Designing a Sustainable Recycling Network for Batteries from Electric Vehicles. Development and Optimization of Scenarios

Hakim Idjis[1,2], Danielle Attias[1], Jean Claude Bocquet[1], and Sophie Richet[2]

[1] Industrial Engineering Laboratory, Ecole Centrale Paris, Grande Voie des Vignes, 92290 Châtenay-Malabry, France
[2] PSA Peugoet Citroen, Route de Gisy, 78943 Velizy Villacoublay, France
{hakim.idjis,danielle.attias,jean-claude.bocquet}@ecp.fr, sophie.richet@mpsa.com

Abstract. Since the 2008 crisis, the automotive industry is shifting towards a new paradigm and repositioning around the green mobility, using mainly lithium battery technology. Given this new development, the issue of recycling batteries arises for ecological, economic and geostrategic reasons. Our work consists in formalizing a methodology to help design a sustainable recycling network applied to batteries, under uncertainty. The proposed approach involves two steps. The first step is about modeling the recycling network and the characterization of the problem's elements, using systemic analysis. The second step consists in developing scenarios about the configurations of this value chain, and then optimizing their functioning. We'll choose different positioning for the actors and make assumptions about logistic data. In this paper, we will try to summarize the issues of recycling lithium battery, explain in detail this approach and present the first results of application.

Keywords: Recycling, Value chain, System analysis and design, Lithium batteries.

1 Introduction

Everyone agrees that we are at the beginning of a second automotive revolution, induced by the decline of the life cycle of the internal combustion engine (ICE) vehicle, the limits of the economic and financial model of the automotive industry and the effect of the current mobility system on the environment. These factors raise a reflection about a new mobility system and its impact on territories, resources allocation and regulations. These new constraints have led the automotive industry to reposition itself around the green mobility. Several technologies exist, including fuel cell technology. However, they are not yet marketable. Thus, the industry turned to hybrid or fully electric vehicles (EVs), using mainly lithium batteries.

Given this new developments, the issue of recycling batteries arises for ecological, economic and geostrategic reasons. This recycling network will be implemented by the original equipment manufacturers (OEMs). This is because, firstly, they have a legal responsibility on batteries at end-of-life [1] and secondly, they are the actors

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who have the most power and resources in the automotive value chain. Currently, the industrial-scale recycling of these batteries is non-existent. The prospective nature of the study encompasses uncertainties, caused by the development of electric vehicle market, the evolution of battery technology and the maturity of recycling processes [2]. The interest of this subject lies in the identification of a configuration of the value chain associated to batteries at the end-of-life. This value chain should be able to comply with regulations while controlling the overall cost of batteries.

This paper will be focused on lithium ion batteries (Li-ion), because it's the most promising technology for vehicles electrification [3] - [4]. In this article, "recycling" will be referred to as the treatment and recovery of batteries after the automotive use, including: reparation, second life applications and materials recycling. The term EV includes: hybrid-electric vehicles (HEV), plug-in hybrid vehicles (PHEV) and battery-electric vehicles (BEV).

Next section provides an overview of the existing literature about end-of-life products recovery, as well as Li-ion battery recycling. The third section illustrates the specificity of our topic. We will identify the drivers for recycling batteries from EVs. We will also describe the related value chain, in order to highlight its complexity, caused by uncertainties and the multicity of stakeholders.

The last section justifies and explains in detail the proposed approach. It also presents the first results of application.

2 Literature Review

The issue of recycling end-of-life products has been treated by several strands of literature: Environmental value chain management (EVCM), green supply chain management (GrSCM), and reverse logistics (RL), may also be called: Closed-loop supply chains (CLSC). Reverse Logistics is emerging as an area suitable for the study of recycling networks. Rogers and Tibben-Lembke [5] define RL *as the process of planning, implementing and controlling the efficient, cost-effective flow of raw materials, in-process inventory, finished goods and related information from the point of consumption to the point of origin for the purpose of recapturing or creating value, or for proper disposal*. Fleischmann, one of the biggest contributors on the logistics of recovery systems, described in [6] a typical structure for products recovery, as a network converging from disposer markets, going through recovery facilities and diverging to re-use market.

Research carried out in products recovery concerns mainly; either the assessment whether or not the recovery of used products is economically more attractive than disposal, or the organization of the recovery network if the disposal option is prohibited by legislation. Many products specific studies were conducted regarding recycling, such as sand, carpet, bottles and waste electrical and electronic equipment (WEEE). We found it; the most pertinent ones for our work are either end-of-life vehicles (ELV) or products disassembled from ELVs (plastics, lead batteries, etc.).

Kumar and Sutherland [7] explored the effect of innovative vehicle designs (material composition, new power-train technologies) on the sustainability of the automotive recovery infrastructure. Maudet-Charbuillet [8] investigated the issue of integrating recycling plastics networks in the automotive supply chain, by proposing a modeling tool used in order to stabilize these networks. Mathieux and Brissaud [9] used material flow analysis to get insights about aluminum material flows and stocks, identification and quantification of relevant processes. Farel et al. ([10] - [11]) provided a five steps method to design a value chain for ELV glazing recycling: modeling material and information flow; establishing value network; structural analysis; scenario generation and simulation and evaluation. Farel et al. [12] for the same issue in [10] used a linear programming model to simulate the conditions of costs and benefits situations for the upcoming glazing recycling chain in 2015 in France. Kannan et al. [13] proposed a heuristics based genetic algorithm (GA) to solve a closed loop supply chain model for spent lead–acid batteries in India.

Regarding Li-ion battery recovery, the number of articles attests to the recent emergence of this issue. Several industrial, academic or joint initiatives have emerged to explore the end-of-life of EV batteries, mainly concentrated in the USA, Europe and Japan. In the USA, the National Renewable Energy Laboratory's Second Use Project Objective is modeling the actual battery degradation behavior; identification, assessment, and verification of PHEV/EV Li-ion second use profitability. One of the results of this project, published in [14] is focused on estimating the possible value of battery second use strategies to reduce the cost and accelerate adoption of PHEV/EVs. *LithoRec* and *LithoRec II*, a consortium of 12 academic and industrial partners, financed by the German federal government aims to assess the development of an industrial scale structure and process for used Li-ion batteries in Germany, in an economic and environmentally-friendly way. The strategic framework for designing a recycling network developed in *LithoRec* is highlighted in [2]. It involves three steps: analyzing problem characteristics; description of actors and requirements that need to be considered and an integrated planning approach of the network.

The reading we make about this literature reveals the following common features:

- Focus on material recycling, actually few articles deal with multiple recovery options at the same time
- Deals mainly on logistics aspects; location of recovery facilities, transport planning and inventory control;
- Considers only quantitative uncertainty; volume and quality of returns, costs and prices;
- Does not consider conflicting objectives from multiple stakeholders
- Focus on the economic objective

We will see in the next section, that the existing literature is not suitable for our topic. The recycling drivers imply the consideration of all the recovery options (reuse and recycling). The value chain complexity implies to go beyond the logistics aspects, and consider the actors positioning and expectations in this value chain.

3 Focus on Electric Vehicle Batteries

3.1 The Geostrategic Issue

Demand and production of lithium have increased substantially since 2000, with nearly 6% average annual growth [15]. Lithium is traditionally used in glass, ceramics, metallurgy, pharmacy... etc. According to the US Geological Survey, these batteries held 21% of the market share in 2009 [16]. This proportion will be higher in the future, with the widespread introduction of electric vehicles.

Market development of lithium, which is expected to double in 10 years, raises the question of the availability of resources and the security of supply. In fact, these resources are more than 70% located in the "ABC" zone: Argentina, Bolivia and Chile. Today, the availability of lithium is not an issue. In EV Traction batteries, lithium carbonate (Li2CO3), accounts for less than 10% of a battery weight and lithium price was nearly 6 $/kg in 2010 [3]. The recycled lithium is more expensive than extracted lithium. So, we understand that today it is not interesting to retrieve lithium from used batteries. It will not be the case in the future, when recycled lithium will represent the largest cumulative source [4]. Although experts do not consider a scenario of lithium depletion [17], the question of emancipation from suppliers remains crucial. Miedema and Moll [18] confronted the supply capacity of lithium to the needed demand from the automotive industry. They concluded that undersupply can be expected in the near future, before a large scale recycling of batteries. The challenge in the future is to meet the growing demand without causing price volatility and to implement early enough recycling networks to provide a capital of lithium in countries using it.

3.2 The Regulatory Issue

Taking into account the effects of human activities on the environment has become one of the criteria for assessing decision-making process in the industrial world. In this context, the automotive industry is fully involved, as it was among the first industries subject to environmental regulations.

Directive 2000/53/EC [19] lays down requirements for the treatment of end-of-life vehicles (ELV) in Europe. In addition, Directive 2006/66/EC [1] sets the legal framework for the treatment of batteries and accumulators in Europe. This directive requires particularly for electric vehicle batteries the implementation of:

- A dedicated collection system at no cost to the end user;
- A system of treatment, recycling and disposal of batteries waste.

3.3 The Economic Issue

The economic stakes are induced by the possibility of a second life use of batteries. In fact, these batteries; when out of use for optimum automotive propulsion could be used as energy storage for stationary or other embedded applications based on their technical, economic and environmental feasibility. Among the possible outcomes, the use in cars exploited over shorter distances is considered, as well as stationary energy storage. The topic of the second life of batteries is attracting interest worldwide, but it is still the object of research projects at an early stage [20].

3.4 The Related Value Chain

Since the EV technologies are recent, the recycling of these batteries is not yet industrialized. Industry players do not necessarily exist today, which raises the question of their emergence and the disruption of the actual value chain. In addition, legislation (recycling targets and the Extended Producer Responsibility "EPR" concept) is pushing towards more cooperation between the OEM, the ELV recovery infrastructure, the consumer, and other stakeholders. OEMs are shifting from traditional paradigms to innovative business models [7].

Value chains for end-of-life products recovery are not considered as "natural value chains", in the sense that their implementation does not meet a market demand. This description of value chains and their origins, explains the difficulties of different actors to project economically viable systems and organize themselves [8].

The key factor to the sustainability of this recovery chain is the ability to prove its economic profitability as a whole. This assumption seems idealistic, considering the differences in the business logics of the stakeholders and the issue of redistributing profit among them.

4 Our Approach

Bringing together the remarks formulated about the literature and the specificity of our topic, we formalize a methodology to help design a sustainable recycling network applied to batteries, under uncertainty. This methodology encompasses the following features:

- Uncertainty and business models for value capture will be modeled by scenarios
- The scenarios will reflect: (i) the governance and the several positioning of the actors in the considered value chain, and (ii) assumptions about quantitative data (volume of returns, batteries quality, etc.)
- Considering the multicity of stakeholders, by optimizing objectives deriving from expressed requirements
- Considering the hole recovery options (reparation, second life applications, recycling)
- Designing a sustainable network, considering economic, social and ecologic performances.

Our approach involves two steps:

- Network modeling & problem characterization
- Scenarios development and optimization

4.1 Network Modeling and Problem Characterization

If we consider the recycling network as a complex system with multiple stakeholders, the tool that seems most suitable for the design and deployment of such a system is the systemic analysis. Applying systemic concepts to the design of complex logistic networks under uncertainty, Patay et al. [21] developed a method called SCOS'M; Systemics for Complex Organizational Systems' Modeling. It comprises five steps:

- Isolate the system and its subsystems to define the scope
- Describe the phases of the system's life cycle

- Describe for each phase of its life cycle, the expectations on the system in terms of satisfaction and performance
- Develop the functions to be performed by the system to meet these expectations
- Determine the parameters and variables of the system allowing the satisfaction of expectations.

This method seems ideal, since it meets some of the requirements of our approach, namely, the multicity of stakeholders, the multicity of performances and the identification of parameters that allow scenarios simulation. At the end of Step 5, we have identified the variables and parameters influencing the economic dynamics of the value chain.

This step is crucial, since it will lead to characterizing a network type and the elements of the problem, by defining the objectives, constraints, variables and parameters. As well as values (economic, environmental, flexibility, security) expected by stakeholders. These elements will help address the second step of this approach.

4.2 Scenarios Development and Optimization

The second step in our approach consists in a projection to the future to formalize possible value chains for recycling batteries, and then optimize their functioning. It is an approach coupling simulation and optimization. Scenarios development is about identifying several configurations for the value chain, by making assumptions about uncertainties, which we could categorize into two kinds: (i) quantitative (volume of returns, batteries quality, costs, etc.) and (ii) qualitative (monopoly of a recycler, internalization of the recycling activity by OEMs, recycling opportunities, etc.).

Regarding quantitative uncertainties, Hoyer et al. [2] identify the following ones:

- Sources (quantity, spatial distribution, composition of battery returns);
- Outputs (reuse opportunity: products, components, materials);
- Process (combination and configuration of processes).

In order to tackle these uncertainties, firstly, we'll link the parameters (results of SCOS'M) to these uncertainties, and then use system dynamics (SD) approach to predict the system's future behavior. The choice of SD has been made given the complexity of interactions existing within the system. Donnadieu & Karsky [22] define SD as a science of change and evolution. It is concerned with understanding the phenomena and their causes, identifying the factors that create change, or otherwise oppose it. System dynamics simulation is a renowned approach to simulate the effect of future changes, several system dynamics-based studies were conducted in the area of recycling ([11], [23], [24]).

Regarding qualitative uncertainties, based on the work of Williamson and the work on global value chains [25], we will imagine different positions of OEMs in this value chain, as well as those of the other actors. Examples:

- OEM will internalize transportation from collection points to recovery facilities;
- There will be a unique recycler in Europe (monopoly)

Assessing the sustainability of a supply chain goes by identifying the appropriate performance indicators, which proves to be a difficult task. The lack of social metrics is a serious challenge [26], while there is a multicity of environmental indicators (energy efficiency, greenhouse gas emissions, waste generated, waste recycling rate, etc.). In our work, we identified the metrics that seem to be most relevant to our topic, namely the economic and environmental balance. "Fig. 1" gives an overview of the causal loop diagram modeling the recycling network. This latter includes the interaction between virgin and recycled lithium, the macroscopic view of costs, benefits and environmental performances, which are also developed in other diagrams.

These scenarios will be used to develop linear programming models for the network design problem. These models will be addressed by an approach coupling simulation and optimization. The simulation enables us to test the scenarios with economic and industrial data, by the mean of SD. The optimization will allow, for each scenario, identifying the optimum solution in terms of: location and sizing of treatment facilities, planning of their implementation, as well as transport planning.

In summary, step 1 of the approach will be used to characterize the elements of the problem modeling the dimensioning of the value chain and optimizing its flows. Step 2 will adopt assumptions about the role of actors, as well as data to enable the optimization of the developed models. The results will be used to estimate sustainability of this value chain. At last, we'll synthesize the results of scenarios analysis in order to bring out the conclusions and recommendations for the recycling network deployment. This approach features some characteristics; developed in this section, that enable meeting the requirements to establish a recycling network for batteries from EVs, such as identifying the actors, the choice of governance and implementation planning.

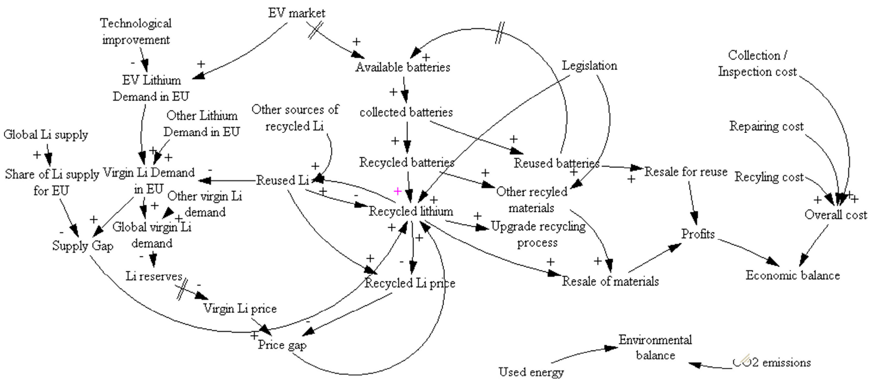

Fig. 1. Overview of the recycling network

5 Conclusion

By regulatory constraints or economic opportunism, the recycling network of batteries from EVs will be implemented. The prospective dimension of the study is a significant challenge, which requires the use of an efficient approach, able to overcome the various uncertainties and provide useful results. The emergence of this topic and the limits of the existing literature have driven us to propose a novel approach, more suitable to the specificity of our topic. This approach is multidisciplinary, involving knowledge from:

- Complex systems engineering
- Business and economic sciences
- Operational research and logistics optimization

In this paper, only modeling results are exhibited. More findings will be included in our future contributions. The perspectives after this first contribution are:

- Data collection and simulation using stock & flow diagrams. The exposed SD model being validated by the car manufacturer, the next step is data collection by the mean of interviews. Meetings are scheduled with experts within the car manufacturing company and its partners;
- The scenarios building methodology and the scenarios elaboration;
- Integration of the multi-objective optimization in the whole approach. Some of the variables identified in the causal loop diagrams are decision variables such as “investment in collection centers” and “Upgrade recycling process”. The idea is to optimize these variables, while evaluating the economic and environmental balances of the recycling network;
- Recommendations about the collaborative governance of the recovery chain, including role-play definition and profit redistribution.

We will strive to ensure the robustness of the results and the inclusion of possible new data. Since we are in a context of value chain emergence, several factors can disrupt established patterns in our work, namely the composition of EV batteries, the arrival of new actors or the evolution of legislation. This dynamic aspect of the subject will be treated with a permanent monitoring of the real value chain, allowing us to make adjustments in our scenarios.

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