

Going Electric: Expert Survey on the Future of Battery Technologies for Electric Vehicles

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Abstract:

The paper describes the results of a survey, carried out with leading EU experts, on the capacity of both fully electric and plug-in hybrid vehicles to reach commercial success in the next twenty years. The success of electric transport is hampered by a combination of low range, scarce efficiency and high costs of batteries. Costs are expected to decrease in response to increasing sales volume and technical improvements, and advances would result from adequate investments in research, development and demonstration (RD&D). Experts' judgements are collected to shed light on the inherently uncertain relationship between RD&D efforts and consequent technical progress, and to assess the complex dynamics that will hinder or support the widespread diffusion of electric vehicles. The analysis of the experts' data results in a number of important policy recommendations to guide future RD&D choices and target commitments both for the EU and its member states.

Keywords: expert elicitation; battery technologies; electric vehicles

1. Introduction

The transport sector is a key contributor to both greenhouse gas emissions (GHGs) and local pollution. The IEA (2012) estimates that 20% of global primary energy use and 25% of energy-related carbon dioxide (CO₂) emissions are attributable to the transport sector alone. If current trends persist, global energy demand for transport and energy related CO₂ emissions are expected to double by 2050ⁱ. The increasing concerns on rising GHG emissionsⁱⁱ and security of oil supplyⁱⁱⁱ make the development of low-carbon and carbon-free technologies for transportation a high priority for policy makers around the world (IEA 2012).

The main challenge ahead lies in lowering the costs of currently available alternative transport technologies. Two main options are under consideration in the public and private realm. First, there is widespread interest in the development of cost-competitive second and third generation biofuels as alternative energy carriers. Second, much attention is focused on the potential diffusion of Electric Drive Vehicles (EVs) both for private and commercial transport (EC, 2011).

This paper describes the results of a survey involving fifteen experts on batteries for EVs from different European countries. Experts' judgements, based on their knowledge and experience can, at least partly, overcome the lack of empirical or modelling data on the effect of public RD&D investments on battery cost development and the presence of non-technological barriers to EVs market diffusion. We developed a solid elicitation protocol based on the rich literature on expert elicitation techniques to gather data on these complex issues. A companion paper (Fiorese et al., 2011) focuses instead on the future of second and third generation biofuel technologies.^{iv}

Aim of the survey was to gather experts' assessments of the current technical state of batteries for fully electric vehicles (Battery Electric Vehicles or BEVs) and Plug-in Hybrid Electric Vehicles (PHEVs)^v and collect probabilistic estimates of their future costs and widespread diffusion in the light duty vehicles (LDV) market^{vi}. Publicly available knowledge regarding both these issues is rather limited. Cost estimates available in the literature vary widely and are frequently non homogenous, as they rely on a range of different assumptions. Moreover, the development of batteries for the LDV market is a strategic niche for a number of car manufacturers, and secrecy is often employed to protect the latest development. As a result, the available knowledge on potentials and costs is limited.

Core of the elicitation process was to assess the effect of government support, in the form of research, development and demonstration (RD&D), on batteries' costs. The cost estimates we collected are conditional on different levels of public RD&D funding aimed at improving batteries and fostering the diffusion of EVs. Baker et al. (2010) engage in a similar endeavour focusing on

the United States. Our study complements their analysis: we provide the first elicitation focusing on the European Union (EU). Our survey engages a notably larger and more diversified number of experts than is normally employed. We also put forward the first experts' assessment of diffusion scenarios in OECD, developing and fast-growing countries.

Our results provide novel evidence on the likely evolution of battery costs in the next decades and on the range of uncertainty surrounding them. We present a number of important policy recommendations to guide future RD&D choices and commitments both for the EU and its member states.

This paper is organized as follows: the next section clarifies why we decided to focus on batteries for EVs and which technologies we surveyed. It also reviews the current status of their technological development, providing a summary of the existing literature. Section 3 describes the expert elicitation protocol and process and Section 4 presents the experts' assessment of technological maturity as well as their suggested RD&D budget allocation through 2030. Section 5 illustrates the experts' projections of BEV and PHEV battery costs under three different EU public RD&D funding scenarios. Section 6 discusses the probabilities assigned by the experts to three scenarios of EVs' diffusion in different geographical markets, the barriers to commercial success and the dynamic of technology transfer and knowledge spillovers. The last section concludes the analysis and discusses the main findings of the study, putting forward important policy implications for RD&D focus and funding.

2. Electric drive technologies today

One of the components of a successful strategy to limit long-terms global temperature increase and limit dependence from fossil fuels is the support of EVs diffusion into the market. In March 2007 the EU launched the "Climate and Energy Package", which was adopted by the European Parliament in December 2008. The plan sets ambitious targets for the EU: by 2020, GHG emissions should be at least 20% lower than 1990 levels, energy efficiency should increase by 20% and the share of renewable in total energy consumption and in transport should reach 20% and 10%, respectively (EC, 2007). In light of this last target, the widespread deployment of cost-competitive EVs, provided power production is progressively decarbonized, is a priority for EU policy makers. It is paramount to ensure that the rising demand for transportation services is met, while addressing climate change concerns.

In the scenario in line with a 2°C stabilization of average global temperature increase, the IEA calls for a 20 million EVs on the market by 2020. This is a very ambitious goal considering the current outlook. From 2001 to 2011, EVs reached over 2.5 million cumulated sales worldwide (IEA, 2011a). In 2011 EVs represented a tiny fraction of the overall vehicle market, with only 40,000 EVs commercialised worldwide. The biggest markets at the global level were Japan and the US, where EVs market share in the private vehicle market is still relatively low, representing 9% and 2%^{vii} of LDVs, respectively (IEA, 2011a).

Although the market is still modest, announced policy targets for BEVs and PHEVs are not (Table 1).

Country	Year	Target
US	2015	1 million cumulative PHEVs
Germany	2020	1 million cumulative EVs (BEVs, PHEVs, FCEVs) (5 million by 2030)
UK	2020	1.2 million cumulative EVs (3 million by 2030)
France	2020	2 million cumulative BEVs/PHEVs
Japan	2020	800,000 cumulative BEVs/PHEVs
South Korea	2020	50,000 cumulative BEVs/PHEVs (50% of sales by 2030's)
China	2020	5,000,000 cumulative PHEVs
UE	2020	5 million EVs sales

Table 1: Targets of stock sales or market share announced by different countries. (Sources: ICCT, 2012; EC, 2011).

Public investments for Research, Development and Deployment have, at least partially, been mobilized in line with these targets. Data on public and private RD&D investment specifically aimed at improving storage for vehicles is not easily available and are often not homogeneous.,^{viii}

A JRC report (Wiesenthal et al., 2011) calculates the corporate and public funding for both internal combustion engines and EVs in 2008 (Table 2).

	Corporate R&D (millions of €)	EC FP7 (millions of €)	Public Member States R&D (millions of €)

Internal combustion engines	5000-6000	16	132
BEVs and PHEVs	1300-1600	23	60-100

Table 2: Approximate R&D investments in automotive technologies in the EU in 2008 (Wiesenthal et al., 2011)

In the EU, corporate R&D funding covered in 2008 about 94% the investments in electric vehicles (Wiesenthal et al., 2010).

One can examine the trend of public RD&D financial support for the whole energy storage category (Figure 1).^{ix} Between 2002 and 2010, the EU, the US and Japan showed an average annual investment in energy storage of 64.5, 59.7 and 51.5 million USD, respectively (IEA, 2011b).

The US, RD&D budget for EVs sharply increased in February 2009 due to the stimulus package^x which also targeted the improvement of advanced batteries systems and vehicle batteries produced in the country. However, the budget sharply decreased in 2010, although it remained higher than in the 2004-2007 period. The EU RD&D budget devoted to energy storage showed positive trend between 2006 and 2009, but declined in 2010. Over the whole period 2002-2010, Italy accounted for 30% of public RD&D investments, followed by Switzerland (20%), France (19%) and Germany (13%). However, the relative weight of the different countries has changed over time.^{xi} In Japan, where public RD&D spending in energy storage jumped in 2007, a “Green Economy and Social Reform” plan was defined, which included a large focus on hybrid vehicles (EC-IILS, 2011).

Other countries are also active in this respect. In the Republic of Korea, a stimulus package provided 1.8 billion USD for low-carbon vehicles (EC-IILS, 2011). In China, stimulus measures provided USD 1.5 billion from 2010 to 2013 to develop efficient energy cars. In addition, through its NRDC Stimulus Package, China planned to invest USD 44 billion from 2010 to 2015 to develop hybrid and electric car technology (EC-IILS 2011).

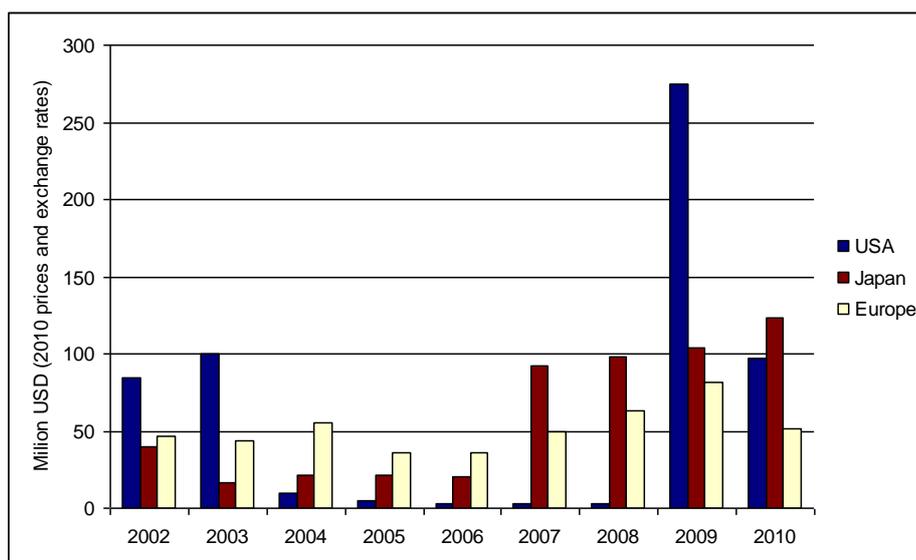


Figure 1: Public RD&D investment in energy storage in selected IEA member countries, 2002–2010 (source: IEA 2011b)

The main challenges to the deployment of EVs are currently linked to advances in battery technology and overall improvements in crucial aspects such as specific energy, specific power, lifetime, and safety (Anderson and Patiño-Echeverri, 2009; Axsen and Kurani, 2010, Hacker et al., 2009).^{xii} Technical bottlenecks directly translate into high battery systems production costs and make EVs not competitive with internal combustions engines alternatives.^{xiii}

A significant amount of uncertainty surrounds the current costs of different batteries for EVs as well as their future projections (Anderman, 2010; IEA, 2012; Kromer and Heywood, 2007). Estimates vary significantly according to the end-user applications (BEV vs PHEV), which require different specific power and specific energy, and to the scale of production (EPRI, 2005). According to the IEA, for example, the cost a battery for BEVs’ medium-high volume production was approximately \$750/kWh at the beginning of 2011 and rapidly declined to \$500/kWh in early 2012, due to technical progress (IEA, 2012). If this trend continues, the cost of batteries could reach USD 325/kWh or less by 2020, bringing BEVs close to cost-competitiveness with internal combustion engine vehicles (IEA, 2012). Battery costs for PHEVs registered values 1.3 to 1.5 times higher than BEVs’ per kWh, but a greater decline is expected in these technologies given the lower total battery capacity needed for PHEVs (IEA, 2009).

Reduction in battery costs could likely be obtained by increasing volume production and enhancing manufacturing improvements as well as packaging efficiencies (Beach, 2008; Kalhammer et al., 2007). Since the cost of primary materials (such as lithium, cobalt, nickel, and manganese) necessarily affects the overall cost of batteries, the supply side will play a key role. The

extent to which batteries are flexible in the use of alternative fungible materials is another important factor. For instance, metal-oxide cathodes can use not only cobalt, but also nickel, manganese and aluminium (Amirault et al., 2009).

High expectations regarding cost reductions are mostly related to the potential of Lithium-ion batteries as the dominant chemistry for EVs. Li-ion batteries have shown higher performance compared to other technologies in terms of both specific energy and specific power (Canis, 2011; Kromer and Heywood, 2007). They have three times the energy density^{xiv} of nickel-metal hydride (Ni-MH) and nickel-cadmium (Ni-Cd) systems (Amirault et al., 2009; EPRI, 2005; Irvin, 2008). Nevertheless, the widespread success of the technology depends on progress on the reliable coupling of lithium-ion cells with robust battery systems for vehicles and, in general, on the high production costs of lithium ion batteries (Hacker et al., 2009). Despite the uncertainty, it is generally assumed that RD&D programs are essential for fast capacity building and large-scale production of EVs, and subsequent abatement of costs and market diffusion (ZWS, 2009)

A variety of battery system for BEVs and PHEVs are currently under development. Figure 1 lists the technologies that were the focus of our survey. The names of the European experts on battery technologies that took part in the elicitation are listed in alphabetical order in Table 3, while their replies in the paper as presented anonymously^{xv}. Our experts belonged to the academic world, the private sector or an international institution.

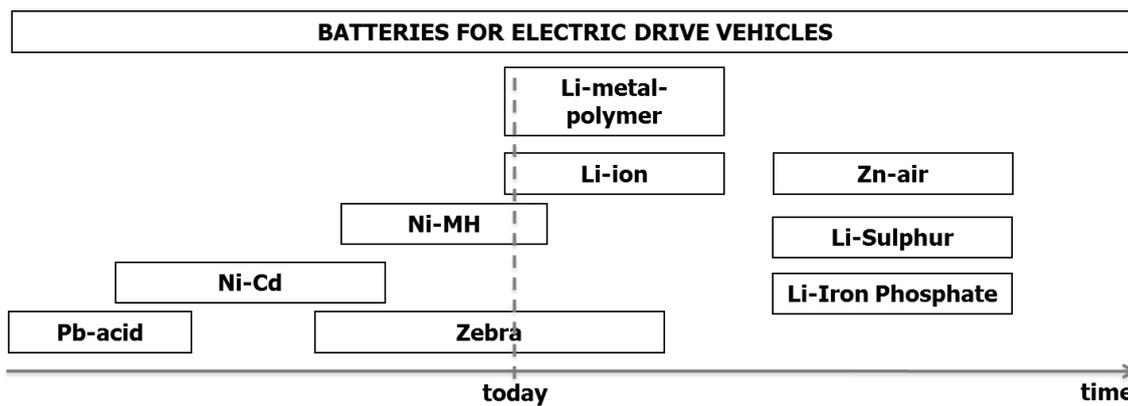


Figure 2: Technology paths that have been assessed in the interviews with the experts and their different states of development

Table 3: List of experts participating in the survey

Name and Surname	Affiliation	Country
Michel Armand	Université de la Picardie	France
Pierpaolo Cazzola	International Energy Agency	Italy
Damien Crespel	Société Véhicules Electrique	France
Claudio Fonsati	Micro-Vett	Italy
Sergio Leonti; Vittorio Ravello	FIAT	Italy
Giuseppe Lodi	FIAMM	Italy
Adolfo Perujo y Mateos del Parque	Joint Research Centre	EU
John L. Petersen	Fefer Petersen & Cie	Switzerland
Bruno Scrosati	Università degli Studi di Roma “La Sapienza”	Italy
Patrice Simon	Université Paul Sabatier	France
Jean Marie Tarascon	Université de la Picardie	France
Christian Thiel	Joint Research Centre	EU
Margaret Wohlgahrt-Mehrens	ZSW ULM	Germany
Karim Zaghib	Ireq	Canada

3 Expert elicitation

Experts’ judgements are particularly useful in probabilistic decision making and have been considered in several studies to support risk evaluation and inform a transparent decision-making process (e.g. Cooke and Goossens, 1999). The elicitation and use of experts’ data to assess the potential of success of carbon-free technologies are relatively recent and scarce. Baker et al. (2009b) and Chan et al. (2011) use expert elicitation to analyse the uncertain role of RD&D investments in leading carbon capture and storage to commercial success. Baker and Keisler (2011)

apply the same techniques to assess the effect of RD&D funding on the factors that determine the cost of cellulosic biofuels, while Baker et al. (2009a), Curtright et al. (2008) and Bosetti et al. (2012) focus on solar technologies. Our study complements the analysis of Baker et al. (2010), who use expert judgement elicitation to assess the relationship between public investments and technical change in battery technologies for EVs. We differ from Baker et al. (2010) because we focus on the EU and we provide an assessment of future diffusion scenarios alongside the cost estimates.

The elicitation process implemented in our survey follows a structured protocol, specifically based on methodologies suggested by the literature on decision analysis and applied to guide all the expert elicitation processes carried out on different carbon-free energy technologies within the ICARUS research project (Clemen and Reilly, 2001; Keeney and von Winterfeldt, 1991; Meyer and Booker, 1991; Morgan and Henrion, 1990; O'Hagan et al., 2006; Phillips, 1999; Tversky and Kahneman, 1974; Walls and Quigley, 2001). The purpose of the protocol was to reduce heuristics and biases in experts' judgements, that represent a major shortcoming of the application of these elicitation processes, and, therefore, to ensure the defensibility and accountability of these judgements. Although we will review here the basic structure and main features of the protocol, the protocol is entirely described in Bosetti et al., 2012.

In particular, we carefully chose the elicitation situation, submitting the questionnaires in face-to-face interviews, and we specifically structured the key question in the survey on the future costs of battery technologies using two different formats in order to test for possible sources of bias, such as overconfidence and anchoring effects. With the aim of ensuring the completeness and success of the review (O'Hagan et al., 2006), we underwent a careful process of selection of a balanced pool of experts with an heterogeneous background (institutions, private sectors and academia), representing the major perspectives and fields of knowledge (engineers, economists and policy makers), to ensure a thorough analysis of both basic and applied research issues as well as policy implications (Table 2).

To be able to contextualise the experts' responses and detect the possible biases, we first asked them to self-assess their level of expertise with respect to the different battery technologies included in Figure 2 on a scale from 1 to 5. The results are shown in Figure 3. All the technical paths we examined are covered by at least one expert declaring a high level of expertise. The experts uniformly declared excellent or good knowledge of Li-ion battery technology, and most of them (10 out of 14) indicated high or medium expertise on a relatively mature technology such as Ni-MH. Despite the innovative character of Lithium Metal Polymer (LMP) battery technology, half

of the experts reported good or excellent knowledge of it. On the contrary, Zebra and Li-air batteries emerged as more sectoral fields of study, while most experts declared to have general knowledge of less diffused technologies such as Li-sulphur and Zn-air. Finally, two experts also highlighted their expertise on other relevant technologies, namely supercapacitors and Lithium Redox Organic.

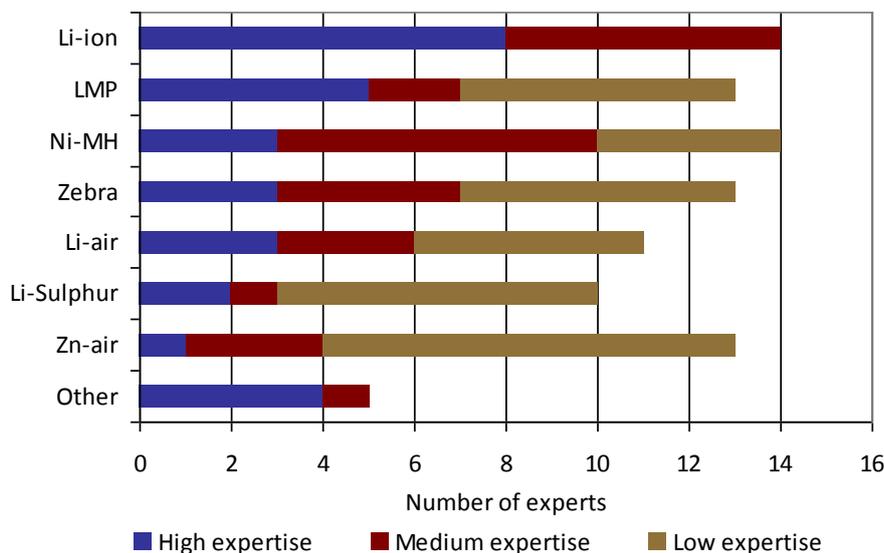


Figure 3: Distribution of the experts in three classes of expertise (high expertise: max level of knowledge >3; medium expertise: max level of knowledge =3; low expertise: max level of knowledge <3) for each of the technological paths

4 RD&D need for EVs

RD&D efforts, financed both through public and private investments, aim at improving battery performances and at reducing the high costs of EVs by developing better and more efficient battery technologies. Public investments in RD&D are an important component of the policy portfolio to support the development of carbon free technologies in general, as well as with respect to storage for electric vehicles (IEA, 2011a).

Before asking the experts to provide estimates of costs conditional of different levels of public RD&D investment, we asked them to reason on the optimal allocation of the public budget among the different technological options presented in Figure 1. An optimal RD&D allocation would maximise the probability of reaching cost-competitiveness by 2030.

Each expert was assigned 100 chips, which were meant to represent the current annual level of public RD&D investments, and was asked to distribute them among the different battery technologies. Answers are reported in Figure 4. On average, each expert chose to fund over 5 technologies, with only 6 out of 14 experts supporting 4 technologies or less. The RD&D funding

portfolio is thus rather diversified, and testifies the necessity to support more than one technology rather than “picking winners”. This notwithstanding, the funding level assigned to different technological options varies widely. Li-ion batteries were allocated, on average, the highest relative share of funding, corresponding to 28.6% of the experts’ budgets, with 9 experts assigning 20% or more of their total budget, 3 experts allocating 50% or more and only one choosing to allocate no money. The experts agreed on guaranteeing constant support to this promising technology, for which work is still needed to ensure safety standards in the use of the battery pack, improve the battery system management, and reduce high costs.

On average Li-air batteries received 15.4 chips per expert, with half of the experts allocating 20% or more of their total budget and almost one third of the experts deciding to devote no money. The maximum chips allocation to this technology was 45% of the budget by one expert who declared high confidence in the potential of this innovative technology to overcome technical barriers and lead EVs to commercial success. All the other experts agreed instead on the need to carefully assess the potential and functionality of this technology, which can still be considered to be in its infancy.

The average allocation to Ni-MH batteries corresponded to 14.6 chips. Allocations are in most cases fairly low, with 3 experts not supporting this technology, 8 allocating 15% or less of their budget to this technology, and only two experts supporting it with 60 chips. Experts’ disagreement concerned the possibility of further improving the technology: nine experts considered Ni-MH technology as already mature, while seven experts indicated that improvements would be necessary to increase energy density, lower processing costs and enhance the rate of self-discharge. Additional concerns regarded materials’ accessibility and the imbalance between current material supply and expected global demand.

LMP, Zebra and Li-sulphur, received on average 10.4, 8.9 and 8.2 chips, respectively. Around 65% of the experts chose to support LMP, with 4 experts providing 20% or more of their total budget. Zebra did not receive any contributions from half of the experts (7 out of 14) and showed a high variation in the allocations from the rest of the experts. Low power density emerged as a crucial issue for the deployment of both Zebra and LMP technologies, together with high processing temperature and safety issues. Li-sulphur was supported by half of the experts, with budget allocations ranging from 10 to 20%. The lack of overall support is due to the necessity to implement advances with respect to power density, cycle life and temperature control. However, according to the rest of the experts, the technology does not show enough chances to get to the market to deserve such an effort.

Finally, Zn-air technology received the lowest average amount of funding (5.7 chips on average), with only one expert assigning 20% of the budget to this technology. The majority of experts pointed to its very low level of technological development: advances should be guaranteed to increase power density but also to extend cycle life and improve the rechargeability process of the battery.

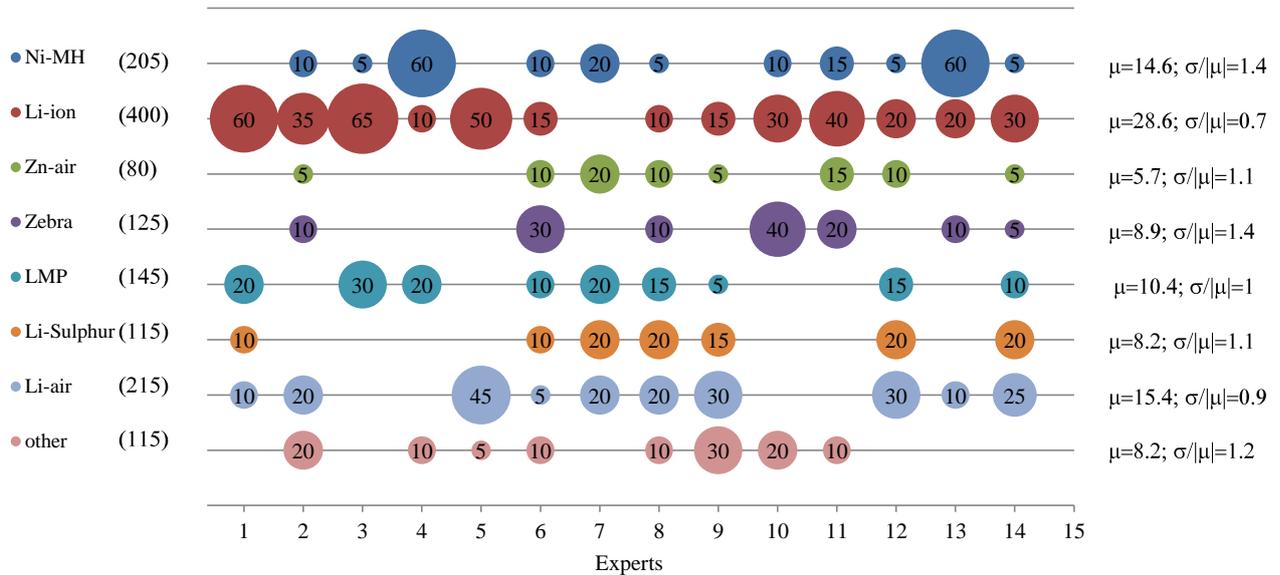


Figure 4: Allocation of the optimal RD&D budget over the 2010–2030 period. The budget is conventionally expressed in 100 “chips” per expert (column), to be distributed among the different technologies. For each technology (row), the total number of chips is provided in brackets, and both the average and variance in chip allocation are provided on the right side of the figure.

Differences between technologies in RD&D funding are not limited to the amounts allocated, but also to the type of RD&D necessary, which in turn depends on the current level of maturity. We therefore asked the experts to indicate whether each technological options is more in need of basic research support, applied research or demonstration activities (Figure 5).

Applied R&D and demonstration play the biggest role for more mature systems, such as Li-ion and Ni-MH. Regarding those options, experts uniformly suggested relying more on the effect of learning-by-doing to gain efficiency, improve safety and bring down costs. According to the experts, also for Zebra batteries more effort should be devoted to engineering and applied research, for controlling heat losses and enhancing performances, and to demonstration and testing activities, to make this technology competitive also with small size batteries. Conversely, experts called for more basic research with respect to innovative technologies such as Li-air and Li-sulphur, where the focus should be on developing novel materials, on increasing driving range and cycle life and on decreasing recharge time. Basic and applied research should be supported to improve Zn-air

technology, which at the moment is considered not suitable for BEVs due to low power and cycle life and to high costs. Finally, the effort to support LMP batteries should be equally distributed among the three typologies of RD&D, to improve technical features and prove technology viability. The suggested focus of the RD&D investment clearly testifies to the feed-back loops between basic research and more advanced stages such as demonstration and pilot plants, which are necessary to improve technologies.

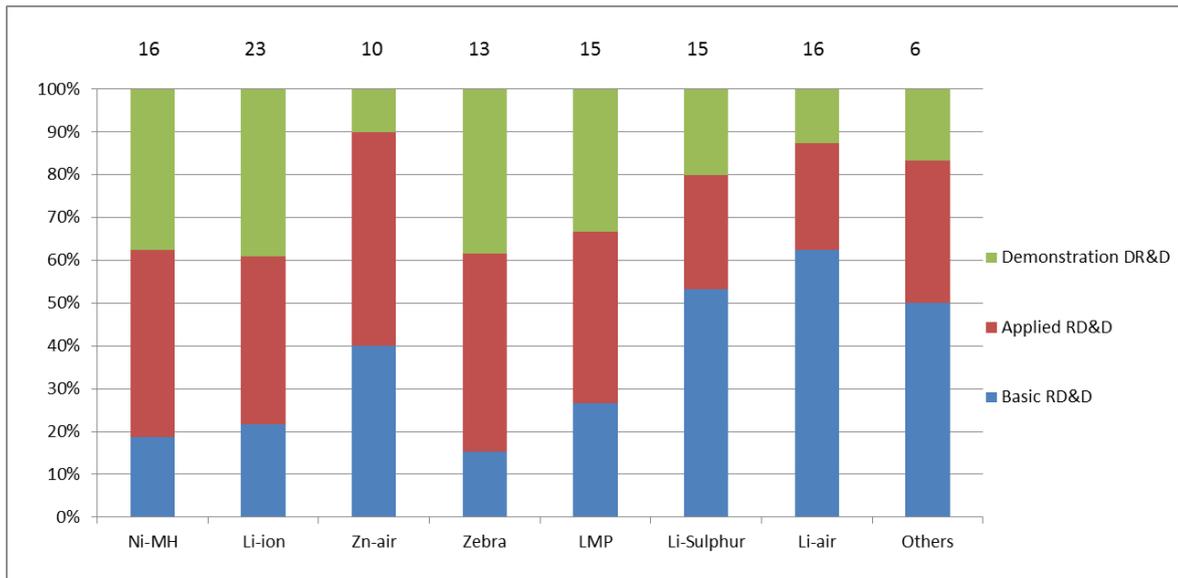


Figure 5: Experts' opinion on which stage of the RD&D is most needed to be improved in each technology. On the top of the figure, the total number of chips assigned to each technology.

5. The effect of RD&D on future costs of BEVs and PHEVs

The section analysing the optimal RD&D budget allocation and assessing the technical potentials and limits of battery technologies was instrumental to tune the experts in. We subsequently asked them the core questions of the elicitations, namely whether and under what conditions the costs of batteries would make the technology cost competitive with fossil drive vehicles. Experts were asked to provide estimates of their expected battery costs in 2030 under different RD&D funding scenarios, to gauge how public investment would affect future costs. The questions were carefully phrased to avoid anchoring effects and provide a more solid estimate. We first asked the experts to indicate the 10th, 90th and 50th percentile of the expected cost in 2030 for each funding level provided. Then we also elicited the probability that battery cost in 2030 will be below certain representative thresholds, effectively asking the experts the same information twice,

in different formats. As a result, we were able to carry out consistency checks for each expert in our analysis. In some cases the considered thresholds were outside the expert range of previous answer and this allowed them to critically assess their potential overconfidence.

The three RD&D scenarios provided to the experts were: (1) Current scenario^{xvi}, where the current annual level of public investment in RD&D as a share of GDP, is maintained until 2030; (2) +50% RD&D scenario, where current funding is increased by 50% through 2030; and (3) +100% RD&D scenario, where funding is doubled through 2030. In all scenarios, we asked the experts to assume that the yearly budget would be constant over time. We elicited cost estimates for both BEVs and PHEVs.

Estimates of the expected cost of batteries in 2030 (Figure 6 and Figure 7) indicate a high degree of variation in the experts' answers. In a "current" public funding scenario, the best estimate of the battery cost (50th percentile) of BEV in 2030 corresponds to \$408/kWh. However, half of the experts provided a best estimate between \$200 and \$400/kWh, while 6 other experts indicated a value higher than \$400, which in one case reached \$750/kWh^{xvii}. A similar pattern characterized the expected costs of batteries for PHEVs. Today PHEVs batteries are 30-50% more costly than BEVs batteries. According to the experts, this wedge is likely to shrink. On average, the reported best estimate of the cost of batteries for PHEVs in 2030 is expected to be 8% higher than the cost of batteries for BEVs in the current RD&D scenario, while becoming 9.7% and 10% higher than the cost of BEV in the +50% and in the +100% RD&D scenarios, respectively.

Half of the experts' estimates (7 out of 14) referred to Li-ion batteries. One expert referred to Zebra technology (expert 9) and all other experts referred to a mix of battery technologies. Estimates of Li-ion batteries costs are on average 24% higher than those referring to a mix of technologies.

A closer look at the estimates highlights the presence of three clusters of experts. The first, composed of experts 1-4, can be labelled as "BAU pessimists": their estimates are consistently higher for the BAU funding scenario, but increased RD&D budgets make a real difference in terms of decrease in expected costs. Li-ion experts 5-7 and 9 ("optimistic") display a high degree of confidence in reaching cost-competitiveness in a BAU scenario. They however assign lower marginal returns to RD&D investment, as the +50% and +100% funding scenarios have little or no impact on their expected costs. The "mix-of-technology" experts seem more optimistic in terms of expected costs in the BAU funding scenario, but the effect of increased RD&D investments is heterogeneous. There is therefore some indication that experts focusing on a single technology tend to have more "extreme" views than those focusing on a mix of technologies. Consistently with other

surveys, when experts consider a wider set of technological options they tend in average to be less overconfident in their projections, and therefore report a wider cost range, in terms of difference between the 90th and the 10th percentiles.

The high variation in experts' estimates is mainly related to the different on crucial aspects such as: future materials purchase, evolution of battery characteristics (energy density, power density and range), and battery production volume. In particular, the most pessimistic experts underlined the difficulty in reducing battery cost below current values, due to the high cost of materials and processing and the numerous technical advances needed, mainly in energy and power density, as well as safety issues.

In general, the experts stressed the importance to improve specific features of battery systems in order to obtain important cost reductions by 2030, such as: cycle life, which should be increased to at least 3000 cycles; calendar life, which should reach 15 years; thermal management of battery, which would enlarge the range of operating temperature without damaging the system; and other important aspects such as improvements in battery recycling processes and development of sophisticated battery management systems.

A comparison with estimates of future costs available in the literature puts our results into perspective. Kromer and Heywood (2007) review different studies with projections of battery costs (Anderman, 2000 and 2003; ANL, 2000, Duval, 2006), and propose a range of cost of Li-ion battery back in 2030, based on optimistic assumptions in terms of incremental improvements in high-energy batteries, and significant improvements in terms of rate capability.^{xviii} The battery cost in 2030 is expected to be \$200–\$250/kWh for BEVs and \$320–\$420/kWh for PHEVs (shaded areas in Figures 7 and 8). A more recent review of battery costs (Anderman, 2010,) report projections to 2020, and indicates ranges from \$375 to \$500/kWh for BEVs and from \$675 to \$900/kWh for PHEVs.^{xix}

As for BEVs, only the estimates provided by the most optimistic experts are in agreement with those indicated in the literature for 2030. Most experts were more conservative, providing expected costs relatively higher than the values in the shaded area. For PHEVs, experts' estimates are more in line with the Kromer and Heywood (2007) projections. Under the current RD&D scenario, three experts indicated expected costs within the reference range, while another four experts provided battery costs below this. The estimated results would be in line with the reference projections only by increasing RD&D funding by 100%.

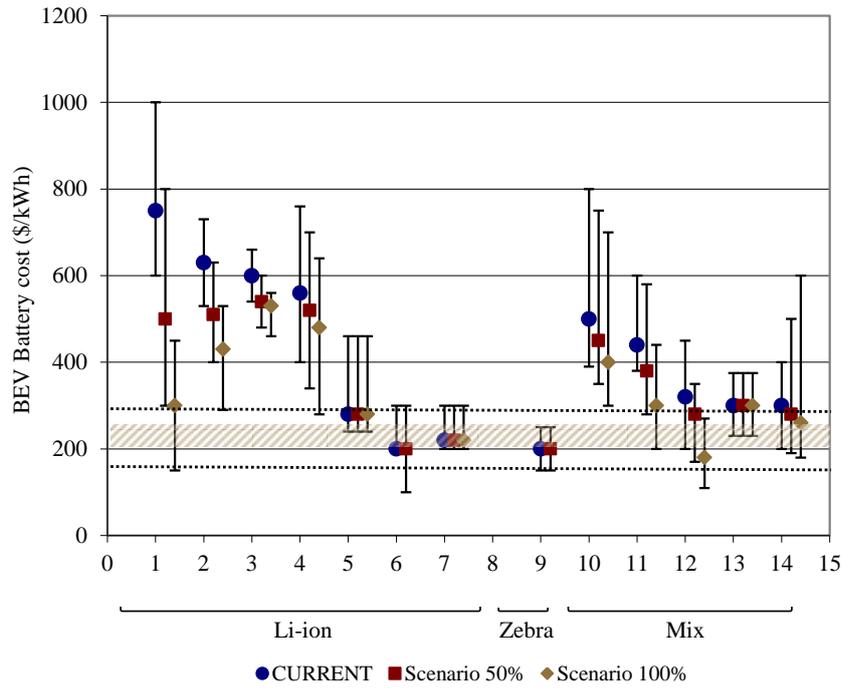


Figure 6: Estimates of the cost of BEV batteries (\$/kWh) in 2030, under three different RD&D funding scenarios. The shaded area represents the projected 2030 BEV battery cost range as estimated in Kromer and Heywood (2007). The dotted lines mark the two cost thresholds that we proposed in the second part of the question (NRC, 2005; Anderman et al., 2000; Anderman 2003; Duvall, 2006).

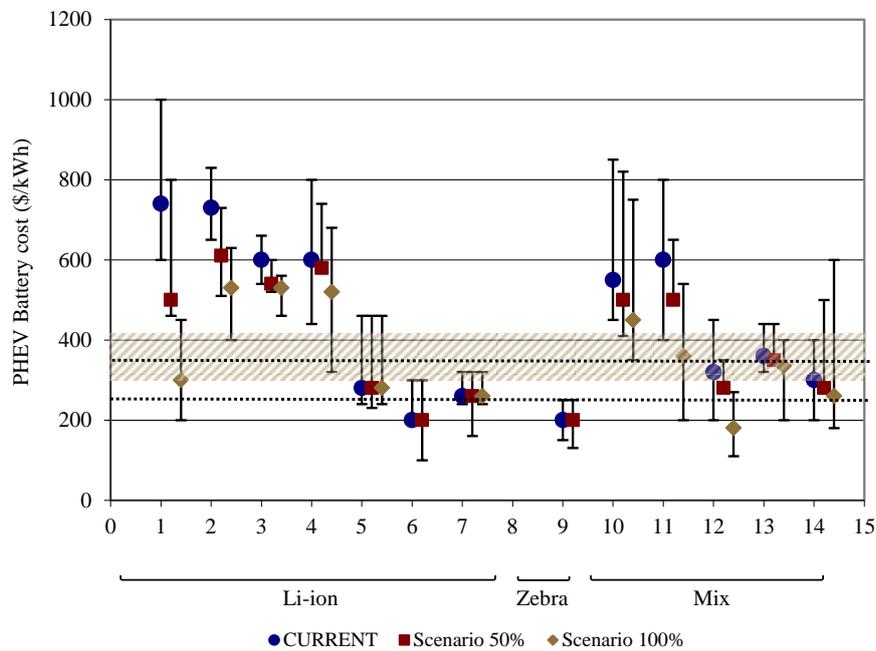


Figure 7: Estimates of the cost of PHEV batteries (\$/kWh) in 2030, under three different RD&D funding scenarios. The shaded area represents the projected 2030 PHEV battery cost range as estimated in Kromer and Heywood (2007). The dotted lines mark the two cost thresholds that we proposed in the second part of the question.

Experts' estimates vary widely also with respect to the impact of RD&D on the battery costs. The answers of 8 out of 14 experts indicated that increases in RD&D spending would result in lower average costs. Figure 8 and Figure 9 plot, for each expert, the 2030 expected cost of BEVs and PHEVs batteries under the current RD&D scenario (y-axes) and the percentage decrease in the 2030 expected cost under the +50% and +100% scenarios (x-axes). In general, experts who expect a cost higher than \$600/kWh in the “current” scenario also expect a higher effect of increasing RD&D on cost reductions (the same experts expect an average decrease of 21% for BEVs and of 19% PHEVs for the +50% scenario). Considering a doubling of RD&D investment (+100% scenario), the same experts foresee an average decrease of costs for BEVs and PHEVs of 42%, compared to the current scenario.

Conversely, few experts believe future battery cost will not be affected by an increase in RD&D funding.^{xx} In particular, two experts who assigned high cost values in the current scenario, were also very pessimistic on the effect of RD&D on costs, and therefore did not foresee big reductions. The argument of “pessimistic” experts is that cost abatements will only be obtained through an increase in manufacturing yields and an intensive effort by private firms to translate research advancements into technological improvements. The effect of learning-by-doing in processing facilities is considered crucial, but at the same time the link between research and industry is seen as particularly weak in Europe, where excellent research activities do not correspond to appropriate industrial exploitation.

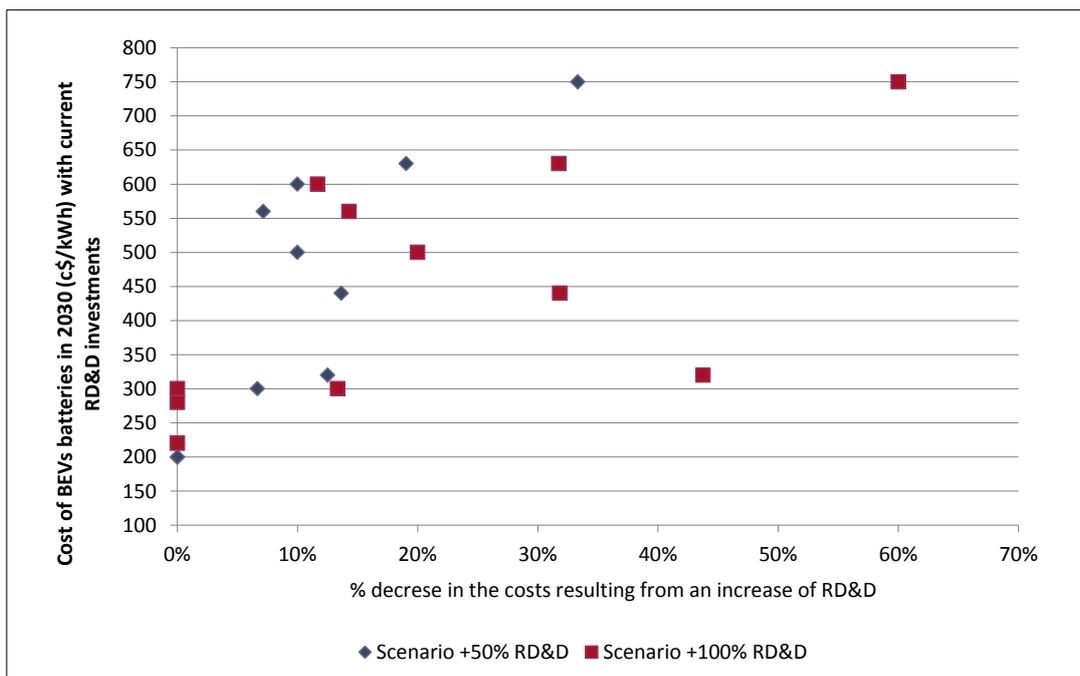


Figure 8: Expected costs of BEV batteries in 2030 under the current RD&D scenario (y-axis) and percentage decrease in the 2030 expected costs under the additional RD&D funding (x-axis)

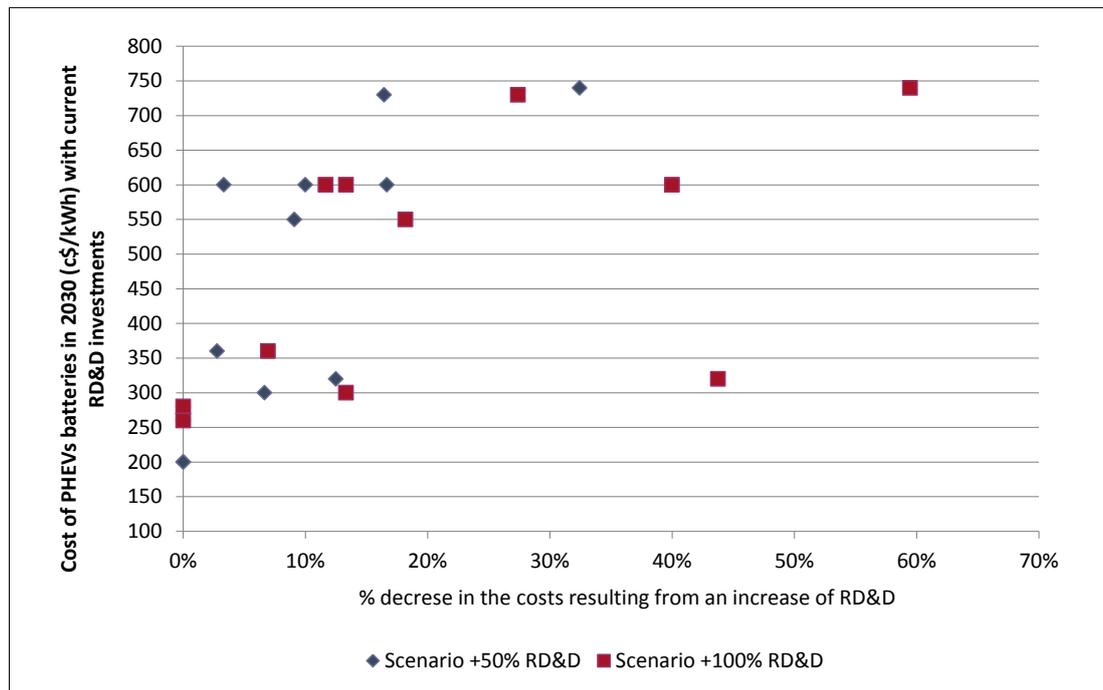


Figure 9: Expected costs of PHEV batteries in 2030 under the current RD&D scenario (y-axis) and percentage decrease in the 2030 expected costs under the additional RD&D funding (x-axis)

The uncertainty in the experts' cost estimates, measured as the difference between the 90th and 10th percentile, varies widely. In both cases (BEVs and PHEVs), according to half of the experts, a 50% increase of public RD&D would reduce or maintain the level of uncertainty surrounding cost projections. The same is true when a further increase of public funding is assumed (+100% scenario). The other six experts indicated a higher degree of uncertainty in evaluating departures from the status quo, which suggests that an increase in the RD&D budget could result in higher investments in less mature technologies, whose success is highly uncertain.

To check for consistency in cost estimates, experts were finally asked to estimate the probability that the cost of batteries in 2030 will be lower than threshold values (two for BEVs and two for PHEVs), under the same RD&D investment scenarios outlined above. The different breakthrough cost levels corresponded to specific targets for BEVs and PHEVs commercialization, reviewed by Kromer and Heywood (2007). About 28% of the elicited probabilities presented some inconsistencies compared to the cost predictions provided by the experts under the three funding scenarios. The presence of discrepancies allowed us to structure and carry out follow-up interviews,

where the experts could check and critically re assessed their answers, that have been then used for the analyses of the present section.

6. Diffusion of EDVs

The fourth section of the questionnaire identified the possible non-technical barriers that could hinder EVs success and assessed potential market diffusion. Figure 11 shows all barriers that were discussed and provides a ranking of their importance together with the suggested solutions.

The most important barrier is linked to the difficulty of changing driving behaviour. This is mainly due to the limited driving range of EVs, which requires a different pattern of usage for the vehicles. Education and marketing are the favoured solutions to tackle this issue. The lack of adequate infrastructure is the second crucial barrier to EVs’ diffusion and, according to the experts, this should be addressed with specific policy interventions and additional investments. Both kinds of interventions should support the construction of battery charging points together with stations where, instead of recharging the vehicle battery, exhausted batteries are swapped with full ones. Most experts agreed on the importance of investing to improve safety standards for EVs’ commercial success and commercialisation. Lobbying and vested interest, the need of a critical mass of users and metal supply were evaluated as less important barriers.

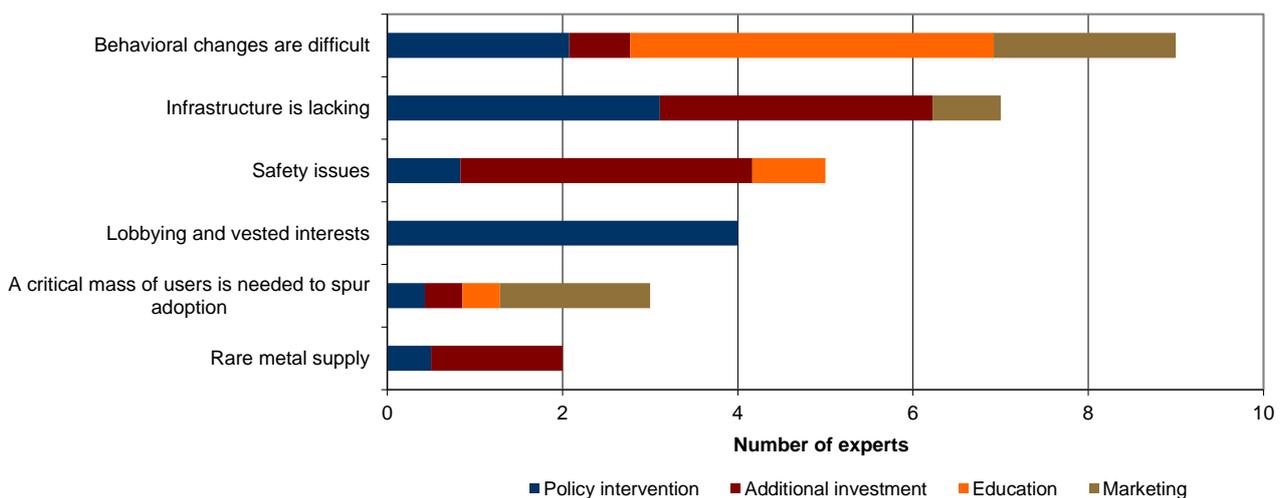


Figure 11: Factors that could represent non-technical barriers to the diffusion of electric drive technologies and potential solutions to overcome these barriers

Most experts optimistically believe that we will experience a radical change in driving behaviour and habits in the future. Public transportation, and in particular electrified transport, will be boosted to satisfy the demand for city travelling. On the other side, the pattern of vehicles' ownership will evolve and car-sharing or similar activities will be more common. To further investigate the diffusion process, experts indicated the geographical areas of the world with the highest probability of being the first to reach commercial breakthrough. According to eight experts, Japan will continue to lead the market and will be the first country to reach cost-competitiveness and success in EVs, followed by China (7 experts), Korea (3 experts), USA and Europe (each indicated by 1 expert).

Experts also provided estimates of likely future diffusion trends of EVs in the private vehicle market (penetration rate). Under the assumptions that EVs would be technically ready to compete with conventional ICE vehicles in 2030, the experts considered the chance of achieving three different penetration rates (20%, 50% and 70%) of BEVs and PHEVs car sales by 2050, in OECD, fast-growing and developing countries (Table 4).

For OECD countries, the most likely penetration scenario is 50%, which is associated with an average probability of 42%. Experts appear to be clustered around two alternative visions, based on their estimates. The first cluster is more pessimistic, encompassing four experts, who assigned a probability of 70%–80% to the lowest diffusion scenario, while in the second cluster eight experts appeared more optimistic with a high chance of reaching the 50% and 70% scenarios. Experts generally agreed that the low-diffusion scenario is the more likely to be achieved in developing countries. However, some experts indicated the possibility that EV diffusion in those countries may be faster than in developed ones because they won't need to undergo a process of substitution. Only eight experts decided to assign a probability for the three diffusion scenarios for fast-growing countries, due to the great uncertainty surrounding the EVs market in those countries, and these experts were equally divided between the 20% and the 50% penetration rate scenarios.

Half of the experts indicated that, if EVs were to become a competitive solution by 2030, electric transport would be able to achieve a maximum level ("ceiling") of diffusion of 70%–80% in the private vehicle market, while four experts expected a much lower ceiling, ranging from 5% to 35%. The variance in the experts' answers and the fact that some of them refused to answer to this question should be interpreted in light of the technological characteristics of this kind of low-emission technology. Several factors should be carefully considered when estimating the penetration rate of EVs, such as the demand for transportation, fleet turnover and consumer choices. Also, the professional background of the experts might have influenced their opinions on EVs'

market diffusion. The majority of the experts, in fact, distinguished themselves for their involvement in research projects or applied development of battery technologies, while only a few experts worked in the car manufacturing sector. The first group of experts provided very precise information on the technology characteristics and cost projections of EV batteries, but felt less at ease in assessing the factors that will affect EVs' diffusion into the market.

Table 4: Probability assigned by the experts to three penetration rates for electric drive technologies in 2050 (OECD, fast-growing and developing countries)

Experts	OECD countries penetration rates			Fast-growing countries penetration rates			Developing countries penetration rates		
	20%	50%	70%	20%	50%	70%	20%	50%	70%
Exp 1	70	25	5	-	-	-	-	-	-
Exp 2	5	50	45	5	55	40	10	60	30
Exp 3	5	70	25	5	70	25	70	15	15
Exp 4	10	75	15	10	75	15	45	50	5
Exp 5	20	80		10	90	-	-	-	-
Exp 6	0	80	20	-	-	-	50	40	10
Exp 7	0	10	90	-	-	-	40	45	15
Exp 8	20	30	50	20	20	60	80	10	10
Exp 9	-	-	-	-	-	-	-	-	-
Exp 10	-	-	-	-	-	-	-	-	-
Exp 11	80	20	-	-	-	-	90	10	
Exp 12	70	20	10	80	15	5	70	30	0
Exp 13	10	20	70	10	30	60	30	30	40
Exp 14	70	20	10	80	10	10	90	5	5
Avg	30	42	34	27	46	31	57	29	14

Experts also commented on how the dynamics of technology transfer among countries could affect the support of national RD&D programmes. The majority of experts (12) explained that the current conditions reflect a relatively successful cooperation among different countries, which results in important knowledge spillovers. However, they agreed on the binding need for each

country to invest in its own RD&D programme to develop absorptive capacity and therefore be ready to adopt breakthrough technologies developed by other countries.

Finally, experts identified the potential negative externalities on the environment and society, which might be associated with the diffusion of EVs. A high concern emerged about the carbon intensity associated with battery production and with the electricity used to recharge batteries. The experts agreed on the necessity to develop an adequate recycling process for exhausted batteries. Additional concerns are related to the impacts of mining and metals extraction. In this respect, a few experts underlined that this is an extremely energy-intensive process, which might offset the benefits of using EVs instead of ICE vehicles. Finally, the toxicity of specific battery-producing processes and supply security were also mentioned, and the experts highlighted that the presence of reserves of critical materials in few countries increases dependency and the uncertainty of their availability both physically and politically.

7. Conclusions

Internal combustion engine vehicles will continue to cover the highest share of the vehicle market for the next two decades. However, an increasing number of countries are investing in RD&D for electric drive vehicles, for their potential benefits in local pollution control, in limiting the dependence on oil and in contributing to the mitigation of GHG emissions (provided power production is decarbonised).

The success of electric vehicles is currently hampered by a combination of high costs, low range, scarce efficiency and safety issues. Overcoming those barriers and supporting electric vehicles large-scale diffusion implies facing both technical challenges and consumers' choices determinants.

The essential component of electric drive vehicles' cost is battery cost. The present analysis collected the estimates of fifteen leading European experts, who assessed the probabilistic impact of public European RD&D investments on the future cost of vehicles battery technologies.

The analysis of the state of maturity of different battery technology options, and of their main technical issues, supported the experts suggestion to allocate future RD&D investment in more than one technological option. At the same time, more advanced technologies, such as Li-ion and Ni-MH systems, which should be closer to the commercial breakthrough, should receive the higher share of future RD&D budget, to support applied R&D and demonstration activities. For both technologies, all the experts perceived the need to gain efficiency, improve safety and bring down costs via

learning-by-doing processes. Conversely, the experts called for more basic research with respect to innovative technologies such as Li-air and Li-sulphur.

Different assumptions on battery performance and characteristics were reflected by the variation in the experts' cost estimates. In a scenario where the current level of investments in RD&D is maintained constant through 2030, more than half of the experts provided an expected battery cost value ranging between \$200 and \$400/kWh for BEVs and between \$200 and \$450/kWh for PHEVs, while the remaining experts provided more pessimistic projections.

Experts who assigned higher cost values in the current funding scenario were often the ones who expected a greater impact from a 50% increase in RD&D in terms of cost abatement and an average 21% reduction of costs in presence of doubling of the investments. Even if the effect of an increase in RD&D funding is positively reflected in the experts' probabilities, some experts remained pessimistic on cost estimates in all funding scenarios within the proposed time frame.

The different perspectives of the experts on the potential success of EVs also emerge from the limited consensus regarding the diffusion scenarios. The most likely penetration scenario after 2050 in OECD countries is 50%, with an average 42% probability of reaching this. In the case of developing countries, experts generally agreed that the low-diffusion 20% scenario is going to be the most likely one, while most experts refused to provide an answer on the penetration rate in fast-growing countries, due to the great uncertainty surrounding the EV market.

The limits to EVs' market diffusion are strongly acknowledged by the experts, who suggest structuring adequate education and marketing solutions to overcome the consumers' inertia and change driving behaviour. Investment for the development of adequate infrastructure and improvement safety standards is also crucial. Behavioural issues are a key concern according to all experts and this was at stark contrast with all other expert elicitation of energy technologies we have performed so far (Bosetti et al., 2012; Fiorese et al., 2012), where consumers' habits were seldom ever mentioned. Most experts optimistically believe that, in the future, public confidence in the role of electric vehicles will grow and we will experience a significant change in driving behaviour and habits. However, to support a radical departure from the current paradigm, the electrification of transport should be supported by a combination of government support and other aggressive measures, such as improved conventional technology, development of low-carbon fuels and fuel production pathways, changes in the patterns of vehicle ownership and demand-side reductions.

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Footnotes

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- ⁱ Global carbon-dioxide (CO₂) emissions from fossil-fuel combustion reached a record high of 31.6 gigatonnes (Gt) in 2011. Global energy demand has nearly doubled since 1980. Energy demand and emissions are expected to double by 2050 compared to 2009 levels (IEA, 2012).
- ⁱⁱ The Energy Technology Perspective (IEA, 2012) considers three scenarios. The 6DS scenario projects an increase of global temperature up to 6°C by 2050 if current trends persist and in absence of mitigation policies, with potentially devastating results. The 4DS scenario considers a +4°C increase in global temperature by 2050 if announced policies are implemented, and finally the 2DS scenario projects a +2°C increase in global temperature by 2050 and a decrease of energy-related CO₂ emissions by more than half in 2050 (compared with 2009), to be achieved through technology innovation and sustainable policy choices.
- ⁱⁱⁱ According to the IEA (2007), the need to ensure the security of oil supply is more urgent than ever. The risk of oil supply disruptions keeps on increasing, due to demand growth, increased concentration of the remaining oil reserves in a fewer number of countries, the concentration of oil use in the transport sector, and insufficient capacity additions (both upstream and downstream) to keep pace with demand growth. In the IEA 2DS scenario countries would save a total of 450 exajoules (EJ) in fossil fuel purchases by 2020 (IEA, 2012)
- ^{iv} Obtaining probabilistic future cost estimates for batteries for EVs is part of a much larger effort to analyze the potential of future low-carbon and carbon-free technology portfolios not only limited to the transport sector (www.icarus-project.org and Bosetti et al 2012).
- ^v BEVs solely use electric power and batteries are recharged by only the internal combustion engine. Conversely, PHEVs combines the propulsion characteristics of a traditional combustion engine with an electric motor, and have much larger high-voltage batteries than BEVs, which can be recharged also by connecting a plug to an external electric power source.
- ^{vi} The LDV market includes automobiles, light trucks, Sport Utility Vehicles (SUV), and vans.
- ^{vii} 2.25% of total light duty vehicles market in the US corresponds to 286,371 PHEVs and BEVs sold in 2011 in the US (EDTA, 2012). 9% of Japan's PHEVs/BEVs sales in 2011 correspond to 242,017 vehicles.(Reuters, 2012)
- ^{ix} The aggregate EU data refers to Austria, Belgium, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Luxembourg, Netherlands, Norway, Poland, Portugal, the Slovak Republic, Spain, Sweden, Switzerland, Turkey, and the United Kingdom (IEA, 2011b)
- ^x In the US, the American Recovery and Reinvestment Act (ARRA) allocates a total of USD 4 billion for advanced batteries and credits for plug-in hybrids (EC-IILS, 2011). In 2009, funding allocated to energy storage represented 2.8% of the total R&D budget, while public investments in vehicle battery/storage technologies represented 25% of the total R&D budget for energy storage (IEA, 2011b).
- ^{xi} For example, Italy provided about 40% of European countries' budget in 2002, but only 13% in 2010. Germany and France showed instead an increase in the investments going from 9% and 1% in 2002 to 41% in 2010 and 43% in 2009, respectively (IEA, 2011b).
- ^{xii} Specific energy measures the available energy on the basis of weight (e.g. BTU/lb, joules/kg or kW-H/kg). Along with the energy consumption of the vehicle, it determines the battery weight required to achieve a given electric range; Specific power describes the rate of available energy on the basis of weight (e.g. watts/kg) and determines the battery weight required to achieve a given performance target. The lifetime of traction batteries is determined by the expected average service life of the vehicle. High safety standards have to be assured due to the high quantity of stored energy in vehicle applications (Hacker et al., 2009)
- ^{xiii} Moreover, the infrastructure allowing battery recharging (grid, charging stations) will require investments by both the private and public sectors (Wood and Clifford, 2010). Several countries have already started to install charging points: according to ICCT (2012), at the end of 2011 Japan had 1600 chargers, and planned to ramp-up in 2012; in China the State Grid company had installed 7000 charging points; in the Netherlands 2,500 charging points were created; Spain had installed 700 charging points; the UK had more than 2,500 chargers and finally Germany had created 1,100 charging stations.
- ^{xiv} Energy density is the amount of energy, on the basis of volume, that can be taken from an energy source, e.g. kW-H/liter.
- ^{xv} Please note that the numbers associated with the experts in the paper are randomly assigned, and that each opinion is anonymously reported. Two experts from FIAT (Italy) replied to the questionnaire jointly and were therefore considered as a single expert. As a result, the tables and graph contain 14 observations.

^{xvi} From 2000 to 2009 the average aggregate investment of EU-27 countries in energy storage corresponded to 47.51 million USD. In 2009, the aggregate R&D investments reached 73.687 million USD. Due to scarcity of data on R&D funding for storage in vehicles, energy storage represented a reference value for the R&D scenarios.

^{xvii} Expert 8 chose not to provide any cost estimate.

^{xviii} These assumptions considers BEVs and indicate: Specific energy of 150Wh/kg; Specific power of 300W/kg; Energy 48kWh; Power 80kW; Cycle life 1000cycles; Calendar life 15years; for PHEVs: Specific energy of 135Wh/kg; Specific power of 750W/kg; Energy 8kWh; Power 44kW; Cycle life 2500 deep cycle + 175000 shallow; Calendar life 15years.

^{xix} In Figure 6 and 7, we compared the experts' cost estimates with the projections reported in Kromer and Heywood (2007), and not with the more recent ones reviewed by Anderman (2010), since the first ones referred to 2030 and could be directly compared with the experts' projections to 2030.

^{xx} For BEVs batteries, 5 and 3 experts for BEVs in the +50% and +100% scenarios, respectively. For PHEVs batteries, 4 and 2 experts in the +50% and +100% scenarios, respectively. Two experts chose not to provide any answer for the +100% funding scenario and one expert did not provide cost estimates for any RD&D scenario.