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CHALLENGES TO RADICAL INNOVATION A CAR FOR THE FUTURE
Part One

Abstract: *The car of the future is one of the most fashionable issues in the press, in political sketches and in academia. This first article is dealing with the various available options for automotive power train: gasoline, diesel, bio-fuels, natural gas, liquefied petroleum gas, hydrogen, hybrid electric, "plug-in" vehicle hybrid electric, extended range hybrid electric, and finally full battery electric vehicle and fuel cell electric vehicle. For each option, the paper analyzes the key characteristics in terms of political, social and cultural acceptability, degree of achievement, current Status and long term perspectives. The content for each characteristic is given by up-to-date literature and interviews with key experts. When available, market data have been collected and are analyzed and discussed. Key indicators as obstacles to or in favor of one given options are also investigated and critically discussed.*

Keywords: *innovation, automobile, electric vehicle, technology management.*

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I think fools are very concerned about the future because they can say anything. They even have a chance to be right. But it is only a matter of chance.

Jean d'Ormesson, Histoire du Juif errant

Since the first oil crisis in 1973 and over the last 45 years, the crucial question of the innovation capability of the automotive industry has been raised by numerous authors[1]. Twenty years ago, it was postulated[2] the fundamental hypothesis of the strong technological inertia of the automotive technical arte fact itself founded on the internal coherency of a technical system constituted since the 1920s, and on its capacity to oppose the emergence of alternative techniques or,at least, to slow this emergence down through its own progress. The article proposed five major issues in favor of such hypothesis:

1. The automotive industry is a strategic sector in the context of globalizing markets and intensifying competition, employing millions of people all over the world in a complex industrial organization (automobile manufacturers, suppliers and subcontractors, distribution and maintenance, oil industry, insurance, etc.), sustaining billions of $ of financial turnover;
2. The automobile constitutes an established, stable and dominant technique: it is a paradigmatic system, fully coherent with other systems (socio-economic, industrial, etc.) and it is also the product-service that is most representative of the mass consumer model, largely dominant for the mobility of people and goods;
3. This technical system is largely dependent upon the regulatory and political context: the road transportation is one of major resources of public budgets (through specific taxation) and as one of the major budgetary lines for policies concerning transportation (infrastructures, traffic, etc.), health and social welfare (traffic accidents) and environment protection (noise, pollution, etc.);

1 In particular by Chanaron, J.J. (1973), *L'innovation dans la construction automobile*, Thèse de doctorat, IPEPS/IREP, Grenoble, novembre; Chanaron, J.J., (1977), Le modèle systémique conceptuel de l'innovation de E. Mottur, in Nicolon, A., *Le Véhicule Electrique*, Paris Editions du CNRS, Coll. Energie et Société, pp. 107-117 ; Chanaron, J.J., (1994), Perspectives de la voiture électrique: les leçons de l'histoire, *Revue de l'Energie*, numéro spécial Energie, Transports, Environnement, n° 463, novembre, pp. 627-635 ; Chanaron, J.J., (1998), Automobiles: a static technology, a « wait-and-see » industry?, *International Journal of Technology Management*, Vol. 16, n°7, pp.595-630 ; Bardou, J.P. ; Bardou, J.P., Chanaron, J.J., Laux, J., Fridenson, P., (1982), *The Automobile Revolution, The Impact of an Industry*, University of North Carolina Press, Chapell Hill; Chanaron, J.J., (2014), Towards an Operational Framework in Forecasting Breakthrough Innovation: The Case of the Clean Automobile, *International Journal of Electric and Hybrid Vehicle*, Vol. 6, N°2, pp. 87-107 ; Chanaron J.J., (2014), Recent Advances on the Design of Batteries and Fuel Cells for Automobiles, *Recent Patents on Mechanical Engineering*, 7, 2, pp. 113-121.

2 Chanaron, J.J., (1998), Automobiles: a static technology, a « wait-and-see » industry?, *International Journal of Technology Management*, Vol. 16, n°7, pp.595-630.

4. Numerous industrial and socio-economic factors join together to render the traditional technological trajectory particularly robust and therefore resistant to major change: the automotive industry has been able to constantly improve the intrinsic technical performances of the internal combustion engine (ICE) such as power, fuel efficiency and pollution and to internalize and therefore monitor research and development in alternative techniques. Industrial factors such as the cost, rhythm and time period for the renewal of a full range of models and the cost and rhythm of the renewal of productive investments are important. Market factors such as total quality and reliability and a relatively stabilized price-performance system, integrating acquisition, possession, use and recycling are equally crucial;
5. Public policies as well as corporate R&D strategies are themselves very 'tied up' by all of the inertia factors identified: the system is actively lobbying political and administrative circles on both national and international levels and supporting a universal "auto-lovers" society[3].

Automotive technology is largely submitted to internal and external constraints that shape a relative inertia to the process of change. From the point of view of corporate strategies, these constraints justify the most'conservative' choices and disqualify ex ante the most radical innovative options. Nevertheless, this does not block the possibility of real progress, but gives preference to gradual and step by step changes, coherent with the interests of the stakeholders of the system.

Any breakthrough strategy is implying major changes affecting the key conditions and characteristics of the design, the manufacturing and the use (up to its recycling) of vehicles. This is also obviously implying major changes in the current balance of power within the automotive industry, if not in the whole manufacturing industry.

This chapter aims at giving some elements of answer to the following key question: have the conditions for a radical innovation changed since the beginning of the twenty-first century in the automotive industry?

I. **The potential alternatives**

Faced with increasing competition in a context of high uncertainty associated with globalization and frequent economic crises as well as the pressures for ecological solutions freed from fossil fuels, the mature manufacturing industries, foremost among which is the automotive industry, seek breakthrough innovations that could contribute to their survival, and, where appropriate, provide them with sustainable competitive advantages - In which direction?

[3] De Bonnafos, G., Chanaron, J.J., De Mautort, L. (1983), *L'industrie automobile*, Paris, La Découverte Maspero, coll. Repères, No. 11.

1.1. Short history of automotive motorization

For more than a century, the Internal Combustion Engine (ICE) has been the dominant design for propelling vehicles and the automotive industry has long been considered static and strongly opposed to radical innovations. It is worth remembering that, nevertheless, at the origins of the automobile, it is the steam, then the electricity which was essential as source of energy of the automobile. In November 1881, G. Trouvé presents an electric car at the International Electricity Exhibition in Paris. The electric car has had a certain success in the last decade of the 19th century, both in Europe, and particularly in France, then in the United States, replacing cabs and other vehicles with animal traction.

For the race Paris-Bordeaux-Paris in 1895, an electric car by C. Jeantaud was on the starting line and four years later, the "Jamais contente" by C. Jenatzy, exceeded for the very first time 100 km/h, reaching 105.88 km/ h on 29th April 1899.

It is the theoretical invention of the four-stroke cycle by Beau de Rochas in 1862 that makes it possible to truly exploit the combustion engine. The German N. Otto became in 1872 the first engineer to apply the principles of Beau de Rochas, according to a cycle now known as the „cycle Otto". In 1876, the German engineer G. Daimler developed, for the firm Deutz, the first fixed gas engine operating on the principle presented by Beau de Rochas. In 1883, the French É. Delamare-Deboutteville circulated a car whose engine is powered by gas. It replaces gas with petroleum carbide by inventing a carburetor with wicks. This vehicle was on the roads for the first time in early February 1884 and the patent was officially registered on February 12th, 1884, which makes him the inventor of the gasoline automobile. But it was not until 1889 that R. Panhard and É. Levassor equipped the first four-stroke engine, the Daimler engine, on a four-seater car. In January 1891, Panhard and Levassor were already driving in the streets of Paris with the first French models equipped with the Benz engine. These are the first commercial cars to be marketed with an ICE.

The competition between the two alternative technologies, gasoline versus electricity, was intensifying. In 1900, out of 4,192 vehicles manufactured in the United States, 1,575 were electric, 936 gasoline, and 1,681 used steam. Then, little by little, gasoline and diesel finally supplanted the electricity because of the intrinsic defects of the electric car compared to the advantages of the technology of gasoline cars. According to Rae[4], „it was inevitable that they should prevail".

In the seventies, the two oil shocks of 1973 and 1978, the technical progress on batteries and fuel cells and the premises of the antipollution movements were an opportunity for an active revival of research on the electric car. But the many

[4] Rae, J.B., (1955), The Electric Vehicle Company: A Monopoly that Missed, *Business History Review*, 29, 4, pp. 298-311.

projects were fizzling in the face of advances in internal combustion engine cars in terms of energy consumption and pollutant emissions.

Since the early 2000s, industry experts, researchers, consultants and leaders, believe that radical changes are now needed to reduce CO_2 emissions, a major factor of global warming, and dependence on oil and fossil fuels. A consensus now seems to be establishing an inevitable transition to new sources of energy. What are the chances of a technological break?

1.2. The emergence of innovative options

The four-system innovation model allows for the creation of a framework for evaluating innovative reference options that are emerging in the private car sector (Table 1).

Table 1. *Different propulsion alternatives*

ICEV	Vehicle with Internal Combustion Engine	Vehicle with gasoline or diesel engine
AICEV	Vehicle with advanced internal combustion engine	Vehicle using new fuels: bio-fuels, natural gas, liquefied petroleum gas, hydrogen
HEV	Vehicle hybrid electric	Vehicle using an ICE and an electric motor
PHEV	"Plug-in" vehicle hybrid electric	HEV with a battery recharging device
ERHEV	Extended range HEV	Electric vehicle in which batteries are charged by a small ICE
FPBEV	Full battery electric vehicle	Electric vehicle using only batteries
FCEV	Full cell electric vehicle	Electric vehicle using only a fuel cell

In each category, several variants may exist. For example, the fuel cell electric vehicle can operate with a hydrogen tank or provide on-demand hydrogen supply with an on-board production of hydrogen from solid compounds such as metal hybrids.

1.2.1. Traditional ICE vehicles

According to car manufacturers and suppliers, and in all markets, the traditional car is still considered to be capable of substantial improvements in its energy consumption and pollutant emissions. Therefore, the French government assigned the ambitious goal of disposing by 2025 of vehicles consuming 2 liters of gasoline per 100 km. This objective has been formalized and raised to the rank of a project of collective interest within the Platform of the Car Industry (PFA) under the name „vehicle 2 L / 100 km and connected".

The focus is on engines. Between 2010 and 2015, the vehicles marketed in Europe saw their average consumption drop by 10 to 15%. This result is due to downsizing, thermal management of the engine, braking energy recovery and the widespread use of Stop & Start. There would still be room for it because, according to the experts, improvements of 40 to 50% would be possible. Thus Syrota[5] estimates at 30 to 40% potential gain in fuel consumption. The French Institute of Petroleum Energies Nouvelles (IFPEN) considers that the goal of 2 L / 100 km is an ambitious but achievable goal. It will also reduce the weight of vehicles. The IFPEN recalls that a reduction of 100 kg allows a reduction of CO_2 emissions of 5 g per kilometer. The ideal would be to go down to 800 or 700 kg, maybe even less.

This path seems promising: this is how at the Paris Motor Show in October 2014 Citroën unveiled the C4 Cactus Airflow 2L concept, which is expected to show a theoretical consumption of 2 liters per hundred kilometers. The vehicle uses „Hybrid Air" technology: a 3-cylinder mini-petrol engine, an energy storage system in the form of compressed air and a set of two hydraulic pump motors. Aluminum and carbon lighten it by 100 kg compared to a current small standard vehicle. It remains to prove such performances in real conditions of use, especially since all calculations were made according to standards of approvals that might be changed in the future[6]. At the same time, Renault unveiled the Eolab which displays 1 liter per 100 km.

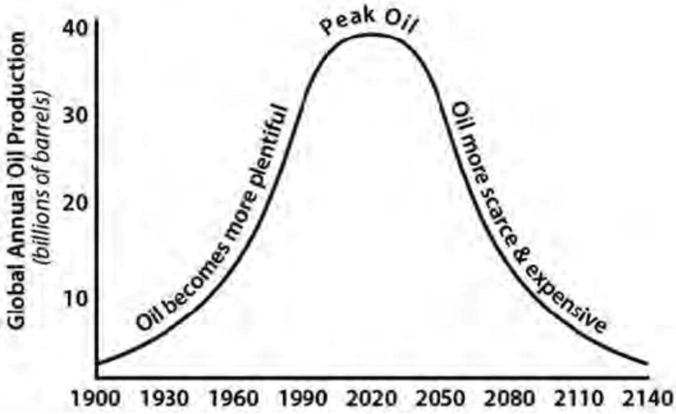


Figure 1. *The oil peak*

Several experts interviewed have indicated that such a „downsizing", if it is applied to all new vehicles in the next ten or fifteen years and everywhere in the world, thus renewing the park in its quasi-totality, either 1.2 billion vehicles

5 Syrota, J., (2008), *Perspectives concernant le véhicule "grand public" d'ici 2030*, Centre d'Analyse Stratégique, Conseil général des Mines, Paris, 28 septembre.

6 *La tribune*, 18/09/2014.

in 2014, would move back by several decades the famous „peak oil world" that no expert today takes the risk of dating (Figure 1). Especially since the exploitation of shale gas has already shown that such a retreat was possible! For now, the environmental damage associated with this hydraulic fracturing operation could well become a potential obstacle to the survival of ICE engines.

The internal combustion engine might remain the dominant technology for another few decades because of its obvious advantages, not only because it is a surprisingly efficient and highly cost-effective technology compared to the alternatives, but also because the infrastructure is universally available.

1.2.2. Advanced ICE vehicle

Not surprisingly, the advanced ICE technology is, in fact, the preferred short-term option of automobile OEMs, mainly because it induces relatively limited changes in the vehicle and the energy distribution infrastructure. The technology is available and economically viable. This option is dictated by the inertia of the technological trajectory - or path dependence - of industry as it has prevailed until now[7].

Table 2. *Key characteristics of CNG engine*

Political, social and cultural acceptability	**Factor**	**Degree of achievement**	**Current Status**	**Long Term Perspective**
	CO^2 performances	Very good	Excellent	Excellent
	Fossil fuel dependence	Total	Total	Reserve for 100 years but geographically distributed
	Infrastructure	Excellent	Different according to countries	Relatively easy and cheap to develop
Technological Possibility	Overall	Total	Total	Excellent
	Safety	Good		
Commercial vendibility	Customer acceptance	Relatively good	Still some resistance over safety	Will disappear
	Pricing	Correlated to oil pricing trend	Subsidized by governments	Might vanish
Industrial feasibility	Cost	Good	Small premium	Will vanish with economies of scale
	Engineering	Good	Good	Will improve
	Component supply	CNG kit available	Fully available	

7 Bye, P., Chanaron J.J., (1995), Technology Trajectories and Strategies, *International Journal of Technology Management*, 10, 1, pp. 45-66.

The compressed natural gas engine is obviously an attractive option since refueling could be done at home in countries where there is a national distribution network. But with respect to the greenhouse gas, this option is still problematic, even if, according to the US Environmental Protection Agency (EPA), compared to conventional vehicles, the vehicles running on compressed natural gas would lead to a reduction in carbon monoxide emissions by 90 to 97%, and a reduction of carbon dioxide emissions by 25%. Nitrogen oxide emissions can be reduced by 35 to 60%, and releases hydrocarbon emissions other than methane by 50 to 75%.

Table 3. *Key characteristics of bio-fuel engines*

Political, social and cultural acceptability	**Factor**	**Degree of achievement**	**Current Status**	**Long Term Perspective**
	CO^2 performances	Very good	Excellent	Excellent
	Fossil fuel dependence	None	None	
	Competition food / transportation	Bad	Bad	Progess in output/ ha and efficiency
	Infrastructure	Good	Good	Relatively easy and cheap to develop
	Ecology	Require genetically modified seeds	Poor	
Technological Possibility	Overall	Total	Total	Excellent
	Safety	Not an issue		
	Raw materials	Limitations	Limitations	Opening to new sources: straw, exotic plants, garbage
Commercial vendibility	Customer acceptance	Relatively good	Good	
	Pricing	Good	Subsidized by governments	Will improve with economies of scale
Industrial feasibility	Cost	Relatively cheap		Will decrease with economies of scale
	Manufacturing	New infrastructure to be built up	Under construction in Brazil, USA and Europe	Will expand rapidly in some countries

Bio fuels are also a very attractive solution in theory. But their massive deployment will require heavy investment in production facilities and the release of huge farmland. In fact, bio fuels are at the center of harsh national and international controversies and for several questions. Faced with the reduction of CO_2 emission levels and the rise of oil prices, considered unavoidable in the long term, are raised the following debates: „food against fuel „, deforestation and soil erosion, the impact on water resources. Their massive deployment will also require genetically modified plants (GMOs) to achieve high levels of productivity, which will indeed contribute to reinforce the radical political opposition to these kinds of seeds in many countries.

1.2.3. Hybrid electric vehicles (HEV)

Three families coexist: first generation hybrid vehicles, rechargeable or plug-in hybrid vehicles and extended range hybrid electric vehicles.

1.2.3.1. Hybrid technology of first generation

Since the success of the Toyota Prius, launched in 1997 and sold since to nearly 6 million units in its different versions and nearly 10 million units with adaptations across Toyota model range, the hybrid car is one of the truly credible alternatives to the classic ICE. There is already an abundant academic literature[8] discussing its well-to-wheel performance and economic and technical performances, including the reduction of CO_2 emissions.

The third and fourth generations of Prius have been commercial successes, particularly in the United States and Japan, but the European market has been below expectations. It is clear that the current technology has limited benefits in terms of CO_2 emissions and fuel consumption, in particular due to the low driving range that Toyota's batteries can offer in electric mode alone.

The technological advantage of current petrol-electric hybrid vehicles (Table 4) is lower in Europe due to the high rate of diesel penetration. But in the US, the difference in fuel consumption and CO_2 emissions is around 25-30% because of the average size of the fleet.

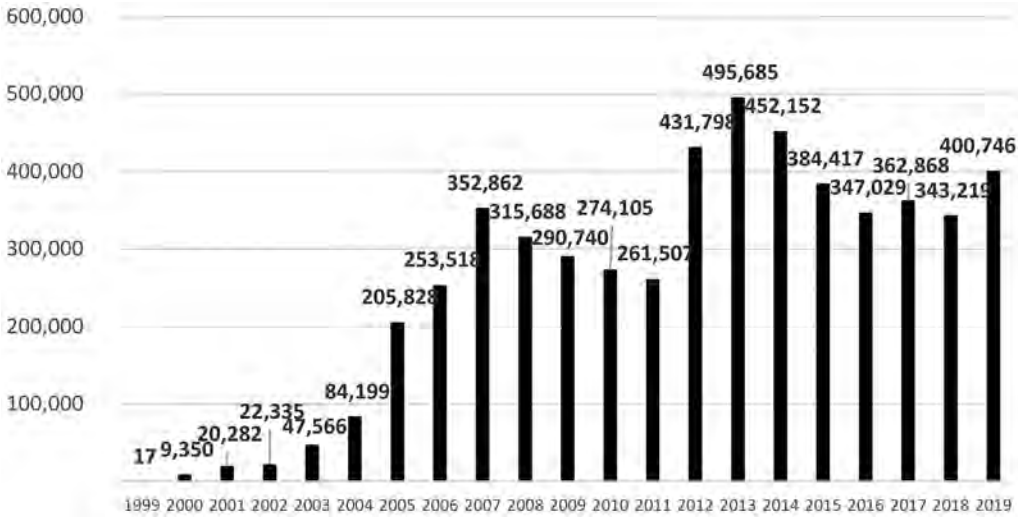
When looking at actual sales figures, especially in the United States where more than 3 million hybrids have been marketed since 1999, growth is obviously significant and should probably remain exponential for a few more years (Figures 2 and 3) and are slightly slowing down in the last three years. Still HEV sales are marginal in total new registrations, 3.2% in 2013, the record year of sales, and in the total fleet of vehicles in use.

8 Chanaron J.J., Teske J., (2007), The hybrid car: a temporary step, *The International Journal of Automobile Technology & Management*, Vol. 7, n°4, pp. 268-288; Alamgir M., Sastry A.M., (2008), Efficient Batteries for Transportation Applications, *SAE, Convergence 2008 Conference*, 20-22 October, Detroit, paper 08CNCVG-0036..

Table 4. *Key characteristics of hybrid electric vehicles*

Political, social and cultural acceptability	**Factor**	**Degree of achievement**	**Current Status**	**Long Term Perspective**
	Environmental friendship	Slightly better		Might be improved with new generations downsized gasoline engine & better batteries
	Fossil fuel dependence	High		Reserve for 40-50 years but could be extended with downsizing
	Infrastructure	Excellent	Total availability	Not an issue
Technological possibility	Overall performances	Good	Similar to current ICE	Should not change substantially
	Range/autonomy	Limited	<20km on electric drive	Lithium-Ion battery will improve
	CO^2 Performances	Limited	≤10-15% improvement	
	Fuel consumption performance	Limited	5-10% in Europe 15-30% in the US	Should improve slowly
			≤	
Commercial vendibility	Customer acceptance	Relatively weak	Customer preference for mono-energy power train	Might benefit from change in behavior
	Pricing	Relatively weak	Premium of US$2,500	Price will decrease with volumes
Industrial feasibility	Cost	Higher	>10-15%	Will decrease with economies of scale and scope
	Engineering	More complex	Under control of very few OEMs	Will improve rapidly
	Manufacturing	Easy		Electronic module is the key component
	Quality	Equivalent	Equivalent	

In a forecast exercise conducted in 2009, using data from sales of hybrid vehicles in the United States over the period 2000-2007, the forecasted sales were nearly 2 million units per year in 2015- 2016, i.e. 6 to 8% of total registrations. Looking at actual sales for 2000-2018, one can see that the increase is actually much smaller and that sales are very sensitive to cyclical fluctuations since they have been falling steadily since 2014.



Source: US Department of Transportation

Figure 2. *Annual sales of hybrid vehicles in the US*

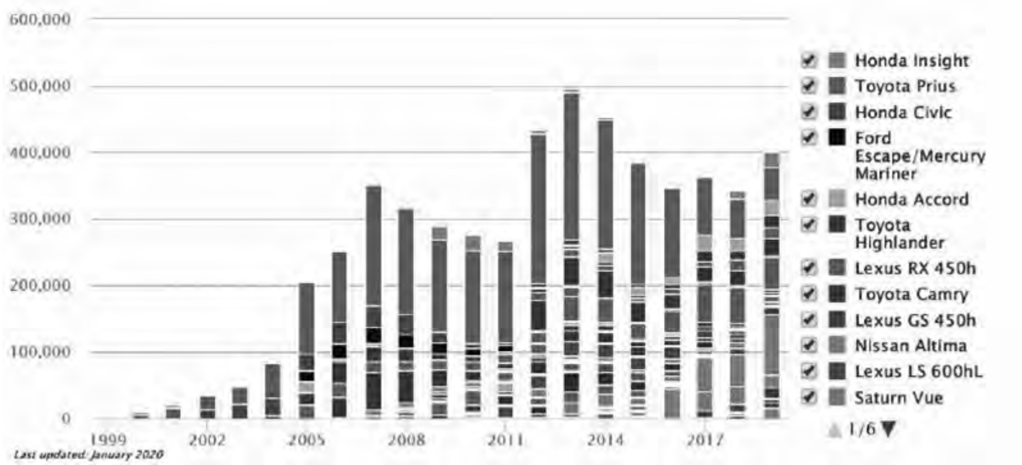
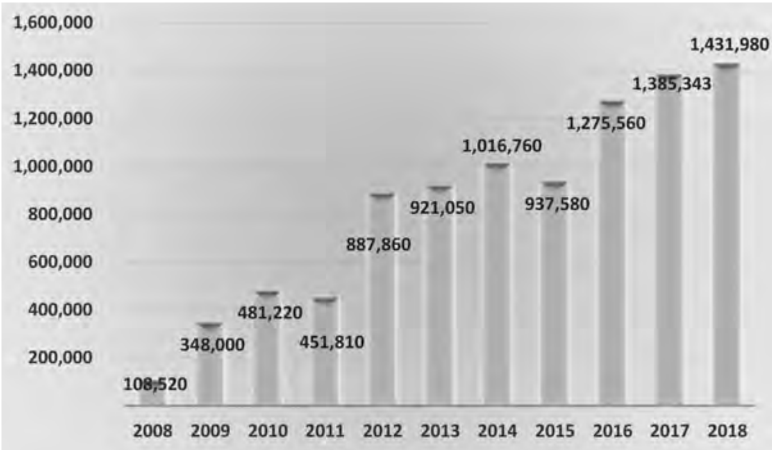


Figure 3. *Sales of hybrid vehicles in the US by model*

In Japan, where hybrid vehicles have been initially developed, annual registrations are growing significantly to reach 1.43 million in 2018. In 2014, there were just under5 million hybrid vehicles on the roads or 6.2% of the total fleet with a trend in annual registrations which is really exponential (Figures 4 and 5).



Source: JAMA.

Figure 4. *Annual registrations of hybrid cars in Japan*

Year	Hybrid vehicles	Plug-in hybrid vehicles	Electric vehicles	Fuel cell vehicles	Clean diesel vehicles	Total
2008	108,518	0	0	0	0	108,518
2009	347,999	0	1,078	0	4,364	353,441
2010	481,221	0	2,442	0	8,927	492,590
2011	451,308	15	12,607	0	8,797	472,727
2012	887,863	10,968	13,469	0	40,201	952,501
2013	921,045	14,122	14,756	0	75,430	1,025,353
2014	1,058,402	16,178	16,110	7	78,822	1,169,519
2015	1,074,926	14,188	10,467	411	153,768	1,253,760
2016	1,275,560	9,390	15,299	1,054	143,468	1,444,771
2017	1,385,343	36,004	18,092	849	154,803	1,595,091
2018	1,431,980	23,230	26,533	612	176,725	1,659,080

Source: Japan Automobile Manufacturers Association

Figure 5. *Breakdown of Next-Generation Vehicle Share in Japan, 2008-2018*

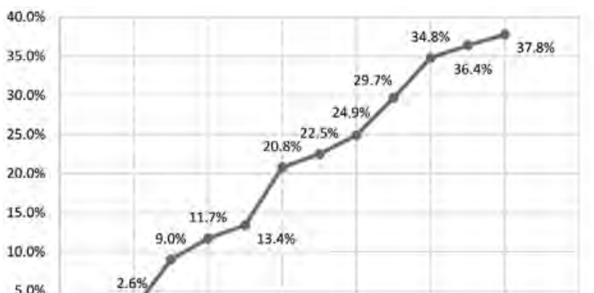


Figure 6. *Share of total clean vehicles in new car registrations in Japan*

1.2.3.2. Plug-in hybrid vehicles

Rechargeable or plug-in hybrid vehicles have the considerable advantage of being much more autonomous than the first-generation technology when running in all-electric mode. They also have the advantage of being considered by automotive industry stakeholders, including customer customers, as a first step towards all-electric battery and fuel cell vehicles. Even Toyota, which has been the true innovator of the first-generation hybrid technology, has recognized that this technology is an intermediate solution and should only last a few decades, with plug-in hybrids replacing the first hybrid models gradually, until performance of batteries or fuel cells meet all the technical and economic requirements of consumers.

While it was announced for 2009, Toyota has been forced to postpone for several years the marketing of a fourth generation Prius with a plug-in system (Table 5). With an electric autonomy of 23 km, it is available since 2012 only and represents a small proportion of sales. The best-informed specialists put forward the argument that extensive tests, particularly at the Grenoble synchrotron, on Lithium-Ion batteries did not give scientists and technicians, and therefore of course Japanese commercials, any guarantee of quality and reliability,as well as stability over time and durability.

Even if there is no doubt that their market share will increase significantly over the next ten years, it seems now clear that the most optimistic scenarios for hybrids that have made reference, considering this technology as dominant with over 90% of new registrations around 2025 will never be verified[9]. It is strongly supported hybrid solutions forecasting a market share of 8% in 2015, 20% in 2025 et 40% in 2035. And the hypothesis advocated by Syrota[10] suggesting that the plug-in hybrid is the only viable solution before 2030 now seems totally wrong. The latest Bloomberg New Energy Finance forecasts (2016) cap the registration of plug-in hybrid cars to 5% by 2025! The largest consulting firms such as IBM, McKinsey, Arthur D. Little and Gartner Group estimate an average 10% market share by 2020.

Table 5. *The four generations of Toyota Prius*

	Type	Production
First generation	Prius I (type NHW10)	1997-2003
Second generation	Prius II (type NHW20)	2004-2009
Third generation	Prius III (type ZVW30)	Since 2009
Fourth generation	Prius IV	From 2016

9 Crozet Y. (2005), Pollution locale et effet de serre dans les transports : Impacts et technologies, *Prospective 2050 des Transports*, LET-ENERDATA, PREDIT, Paris ; Heywood J., & al., (2008), *On the Road in 2035*, MIT, July.

10 Syrota, J., (2008), *Perspectives concernant le véhicule “grand public” d’ici 2030*, Centre d’Analyse Stratégique, Conseil général des Mines, Paris, 28 septembre.

It is obvious that the technological bottleneck remains the battery and the so-called „all-electric autonomy" which is the only variable likely to make a lasting and profound change in the behavior of consumers in the face of the preservation of the environment and the decrease the use of fossil fuels.

1.2.3.3. The extended range hybrid electric vehicle

This is a third option in the hybrid technology portfolio. The vehicle should operate on its power train and use a small internal combustion engine or other device (compressed air, for example) to continuously recharge the batteries. This choice was made by General Motors (GM) for the Chevrolet Volt available since 2010 (Stanek, 2008). On the battery alone, the Volt can run about 60 kilometers and 500 km with the range extension system. Volt's sales were very disappointing compared to the initial forecasts (Figure 7): 68,228 units sold between 2009 and April 2014. A little more than 9,000 Opel Ampura sold in Europe between the end of 2011 and April 2014 should be added. In a full year, such as 2016, Volt sales accounted for 0.15% of registrations in the United States! In 2018, GM sold 18,400 Volt, but at the same time, nearly it sold 1,400,000 pickups very greedy in gasoline or diesel. In February 2019, due to a massive restructuration, GM decided to stop manufacturing the Volt.

1.2.4. The all battery electric vehicle

The electric car powered by electrochemical batteries, as we have seen, predates the internal combustion engine car, but the advantages of efficiency, autonomy and costs of the latter have outweighed those of the electric car, yet largely underlined at the time: absence of vibration, smell and noise, immediate start, among others.In 1912, an electric roaster was sold for 1,750 dollars when a gasoline car was sold for 650 dollars!

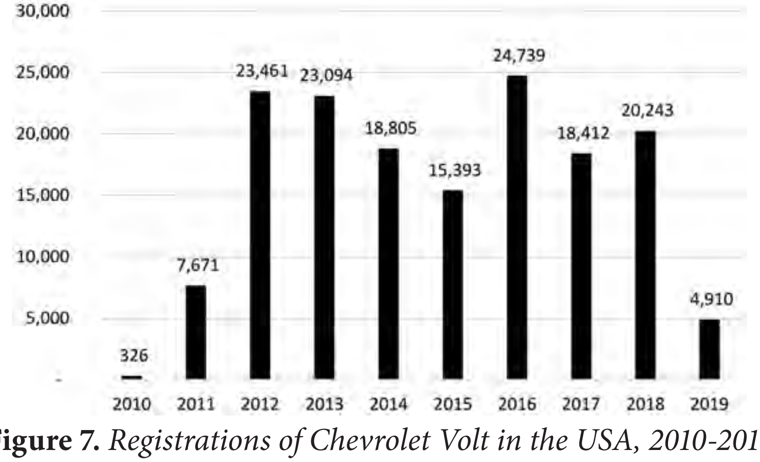


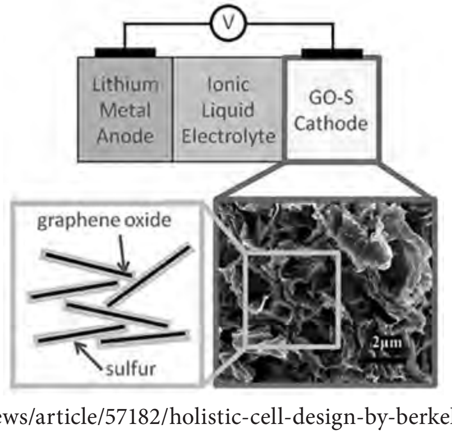
Figure 7. *Registrations of Chevrolet Volt in the USA, 2010-2019*

After a first phase of renewed interest following the oil shocks of 1973 and 1978, unfortunately too short, the pressures to significantly reduce the weight of fossil fuels and the reduction of CO_2 emissions, source of global warming, have brought back in light the all-electric traction chain with high-performance batteries. The development of lithium-based batteries, mainly driven by manufacturers of laptops and cell phones, has led to renewed interest from automobile manufacturers, led by Renault and Nissan, rapidly followed by all major competitors supported by public authorities around the world, ready to subsidize this emerging technology, as well as newcomers, such as Tesla, and public research laboratories encouraged to increase the budgets allocated to electrochemistry and new materials.

However, there are still many obstacles to the widespread adoption of battery electric vehicles. The main one seems to be the performance of the batteries, i.e. the energy density (Wh per kg), the power density (W per kg) and the number of recharge cycles. Indeed, in the current state of technology, for a tank of 36 kg of diesel (for diesel engine) to which we must add 7 kg for the tank itself, a total volume of 46 liters, it would take 540 kg of lithium-ion cells (830 kg in total with the envelopes) for a total volume of 700 liters with a vehicle with equivalent energy efficiency (measured in specific energy and density).

Obviously progress are still expected on the various lithium-based options. Researchers at the Lawrence Berkeley National Laboratory (LBNL) in the United States have recently demonstrated significant improvements in the properties of lithium-sulfur batteries, which until now had the unfortunate tendency to degrade rapidly and have a limited number – about 300 – of recharge cycles (Figure 8).

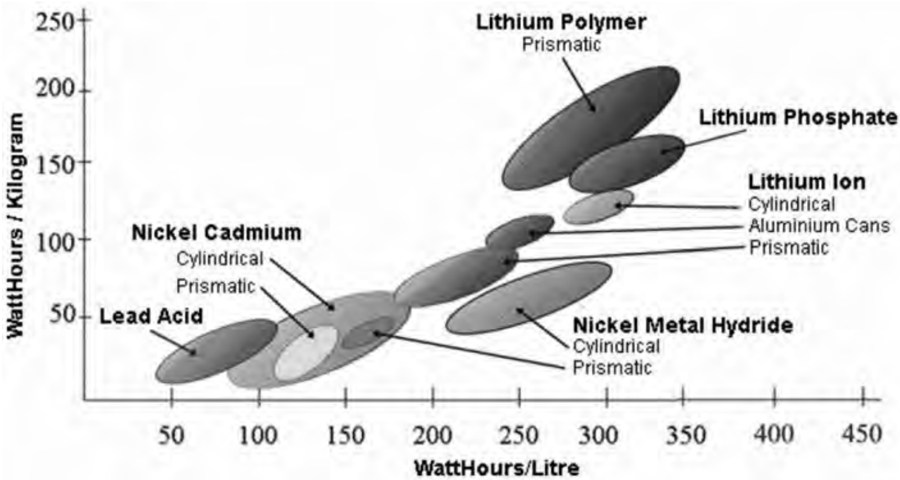
The experiment, still in at research stage in laboratory, has developed a lithium-sulfur battery that has more than twice the specific energy of lithium-ion batteries, and which lasts more than 1,500 charge-discharge cycles with minimal decay of the battery capacity. This is the longest life cycle reported so far for the lithium-sulfur battery (Figure 8).



Source : http://eetd.lbl.gov/news/article/57182/holistic-cell-design-by-berkeley.

Figure 8. *The Li-S battery from the Lawrence Berkeley National Laboratory*

According to the LBNL, for electric vehicles aiming at a range of 500 kilometers, the battery must provide a specific energy at the cell level of 350 to 400 watts-hours per kilogram (Wh/kg), which is twice the specific energy (about 200 Wh/kg) of current lithium-ion batteries. The batteries should also have at least 1,000, and preferably 1,500, charge-discharge cycles without significant loss of power or storage capacity.For a car traveling 12,000 km per year and whose battery would voluntarily be limited to an autonomy of 200 km, it would need only about 75 refills a year, or 8 years to reach 1,000 refills. It should be noted however that the transition from the laboratory stage to mass production will take several years, at least ten according to LBNL officials.



Source : Posted by MSE Supplies on Feb 02, 2016.

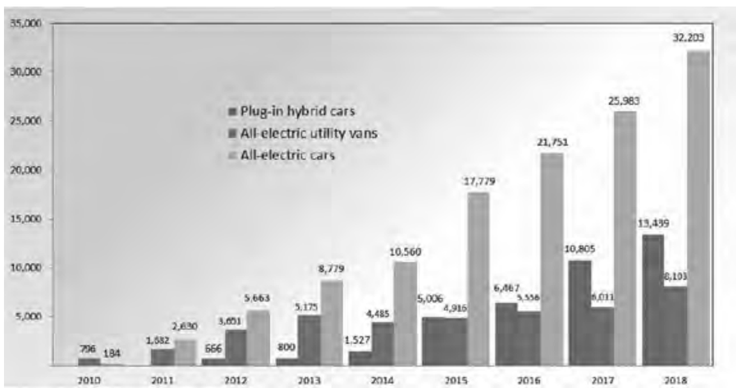
Figure 9. *Potential improvement of batteries*

In any case, research laboratories, battery manufacturers and car manufacturers are trying all means to increase battery performance (Figure 9). Renault and its Nissan partners, who were the first „big" manufacturers to offer standard battery vehicles in their range, have managed to more than double the autonomy of Renault Zoe and Nissan Leaf between 2014 and 2019. Now the Renault Zoe of 2019 has an „average" autonomy of 140 km, that the „best" drivers manage to reach 170 km but that the „less good" drivers reduce to 110 km!

Another major obstacle is the „gas-up" factor, i.e. the time needed to fully recharge the battery since partial refills can reduce its lifetime. There are now „normal" charging stations with which it takes 3 to 4 hours for a full charge. Fast charging stations, less than 30 minutes long, are being deployed on major motorway corridors in Europe. The Californian manufacturer of luxury electric cars, Tesla, is currently deploying its Tesla supercharger that recharges its S model in 30 minutes for nearly 400 km of autonomy. A supercharger can recharge about half of the battery in 20 minutes.According to its CEO, who released to have new batteries with more than 600 km of range from 2018, all S models equipped with a battery of 85 kWh can use superchargers, just like vehicles with batteries of 60 kWh. Superchargers will be positioned at strategic and convenient locations along the busiest roads throughout Europe. Superchargers are free and will remain so for model S owners.

One must also count on the social and cultural brakes which, for the moment, undoubtedly delay a more massive adoption of battery vehicles. The results speak for themselves: annual sales are still marginal: 46,000 all-electric vehicles sold in the United States in 2013 including 17,650 Tesla or 0.5% of passenger car sales. And even if the market has since then grown substantially (figure 10), this is still a very low portion of the total market and there is indeed spectacular! 245,000 cars in 2019 of which more than 80ù for Tesla.

Figure 10. *US electric vehicle sales (January-December 2019)*



Source : http://www.automobile-propre.com/dossiers/voitures-electriques/chiffres-vente-immatriculations-france/.

Figure 11. *Registrations of electric cars in France since 2010*

In France, in 2013, 8,779 private electric vehicles were registered on the year against 5,663 registrations registered in 2012. Then the progression accelerates: 10,560 in 2014, 17,779 in 2015, 21,751 in 2016, 25,953 in 2017, 32,203 in 2018 (Figure 10). This represents just 1% of total passenger car registrations (2,015,186 units) in 2016 to which we can add a little more than 5,200 light trucks, or 1.5% of total sales.

At worldwide level, according to the International Energy Agency (IEA)1,345,000full electric vehicles have been sold in 2018, of which 60,7%, i.e.815,870 units,have found takers in China. The global fleet is estimated at 3,400,000 vehicles in 2018, representing less than 0.3% of the total fleet estimated tomore than one billion vehicles.

China now stands as the world's largest market for electric vehicles, passenger cars as well as commercial vehicles, and therefore as the world's leading manufacturer. And the progression has been spectacular since 2015, partly due to sales of commercial vehicles, delivery vans and buses (Figure 12, 13 and 14).

In most countries, such sales have been "supported" by substantial public financial incentives. Without such subsidies, there is some reasons to believe that sales would have been limited to a few thousand customers, so called "early adopters" of new green technologies. In the future, it may be necessary to maintain or even strengthen public support. Observers attribute the dramatic jump of electric car registrations in Norway since the beginning of 2014, more than 12% of total sales, to direct subsidies, free tolls, free parking and ferries and the massive presence of public charging stations and to the authorization to drive in the corridors reserved to public buses.

Table 6. *International Energy Agency's EV sales data, 2005-2018*

	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Australia							0.05	0.17	0.19	0.37	0.76	0.67	1.21	1.80
Brazil								0.07	0.13	0.06	0.06	0.13	0.07	0.09
Canada							0.22	0.62	1.64	2.83	4.38	5.22	8.71	22.66
Chile							0.01	0.01	0.01	0.00	0.01	0.02	0.12	0.11
China					0.48	1.09	4.75	9.64	14.61	48.91	146.72	257.00	468.00	815.87
Finland							0.03	0.05	0.05	0.18	0.24	0.22	0.50	0.78
France	0.01	0.01	0.01	0.00	0.01	0.19	2.63	5.66	8.78	10.57	17.27	21.76	25.98	31.06
Germany	0.02			0.07	0.02	0.14	1.40	2.21	5.31	8.35	12.08	11.32	25.07	36.06
India			0.37	0.16	0.35	0.45	1.43	0.19	0.41	1.00	0.45	2.00	1.20	3.30
Japan					1.08	2.44	12.61	13.47	14.76	16.11	10.47	15.46	18.10	26.53
Korea						0.06	0.27	0.51	0.60	1.31	2.92	5.10	13.30	29.63
Mexico							0.00	0.09	0.01	0.05	0.09	0.25	0.23	0.20
Netherlands				0.01	0.03	0.12	0.86	0.79	2.25	2.66	2.54	3.74	8.63	25.07
New Zealand				0.00	0.00	0.01	0.01	0.02	0.03	0.11	0.30	1.16	2.94	4.36
Norway			0.01	0.24	0.15	0.39	1.84	4.18	8.20	18.09	25.78	24.22	33.03	46.14
Portugal						0.72	0.19	0.05	0.14	0.19	0.67	0.81	1.89	4.43
South Africa									0.03	0.01	0.12	0.10	0.07	0.07
Sweden						0.00	0.18	0.27	0.43	1.24	2.96	2.95	4.36	7.15
Thailand						0.00	0.01	0.01	0.01	0.01	0.01	0.00	0.03	0.20
United Kingdom	0.22	0.32	0.45	0.22	0.18	0.26	1.21	1.71	2.68	6.81	10.10	10.51	13.55	15.74
United States	1.12			1.47		1.19	9.75	14.65	47.69	63.42	71.04	86.73	104.49	238.82
Others	0.53			0.08	0.03	0.14	2.45	3.84	5.13	8.72	14.21	14.20	22.86	34.97
Total	**1.89**	**0.34**	**0.84**	**2.25**	**2.32**	**7.21**	**39.9**	**58.21**	**113.1**	**191.**	**323.18**	**463.57**	**754.33**	**1 345.03**

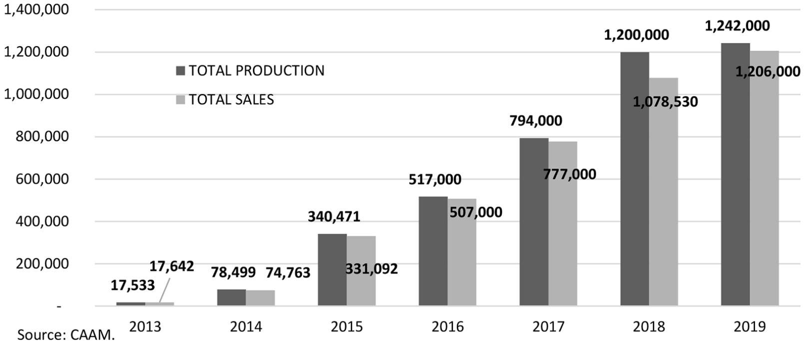


Figure 12. *Total production and sales of PHEV and BEV in China*

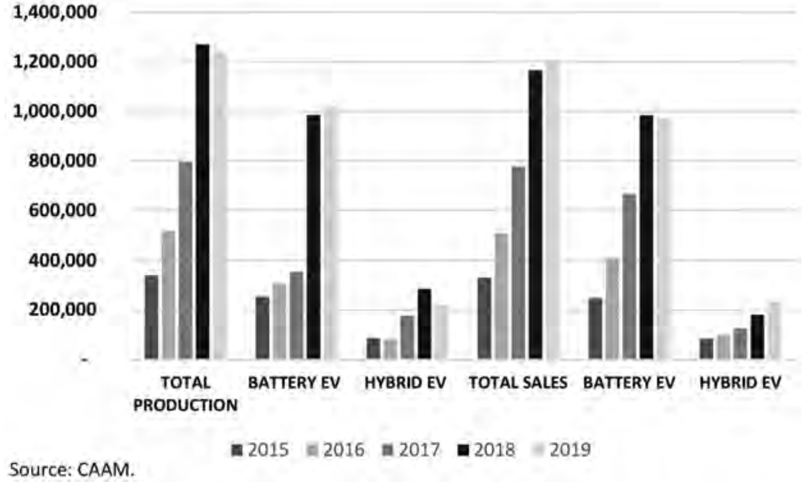


Figure 13. *Productionand sales of EV by category in China, 2015-2019*

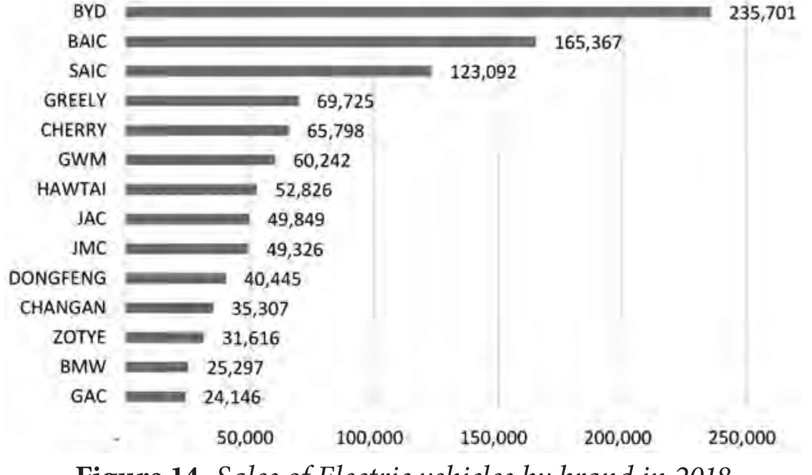


Figure 14. *Sales of Electric vehicles by brand in 2018*

In 2018, sales per brand and model are shown in figure 14.

A major unknown element for lithium batteries, rarely mentioned by stakeholders, is the availability and price of this raw material (Table 7 and Figures 15 and 16). Lithium is much less abundant than the usual alkalis and alkaline earths (Na, K, Mg, Ca) and it exists in a concentration that allows profitable economic exploitation only in very few places on earth. The price of lithium carbonate tripled between 2000 and 2013 to stabilize at $6,500 per ton. Prices then picked up again in 2015 to an annual average of $7,400, doubling over the last two months: $13,000 per ton, triggering a “startling” increase: $19,000 in January 2016 and $22,000 at the end of March 2016. At the end of 2017, the price seemed stabilized at $20,500 per ton.

Table 7. *Production and world reserves of lithium in 2019*

	Mine production		Reserves[5]
	2018	2019[e]	
United States	W	W	630,000
Argentina	6,400	6,400	1,700,000
Australia	58,800	42,000	[6]2,800,000
Brazil	300	300	95,000
Canada	2,400	200	370,000
Chile	17,000	18,000	8,600,000
China	7,100	7,500	1,000,000
Namibia	500	—	NA
Portugal	800	1,200	60,000
Zimbabwe	1,600	1,600	230,000
Other[7]	—	—	1,100,000
World total (rounded)	[8]95,000	[8]77,000	17,000,000

Source : https://pubs.usgs.gov/periodicals/mcs2020/mcs2020-lithium.pdf.
https://www.planetoscope.com/matieres-premieres/671-production-mondiale-de-lithium.html

Some experts dispute the United States Geological Survey (USGS) estimate of reserves and argue that the geopolitical situation in producing countries, especially China and Russia, can also have a strong influence. It should also be added that the recycling of lithium is possible but costly and that the quantities put on the market increase regularly with the opening of recycling plants.

It should also be mentioned that the lithium economy is structured as a very closed oligopoly:according toBusiness Week, “SQM, under the control of the multibillionaire Julio Ponce, is the leading stakeholder, followed by Rockwood, under KKR & Co fromHenry Kravis, and FMC, based inPhiladelphia”[11].

Lithium is not the only rare earth to shape the future of the full battery electric vehicle. Cobalt seems also crucial. Its price doubled in 2017 and its geopolitics is also at stake: more than 50% of the world annual production and reserves are located in the Democratic Republic of Congo in Africa, a particularly unstable region.

11 Business Week, 22/06/2012.

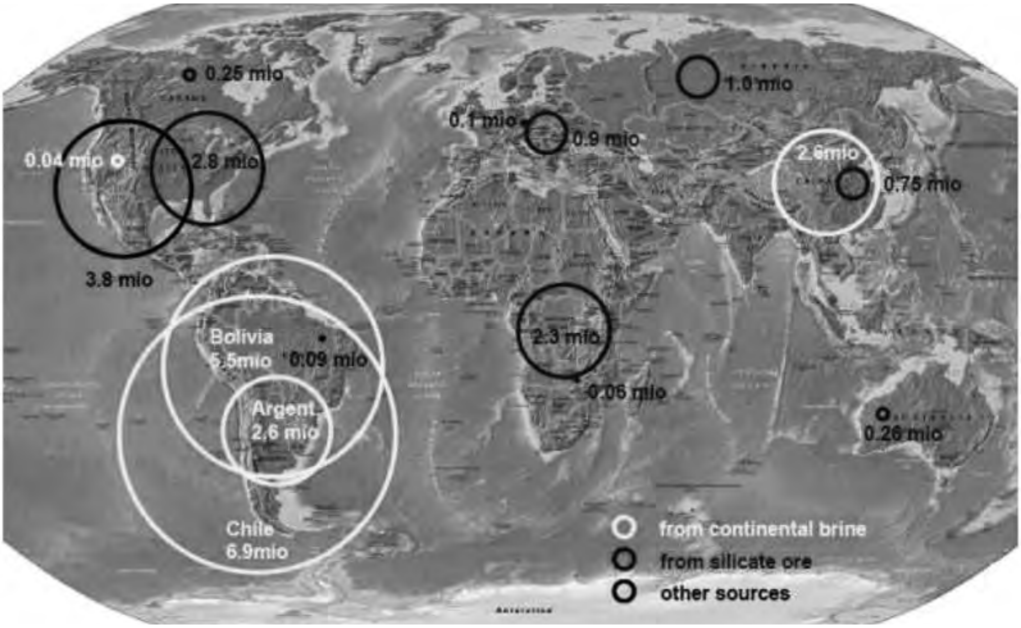


Figure 15. *World production of lithium in 2018*

Source: https://www.benchmarkminerals.com/wp-content/uploads/2019/06/Benchmark-Minerals-Lithium-Carbonate-Price.png.

Figure 16. *Evolution of the price of lithium carbonate*

On another hand, the evolution of the price of oil products is also a major uncertainty. It is worth pinpointing that the decrease of the price of crude oil at less than $45 per barrel is the main explanation of the decrease in the sales of alternative technologies in 2016 (Figure 17).

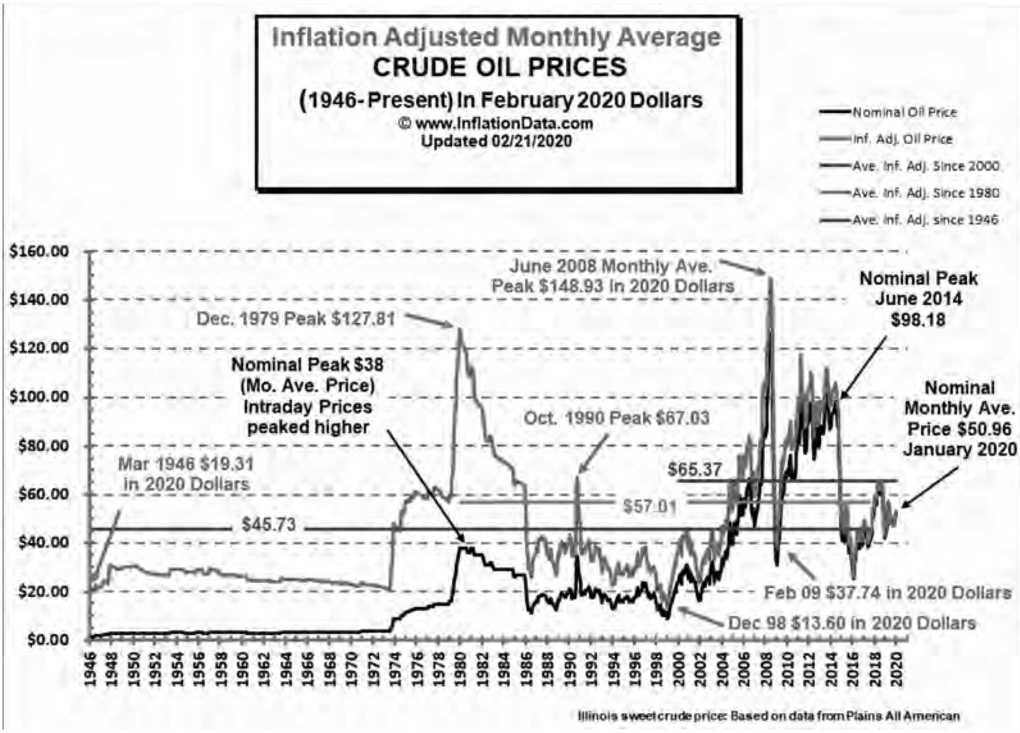


Figure 17. *Price of crude oil 1946-2020*

Last but significant obstacle: the production and distribution of primary electrical energy to power the charging stations.It is difficult to evaluate the demand for electricity in a situation of absolute uncertainty regarding short, medium and long term public energy policies, the success of the development of electric vehicles and the possible savings related to electricity consumption, etc.

An electric car that would consume 25 kWh per 100 km and drive 10,000 km a year would require 2.5 megawatt hours (MWh) a year. For 2 million electric vehicles, the annual requirement would therefore be around 5 TWh, i.e. less than 1% of the 475.4 TWh of total consumption in 2015 in France. On the other hand, between a slow recharge of 3 kW and a fast recharge of 43 kW, the power requirement is between 6 and 80 GW for all these vehicles. If 2 million vehicles were recharged quickly at the same time, they would call 62% of the national production capacity fleet. Electric cars are therefore primarily a problem of installed power.

ENEDIS, the French electricity distribution company, estimates that, for only 1 million EVs that would fill their batteries simultaneously, there will be a power demand of 22 or 40 GW, or 22% and 40% of the total available power of the French generating capacity, for respective recharge scenarios of 100% accelerated and 100% fast. According to RTE, French Electricity Transmission Network, the service company that manages the high-voltage electricity transmission network in France, there is no reason for the charging actions to be synchronous. For a fleet of 4.5 million vehicles, the contribution to the peak of the evening, would be of the order of 5 GW, or even 3 GW with an efficiently controlled energy mix.

There remains obviously the difficult question of the origin of this primary electricity: if it originates from coal or oil, the environmental interest of the electric car is reduced to nothing. If it comes massively from nuclear power, it raises issues of safety and recycling of radioactive waste, and will inevitably come up against non-negotiable political opposition.

Table 9. *Key characteristics of full battery electric vehicles*

Political, social and cultural acceptability	**Factor**	**Degree of achievement**	**Current Status**	**Long Term Perspective**
	Environmental friendship	Excellent	Excellent	
	Fossil fuel dependence	None	Excellent	
	Infrastructure	Weak	Weak	Recharging stations, national grids to be adapted
Technological possibility	Overall performances	Very poor, far from expected levels	Limited mileage autonomy	Must improve substantially
	Range/autonomy	Limited	<100-150km	Lithium-Ion battery will probably improve but alternatives should be investigated
	Durability/ Number of recharging cycles	Relatively good	Still in question for real use conditions	Must improved
	Recharging time	Long	Too long: Consumers want the ability to be able to do a quick recharge	Must improve radically
	Recharging infrastructure	Not available	To be extended Grid to be up-graded	Must be improved and expanded
	CO^2 Performances	Limited when electricity is produced from fossil fuels (oil and coal)	Poor in North America and Japan, Better in nuclear energy oriented countries	
	Energy consumption performance	Good	Good	Should improve slowly

	Technological options	Prototypes	Very few	Basic research and applied development are required
Commercial vendibility	Customer acceptance	Relatively weak	Customer preference for petrol	Might benefit from change in behavior thanks to hybrid technology
	Pricing	Relatively weak	Very high premium	Price will decrease with volumes
	Maintenance/ Repair	Good	Costly if change of battery stack required	Should be improved
Industrial feasibility	Cost	Much higher	No reliable data so far 7,000€ for 120 km range	Will indeed decrease with economies of scale and scope
	Engineering	Simpler than ICE	Under control of some OEMs and battery manufacturers	Will improve rapidly
	Manufacturing	Relatively easy	Still limited for high volume and high performance batteries	Battery manufacturing is the key element
	Quality	Equivalent	Equivalent	

According to many scientists and to the majority of industry experts, the road will be long before a power train based on high-performance batteries can really compete with the conventional internal combustion engine which will also obviously progress in energy and environmental efficiency. It will take a long time and be extremely difficult to beat gasoline and diesel.

1.2.5. The fuel cell electric vehicle

For at least three decades, the hydrogen fuel cell as an alternative to the combustion engine for the automobile has been the near-universal dream for scientists and engineers in research and development of public laboratories and car manufacturers without other tangible results than simple prototypes[12]. However, both basic and applied research continues at a very fast pace, with an increasing number of patents filed in the United States, Europe, China, Japan, and South Korea.

A fuel cell is an electrochemical device for producing electricity from a fuel (on the anode side) and an oxidant (on the cathode side), which react in the presence of an electrolyte. Unlike conventional closed-circuit batteries, the fuel cell operates in an open circuit and „burns" hydrogen. For automotive use, the hydrogen fuel cell

12 Chanaron, J.J., (1994), Perspectives de la voiture électrique : les leçons de l'histoire, Revue de l'Energie, numéro spécial Energie, Transports, Environnement, n° 463, novembre, pp. 627-635.

uses hydrogen as fuel and oxygen (usually air) as an oxidizing agent. Only water is rejected in the atmosphere.

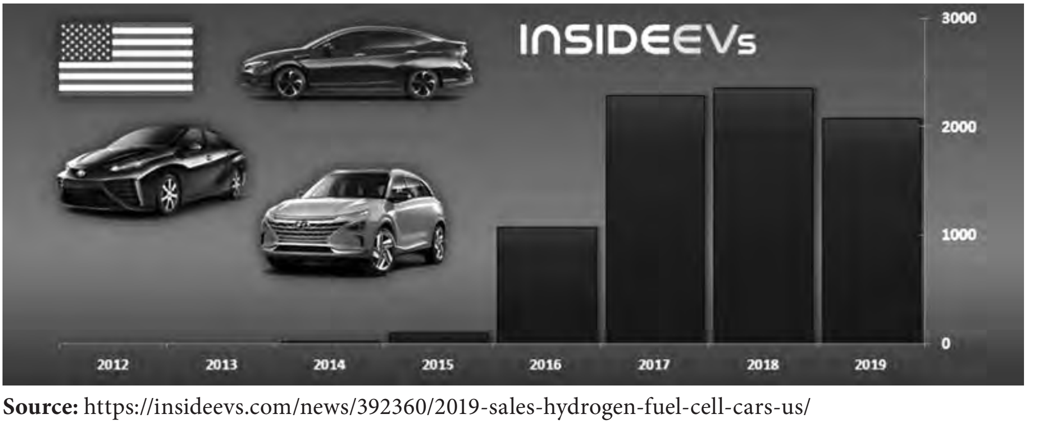
Obviously, the unit cost of fuel cells for power train, which is very high today, will gradually decrease. According to the forecasts of Daimler Benz, it could be, in the long term, a little more expensive than the internal combustion engines known as „advanced" but less expensive than the hybrid systems, because of the double motorization.

Toyota has launched on the market its first zero-emission fuel cell sedan in April 2015 in Japan, priced at 50,000 Euros net of taxes, probably with a large loss per unit, then in California and Europe[13]. Honda followed a few months later. With a little delay, they follow the Korean Hyundai that has marketed since June 2014, but in long-term lease (LLD), its ix35 Fuel Cell with 500 km autonomy for 365 Euros per month (Figure 18).

Hydrogen is a gas that is difficult to store because of its low density, high volatility, and leakage capacity through any very small cracks[14]. Its liquefaction temperature at minus 253 ° C requires a lot of energy (about 50% of the energy content). It is also a highly flammable and explosive gas, which obviously raises issues of safety of insertion of hydrogen-powered vehicles into actual road traffic.

In the current state of technology, only gaseous storage seems practicable to allow autonomy comparable to that offered by oil: it then takes a tank of 150 liters, weighing 100 kg with a pressure at 700 bar. Cost if such a tank is approximately$2,000. A pressure at 350 bars reduces the autonomy or requires a larger tank. Full-scale tests have been taking place in California since 2014 and in Europe since 2016. In April 2017, such tests with Hyundai Tucson Fuel Cell covered more than 2 million miles.

Sales of FCEV in the US are not really significant (Figure 18).



Source: https://insideevs.com/news/392360/2019-sales-hydrogen-fuel-cell-cars-us/

Figure 18. *Sales of PHEV in the USA, 2012-2019*

[13] La Tribune, 25/06/2014.

[14] Beeker, E., (2014), Y a-t-il une place pour l'hydrogène dans la transition énergétique ?, France Stratégie, La Note d'Analyse, août, n°15.

The vast majority of observers believe that the market for fuel cell cars should not really develop before 2025 as the uncertainties, or even the technological, economic and socio-political bottlenecks associated with the „hydrogen society" still prevail. Although this is often presented as the energy of the future. The main bottlenecks are associated with the price of materials, including platinum, and components such as membranes and the production and distribution of compressed or liquid hydrogen and membrane failures.

Table 10. *Key characteristics of fuel cell vehicles*

Political, social and cultural acceptability	Factor	Degree of achievement	Current Status	Long Term Perspective
	Environmental friendship	Excellent	Excellent	Very likely after 2020
	Fossil fuel dependence	None	Excellent	Perfect
	Safety	Weak	Weak due to H_2 leaks and refueling risk	To be improved
	Infrastructure	Weak	Weak	Huge need with high cost of producing and distributing H_2
Technological possibility	Overall performances	Still weak, far from expected levels	Limited mileage, high temperature, problem in cold weather, life cycle unknown	Must improve substantially
	Range/autonomy	Acceptable	<500-600km for the latest generation	Range will probably increase
	Durability/Number of refueling cycles	Relatively good	Still in question for real use conditions	Must improved
	Anode and membranes	Poor	Platinum anodes are very expensive Current membrane are not resistant enough to high temperature	Basic research and applied development are required
	CO^2 Performances	Perfect if H_2 is not produced by electrolyze from fossil fuel power generators	Good	
	Energy consumption performance	Good	30 to 50% electrical efficiency	Should improve slightly
	Technological options	On-board H_2 refining, Liquid H2	Basic research	
Commercial vendibility	Customer acceptance	Relatively weak	Customer preference for petrol	Might benefit from change in behavior thanks to hybrid technology and other electric vehicles
	Pricing	Relatively weak	Extremely high premium	Price will decrease with volumes

	Maintenance/Repair	Good	Costly if change of cell and battery is required	Should be improved
Industrial feasibility	Cost	Much higher	No reliable data available so far Platinum on anode is very expensive	Will indeed decrease with economies of scale and scope
	Engineering	Simpler than ICE	Under control of some OEMs and fuel cell manufacturers	Will improve relatively rapidly
	Manufacturing	Relatively easy	Still limited for high volume and high performance cells	Cells manufacturing is the key element
	Quality	Equivalent	Equivalent	

Sales volumes of hydrogen cars are almost confidential today. Only a little over 3,000 Toyota Mirai have been sold for the last three years, including 2,000 in Japan itself and just over a hundred in Europe. In 2017, about twenty copies will be delivered in France to business customers: Air Liquide, Engie, Plastic Omnium for its CEO, the CEA (Atomic Energy Commission) for research, STEP for its Hype taxis ... Toyota believes that by 2025, 200,000 fuel cell cars will be sold in Japan[15].

In the current state of the technologies already available on the various markets, significant progress has been made to reduce the polluting emissions of thermal vehicles. And whatever motorization is chosen! The US Environmental Agency (EPA) believes that the „Clean Air Act" voted by the Congress in 1970 giving it all power to regulate pollution from automobiles and other forms of transportation, was a huge success: for cars, the current passenger cars levels are 98-99% cleaner than those of the 1960s for most polluting emissions. Fuels are also much cleaner: lead has been eliminated and sulfur emissions have been reduced by 90%. The American cities have seen the air quality greatly improved despite the increase in the population and daily trips made. EPA standards have „boosted" technological innovations in the industry.

The EPA notes, however, that by the end of 2017, pollution generated by land transport is still responsible for fog and degraded air quality that have a negative impact on the health and well-being of citizens. hydrocarbon particles (PM), nitrogen oxides (NOx), and volatile organic compounds (VOCs). The transport sector would thus be responsible for more than 55% of total NOx emissions in the United States; less than 10% of VOC emissions; and less than 10% of PM2.5 and PM10 emissions.

It is therefore obvious that only so-called „zero emission" vehicles are able to meet a requirement of total depollution of automobiles.

* * *

[15] Challenges, 25/10/2017.

Obviously, the COVID-19 pandemic crisis which started early 2020 is not helping us in assessing what could happen to the automotive market and the competition amongst the various technological options in the coming years.

Many car manufacturers will highly suffer financially and some of them might face bankrupt. Only a few OEMs will be able to pass the crisis without changing radically their long term strategy. For most OEMs, the extremely high cost of research and development (R&D) for radical innovations such as full-battery or fuel cell vehicles will probably have to be delayed for years. Governments will also have to delay their environmental regulations and legal enforcement measures. As of April 2020, several European automobile manufacturers already agreed to applying for a moratorium of CO^2 reductions norms with the European Commission. Therefore the future of the electric automobile is questionnable[16].

Literature

- Alamgir M., Sastry A.M., (2008) : Efficient Batteries for Transportation Applications, SAE, *Convergence 2008 Conference*, 20-22 October, Detroit, paper 08CNCVG-0036.
- Bardou, J.P., Chanaron, J.J., Laux, J., Fridenson, P., (1977) : *La Révolution Automobile*, Paris, Albin Michel, coll. l'Aventure Humaine.
- Bardou, J.P., Chanaron, J.J., Laux, J., Fridenson, P., (1982): The Automobile Revolution, The Impact of an Industry, University of North Carolina Press, Chapell Hill.
- Bye, P., Chanaron J.J., (1995): Technology Trajectories and Strategies, *International Journal of Technology Management*, 10, 1, pp. 45-66.
- Chanaron, J.J. (1973) : *L'innovation dans la construction automobile*, Thèse de doctorat, IPEPS/IREP, Grenoble, novembre.
- Chanaron, J.J., (1977) : Le modèle systémique conceptuel de l'innovation de E. Mottur, in Nicolon, A., Le Véhicule Electrique, Paris Editions du CNRS, Coll. Energie et Société, pp. 107-117.
- Chanaron, J.J., (1994) : Perspectives de la voiture électrique : les leçons de l'histoire, *Revue de l'Energie*, numéro spécial Energie, Transports, Environnement, n° 463, novembre, pp. 627-635.
- Chanaron, J.J., (1998): Automobiles: a static technology, a « wait-and-see » industry?, *International Journal of Technology Management*, Vol. 16, n°7, pp.595-630.
- Chanaron J.J., (2013): Innovation Valuation: Guesswork or Formalized Framework? A Literature Review, in Akhilesh, K.B., (2013), *Emerging Dimensions of Technology Management*, Springer India, pp. 17-33.

[16] Challenges, 01/05/2020.

- Chanaron, J.J., (2014): Towards an Operational Framework in Forecasting Breakthrough Innovation: The Case of the Clean Automobile, *International Journal of Electric and Hybrid Vehicle*, Vol. 6, N°2, pp. 87-107.
- Chanaron J.J., (2014): Recent Advances on the Design of Batteries and Fuel Cells for Automobiles, *Recent Patents on Mechanical Engineering*, 7, 2, pp. 113-121.
- Chanaron, J.J., Metcalfe, S.M., (2007): Schumpeter's Innovation Theory, in Carayannis, E., Ziemnowicz C., (2007). Re-Discovering Schumpeter: Creative Destruction Evolving into 'Mode 3', MacMillan-Palgrave, New York, pp. 52-67.
- Chanaron J.J., Teske J., (2007): The hybrid car: a temporary step, *The International Journal of Automobile Technology & Management*, Vol. 7, n°4, pp. 268-288.
- Crozet Y. (2005) : Pollution locale et effet de serre dans les transports : Impacts et technologies, *Prospective 2050 des Transports*, LET-ENERDATA, PREDIT, Paris.
- De Bonnafos, G., Chanaron, J.J., De Mautort, L. (1983), *L'Industrie Automobile*, Paris, La Découverte Maspero, coll. Repères, No. 11.
- Heywood J., & al., (2008): *On the Road in 2035*, MIT, July.
- Rae, J.B., (1955): The Electric Vehicle Company: A Monopoly that Missed, *Business History Review*, 29, 4, pp. 298-311
- Syrota, J., (2008) : Perspectives concernant le véhicule "grand public" d'ici 2030, Centre d'Analyse Stratégique, Conseil général des Mines, Paris, 28 septembre.

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IZAZOVI RADIKALNIM INOVACIJAMA AUTOMOBIL ZA BUDUĆNOST
Prvi deo

Sažetak: *Automobil budućnosti je jedno od najpopularnih modernih pitanja u medijima, političkim skicama i akademskim zajednicama. Prvi članak bavi se različitim dostupnim opcijama za automobilski pogonski sklop: benzin, dizel, bio-goriva, prirodni gas, tečni naftni gas, vodonik, hibridni električni, hibridni električni „plug-in", hibridni električni proširenog dometa i na kraju potpuno baterijsko električno vozilo i električno vozilo sa gorivim ćelijama. Za svaku od opcija, rad analizira ključne karakteristike u smislu političke, socijalne i kulturne prihvatljivosti, stepena dostignuća, trenutnog statusa i dugoročnih perspektiva. Sadržaj svake karakteristike daje se kroz savremenu literaturu i intervjue sa ključnim stručnjacima. U zavisnosti od dostupnosti, prikupljeni su i podaci o tržištu koji se analiziraju i o kojima se raspravlja. Takođe se istražuju i kritički razmatraju ključni indikatori slabosti ili snage pojedinačne date opcije.*

Ključne reči: *inovacije, automobile, električno vozilo, upravljanje tehnologijom*