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Will there be enough platinum for a large deployment of fuel cell electric vehicles?

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Summary

This study focuses on the critical materials that make up hydrogen fuel cell electric vehicles. It addresses the issue of platinum, a catalyst for the electricity production reaction. All types of vehicles are considered, in order to have a broader inventory than many studies on the subject: Light Duty Vehicles, Light Commercial Vehicles, Buses, Coaches, Trucks and Heavy Trucks.

Platinum is produced in countries that show uncertain stability. The question of reserves and resources is central, and world referent agencies and companies data were used. To reach 20% penetration rate of fuel cells Light Duty Vehicles in 2050 while preserving platinum resources until 2100, it is essential to make significant progress on the platinum load per unit of power, and to encourage consumers to collect close to 100% of their fuel cells. If platinum catalyzed fuel cells are only used in buses and trucks, penetration rates can be much higher. Nevertheless, the use of fuel cells as "Range-Extenders" for electric vehicle batteries will greatly reduce the future risk of platinum supply scarcity. Close attention must also be paid to the processes of transfer of resources to reserves.

1. Introduction

In order to stabilize the CO₂ content of the atmosphere at a level of 450 ppm (parts per million) in 2050, a scenario consistent with the objective of limiting the increase in global average temperature to +2°C in 2100, it will be necessary to reduce CO₂ emissions by 80% by 2050. This objective is translated by a 95% reduction in emissions in the road transport sector [1]. It is therefore necessary to encourage the development of a new type of mobility based on electric technologies. There are currently three such technologies: Battery Electric Vehicles (BEVs), Fuel Cell Electric Vehicles (FCEVs) and Plug-in Hybrid Electric Vehicles (PHEVs).

Hydrogen vehicles use fuel cell technology, which in the case of PEMFCs (Proton Exchange Membrane Fuel Cells) require a certain amount of platinum to catalyze the reaction at their electrodes. Platinum is a rare and precious resource, and extremely critical as there is currently no other material capable of playing its role in fuel cells. Platinum is already widely used in jewelry, the steel industry, and in the automotive industry for the construction of catalytic converters (up to 100 t/year for the latter out of the 200 t/year available on the market). With the rise in individual mobility in emerging countries (China, India, etc.), a significant increase in demand for platinum for the catalytic converters is to be expected between now and 2050.

This study considers world terrestrial mobility. The 2030 - 2050 timeframes chosen for the study correspond respectively to the expected date of the "take-off" of the FCEV market and the deadline for several de-carbonization targets set by governments.

2. Literature

a. A large deployment of FCEVs is foreseen in the future

FCEV deployment prospects are rather ambitious in many projects. The market shares are of 16 to 40% in the French PROTECH2 [2] and HyFrance3 [3] projects, 5 to 50% according to Hydrogen Mobility Europe [4], up to 66% according to Dogan Keles et al. [5] and even 80% for the European HyWays project [6] (values given for 2050). Forecasts for the years 2030-2050 indicate that the demand for hydrogen electric vehicles will continue to grow. It is due to lower costs, optimization of the energy consumed, extended range and the multiplication of hydrogen refueling stations [7]. The USA, mainly California, Japan and Europe are the most ambitious regions in this field. In addition, FCEVs need to be adopted by consumers. Their acceptance depends on positive consumer attitudes towards the vehicles. Many studies show an increasingly positive acceptance of FCEVs. The confidence in vehicles in terms of safety is very high, above 75%, and has been growing for the last ten years [8, 9]. The development of the infrastructure, and more specifically the stations, is also very positively perceived [10, 11]. The acceptance reaches 66% for a location in the neighborhood of the respondents [12]. And by including external costs, economic benefits of the FCEV were highlighted as well as the generation of positive social net present values by C. Cantuarias-Villessuzanne et al. [13]. Thus, all parameters seem to point towards a massive deployment of FCEVs by 2050.

b. The issue of platinum availability is known, but not really analysed.

In general, the degradation processes of the fuel cells' performances continue to be analysed in depth [14], including the impact of vehicle driving cycles [15]. The platinum fuel cell catalyst remains a central issue in many studies. But they are mainly oriented towards the cost of cells, rather than on the availability of this material itself, as the main obstacle to manufacturing PEMFC at reasonable prices [16, 17, 18]. And authors and organizations highlight the progress made in platinum content and the inevitable technological breakthroughs to come [19].

If the issue of material availability seems to be increasingly present in the literature, this aspect remains marginal. As early as 2004, R.J. Spiegel assessed the issue of platinum reserves on the deployment of FCEVs, but concluded that the influence of this problem was very minor [20]. However, he based his assessment on the very optimistic USGS (United States Geological Survey) data and did not distinguish between reserves and resources. He also considered the (very ambitious) DoE target of 12g Pt for a 70 kW vehicle in 2010 (actually, it is twice as much in 2020) and a recycling rate close to 100%. But above all, only vehicles on American territory were considered, and the sales scenarios were limited to a few million vehicles by 2030, which explains the very optimistic conclusions. C Sealy [21] published in 2008 a global synthesis of the problems that platinum cost and availability could pose for the development of FCEV vehicles. The main points to note are the importance given to recycling, particularly with regard to cost. He pointed out the fact that supply problems will not be seen in the short term, and that an alternative to platinum will one day have to be found if FCEV development is to take place over the very long term. Chi-Jen Yang [22], who analyzed the influence of a possible platinum crisis on FCEV deployments, believes that governments should prioritize R&D to decrease platinum usage over the search for catalysts other than platinum. Boudreau et al [23] have addressed the problems associated with the production of fuel cell vehicles and a limited supply of platinum. If a global market for FCEVs develops, he concludes that a maximum of 15% penetration of FCEVs in the automotive market is conceivable. The study published by Y. Sun, M. Delucchi and Joan Ogden in 2011 [24], is the closest to our problem. In particular, Fig. 1 shows the evolution of platinum charges over time.

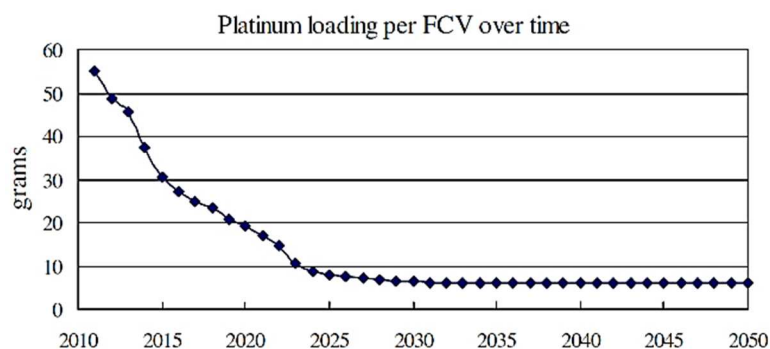


Fig. 1. Projected changes in platinum loads (g/FCEV) as a function of time [24].

According to them, using historical data and a scenario for platinum recycling, for a scenario where FCEVs reach 40% of light-duty vehicles (LDVs) by 2050, the increase in platinum price would be about 70% over the current one. Total demand for platinum would not exceed 600t/year in 2050, three times the current demand. According to the International Platinum Association they cite, there would be "enough accessible reserves to increase supply to 5-6% per year for the next 50 years".

On the geologists' side, Gavin M. Mudd [25] carried out a detailed assessment in 2012. For each company and for each PGE (Platinum Group Elements) production location, there are disagreements between geologists on the long-term availability of platinum. According to him, in the decades to come, the questions will be economic, environmental, social and political, but certainly not geological. These observations are shared by Bonnie J. Glaister and Gavin M. Mudd, in a study [26] which deals with the environmental consequences of platinum extraction, mainly in terms of electricity consumption.

c. At the same time, substantial R&D is undertaken for platinum-free or other catalyst fuel cells

ACAL Energy has developed "low-cost" PEMFCs that use an aqueous cathode technology (ACAL Energy FlowCath®) that avoids the problems of cell durability [27, 28]. Rajesh Bashyam and Piotr Zelenay [29] have developed a new type of nanocomposite: "non-precious metal/heteroatomic polymer" (e.g. cobalt-polypyrrole) catalyst for the cathode. This nanocomposite is capable of combining a high oxygen reduction performance and good durability (the effects of stabilizing the non-precious metal in the acid environment of the cathode, and of developing new active reaction sites). Finally, the CEA is involved in research into alternative catalysts, in particular the Laboratoire de Chimie et Biologie des Métaux, IRaMiS (CEA Saclay) and a team from LITEN (CEA Grenoble). The latter have combined nanoscience and bio-inspired chemistry to develop a material capable of catalyzing without platinum. This result, a major step towards a more competitive hydrogen economy, was published in the journal Science [30]. In 2015, a fuel cell without noble metals ("bio-inspired" catalysis) was also developed by the CEA [31]. The efficiency of hydrogenases is also being analyzed [32]. Also, high temperature fuel cells, SOFCs (Solid Oxide Fuel Cells), which operate at around 700°C, or even lower today, and can thus do without Platinum, may represent a major alternative to PEMFCs, but are not planned for mobility uses. Already widely used in Japan for stationary domestic needs [33, 34], they are the subject of intensive research at the CEA. This has led to significant progress on materials and costs and to the development of the reversible use of this type of fuel cell, allowing this same component to also play the role of electrolyzer [35, 36].

d. The platinum market and its risks

Johnson Matthey [37] provides a comprehensive database of platinum demand, production and recycling on its site. Bullion Vault [38] is also a very comprehensive source, constantly updated. Since 2014, a regular global supply and demand of around 250 tonnes per year can be observed. The preponderant shares are occupied by autocatalysis (catalytic converters in Johnson Matthey's definition), (34%), and jewelry (24%). Industrial use is ca. 28% and investment ca. 13% (values in 2019), but the later may vary substantially from one year to another.

It should be noted that according to K. Cullbrand and O. Magnusson [39], autocatalysis accounts for about 40% of current global demand. This is a rather minor component in terms of the mass of critical materials used in the manufacture of land vehicles (3%) but is not negligible in terms of cost (ca. 300\$/vehicle).

Annual world production is around 200 tonnes, essentially in South Africa (75%), Russia (12%), Zimbabwe (9%), Canada and USA (4%) [40]. The remaining 250 tonnes of demand comes from recycling.

The qualification of the criticality of a material is an extremely complex process, and critical metals are generally defined by the two criteria of: Economic Importance (EI) and Supply Risk (SR) [41, 42, 43]. The EI criterion is a function of the material utilization rate in a given economic sector, the value added in that sector and the difficulty of replacing the material in question in economic terms. The supply risk (SR) is mainly based on the availability of the substitute in sufficient quantities, on its possible criticality. In a 2020 European report [44], the criticality of platinum supply is qualified as moderate. This material is mainly present in technologies such as fuel cells, drones, robotics and ICT (Information and Communication Technologies).

3. Objective and Scope of the study

The literature is rather poor in terms of analysis of the availability of platinum in the coming decades in case of massive deployment of FCs using it as a catalyst. It is rather the cost issues that are addressed. It is mainly scattered data and results that are provided, with no real vision of temporal evolutions, and even less in connection with diversified policies of exploitation of this limited resource. Finally, a large part of this literature displays, which is very good, a great confidence in the research for an ultimate reduction of the platinum content and the development of a Pt-free catalysis, but the quantified reasons for such researches are not developed.

In contrast, this study aims at realizing a first synthesis of the availability of platinum by considering both the scenarios of fuel cell deployments, and the conditions of its availability. The objective is to provide an overview of the present and future availability of platinum for the mass deployment of hydrogen fuel cell vehicles using this material as a catalyst, bearing in mind that this resource is non-renewable and limited. It is therefore necessary to link this availability to the scenarios of mobility developments in the decades to come. On the one hand, a distinction will be made between the various types of vehicles that may be concerned, whereas most analyses are limited to LDVs. On the other hand, the evolution of the world's platinum resources over time will be observed by considering various policies for their exploitation.

Furthermore, this study will not cover all application areas of fuel cells, it can be shown that this is not necessary.

The PEM (Proton Exchange Membrane) electrolyzers can be eliminated from this platinum-focused study. According to P Millet [45], there is approximately the same amount of platinum per unit area in PEMFCs and PEMs, to within 10 or 20%. There is approximately 0.5 mg/cm² of platinum at the cathode and 1-2 mg/cm² of IrO₂ at the anode in a PEM, 0.05-0.1 mg/cm² of platinum at the anode and 0.5 mg/cm² of platinum at the cathode in a PEMFC. When considering the entire hydrogen chain, production and consumption efficiencies, as well as the life and usage times of the systems (for instance 1kg of hydrogen produced in a PEM electrolyzer and used in a fuel cell), there is no need to take into account the usage of platinum in PEM electrolyzers compared to the consumption of platinum in PEMFCs, the ratio being at least 10.

Forklift trucks, wheelchairs and nomadic systems were also not included in this study. Indeed, considering the number and renewal of forklift trucks worldwide [46], as well as their average power (70 kW [47]), the annual requirement is around 21 tonnes of platinum (hypothesis of 0.3g Pt/kW - Platinum load required to ensure a 5000h lifetime for the PEMFC) if the entire new fleet is fully equipped with PEMFCs. If the number of wheelchairs in the world [48, 49] is 100 times higher than in France (population ratio), the annual renewal requirement for a world fully equipped with fuel cells would be around 1 tonne. But the renewal of "nomadic" applications (laptops, tablets, smartphones) may be more critical: for a world population of 9 billion people in 2050 each equipped with an application [50], with a 3-year lifetime per system, 3 billion devices must be produced per year [51]. Assuming a dimensioning value of 100W/apparatus [52], if 20 to 50% of the fleet is equipped with fuel cells, the platinum requirement will be 20 to 50 t/year. Thus, attention should be paid to this market, even if it is not considered in this study.

4. Platinum Demand Scenarios

4.1 Current Markets

The determination of platinum demand is based primarily on data from Johnson Matthey [53], a comprehensive database of platinum demand, production and recycling. This database is consistently referred to in the many studies that deal with platinum. The respective primary and recycling supplies proportions are 75% and 25%.

On the basis of the 4 main sectors identified, Industry, Mobility (auto catalysts), Investment and Jewelry, hypotheses for the evolution of the markets concerned have been formulated until 2050. It is very difficult to forecast such evolutions, as future geopolitical contexts can fluctuate extensively. Linear evolutions assumptions seemed to be a relevant choice, and therefore the world demand for platinum should rise from 250t/year in 2015 to ca. 450t/year in 2050.

To these already active markets will be added those of mobility, potentially much larger if a fleet of fuel cell vehicles is developed. The platinum for FC should then replace that of catalytic converters, but not eradicate its use. Reuters [54] announced in 2018 that the volume of platinum used in fuel cell cars could be reduced to "micro levels" within three years (i.e. 2021) and totally eradicated in a decade, which is too optimistic. The variables to be considered for such an exercise are the annual production of FCEVs according to one or more determined scenarios, the quantity of platinum per FCEV, the lifetime of the fuel cell contained in the vehicle, the possibilities of recycling platinum after use of the cell, the total annual demand for platinum, and the supply capacities.

4.2 Future Markets

The land vehicle fleets diversity and deployment projections, as well as the current and future platinum content of these vehicles (catalytic converters and PEM fuel cells) are the key data to be assessed. The resources, reserves and performance of recycling methods will then make it possible to define the supply required to meet this demand.

The four types of vehicles identified and studied are: LDVs or Light Duty Vehicles (private non-commercial vehicles), LCVs or Light Commercial Vehicles (less than 3.5t), THTs or Trucks and Heavy Trucks, and BCs for Bus and Coaches.

A frequently used method for vehicle fleet projections considers the population data and projections of the US-DESA [55] (US Department of Economic and Social Affairs), for each year from 2010 to 2050, combined with the expected evolution of the global motorization rate. The method used is a mix of prospective data from the IEA (International Energy Agency) Energy Technology Perspectives (ETP) 2015 [56], generally based on LVDs alone, and current data and past trends from the OICA (International

Organization of Motor Vehicle Manufacturers), which for its part considers all vehicle categories. Thus, for vehicles other than LDVs, projections are made in line with the IEA projections for LDVs, based on past trends for all categories of the OICA fleet.

4.2.1 Evolution of the various vehicles' fleets

Fig. 2 shows the scenario for the evolution of LDV motorizations by 2050 according to the IEA's ETP 2015.

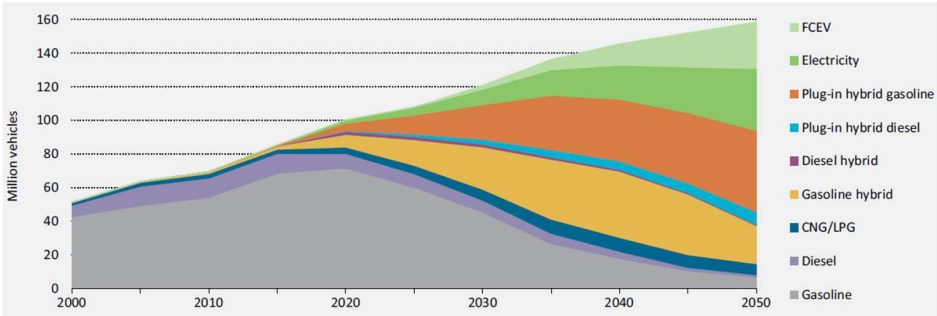


Fig. 2. Global portfolio of technologies for LDV (ETP 2015 scenario 2DS) [56]

160 million LDVs will be sold in 2050. Conventional vehicles consuming hydrocarbons are represented by ICEs (Internal Combustion Engines). This includes all hybrid vehicles with a petrol or diesel base, vehicles powered by CNG (Compressed Natural Gas), and vehicles running on LPG (Liquefied Petroleum Gas).

The Fig. 3 results were obtained by combining recent global trends in the light-duty vehicle (LDV) fleet provided by the Paris-based OICA with IEA projections of the LDV fleet to 2050. It is assumed that the proportions between each of the vehicle types are assumed to remain the same as today. This race for "green mobility" will lead to a drop in consumption and recycling of catalytic converters and particle filters, in favor of a massive demand for fuel cells.

Fig. 3 summarizes the evolution of each of the 4 fleets: LDV, LCV, THT and BC.

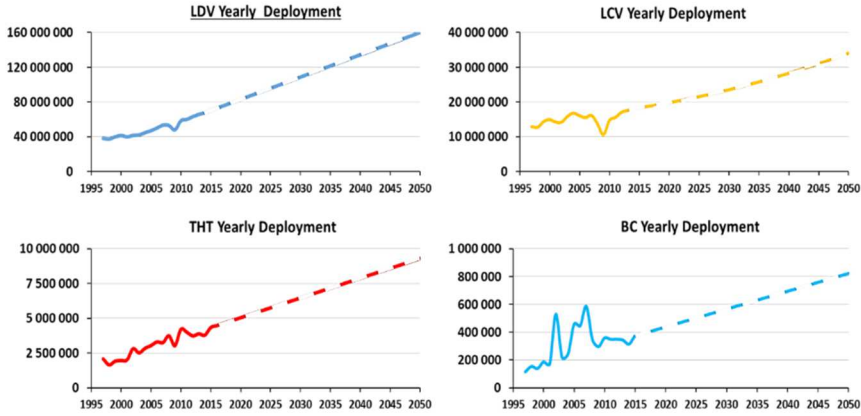


Fig. 3. Global fleet balance sheets by vehicle type, based on a combination of IEA LDV forecasts and OICA fleet histories.

All these values lead to a total sales market of 200 million land vehicles in 2050. This is the primary source of demand for platinum at that date.

4.2.2 Vehicles' power

The census of LDV-type FCEVs currently on the market leads to an average power of 100 kW [57]. The DoE [58] proposes a slightly lower value of 80 kW, but the value of 100 kW is a reasonable dimension.

Precise summary data are not available for LCV fleets, which include vans and SUVs, and whose average power has been estimated at 150 kW. According to a study published in 2014 [59], the power of a fuel cell bus is 186 kW gross and 160 kW net. An average power of 175 kW has been chosen for PEMFCs, as confirmed by the FuelCells website [60], which lists all hydrogen buses in the world [61]. The site lists more than a hundred such vehicles from the 1990s to the present day. Concerning THTs, based on the specifications of recent hydrogen-powered heavy goods vehicles, an average power of 300 kW has been selected.

4.2.3 Platinum Fuel Cell Charging by Vehicle Category

The platinum loading requirements for FCs are different for small (LDV, LCV) and large (BC and THT) vehicles, depending on the required service life and usage patterns.

- Light Duty Vehicles (LDV) and Light Commercial Vehicles (LCV)

While the aim is to minimize the amount of platinum, insufficient platinum content will lead to a diffusion into the adjacent matrices of membrane and GDL (Gas Diffusion Layer), reducing PEMFC performance. For an LDV, the amount of platinum that currently optimizes PEMFC performance is 0.3 gpt/kW [62], a value that ensures the vehicle's service life (5000 hours). Thus, if the study by Y. Sun et al [26], as well as other studies, predict a decrease in platinum loading per vehicle from 30 gpt/vehicle in 2015 to 7 gpt/vehicle, or about 0.1 gpt/kW in 2030 and stable until 2050 (Fig. 1), this will be one of the elements of optimistic scenarios for this study. As the architecture of LCV vehicles is more or less the same as that of the LDVs, the same platinum loading value of 0.3 gpt/kW is given.

- Buses & Coaches (BC), Trucks and Heavy Trucks (THT)

This category of vehicle differs significantly from LDV and LCV in terms of platinum load, for reasons of use: average speed, maximum speed, inertias, and mainly service life. B. James et al [63] have accurately analyzed the platinum load and cost structure of fuel cell systems. The value of 0.719g Pt/kW is advanced, which is more than double the loading of the LDV and LCV. For the THT, the assumption is that BC and THT have an identical platinum load.

The reduction in the platinum load for this type of vehicle remains in our assumptions limited from 0.7 to 0.5 gpt / kW, because THT and BC have much greater operating time constraints than those of light vehicles: 25,000 hours instead of 5,000 hours.

5. Platinum Offer and Recycling

5.1 Resources and reserves, and integration of resources into reserves

The world's platinum supply is divided into two categories, reserves and resources. It is important to distinguish and qualify these two notions, as the way in which resources are integrated into reserves can upset the results of the scenarios.

Resources are platinum deposits with a concentration of natural solids in the earth's crust in such form and quantity that economic extraction is currently or potentially feasible. The location, concentration, quality and quantity are known or estimated from specific geological data. Reserves correspond to the known quantities of platinum that are recoverable using current technical means in an economically viable manner, particularly in terms of operating costs and subject to there being sufficient quantities. This does not imply that extraction facilities are in place and operational. Resources are much more difficult to define and estimate, are sometimes referred to as "geological fiction" [64], and may be underestimated or overestimated while reserves are quantifiable and real.

The databases are those of the USGS [65] and those published by mining companies [66]. A public report by BRGM [67] compares and synthesizes the results, and other databases such as Statista [68] are also useful but do not allow to go back to all sources. For example, according to the USGS, the world's PGM (Platinum Group Metals) resources are estimated at over 100,000 tonnes. While the resource estimate is broadly in line with that of BRGM (83,000 tonnes in 2012) and mining companies (93,000 tonnes in 2012), reserve estimates vary significantly from one source to another: 69,000 tonnes for Pd and Pt reserves according to the USGS, vs. 15,000 tonnes according to BRGM and mining companies, including about 8,000 tonnes of Pt.

The databases distinguish between resources and reserves, but not all of them. It is very important to make this distinction, because while the reserves are easily known and exploitable, they will not be sufficient to cover all future needs, as the calculations will show. Therefore, new mining of identified deposits needs to be planned in order to make the use of the platinum contained in the resources practical. This is called integration of resources into reserves.

The basic assumption of 8,000 tonnes of platinum reserve, a quantity immediately exploitable subject to sufficient mining production, is chosen because it is prudent. The value of 45,000 tonnes of platinum resource is half of 90,000 tonnes (the average of estimated resources) since the quantities of Pt and Pd are generally similar. A scheme for the integration of resources into reserves is constructed. Jingshu Zhang [69] estimates that the mining industry may be able to increase its production by up to 4% / year. Hocquard C. [66], for his part, estimates that this growth can reach 15%/year. The effort to develop resources will depend on demand and its degree of urgency, which is why 6 scenarios have been analyzed for the integration of resources into reserves. A « progressive » integration scenario and a « sinusoidal » integration scenario (12-year periods alternating fast and very slow integration), so that the resources are exhausted in each case in 2050, 2075 and 2100: Fig. 4.

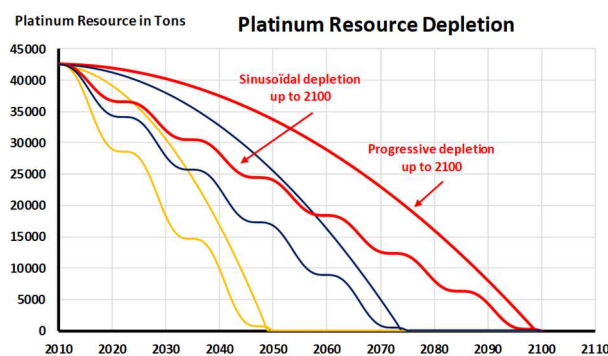


Fig. 4. Platinum resources depletion scenarios, up to a complete depletion in 2050, 2075 and 2100, and following a progressive and a sinusoidal scenario.

« Sinusoidal » integration is similar to economic cycles given in the literature, over a twelve year period, in which periods of sustained growth (expansion, high demand) follow periods of much more moderate growth or crisis (contraction) [70, 71, 72]. This results in accelerations and decelerations in the pace of resource flows into reserves.

5.2 Platinum recycling

Platinum recycling is a key variable for the FCEV integration scenarios. The recycled platinum market is called "secondary reserve" [66], which is why platinum recycling is built into our model and into all our scenarios.

Two fields of recycling are identified: that from conventional sectors (jewelry, industry and autocatalysis), and that from FCEV fuel cells. The first type of platinum recycling is based on data from Johnson Matthey which extends from 1982 to the present day. In the model, the "rate of platinum recycled" is a variable

that combines; the "platinum collection rate", the "platinum recycling rate", the "fuel cell lifetime" and the "fuel cell replacement rate over the life of the vehicle".

State incentives and laws will in the future determine the collection rates of platinum from fuel cell vehicles. These rates will be more easily applicable to utility and commercial fleets (LCVs, Heavy Trucks and Buses) since these vehicles will be in the hands of professionals who will be highly incentivized to recycle their end-of-life vehicles. This is why it is legitimate to consider a "basic" collection rate, 60%, and a very high collection rate, of the order of 95 to 100%, for all types of vehicles. It will show the influence of the increased rate. The "basic" collection rate of 60% corresponds to what is observed today in terms of overall reuse rates for platinum and palladium, after collection and recycling [73]. The recycling rate of platinum from a fuel cell is already very high: from 90 to 95%, mainly due to the design of the substrate and the matrix, as well as the sufficiently high load. A lower platinum load, as envisaged by DoE, can make recycling more expensive and less efficient.

Finally, with regard to the lifespan of vehicles and fuel cells, the calculation tool distinguishes between these two parameters, which makes it possible, for example, to consider vehicles for which a FC must be changed during the lifespan.

6. Scenarios and Results

All the data, parameters and models were integrated into an Excel tool built for this purpose. This tool evaluates the availability, and the upward and downward evolution, of platinum as a reserve in 2050, based on resource depletion dates assumptions. Indeed, constructing scenarios of vehicle fleets beyond 2050 seems risky because within 30 years, several technological breakthroughs may have taken place, and anyway one cannot envisage a single resource depletion horizon in 2050.

A limited number of scenarios are presented here to show the major trends and the impact of the main parameters. The scenarios and assumptions consider the way in which resources are integrated into the reserves, the expected progress on platinum charges, the rate of vehicle recovery before recycling fuel cells, the type of vehicle concerned by this technology, and the importance of the choice of powertrain architecture.

7.1 Scenario without PEM FCEV deployment

This baseline scenario assesses the impact on reserves (around 8000 tonnes) of conventional sectors consuming and recycling platinum alone, with and without the provision of resources. No deployment of PEMFC fuel cell vehicles is envisaged: the option that integrates the resources (45,000 tonnes) in a linear and complete manner between 2010 and 2100, allows the reserves to still be positive in 2050, and to grow until 2100. Without integration of resources, platinum will run out as early as 2045 due solely to the development of current markets.

7.2 PEM FCEV deployment of LDV only

This is very often the only case studied in the literature. A first scenario considers a sales rate value of 20% in 2050, which leads to 14.2% of PEMFCs in the total vehicle fleet by that date. 32 million FCEVs will be produced in 2050, with the total worldwide fleet of FCEVs reaching 355 million by that date. The current platinum reserves are available immediately and the resources are made exploitable following a sinusoidal then linear regression from 2010 to 2100: Fig. 5.

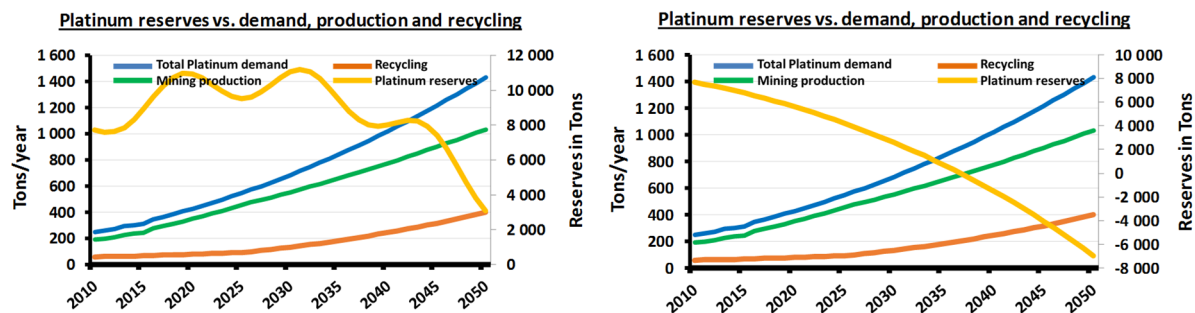


Fig. 5 - Evolution of Platinum reserves by 2050, with full sinusoidal (left) and linear (right) integration of resources up to 2100, given 60% collection rate and no progress on PEMFC platinum charge (0.3g/kW).

As noted in all the case studies, linear integration of all resources up to 2100 is more penalizing in 2050 than sinusoidal integration: platinum reserves may be in deficit by 7,000 tonnes in 2050 in the case of a progressive (linear) integration. This scenario is clearly not viable in 2050, unless there is a 2035 mid-term milestone and a sinusoidal integration. With a sinusoidal integration, the reserves decrease but remain positive (3 000 tonnes) in 2050.

A new assumption considered an evolution of the platinum load from 0.3 g/kW in 2010 to 0.1 g/kW from 2030, and staying at this level until 2050, and a 90% FC collection rate (assuming an adequate state incentive for example). The reserves increase up to 12 000 tonnes in 2050. It can be seen that these more restrictive assumptions significantly modify the risks of platinum shortages, provided that a sinusoidal integration of resources is preferred. Moreover, the demand for platinum for hydrogen-powered LDVs would no longer be the majority of the total market, being limited to 40%, but the demand for all vehicles would represent two thirds of the total market.

A much more dynamic scenario, which would consist in achieving 60% of LDV sales in fuel cell vehicles (which would then represent 43% of the total rolling stock) would require an objective of total integration of resources in 2075 and not in 2100, in a sinusoidal manner. Therefore, in 2050 there would still be a level of reserves close to that of 2015 (7,500 tonnes), albeit a decreasing level.

7.3 PEM FCEV deployment of LCVs alone

With an average power of 150 kW, the total number of LCVs is, and should remain, 3 to 4 times lower than that of the LDVs. It is quite realistic to envisage very high penetration rates for the deployment of LCVs alone, driven by professionals. Thus, a sales' penetration rate reaching 100% in 2050 (15% of the total fleet), with a sinusoidal integration of resources by 2100, a collection rate of 90% and a platinum load gradually reaching 0.1g/kW, will lead to a slight increase in reserves in 2050 (around 9,700 tonnes), but to a strong decrease (-4,600 tonnes) in the case of no change in platinum loading and 60% collection rate. This example illustrates once again the importance of R&D to limit the Pt content, and of recovery incentives at all levels, as well as the choice of vehicle categories for which a transition to hydrogen is desired.

7.4 PEM FCEV deployment of THT and BC only

Similar to the first LDV scenario, i.e. a sales penetration rate that reaches 20% in 2050, and a sinusoidal certification process of the resources up to 2100, the impact of a PEM FCEV deployment of THTs alone will be much less, despite a much more intensive unit use of platinum: average power 300 kW, 0.7 to

0.5g of platinum per kW, 5-year PEMFC lifetime, 90% collection (professionals users) and recycling rate. Calculations have shown that the impact of extending the lifetime to 10 years is low.

Thus, sales in 2050 will amount to 1.9 million vehicles per year (instead of 32 million for PEM FCEV LDV), and the penetration rate in the total fleet will be 0.6%. Reserves will then grow to 14,100 tonnes if platinum content has been decreased, 13,300 tonnes if not. Moreover, the stock of reserves is still acceptable for 100% penetration of THT sales in 2050, provided that the level of platinum used in the battery decreases: 6,300 tonnes.

As far as BCs (Buses and Coaches) are concerned, regardless of the resource certification process, the deployment of this single type of vehicle with fuel cell is acceptable with a sales penetration rate of 100% in 2050, leading to 15,200 tonnes of resources in 2100 with a sinusoidal certification process, and 5,100 tonnes in case of linear integration. This is because the annual BC production does not exceed 1 million vehicles produced in 2050.

7.5 PEM FCEV deployment of all types of vehicles: LDV, LCV, THT and BC

If all vehicles are affected by a transition to fuel cells, with a 20% penetration rate in 2050, Fig. 6 shows that if the reserves are to remain positive, this must be accompanied by a decrease in the platinum content of fuel cells (- 0.2g/kW) and a collection rate of 90% instead of 60%: from - 9,700 tonnes to + 4,800 tonnes in 2050. However, the reserves will continue to decline in all cases.

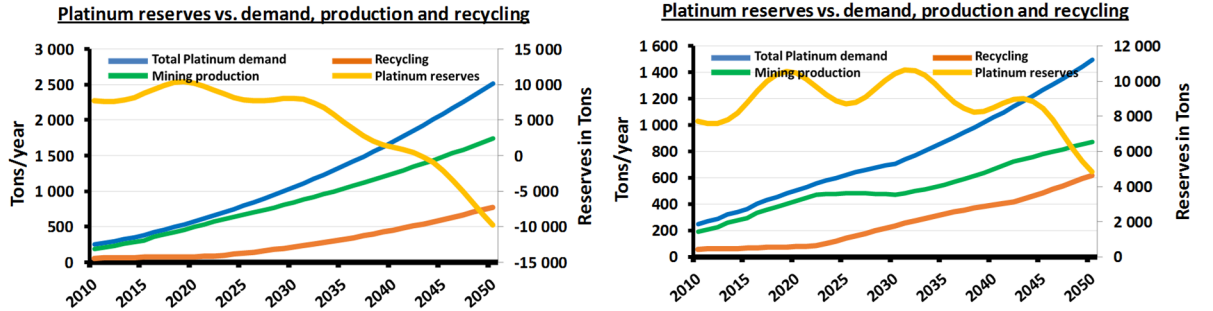


Fig. 6 - Evolution of Platinum reserves by 2050, case of PEM FCEVs in the whole park, for 20% sales penetration rates without progress on the platinum content of PEMFC (left, 60% collection rate) and with progress (right, 90% collection rate) if all resources are integrated into the reserves by 2100.

In the best of these two cases, a more voluntarist policy (aiming, for example, at 40% penetration of sales in 2050), would lead to insufficient reserves in 2050 (900 tonnes) even if resources were fully integrated in 2075, but would be beneficial if all resources were integrated in 2050 (+ 17,800 tonnes). Corresponding policies therefore appear very risky in terms of global depletion of this material, mainly after 2050, and for a presence of hydrogen vehicles in the fleet that would hardly exceed 40 to 50%.

But it should be noted that, similarly to the case of the deployment of LDVs alone, the case for which the resources are fully integrated in 2075 shows a stock of reserves that remains positive in 2035: 9,400 tonnes, which makes this scenario viable in the short (and medium) term, only.

7.6 The Range-Extender: a game changer?

A "Range-Extender" is an electric vehicle powered with a battery, to which a fuel cell powered by a hydrogen tank is added to increase the autonomy, working in parallel and by recharging the battery. This makes it possible to keep batteries of modest dimensions in place (max 100 km range) that are rechargeable on the network for short journeys, and to overcome the inconvenience of overly long recharges, since a tank of a few kilos of hydrogen, at 350 or 700 bars, can be recharged in a few minutes. So far, France is the only country to have carried out a study on hydrogen mobility, H2 Mobilité France [74], which integrates this type of technology, largely developed by Symbio [75]: Kangoo ZE-H2 of La

Poste [76], amongst others. At present, the deployment of the Range-Extender is more oriented towards commercial vehicles (LCVs), to gather feedback from professionals.

The Range-Extender architecture has already proved its worth in terms of the overall cost of mobility [77]. But the major fact that impacts this study is that fuel cells are very modest: 5 to 20 kW, and depend on vehicle usage and average speed. Peaks in engine power are provided by the battery, with the PEMFC and tank assembly ensuring a regular recharging of the vehicle corresponding to its' average speed: low for delivery vehicles (5 to 10 kW) and slightly higher for road vehicles (10 to 20 kW). Thus vehicles with a small battery have a small fuel cell, which is generally 5 times less powerful (20 kW) than if it had to provide the power peaks (100 kW) of a fuel cell vehicle alone.

This motorization architecture, therefore divides the quantity of platinum required by about 5, while maintaining a significant autonomy provided by the PEMFC plus the hydrogen tank. Fig. 7 shows that in the case of deployment of all vehicle categories, reserves remain positive, even increasing between now and 2050 in a situation of reduced platinum charge and a collection rate of 90%, for an overall penetration rate of 20%. The demand for platinum for PEM FCEV vehicles in 2050 will then be slightly lower than that for catalytic converters, 30% and 31% respectively.

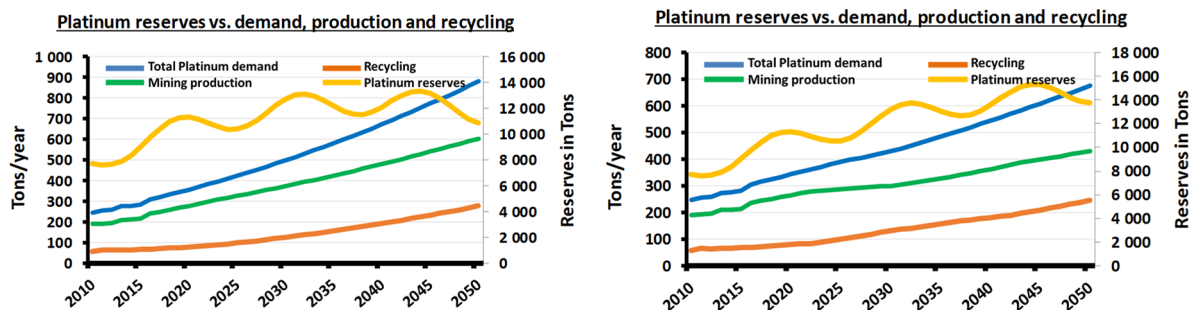


Fig. 7 - Evolution of Platinum reserves between now and 2050, case of PEM FCEVs in the entire Range-Extender park, for 20% sales penetration rates without progress on the platinum content of FC (left, 60% collection rate) and with progress (right, 90% collection rate) if all resources are included in the reserves by 2100.

Such use of fuel cells thus allows for much higher sales penetration rates: if this rate is 50%, reserves increase slightly, up to 10,400 tonnes in 2050.

7. Discussion

There are a large number of parameters and assumptions that affect the availability of platinum for FCEV MEPs in the coming decades. Table 1 summarizes the main trends that can be observed regarding platinum reserves. It depends on the collection rate of spent fuel cells on the one hand, and on the other hand on the progress envisaged on the platinum content required per unit of vehicle power. For simplicity, it is assumed that the resources will not be depleted before 2100, and that they will be exploited at a rate adapted to the shorter-term forecasts of supply and demand ("sinusoidal" integration mode). Table 1 shows the projected status of reserves in 2050, as well as in 2035, a mid-term milestone between now and 2050 that focuses on the case of the deployment of the entire ground vehicle fleet, a major case.

Platinum Reserves Tons in 2050 / Ressources integrated in 2100 ("sinusoidal") / Pt rate down to 0.1g/kW (LDV, LCV) and 0.5g/kW (THT, BC) in 2050					Platinum Reserves Tons in 2050 / Ressources integrated in 2100 ("sinusoidal") / Collection Rate 90%				
PEMFC Vehicles		Collection Rate	Sales penetration rates			Pt Rate in 2050	Sales penetration rates		
			20%	50%	100%		20%	50%	100%
Small and medium vehicles	LDV	60%	11 500 →	4 600 →	-6 800 →	0.3g/kW	4 400 →	-13 000 →	
		90%	12 047 →	6100 →	-3 800 →	0.1g/kW	12 047 →	6100 →	-3 800 →
	LCV	60%	15 000 →	13 600 →	11 100 →	0.3g/kW	12 300 →	6800 →	-2 400 →
		90%	15 200 →	13 900 →	11 800 →	0.1g/kW	15 200 →	13 900 →	11 800 →
Large vehicles	THT	60%	13 200 →	8 900 →	1 800 →	0.7g/kW	13 300 →	9 300 →	2 600 →
		90%	14 100 →	11 200 →	6 300 →	0.5g/kW	14 100 →	11 200 →	6 300 →
	BC	60%	15 900 →	15 700 →	15 300 →	0.7g/kW	15 900 →	15 700 →	15 300 →
		90%	15 900 →	15 800 →	15 500 →	0.5g/kW	15 900 →	15 800 →	15 500 →
All vehicles	All vehicles	60%	2 700 →	-17 000 →		0.4g*/kW	-6 000 →	-39 000 →	
		90%	4 800 →	-11 900 →		0.2g*/kW	4 800 →	-11 900 →	
	Range-Extender	60%	12 900 →	8 200 →	400 →	0.4g*/kW	11 600 →	5 000 →	-6 000 →
		90%	13 400 →	9 600 →	3 200 →	0.2g*/kW	13 400 →	9 600 →	3 200 →
Changing in reserves		Increase →	Stable →	Decrease →	* medium equivalent value				

Platinum Reserves Tons in 2035 / Ressources integrated in 2100 ("sinusoidal") / Pt rate down to 0.2g/kW (medium equivalent value) in 2050					Platinum Reserves Tons in 2035 / Ressources integrated in 2100 ("sinusoidal") / Collection Rate 90%				
PEMFC Vehicles		Collection Rate	Sales penetration rates			Pt Rate in 2050	Sales penetration rates		
			20%	50%	100%		20%	50%	100%
All vehicles	All vehicles	60%	8 800 →	1 000 →		0.4g*/kW	5 400 →	-7 500 →	
		90%	9 300 →	2 300 →		0.2g*/kW	9 300 →	2 300 →	
	Range-Extender	60%	13 000 →	11 400 →	8 800 →	0.4g*/kW	12 300 →	9 700 →	5 400 →
		90%	13 100 →	11 700 →	9 300 →	0.2g*/kW	13 100 →	11 700 →	9 300 →
Changing in reserves		Increase →	Stable →	Decrease →	* medium equivalent value				

Table 1 - Available reserves in Tons of platinum in 2050 and 2035, according to vehicle types and collection rates of 60% and 90% (left side), and the envisaged progress on the platinum content per kW (right side)

In order to better visualize the importance of major parameters such as the vehicle engine (presence or absence of Range-Extender) and the target sales penetration rate in 2050, Figure 8 shows the situation of platinum reserves in 2035 and 2050 in case of FCEV deployment for the whole vehicle fleet. It is assumed that the research efforts have been successful (reduction of platinum loads), and that the collection of used fuel cells is 90%.

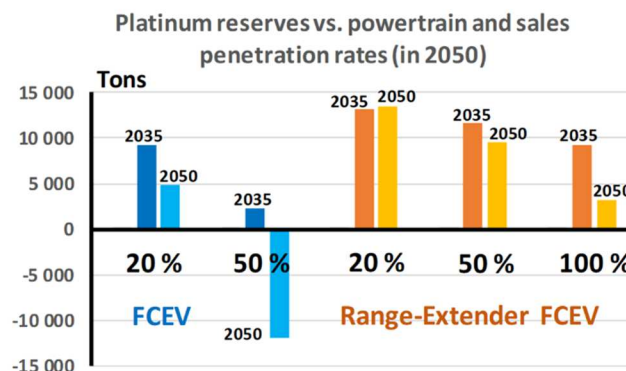


Fig. 8 - Evolution of Platinum reserves in 2035 and 2050, case of PEM FCEVs and Range-Extender powertrains for all types of vehicles, for 20%, 50% and 100% penetration rates in 2050 – "sinusoidal" inclusion of resources into reserves in 2100, 90% collection rate, progress in platinum load.

In general, the results show the importance of the two constraints, namely the increase of the collection rate of spent fuel cells, and the reduction of the platinum load which becomes even more important with high penetration rates. It also appears that the deployment of heavy vehicles alone is much less constraining than that of light vehicles, especially for high penetration rates: a strategic choice will therefore have to be made in this respect.

Worldwide availability of platinum is critical for a massive deployment of PEMFC vehicles.

Firstly, outside of any PEM FCEV deployment project, new platinum resources will have to be brought into operation in order to meet the ever-increasing demand of today's markets. A very gradual start-up should be sufficient.

But the deployment of light vehicles (LDV, LCV) alone, and in proportions that remain modest: 20% of sales in 2050, i.e. 14% of the rolling stock in this category, can hardly be exceeded if reserves are to be kept at reasonable values. In this case, it becomes imperative to reduce the platinum load of fuel cells by a factor of 3, and to recover at least 90% of used fuel cells. This last constraint is of an economic and political nature, through incentives and adapted regulations. In addition, following periods of acceleration and deceleration, named here « sinusoidal » integration of resources in reserves, should make it possible to maintain reserves at an acceptable level. Unless one imagines a possible progressive integration of resources in 2075 and not in 2100, which is very risky.

The case of heavy vehicles alone, THT and BC, is much less constrained than that of LDV. Production is much lower, despite much higher platinum loads and faster rotation rates, and despite high platinum contents, if the collection rate is at least 90%, deployment of heavy-duty vehicles alone seems possible for up to 50% or more of sales penetration by 2050. Penetration rates of 50%, or even 100% for the BCs, are possible too, but this supposes that the choice has been made to select a single type of vehicle, a professional one.

Deployment of the entire fleet at 20% is very risky, as the reserves will have decreased significantly by 2050, and will continue to decrease, even if all the parameters favorable to maintaining positive reserves in 2050 are implemented: 0.1g Pt/kW, collection rate of at least 90%, rapid exploitation of resources. Except with the assumption of a complete exhaustion of resources in 2075 or 2050, which becomes too critical. Nevertheless, until the short/medium term, for example 2035, platinum availability should be assured, but that result must be very carefully considered.

Thus, except in special cases of deployment of specific fleets, reducing the platinum charge of PEM FCEVs is no longer an option but an obligation, as is the most complete collection possible, if one wishes to achieve a substantial substitution of present vehicles by hydrogen fuel cell electric vehicles using platinum. In addition to this, it appears that a strategy for anticipating reserves and resources must be at the heart of the concerns of manufacturers associated with geologists and mining specialists: at what rate is it necessary to invest in operations to recover resources from reserves?

Unless Range-Extender powertrains are deployed

Only the Range-Extender motorization option could finally allow the entire fleet to be 50% FCEV in the long term, provided that the collection of used fuel cells is excellent, and that platinum content progress is successful. A widespread deployment of electric motorization architecture enables the tensions on platinum, and rare metals in general, of this hybrid energy storage to be considerably reduced. In addition, deliberately limiting the energy contained in the battery to short distances is also an advantage for the availability of the critical materials of this major component.

Or unless fuel cells without platinum catalysts are considered.

Despite substantial R&D now being undertaken throughout the world to develop platinum-free, or extremely low (hollowed nanoballs) fuel cells, the real question then becomes whether the quantities of platinum can be reduced to the bare necessity, or even to zero. In the meantime, market tensions for this rare metal are to be feared if the usage of PEMFC fuel cells continues.

Conclusions

Analysis of the criticality of platinum in the deployment of advanced technologies, in this case fuel cell electrical mobility, requires the most complete databases possible on this material (demand, reserves, resources, recycling) and the industrial sectors concerned (needs and associated performance, fleets and production of each type of vehicle, motorization architectures).

Light Duty Vehicles represent the largest demand for platinum, larger even than Trucks and Heavy Trucks despite their much higher power and loads. In order to gradually achieve FCEV sales rates of 20% or more by 2050, it seems essential to make significant progress on the platinum charge per unit of power, as well as to implement a rigorous comprehensive collection policy: at least 90% collection rate of used fuel cells.

The certification of reserve resources (period, speed, etc) is also a determining factor in the viability of a FCEV deployment scenario. Except for some particular cases, it is much better to use a long term market-demand driven strategy to meet the 2050 requirements, and not an arbitrary progressive one. All the scenarios reveal the importance of technological choices made today, and of ongoing research that will limit needs as much as possible, or even do without platinum for this technology: bio-inspired solutions for example, which future developments cannot ignore.

There is, however, the motorization architecture of the Range-Extender which makes it possible to reduce by a factor of 5 the needs for identical performances and uses, by associating batteries and fuel cells in vehicles. If PEMFC technology remains in the running, this would considerably ease tensions, particularly in terms of resources but also in material costs.

If deployment is really planned for all vehicles, platinum availability should be assured until the medium term, for example 2035, if R&D progress and collection rates are met, and for a target of 20% of sales in 2050.

By observing the major trends and in particular the risk of a shortage of platinum catalyst, it has been clearly established through a limited number of scenarios of PEM FCEV deployment, that the strategies to be implemented must be well defined from the outset. It is important to adjust the rate of exploitation of the resources to transform them into available platinum reserves.

This work is a first step towards more advanced analyses, most probably in the field of mining: what are the real possibilities of exploiting resources? It shows that from simple considerations of scenarios of FCEV deployments in the coming decades and assumptions of more or less long term exploitation of reserves, large differences appear concerning the sustainability of platinum reserves. This also gives a more precise, quantified value to the research undertaken in the field of catalysis for fuel cells.

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