

A COST ANALYSIS OF ELECTRIC VEHICLE BATTERIES SECOND LIFE BUSINESSES

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In the following years thousands of electric cars are expected to be sold. Knowing that these batteries are not useful anymore for traction services after they have lost a 20% of its capacity, there will be thousands of batteries able for re-use. The re-use represents a considerable environment improvement compared to the immediate recycling. According to battery recycling enterprises, not even half of them are collected back after their use but car manufacturers should ensure that their electric vehicle batteries will be processed. A second life added value might help a better deposition and management control.

Although interesting, the second life re-use is not simple. Vehicles should first arrive to the dispersed authorized processing centers in the country. Once there, batteries should be extracted, packed according to legal regulations and transported to the restoration plant, where they will be tested, their components revised and they will be prepared for the second life application.

All this implies personal, transport, installation amortization and spare part costs. This work will present how appropriate the idea of the battery recovery for second life applications is.

Keywords: *Second-life; Reuse; Battery; Lithium; Electric Vehicle*

EL NEGOCIO DE LA SEGUNDA VIDA DE BATERÍAS DE COCHES ELÉCTRICOS: ANÁLISIS DE COSTES ASOCIADOS

En los próximos años se espera vender miles de coches eléctricos. Sabiendo que cuando sus baterías pierden el 20% de su capacidad dejan de ser utilizables para el sector de la automoción, aparecerán entonces miles de baterías que podrán ser reutilizadas. Esta reutilización supone una mejora ambiental considerable respecto al reciclaje inmediato. Según las empresas encargadas del reciclajes de pilas, ni tan siquiera la mitad de las pilas llegan a los centros de tratamiento, pero los fabricantes de coches deben asegurar que serán tratadas como corresponde. Dándoles un valor añadido de segunda vida, se pretende controlar mejor su depósito y gestión posterior.

Aunque interesante, la reutilización en segunda vida no es sencilla. Los vehículos usados tienen que llegar a los distintos centros autorizados de tratamiento del país, una vez allá las baterías deben ser desmontadas del vehículo, encajadas según la legislación vigente y transportadas a la planta de rehabilitación, donde se testearan sus capacidades, se verificará el estado de sus componentes y serán preparadas para su segunda aplicación.

Todo ello significa unos costes de personal, transporte, amortización de instalaciones y recambios. Este trabajo permite saber hasta qué punto es acertada la idea de la recuperación de baterías para segundos usos.

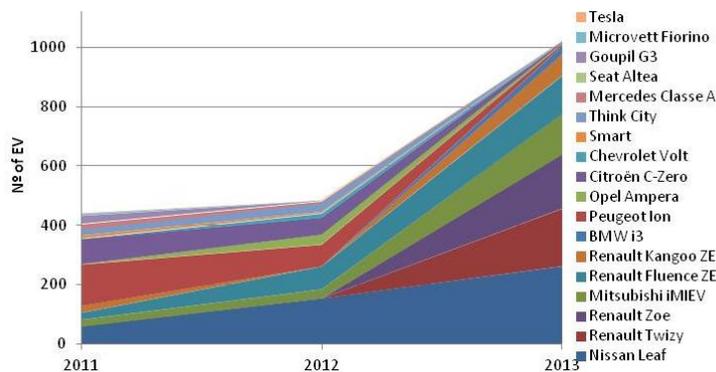
Palabras clave: *Segunda-vida; Re-uso; Baterías; Litio; Vehículo eléctrico*

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1. Introduction

The Electric car is presented as a possible future solution to reduce the CO₂ emissions from the transportation sector. It has been observed that government's efforts on the transport sector CO₂ emissions are a key factor to accelerate or retain the Electric Vehicles (EV hereinafter) entrance into the automotive market. Anyhow, even in the less optimistic case, thousands of EVs are expected to be sold during the following years (Anable et al, 2012). In fact, in the Spanish market (Figure 1), the number of EVs registered in 2013 doubled the quantity from 2012 and it surpassed the 1.000 cars for the first time. Anyhow, it should be noticed that two car manufacturers (Nissan, Renault) cover more than the 80% of the EV market.

Figure 1. Evolution of EV registered in the last years in Spain



Note: ANIACAM (Asociación Nacional de Importadores de Automóviles, Camiones, Autobuses y Motocicletas)

The EVs are actually powered by batteries, most of them based on lithium technologies (Scrosati & Garche, 2010). As most of things in life, batteries get degraded with its use (Broussely et al., 2005). For traction use it is considered that they are not appropriate anymore when they have lost between a 20 and 30% of their capacity or power. At this point they should be removed from the car and, normally, collected for recycling.

European directives try to force batteries and accumulators wastes collection by putting some pressure on battery manufacturers, charging them the recollection costs (Directive 2006/66/EC) and setting collection targets of at least a 45% of the sold batteries by 2016. Although intended, this does not usually happens for the small batteries on the market and, in fact, this target seems hard to achieve because of the inefficient battery and waste electrical and electronic equipment collection network and because, in many cases, batteries are fully integrated in some appliances (Weyhe, 2013).

Anyhow, EV batteries don't follow the same directive, and the recuperation and recycling responsibility falls on car manufacturers. For them, up to 85% of the car weight should be recycled and another 10% can be energetically recovered. Therefore, it is important not to lose any of them after its car-life, even if recycling batteries costs, nowadays, hundreds of Euros (Lithorec, 2012).

There's one alternative to recycle though. Even if the EV batteries are not performing as well as brand new ones, they are still in quite good conditions compared to the average energy storage systems used on stationary applications. Therefore, some economic and useful value might still be extracted from them with second uses before recycling.

From this point of view, second life's added value might help to improve deposition and control because its owner has something to gain. This is, indeed, not the only positive result: Second life might also lower a bit the EV prices and make them slightly more attractive against the internal combustion (IC), it won't have an extreme impact, but everything is

welcome from the cost-reduction side (Canals, Amante, & González, 2014). Still into economics, re-using batteries might evolve into lower battery prices for stationary grid applications and, hence, the implementation of micro-grids and decentralized energy production as well as the definitive integration of smart-grids and their supposed benefits within (Roberts & Sandberg, 2011), (Eyer & Corey, 2010). And finally, a direct environment impact reduction is driven from the use of second life's EV batteries (Ciccioni, et al. 2012). If re-use finally exists, it is clear that less new batteries should be manufactured.

All these encouraging aspects brought the idea of re-using them for Battery to Grid (B2G) applications and first economical approaches, with not very accurate life-length assumptions, had been presented (Ciccioni et al., 2012), (Sovacool & Hirsh, 2009).

Even though interesting, the second life re-use is not a plug-and-play story. Batteries should be collected, revised, tested and arranged if necessary. Then, regarding its state of health (SOH), they should be classified and stored until the second-life installation is prepared. All these works on batteries should be translated into costs. The subtraction of these costs to the 2nd life application's incomes and profit will resolve the "willing to pay" value for these used batteries. If these values are high, all the positive aspects will go on, but if it is too low or negative there will be not much hope.

This work will present the estimated costs for re-habilitation of EV used batteries. This is the first step needed to continue with the second-life's debate.

2. Methodology

This paper will begin with a brief analysis of the battery circuits during its first use in vehicles and their collection for re-use or recycle. The recollection costs will be estimated from received offers by battery management integrated systems.

There are three main types of electric cars: Hybrid (HEV), Plug-in Hybrid (PHEV) and full electric (EV). Second life has sense with big battery packs; therefore, the study will only consider batteries from PHEV and EV.

For these batteries, there are two main strategies to face rehabilitation. The first one is meant to re-use the batteries without much intervention. That is, trying to re-use the batteries in the same configuration as it is used in the car: same shape, same refrigeration systems, same covers... as if it was a black box (Carranza, 2013). The second one opts to dismount the battery in modules or cells and re-arrange them in a better configuration for the second use (Cready et al., 2003). Some of their main characteristics are presented in

Table 1. In this work, both strategies will be analyzed.

A cost analysis based on recollection costs, functional and health tests, re-habilitation plant investments amortization and production time costs will be calculated. Knowing that nowadays, and until at least ten years, the number of batteries available will still be low, two approaches will be presented: One for a re-habilitation plant using 176 batteries per year at most, where workers are far from being saturated and they have many waiting or spare time; And another one considering enough batteries to support a productively better optimized factory. That is:

- For the direct re-use strategy: 6 test benches working simultaneously providing a total of 1056 batteries per year for both PHEV and EV with one worker per turn.
- For the module reconfiguration: two workers per turn to run 3 test benches for 528 PHEV re-purposed batteries annually and 2 test benches to work on 352 EV batteries.

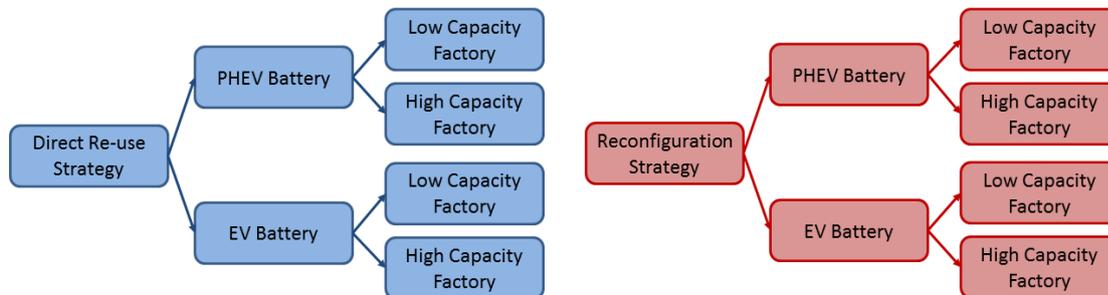
Table 1. Comparison of the two basic rehabilitation strategies.

Direct re-use		Module reconfiguration	
Pros	Cons	Pros	Cons
Faster battery check	Rigid final product not suitable for all 2 nd life applications	Optimized final product for specific 2 nd life application	Much more preparation time
Easier rehabilitation process	Big battery manipulation	Manipulation of manageable modules	Need to build the new configuration.
Re-use of all components	Need of additional interfaces for communication.	Adapted BMS and refrigeration system	Design and programming of new components
Cheaper *	Stackable at battery level	Stackable at module level	More expensive *

For this work, the re-habilitation plant will be located near one of the most important car manufacture centers in Spain, close to the city of Barcelona. Although theoretically this re-habilitation plant could take batteries from all EV manufacturers, we planned just working with one battery type only. It has to be taken into account that there is a huge diversity in batteries and that there is many confidential information contained in a battery pack. In addition the responsibility of these batteries all along its lifetime will fall under the car manufacturers. Therefore, car manufacturers will surely work hand-to-hand with only one Company, like it is the case of the (4r-energy) venture.

All the analyzed alternatives are summarized in Figure 2.

Figure 2. Summary of the studied alternatives



3. Discussion

Cars are manufactured mostly in one production plant in Europe and then, spread all around the territory or even abroad and overseas to car dealerships. Batteries should follow the same path but the opposite way (Figure 3). In the EU and in Spain in particular, after the end of useful life, cars should be disposed at the CATs for dismantling. They can arrive there by different meanings:

- The owner leaves the car to the dealership where he will buy a new one. Then, the car dealers should send the car to the CAT for dismantling.
- The owner brings the car directly to the CAT.
- There are municipal services that pick-up abandoned cars.

The first option is the most followed because of the government incentives in renewing the automobilist park (*Plan Pive 5*, 2014), and because of the easiness given by dealers. In any case, all these related costs are not taken into account in this analysis because they do not differ from the actual situation of IC cars, so there should be no extra cost. Anyhow it serves to know the starting locations for battery collection. From Table 2 it can be seen that different car brands follow similar selling strategies, concentrating their efforts in the same cities.

Table 2. Car dealerships distribution in five cities for different car manufacturers

Barcelona	Sevilla	Bilbao	Madrid	Santiago de C.	Car Manufacturer
39	10	10	43	13	SEAT ("Concesionarios SEAT," n.d.)
21	9	10	49	2	RENAULT ("Concesionarios RENAULT," n.d.)
18	4	8	26	2	CITROËN ("Concesionarios CITROEN," n.d.)
14	1	5	15	1	MAZDA ("Concesionarios MAZDA," n.d.)

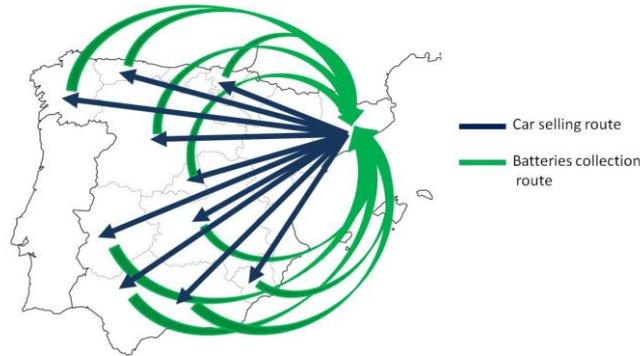
There are more than 1200 CATs spread all around Spain, most of them are located near the places where more cars are sold (DGT, 2014).

Once there, the vehicles are dismantled and their battery removed. These costs will still not be taken into account in the calculations because it does not differ from the actual situation. This is the last common path from IC vehicles and therefore, the last non specific cost attribution.

It will be considered that no battery statement will be done at the Treatment Authorized Centers (CAT) where cars are deployed at the end of their lives. According to legislation, damaged batteries are considered hazardous merchandises (Ministerio de Asuntos exteriores y Cooperación, 2013), so their transportation should be done in special conditions: They should be placed inside two containers and at least one of them sealed and fire-resistant. This increases the transportation costs. Hence, although batteries conditions will not be determined, only batteries from crashed cars will be considered as damaged batteries. In fact, these batteries, for safety reasons, won't be used for re-habilitation and their managements costs will be added to the final value. According to the Spanish Government (Ministerio de Interior, 2013) and from interviews done on local CATs, the number of crashed cars arriving at their installations is lower than a 10%.

Then, batteries will be transported to the re-habilitation plant (Figure 3). As there are more treatment centers than registered EVs in Spain, it is highly improbable that one particular CAT receives more than one battery per month. Hence, it will be considered that each battery will be collected individually from the CATs when they eventually receive an EV and take the battery off.

Figure 3. Car selling and batteries collection opposed paths. Own source



Once batteries are at the factory, they should first be checked at determined conditions using climate chambers and precise electronic equipment. Nowadays, these tests are neither fast nor simple (Schweiger et al., 2010), (Zenati et al. 2012). In fact, the VDA initiative, formed by the vehicle manufactures, has defined in the “Test specification for li-ion battery systems” a capacity and power pulse tests that, if strictly followed (Table 3), take about 126,25 and 78,6 hours respectively. That is, of course, too much for any business to run, therefore we will consider that a time improved test will be executed lasting no more than 24h.

Table 3. Capacity and Power pulse tests description from VDA-Initiative (2007/03/05)

Capacity test	Power test
Standard Cycle	Acclimatization at 40°C
Acclimatization at -25°C	Standard Cycle
Discharge 1C	Acclimatization at 40°C
Charge at cell nominal (C/3 normally)	Discharge 1C until 80% SOC
Wait 30 minutes (for temp. stabilization)	Acclimatization
Repeat 3 times Charge/discharge cycle	Pulse:
	Discharge at I_{max} for 18s;
	Relaxation for 40s;
	Charge at $0.75 \cdot I_{max}$ for 10s
	Relaxation for 40s;
Acclimatization to RT	Discharge until next SOC step
Discharge 10C	Repeat for SOC 65%, 50%, 35%, 20%
Charge at cell nominal (C/3 normally)	Standard Charge 1C
Wait 30 minutes (for temp. stabilization)	Acclimatization at RT °C
Repeat 3 times Charge/discharge cycle	Standard Cycle
Acclimatization to 40°C	Repeat Pulse test for all SOC steps
Discharge 20C	Acclimatization at 0°C
Charge at cell nominal (C/3 normally)	Standard Cycle
Wait 30 minutes (for temp. stabilization)	Repeat Pulse test for all SOC steps
Repeat 3 times Charge/discharge cycle	Acclimatization at -25°C
Acclimatization to RT	Standard Cycle
Standard Charge	Repeat Pulse test for all SOC steps

Depending on their performance results, they will be classified according to the second life applications needs. Then, special arrangements and maintenance tasks will be done, such as the implementation of communications interfaces to adapt the BMS (Battery Management System) strategies to the needs of second use applications or change degraded materials. Finally, they will be checked again in order to validate the complete functionality, this final check won't be as demanding as the first one because it is not intended to search the battery SOH, it just checks if it will be able to execute the requested services. It should be noted that batteries coming from crashed cars will be immediately sent to recycle plants.

For the module reconfiguration strategy, batteries will be dismantled before the first functional check, and then each module will be verified independently following the same procedures. Once checked and selected, the modules will be regrouped in categories to build a new battery pack completely different from the original car battery, it can be smaller or even bigger. The main difference is that in this case, the refrigeration systems and the BMS will be completely new, while in the previous case they will also be re-used.

Then, the rehabilitated batteries will be stored in the special warehouse, with all the safety systems required, waiting for its shipment to their new installation.

4. Results

The most valuable element in lithium batteries to recycle is Cobalt. Therefore, recycling plants just pay to receive the ones containing more than a 5% of its weight. As EV batteries have much less than this percentage of Cobalt, it is the manufacturer who has to pay for them to get recycled. Taking an average of different offers received, it has been calculated that the collection of a Plug-in Hybrid Electric Vehicles (PHEV) battery should cost around 170 € while EV ones will rise up to 316 €. Their packaging is considered to cost 20 and 38 € depending on the battery size and weight.

Calculations follow with the re-manufacture plant costs, which will take investments, consumables and personal costs.

In order to have an approximation to the plant dimensions and costs it is important to know the production time and processes. In general, EV batteries are twice as big as PHEV ones, then, the dismantling and module reconfiguration strategy using EV batteries needs more time than using PHEV ones. This is not such a problem running the Direct re-use strategy, as the battery is treated as a pack no matter the size. In Table 4 there is the comparison of the production time associated to each of the strategies followed and the battery size to prepare. It can be appreciated that the difference between both strategies is 10,5 and 20.9 hours for PHEV and EV batteries respectively. That is equivalent to say that the reconfiguration strategy needs 3,5 and 6 times more manipulation time than using the direct re-use strategy.

Table 4. Time distribution of direct re-use and module reconfiguration strategies

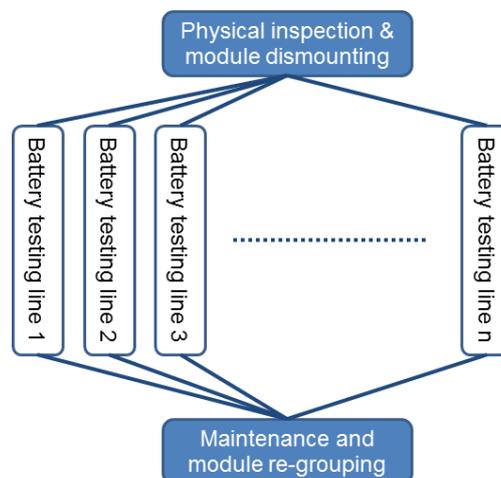
Direct Re-use		Module reconfiguration		
Operation	PHEV & EV	Operation	PHEV	EV
	time (h)		time (h)	time (h)
Physical inspection	0,5	Physical inspection	0,5	0,5
		Battery dismantling in modules	5	9
Test preparations	1	Test preparations	2	3,6

Battery test	24	Battery test	24	24
Disconnection and battery classification	0,5	Disconnection and modules classification	1	1,8
Interface mounting and maintenance	1	Battery re-habilitation	5	9
Functional battery tests	0,5	Functional Battery tests	0,5	0,5
Storage	0,25	Storage	0,25	0,25
Shipping	0,5	Shipping	0,5	0,5
TOTAL	28,25	TOTAL	38,75	49,15

As presumed, bottleneck is found in the battery test and test preparation operations. The duplicity of testing benches or lines would help to substantially reduce waiting times (Figure 4). For the direct re-use strategy, starting with one worker doing both initial and last operations (Physical inspection and maintenance), up to 6 batteries could be tested simultaneously, having one battery ready every 4.7 hours (n=6).

On the other hand, for module reconfiguration, the working on battery time is 14.75 or 25,15 hours. In this case, for an EV battery almost the same time is used in preparing the battery an testing, meaning that workers are saturated. Then, if we want battery tests benches duplicity to provide time reductions, the dismantling and mounting operations should be done by different operators. If two workers are contracted per turn, up to three lines could be installed for PHEV and two for EV batteries.

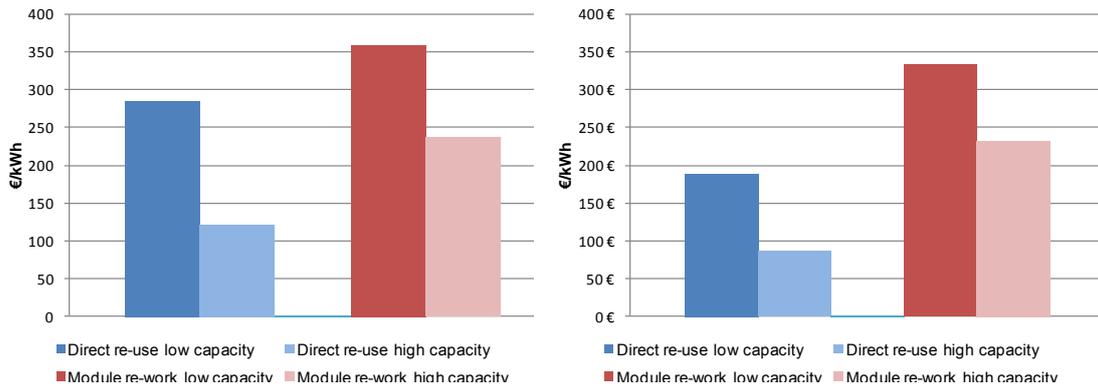
Figure 4. Duplicity of battery test benches or lines schema



Many combinations can be studied regarding these options but reality should not escape from our scope. Taking a look at the number of registered cars in Spain (Figure 1) it can be appreciated that the bestselling model delivered just 270 cars (less than one car per day). That means that, from now until 10 years, no more than that will arrive yearly to the rehabilitation factory. That is why we had chosen to provide two approaches, one for the first steps, when there are not many batteries around, and another one considering a high capacity re-habilitation factory.

The economical results are shown in Figure 5. It can be appreciated that at higher capacities, the costs of re-habiltated batteries is reduced. It can also be noticed that direct re-use is always cheaper than re-worked batteries under similar productivity environment. The best prices are 122 €/kWh from PHEV batteries and 87 € from EV.

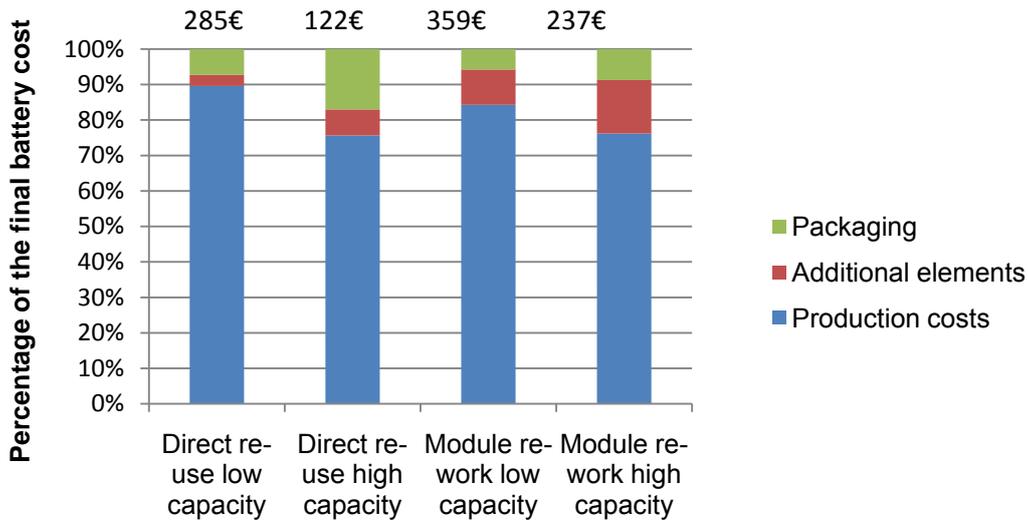
Figure 5. Cost per kWh of a re-habilitated battery.



Note: Left, cost from a PHEV second life battery. Right, costs from EV second life batteries.

Packaging and maintenance or materials have fixed costs, that is, not depending on the strategy followed. Hence, when entering more into the cost detail distribution (Figure 6), it is visible that their impact is heavier in the high capacity options. It is also understandable that the module re-working strategy needs more materials to build a “new” battery, thus, higher costs and bigger impact. Of course, the production costs take the bigger part in all four studied cases, being always above a 70% of the total.

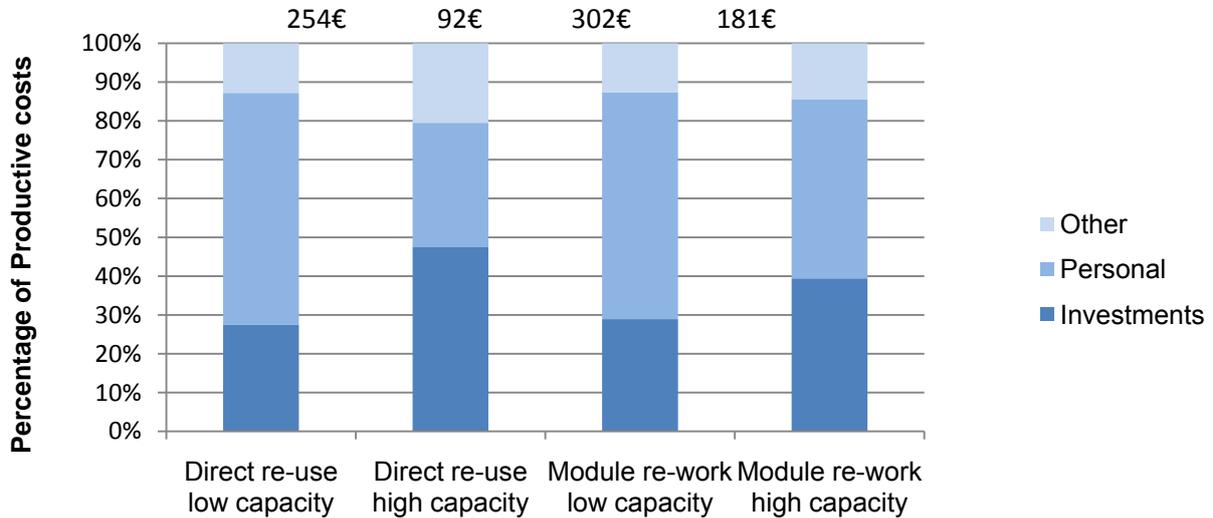
Figure 6. PHEV Battery total cost distribution



Finally, looking at the production costs (

Figure 7), it is visible that the impact of labor costs, investments amortizations and other costs (electricity, maintenance, etc.) also change along the strategy and productivity solution chosen. Obviously, labor costs are more determining in low capacity solutions than in more capable alternatives, where investments take the lead. For example, direct re-use in a high capacity configuration, which has up to six test lines in parallel, has an investment impact above the 50% of the final production cost.

Figure 7. Distribution of PHEV productive re-habilitation costs for each solution



A list of installation needs is presented in order to better understand the investments involved in second-life battery reconfiguration: Climate chambers, High power and energy testing equipment, prepared warehouses and storage racks, conveyors, forklifts, office equipment and industrial plant annual rent.

In the end, it is evidenced that the faster production goes, the lower the price becomes and the smaller labor cost impact is. It is also visible that the cost reductions are more visible in direct re-use

5. Conclusions

Nowadays, new batteries cost near 800 €/kWh and the expected prices for 2020 are around 400 €/kWh (Neubauer et al. 2012), (Price, Dietz, & Richardson, 2012).

The costs of re-habilitated batteries, no matter which of the strategy, are always under 360 €/kWh. The best price obtained is 87 €/kWh from direct re-use of EV batteries on a high capacity factory. Indeed, it is 4 times cheaper than a low capacity re-worked one.

If the number of received batteries is expected to stay above the 500 units per year it is highly probable to have a profitable business. The difference from our best price and the expected cost of brand new ones is four times lower. That represents a substantial potential for second-use batteries to have a niche in the energy storage market.

Anyhow, we can conclude that it's better not to count much on the module reconfiguration strategy, at least at the beginning, because there's not enough margin between the re-purposed cost and the expected price from new batteries. In fact, the direct re-use solution clearly takes the lead.

We can also affirm that EV batteries provide better economic results than PHEV ones because they have more modules, thus, capacity in relation to the time invested in the process.

This first approach shows up that results get better when more EV batteries are available. In fact, even the most intensive solution presented has a major manual work. Industrialization can easily provide lower costs if there are enough re-manufactured batteries to invest in.

Another expected improvement will surely come with a more efficient battery SOH assessment test, which is something car manufacturers are already working on. Actually, car manufacturers are also working on the development of a BMS prepared for first and second uses which will facilitate their integration in the net.

From the obtained results, we can suggest that re-used batteries will speed up the entrance of storage systems into grid ancillary services.

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