European Meeting on Applied Evolutionary Economics

7-9 June 1999, Grenoble France

COPING WITH THE EXPLORATION / EXPLOITATION TRADE-OFF IN THE EMERGENCE PHASE:
THE CASE OF ADVANCED BATTERIES FOR ELECTRIC AND HYBRID VEHICLES

Philippe LARRUE, Equipe Industries, Innovation, Institutions (E3i),
IFREDE, University Montesquieu Bordeaux IV, France

abstract

The purpose of this paper is to provide elements of a non-deterministic view of the technological dynamics of advanced batteries for EVs during the phase of emergence. We argue that the barriers faced by this emergent technology can only be understood within a the study of the complex set of feed-backs between the technology and the industrial structures that sustain the activities of research, development, and demonstration. Pre-paradigmatic phases, although they are recognized to be of great importance with regards to the future dynamics of the technology, has not gained much attention from evolutionary economics. This stage is characterized by technological uncertainties, « shaky » relations between actors and fuzzy frontiers between industries. The main problem of the phase of emergence is not only that nothing equivalent existed before, but also that actors inherit from technological and organizational « elements » (options, knowledge base, industrial structures) which, under conditions of increasing returns, can stop the innovation process or drive it in sub-optimal directions. Public and private actors must then cope with great uncertainties, and evaluate to which degree they can (or want to) rely on these existing elements or enter into a search process in order to build new ones. This dilemma can be conceptualized as the exploration/exploitation trade-off. We first present two simple and complementary frameworks of the exploration/exploitation trade-off, and briefly reposition this trade-off in the recent trends of technology policies devoted to emergent critical technologies. We then try to defend the idea that although there is not an « optimal solving » of this trade-off, the collective coordination process that (may) takes place in the research consortia offers the innovation process its greatest chances of success. In the last section, we study more precisely how this trade-off is effectively solved in the United States Advanced Battery Consortium.

INTRODUCTION

In 1990, the California Air Resource Board (CARB) voted very strict environmental laws aimed at reducing the air pollution in big cities like Los Angeles. These laws, known as the ZEV mandate, oblige the seven top car manufacturers to sell a certain percentage of Zero Emission Vehicles (ZEV). At that time, only pure Electric Vehicles (EVs) were certified as ZEV, and only batteries were considered able to be used as energy sources in EVs. These laws have triggered, once again, a huge amount of R&D activity towards EVs and their energy sources. From its early beginning at the end of the nineteenth century, the development of the EV has experienced different cycles of infatuation and quasi abandon. In general, its return to the heart of the economic and public scene has come from non-technical factors like military stakes during the second world war, environmental stakes relating to urban-air quality in the US during the sixties, the rise of the price of oil and the desire for energy independence during the seventies, and recently environmental matters once again. On the other hand, its failures are usually said to be due to technical factors, because of the weakness of the battery. Thus, EVs never reach the internal techno-economic dynamics necessary to survive, and the activity in this domain

We are grateful to the ADEME (the French governmental agency for environment and energy) and the EDF (the French electricity utility company) which together are funding the Ph.D.-thesis of Philippe Larrue. We also thank the Regional Council of Aquitaine for its financial support to our ground investigation in the United-States during the summer 1998.

soon returns to its very minimal level once the external impulse is gone.

Consequently, although they have been well known and mass-produced for more than a hundred years (Salkind, 1987), and have also greatly increased their performance under the pressure of the consumer electronics market, batteries are still considered as the major bottleneck « on the road to EVs ». Despite the tremendous amount of money, time, and human resources that are spent in the research dedicated to the various options of this technology, and despite the (apparent) willingness of consumers to replace their polluting Internal Combustion Engine Vehicle (ICEV) with a non-polluting but less performing vehicles, batteries 'power, energy, cycle life are too low, and costs remain high[1]. In many respects, one may claim that battery technology seems to belong to a « weak » technological regime, poor in technological opportunity. Although many technological options are theoretically possible[2], and many are effectively used for specific applications, they almost all suffer from drawbacks which make them very bad candidates for many applications, and particularly for the most demanding one: the EV. All options have very different inflexible configuration of performance in terms of energy, power, cost, cycle life, operational characteristics, etc. In addition to this « false diversity », the rate of progress of each option is very slow. The comparison of the rates of increase of information storage capacity over the last 20 years with the rates of increase in energy storage capacity, stressed by Pavitt in a recent paper (1998), is a clear demonstration of that fact.

From this point of view, the explanation of the many failures of EVs and their energy sources is obvious: « *the range of apportunities in different technological fields depends heavily on what nature allows us to do* » (ibid.). Similarly, the idea that « *they haven't succeeded in one hundred years, so they will not do so in ten years* » was addressed by many actors we interviewed. And the fact that activities toward EVs are currently decreasing in favor of Hybrid Vehicles[3] (HEVs hereafter) and Fuel Cell Vehicles (FCEVs) may be prove of the predictable failure of EVs, due to the « natural » inability of batteries to provide the required performance levels.

The purpose of this paper is to provide elements of an alternative and less deterministic view of the technological dynamics of advanced batteries for EVs. We argue that the barriers faced by this emergent technology can only be understood within a the study of the complex set of feed-backs

---

[1] To be short, the battery power density determines the acceleration of the EV, the energy density its autonomy. The cycle life is the number of charge/discharge the battery can afford. Since the battery is very expensive, this has to be integrated in the EV cost (unless the battery last longer than the EV, which is not the case).

[2] These technological options are identified by the electrochemical couple, i.e. the basic materials used in the anode and cathode, and the electrolyte Lead-acid, Nickel/Cadmium, Nickel-Metal Hydride, Sodium/Sulfur, Lithium-ion, Lithium-Polymer, Zinc-air, Zinc/Bromine, etc.

[3] HEVs combine two motors, one electric motor and one « regular » internal combustion engine. There exists an infinity of possible design, from the « mild hybrid » where the electric motor is used only to provide the vehicle with some additional power, to the « range extender concept » where the vehicle is almost a pure EV. The recent success of the Toyota *Prius* can

between the technology and the industrial structures that sustain the activities of research, development, and demonstration. The mutation, variation and selection processes that affect the various options of batteries cannot be disconnected from the kind of coordination that governs the relationships between the different actors of this innovation process. Therefore, the question must be addressed in terms of co-evolution of industrial structures in a broad sense (i.e. not only market structures, but also the modes of *ex-ante* coordination between the actors) and the technology (i.e. the sets of known and unknown technological options potentially, or believed to be, able to provide a specific application with the service characteristics required).

We focus upon the very early phase of an innovation process, namely the period of emergence, characterized by technological uncertainties, « shaky » relations between actors and fuzzy frontiers between industries. In this preliminary period, the basic heuristic and coordination provided by Dosi's paradigm, answering to a greater or lesser degree the actors' main question « *where do we go from here* » (Dosi, 1988,), have still to be generated. What are the effective and potential performances of the various options ? Is there any other hidden options which are not known at the present time but which could achieve greater performance levels ? What kind of EVs (in terms of required performance for the battery) should R&D focus upon ? All these questions are still wide open, and interact with other organizational issues: What could be the right balance between rivalry and cooperation between battery suppliers, between automakers ? To which degree should scientific laboratories be connected to the R&D activities of firms ? Should the activities regarding batteries for EVs be linked with those of batteries for other applications such as portable electronics or large stand-by power devices ?

Unfortunately, the emergence phase has not gained much attention from evolutionary analysis. The strong uncertainty of the pre-paradigmatic phases are clearly underlined, but the paradigm emergence still belongs to the scientific world and its unpredictable logic of discovery (Amendola, Gaffard, 1988). The paradigm is exogenous and separated from the trajectory's « *normal activity* ». Therefore, the major limit of this approach remains the dichotomy between two types of dynamics: the dynamics of the generation of a space of technological opportunities, and the one of selection/focalisation within this given space of options (Jullien, 1996). It seems that the exogeneity of technical progress has been more displaced than fully integrated in the explanation (Willinger, Zuscovitch, 1991).

As we will argue later, the problem of the phase of emergence is not only that nothing equivalent existed before, but also that actors inherit from technological and organizational elements (options, knowledge base, industrial structures) which, under conditions of increasing returns, can stop the innovation process or drive it in sub-optimal directions. Public and private actors must then cope with

---

be seen as an indicator that mild hybrids, which are using a very small battery, could be the next standard.

great uncertainties, and evaluate to which degree they can (or want to) rely on these existing elements or enter into a search process in order to build new ones. This dilemma can be conceptualized as the exploration/exploitation trade-off. The main ideas underlying our work are that i) emerging technologies do not (necessarily) fit into these pre-existing elements as they come from past activities of the concerned industries, and therefore require exploration ; ii) without a strong *ex-ante* coordination process, organizations have a natural tendency to the « over-exploitation » of the current competencies and technological trajectories, within the frontiers of the topical industrial and institutional structures.

We first present two simple and complementary frameworks of the exploration/exploitation trade-off, and briefly reposition this trade-off in the recent trends of technology policies devoted to emergent critical technologies. We then try to defend the idea that although there is not an « optimal solving » of this trade-off, the collective coordination process that (may) takes place in the research consortia offers the innovation process its greatest chances of success. In the last section, we study more precisely how this trade-off is effectively solved in the United States Advanced Battery Consortium.

We mainly use two sources of information:
- an extensive survey of the literature concerning electrochemical systems and EVs (reports, communication documents, conference proceedings, newspapers etc.).
- interviews with key actors. Several in-depth interviews have been conducted in the United-States and in Europe in industrial firms (Alcatel-Recherche, Beta R&D, Bolloré, CEA, Chrysler, EDF, Ford, GM, Hydro-Quebec, Panasonic, Renault, Saft, USABC, Varta, Yuasa, Zebra-batteries), in scientific laboratories (ICMCB, INPG, University of Montréal), and in public institutions (Department of Energy, European Community).

In addition, an on-line[4] questionnaire called « *EVquest* » has been sent to nearly 1500 persons directly involved in EVs and/or electrochemical systems. The results will be presented in a later paper.

I THE EXPLORATION/EXPLOITATION TRADE-OFF IN THE EMERGENCE PHASE

In these early phases, technological choices are very complex and have a strong influence on the future of the innovation process. In order to understand the complexity of this decision process one must refer to the main hypothesis of evolutionary theories, that is the reject of the distinction between the choice set and the action of choosing (Nelson, Winter, 1982). This hypothesis means that the potential performance levels of the various known options are uncertain and their effective realization depends on actors'technological choices. Moreover, given the fact that the frontiers of the paradigm are *a priori*

---

[4] http://www.montesquieu.u-bordeaux.fr/evquest.

unknown for the actors of the innovation process, some unknown options may exist and can only be discovered through experimentation. In this framework, a new question arises: should the actors focus their limited time and resources on the known technological options that are already more or less developed, or should they implement exploratory activities in order to acquire basic information about the potential performance levels of the known options and maybe discover new ones ?

I.1 MARCH'S LITTLE MODEL AND OLD WISDOM

James March provides us with the first simple model of this trade-off between « *the exploration of new possibilities and the exploitation of old certainties* » (1991). The author's point of departure is the statement of the vulnerability of exploration. Although the two logics are not exclusive, they compete for scarce resources. In this competition, the exploitation, defined as the « *refinement and extension of existing competences, technologies and paradigms* » (Ibid.), has a clear advantage over the exploration of new alternatives because organizations have natural incentives to favour exploitation. This can be firstly explained in terms of risk aversion and preference for short-term benefits and, more generally, in terms of bounded rationality. But there is also a dynamic effect that reinforces this static advantage, which comes from the specificity and the cumulativness of knowledge and competences gathered inside organizations: the process of learning by doing and by using increases the exploitation ability to improve existing technologies faster than the process of learning by searching increases the exploration ability to discover new opportunities. In addition, at the inter-organizational level, the advantage of exploitation is strengthened by various increasing returns (network effects, knowledge spillovers, complementary technologies, etc.). March also stresses the underlying danger of this natural advantage: the exploration feeds the exploitation, and in the long term if the exploration is too weak there will be nothing more to exploit. On the basis of these two elements the author builds a model that underlines the advantages of exploration in a case of competition for relative position between organizations. This model can be easily translated to the case of competition in which various firms compete in order to achieve the best levels of technological performance (cf. annexes). In the simulation model, the levels of technological performance of the various organization follow a normal probability distribution with specific means and variances. One of the main result is that the more competitors one organization has, the more increases in the variance may compensate for decreases in the mean. When the number of competitors goes to infinity, the mean has no more influence on the organization's probability to beat its numerous competitors.

Translated into terms of exploration and exploitation, this result pleads for exploration in the case of competition for relative technological performances. Indeed, given the fact that exploration widens the scope of technological options, we can assume that it is associated with increase in the variance of technological performances. Exploration permits the possibility of better technological performance in the case of a discovery, or of a more reliable choice between the known options. But it can also provide the occasion to « lose everything » if there is no discovery, or if the process of learning by searching which gives information about the performance levels of the known options, does not advance quickly enough to beat the competitor who has chosen the solution of a « blind bet ». The exploitation has the direct effect of increasing the mean performance by consumption of the current competencies, but reduces the scope of opportunities.

Of course these results cannot be used as unquestionable evidence of the superiority of exploration. One can easily plead for exploration only with logical arguments, or with its « *old wisdom* » as March says. Thus, beyond these results, the main interest of this model lies within the elementary framework it provides to consider the balance between exploration/exploitation as a strategic trade-off: « *it is possible to see both the mean and the reliability of a performance distribution at least partially as choices made strategically* » (Ibid., 84). At the actors' level, the sustainable (more than optimal) balance between exploration and exploitation can be thought as a result of a cost-benefit analysis, given some basic conditions in which they implement their activities (timetable of the competition, costs of the exploration, etc.). According to this elementary framework, the emergence of novelty becomes endogenized in actors 'behaviors, while maintaining its essential discovery nature.

I.2 THE HIRSHLEIFER'S PROBABILISTIC FRAMEWORK OF THE DISCOVERY SITUATION

Although Jack Hirshleifer (1971), does not use the terms of exploration and exploitation, his analysis provides us with some complementary elements. Dealing with expectations under uncertainties, he distinguishes between two situations: the situation of « *forknowledge* », in which the future state of the world does not depend on human actions (e.g. the weather forecast), and the one of « *discovery* » in which « *nature will not autonomously reveal the information* » (Ibid., p. 563).

The first case is obviously less complex than the latter one, so far as it is only a question of who will have the quickest and more accurate expectation of a future event completely independent of the different expectations. The discovery situation refers to the detection of properties of the nature, in our case the eventual development of a new technology. Given the fact that this new technology will not show-up by itself, it can provoke self-fulfilling expectation: if nobody expects that a certain technological path is relevant, then nobody will take this path, and the technology will never emerge...

According to a probabilistic framework (cf. annexes) the author distinguishes between the probability the actors assign to the various options i 'to be the « good technology » (pa_i), from the probability (pA_i) that this is true and « *this fact is successfully exploited in the time-period envisaged* » (Ibid, p.570). In this framework, the exploration refers to basic research and the implementation of « all » the existing options, which provides actors of the innovation process with information about the probabilities pa_i. The exploitation is the implementation of one option, on the basis of the current state of actors beliefs about the technologies potential performances. If one chooses the option 1 and a1 is true, then the corresponding « *good news* » event probability will be strong. But the more secure way to increase the probability (pA_1) is the allocation of some resources to the search of information about the topography of the space of technological options (pa_i). In fact, the improvement of the pa_i, indirectly increases the pA_i in the long term. There is a trade-off between immediate returns on technologies and gains in information (Cowan, 1991).

Although this relation is hard to measure, some studies have already shown that investment in basic research appears to garner high private rates of return. But many of them fail to appreciate one of the main positive effect of exploration: it identifies valuable R&D opportunities and avoids wasting time and money in « incorrect » paths (David, Mowery, Steinmuller, 1991). As Rosenberg claims, for R&D investment, « *future pay-off is determined not merely by its size but by its allocation* », i.e by the effectiveness with which its components are directed toward specific improvements in performance levels and reduction in costs (1994, p. 325 Granstand).

On the one hand, basic research strengthens the knowledge base of the known options, the ones belonging to the topical state of the art (Steinmuller, 1994). Many case studies show that the fundamental understanding and research services (measurement, simulation models) coming from « science » are used extensively by firms during R&D activities (Brooks, 1994). This *ex-ante* learning about performance and pay-offs of the various options also lowers the cost of development, by decreasing the number of trials and errors concerning the adaptation of the existing technologies to the new application. In high-tech industries these development costs are high precisely because of the absence of a reliable scientific base « *to serve as a guide to the complex process of new product design and development* » (Rosenberg, 1992, p. 72).

On the other hand, basic research widens the scope of opportunities by discovering new technological options for the application targeted. It may happen that the definition of the application itself will evolve, or that new applications will be made possible thanks to new characteristics and relations between parameters in the knowledge base. The emergence phase, in which there is not any established paradigm that guides the activities inside certain boundaries, must then be seen as an open system which does not necessarily fit into pre-existing technologies, knowledge and structures.

Therefore, in a context of competition between exploration and exploitation for scarce resources, the investment in the search of basic information: i) increases the return on the amount of resources allocated to the development of the good option(s) once it (they) has (have) been revealed ; ii) decreases the amount on these exploitation resources. Thus, the excess of exploration consists of pursuing the search for information to a level where the remaining resources would not permit successful development of the « good » option[5]. According to Foray (1991), the information search in order to improve the pai (and the associated « negative heuristics » pbi) must logically stop to the point where the cost of additional information is equal to its incremental expected gain.

We resume in the next table the principal costs and benefits that must be considered while solving the exploration / exploitation trade-off.

		Exploration	**Exploitation**
Costs	**Nature of costs**	• Costs of diversity (division of research efforts among several options) • Costs of the basic research • Short-term opportunity costs coming from the non-allocation of the resources to the development activities	• Opportunity costs in the case of: - lock-in a sub-optimal option - complete failure of the innovation process - non-valorization of the options on various applications • Costs of the trial and error process coming from the undertaking of the development activity with a weak knowledge base (« empirical-based » development)
Benefits	**Nature of benefits**	• Increase the return on exploitation in the long term by: - the discovery of new options - savings in the development activities (less trials and errors) - provide fundamental assets that will be used by firms during the exploitation	• Direct short term return on investment • Possibility of « jackpot » if the *a priori* chosen technology is the good one

The variables affecting these costs and benefits are numerous. We enumerate the main ones for the general situation. Firstly, they depend on the time schedule of the innovation process (temporal horizon of the strategies, dateline set by a regulation) and on the « real » underlying topography of the technological landscape (i.e. the real state of the world: existence of unknown options with better performance, real performance of the existing technology for the new application, etc.). The costs of exploration will vary greatly among the different scientific / technological fields depending on the costs of research equipment, the complexity, novelty, and specificity of the knowledge base. The costs of exploitation depend on the specificity of the innovation process, which gives the exploitation investment the status of a sunk cost. More generally, this opportunity cost of exploitation has to be thought of as a cost of loss of diversity, which can be almost infinite if the « abandoned » options hold some unique service characteristic (Cowan, 1991).

---

[5] Of course, « good » or « bad » are not intrinsic qualities of technological options. They are progressively revealed as « good » through the user-producer interactions.

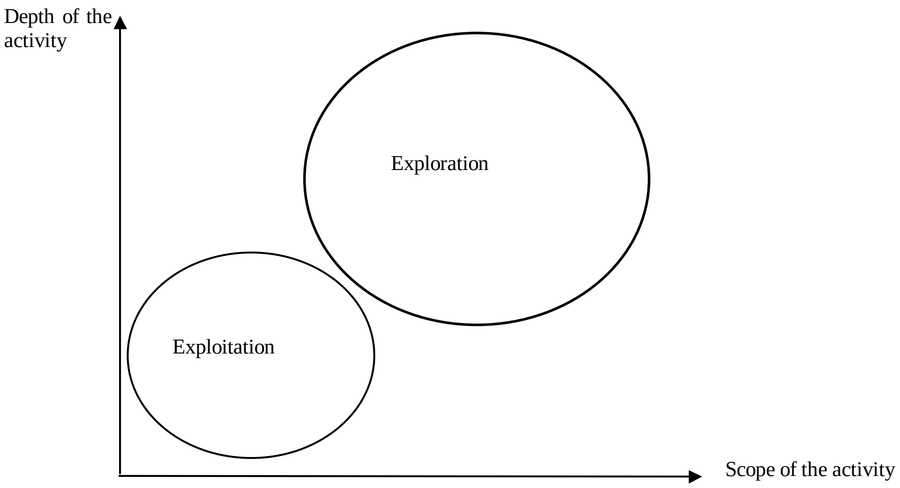
I.3 THE TWO AXIS OF THE EXPLORATION/EXPLOITATION TRADE-OFF

With these two elementary formalizations, we have set the basic principles of the exploration/exploitation trade-off. Exploration firstly concerns the number of technological options investigated, because of the uncertainty about their potential performance for the targeted application. We have also stressed the necessity to open exploration to the evolution of the set of applications in the emergence phase « *during which by definition it is impossible to conceive any best use of the technology* » (Cohendet, Llerena, 1997, p.227-228). The configuration of the application targeted, in terms of required performance, evolves as it is confronted with technological possibilities and through the user-producer relationships that progressively (« conventionally ») stabilize the targeted product design. In addition, the exploration can shed light on other possible applications of the options investigated.

We have also stressed a « vertical » dimension to the exploration. Indeed, in the case of advanced batteries, each electrochemical couple (anode/cathode) can be seen as a generic technology which contains many different paths. If we represent the morphology of the technological space as a tree (Garrouste, 1991) we can consider the position of the activity in this tree, i.e. whether it is at the level of a branch or of the tree-trunk. The closer the activity is from the trunk, the more it integrates potential development paths. This is of particular importance when horizontal moving (from branch to branch) is difficult, and requires that one steps back to an upstream phase of development of the technology. It is particularly the case for batteries where the substantial modification of the balance between the different service characteristics is often impossible.

Two axes must then be distinguished:

- an axis representing the scope of the activity both in terms of technological options and potential applications targeted
- an axis representing the depth of the activity (more or less generic/applied)



II EXPLORATION AND EXPLOITATION IN TECHNOLOGY POLICIES

The aim of the previous section was not to set basic research in opposition to development, and the debate concerning the balance between them in a context of scarce resources is still open (Boyer, Didier, 1998). Nonetheless, these « little models » gave us some arguments to underline the benefits of exploration when conditions of uncertainty and increasing returns prevail, and to stress the mechanisms underlying the organizations 'natural tendency to exploitation. According to Foray (1994), the solution to this problem could be the organization of coordinated sets of experimental projects, and the implementation of cooperation and diffusion of information between these projects. These vertical (within each project) and horizontal (between projects) coordination processes are at the core of research consortia. Therefore, we attempt to defend the idea that pre-competitive research consortia can, under certain conditions, offer an efficient organization form to solve this trade-off collectively and temporary, and to implement the corresponding research and innovation activities.

II.1 A NEW MODEL OF TECHNOLOGY POLICY

Until recently, it appears as if the policy maker was only supposed to correct the underinvestment in long term research, induced by the inherent market failures of these early phases. Exploration was limited to the technological features of the innovation process, without emphasis on the organizational changes that it requires to sustain these activities. Both in practice and theory, it is being increasingly recognized that this is far from sufficient and appropriate. Public authorities must initiate and sustain both exploration and the setting of an institutional framework that reduces uncertainties and facilitates interactions between the various actors of the emergent innovation process.

The initial Ergas typology of technology policy

This evolution of technology policy can be replaced in the well known typology of Ergas (1987). He distinguishes between two models of technology policy:

- the mission-oriented policy is particularly relevant to the after-war technology policies in force in the US, the UK, and France, and « *can be described as big science deployed to meet big problems* » (ibid., p.53). Based in great part on a linear, technology-push, view of the innovation process, this model lies upon the assumption that once the public authorities have strengthened the scientific knowledge base, market signals will « automatically » drive the industry to successfully exploit the new opportunities discovered. The US and French experiences have demonstrated the inefficiency of such a policy, which creates some isolated « *islands of high-technology* » (Humbert, Marteil, 1994). The industrial return on public investment in « big science » is all the more weak in so far as i) a great share of this investment is directed towards the defense and spatial industries which are disconnected from civil industries ; ii) it is usually foreign countries specialized in the innovation/diffusion process that will benefit from these returns. Ergas identifies concentration (on a few privileged firms and industries, cf. the « national champions » in the French case, and on the upstream phase of the innovation chain) and centralization (of the decision process at the level of a powerful governmental agency) as the dominant features of this model.

- On the other hand, diffusion-oriented policies are characterized by decentralization and a wide scope of intervention. The actors are involved in the decision process, and the actions performed are much more pervasive. This is, for instance, the case in Germany and some Scandinavian countries, where a clear priority is given to professional training, education, and technology transfer. However the price to paid for such lack of exploration is a scientific base that is too weak to feed industrial innovation, and a certain conservatism towards new paradigms.

The confrontation of the « old » and « new » policy models in the case of advanced batteries

To a lesser degree, post-war Japan also belongs to this latter category. MITI has shaped an industry that is highly dependent on international technology transfer from occidental countries, but very successful in incrementally improving these « generic » technologies and in bringing them to market. Nonetheless, in the sixties, this configuration was working out to be inefficient. Therefore, public and private stakeholders expressed a clear willingness to increase the creative capabilities of the Japanese economy, while maintaining its ability to diffuse and valorize technological opportunities on the marketplace. This policy model « mission of diffusion oriented » focuses upon some critical and promising technologies within wide cooperative programs of technology development. These programs investigate the basic science associated with each of these critical technologies thanks to the participation of various university and national laboratories, while promoting the intersectoral industrial partnerships in order to innovate and diffuse the knowledge in effective commercial products. Public authorities have a strategic and delicate role to play: they must prove their abilities to convince industrial firms to act of their own free will... (Humbert, Marteil, 1994). This ability, said to be one of the key of the success of the MITI, sheds light upon the very complex public/private overlapping that allows a strong coordination towards privileged research directions and the decentralization of the effective implementation of these directions.

In the US and in France, public expenditure in battery technology has been allocated to a great degree through military and aerospace research contracts. Advanced batteries are used in submarines, missiles, satellites, and some developments of electric military vehicles are also undertaken[6], but the progress that is accomplished are transferred in the civil industry very slowly. Apart from obvious isolation of these industries, this is also due to the difficulty of adapting the military/aerospace batteries to the

---

[6] Obviously, this researches is not triggered by environmental matters, but by the fact that an EV is almost completely quiet.

performance levels required in consumer applications: within each device, the trade-off between costs and energy/power are very different. In short, a kWh in a battery for a satellite has a much greater value than in an EV or an electronic consumer product[7]. Therefore, aerospace has pursued a trajectory that focuses on energy and power irrespective of price. Similarly, in military applications, costs were not the principal target as national security has no price. The problem is that once the design of the battery is done, it is very difficult to « curve the trajectory » in order to adapt it to another application. In Japan, where military activities were very reduced after the second world-war, research focused on civil industry and consumer markets. In 1974, MITI started the *Sunshine Project* to develop new energy technologies, and in 1978 the *Moonlight Project* was begun to develop energy conservation technology. Both projects maintained strong R&D schedules for advanced batteries under the close cooperation of industry, government and academic organizations. They have provided effective results in terms of basic technology and market opportunities in peripheral applications. In 1989, a third program called the R&D Project on Environmental Technology was launched. These three projects have been unified in 1993 into one program called the New Sunshine Program, which deals simultaneously with energy and conservation issues.

Given the long term time scale of these programs, and the as yet very immature EV battery technology, it is too early to make final conclusions about the efficiency of the Japanese strategy. But we do notice some striking facts: i) the 3Cs' battery market (Camera, Camcorders, Consumer electronics) is currently almost limited to two technologies, Nickel-Metal Hydride and Lithium-ion. Although these technologies originate from US and European laboratories, Japanese battery manufacturers now widely dominate this market ; ii) in 1980-90 period, it was commonly believed that North-American firms were leading the field of EVs. Ford's research of Sodium-Sulfur EV batteries, or the « Impact » vehicle of GM (which became later the well-known « EV1 ») at the beginning of the 90's, supported this view. This idea is far from universally accepted since the launch of the Nissan EV (the first EV with a Lithium-ion battery from Sony) and the recent success of the Toyota Prius (with Nickel-Metal Hydride batteries from Matsushita), which is the first HEV ever commercialized.

Research consortia as a new organizational form of the multi-stage technology policies

It is acknowledged that the success of the Japanese intervention model has highly influenced the evolution of occidental technology policies towards a similar « *multi-stage strategy* » (Tassey, 1991). Starting from very few exceptional cases in the beginning of the 80's, the number of US research consortia soon outnumbered the Japanese one, and reached 300 in 1991[8].

---

[7] Each improvement in the amount of energy that the battery can supply provides the opportunity to reduce the weight of the battery without decreasing its performance level. Given the limited weight allowed in the spaceship, the weight saved can be used to carry heavier satellites. The actual cost of the launching of a satellite of 5 tons is around 200 000 FF/Kg...

[8] For more precise details of research consortia, see for instance : Aldrich, Sasaki, 1995 ; Katz, Ordover, 1990.

In the domain of advanced batteries, it became clear for many actors in the mid-eighties that « *the most direct and effective manner for the US to retain a leading market share would be to develop a strong federal research program that interacts with the US industry* » (NAS, 1986). The first research consortium was the United-States Advanced Battery Consortium (USABC), established only one year after the ZEV mandate by the Big Three (Ford, GM, Chrysler) through their common research umbrella, the US Council for Automotive Research (USCAR). This consortium is exclusively dedicated to advanced batteries for EVs. Lead-acid battery[9], which is not considered as an advanced battery, was excluded from the USABC because of its weak performance and its well-established industry. Given the potential EV market defined by the ZEV mandate, which obliges the top seven automakers to sell 2% of EVs in 1998, 5% in 2001, and 10% in 2003[10], and the threat of progress of advanced batteries through the USABC, the Lead-Acid battery developers belonging to the International Lead-Zinc Research Organization (ILZRO) have created their own consortium, the Advanced Lead-Acid Battery Consortium (ALABC). The Japanese response to USABC occured in 1992 with the Lithium Battery Energy Storage program (LIBES) dedicated to advanced batteries for EVs and stand-by power applications (integrated into the previously mentioned « New Sunshine Program »). The European Community has also increased its pre-competitive effort on non-polluting vehicles and their various components in the forth and fifth Research Frameworks.

Although research consortia are not to be viewed as the only results of the shifting of technology policy, they are without any doubt the privileged organizational form of this new model in the emergence phase. They serve to gather potential competitors (producers and users), public authorities, and scientific laboratories, in the same emergent technological domain. They are usually settled at the generic technology research stage, i.e. when one or more applications, even if not strictly defined, becomes the motivating factor of the research activities. At this stage, for the first time, the general relations, laws, and attributes coming from the fundamental research stage are being bundled together as a possible product (Tassey, 1991). Given their pre-competitive status, research consortia are supposed to end when the R&D becomes « specific » to the firms involved, which of course is a very fuzzy limit.

---

[9] The same battery technology that has been used for almost a century in ICEV for starting, lightning and ignition.

[10] This works out to be about 40 000 EVs in 1998, and 200 000 in 2003. These numbers must be at least doubled, because 12 states from the North-east of the USA have decided to follow the Californian laws, instead of the (less stringent) Federal ones.

II.2 THE EFFICIENCY OF RESEARCH CONSORTIA FOR THE SOLVING OF THE STRATEGIC TRADE-OFF

The traditional advantage granted by analysts to inter-organizational arrangements are well known: they allow actors of the innovation process to leverage research funding, to share the high risks associated to these uncertain and long-term technologies, to reduce duplication of R&D investments, and to exploit economies of scale in the R&D process. They also provide the opportunity to gather complementary cognitive or material assets, and to cooperate on problems where strong science-industry relations are required, while maintaining the public (at least for the participants) character of the knowledge that results from the generic technology research. In this section, we underline the efficiency of research consortia in the specific case of emergent technology.

The exploration phase to counter negative increasing returns

The increasing returns that affect the research activity have been widely studied in the evolutionary literature. The concepts of « *focusing devices* » (Rosenberg), « *technological paradigms and trajectories* » (Dosi), or « *dominant designs* » (Utterback) for instance, all describe the various aspects of the mechanisms that drive the focalisation of the activities on a limited number of technological options (or on a restriction in the space of technological characteristics).

On the one hand, by maintaining the technological variety until enough information is accumulated about the potential performance of the different options, research consortia delay the standardization processes. Through the coordinated sharing of the set of options, they organize the interplay between learning and selection mechanisms and (may) avoid costly lock-in situations. Through the history of advanced batteries the list of winners has changed many times. Even in a short period: « *for example, in 1991, the Nickel-Iron and Sodium-Sulfur batteries were considered the most promising, but are no longer the leading contenders* » (OTA, 1995). Today, the « winning » EV batteries are the same technologies as the ones used for portable electronics applications[11], and none of them have yet clearly demonstrated their performance in an EV. These exploitation dynamics can be especially « dangerous » if the batteries for EVs are not on the same trajectories as the advanced batteries for the « 3Cs » markets, i.e. if the batteries for EVs cannot be a « simple » scale-up of the small advanced batteries. Some actors have clearly expressed this risk during our interviews, or in reports: « *the specific technology implementation, manufacturing techniques, and cost factors that influence the directions of the 3Cs 'program are unlikely to be relevant to EV battery packs* » (Moore, 1993).

On the other hand, the clearly defined goals, rules, and time schedule established in research consortia facilitate the sharp selection required for the passage from the phase of exploration to that of exploitation. When technologies are supported on a non-coordinated « one-by-one » basis, the temptation for the policy maker to let certain options live, even if they do not achieve the performance levels required within a « reasonable » period of time, may be important for several reasons. Through the mutual control of the various participants, consortia seem less vulnerable to solicitation of postponement and « mercy »...

The exploration phase to valorize positive increasing returns

Many cognitive or material resources produced during the exploration phase can be classified as quasi-public goods, and belong to what Tassey calls the technological infrastructure (1991, 1996). This term defines the elements of an industry's technology that are jointly used by competing firms, i.e. the generic technology (basic knowledge and concept) and the infratechnologies.

In the case of advanced batteries, the first element principally concerns materials characterization. The performance levels required for EVs demand a return to this level of research. It is stressed in many studies that some problems in battery technology have never been explained because the state of the art in materials characterization does not permit correct distinction of the sets of interacting parameters (Delmas and alii., 1998). This type of long term prospective research is also the condition necessary for discovering *« new materials with new properties leading to storage systems, which could be the ones of the future »* (Ibid., 1998). But, as in the semi-conductor industry where such systematic characterization was also necessary, the battery makers are not incited to carry-on this research because: i) they may derive from a different science and technology base than their traditional one ii) they are expensive iii) they cannot be directly embodied in the product (non proprietary).

Infratechnologies (instruments, test methods, simulations) are also a major feature of advanced battery's technological dynamics. There is an infinite number of ways of evaluating battery's in-laboratories or in-road performance. They are used for two different reasons: i) firstly to compare the results of the various batteries offered at the different level of development (cell, module, full battery-pack) ii) secondly, in each research project, they permit the assessment of true battery performance, and guide the research activities. This is particularly important for performances, as such as cycle life (number of charge-discharge before the battery « dyes ») and reliability, and helps avoid expensive and long tests[12]. It is a very difficult to implement test procedures that reproduce real world conditions (acceleration, hills, frequent stops, change of temperature, etc.), and very crude tests norms have been used for years. Disappointment was then common when they were tested in real conditions...

---

[11] Namely, Nickel-Metal Hydride, Lithium-Ion, Lithium-Polymer

[12] Let's assume that an advanced battery need 4 hours to be charge and 4 hours to be discharged. If one want to know if the battery can sustain 1000 cycles, the experience will last about...one year. We then clearly understand the stake of developing test methods and simulation models.

If these three elements of technological infrastructure are public goods, they are also industry specific, and have a « *sufficiently focused industry user population to raise the benefit per firm to a level that warrants the investment necessary to make participation in a consortium worthwhile* » (Tassey, 1996). In other words, the superiority of research consortia is derived from the fact that they permit the emergent industry to internalize the externalities coming from these quasi-public goods (also sometimes called « *industry-specific-public-goods* »). More generally, the exploration phase will be the occasion for the various actors gradually to become « *conscious that there is a new industry, and that it has collective interests and needs* » (Nelson, 1994).

Exploration and the establishment of new actors' connections

Research consortia can gather a very wide scope of participants, belonging to different industries and scientific disciplines. In so far as the exploration must be systematic, it cannot be exhaustive. The exploratory stage must be characterized as one of articulation between technological opportunity and user needs. Under conditions of great uncertainty, this articulation of the technology to one or more applications can only be done through actors interactions within a formal or informal organization. This may demand new connections between different industries. The organization must then be wide and varied enough to integrate the possible opportunities of linkages between various actors. In other words, the research consortia permit to overcome existing industrial structures. Similarly, the new opportunities that are to be successfully exploited will require the connection of different bodies of scientific knowledge, and the wide scope of research consortia will help overcome existing disciplines' specialization. Moreover, with the collective setting of clear performance goals, research consortia also create a relevant environment for this interaction towards a « still-to-be » product or process innovation. These evolving and mutually agreed definition of the product to be delivered play the role of an interface between the various parties. As Andersen argues, this « *principle of commodity abstraction* » is essential in order to ease information flows between them (Andersen, 1991).

The case of advanced batteries for EVs is a real « living laboratory » in which to study such a structural evolution: it requires the creation of interaction channels between the automobile industry and the growing and disparate advanced battery industry. These two industries are meeting for the first time because of EVs, and their effective cooperation requires a complex organizational learning process. Firstly, as we said earlier, there is no clear view of what kind of EVs should be targeted, and for each of them, the translation of this vehicle design into battery performance is a hard task. The phase of exploration in research consortia is the occasion to define a commonly agreed-on set of goals, and to set a schedule for these to be achieved.

Research consortia, « *narrow policy window* », and « *blind giant paradox* »

Research consortia are also a way to allocate public funds more efficiently for exploration between the various organization and technologies. This is especially important for advanced batteries in which long term industrial research is very weak. Indeed, except when the military industry offers a secure market (which is the case less and less often), electrochemical suppliers have a very short-term time horizon: « *narrow profit margins require industry to spend 90% of their small R&D budget to improve present products in order to remain competitive in existing markets. Industrial sponsorship of long term, high risk battery R&D is very small because there are no existing markets for consumer electric vehicles and utility load-levelling devices. This mean that long term, high risk R&D is practically non existent. Government participation allows industry to broaden its perspective and to engage in research which it would otherwise have to ignore or postpone* » (Brogan, Landgrebe, 1984). Similarly, the electricity utility companies, which have maintained strong efforts in the domain of advanced batteries[13], are today very poorly positioned. Under the pressure of deregulation « *many utilities are shifting their R&D from collaborative and longer term projects to proprietary R&D and to projects with a short term payback* » (Executive Office of the President of the US, 1997). However, to allocate public funds, the policy maker in the emergence phase is subject to informational asymmetries: « *EV battery development history is replete with examples of programs that were initiated but failed to meet their stated goals. Many of these cases can be explained by naivete on the part of the funding organization and less than honest or simply extremely optimistic positions taken by developper. Most funding organizations have had high expectations given to them by the developper that promised the 'super battery 'with high performance and long life* » (Mader & Associates, 1994). The automakers for their part are affected by the ZEV mandates and have, in contrast, an understandable interest in emphasizing the difficulties in achieving the mandates requirements (OTA, 1995).

The policy maker (the « *blind giant* ») experiences a lack of relevant information and is subject to bounded rationality like the other actors (Oltra, 1998). This is all the more important as it occurs in a period when public authorities have great power to influence the trajectories of the technologies. As David writes: in the presence of self-reinforcing mechanisms « *there may be only comparatively brief and uncertain 'windows in time 'during which effective public interventions can be made at moderate resource costs* » (David, 1987). In this context, research consortia offer two advantages: i) the active participation of governmental agencies in the programs allows them to collect more reliable information, and to have a closer look at the real progress accomplished ; ii) while delaying the selection of the few winning options until more information is collected concerning each option, research consortia serve to enlarge the « *narrow policy window* ».

---

[13] Batteries for EVs, because it could be an additional market for the electricity they supply, or for large stand-by applications that allow to store energy and leverage the seasonal or daily peaks of electricity demand.

III. A CASE STUDY OF THE EXPLORATION/EXPLOITATION TRADE-OFF: THE UNITED STATES ADVANCED BATTERY CONSORTIUM

In the former sections we have tried to defend the efficiency of research consortia in the emergence phase on a pure theoretical basis. We try now to find these elements in the effective implementation of one consortium aimed at developing advanced batteries for EVs: the United States Advanced Battery Consortium (USABC). As we said earlier, our purpose is not to present research consortia as an optimal organization form, but to stress the specific coordination that takes place in consortia and that allows participants to manage the exploration/exploitation trade-off efficiently. As limited in this paper, we only address the problem of the initial technological choices when great uncertainty prevails.

III.1. THE TECHNOLOGICAL LANDSCAPE AT THE BEGINNING OF THE NINETIES

Past activities concerning advanced batteries for EVs and other applications have left a very « hilly » landscape. Few options have been tested on the road (principally Lead-Acid [L-Acid], but also Nickel-Cadmium [Ni/Cd], Nickel-Iron [Ni/Fe], Nickel-Zinc [Ni/Zn], and Sodium-Sulfur [Na/S][14]). The results are far from satisfactory, at least for the automakers who are still looking for an EV able to compete with todayʼs vehicles. Moreover, one of the main uncertainty persists: will it be possible to mass produce these batteries, while maintaining these (poor) performance, at a reasonable cost ? At this time there is no commercial series, and these batteries are « hand-made » prototypes exceeding the reasonable cost/kWh from a factor 10 or more. Among the other options, some are already, or will soon be, produced for the portable electronic market (small Nickel-Metal Hydride [Ni-MH], Lithium-ion [Li-ion]) but their scale-up is risky, and some are used in small numbers/high prices for military applications (Nickel-Hydrogen [Ni-H], Lithium-Metal [Li/Fe]). Some other options have almost never been tested in real conditions for any applications, but exhibit encouraging results at the cell or module levels. The performance of the batteries is highly uncertain and, moreover, is usually investigated by only one organization in the world (Lithium-Polymer [Li-P] by Hydro-Quebec, Zinc-air [Zn-air] by Electric-Fuel, Nickel-Sodium Chloride [Ni/NaCl] by Beta R&D, Vanadium Redox by an Australian start-up from the University of New South Wales). Finally, some exotic miraculous technologies exist through concepts, patents, rumors, or fantasies (all plastic batteries, « tin » battery). All these options have their own characteristics, principal attractions (established industry for the L-Acid, high power [Ni-MH] or high energy [Na/S], long cycle life [Ni/Cd], maintenance free [L-acid], low cost electrodes materials [Na/S], etc) and limiting factors (High operating temperatures [Na/S, Na/NiCl, and Li-Fe], high costs and no established supplier base [all but L-Acid], etc.). Hence, the effective performance levels are either disappointing, either uncertain, ...or both. It is worth noting that no exclusive links or sales contract are yet established between automakers and battery developers. Their relationships do

---

[14] We only give the main ones. One could find in the scientific/business literature dozens of technologies said to have

not go beyond research cooperation (sometimes for a long time as with Saft and the French automakers) or sales of prototypes for testing.
As regards the required performance levels the situation is also far from clear. There is, as yet, no consensus on what performance levels should be targeted. The automakers already have EV plans which require various performance configurations: General Motors is focusing upon its « sport-EV » (the Impact), Chryler upon its EV-Van (the EPIC), Ford upon its EV-pick-up (The EV Ranger), French automakers upon their EV as a second urban vehicle (electric versions of Peugeot 205, Citroën AX, Renault Clio), and little information has emerged from Japanese automakers. Obviously, this situation is even worse for HEVs, which can take an infinite number of possible configurations.

The methods for battery assessment and testing are also very crude: traditionally, bench-testing of traction batteries has involved applying discharge regimes under constant-current conditions. Although this can be a useful approach for battery comparison purposes (if all battery makers use the same conditions, which is not the case), « *it does not lead to confident predictions of the performance experienced in actual EV service, where the load on the battery is far from constant* » (Rand and alii., 1998). The best method of simulating EV service involves the application of charge/discharge regimes which reproduce the variable load encountered by the vehicle in its intended application. Some experiments have been conducted, but no single schedule of standards has been adopted universally for the representation of EV usage patterns (ibid., 1998). Moreover most of them are not purpose-built for the EV, and were originally developed for evaluating the exhaust emissions or the fuel economies of ICEVs (like the FUDS[15]).

III.2. THE BEGINNING OF THE USABC AND THE FIRST NEGOTIATION

Prior to the USABC, the Department Of Energy (DOE) participated actively in EV and battery research through the funding of numerous research projects and through the National laboratories (Argonne, Lawrence Livermore, Sandia etc.). But the projects were supported on a one-by-one basis, or within large programs (the Electric and Hybrid Vehicle Program since 1976) which were more an umbrella than a real private/public organization with an identified strategy. « *During the past 20 years, funding for R&D programs such as DOE's Electric and Hybrid Vehicle Program has fluctuated wildly, making it impossible to sustain a coherent effort* » (OTA, 1995). The acknowledgment of the need for coordinated exploration of the possible range of options and applications was one of the official purposes of the DOE's participation in research consortia: « *Depending on the desired vehicle function, location, and driving conditions (...) different combinations of technologies may be most appropriate. The federal R&D program is conscious of these uncertainties, and is structured to pursue several options simultaneously, so as not to miss promising opportunities* »

---

great performances for EVs, but which do not survive after two or three years : Aluminium-air, Iron-air, etc.

[15] Federal Urban Driving Schedule

(OTA, 1995).

One of the first problems that the US public authorities addressed while trying to set this new exploration strategy was to assess who should lead the initiative with them. As we said, exploration is not only a matter of technology, but also a question of industrial structures: « *there is a continuing debate about the way federal R&D finding can best catalyze the emergence of advanced vehicle technologies. On the one hand, there are advantages to supporting work by major automakers and their suppliers, because the automakers are in position to rapidly commercialize a successful innovation in mass-market vehicles. On the other hand, many observers are concerned that federal efforts to develop leapfrog technologies rely too heavily on the existing industry* » (OTA, 1995). In our case, and overall within our general theoretical framework, exploration does not only concern the search for new technologies but may also require the support of the creation of new industrial structures.

Nonetheless, in January 1991, the Big Three (Ford, GM, Chrysler) created the USABC, and were joined some months later by the DOE and the Electric Power Research Institute (EPRI, the permanent research consortia of the electricity utility companies). The USABC was considered as an example of a research consortium, firstly because of the amount of funding (around $300 millions until today[16]), but also because it initiated a new kind of relationship between automakers and public authorities (usually very conflicting). The official purpose of the USABC is to « *work with advanced battery developers and companies that will conduct R&D on advanced batteries to provide increased range and improved performance for EVs in the latter part of the 1990s* » (NRC, 1998).

The first two years of the USABC's existence were taken up with the logistics of creating the organization and its operating principles, defining goals, and then soliciting corresponding proposals and negotiating contracts. During this period, which was essential for the solving of the exploration/exploitation trade-off, DOE had an active and extensive role, in particular to counterbalance the own Big Three's strategies. Indeed, difficult negotiations took place concerning the translation of the general purpose into a precise and effective strategy: the automakers wanted to set high long-term goals, arguing that low or medium battery performance would not permit the development of an acceptable EV for consumers: « *Despite DOE estimates, [automakers] officials doubt that EVs with mid-term batteries can achieve any significant market penetration* » (GAO, 1995). The DOE did not agree with this plan: « *DOE officials who had considerable experience with advanced battery research convinced the automobile companies that considerable uncertainty existed as to whether long-term batteries could be successfully developed* » (GAO, 1995). Therefore, the DOE suggested that it would be prudent to enlarge the option portfolio, and also pursue a second set of more readily achievable mid-term goals. This desire of the

Big Three can be easily explained: i) It is essential for them to diffuse the idea that the EV cannot be something different from what they produce today. The idea that « *there won't be any EV on the road until the 200 miles battery is discovered* » seems to be the Big Three's leitmotiv. It seems clear that the battery technology breakthrough they are looking for, allows them to avoid a more radical change in their own industry...; ii) At the same time they set the USABC, the Big Three actively are entering into a huge and costly lawsuit against the CARB in an attempt to make them back the ZEV mandate. USABC long-term goals were a way to prove their goodwill, while reinforcing their argument that EV will not be on the road in 1998.

Of course, the relationships between the automakers were also a problem, given the fact that they all had different vehicle strategies. After a first attempt from General Motors to closely link the USABC to its Impact concept, the benefit from cooperating finally gained credence: « *Senior executives, particularly at Ford, appear willing to forgive GM's excesses to gain the advantage of sharing costs* » (The Clip Sheet, December 10 1992).

III.3. SCOPE AND DEPTH OF THE USABC

Finally, two sets of performance goals were set, and are used as a reference to assess the progress accomplished by battery developers both inside and outside the consortium.

According to these goals, the USABC mailed 130 Request For Proposal Information (RFPI), and received 59 proposals based on 16 different technologies (GAO, 1995). All the North-American and European advanced battery developers were solicited. Because of competitive imperatives, the Japanese firms were excluded. A Ford official clearly explains this choice:« *We believed that Japanese battery manufacturers would preferentially sell to a japanese carmaker* »[17].

This resulted in a wide portfolio of options: Ni-MH, Na/S, Li/Fe, Li-ion, Li-P. A contract was also negotiated for the Ni/NaCl battery, but it failed because of problems of intellectual property rights. Moreover, two contracts were doubled on Ni-MH and Li-P: « *USABC believes both the competition and the varying approaches that result from having two contractors work on the same technology will increase the chances of success* » (GAO, 1995). In fact, all the promising options have been investigated, except the L-Acid (already developed, and low performance) and Ni/Cd (forbidden in the US because of the toxicity of the Cadmium). An important part of the funding has been awarded to national laboratories to develop a clear test objective and test methods consistent with regards to all the tests units. The FUDS test method has been replaced by the Dynamic Stress Test (DST). As for the goal performances, theses tests methods are now widely used even outside the consortia, and play the role of standards.

---

[16] With the following cost-sharing : Big Three and contractors 46% ; DOE 47% ; EPRI 7%

[17] Automotive News, 2/12/91. At its early stages, the USABC received a cooperation proposition from the MITI, but for the same reason it was refused. The Japan EV Association (JEVA) also « *wanted to open the information channel with United-*

But it is also clear, and the USABC program managers have been very clear on that point during our interviews, that USABC is, above all, an engineering program, and does not intend to returns to fundamental research. The DOE maintains a program called the Exploratory Technology Research Program, which aims to identify new electrochemical couples (like Lithium-Sulfur). But this program is not really connected to the USABC, and its budget has been reduced by half since the DOE's participation in the USABC. The national laboratories also provide their scientific expertise to the USABC through Cooperative R&D Agreements (CRADAS), but their role is only to assist the firms' development process (resolve critical issues, testing and evaluation) not to create new opportunities.

Moreover, EVs are the only targeted application of the USABC. Large-scale stand-by power applications are never mentioned in any documents. The explanation for this, according to several people interviewed, is that automakers clearly do not want to share control of the USABC with the powerful utility companies. These companies participate in the USABC but only as electricity providers and not as potential users of the batteries for their specific needs. Consequently, during the entire phase I (92-96), the EPRI managers were non-voting members in the Management Committee (GAO, 1995).

Thus, the USABC is characterized by a wide scope of options, a focused application, and little depth. This configuration is very different from that of the Japanese LIBES program which is focused on one kind of option, but which is deep, and extended on the space of application. Indeed, LIBES is only investigating lithium battery technologies, but at a very fundamental level. Moreover, the program is twofold. One part is dedicated to high energy batteries (for EVs), and the other part is dedicated to long cycle-life batteries (for stand-by applications). This configuration gave rise to eight different kinds of lithium technology (four by application) investigated by different advanced battery manufacturers (Sanyo, Yuasa, Matsushita, Hitachi, Toshiba, Japan Storage Battery, etc.). In this program, the MITI is very powerful and among the private organizations no category of actors seems to dominate the others as it is the case in the USABC.

III.4. EVALUATION, LESSONS LEARNED, AND CHANGES IN THE INITIAL TRADE-OFF

Like other consortia, USABC has undergone numerous evaluations, managed by independent committee. Some of their main (negative) recommendations are the following:

- « *DOE should focus more on research that advances the science of electrochemical systems that have the potential to meet the long-term performance and cost criteria for EVs, as opposed to development of systems based on existing science. A significant portion of the scientific research should be focused on battery technologies that have not been included in the*

States » as a Matsushita program manager told us. He concluded : « *maybe it comes from cultural differences...* ».

USABC program » (NRC, 1998).

- « *participants in a follow-on program to the USABC should allocate some program funds to examining a broader spectrum of EV concepts and related market opportunities* » (ibid., 1998)

- « *the bulk of the USABC funding (>80%) is being applied to advancing battery technologies originally applied in the 3Cs 'market segment* » which could prove dangerous (Moore, 1993)

- one must acknowledge that the USABC partially failed to accomplish its phase 1 mission (GAO, 1995). Indeed, after the selection process: i) although its autonomy, power, and cycle life has increased, the remaining mid-term technology (Ni-MH) is still far from the initial cost target ; ii) the feasibility of the remaining long-term technology (Li-P) is still unclear. In the meantime, it seems that the Japanese do not wait for a breakthrough in battery technology and begins to produce small advanced battery for HEVs.

These types of criticism have provoked major changes in the research consortia:

- a new RFPI has recently been sent, informing the battery makers that « *the USABC is considering expanding its scope of research projects directed toward developing high-performance batteries for EVs* » (USABC press information release, April 29, 1997). With this proposal, the question that was asked to the advanced battery industry was clear: « *can you reach that performance levels, even with new chemistries* ?[18] »

- The utility companies have been more fully integrated in the decision making process of the USABC, and henceforth on a voting member of the management committee. Consequently, this gives rise to negotiations about the way EVs and stand-by applications could be linked in order to lower cost and increase the chance of success of this innovation process.

- A new set of performance goals has been established between the mid-term and long-term one. This new intermediate criteria called the « commercialization criteria » are supposed to represent the automobile manufacturers minimum needs for an initial market launch, without waiting for a future breakthrough. « *By pushing promising technologies to the table faster, the US can take advantage of its technology leadership* » (USABC News, Winter 1996). Of course, this must be linked to the recent Japanese successes in the domain of EVs.

- Major changes concerning the intellectual property rights and control rules are also considered, according to the « lessons learned » procedure (Abacus Technology Corporation, 1993, 1996).

CONCLUSION

This case study gave us the opportunity to show that i) the USABC allowed the participant to reach a consensus about the exploration/exploitation trade-off. This consists in preserving the technological diversity until the uncertainty about the possible future pay-off of the various options is reduced ; ii) the degree of exploration is highly dependent on the strategies of the various participants, and on the balance of the bargaining power between them. Nonetheless, the very active role played by public authorities can counterbalance the power asymmetries between the private firms. In the same way, procedures of evaluation and control allow the key-actors to learn about the results of the initial technological choices and to correct them.

More fundamentally, during the emergent phase, research consortia become identified and credible representatives of the emergent industry. This authorizes better coherence between the rhythm and direction of the technological progress, and the institutional environment. For instance, the CARB had a representative in the USABC Technical Advisory Committee that allowed the Californian public authorities to gain « objective » information about the technological progress. In 1996, after it funded an independent evaluation of the USABC's progress (CARB, 1995), the CARB acknowledged its initial over-optimistic expectations. Therefore, the CARB decided to back the 1998 and 2001 ZEV datelines and to give partial credits for HEVs in the remaining 2003 dateline.

---

[18] According to the USABC contract manager.

Bibliography

Abacus Technology Corporation, 1993, *Lessons learned under the United States Advanced Battery Consortium (USABC),* Final Report, November 8, Prepared for the DOE Office of Transportation Technologies, 15 p.

Abacus Technology Corporation, 1996, *Review of the Department Of Energy's implementation of the 1993 USABC lessons learned study*, Final Report, May 17, Prepared for the DOE Office of Transportation Technologies, 14 p.

Amendola M., Gaffard J.L., 1988, *La dynamique économique de l'innovation,* Economica, Paris.

Andersen E.S., 1991, Techno-economic paradigms as typical interfaces between producers and user, *Journal of Evolutionary Economics*, N°1, p.119-144.

Aldrich, H.E., Sasaki T., 1995, R&D consortia in the United States and Japan, *Research Policy*, 24, p. 301-316

Aoki, 1991, *Economie japonaise: information, motivations et marchandage*, Economica, Paris.

Boyer R., Didier M., 1998, Innovation et croissance: Relancer une dynamique de croissance durable par l'innovation, in: Boyer R., Didier M. (eds.), *Innovation et croissance*, La Documentation Française, Paris, p. 198.

Brooks H., 1994, The relationship between science and technology, *Research Policy*,. Vol. 23.

California Air Resources Board, 1995, *Performance and availability of batteries for EV's: a report of the battery technical advisory panel*, CARB.

Cohendet P., Llerena P., 1997, Learning, technical change, and public policy: how to create and exploit diversity, in: E.Edquist, *Systems of innovation*, Pinter Publisher, London.

Cowan, 1991, Rendements croissants d'adoption et politique technologique, in: de Bandt J., Foray D., *L'évaluation économique de la recherche et du changement technique*, Edition du CNRS, Paris, p. 381-398.

David P., Mowery D.C., Steinmueller W.E., 1991, L'analyse économique des rendements de la recherche de base: une étude de cas, la physique des particules, in: de Bandt J., Foray D., *L'évaluation économique de la recherche et du changement technique*, Editions du CNRS

Delmas et alii, 1998, Matériaux pour le stockage et la transformation électrochimique de l'énergie, Cahier de synthèse du CNRS.

Dosi G, 1988, Sources, procedures and microeconomic effects of innovation, *Journal of Economic Literature*, Vol XXVI, p.1120-1171.

Dosi G., Orsenigo L., 1988a, Structure industrielle et évolution technologique, in: Heertje A., *Innovation, technologie et finance*, 13-33.

California Air Resources Board, 1995, *Performance and availability of batteries for EV's: a report of the battery technical advisory panel*, CARB.

Executive Office of the President of the United States, 1997, *Report to the President on Federal energy R&D for the challenges of the twenty-first century*, President Committee of advisors on science and technology, Panel of R&D, General Publication Office, p.135

Foray D., 1991, Economie et politique de la science: les développements théorique récents", *Revue française d'économie*, Vol VI, N°4, pp 53-87.

Foray, 1994, Les nouveaux paradigmes de l'apprentissage technologique, *Revue d'économie industrielle*, N°69, p.93-104.

Frenken K., Leydesdorff L., Saviotti P., 1997, Co-evolutions in aircraft technology: decomposing systems of innovation using information theory, Fourth International ASEAT-workshop, Septembre 1997, Manchester.

Garrouste P., 1991, Eléments théoriques pour une approche systémique de la technologie, in: De Bandt J., Foray D., *L'évaluation économique de la recherche et du changement technique*, Editions du CNRS, Paris.

General Accounting Office, 1995, *Electric vehicles: efforts to complete advanced battery development will require more time and funding,* report to the US Senate.

Jullien B., 1996, Epuisement ou renouvellement des paradigmes ? Les deux visages de l'apprentissage, Séminaire du groupe « Evolutionnisme », Paris I, 21-03-1996.

Katz M.L., Ordover J.A., 1990, R&D cooperation and competition, *Brooking Papers on Economic Activity: Microeconomics*, 3, p. 137-203.

Mader J., 1994, Electric vehicle battery: development status, Mader & Associates, 15 p.

Mansfield, 1991, The social rate of return from academic research, *American Economic Review*, 81.

March J.G., 1991, Exploration and exploitation in organizational learning, *Organization Science*, Vol. 2, No.1.

Mowery D.C., Rosenberg N., 1993, The U.S. national innovation system, in: Nelson R.R., *National innovation systems: a comparative analysis*, Oxford University Press.

Mowery, 1994, *Science and technology policy in interdependent economies*, Kluwer Academic Publishers, Norwell Ma., p.338.

National Academy of Science, 1986, *New horizons in electrochemical science and technology*, National Academy Press, Washington.

National Research Council, 1998, *Effectiveness of the United States Advanced Battery Consortium as a government-industry partnership*, National Academy Press, Washington, 80 p.

Nelson R.R., 1994, The co-evolution of technology, industrial structure, and supporting institutions, *Industrial and corporate change*, vol.3, N°1, p.47-63.

Nelson, Winter, 1982, *An evolutionary theory of economic change*, Harvard University Press.

Office of Technology Assessment, 1995, *Advanced automotive technology: visions of a super-efficient family car*, OTA-ETI-638, General Printing Office, 300 p.

Oltra, 1998, An evolutionary analysis of technology policy, in: Groenewegen J., Vromen J., *Work, unemployment and need: theory, evidence, policies*, Edward Elgar Publishers, Forthcoming.

Paulré B., 1996, Les ambiguïtés de l'évolutionnisme contemporain, Colloque: l'Evolutionnisme: fondements, perspectives et réalisation, Paris-Sorbonne, 19-20 Septembre 1996.

Pavitt K., 1998, Technologies, products and organization in the innovating firm: what Adam Smith tells us and Joseph Schumpeter doesn't, *Industrial and Corporate Change*, Forthcoming.

Rand D.A.J., Woods R., Dell R.M., 1998, *Batteries for electric vehicles*, Society of Automotive Engineers, Warrendale.

Rosenberg N., 1992, Science and technology in the twentieth century, *in:* Dosi G., Giannetti R., Toninelli P.A., C., *Technology and entreprise in a historical perspective*, Clarendon Press, Oxford, p. 63-96

Salkind A., 1987, *Proceedings of the symposium on History of battery technology*, The Electrochemical Society Press, Pennington NJ, 295 p.

Saviotti P., Metcalfe J.S., 1984, A theoretical approach to the construction of output indicators, *Research Policy*, Vol 13, p.141-152.

Steinmueller W.E., 1994, Basic research and industrial innovation, in: Dogson M., Rothwell R., *The handbook of industrial innovation*, Edward Elgar Publisher.

Tassey G., 1991, The functions of technology infrastructure in a competitive economy, *Research Policy*, 20, p. 345-361.

Tassey G., 1996, Infratechnologies and economic growth, in: Teubal et alii, *Technological infrastructure policy, an international perspective*, Kluwer Academic Publishers, Dordrecht. P. 373

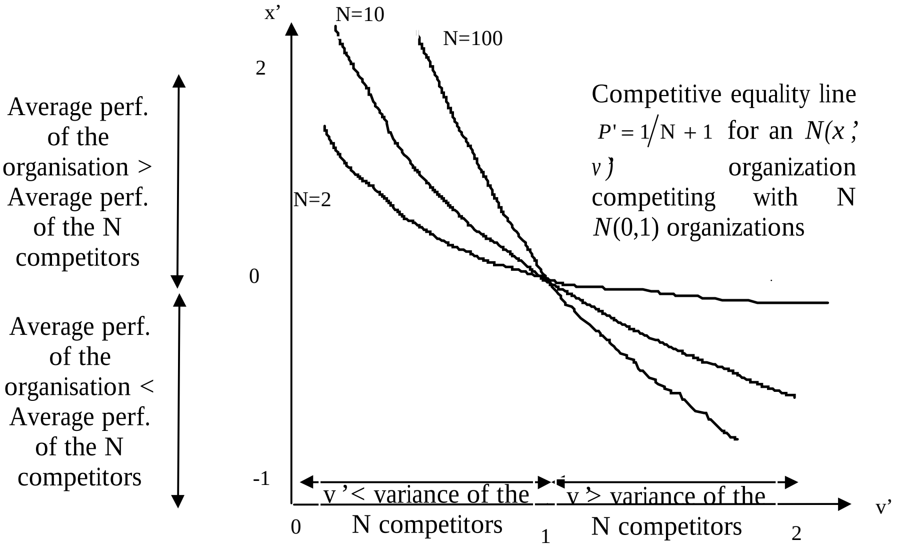
Willinger M., Zuscovitch E., 1991, Efficience, irréversibilités et constitution des technologies, Working Paper B.E.T.A.

Annexes

March’s simulation model of the exploration/exploitation trade-off

We suppose that the effective technological performance realized by an organization A follows a normal probability distribution $N(x';y')$. This organization has N competitors with a common normal probability distribution $N(0,1)$. If the average value $x' = 0$ and the variance $y' = 1$, this is to say that all the N+1 organizations have the same distribution probability of technological performances, then they all have $P' = 1/N+1$ chances to achieve the best performance and outperform their N competitors.

We now study the evolution of P’, the probability for the organization A to achieve the best technological performance, when the parameters x’ and y’ vary. The organization has a competitive advantage [disadvantage] if $P' > P$ [$P' < P$]. In the figure, each curve in the space (x’;y’) represents the points for which $P' = P$, for various numbers of competitors N[19].



The Hirshleifer’s framework revisited

Let’s assume an innovation process that aims at discovering a technology for a specific application. The state of the art in this technological field gives two known options (1 and 2), both with uncertain abilities to reach the required performances for the application. We can then consider three possible states of the world: state a1 [b_1], the option 1 is able [unable] to reach the performances required ; state a_2 [b_2], the option 2 is able [unable] to reach the performances required ; state a_3 [b_3], there is a third unknown option able [unable] to reach the performances required. We can consider that the actors of the innovation process assign probabilities to these three states, respectively pa_1, pa_2, pa_3[20]. We can consider also the joint events A_1, A_2, A_3 where respectively state a_1, a_2 or a_3 is true and « *this fact is successfully exploited in the time-period envisaged* » (Ibid, p.570). The probability of these « *good news* » events are pA_1, pA_2, pA_3, with of course $pA_i < pa_i$, and the probability of the « *bad news* » events are pB_i for each option. One of the problem of the discovery situation is that only the human intervention will effectively reveal the good technology: « *in the discovery situation no news is bad news* » (Ibid).

---

[19] For each value of v’ on [0;2] (steps of 0.05), the value of x’ for which $P' = P$ is estimated, based on 5000 simulations.

[20] In order to simplify the example we assume here that $pa1 + pa2 + pa3 = 1$.

Annexes

Name of the consortia [and country]	Birth	Specific aim	Main Participants (decreasing range of importance in the consortium)
US Advanced Battery Consortium (USABC) [United-States]	1991	Developing advanced batteries for EVs	Chrysler,,Ford, GM Department Of Energy (DOE) Federal laboratories Electric Power Research Institute (EPRI) Several battery developers
Advanced Lead-Acid Battery Consortium (ALABC) [Worlwide]	1992	Developing Lead-Acid batteries for EVs	Battery developers and material suppliers belonging to the International Lead-Zinc Research Organization (ILZRO)
Lithium Battery Energy Storage program (LIBES) [Japan]	1992	Developing Lead-Acid batteries for EVs and stand-by power applications	MITI Battery developers Electricity utility companies National laboratories Automakers
PNGV [United-States]	1992	Developing a 80 miles per gallon efficient vehicle (EVs, HEVs, or FCEVs)	Chrysler,,Ford, GM Department Of Energy (DOE) Federal laboratories Several automotive and non-automotive suppliers including the military and aerospace industry
PREDIT [France]		Advanced road and railway transport systems (including EVs, HEVs, FCEVs)	French Ministry of Research Renault, PSA Alsthom, etc. Several suppliers (like Saft for instance)
European projects (JOULE, THERMIE, IMT)		Various projects at the general levels of vehicles (EVs, HEVs, FCEVs, alternative fuels etc.) or components (Lead-acid batteries, advanced batteries, fuel-cells, flywheel etc.)	DGXII European Car-manufacturers Several suppliers (battery, power and control electronics, etc.)

USABC contracts awarded 1992-97		
- Ovonic (EU), 25,4 M$ (1992) then 8M$ (1996)	Ni-MH	(Mid-term)
- Saft-America (EU), 20,7 M$ (1992) then 11M$ (1996)	Ni-MH	(Mid-term)
- Silent Power (UK), 12,1 M$ (1993)	Na-S	(Mid-term)
- Varta and Duracell (Allemagne et EU), 18M$ (1995) then 14,5M$ (1997)	Li-ion	(Mid-term
- Saft-America (EU), 17,3 M$ (1992)	Li-Fe	(long-term)
- WR Grace and Johnson Controls (EU), 27,4 M$ (1993)	Li-P	(long-term)
- 3M and Hydro-Québec (EU et Ca), 32,9 M$ (1993), then 27,4M$ (1996)	Li-P	(long-term)

USABC Goal performance	Specific energy (Wh/kg)	Specific power (W/kg)	Cycle life	Costs ($/kWh)
USABC mid-term criteria	80-100	150-200	600	150
USABC commercialization criteria	150	300	1000	150
USABC long-term criteria	200	400	1000	100