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# **Analyse comparative de méthodes d'évaluation environnementale : application au cas de batteries en plomb**

## **Comparative analysis of environmental assessment methods: application to lead battery cases**

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### **Résumé**

L'objectif de cette étude est de comparer différentes méthodes d'évaluation des impacts environnementaux afin de mettre en évidence leur complémentarité. Bouman et al. (1999) ont analysé les méthodes AFS (Analyse des Flux de Substance), ACV (Analyse du Cycle de Vie) et Equilibre Partiel (méthode économique) en les appliquant sur le cas très simplifié de petites batteries au plomb et de batteries hypothétiques en « plastique ». Nous avons repris le principe de cette étude en appliquant une AFS, une ACV et une analyse économique au cas de batteries plomb-acide (PbA) et de batteries nickel-hydrure métallique (Ni-MH) pour véhicules électriques. L'AFS a permis de mettre en évidence d'une part, de faibles émissions de plomb dans l'environnement lors des étapes de fabrication et de recyclage des batteries PbA et, d'autre part, des émissions relativement importantes en nickel lors de l'étape de fabrication des batteries Ni-MH. L'ACV a montré que les batteries Ni-MH primaires (sans matériaux recyclés) ont plus d'impacts sur l'environnement que les batteries PbA primaires, alors que ce résultat s'inverse lorsque du plomb et du nickel recyclés sont utilisés. Selon l'analyse économique effectuée, les batteries Ni-MH coûtent beaucoup plus cher que les batteries PbA : cette différence est moins marquée avec l'augmentation du marché en raison d'un effet d'échelle. Enfin, une analyse multicritère permet de conclure que la meilleure solution est de garder les deux technologies : il est donc intéressant de ne pas se contenter d'utiliser une méthode d'évaluation, mais d'en comparer plusieurs.

**Mots-clés :** analyse du cycle de vie, analyse des flux de substance, recyclage, optimisation multicritère.

### **Abstract**

The objective of this study is to compare different methods of assessing environmental impacts in order to highlight their complementarities. Bouman et al. (1999) have used SFA (Substance Flow Analysis), LCA (Life Cycle Assessment) and Partial Equilibrium (which is an economic approach) methods by applying them on a highly simplified comparison of small all-lead batteries and hypothetical all-plastic ones. Following this idea, the objective of this study is to perform and compare SFA, LCA and an economic analysis on the more realistic cases of lead-acid batteries (PbA) and nickel-metal hydride batteries (Ni-MH) for electric vehicles. The SFA allowed us to identify low lead emissions into the environment at production and recycling stages of PbA batteries, whereas relatively large nickel emissions at the manufacturing step of Ni-MH batteries are observed. According to LCA, Ni-MH primary batteries (without recycled materials) have more impacts on the environment than primary PbA batteries, but this result is reversed when the batteries are made from recycled lead or nickel. The economic analysis showed that Ni-MH batteries are much more expensive than PbA batteries but if the decrease in price due

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to the scale effect is considered, the difference will decrease when the market will grow up. A multiobjective optimization finally proved that the best solution is to keep both battery technologies: it is therefore interesting to use not merely one method, but to compare several strategies.

**Key-words:** life cycle assessment, substance flow analysis, recycling, multiobjective optimization.

## 1. Introduction

The purpose of this work is to compare different environmental assessment methodologies, to highlight their difference, their complementarities and the interest of using them together. Three approaches, namely Substance Flow Analysis (SFA), Life Cycle Assessment (LCA) and an economic analysis (EA) were performed in order to guide the choice of the best technology of batteries between two technologies envisaged by the industry (lead-acid and nickel-metal hydride, Passier et al., 2007) for electric vehicles according to both environmental and economic concerns. Indeed, many studies aim at evaluating environmental impacts of a product, but the analysis is generally limited to the application of a given method. The scope of this paper is to demonstrate the interest of using them concurrently in order to obtain a more reliable result. The considered batteries have the characteristics described in table 1.

Table 1. Characteristics of the batteries (Rantik, 1999)

	PbA battery	Ni-MH battery
Energy density (Wh/kg)	35	75
Vehicle range per cycle (km)	80	125
Energy consumption (Wh/kg/km)	0.12	0.12
Battery life cycle	700	600
Total energy efficiency (%)	66	57

The different approaches must be conducted on the same service delivered by the system, thus providing a reference to which the inputs and outputs can be related. Since lead-acid (PbA) and nickel-metal hydride (Ni-MH) batteries do not have the same efficiency, the service or the so-called functional unit must be chosen so as to determine the required number of each type of battery to meet this service. For this purpose, a car lifetime set at 200 000 km was used as a reference. Taking into account that Ni-MH batteries are more efficient than PbA batteries, four PbA batteries (weight of 491 kg each) are needed to power a car during 200 000 km, whereas only three Ni-MH batteries (weight of 325 kg each) are required to provide the same function (Rantik, 1999). The methodology is based on the successive application of SFA, LCA and EA, since the analysis of substance flows will give us the necessary data to carry out the life cycle assessment. Both environmental analysis results are then used to carry out the economic analysis.

## 2. Substance Flow Analysis

### 2.1 Methodology

A Substance Flow Analysis (SFA) is an analytical tool based on a mass balance performed all along a process used for achieving the understanding of the flow of substances through a given system defined in space and time. The substances may be elements, chemical compounds or groups of chemical compounds. SFA allows identify the losses and emissions of this substance and the potential sources of environmental impacts. In this case, two major critical substances are identified, that are lead and nickel respectively used in PbA and Ni-MH batteries. Figure 1 shows the steps that are taken into account for the SFA of lead during the life cycle of PbA batteries. An identical flow diagram has been established for nickel related to a Nickel-Metal Hydride (Ni-MH) battery.

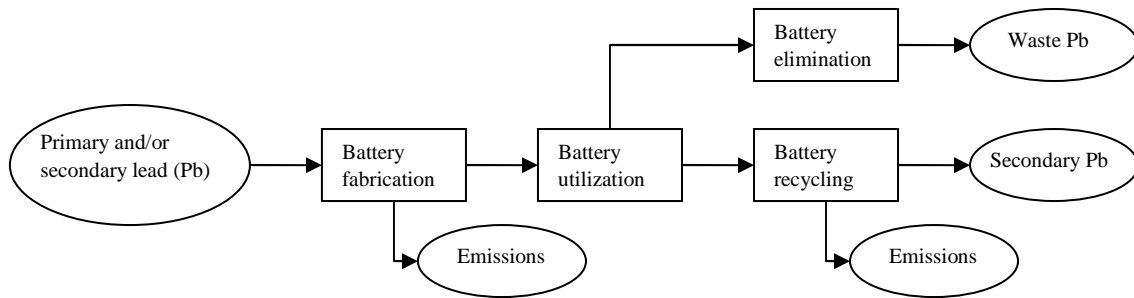


Figure 1. Substance Flow Analysis of lead during life cycle of lead-acid battery

## 2.2 Results

The SFA was conducted on two scenarios for each battery: the former one involves only primary material (from ore) and the second is based on a proportion of secondary material (from recycling), the ratio of secondary material being chosen according to Rantik (1999) and Argonne National Laboratory report (2010), as well as data on quantities of metal consumed and released in the environment at each step. Table 2 shows the results obtained: lead emissions caused by the fabrication and recycling of PbA batteries are very limited and can be neglected as compared to the wastes due to the fact that only 90% of the batteries are recycled (BIO Intelligence Service, 2003). However, concerning Ni-MH batteries, the emissions of nickel during the battery manufacturing is quite important, representing about 2.7 % of the total amount of nickel introduced, and 21 % of the total losses (emissions + wastes).

Table 2. Results of Substance Flow Analysis on Lead-Acid and Nickel-Metal Hydride batteries

	PbA battery		Ni-MH battery	
	Primary	Secondary	Primary	Secondary
	Weight (kg)		Weight (kg)	
<b>Fabrication</b>			<b>Fabrication</b>	
Primary lead	299.52	149.76	Primary nickel	97.57
Secondary lead	-	149.76	Secondary nickel	-
Lead emissions in air <sup>a</sup>	6.1.10 <sup>-4</sup>	6.1.10 <sup>-4</sup>	Nickel emissions in environment <sup>a</sup>	2.6
Lead emissions in water <sup>a</sup>	2.4.10 <sup>-3</sup>	2.4.10 <sup>-3</sup>		2.6
<b>Recycling</b>			<b>Recycling</b>	
Secondary lead	269.57	269.57	Secondary nickel	85.47
Lead emissions in air <sup>a</sup>	2.3.10 <sup>-3</sup>	2.3.10 <sup>-3</sup>	Nickel emissions in environment <sup>a</sup>	-
Lead emissions in water <sup>a</sup>	3.4.10 <sup>-5</sup>	3.4.10 <sup>-5</sup>		-
<b>Elimination</b>			<b>Elimination</b>	
Lead waste	29.95	29.95	Nickel waste	9.5
				9.5

<sup>a</sup> Only lead (respectively nickel) emissions from lead (respectively nickel) used for the battery is considered: emissions due to electricity consumption, transportation, etc. are not taken into account.

In both cases, but more especially for PbA batteries because of the large amount of lost lead, it would be very interesting to increase the amount of recycled batteries to 100%. Moreover, for Ni-MH batteries, it would be necessary to look more closely at the fabrication process to understand why there are so many emissions and to improve this critical step.

## 3. Life Cycle Assessment

### 3.1 Methodology

A Life Cycle Assessment (LCA) enables to determine the total burdens linked to a product or a process, from raw material acquisition to waste elimination, optionally including recycling. The principles of LCA are defined in international norms in the ISO 14040 series (14040 to 14044) (ISO, 1997) and follow four major goals: defining objectives and scope of the study, analysis of inventory, impact assessment and interpretation of results (Jolliet et al., 2005). To take into account that the recycling industry will grow at

the same time as the battery market, the assumption was made that, for each set of batteries, the former is made only with primary material, while the latter batteries are partly composed of secondary material. As aforementioned, four PbA batteries or three Ni-MH batteries are yet needed to power a car travelling 20 000 km per year during 10 years. Thus, LCA was performed for one set of PbA batteries (one primary and three secondary batteries) and one set of Ni-MH batteries (one primary and two secondary batteries). The scope of the study includes the fabrication of the materials used in the battery from ore, until the recycling of batteries. As before, the inventory was carried out with the data on materials, emissions and energy quantities proposed in Rantik (1999).

### 3.2 Results

LCA was conducted with SimaPro software, using Ecoinvent database, with Impact 2002+ as an impact characterization method. For this preliminary study, the final results are given as an impact “point”, which represents an aggregate adimensional indicator. These results must be appreciated in a relative comparison basis, the quantitative value being difficult to interpret. Figure 2 shows the results of the LCA carried out for both scenarios.

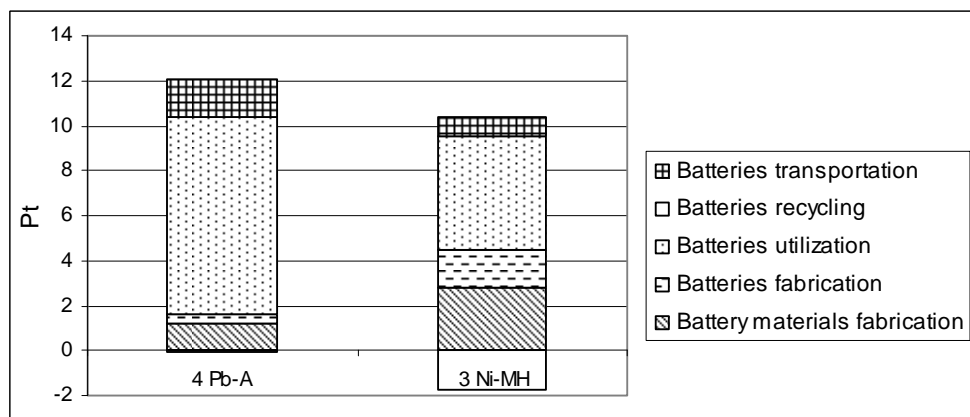


Figure 2. Results of the LCA of a vehicle powered by PbA batteries and another powered by Ni-MH batteries

Figure 2 shows that despite nickel-metal hydride batteries cause significant nickel emissions, which are very toxic, their total impact are less important than for lead-acid batteries. This is mainly due to the fact that they consume far less energy than PbA batteries, and there are fewer impacts due to transportation as there are only 3 batteries vs. 4 for one set of PbA batteries. Moreover, materials fabrication for Ni-MH battery leads to a more marked impact, recycling also leads to greater benefits (the benefits associated with PbA battery recycling are so low that they can hardly be seen in Figure 2).

## 4. Economic Analysis

### 4.1 Methodology

The purpose of Economic Analysis (EA), used as an environmental impact assessment method, is to link the product price to the problematic substances, and then see how one can interfere with taxes on some substances, subsidies on recycling, etc. However, in that case only the gross price is considered, without taking into account any taxes or subsidies. The calculation was simplified by defining cost as a function of the current price of a set of batteries with a coefficient reflecting the scale effect. The cost relative to one set of each battery will be calculated according to the following equation:

$$Cost = a \cdot P + (1 - a) \cdot P \cdot \lambda^{\frac{N}{10,000}} \quad (1)$$

with:

- a: fixed part of battery price, not impacted by scale effect ( $0 < a < 1$ )
- P: initial price of a set of batteries
- $\lambda$ : price reduction coefficient due to scale effect
- N: number of set of batteries

## 4.2 Results

The prices for primary batteries were taken from (Matheys et al., 2004) and weighted with data from (BIO Intelligence Service, 2003) to calculate secondary battery prices. It must be emphasized that the market for electric vehicles batteries is not yet mature and that even if both types of batteries are still in the decreasing phase of the scale effect, they are not at the same stage of development. The purpose of this study is yet to demonstrate the validity of a cross comparison of various impact analysis methods. Since the Ni-MH battery market is more recent than for PbA batteries, it was considered in the computations that the effect of decrease in price is more pronounced for Ni-MH batteries.

Thus, the following parameters were used in the equation (1):

- fixed part of the price:  $a = 0,5$
- initial price:  $P_{PbA} = 9,750 \text{ €}$  /  $P_{NiMH} = 39,730 \text{ €}$  (Matheys et al., 2004)
- reduction coefficient:  $\lambda_{PbA} = 0.99$  /  $\lambda_{NiMH} = 0.85$
- $N = 100\ 000$  sets of batteries

A significant result illustrated in Figure 3 is that the scale effect tends to reduce the discrepancy between the costs of the two kinds of batteries.

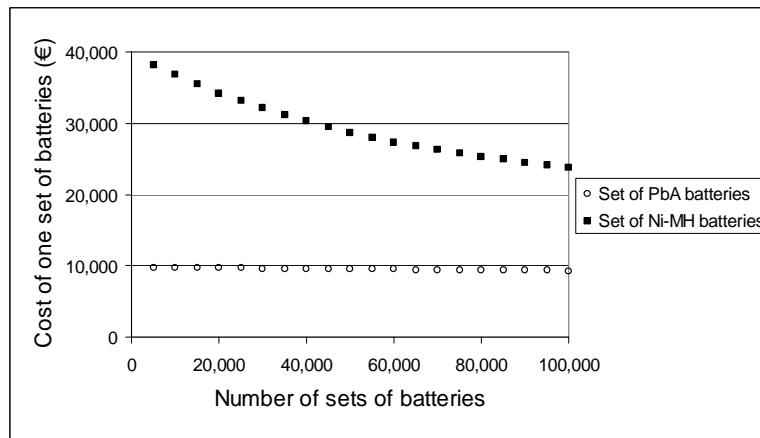


Figure 3. Results of the economic analysis

## 5. Biobjective Optimization

### 5.1 Methodology

Since economic and environmental criteria exhibit antagonist behaviours, a biobjective optimization strategy was performed. For this study, it was assumed that 100,000 cars need to be powered by PbA and/or Ni-MH batteries. The optimization variable  $y$  is the ratio between the number of sets of PbA batteries and the total number of sets of batteries.

#### 5.1.1 Economic criteria

All costs were considered similar for the different batteries, except investment cost. Thus, the cost objective  $C$  only depends on the number of each set of batteries. The cost  $C$  is considered as a weighted sum of the individual costs of each kind of battery following the expression of Eq. 1:

$$C = N \cdot \left[ y \cdot \left( a \cdot P_{PbA} + (1-a) \cdot P_{PbA} \cdot \lambda_{PbA}^{\frac{y \cdot N}{10,000}} \right) + (1-y) \cdot \left( a \cdot P_{NiMH} + (1-a) \cdot P_{NiMH} \cdot \lambda_{NiMH}^{\frac{(1-y) \cdot N}{10,000}} \right) \right] \quad (2)$$

#### 5.1.2 Environmental criteria

The environmental burden ( $I_{total}$ ) of the batteries was assumed to be directly proportional to the number of batteries produced, without any scaling or coefficient factor and can be expressed as follows:

$$I_{total} = N \cdot (y \cdot I_{PbA} + (1-y) \cdot I_{NiMH}) \quad (3)$$

In this expression,  $I_{PbA}$  and  $I_{NiMH}$  represent respectively the impacts of PbA and Ni-MH sets.

## 5.2 Results

Using the same parameters as for the economic analysis, a biobjective optimization approach was performed and the results are presented in Figures 4 and 5.

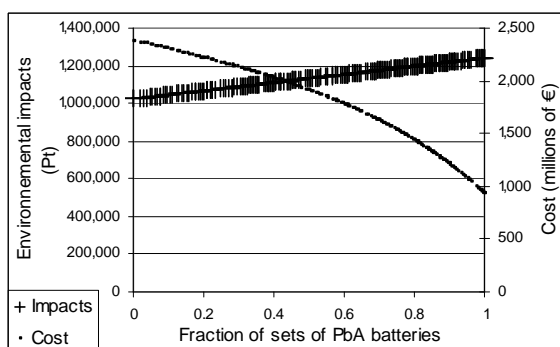


Figure 4. Environmental and economic impacts depending on the fraction of sets of PbA batteries

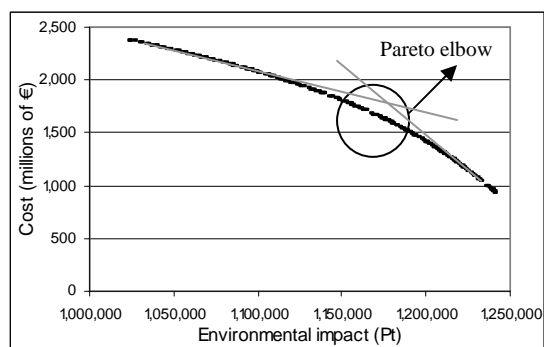


Figure 5. Cost as a function of environmental impacts: Pareto front

Figure 4 shows the environmental impacts (linear increasing curve) and the cost (decreasing curve) as a function of the fraction of sets of PbA batteries. It can be observed that the two curves intersect at about  $y = 0.45$  and that the price decrease is faster than the impact increase. Figure 5 displays the Pareto front, which is the set of non-dominated solutions. Generally, a solution is chosen in Pareto elbow, which is the place on the curve where the shift is most important: here it is for a price of about 1,700 € and an environmental impact of about 1,185,000 points. By reporting these values in the graph in Figure 4, a value of  $y$  between 0.45 and 0.65 is obtained.

## 6. Conclusion

As expected, the different approaches used in this study lead to complementary results:

- SFA shows that PbA batteries generate lower lead emissions than nickel from Ni-MH batteries.
- LCA demonstrates conversely that the impact of Ni-MH batteries is less important than for PbA batteries, under the condition that secondary nickel is used for at least two of the three batteries.
- According to the economic analysis, PbA batteries represent a better option, despite the fact that four PbA batteries are needed against three Ni-MH batteries.

These results prove the interest to use different methods to evaluate a product and to mix the use of various technologies batteries in order to take into account the various trade-off situations that may occur.

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