manually stacking a sequence of negative plate, separator and a positive plate. These separators are made of materials such as non-conductive plastic, or glass fiber. There is always one more negative plate than positive so that the end plates are always negative. All positive (and all negative) plates are welded together. Two or more cells (depending on the battery capacity) are welded in series. Connections from the first to the last cells represent the negative and positive terminals of the battery [71]. An alternative to the manual operation is the cast-on connection, where positive and negative tabs are independently welded to produce an element, and elements are automatically placed into a battery case. Then, a top is placed on the battery case, and the terminals on the top are welded to two individual points that connect the positive and negative plates to the positive and negative terminals, respectively [70].

At the end of the assembly line, automatic checks are performed. Depending on whether dry or wet-charged products are being manufactured, some other machinery may be used (i.e., vent plug placing, labeling, shrink wrapping, powered conveyors leading to acid-filling machines for wet-formed production, etc.) [72].

Quality control

Quality control should be performed continuously and should include: cadmium electrode testing of both positive and negative plates, measurement of the moisture content of positive plates, water absorption testing of negative plates, determination of the ohmic resistance of cell packs, and determination of the efficiency of the oxidation inhibitor. At the same time, operators should routinely check the temperature of the ovens used for drying positive plates, control the plate washing, and perform oxygen-analysis measurements. The cadmium electrode test is one of the most important tools available for continuous monitoring of positive and negative plates. Plates can be tested immediately after the drying machine during storage in the factory and before assembly [73].

Environmental issues

The lead oxide in the air is poisonous, and a potential danger for the worker's health. To provide worker protection, as well as a higher production rate, the degree of automation in the battery manufacturing process is very important. Advanced automatic systems in the battery production can be found in the plate manufacturing, plate stacking, and quality inspection [72, 74].

Recycling

Recycling of automotive batteries for the recovery of lead is very important, because this is one of the most used metals, and is highly toxic for the environment if it is not treated adequately. Two methods for battery recycling are identified: pyrometallurgy and hydrometallurgy processes. The pyrometallurgical process is the most used one. In this process, the batteries are crushed and separated into streams: lead materials, polypropylene scrap, and sulphuric acid. The leadcontaining materials are smelted to produce lead bullion and a molten silicate solution containing all of the lead oxides. This is smelted and reduced with carbonaceous material and fluxing agents in a lead blast furnace, similar to those used in the primary smelting of lead oxides. The low-lead slag is environmentally inert and is disposed in industrial landfills. Nevertheless, monitoring and preventing the escape of dust and fume is crucial and every stage has different sources of environmental impact [75, 76]. Hydrometallurgical methods are relatively new, but their economic and industrial viability is being proved. Hydrometallurgy is a chemical metal processing technology to dissolve a metal by using water, oxygen and other substances on a pressurized vessel. Usually there are further series of chemical processes, involving a number of separation and purification steps, which result in the production of a high purity metal. This process recovers a higher percentage of the metal concentrated, which is more environmentally friendly, and uses less energy [75].

3.6.2 Valve-regulated Lead-acid (VRLA) batteries

VRLA technology is not new. Changes and requirements for grids, paste chemistry and processing, separator development, containers and vents, thermal management, and monitoring/control technologies have been studied since the 90's [77]. VRLA batteries are characterized by immobilization of the electrolyte, which offers advantages such as prevention of acid spilling, reduced gassing rates, and the possibility of partial state of charge (PSoC) performance, since acid stratification (charging/discharging cycles repeated without acid mixing) does not occur [78]. Moreover, AGM VRLA battery development is based on previous work on active material formulations with specific additives to improve battery life under HRPSoC cycling conditions [79]. VRLA batteries have been designed to meet HRPSoC demands, as a response to the limitations of lead-acid batteries, in particular, for stop&go systems. The concept is simple: the engine is automatically cut off when the vehicle comes to a halt and is automatically restarted when the driver engages a gear, or for an automatic transmission, when the driver releases the brake. This results in heavy charge/discharge cycles. Based on this requirement, VRLA batteries have been tested with positive results, and have shown responses at higher specific power than lead-acid batteries [80].

VRLA manufacturing process does not have many differences to lead-acid batteries, but some aspects must be considered:

Alloys and grid preparation Alloys for VRLA batteries must have low corrosion rates, and must form a good corrosion layer with the positive active material [81]. While these components do not affect the energy production from the cell, they have processing/performance characteristics such as mechanical strength, corrosion resistance and conductivity [77].

Pasting and plate making Because of the cycling nature of 36/42 V applications, higher paste densities are required. Moreover, to achieve plate thickness and uniformity levels, orifice pasting techniques, or roll coating have to be employed. In order to have uniform plate stack compression and minimal damage on battery assembly, tapered-plate pasting is required [81]. Paste composition also needs considerable attention, because in most applications, the positive active material (PAM) is a limiting factor [77].

Separator/electrolyte development In valve-regulated products, the role of the separator is very important, and it is related to the distribution of electrolyte between the two plates and into and across the plate surfaces. Depending upon the action of the separator, the plate/separator porosities, and the surface areas employed, the electrolyte will distribute unevenly within a given cell, and from cell to cell. The oxygen recombination process in VRLA batteries is affected by volume and plate pore film thickness, which determines each cell's behavior. This can lead to some cells being overcharged and others undercharged [77].

Curing and drying New curing approaches have been developed to achieve a more uniform treatment, while maintaining a high throughput. Strict control of temperature/humidity conditions in the plant environment ensures minimal plate carbonation during and after drying [81].

Filling and formation Uniform electrolyte distribution must be achieved in the filling process. This becomes more difficult by the use of thin-plate designs and high plate stack compression levels. In order to ensure superior cycling performance and long shelf-life, plate formation has to result in lead dioxide (PbO_2) levels in excess of around 90%. With the use of high-density pastes, this is difficult to achieve in short periods [81].

Assembly Cells are assembled with a valve that causes a small internal overpressure and prevents a easy escape of gasses. It opens every certain time to allow the escape of hydrogen that is not oxidized within the cell [78]. Furthermore, stronger case and lid assemblies are required so that higher plate stack compressions and vent valve release pressures can be employed. The top and cell-to-cell connections are critical, and are the main source of battery failures. Correct assembly checks such as high potential and polarity reversal are normally conducted [81].

Quality control

VRLA technology requires reliable, closely controlled production processes. Plate thickness, reproducible weight of active material filling, reproducible composition of materials on assembly, quantity of electrolyte filling and pressure on the electrode plates on assembly are among the parameters that require much closer tolerances and control. Moreover, the costs exceed those of classic automotive batteries.

Monitoring and control of battery parameters such as voltage, current, and impedance are necessary in large systems such as EVs. Fault detection softwares identify bad connections, weak modules, etc. Control functions are also applied to charge and discharge, in order to ensure cell balancing. This helps to extend both discharge performance and battery life. Moreover, monitoring of environmental impact related to the use of lead, and hydrogen expulsion is mandatory [77].

3.7 Nickel-Based Technology

Alkaline batteries are nickel-based and use an alkaline solution as the electrolyte. A wide range of commercial batteries using nickel in the positive electrode have been developed since late 19th century. These batteries include nickel-iron (NiFe), nickel-zinc (NiZn), nickel-cadmium (NiCd), nickel-hydrogen (NiH_2), and nickel-metal hydride (NiMH) batteries. These batteries are discussed below, showing NiMH as a serious contender for automotive applications. On the other hand, NiZn and NiFe batteries are rarely used, while and NiH_2 is used mainly in aerospace applications, and NiCd has presented important environmental issues [43].

3.7.1 Nickel-cadmium (NiCd) batteries

The NiCd battery was one of the main competitors to the lead-acid battery for use in electric vehicles because they have almost twice the specific energy of lead-acid batteries. In general, NiCd batteries can be assigned to two broad categories: vented and sealed. Sealed NiCd batteries were used in portable devices up to 1990, and vented batteries have been developed for industrial and automotive use. In both types, NiCd batteries use metallic cadmium for the negative electrode and nickel oxide hydroxide (NiOOH) for the positive. The electrolyte is a solution of potassium hydroxide (KOH) containing some lithium hydroxide (LiOH), to improve cycle life and high temperature performance [43, 82]. Unlike the lead-acid batteries, the electrolyte does not participate in the cell reaction of NiCd batteries; it acts only as ion conducting medium. Therefore just a small amount of electrolyte is needed and the electrodes can be narrowly spaced. Thus, the internal resistance can be minimized to make NiCd batteries suitable for extremely high loads [44].

The main advantages of NiCd batteries are high specific power, a long life cycle, a wide range of operating temperatures, a good high-discharge rate, low capacity loss, and good long term storage. The high-discharge is related to the cell construction, while the rate of capacity loss depends on the electrode structure. In addition, NiCd batteries are capable of long cycling even at high DODs. Regarding the principal drawbacks, it is common that the operating voltage of each cell is about 1.2V, so 10 cells are needed in each 12V battery, compared to 6 cells used in lead-acid batteries. This explains the higher cost of this type of battery. Moreover, cadmium has been identified as a harmful and carcinogenic product, with a high environmental impact [43].

3.7.2 Nickel-hydrogen (NiH_2) batteries

The NiH_2 cell utilizes H_2 as a negative electrode, while the positive electrode is nickel hydroxide ($Ni(OH)_2$), and the electrolyte is potassium hydroxide, the same as in NiCd batteries. The hydrogen electrode consists of a thin film of platinum to improve chemical stability and catalytic properties, and is supported on a nickel foil substrate with a gas diffusion membrane. The positive electrode is a porous powder substrate, supported by a nickel screen, and impregnated with nickel hydroxide. The separator is a thin porous zirconium oxide (ZrO_2) ceramic cloth supporting the KOH solution. They provide high temperature resistance and chemical resistance for long-life batteries. Additionally, the electrode material acts only as a catalytic surface that provides or absorbs electrons. NiH_2

batteries are hermetically sealed, because in the charged state, hydrogen remains as gaseous hydrogen within the cell. In the discharged state, hydrogen is absorbed by the nickel hydroxide. The generation and consumption of gaseous hydrogen during charging and discharging give a direct relationship between the internal cell pressure and the state of charge. The electrodes are arranged as a stack in the center, the electrolyte is soaked by the separator, and the edges of the electrodes are sealed to prevent short circuits around the separator [44, 82].

NiH_2 cells can be manufactured in different configurations: individual pressure vessel (IPV) cell, common pressure vessel (CPV) cell, and single pressure vessel (SPV) cell. The IPV cell contains a single or double electrode stack in a cylindrical pressure vessel, with voltages around 1.25 volts. The CPV cell has two stacks in series in a vessel, with voltage of 2.5 volts. In the SPV configuration, a number of cells are connected in series and placed in a single vessel [82].

Among major advantages of NiH_2, high specific energy, long life, good discharge rate, and ease to control SoC are identified. Also, these batteries are sealed, and therefore, maintenance free. However, the main disadvantages are low energy density and high cost, which limit their use mainly to aerospace projects [44].

3.7.3 Nickel-iron (NiFe) batteries

NiFe batteries are based on iron as a negative electrode and nickel oxide hydroxide (NiOOH) as a positive. They are characterized for being robust, with high resistance to shocks and vibrations, and long cycle life. However, high self-discharge, low efficiency, low energy and power density, poor performance at low temperatures, and higher cost than lead-acid batteries are the drawbacks of this battery. It has been considered for possible EVs applications, with little success [82].

3.7.4 Nickel-zinc (NiZn) batteries

These batteries have NiOOH as a positive electrode and zinc (Zn) as a negative electrode. These batteries have a higher specific energy than NiCd batteries due to the Zn electrode. Also, NiZn batteries have a relatively low cost, good rate capability, good cycle life, and do not have any environmental issues. However, they have some inconveniences related to the use of Zn in the anode, like solubility in the potassium hydroxide (KOH) solution, and dendrite growth on charge, which have limited their commercial application. Some approaches have been tested, like the use of a less concentrated KOH solution, or the use of a microporous polypropylene separator, to avoid zinc migration towards Ni electrode. Tests in electrical vehicles show a similar performance to NiMH batteries at a lower cost, but their limited cyclability and short life have not permitted their introduction in commercial applications [82].

3.7.5 Nickel-metal hydride (NiMH) batteries

NiMH battery technology was introduced years ago as a substitute of the Nickel-Cadmium (NiCd) battery, which has a limited energy density, some severe environmental concerns associated with cadmium, high cost, and Nickel-Zinc battery, which has a short life [37]. All currently commercially available HEVs use NiMH technology as the energy storage system (ESS). NiMH batteries have experienced great advances in the past 15 years, with an evident increase in energy and specific power.

The NiMH battery used in today's HEVs is relatively small, has favorable life-cycle characteristics, high power, light weight, high level of safety, good thermal performance, and a configurable design [83]. In fact, NiMH batteries are the only tested and considered reliable electric power source for HEVs [36, 37, 84]. The first NiMH design had limitation related to operating temperatures, while today's batteries can provide suitable power even at cold temperatures. Many of these performance advances are the result of innovations to the metal hydride and nickel hydroxide materials [42, 46, 84]. However, the expensive raw materials make the cost a serious issue [34].

Manufacturing process

Electrodes NiMH batteries are composed of nickel hydroxide on the positive electrode, and hydrogen stored in an alloy consisting of vanadium, titanium, nickel, and other metals on the negative electrode. The electrodes must be balanced to permit that the cell is always positive-limited. This means that the negative electrode has a greater capacity than the positive. The positive will reach full capacity first as the cell is charged, and the oxygen gas generated will recombine in the negative electrode. This cycle provides a way of manage overcharge currents efficiently [37, 85, 86].

Electrolyte The NiMH cell use an alkaline electrolyte, based in a solution of potassium hydroxide with high conductivity. To improve cell performance and long cycle life, the electrolyte concentration must remain constant over the entire range of state of charge or discharge [87].

Separator The separator is made of nylon blend, to provides electrical isolation between the electrodes while still allowing efficient ionic diffusion between them [85].

Assembly The electrode groups consist of alternately stacked positive electrodes and negative electrodes inter-leaved with separators. Inserting these electrode groups into a resin battery case, and sealing with a cover equipped with a valve after filling with alkaline electrolyte, form the cell. A battery module consists of cells connected in series by metal plates, and these are configured to permit airflow between the cells to ensure an uniform temperature distribution. A sealing plate is equipped with a valve to prevent bursting with an increase of internal pressure. To obtain high power characteristics, the reaction area of the electrodes has been optimized, reducing resistance for current collection and improving electrolyte composition [82, 85, 88].

In all cases, the materials have complex microstructures that allow the hydrogen storage alloys to operate in the aggressive environment within the battery. An important design factor within the metal hydride surface oxide is to maintain a balance between passivation and corrosion. Passivation causes the active material to become electrically insulated from the grid, which can limit the capacity of the battery available for discharge and the cycle life. In turn, corrosion is highly destructive. Oxidation and corrosion of the anode metals consumes electrolyte, changes the SoC balance, and creates corrosion products capable of causing premature oxygen evolution. However, porosity within the oxide is important to allow ionic access to the metallic catalysts and promote high rate discharge [84].

NiMH batteries in commercial vehicles

Today, several automakers have used the NiMH battery packs in commercial vehicles. Some of them are presented below [59], [89]-[94].

- Toyota Prius: The Toyota Prius appeared in the U.S. in 2000, with a model change in 2004. The second generation Toyota Prius (with the Hybrid Synergy Drive system) has an Advanced Technology Partial Zero Emission Vehicle (AT-PZEV) rating (given by California Air Resources Board). Prius has a battery pack with 28 prismatic NiMH modules from Panasonic, each containing six 1.2 volt cells connected in series to produce a nominal voltage of 201.6 volts, and a total of 1.6 KWh of energy capacity. The total number of cells is 168 (the first generation Prius consists of 228 cells packaged in 38 modules). The weight of the battery pack is 53.3 kg. In addition, Prius uses the conditioning air for cooling the battery. Given that power capability increases with higher temperatures and decreases at lower temperatures, it has a control system to monitor the battery temperature and charge level. A picture of the battery pack is shown in Figure 3.5.

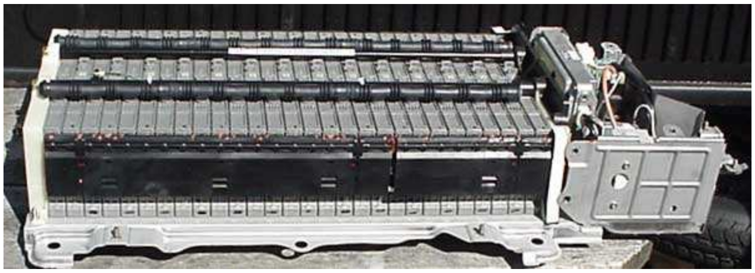

Figure 3.5: Toyota Prius battery pack [59]

- Toyota Camry: The Camry was the first hybrid model to be assembled in the U.S. Camry drivetrain is composed of a 2.4 liter, four-cylinder gasoline engine, a 105 kW electric motor, and a 244 volt battery pack. The battery pack consists of 34 NiMH modules, each of which contains six 1.2 volt cells. The Camry Hybrid moves from 0 60 mph in about 8.9 seconds, about a second faster than the Prius. A battery pack's picture is shown in Figure 3.6.

Figure 3.6: Toyota Camry battery pack [92]

- Toyota Highlander: The NiMH battery of the Highlander Hybrid has 240 cells that deliver a nominal voltage of 288 volts, but the motor generator units can operate on voltages from 280 to 650 volts. This battery pack provides 40% more power than the Prius battery, and is 18% smaller. Each module has its own battery monitoring and cooling control system, which reduce efficiency problems due to heat, and ensure the required electric power to the motor. A picture of Highlander's battery pack is shown below (Figure 3.7).

Figure 3.7: Toyota Highlander battery pack [59]

- Ford Escape: Introduced in 2004, Ford Escape combine SUV (Sport utility vehicle) capability with the fuel economy and low environmental impact of a full hybrid. The battery pack is made by Sanyo, and consists of 50 modules, and 250 NiMH cells. Each battery cell has 1.3 volts and is contained in a stainless steel case. The nominal voltage is 325 volts. A picture of Escape's battery pack is shown in Figure 3.8

Figure 3.8: Ford Escape battery pack [93]

- Honda Insight: Figure 3.9 shows the Insight's battery pack. This has a nominal voltage of 144 volts, and is made of 120 Panasonic NiMH D cells of 1.2 volts, and is monitored for the Integrated Motor Assists (IMA) power control unit.

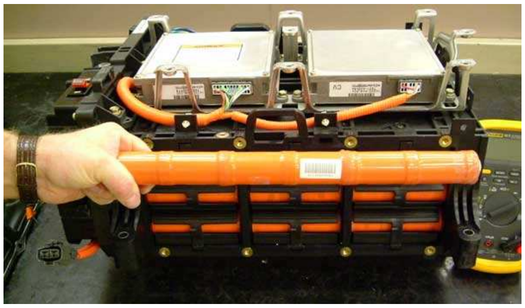

Figure 3.9: Honda Insight battery pack [59]

- Saturn Vue: Saturn Vue uses a belt alternator starter (BAS) system, where a large electric motor assists the traditional gas engine during acceleration. The electric motor is powered by a 1.8 kWh, 300V NiMH battery, which is partially charged through regenerative braking. The battery pack is made by Cobasys, consists of 22 NiMH modules and weighs about 55 lbs (Figure 3.10). The hybrid system is used to provide the power for the accessories (12v), and the power to charge the battery.

Cost

The biggest disadvantage of NiMH batteries is the cost. The battery cost consists of two parts, manufacturing cost and material expense [34]. The manufacturing cost depends on

Figure 3.10: Saturn Vue battery pack [59]

production volumes and manufacturing technology. The material cost depends on the negative electrode, positive electrode, separator, cell hardware and others, where the negative electrode is the highest one, around 45% in total material cost. Therefore, developing a cheap electrode is important for cost reduction of NiMH batteries [95].

Safety

Generally, NiMH cells contain a resealable safety vent into the top. In the case of charger failure or improper cell/charger design, oxygen or even hydrogen can be generated faster than it can be recombined. In these cases, the safety vent will open to reduce the pressure and prevent cell rupture, and then will reseal once the pressure is relieved [85].

Recycling

To recycle the current generation of NiMH batteries, manufacturers destroy the battery to find the metals between the plastic, plates, steel case and the wiring, to make sure the materials are processed for disposal. Some automakers offer a compensation to help ensure the battery is returned to a dealership and properly recycled [96].

After the market launch of NiMH batteries, the German company NIREC started works on the recycling of these batteries in order to put nickel back into the cycle of materials. The system is based on the separation, reclamation and use of the high quality nickel content and the potential risk of hydrogen. Due to the possibility of hydrogen being released when the NiMH batteries are broken down, the process must be done in a vacuum environment. The batteries first pass through a cutting chamber to open up the casing and release the stored hydrogen, then go into a collecting tank. After a stabilization period, the material can be taken out. After separation of the plastic content, a usable product is obtained with a high nickel content, which can be reused in stainless steel production (see Figure 3.11) [44].

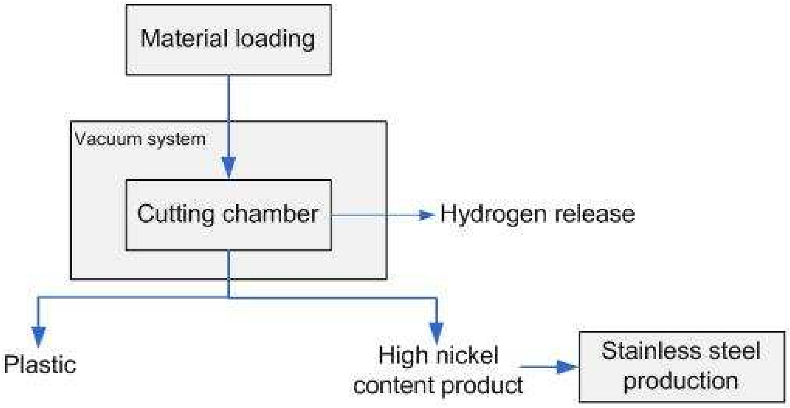

Figure 3.11: Recycling process for the NiMH battery at NIREC (based on [44])

3.8 Lithium Technology

Since late 80s, rechargeable lithium cells have been studied. They offer an increased energy density in comparison with other rechargeable batteries, but with a still high cost. This technology is becoming the principal choice for future development of PHEVs, and better performance than NiCd or NiHM cells is expected. Two types of lithium batteries have been studied recently: Lithium-Polymer and Lithium-ion batteries.

3.8.1 Lithium polymer batteries (LPB)

Lithium polymer batteries use lithium metal for the negative electrode, metal intercalation oxide for the positive, and a polymer electrolyte. The lithium combines with the metal oxide to form a lithium metal oxide and release energy. When the battery is recharged the chemical reaction is reversed [44]. This battery has shown some difficulties related to safety, and a decrease in performance due to passivation [43]. In addition, the operating temperature of this battery must be kept above 40 °C, as below this, the electrolyte has a low conductivity and therefore, a low performance. Therefore, heated element layers are used to form the cell stack, and insulation is placed surrounding it, to ensure the correct temperature no matter the external conditions. The main application for these batteries is in telecommunications as backup power, but they have also been studied for use in electric vehicles. However, they have been largely replaced by the lithium ion battery [82].

AVESTOR, a battery manufacturer, has been focused to the lithium metal polymer battery (LMPB) development. The LMPB is an advanced battery technology under development for both EV and HEV applications. A lithium metal polymer cell is made by laminating together five thin materials including an insulator, a lithium foil anode, a solid conductive polymer electrolyte, a metal oxide cathode and a current collector. This laminate is very thin, and it is formed into a prismatic shape to construct an electrochemical cell (EC), as shown in Figure 3.12. Different cells can be fabricated using the same manufacturing equipment. This flexibility allows LMPB product configurations to be adapted to different vehicles with little changes in the process and production cost. Because of the solid state nature of LMPB, the cells can be wired into parallel and/or series arrangements within a single container to build the desired module capacity and voltage [97, 98].

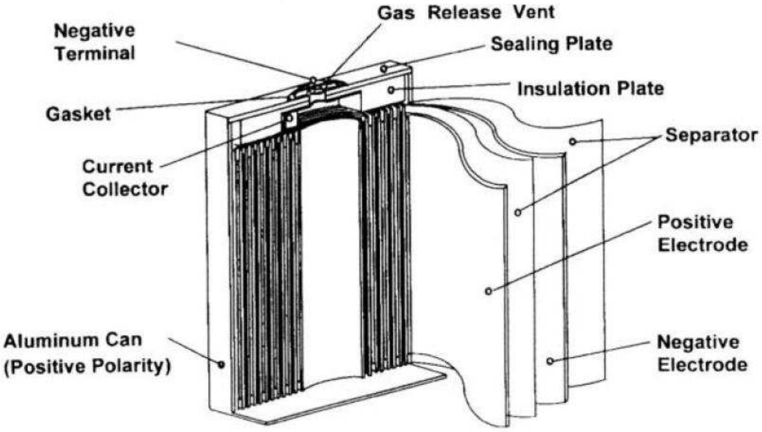

Figure 3.12: Structure of a Prismatic Li-ion battery cell [101]

3.8.2 Lithium-ion (Li-ion) batteries

The recent development in Li-ion batteries leads to a good anticipation in terms of performance and cost, potential application in EV, and customer acceptance [35]. In comparison with other rechargeable batteries, Li-ion provides very high specific energy and a large number of charge/discharge cycles. However, Li-ion batteries are only commercially available in small sizes at this time. Large numbers of cells have to be assembled in series/parallel configurations to achieve the desired battery sizes. This, combined with safety issues, and requirement in vehicle autonomy, high energy density, high charge-discharge efficiency, good load and temperature storage characteristics, accurate detection of battery SoC, long battery expected life, and good recyclability, present the challenges of making highly efficient and reliable battery packs for EV [33, 49, 99, 100].

In addition to automotive companies, other manufacturers have invested in the Li-ion technology. SAFT, a leading designer and manufacturer of advanced technology batteries, has been focused in Li-ion energy storage technology. SAFT's initial development focused on prismatic designs. After evaluation, it was determined that a cylindrical form factor offered certain performance and manufacturing advantages, specifically with respect to quality control, automated assembly and reproducibility on an industrial scale (see Figure 3.13). To meet the different energy and voltage requirements of individual automakers, a six cell module was designed to provide three different voltages and capacities, by internally connecting the cells in different fixed, series and parallel connections. In addition, SAFT's design places individual cell monitoring and control at the module level, and uses liquid to cool the module and provide effective thermal management [97].

Manufacturing process

"Basically, there is no difference between the technology implemented in small portable Li-ion cells and large industrial cells" [102]. The manufacturing process is shown in Figure 3.14, and explained as follows.

Electrodes Electrode manufacturing processes consist of coating metallic foils with a slurry containing the active material, an electronic conductor, and a binder dissolved in

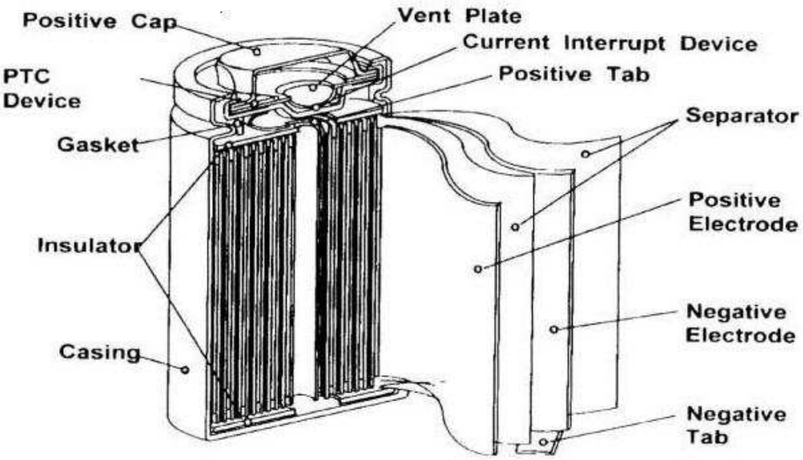

Figure 3.13: Structure of a Cylindrical Li-ion battery cell [101]

a solvent. After drying, this coating is calendered to the desired thickness and density. The electrode thickness depends on the maximal power required. This allows a wide range of power and energy ratio designs with the same basic electrode manufacturing process [101, 102]. The material used for the cathode is a metal oxide. SAFT and Polystor use nickel, or mixed nickel/cobalt-based cathodes, while Sony, Varta and Shin-Kobe (Hitachi) are developing cells with manganese-based cathodes. The anode, or negative electrode, is generally made of graphite coated on copper foil, but other forms of carbon can be used [103].

Electrolytes The electrolyte in a lithium ion cell consists of a lithium salt dissolved in one or more organic liquids. There is no significant difference in the nature of electrolytes, where Lithium Hexafluorophosphate ($LiPF_6$) is the most common salt, and cyclic or linear carbonates are the basis of the organic solvents [102]. Lately, there is a high interest in developing flame-retardant electrolytes, using additives, rather than replacing the organic solvents [103].

Separators Separators, all in the form of thin microporous membranes, may be either in polypropylene or polyethylene, or mixed polymers [102]. Separators for either high-energy or high-power Li-ion batteries are typically made from polyolefin using layers with 50% porosity. The separators keep the positive and negative electrodes apart, and serve as a

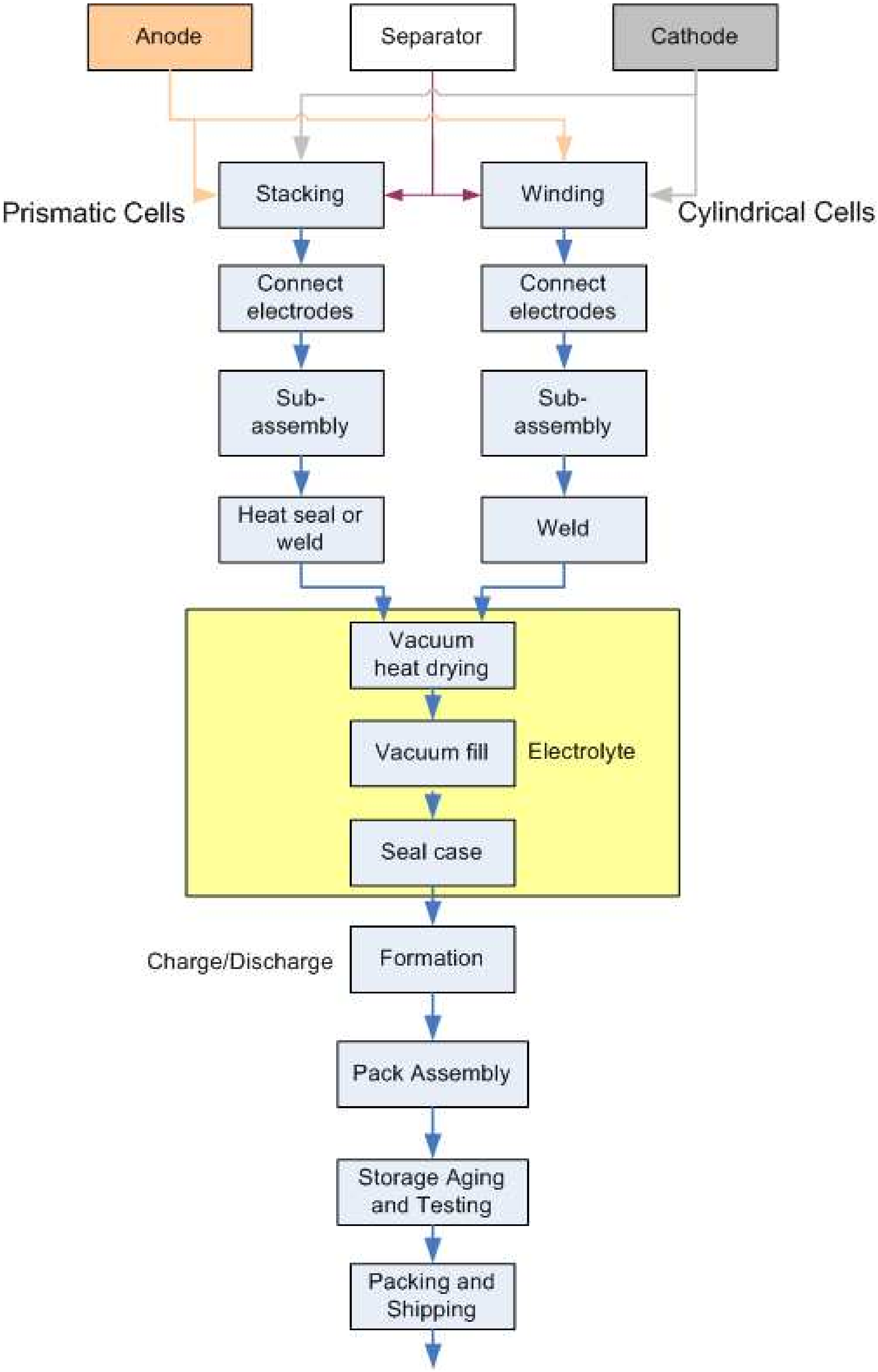

Figure 3.14: Manufacturing process for the Li-ion battery (based on [101])

safety device: if a cell becomes too hot, the low melting polymers melt, closing off the pores through which the ions travel, and cutting off the cell current [103].

Cell design The main feature of Li-ion cells is that the current is carried by lithium ions, from the positive electrode (cathode) to the negative electrode (anode) during charging, and from negative to positive during discharging. The basic cell chemistry and design are the same for all types of Li-ion automotive cells. Thin layers of cathode, separator, and anode are rolled up and inserted into a cylindrical can. The gaps are filled with liquid electrolyte. The size of the cell and the quantities of different materials contained in the cell are the main difference between a cell optimized for high energy density (for EV) and the one for high power (for HEV). Both cells can utilize the same basic spiral-wound design, same materials, and even the same current collectors and separators. However, the high-power cells must be smaller than the high-energy cells in order to dissipate the higher heat load generated. In addition, high-power batteries require less total energy, so that the battery packs for HEVs can be made smaller and lighter [103].

Cell assembly There are multiple designs for assembling cells into a battery pack for electric and hybrid vehicles. The most commonly used is the modular design, where cells are packaged together into a module. Given that Li-ion cells can suffer serious damage on overcharge or overdischarge, control devices are included in each module. In batteries with organic electrolyte, the end of charge and discharge voltages must be monitored for each cell or parallel grouping, with specific battery management features. Depending on the requirements of the vehicle, the modules can be combined into different sizes of battery packs [101, 102]. Most automotive cell designs are cylindrical, although some manufacturers produce prismatic cells. Prismatic cells offer better volume filling in assembly, but they are more sensitive to deform on cycling or aging. Cylindrical cells have better mechanical characteristics and dimensional stability within the electrode stack. Because of the small electrode's thickness, the cell stack is built by rolling the electrodes in spiral. The coil may be cylindrical or flattened to make a rectangular shaped cell [101, 102].

The process to assemble cylindrical cells is described as follows: the electrodes are formed from pastes of active material powders, binders, solvents, and additives. Then the coating machines spread them on current collector foils, such as aluminum (Al) for the cathode side and copper (Cu) for the anode side. After homogeneous thickness and particle size are achieved, they are cut to the correct width. The stacks are formed by putting separator, anode, separator, cathode, and then are rolled up to cylindrical cells, inserted in cylindrical cases, and welded to a conducting tab. Then, the cells are filled with electrolyte. The electrolyte has to wet the separator, soak in, and wet the electrodes. The wetting and soaking process are the slowest steps and determine the speed of the line. Some insulators, seals, and safety devices are also attached and connected. Finally, the cells are charged, discharged (formation process), and tested to satisfy manufacturer's requirements [101, 104, 105].

Battery assembly Once the individual cells are ready, they are assembled together into a module. The individual cells are placed one on top of another, and isolated with foam, so that they do not touch each other. Each module has a determined number of cells with total energy in the range of 1 to 2 kWh. Li-ion cell's flexibility allows direct parallel connection to get the desired capacity without other electronic components, and the ability to work in any position. Given that Li-ion cells can suffer serious damage on overcharge/overdischarge, each cell or module has an electronic board for specific battery management, monitoring and control. Depending on the requirements of the vehicle, the modules can be combined into different sizes of battery packs. Finally, a battery system consist of an assembly of modules electrically connected in series, a cooling system (air or liquid), a fuse for protection against short circuit, a contactor to insulate the battery from the vehicle, and a ground fault detector. These subsystems are usually managed by a controller that collects information and communicates with the automobile [101, 102].

Many manufacturers are planing to build their own battery assembly plants. In GM plant, three primary assembly processes are identified: the battery module pre-assembly, where cells are processed and installed into one of three battery modules. The final assembly area is where final assembly and testing of the three modules required for each battery pack takes place. Also in this area, the prismatic-shaped cells are processed and installed by flexible automated equipment into modules, which are then delivered to the battery pack main line. The battery pack main line area has an Automated Guided Cart (ACG) system that includes operations for thermal and electrical assembly, quality and dimensional checks. Battery pack's final testing, verification and packaging for shipment are made in this area too [52, 63, 64]. The Volt's battery pack is made up of multiple linked battery modules and more than 200 battery cells, storing 16 KWh in a 5-foot-long container weighing 400 lbs [52, 64].

Process Control Additionally to having a well-designed battery, process control is just as important. This manufacturing process is based on tight tolerances and strict control though the process. Contamination or physical damage on the electrodes have to be identified, because they can cause penetration of the separator, resulting in internal short circuits in the cell. Protection method for prevention or control is needed [108]. Moreover, during formation, as no overcharge detection mechanism exist in batteries with organic electrolyte, special battery management features must be implemented for each cell or module, in order to monitor charge and discharge voltages. The fuel gauge is a very used mechanism to acquire real time information about the actual SoC [102].

Packaging and shipping The packaging is a critical step after assembly. It is important that there is no reaction of the electrolyte with the packaging material or release of water from the material into the electrolyte [106]. Typically, aluminum cases for Li-ion batteries are used, since it is lighter and cheaper. Plastic is not used because it could be dissolved by the organic electrolytes [103].

Materials for Li-ion EV batteries may change, as well as the health and safety hazards, environmental concerns, and shipping requirements. Basically, the shipping requirements imposed by the U.S. Department of Transportation (DOT) regulations can change depending upon 4 different cases, if the battery is cycled or uncycled (a cycled Li-ion battery is one in which the carbon electrode has been lithiated as a result of subjecting the battery to at least one charging cycle) [107]:

- Uncycled dry battery: Given that there is no free electrolyte in the battery, and the non lithiated carbon electrode is not considered hazardous, no special requirements have to be met.
- Uncycled wet battery: If there is free electrolyte in the battery, and it is considered hazardous (flammable, corrosive, poison), the battery will be subject to the provisions of the DOT transport regulations.
- Cycled battery, fully discharged state: fully discharged state means the battery has been discharged to an extent that all or most of the lithium has been removed from the carbon electrodes; if there is presence of lithium in the carbon matrix, on contact with water, the lithiated carbon electrode would probably evolve flammable gas (hydrogen), and be considered a hazardous material. Also, it is necessary that there is not enough stored electrical energy in the battery such that there is no risk of a dangerous evolution of heat or gas as a result of internal or external short circuit.
- Cycled battery, charged state: in this case, the lithiated carbon electrode evolves hydrogen on contact with water at a high rate and there is sufficient stored energy in the battery to suppose a significant hazard in transport. This case poses the highest level of risk and the applicable regulatory requirements must be determined.

Safety

Li-ion battery technology is not intrinsically safe. Short circuit, overcharge, overdischarge, and high temperature can lead to thermal runaway, fire, and explosion [105]. When an overvoltage affects the cells, overcharge can be avoided using redundant voltage thresholds. If a short or overloading occur, overheating can be avoided by limiting the maximum current, with fuses or thermal sensors [102]. Because Li-ion cells do not have an inherent balance mechanism, they need an active external system, especially in EVs, where many cells are used in series. A basic external control system consists of a bypass circuit controlled by a microcontroller. When a cell reaches a given SoC (or discharge) before other cells, the bypass circuit is activated, discontinuing the charging (or discharging) process for that cell until balance is reached. In this way, balance is maintained between the cells and damage to individual cells is avoided [103].

In addition, to the fact that Li-ion batteries have highly oxidizing materials, their safety is compromised because the cells have a poor heat dissipation. Other safety mechanisms are also considered by manufacturers, such as pressure release valves, one-shot fuses, reversible and irreversible positive temperature coefficient elements, shutdown separators, chemical shuttles, non-flammable electrolytes and coatings. Compared to lithium metal batteries, Li-ion cells are considered safer [109].

Cost

Current Li-ion battery cost per KW is still high. In theory, lithium based cells for HEVs should be inexpensive because the raw material is a natural resource, but the costs are still high due to expensive development processes and production costs (materials processing, manufacturing of the cells, and packaging) [42, 105].

Even when Li-ion battery cost is still higher for comparable applications than those of NiMH batteries, the cost projected for mass-produced EV batteries is comparable or lower. To fabricate a battery of the same capacity and voltage, 70% fewer cells of the same size are required. Also, little or no need for changes and cost increases are estimated when going from PHEV designs to EV designs, because both have similar specific power capabilities. Finally, the cost of raw materials are expected to decrease more with high production volume than NiMH materials. As a result, the projection for mass-produced Li-ion batteries to meet the cost requirements for PHEV applications is positive [110].

Environmental issues

The use of organic solvents in the electrode manufacture implies a high cost and multiple environmental concerns because of their toxicity, which may reduce the potential to take manufacturing cost down to the level required for wide adoption in many applications. Because of this, different approaches has been provided. For example, International Battery Company focuses on manufacturing Li-ion cells using a water soluble binder based process for both the cathode and anode, where water is used as a medium to dissolve and disperse the binders and the electrode materials. By eliminating the solvent from the manufacturing process, the material cost and capital investment can be reduced [111].

Additionally, environmental regulations are important considerations in developing any new battery technology. Li-ion battery manufacturing processes can generate water and air emissions and solid waste. Paper [107] presents U.S. Environmental Protection Agency (EPA) regulations related to these issues that have been included in the following acts: the Clean Water Act (CWA), the Clean Air Act (CAA), and the Resource Conservation and Recovery Act (RCRA).

In the CWA, there are 65 categories of "priority pollutants", and some of them can be used in Li-ion manufacturing processes, including nickel, arsenic, copper, and associated compounds. The National Pollutant Discharge Elimination System (NPDES) requires facilities to obtain permits to start discharge of pollutants to surface waters. Industrial discharge and permits issued by the publicly owned treatment works (POTWs) are required to satisfy general pretreatment standards. In Li-ion manufacturing, substances other than lithium and hydrogen that can be contained in the electrolyte have to be pretreated because of their flammable characteristics.

Battery manufacturing is listed as a major source category in the CAA. Li-ion battery manufacturing uses hazardous air pollutants like manganese, nickel, cobalt, and arsenic (and their compounds). Additionally, other volatile organic compounds like carbon monoxide and nitrogen oxides can be generated during manufacturing. The facility may have to accomplish with applicable pollutant requirements specified in the State Implementation Plans (SIP). Each state is responsible for ensuring that the air quality is maintained at a level consistent with the National Ambient Air Quality Standard (NAAQS) program.

Finally, the RCRA controls the discharge of solid waste that the EPA considers as hazardous, corrosive, flammable, reactive, or toxic. For example, lithium may be reactive, and arsenic may be toxic, and therefore hazardous when discarded. Based on this, RCRA imposed waste minimization requirements on hazardous waste generators, which include source reduction and recycling.

Recycling

Recycling of automotive batteries is easier than recycling of small portable cells. First, collection plans have been used for returning of automotive batteries with each new battery purchase and stripping batteries from wrecks before shredding. Second, the batteries are large enough to permit separation by type, to maximize the value of recovered materials. Third, there is enough material in large pieces to justify partial disassembly. The recycling approaches typically include discharging the cells, venting the electrolyte solvent, shredding the entire package, and recovering the solvent flashed off [103]. For safety, most processing schemes include cryogenics, inert atmospheres, or other techniques to reduce the contact to the components. However, a generic process is proposed by the National Renewable Energy Laboratory (NREL), for recovery of materials from Li-ion cells without cell venting or disassembly [103, 107].

Recently, the US Department of Energy (DOE) granted \$9.5 million to Toxco, to build the first recycling facility for Li-ion vehicle batteries in America. Toxco is a leading battery recycler and works on single-charge and rechargeable lithium batteries found in electronics devices and industrial applications [96]. Its process consist in chilling the batteries to $-325\,°\mathrm{F}$ in liquid nitrogen (see Figure 3.15). Large batteries are sheared into three pieces in a caustic bath, to dissolve the lithium salts, and neutralize the acidic elements. The salts are used to produce lithium carbonate. Hydrogen and organic burn off at the surface of the process bath. Cobalt can be recover from the sludge. The large pieces remaining are sent to a hammer mill, to recover ferrous and nonferrous metals. Plastics and paper float to the top and are recovered for disposal or recycling. The carbon sludge is filtered out, but is not economical to reuse it [96, 103].

Moreover, Sony recycling process involves calcining to bake out the electrolyte, which deactivate the cells for disassembly; in the case of large batteries, these are vented first [103]. In turn, Accurec developed the RVD (recycling through vacuum distillation) procedure for lithium manganese oxide batteries. In France, SNAM (from French: National Union of Metal Products and their Derivatives) also offers a reprocessing procedure for lithium secondary systems; after deactivation, the metals are separated and returned to the production

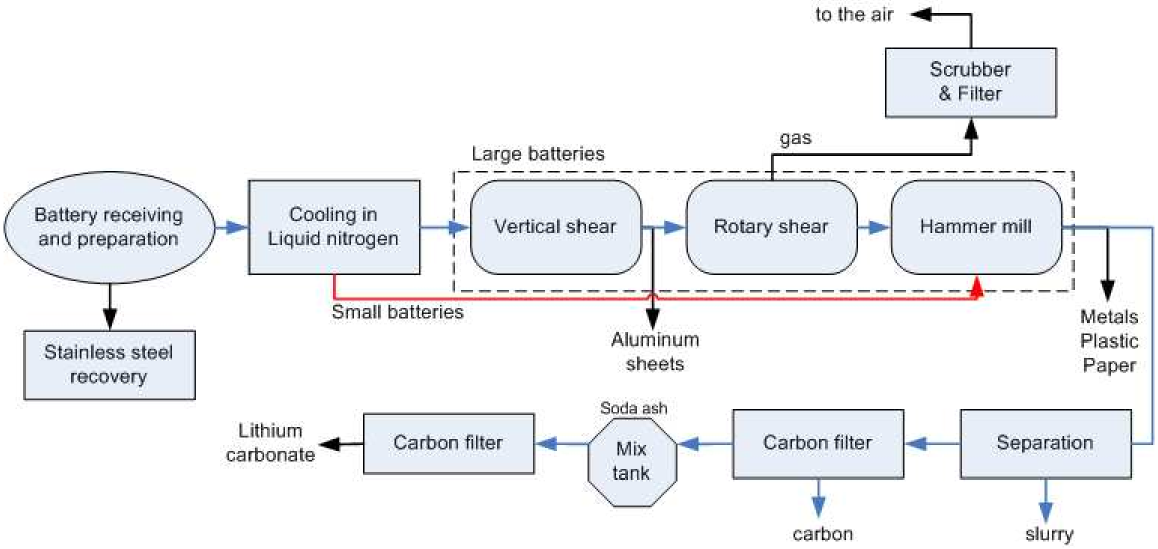

Figure 3.15: Recycling process for the Li-ion battery at Toxco (based on [103])

cycle [44]. In addition, Nikkei reported recently that Japan's Nippon Mining&Metals Co. and GS Yuasa Corp., are going to start lithium recycling from scrapped electric and hybrid vehicles batteries. Nippon developed a technology to extract lithium from the batteries, and plans to have its trial plant in 2011. GS Yuasa, a major producer of automotive batteries, will begin collecting used Li-ion batteries to develop its recycling process based on the lithium utilization in different parts of the batteries [96].

Li-ion batteries recycling is not a mature process, even when the cobalt recovery makes it economically attractive. Most batteries contain small amounts of lithium carbonate, and the material is relatively inexpensive compared to other metals, such as nickel and cobalt. Unlike lead-acid car batteries, advanced Li-ion batteries do not use harmful acids or metals to store electrical power. Li-ion batteries use copper, cobalt, iron and nickel that are considered safe for landfills and incinerators after appropriate treatment, according to the EPA [96, 103].

3.9 Sodium-Based Technology

Since 1980, a number of batteries using negative electrodes based on sodium were developed. These batteries are characterized for using one or more liquid electrodes and a solid ceramic electrolyte. Hence, their operation at high temperatures makes them practical to be used in

EVs, but no in small applications. However, their development for commercial application has not been successful [43].

3.9.1 Sodium-sulphur (NaS) batteries

The NaS battery has a negative electrode made of molten sodium, a positive electrode made of molten sulphur, and an electrolyte that consists of a solid β-alumina ceramic, which conducts the sodium ions and also separates the two electrodes. Small cells are built, joined together, and placed in an evacuated chamber to reduce heat losses. The container must provide very good thermal insulation, and it is usually very heavy, which makes the battery inappropriate for small applications. In addition, this battery needs a good temperature control system to reach its operation temperature (around 350 °C) before it is used, to ensure that Na and S are liquid, and the solid electrolyte has a high Na conductivity [43].

In general, a ceramic tube hermetically sealed is connected to the negative and positive poles formed by the cell case. The sulfur is contained between the ceramic tube and the cell case. A carbon-felt is added to provide conductivity, given that sulfur and polysodium sulfur are electrically nonconductive. The cell case is made out of aluminum and the inside is coated with a conductive layer to protect the cell against corrosion [44]. The energy density of the NaS battery is very high compared with the lead-acid and the NiCd, which makes it suitable for energy storage. Also, this battery presents good power density, high cycle life, independence of external temperature, and moderate cost [82]. However, some vehicle tests showed some safety issues related to the reactions between the active materials, and risk of spontaneous fire was detected [43].

3.9.2 Sodium-metal chloride (Na/$NiCl_2$ or Zebra) batteries

The initial research with this battery was conducted in South Africa for EV applications, and the name Zebra (zero emission battery research activity) is commonly used. This battery is similar to the NaS battery, but has solved NaS safety problems by using a solid positive electrode, which is separated from the molten sodium metal by both solid and liquid electrolytes to prevent undesirable reactions. The zebra cell uses solid nickel chloride ($NiCl_2$) for the positive electrode and molten sodium for the negative electrode. It has two electrolytes: a beta ceramic electrolyte surrounding the sodium, and a secondary electrolyte, sodium-aluminium chloride, used in the positive electrode chamber [43].

Cell assembly

$Na/NiCl_2$ cells are produced in the discharged state to avoid the handling of metallic sodium. All the required sodium is inserted as a salt. The current collector is a wire with an inside copper core, and it is connected to the positive pole and to an outside nickel plating to be consistent with the cell chemistry. The cathode material, a mixture of salt with nickel powder and some samples of iron and aluminum, is filled into a β-alumina tube. This tube is corrugated to reduce the resistance and is surrounded to the cell case, using a thin steel sheet that forms a gap around the tube. The cell case is formed using a rectangular tube welded and formed from a nickel-coated steel strip and a laser-welded bottom cap. Finally, the cell case forms the negative pole [44].

Battery assembly

ZEBRA cells can be connected in parallel and in series. It is possible to connect several cells in series, without parallel connections, because cell imbalances are leveled out by chemical reactions. Different battery types have been made with one to five parallel strings, up to 220 cells in series, and 100 to 500 cells in one battery pack. The standard battery type *Z5* has 216 cells arranged in one or two strings (557V and 278V respectively). In addition, cooling plates are used between every second cells to permit air circulation [44]. An issue with Zebra batteries is that they operate at a temperature of about 300 °C, so heat insulation is needed. A double skinned stainless steel box is used for thermal insulation and mechanical support. All the air is removed from the insulation, to maintain the vacuum for several years. The main disadvantage of this battery type is that it needs to be connected to a main energy supply when it is not in use, to keep the operation temperature [43]. However, this battery presents many advantages, such as high energy density, a good tolerance to overcharge and overdischarge, good cyclability, independence to external temperature, low corrosion, and intrinsic safety, which make it a good option for further development of EV applications [82].

Recycling

The main process in zebra batteries recycling is dismantling. The process is certified and does not suppose a high cost. In summary, the stainless steel and silicon dioxide (SiO_2) that form the box are recycled by established processes. Given that the cells contain nickel (Ni), iron (Fe), salt, and ceramic, they can be added to the steel melting process of the stainless steel production. Nickel and iron help in the material production, and the ceramic and salt are used to form the slag [44].

3.10 Summary

In this chapter, the main characteristics for hybrid and electric vehicles are presented, as well as the powertrain configurations used, and the battery parameters needed to understand their performance. It can be seen that power and energy stored are the main specifications for the battery design. However, designers must also have in mind other aspects like safety of the energy storage system, temperature operational ranges, stability over life in terms of ageing and calendar life, and production issues like cost and raw materials. In addition, energy and battery management concepts have been presented in order to understand the importance of maintaining the battery in the appropriate operational environment by using a BMS. Also SoC, SoH and SoF have been defined, as well as some approaches to determine battery status.

Additionally, a review of the state of the art in battery manufacturing for hybrid and electrical vehicles is presented. Some well-known technologies that have been considered for these applications, such as lead-acid, nickel, lithium, and sodium-based batteries are studied, and their main advantages and limitations for commercial development are reviewed. The main contestants for present and future development of hybrid and electric vehicles, NiMH and Li-ion batteries are analyzed, and their manufacturing processes, as well as some recycling and environmental issues are addressed. The NiMH battery used in actual HEVs is relatively small and light, has good life-cycle characteristics, high power, high level of safety, and improved thermal performance. However the cost is still high, and the recycling processes are under development. On the other hand, Li-ion batteries are characterized for high energy density, high charge-discharge efficiency, good load and temperature storage characteristics, long battery expected life, and good recyclability. The main drawback is safety, but different procedures and transportation requirements have been defined. It can be seen that substantial effort needs to be devoted to large volume manufacturing of batteries for EVs and HEVs in the near future, which will make this area with great challenges and promising research opportunities.

Chapter 4

CONCLUSIONS AND FUTURE WORK

One of the main challenges of the 21st century is the development of a sustainable world economy, especially regarding the transportation sector. Increments in world population, energy consumption and green house gas emissions, as well as the depletion of fossil fuel reserves have boosted different approaches for clean transportation development based on new energy sources and energy reduction improvements. Therefore, energy must be obtained from renewable resources, and produced by cleaner and more efficient technologies, while the production processes must be redesigned to use it more efficiently, promote its conservation, and improve productivity and quality.

In vehicle manufacturing, paint shop units consume the largest amount of energy in the plant. This thesis presents a case study in an automotive paint shop and shows how energy use can be reduced by a redesign of the repair capacity, so that unnecessary repaints are minimized. This change in the process design results in significant reduction of energy consumption. In this case, almost 4% energy reduction can be obtained. Clearly, this also implies a great environmental benefit due to less emissions are generated. The benefit over the long-term on energy reduction, productivity and quality will be reflected in larger production volume, earnings, and customer satisfaction. Furthermore, this model can be used for plant engineers and managers as a quantitative tool to evaluate energy reduction efforts in order to meet environmental regulations.

On the other hand, recent developments on renewable energy sources for new generation vehicles have an increasing importance in transportation industry. Biofuels, hydrogen, and electric power are target of exhaustive research from different governments and several scientific laboratories. But short-term, the main solution being adopted for major automakers is the development of batteries for hybrid and electric vehicles. Hybrids have become the actual transition technology from pure electrics to other future options like fuel cell vehicles. The convenience factor of energy regeneration during driving in hybrid electric vehicles (HEV), combined with actual developments of plug-in hybrid electric vehicles (PHEV) where the battery can be externally charged, and the near future of all battery electric vehicles (BEV) promise an increase in fuel efficiency and reduction of greenhouse gas emissions.

Different technologies based on lead-acid, nickel, sodium and lithium have been tested in the last 30 years with promising results, which have increased interest in their research and development for mass production. Manufacturing processes, process control, cost, recycling and environmental issues have been reviewed for the main candidates of each group. Recently, two major battery technologies are in the spotlight of major automakers and battery manufacturers: NiMH and Li-ion. NiMH batteries, actually used for most of the HEVs in the market, are characterized for good life cycle, high level of safety, and smaller high power cells designed to dissipate higher heat loads generated, which make these batteries relatively smaller and lighter. In turn, Li-ion batteries are characterized for long battery life, high charge-discharge efficiency, good thermal performance and optimized high energy density cells, ideal for EV. However, considerable efforts need to be dedicated for the development and mass production of advanced batteries to overcome factors related to high cost in raw materials, manufacturing technology and process control, high safety in production processes, shipping and handling, and new recyclability methods, which make this a promising area for research opportunities.

In future work, the model presented in Chapter 2 can be extended to the analysis of emissions generated in paint shops at the car manufacturing plants. When a car gets painted, paint fumes containing potent greenhouse gases are captured and incinerated using a process that consumes huge amounts of natural gas which creates significant carbon dioxide and nitrogen oxide emissions. Following a similar analytical method based on rework and repair capacity will enable companies to monitor CO_2 and nitrogen emissions, and record data to meet the environmental legislations and standards. Moreover, this model can be helpful to analyze each process in more detail, and extended to be combined with Production Systems Engineering (PSE) parameters, i.e. performance analysis and prediction. This includes inspection allocations, buffer design, machine speed, batch size, line layout, and work load balancing, etc., which are related directly to energy efficiency and product quality.

Recently, hybrid and electric vehicle battery assembly plants have been implemented in the U.S. for battery manufacturers and major automakers. Therefore, efforts must be concentrated on the design, analysis and control of the production processes. Design parameters such as layout, capacity, reliability, cycle time, etc., may be analyzed to optimize the manufacturing system efficiency and the product quality. Since these systems imply new technologies and production processes, analysis and prediction of production performance, including throughput, work-in-process, and customer demand satisfaction are required.

In addition, quality control mechanisms must be implemented, i.e., quality inspection, quality containment and rectification, in order to ensure high quality products that meet company standards. The effective use of repair and rework provides the opportunity to improve system performance, and as showed before, the efficient use of resources. Finally, processes like remanufacturing and recycling need to be studied in order to leverage resources and decrease the environmental impact. An adequate management of remanufacturing of products not only lessens cost, but also eases environmental burdens. At the same time, efficient and safe use of demanufacturing processes and recycling of raw materials provide not only an excellent method for disposal of hazardous waste, but also an important procedure for reutilization of resources and environmental conservation.

APPENDIX

Proof of Theorem 1: The following two cases are considered: Case 1, when minor repair has sufficient capacity, and Case 2, when minor repair does not have enough capacity.

Case 1: When minor repair has enough capacity, no jobs needing minor repair will be rerouted to rework ($N \geq n_s(t)$). Then:

$$\begin{aligned} n_r &= n[1-q(t)]\alpha_r + n_r[1-\rho q(t)]\alpha_r + n_x\beta_{xr} + n_s\beta_{sr} && \text{(A.1)} \\ n_x &= n[1-q(t)]\alpha_x + n_r[1-\rho q(t)]\alpha_x + n_s\beta_{sx} && \text{(A.2)} \\ n_s &= n[1-q(t)]\alpha_s + n_r[1-\rho q(t)]\alpha_s + n_x\beta_{xs} + n_s\beta_{ss} && \text{(A.3)} \\ n_g &= nq(t) + n_r\rho q(t) + n_s\beta_{sg} + n_x\beta_{xg} && \text{(A.4)} \end{aligned}$$

Substitute equation (A.2) into equation (A.3):

$$\begin{aligned} n_s &= n(1-q(t))\alpha_s + n_r(1-\rho q(t))\alpha_s + [n(1-q(t))\alpha_x + n_r(1-\rho q(t))\alpha_x + n_s\beta_{sx}]\beta_{xs} \\ &\quad + n_s\beta_{ss} \\ &= n(1-q(t))(\alpha_s + \alpha_x\beta_{xs}) + n_r(1-\rho q(t))(\alpha_s + \alpha_x\beta_{xs}) + n_s(\beta_{sx}\beta_{xs} + \beta_{ss}) \\ &= \alpha'_s[n(1-q(t)) + n_r(1-\rho q(t))] \end{aligned}$$

where

$$\alpha'_s = \frac{\alpha_s + \alpha_x\beta_{xs}}{1-\beta_{ss}-\beta_{sx}\beta_{xs}} \qquad \text{(A.5)}$$

Substituting n_s into equation (A.2):

$$\begin{aligned} n_x &= n(1-q(t))\alpha_x + n_r(1-\rho q(t))\alpha_x + \alpha'_s[n(1-q(t)) + n_r(1-\rho q(t))]\beta_{sx} \\ &= [n(1-q(t)) + n_r(1-\rho q(t))](\alpha_x + \alpha'_s\beta_{sx}) \\ &= \alpha'_x[n(1-q(t)) + n_r(1-\rho q(t))] \end{aligned}$$

where

$$\alpha'_x = \frac{\alpha_x - \alpha_x\beta_{ss} + \alpha_s\beta_{sx}}{1 - \beta_{ss} - \beta_{sx}\beta_{xs}} \tag{A.6}$$

Replacing n_s and n_x into equation (A.1):

$$\begin{aligned}
n_r &= n(1-q(t))\alpha_r + n_r(1-\rho q(t))\alpha_r + [\alpha'_x[n(1-q(t)) + n_r(1-\rho q(t))]]\beta_{xr} \\
&\quad + [\alpha'_s[n(1-q(t)) + n_r(1-\rho q(t))]]\beta_{sr} \\
&= (\alpha_r + \alpha'_x\beta_{xr} + \alpha'_s\beta_{sr})[n(1-q(t)) + n_r(1-\rho q(t))] \\
&= \alpha'_r[n(1-q(t)) + n_r(1-\rho q(t))]
\end{aligned}$$

and

$$\alpha'_r = \alpha_r + \frac{\alpha_s(\beta_{sr} + \beta_{sx}\beta_{xr}) + \alpha_x(\beta_{xr} + \beta_{xs}\beta_{sr} - \beta_{ss}\beta_{xr})}{1 - \beta_{ss} - \beta_{sx}\beta_{xs}}. \tag{A.7}$$

Therefore

$$n_r = \frac{n[1-q(t)]\alpha'_r}{1 - [1-\rho q(t)]\alpha'_r}, \tag{A.8}$$

and

$$n_s = \frac{\alpha'_s n[1-q(t)]}{1 - [1-\rho q(t)]\alpha'_r}. \tag{A.9}$$

Then, using equation (4), the total energy usage in painting in day t, for $(N \geq n_s(t))$:

$$\begin{aligned}
E(t) &= c \cdot (n + n_r(t)) \\
&= c\Big[n + \frac{n[1-q(t)]\alpha'_r}{1 - [1-\rho q(t)]\alpha'_r}\Big] \\
&= cn[\frac{1 - \alpha'_r[1-\rho q(t)] + \alpha'_r[1-q(t)]}{1 - \alpha'_r[1-\rho q(t)]}]
\end{aligned} \tag{A.10}$$

Case 2: When minor repair does not have sufficient capacity ($N < n_s(t)$), some jobs that only need to go to minor repair will be rerouted to rework . Then:

$$n_r = n[1-q(t)]\alpha_r + n_r[1-\rho q(t)]\alpha_r + n_x\beta_{xr} + N\beta_{sr} + \tilde{n}_s - N \tag{A.11}$$

$$n_x = n[1-q(t)]\alpha_x + n_r[1-\rho q(t)]\alpha_x + N\beta_{sx} \tag{A.12}$$

$$\tilde{n}_s = n[1-q(t)]\alpha_s + n_r[1-\rho q(t)]\alpha_s + n_x\beta_{xs} + N\beta_{ss} \tag{A.13}$$

$$n_g = nq(t) + n_r\rho q(t) + N\beta_{sg} + n_x\beta_{xg} \tag{A.14}$$

Substituting equation (A.12) into equation (A.13),

$$\begin{aligned}\tilde{n}_s &= n(1-q(t))\alpha_s + n_r(1-\rho q(t))\alpha_s + [n(1-q(t))\alpha_x \\ &\quad + n_r(1-\rho q(t))\alpha_x + N\beta_{sx}]\beta_{xs} + N\beta_{ss} \\ &= [n(1-q(t)) + n_r(1-\rho q(t))](\alpha_s + \alpha_x\beta_{xs}) + N(\beta_{sx}\beta_{xs} + \beta_{ss})\end{aligned}$$

Replacing $\tilde{n}_s$ and n_x into equation (A.11):

$$\begin{aligned}n_r &= [n(1-q(t)) + n_r(1-\rho q(t))]\alpha_r + N\beta_{sr} + [n(1-q(t)) + n_r(1-\rho q(t))](\alpha_s + \alpha_x\beta_{xs}) \\ &\quad + N(\beta_{ss} + \beta_{sx}\beta_{xs}) - N + [n(1-q(t)) + n_r(1-\rho q(t))]\alpha_x\beta_{xr} + N\beta_{sx}\beta_{xr} \\ &= [n(1-q(t)) + n_r(1-\rho q(t))](\alpha_r + \alpha_s + \alpha_x\beta_{xs} + \alpha_x\beta_{xr}) \\ &\quad + N(\beta_{sr} + \beta_{ss} + \beta_{sx}\beta_{xs} + \beta_{sx}\beta_{xr} - 1)\end{aligned}$$

Using equations (1) to (3):

$$n_r = [n(1-q(t)) + n_r(1-\rho q(t))](1-\alpha_x\beta_{xg}) - N(\beta_{sg} + \beta_{sx}\beta_{xg})$$

Thus,

$$n_r = \frac{n(1-q(t))(1-\alpha_x\beta_{xg}) - N(\beta_{sg} + \beta_{sx}\beta_{xg})}{1 - [1-\rho q(t)][1-\alpha_x\beta_{xg}]} \tag{A.15}$$

Then, using equation (4), the total energy usage in painting in day t, for $(N < n_s(t))$:

$$\begin{aligned}
E(t) &= c \cdot (n + n_r(t)). \\
&= c\Big[n + \frac{n(1-q(t))(1-\alpha_x\beta_{xg}) - N(\beta_{sg}+\beta_{sx}\beta_{xg})}{1-[1-\rho q(t)][1-\alpha_x\beta_{xg}]}\Big] \\
&= \frac{cn[1-(1-\rho q(t))(1-\alpha_x\beta_{xg}) + (1-q(t))(1-\alpha_x\beta_{xg})]}{1-[1-\rho q(t)][1-\alpha_x\beta_{xg}]} \\
&\quad - \frac{cN(\beta_{sg}+\beta_{sx}\beta_{xg})}{1-[1-\rho q(t)][1-\alpha_x\beta_{xg}]} \qquad \text{(A.16)}
\end{aligned}$$

■

Proof of Corollary 1: When minor repair capacity is insufficient,

$$\begin{aligned}
\frac{\partial E(t)}{\partial N} &= -\frac{c(\beta_{sg}+\beta_{sx}\beta_{xg})}{1-[1-\rho q(t)][1-\alpha_x\beta_{xg}]} \\
&< 0,
\end{aligned}$$

Therefore, $E(t)$ is monotonically decreasing with respect to N. As a result, $\overline{E(t)}$ observe the same monotonic properties.

■

Proof of Corollary 2: From equation 5 for $N \geq n_s(t)$,

$$\begin{aligned}
\frac{\partial E(t)}{\partial q} &= -\frac{n\Big[\alpha'_r\rho + \alpha'^2_r q\rho(\rho-1) - \alpha'_r(\rho-1)[1-\alpha'_r(1-\rho q)]\Big]}{[1-\alpha'_r(1-\rho q)]^2} \\
&< 0
\end{aligned}$$

we can show that

$$\begin{aligned}
\frac{\partial^2 E(t)}{\partial q^2} &= \frac{n\Big[2\rho^2[\alpha'^2_r + \alpha'^3_r q(\rho-1)][1-\alpha'_r(1-\rho q)]\Big] - n\Big[2\alpha'^2_r\rho(\rho-1)[1-\alpha'_r(1-\rho q)]^2\Big]}{[1-\alpha'_r(1-\rho q)]^4} \\
&> 0.
\end{aligned}$$

From equation 5 for $N < n_s(t)$,

$$\begin{aligned}\frac{\partial E(t)}{\partial q} &= \frac{-cn(1-\rho+\rho\alpha_x\beta_{xg}-\alpha_x\beta_{xg})(\alpha_x\beta_{xg}) - \big[cn - cN(\beta_{sg}+\beta_{sx}\beta_{xg})\big](\rho-\rho\alpha_x\beta_{xg})}{\big[\alpha_x\beta_{xg}+q(\rho-\rho\alpha_x\beta_{xg})\big]^2} \\ &< 0\end{aligned}$$

and

$$\begin{aligned}\frac{\partial^2 E(t)}{\partial q^2} = &\left[\frac{[cn(1-\rho+\rho\alpha_x\beta_{xg}-\alpha_x\beta_{xg})(\alpha_x\beta_{xg})] + \big[c[n-N(\beta_{sg}+\beta_{sx}\beta_{xg})](\rho-\rho\alpha_x\beta_{xg})\big]}{\big[\alpha_x\beta_{xg}+q(\rho-\rho\alpha_x\beta_{xg})\big]^4}\right] \\ &\cdot\Big[2\big(\alpha_x\beta_{xg}+q(\rho-\rho\alpha_x\beta_{xg})\big)(\rho-\rho\alpha_x\beta_{xg})\Big] \\ &> 0\end{aligned}$$

Thus $E(t)$ is a convex function. By Jensen's inequality [112], the conclusion is obtained.

■

Proof of Theorem 2: To calculate the average energy used values, the condition $N > n_s(t)$ must be written in terms of $q(t)$ (using equation (A.9)):

$$\begin{aligned} N &\geq \frac{\alpha_s' n[1-q(t)]}{1-[1-\rho q(t)]\alpha_r'} \\ N - N\alpha_r' + N\rho\alpha_r' q(t) &\geq n\alpha_s' - n\alpha_s' q(t) \\ q(t) &\geq \frac{n\alpha_s' - N(1-\alpha_r')}{n\alpha_s' + N\rho\alpha_r'} \end{aligned}$$

The minimum first time quality necessary to avoid rerouted jobs is q_s:

$$q_s = \frac{n\alpha_s' - N(1-\alpha_r')}{n\alpha_s' + N\rho\alpha_r'}. \tag{A.17}$$

Then, $N > n_s(t)$ implies that $q(t) \geq q_s$. Therefore, $E(t)$ can be written as:

$$E(t) = E(E(t)/q(t) \geq q_s)Prob(q(t) \geq q_s) + E(E(t)/q(t) < q_s)Prob(q(t) < q_s).$$

When $q(t) \geq q_s$, no jobs are rerouted. Then, the following cases are considered: $q_a \leq q_s \leq q_b$, $q_s < q_a$ and $q_s > q_b$.

Case 1: When $q_a \leq q_s \leq q_b$:

Using $E(t)$ from equation (A.10) to calculate the expected value for $E(E(t)/q(t) \geq q_s)$:

$$\begin{aligned} E(E(t)/q(t) \geq q_s) &= \int_{q_s}^{q_b} cn\left[\frac{1-\alpha_r'[1-\rho q]+\alpha_r'[1-q]}{1-\alpha_r'[1-\rho q]}\right] \times \left[\frac{1}{q_b-q_s}\right]dq \\ &= \frac{cn}{q_b-q_s}\int_{q_s}^{q_b}\frac{1+(\alpha_r'\rho-\alpha_r')q}{(1-\alpha_r')+\alpha_r'\rho q}dq \\ &= \frac{cn}{q_b-q_s}\left[\left(\frac{1}{\alpha_r'\rho}-\frac{(\alpha_r'\rho-\alpha_r')(1-\alpha_r')}{(\alpha_r'\rho)^2}\right)\right. \\ &\quad \times\left[\ln(\alpha_r'\rho q_b+1-\alpha_r')-\ln(\alpha_r'\rho q_s+1-\alpha_r')\right] \\ &\quad \left.+\frac{(\alpha_r'\rho-\alpha_r')}{\alpha_r'\rho}(q_b-q_s)\right] \qquad \text{(A.18)} \end{aligned}$$

Using $E(t)$ from equation (A.16) for $E(E(t)/q(t) < q_s)$:

$$\begin{aligned} E(E(t)/q(t) < q_s) = \Bigg[\int_{q_a}^{q_s}\frac{cn[1-(1-\rho q)(1-\alpha_x\beta_{xg})]}{1-(1-\rho q)(1-\alpha_x\beta_{xg})}dq + \int_{q_a}^{q_s}\frac{cn[(1-q)(1-\alpha_x\beta_{xg})]}{1-(1-\rho q)(1-\alpha_x\beta_{xg})}dq \\ -\int_{q_a}^{q_s}\frac{cN(\beta_{sg}+\beta_{sx}\beta_{xg})}{1-(1-\rho q)(1-\alpha_x\beta_{xg})}dq\Bigg] \times \left[\frac{1}{q_s-q_a}\right] \end{aligned}$$

$$\begin{aligned} E(E(t)/q(t) < q_s) = \frac{1}{q_s-q_a}&\left[\left(\frac{cn}{(\rho-\rho\alpha_x\beta_{xg})}-\frac{cn(\alpha_x\beta_{xg}+\rho-\rho\alpha_x\beta_{xg}-1)}{(\rho-\rho\alpha_x\beta_{xg})^2}\right.\right. \\ &\left.-\frac{cN(\beta_{sg}+\beta_{sx}\beta_{xg})}{(\rho-\rho\alpha_x\beta_{xg})}\right) \times \left[\ln\Big((\rho-\rho\alpha_x\beta_{xg})q_s+\alpha_x\beta_{xg}\Big)\right. \\ &\left.-\ln\Big((\rho-\rho\alpha_x\beta_{xg})q_a+\alpha_x\beta_{xg}\Big)\right] \\ &\left.+\frac{cn(\alpha_x\beta_{xg}+\rho-\rho\alpha_x\beta_{xg}-1)(q_s-q_a)}{\rho-\rho\alpha_x\beta_{xg}}\right] \qquad \text{(A.19)} \end{aligned}$$

Therefore, the average energy used equals to:

$$
\begin{aligned}
E(E(t)) \quad = \quad & \frac{cn(q_b-q_s)}{(q_b-q_a)(q_b-q_s)}\Bigg[\Bigg(\frac{1}{\alpha'_r\rho}-\frac{(\alpha'_r\rho-\alpha'_r)(1-\alpha'_r)}{(\alpha'_r\rho)^2}\Bigg) \\
& \times\Big[\ln(\alpha'_r\rho q_b+1-\alpha'_r)-\ln(\alpha'_r\rho q_s+1-\alpha'_r)\Big] \\
& +\frac{(\alpha'_r\rho-\alpha'_r)}{\alpha'_r\rho}(q_b-q_s)\Bigg]+\frac{c(q_s-q_a)}{(q_b-q_a)(q_s-q_a)} \\
& \times\Bigg[\Bigg(\frac{n}{(\rho-\rho\alpha_x\beta_{xg})}-\frac{n(\alpha_x\beta_{xg}+\rho-\rho\alpha_x\beta_{xg}-1)}{(\rho-\rho\alpha_x\beta_{xg})^2} \\
& -\frac{N(\beta_{sg}+\beta_{sx}\beta_{xg})}{(\rho-\rho\alpha_x\beta_{xg})}\Bigg)\times\Big[\ln\Big((\rho-\rho\alpha_x\beta_{xg})q_s+\alpha_x\beta_{xg}\Big) \\
& -\ln\Big((\rho-\rho\alpha_x\beta_{xg})q_a+\alpha_x\beta_{xg}\Big)\Big] \\
& +\frac{cn(\alpha_x\beta_{xg}+\rho-\rho\alpha_x\beta_{xg}-1)(q_s-q_a)}{\rho-\rho\alpha_x\beta_{xg}}\Bigg] \\
\quad = \quad & \frac{cn}{(q_b-q_a)}\Bigg[\Bigg(\frac{1}{\alpha'_r\rho}-\frac{(\alpha'_r\rho-\alpha'_r)(1-\alpha'_r)}{(\alpha'_r\rho)^2}\Bigg) \\
& \times\Big[\ln(\alpha'_r\rho q_b+1-\alpha'_r)-\ln(\alpha'_r\rho q_s+1-\alpha'_r)\Big] \\
& +\frac{(\alpha'_r\rho-\alpha'_r)}{\alpha'_r\rho}(q_b-q_s)\Bigg]+\frac{c}{(q_b-q_a)} \\
& \times\Bigg[\Bigg(\frac{n}{(\rho-\rho\alpha_x\beta_{xg})}-\frac{n(\alpha_x\beta_{xg}+\rho-\rho\alpha_x\beta_{xg}-1)}{(\rho-\rho\alpha_x\beta_{xg})^2} \\
& -\frac{N(\beta_{sg}+\beta_{sx}\beta_{xg})}{(\rho-\rho\alpha_x\beta_{xg})}\Bigg)\times\Big[\ln\Big((\rho-\rho\alpha_x\beta_{xg})q_s+\alpha_x\beta_{xg}\Big) \\
& -\ln\Big((\rho-\rho\alpha_x\beta_{xg})q_a+\alpha_x\beta_{xg}\Big)\Big] \\
& +\frac{n(\alpha_x\beta_{xg}+\rho-\rho\alpha_x\beta_{xg}-1)(q_s-q_a)}{\rho-\rho\alpha_x\beta_{xg}}\Bigg] \qquad \text{(A.20)}
\end{aligned}
$$

Case 2: When $q_s < q_a$:

Replacing q_s with q_a in equation (A.18), we have:

$$\begin{aligned} E(E(t)) &= \int_{q_a}^{q_b} cn\left[\frac{1-\alpha'_r[1-\rho q]+\alpha'_r[1-q]}{1-\alpha'_r[1-\rho q]}\right]\times\left[\frac{1}{q_b-q_a}\right]dq \\ &= \frac{cn}{q_b-q_a}\Bigg[\left(\frac{1}{\alpha'_r\rho}-\frac{(\alpha'_r\rho-\alpha'_r)(1-\alpha'_r)}{(\alpha'_r\rho)^2}\right) \\ &\quad\times\Big[\ln(\alpha'_r\rho q_b+1-\alpha'_r)-\ln(\alpha'_r\rho q_a+1-\alpha'_r)\Big] \\ &\quad+\frac{(\alpha'_r\rho-\alpha'_r)}{\alpha'_r\rho}(q_b-q_a)\Bigg] \end{aligned} \tag{A.21}$$

Case 3: When $q_s > q_b$: Replacing q_s with q_b in equation (A.19), we obtain:

$$\begin{aligned} E(E(t)) &= \Bigg[\int_{q_a}^{q_b}\frac{cn[1-(1-\rho q)(1-\alpha_x\beta_{xg})]}{1-(1-\rho q)(1-\alpha_x\beta_{xg})}dq+\int_{q_a}^{q_s}\frac{cn[(1-q)(1-\alpha_x\beta_{xg})]}{1-(1-\rho q)(1-\alpha_x\beta_{xg})}dq \\ &\quad-\int_{q_a}^{q_s}\frac{cN(\beta_{sg}+\beta_{sx}\beta_{xg})}{1-(1-\rho q)(1-\alpha_x\beta_{xg})}dq\Bigg]\times\left[\frac{1}{q_b-q_a}\right] \\ &= \frac{c}{q_b-q_a}\Bigg[\Bigg(\frac{n}{(\rho-\rho\alpha_x\beta_{xg})}-\frac{n(\alpha_x\beta_{xg}+\rho-\rho\alpha_x\beta_{xg}-1)}{(\rho-\rho\alpha_x\beta_{xg})^2} \\ &\quad-\frac{N(\beta_{sg}+\beta_{sx}\beta_{xg})}{(\rho-\rho\alpha_x\beta_{xg})}\Bigg)\times\Big[\ln\Big((\rho-\rho\alpha_x\beta_{xg})q_b+\alpha_x\beta_{xg}\Big) \\ &\quad-\ln\Big((\rho-\rho\alpha_x\beta_{xg})q_a+\alpha_x\beta_{xg}\Big)\Big] \\ &\quad+\frac{n(\alpha_x\beta_{xg}+\rho-\rho\alpha_x\beta_{xg}-1)(q_b-q_a)}{\rho-\rho\alpha_x\beta_{xg}}\Bigg] \end{aligned} \tag{A.22}$$

■

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- Production System Design to Achieve Energy Savings in Automotive Paint Shop, under review for publication in the International Journal of Production Research.