The Electrification of Transportation

A Solution for the Ecological Transition

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Editorial

Imagine it is 2050 and you are explaining to your grandchildren what life was like before electric cars.

In cities everywhere you could hear motors purring. Car aficionados could recognize an engine's type by its rumble alone, and the irritation brought on by a motorcycle revving close by was part of the tapestry of daily life in a city. We would also tell them about the pollution that filled our lungs while travelling on foot, by bike, or even by car. Perhaps we would even feel a little nostalgic when describing the wafting fumes we inhaled while filling the tank at the gas station. And finally, we would talk about how families used to own one, two, even three cars. About how things were not the same back then. How we did not know about CO_2. About how we did not believe that we could ever run out of oil. About how oil was a sign of wealth and prosperity and some even considered it the investment of a lifetime.

And it is likely that at that point our children or our grandchildren would interrupt, exclaiming that they do not understand how we could ever have lived that way, looking at us as if we were dinosaurs.

Today, we are at the brink of an automotive revolution which is going to change people's daily lives just as cell phones and the internet have. Electrification won't stop with cars and trucks. Once we have solved the problem of how to store enough energy and hydrogen aboard a vehicle, our entire transportation system will rapidly shift towards electricity.

As responsible investors conscious of the challenges facing society, we want to invest the savings entrusted to us in companies committed to this transition: the companies who are building the transportation systems of the future.

Happy reading!

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Foreword

Electrifying the transportation system represents an upheaval for the automotive industry and the entire transportation sector. The upcoming transition will force companies to reexamine how they think about mobility and to develop new and evolving technologies to meet the challenges it brings. As the transition towards electrifying our transportation systems begins to gather momentum, this study aims to identify the major challenges and solutions of the electric vehicle sector, and to identify the parts of the sector with high added value in order to support companies which will play key roles in the energy transition.

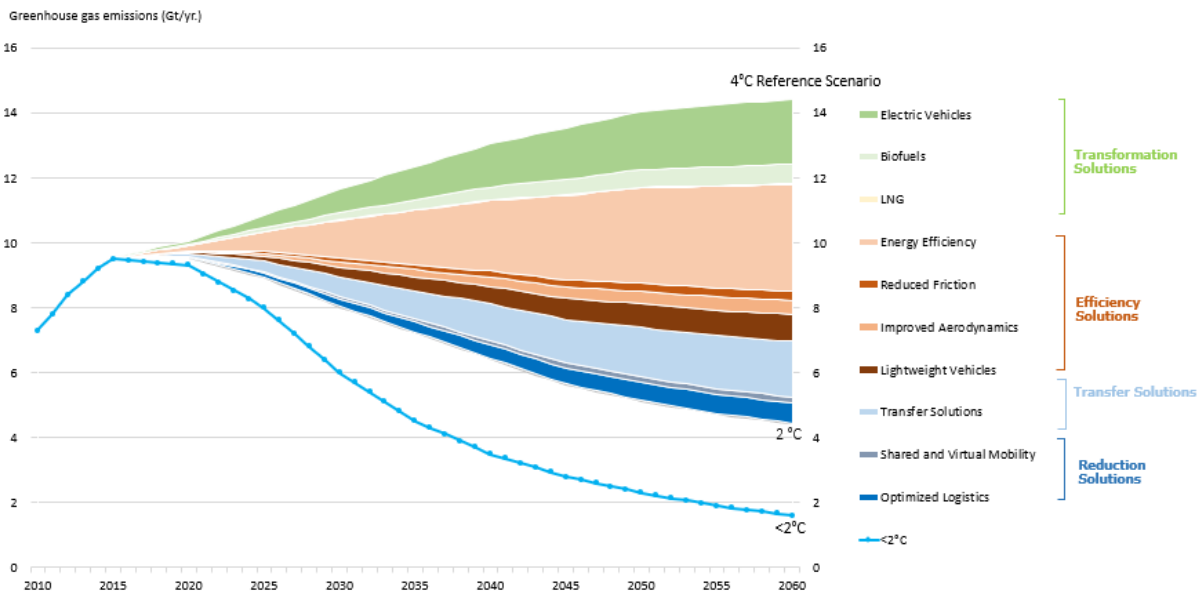
Why electrify the transportation system?

Because today's transportation system threatens both the environment and our health. Although electrification will surely have its own set of social and environmental challenges, it will allow us to reduce the impact that our transportation systems have on the environment, to free ourselves from our dependence on oil, to preserve the diversity of our ecosystems, and to create calmer, quieter, and cleaner cityscapes.

Is electrification the only solution?

No. The transition towards sustainable mobility will involve a wide range of solutions: choosing rail travel, public transit, soft mobility solutions such as traveling on foot or by scooter or bicycle when possible (alternative solutions), optimizing gasoline-powered or diesel vehicles to be more energy efficient to reduce their impact on both the environment and human health (efficiency solutions) and rethinking mobility to reduce unnecessary movements of people or goods (reduction solutions). However, most climate scenarios rely on the electrification of vehicles and the switch to biofuel for maritime and air transport (transformation solutions). Even in the most ambitious climate scenarios, the strong presence of individual vehicles leads to a radical shift towards electric motors. Moreover, even the +4°C baseline scenario shows that a technological breakthrough is necessary between 2020 and 2050 in order to alter our current trajectory.

Figure 1: Potential for reducing greenhouse gas emissions by type of solution



Sources: Mirova/ (IEA, 2017)

Do electric vehicles really help fight climate change?

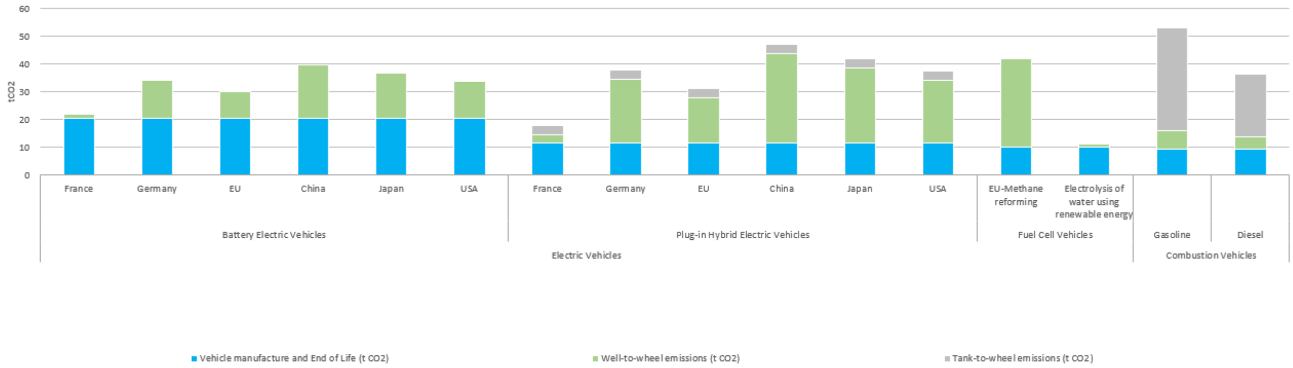
Yes. As is the case for all new technologies, the impact of electric vehicles should be studied in more depth. All the parties involved, industry leaders, politicians, investors and users should ask themselves the right questions before launching a whole system into a transition. Climate-related benefits are a primary point to consider.

Electric vehicles do not emit CO_2 when used. Their overall carbon footprint includes greenhouse gas emissions from:

- Electricity production (which can contribute a lot or a little depending on the country) for fuel battery-powered electric vehicles and hydrogen production for electric vehicles which run off fuel cells;
- The production of electric vehicles, and especially the production of the storage batteries, fuel cells, and hydrogen containers required for each type of vehicle.

Taking all of these factors into account, electric vehicles are better for the climate than gasoline-powered vehicles, regardless of location and vehicle segments, although the divide shrinks in countries where most of the electricity production comes from coal. In such areas, the difference between the carbon footprint of an electric sedan and that of a diesel-powered vehicle is almost nil.

Figure 2: Comparison of electric and conventional vehicles' carbon footprints over 180,000 km – sedan segment



Sources: Mirova / (Zubi, Carvalho, Dufo-Lopez, & Pasaoglu, 2018) and (Ager-Wick Ellingsen, Singh, & Hammer Strømman, 2016) for the production of electric and conventional vehicles, (GREET, 2017) for the production of fuel cell vehicles/ (OECD/IEA, 2015) for the carbon footprint of electricity production by country/ (JEC - Joint Research Centre-EUCAR-CONCAWE collaboration, 2014) for well-to-wheel emissions tank-to-wheel emissions for combustible and fuel cell vehicles/ (US DOE, 2018) for the EPA's fuel consumption estimates for models in circulation in 2018

However, there have already been numerous attempts to make individual gas and diesel-powered conventional vehicles more energy efficient. This means that the margin for future progress is slim for these vehicles while electric vehicles are a new technology and are still evolving. Therefore, greenhouse gas emissions linked to electric vehicles (and, consequently, their carbon footprint) will likely be reduced in the future by:

- The parallel development of renewable energies which will reduce the amount of CO_2 released during electricity production;
- Electrochemical advances in batteries and electrolyzers/fuel cells;
- The transition to mass production to respond to a rising demand for electric vehicles.

Finally, climate-related benefits are not the only positive outcomes. Electrifying our transportation systems will go a long way towards stopping our dependence on fossil fuels and reducing pollution.

The mobility sector will no longer be dependent on fossil fuels, but won't it just become dependent on metals, another nonrenewable resource?

No. It is true that the types of electric vehicles currently being produced contain about 20 kg of critical metals while conventional vehicles contain almost no critical metals. Critical metals are metals with supply problems (reserves, production concentration, social and environmental costs linked to extraction) due to the increase in production of energy transition technologies. Critical metals used in electric vehicles include cobalt and rare earth elements, as well as platinum, which is used in fuel cell vehicles. However, several solutions exist:

- Since the first generation of electric vehicles was produced, advances in electrochemistry have allowed us to reduce the amount of critical metals used in electric vehicles. The most recent generations use less than ~4 kg (~3.5 kg of cobalt and 500 g of rare earth elements).
- Hopefully, technological advances between now and 2030 regarding storage batteries, fuel cells and electric motors will allow us to almost eliminate the need for critical metals in electric vehicles.
- Even if certain metals are nonrenewable resources, they can be recycled. For certain critical metals, production lines have not yet been developed but will be in the years to come in order to support the development of green and digital technologies, all of which require rare earth elements.
- Similarly, we can expect to witness the development of production lines that currently depend on China which has maintained relatively low prices up until now in order to keep control of the market. Rising demand along with the increasing number of technologies and applications which require rare earth elements, gallium and other critical metals from China, are inextricably linked to a growing consideration of companies' environmental and social practices which will lead to a rise in the price of these metals. This rise in price will fund the development of new deposits and refining processes in line with environmental and social standards and will also create standardized recycling systems.

It seems that electric vehicles will destroy jobs. Is that true?

It is merely a change in value chains. Electric vehicles are changing how added value is distributed: although some jobs in the automotive sector may disappear, a large number of jobs will be created in related areas such as electrochemistry, treatment and recycling of metals, electricity provision and hydrogen production. As the value chain evolves, some activities such as the production of raw materials and batteries will likely shift to other geographic areas.

Are hybrid electric vehicles included in electric vehicles?

No. For the purposes of this study, an electric vehicle is defined as a vehicle whose primary source of power is electric. In hybrid vehicles, the electric motor only assists the main internal combustion engine. Gasoline is still the primary fuel of hybrid vehicles. Today, there are three types of vehicles which meet our definition of an electric vehicle: plug-in hybrid electric vehicles (PHEVs, which run solely on electricity until they hit 50 km), battery electric vehicles (BEVs), and fuel cell vehicles (FCVs).

Are fuel cell vehicles in competition with electric vehicles?

It is hard to say. The two types of vehicles are still being developed, and at this stage, their use is not the same. Electric vehicles are well-suited for use as passenger cars and two-wheeled vehicles in the short term, while fuel cells are better suited for heavy vehicles which travel longer distances, such as trucks. It is difficult to predict what will happen over the long term, as these vehicles are just beginning to be used in the rail, sea, and air segments.

If we compare a battery electric vehicle with a traditional combustion-powered vehicle as a user, can we expect the same performance in terms of cost and autonomy?

Not immediately, but soon. Significant advances in battery technologies and energy storage solutions, which are the keystone of this sector, result in:

- Increased range. The range of electric vehicles has doubled over the past 5 years (~300 km as of 2018). If progress continues, solid-state batteries will allow electric vehicles to compete with conventional vehicles by 2025-2030.
- Competitive prices. Electric vehicles are expected to cost roughly the same as conventional vehicles on a global scale by 2025, without subsidies. It should be noted that, if subsidies are taken into account, the cost of electric vehicles is already nearly on a par with that of conventional vehicles in certain areas.

However, one of the remaining big obstacles is persuading drivers to change their habits when it comes to refueling their vehicles. Although advances in batteries and charging stations hopefully mean that drivers will be able to refuel in about ten minutes in the future, for now electric vehicles must still be charged either at home or at work on a daily basis. Because not everyone is able to do this, electric and conventional vehicles will have to coexist until we come up with the technology to reduce the charging time necessary for an electric vehicle to the equivalent of the time it takes to refuel a conventional vehicle.

What are the advantages of these technologies other than reducing the environmental impact of the transportation sector?

Hydrogen and batteries with improved storage capabilities bring a lot more to the table than just reducing the sector's environmental impact. These technologies also address some challenges of the energy transformation sector and, more specifically, the development of renewable energy. Renewable energy is intermittent by nature which means that storage solutions are essential to bring production in line with demand. Storage batteries help to meet this need. Moreover, hydrogen can be produced from water by electrolysis, a process which can take place on-site at renewable energy power plants when an excess of energy is being produced, which would also help to solve the problem of intermittent renewable energy production. As we continue to develop hydrogen as a solution for storing energy, hydrogen will naturally come to be seen as a clean fuel solution for mobility.

Listed companies which contribute to the development of electric vehicles

Companies	Countries	Market Capitalization (€m) As of Jan. 31, 2019	Exposition / Technologies
Battery manufacturing			
Tesla Inc	USA	46,158	- Battery manufacturing: expert in manufacturing NCA and NMC cathodes with Panasonic Corp; 15 % of the global battery market in 2017; capacity: 20,000 MWh available, 15,000 MWh under construction, 70,000 MWh announced with Panasonic Corp - Charging points (2018): 12,200 - 100% electric vehicle manufacturer for Tesla Inc
Contemporary Amperex Technology Co Ltd	China	21,671	- Battery manufacturing: 100% of revenue from storage batteries, 16% of the global battery market in 2017; Capacity: 17,000 MWh available, 53,260 MWh under construction, 104,260 MWh announced; Area of expertise: NMC and LFP cathodes; major clients (outside China): Volkswagen - Recycling: via an affiliate, Brunp; capacity: 6 kt in 2017
BYD Co Ltd	China	15,591	- Battery manufacturing: NMC batteries for automobiles (53% of revenues in 2017) and batteries for storing solar energy (8%); 10% of the global battery market in 2017; expertise in NMC cathodes; Capacity: 26,000 MWh available, 34,000 under construction - Recycling: recycling plant in Shenzen - 100% electric vehicle manufacturer
Samsung SDI Co Ltd	South Korea	12,015	- Battery manufacturing: 15% of 2017 revenues; expertise in NMC cathodes; capacity: 5,000 MWh available, 1650 MWh under construction, 2,000 MWh announced; main client: Volkswagen
Guoxuan High-Tech Co Ltd	China	1,796	- Battery manufacturing: NMC for automobiles (85% of 2017 revenues); 4% of the global battery market in 2017; expertise on LFP and NMC cathodes manufacturing; capacity: 10,500 MWh available, 2,000 under construction; main clients: JAC, Zoyte
Tianneng Power International Ltd	China	911	Batteries for electric bikes (81 % of 2017 revenues), automobiles, forklift trucks and stationary energy storage
Flux Power Holdings Inc	USA	73	Batteries for forklift trucks and aircrafts (consumption on the ground)
Cathodes			
Umicore SA	Belgium	9,230	- Cathodes: NMC, LCO; capacity: 8 kt in 2016 (120 kt announced) and 15% of the NMC market in 2017 - Recycling: pyrometallurgy, hydrometallurgy; biggest cobalt recycler in the world; partnership with Tesla; capacity: 7 kt in 2017
Johnson Matthey PLC	United Kingdom	6,859	- Cathodes: eLNO and LFP (5 kt in 2016 with 8% of the LFP market in 2017) - Catalysts for hydrogen production
Beijing Easpring Material Technology Co Ltd	China	1,524	- Cathodes: NMC/LCO/NCA; NMC capacity: 5 kt in 2017
Ecopro Co Ltd	South Korea	562	NCA: 9 kt in 2016 with 5% of the NCA market in 2017
L&F Co Ltd	South Korea	661	NMC: 9 kt in 2016 (18 kt announced) with 11% of the NMC market in 2017
Anodes			
SGL Carbon SE	Germany	880	11% of 2017 revenues from anodes for lithium-ion batteries
Wacker Chemie	Germany	4,512	Graphite and silicon anodes
Toyo Tanso Co Ltd	Japan	387	Graphite and carbon fiber anodes for vehicle weight reduction
Ilika PLC	United Kingdom	30	Silicon anodes; R&D on solid batteries; partnership(s)/investor(s): Toyota
Electrolytes			
Solvay SA	Belgium	10,270	Fluorinated electrolytes; partnership with Solid Power Inc on solid batteries
Arkema SA	France	6,537	Fluorinated electrolytes
Shenzhen Capchem Technology Co Ltd	China	1,230	Fluorinated electrolytes
Metal production and recycling			
Aurubis AG	Germany	2,160	Copper, cobalt and nickel production and recycling
Boliden AB.	Sweden	6,100	Copper, cobalt and nickel production and recycling
Neometals Ltd	Australia	114	Production and recycling (3, 650 kt capacity announced)
American Manganese Inc	Canada	16	Production and recycling (1, 100 kt capacity announced)
Charging points for battery electric vehicles			
ABB Ltd	Switzerland	35,922	Charging points manufacturing
NARI Technologies co Ltd	China	11,878	Charging points manufacturing
Qingdao TGOOD Electric Co Ltd	China	2,261	Number of charging points: 168, 100
Alfen Beheer BV	Netherlands	260	Charging points manufacturing
Innogy SE	Germany	22,709	Number of charging points: 4,600
Fortum	Finland	17,837	Number of charging points: 4,612 via Charge&drive
Blink Charging Co	U.S.	55	Number of charging points: 3,500
E.ON SE	Germany	21,282	Number of charging points: 6,000
Enel SpA	Italy	53,273	Number of charging points: 2,000
EDF	France	44,988	Number of charging points: 5,000 via Izivia (former Sodetrel)
Semiconductors			
Infineon Technologies AG	Germany	22,743	Power semiconductors (SiC) and Microcontrollers AURIX/ XMC for fast charging
STMicroelectronics	Switzerland	13,285	Power semiconductors (SiC)
Hydrogen			
NEL ASA	Norway	643	Electrolyzers for hydrogen production; Proton exchange membrane fuel cell (PEMFC)
Hydrogenics Corp	Canada	100	Electrolyzers for hydrogen production; Proton exchange membrane fuel cell (PEMFC)
ITM Power PLC	United Kingdom	73	Electrolyzers for hydrogen production
McPhy Energy SA	France	71	Electrolyzers for hydrogen production
Ballard Power Systems Inc	Canada	696	Proton exchange membrane fuel cell (PEMFC)
Bloom Energy Corp	USA	871	Proton exchange membrane fuel cell (PEMFC)
Ceres Power Holdings PLC	United Kingdom	279	Proton exchange membrane fuel cell (PEMFC)
FuelCell Energy Inc	USA	47	Proton exchange membrane fuel cell (PEMFC)
Plug Power Inc	USA	288	Proton exchange membrane fuel cell (PEMFC)
PowerCell Sweden AB	Sweden	217	Proton exchange membrane fuel cell (PEMFC)
Linde PLC	United Kingdom	76,613	Energy production from steam reforming and distribution stations
Air Liquide SA	France	45,154	Energy production from steam reforming and distribution stations
Faurecia	France	5,209	Fuel cell systems
Kawasaki Heavy Industries Ltd	Japan	3,665	Portable hydrogen storage system
Plastic Omnium SA	France	3,500	Fuel cell systems

Sources: Mirova / BNEF / Company publications

Unlisted companies which contribute to the development of electric vehicles

Companies	Countries	Exposition / Technologies
Battery manufacturing		
NorthVolt AB	Sweden	- Battery manufacturing: expertise in the manufacture of NMC cathodes; Capacity: 8,125 MWh under construction, 24,000 MWh announced; partnerships with BMW and Umicore for recycling
Farasis Energy (Gan Zhou) Inc.	China	- Battery manufacturing: expertise in the manufacture of NMC cathodes; Capacity: 5,000 MWh available, 10,000 MWh under construction, 10,000 MWh announced
Dynavolt Renewable Power Technology Co Ltd	China	- Battery manufacturing: expertise in the manufacture of NMC and LFP cathodes; Capacity: 1,000 MWh available, 6,000 MWh under construction, 10,000 MWh announced
Cathodes		
Shanghai Shanshan Tech Co., Ltd.	China	- Cathode manufacturing: LCO/NMC/LFP with 11% of NMC market in 2017 ; - Anode manufacturing: 50 kt announced) with 5% of market in 2017 - Electrolyte manufacturing: LiPF6 (5% of market in 2017)
Nichia Corp	Japan	LCO/NMC/LMO/LFP : 13 kt in 2016 (32 kt announced) with 9% of NMC market in 2017
Ningbo Jinhe New Materials Co Ltd	China	LCO/NMC: 15 kt announced) with 9% of NMC market in 2017
Pulead Technology Industry Co Ltd	China	LFP : 10 kt in 2016 with 9% of LFP market in 2017
Anodes		
Paraclete Inc	Japan	Silicon Anode
Enevate Corp	USA	Silicon Anode
BTR New Energy Materials Co., Ltd.	China	Silicon Anode
Ningbo Shashan New Material Technology Co Ltd	China	Silicon Anode
XG Sciences	USA	Silicon Anode
Nexeon Ltd	United Kingdom	Silicon Anode
Amprius Inc	USA	Silicon Anode
Solid batteries		
Ionic Materials Inc	USA	R&D for solid batteries; polymer electrolyte; Partnership(s)/Investor(s): Hyundai, Renault, Nissan
Fisker Inc	USA	R&D for solid batteries; polymer electrolyte; Partnership(s)/Investor(s): Caterpillar
Front Edge Technology Inc	USA	R&D for solid batteries; polymer electrolyte; Partnership(s)/Investor(s): STMicroelectronics
Ionic Materials Inc	USA	R&D for solid batteries; polymer electrolyte; Partnership(s)/Investor(s): Hyundai, Renault, Nissan
Prieto Battery Inc	USA	R&D for solid batteries; polymer electrolyte; Partnership(s): Intel/Stanley, Black & Decker
QuantumScape Corp	USA	R&D for solid batteries; polymer electrolyte; Partnership(s): Volkswagen
Sakti3 Inc	USA	R&D for solid batteries; polymer electrolyte; Partnership(s)/Investor(s): Dyson
Seeo Inc	USA	R&D for solid batteries; polymer electrolyte; Partnership(s)/Investor(s): Bosch
Solid Power Inc	USA	R&D for solid batteries; polymer electrolyte; Partnership(s); Li-metal anode; Partnership(s)/Investor(s): Solvay
SolidEnergy Systems Corp	USA	R&D for solid batteries; polymer electrolyte; Partnership(s); Li-metal anode; Partnership(s)/Investor(s): GM
Battery electric vehicle charging points		
Broadband TelCom Power Inc	USA	Home / public charging point
Vattenfall AB	Sweden	Number of charging points: 9,000 via InCharge
ClipperCreek Inc	USA	Home / public charging point
Electric Motor Werks Inc	Germany	Home / public charging point
ELIX Wireless Inc	Canada	Wireless charging
Leviton Manufacturing Co Inc	USA	Home / public charging point
WiTricity Corp	USA	Wirelss charging
Shanghai Potevio Co Ltd	China	Number of charging points: 21,700
ChargePoint Inc	USA	Number of charging points: 26,000
EVBox BV	Netherlands	Number of charging points: 20,000; acquired by Engie
New Motion Ltd	Hong Kong	Number of charging points: 64,000; acquired by Shell
State Grid Corp of China	China	Number of charging points: 84,900
Allego BV	Netherlands	Number of charging points: 8,000; acquired by Meridiam
Chargemaster PLC	United Kingdom	Number of charging points: 6,500; acquired by BP
PlugSurfing GmbH	Germany	Charging points maps and softwares
POD Point Ltd	United Kingdom	Charging points maps and softwares
Recargo Inc	USA	Charging points maps and softwares
Hydrogen		
Borit NV	Belgium	Proton Exchange Membrane Fuel Cell (PEMFC)
Ceramic Fuel Cells Ltd	Australia	Proton Exchange Membrane Fuel Cell (PEMFC)
Efoy Investering AS	Norway	Proton Exchange Membrane Fuel Cell (PEMFC)
GreenHydrogen.dk ApS	Denmark	Proton Exchange Membrane Fuel Cell (PEMFC)
H2Gen Innovations Inc	USA	Proton Exchange Membrane Fuel Cell (PEMFC)
Intelligent Energy Ltd	United Kingdom	Proton Exchange Membrane Fuel Cell (PEMFC)
N2telligence GmbH	Germany	Proton Exchange Membrane Fuel Cell (PEMFC)
NedStack Holding BV	Netherlands	Proton Exchange Membrane Fuel Cell (PEMFC)
Palcan Power Systems Inc	Canada	Proton Exchange Membrane Fuel Cell (PEMFC)
Symbio FCell SA	France	Proton Exchange Membrane Fuel Cell (PEMFC)
WATT Fuel Cell Corp	USA	Proton Exchange Membrane Fuel Cell (PEMFC)
WL Gore & Associates Inc	USA	Proton Exchange Membrane Fuel Cell (PEMFC)
Faber Industrie SpA	Italy	Hydrogen compression technologies
FirstElement Fuel Inc	USA	Hydrogen stations under the brand True Zero
Hydrogenious Technologies GmbH	Germany	Hydrogen compression technologies
Sera Compress GmbH	Germany	Hydrogen compression technologies
Steelhead Composites LLC	USA	Hydrogen compression technologies
Takaishi Kogyo KK	Japan	Hydrogen compression technologies

Sources: Mirova / BNEF / Company publications

Summary

Introduction

Today, mobility is an important component of developed societies. Embedded in our day-to-day lives, mobility is at the very heart of modern civilization and is widely taken as given. The globalization of flows of people and goods, and the exceptional contraction of time and distance which have been made possible by a series of technical revolutions have today surpassed the limits of our planet.

This mobility is all made possible by a cheap and abundant fossil fuel: gasoline. Transportation accounts for nearly 15% of human-related greenhouse gas emissions and is responsible for a significant amount of pollution, which will negatively affect the ecosystems around us as well as present and future generations.

This is why transitioning to new forms of mobility which will allow us to keep global temperatures from rising by more than 2°C is more urgent now than ever before. We must rethink our transportation systems and move towards new and more sustainable forms of mobility.

Transitioning towards sustainable mobility requires a four-point approach (Mirova, 2018):

- Switching from combustion to electric vehicles and from fossil fuels to alternative fuels;
- Optimizing existing conventional vehicles so that they run as efficiently as possible and emit as little pollution as possible;
- Moving towards forms of transportation which require little energy;
- Reducing emissions by reducing the need for travel and the distances travelled.

This study will focus on the switch from conventional vehicles to electric vehicles, which include battery electric vehicles, plug-in hybrid electric vehicles, and fuel cell vehicles.

In 2018, nearly 2 million electric vehicles are expected to be sold worldwide (BNEF, 2018). The sector's takeoff will trigger a rapid low carbon transition. Driven by proactive policies and ambitious development goals, the electric vehicle market has reached a turning point and we must decide what role electric mobility will play in the global ecological transition.

Switching from combustion to electric engines is part of the solution. However, this change will be most effective when combined with other changes such as redefining individual mobility, changes in usage patterns, and the rapid beginning of the global energy transition. Finally, when discussing how electric vehicles will contribute to the ecological transition, we must also question their environmental virtues, examine under what conditions they can best contribute, and prepare to face new environmental and social externalities. This means identifying the technologies and trends which will be at the core of the upcoming revolution, ways to speed up development and potential obstacles, and the risks and opportunities which are emerging throughout the value chain. From extracting key resources to building charging infrastructure and manufacturing automobiles, this study aims to identify the key economic players in the transition, new economic models, and ways in which the conventional sector can adapt.

I. Responding to the challenges of the ecological and social transition of the transportation system

The transportation sector is facing four major environmental and social problems, because it is:

- A significant contributor to climate change;
- Highly dependent on oil;
- A major source of air pollution;
- A source of noise pollution for the surrounding, especially urban areas.

Transitioning from conventional vehicles to electric vehicles provides solutions to these issues.

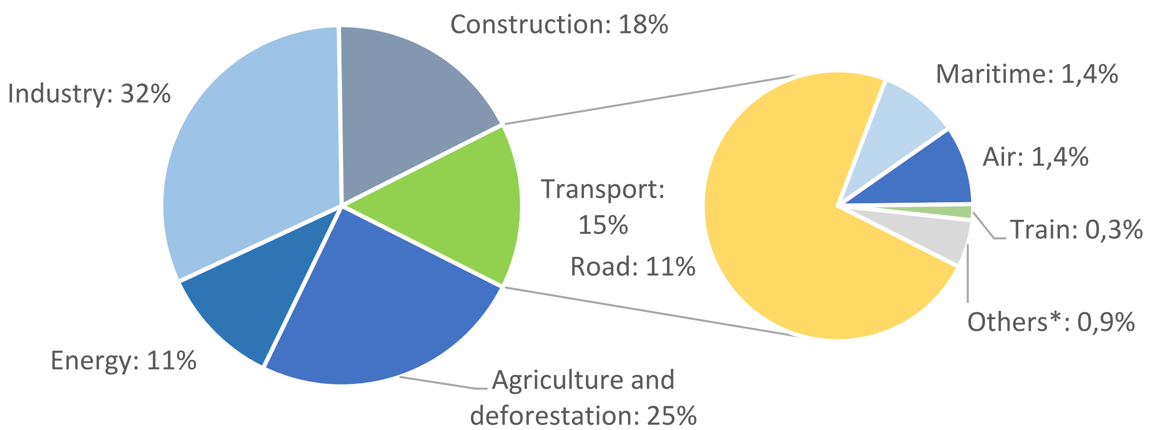
A. The transportation climate transition

MAKING THE SWITCH TO ELECTRIC ENGINES IS A NECESSITY

The transportation sector is responsible for 23% of global CO_2 emissions from fuel combustion (IEA, 2017) and 14% of global greenhouse gas emissions (IPCC, 2014). Moreover, these numbers are climbing: the percentage of emissions caused by transportation rose by 2.5% each year between 2010 and 2015 (IEA, 2017). The transportation transition occupies an important place in energy transition scenarios aiming to meet the goals set by the Paris Agreement (European Commission, 2015).

The contributions of certain subsectors are underestimated. Air transport for example, might have up to double the estimated impact due to contrails.

Figure 3: Direct and indirect greenhouse gas emissions by transportation subsector (2010)



*electricity generation, pipeline transport, N2O and HFC emissions

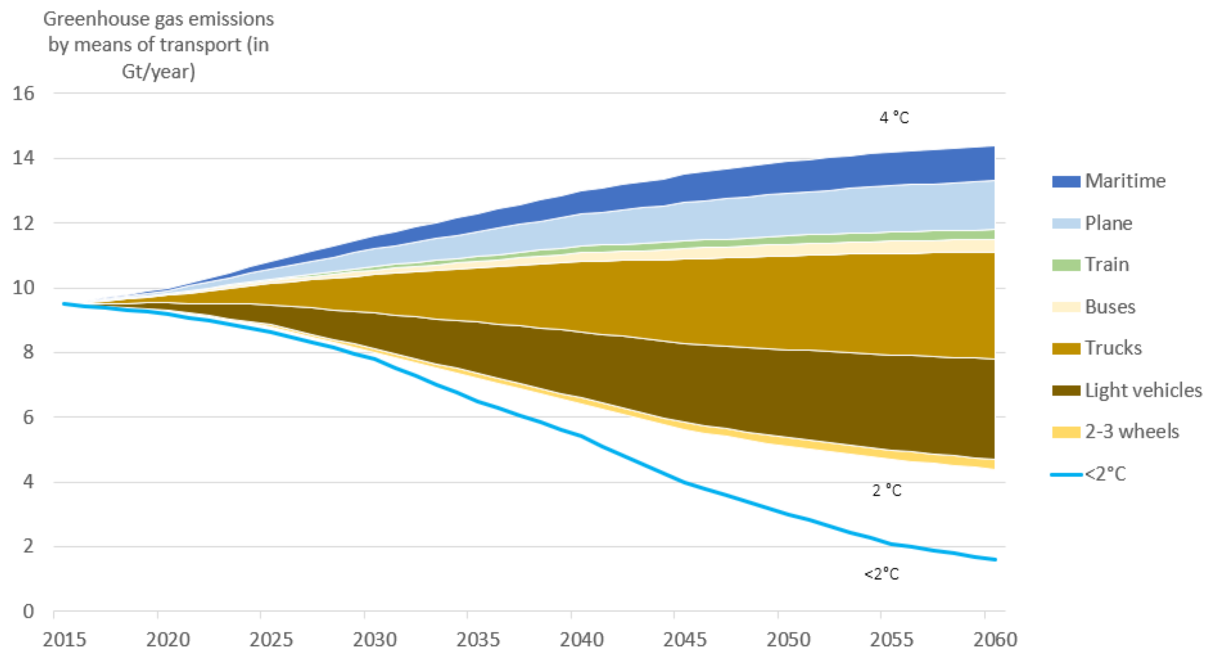
Sources: Mirova / (IPCC, 2014) / (IPCC, 2014) / (ICCT, 2018).

The International Energy Agency (IEA) has outlined three climate scenarios:

- The Reference Technology Scenario (RTS) takes into account technological advances as well as the commitments which countries have already made to fighting climate change. The scenario remains ambitious and would lead to a temperature increase of 4°C;
- The 2°C Scenario (2DS) lays out a trajectory which involves reducing the average global temperature increase to 2°C by 2100, reducing annual emissions by 70% by 2060, and reaching carbon neutrality before 2100;
- The Beyond 2°C Scenario (B2DS) is the most ambitious of the three and involves limiting global average temperature increases to 1.75°C by 2100. It also aims to achieve a carbon neutral energy sector as early as 2060 by decreasing annual emissions by 70% by 2060.

Limiting temperature increases to 2°C in 2100 means reducing transportation emissions by 60% between 2015 and 2060. The graphic below shows the necessary reductions by mode of transportation.

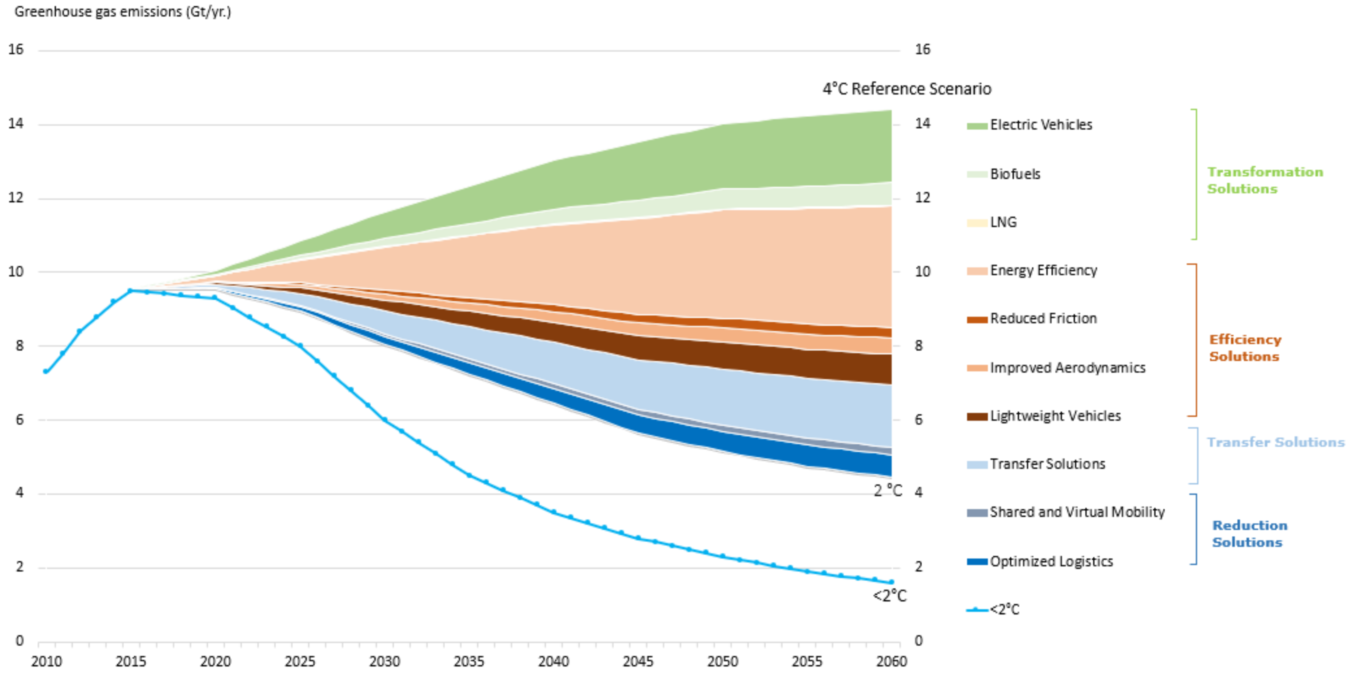
Figure 4: Reduction potential by mean of transportation



Sources: Mirova/ (IEA, 2017)

The solutions needed to reduce greenhouse gas emissions linked to transportation can be grouped into four main approaches.

Figure 5: Potential for reducing greenhouse gas emissions by type of solution



Sources: Mirova/ (IEA, 2017)

Although improvement and transfer solutions still present a significant reduction potential[1], particularly for road freight transport and air and sea sectors, the transition towards electric motors is in a good place. Moreover, improvement solutions focus on continuous technological progress while transformation solutions present a radical technological change, which explains why the subject is a priority. Although the transition to electric motors primarily concerns road transport, it will nevertheless be a source of solutions for other modes of transport in the long term. Indeed, the large-scale development of electric mobility technologies (battery, fuel cell) for on-road vehicles could make other advances possible by applying these technologies to other modes of transport (sea, air). It is therefore necessary to envisage a way in which various means of transportation (passengers as well as goods) can transition at the same time, a way which could benefit from technological synergy and which must be part of a global reflection on mobility, as illustrated by the importance of modal shifts.

MARKET PENETRATION OF ELECTRIC MOTORS BY MODE OF TRANSPORTATION

In order to achieve its climate scenarios, the International Energy Agency (IEA) has produced projections for electric motor penetration of the market by sector[2].

Road transport: on the frontline of electrification

Today, the number of electric vehicles in circulation, including plug-in hybrid electric vehicles, battery electric vehicles, and fuel cell vehicles, makes up only a small fraction of the total number of vehicles in circulation: light commercial vehicles make up only 0.4%, buses make up 13%, and heavy goods vehicles and 2-3 wheelers make up such small fractions of the total

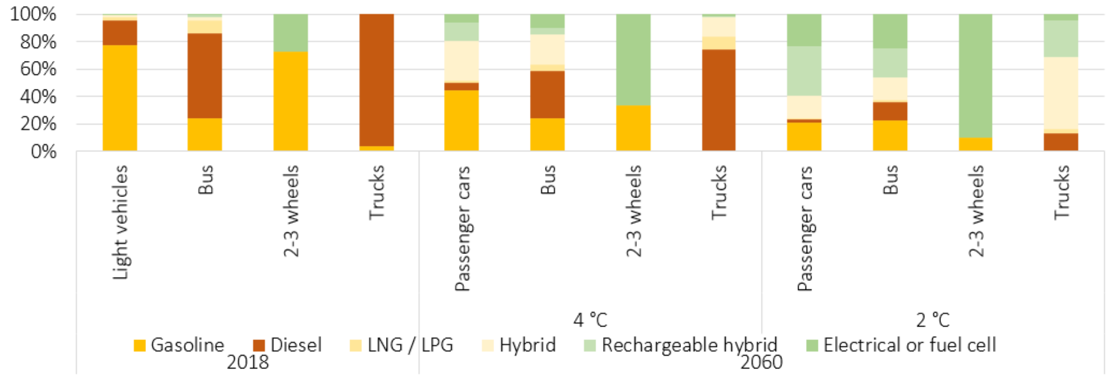
[1] (Mirova, 2013)

[2] These projections only apply to the IEA scenarios, the expected growth prospects are presented in the "Prospects" section

number that they are practically negligible. To meet a 2°C scenario, strong growth is expected in these segments. In 2060, it will include:

- 1,250 million light vehicles or 60% of light vehicles worldwide;
- 24 million buses or 46% of buses worldwide;
- 52 million heavy goods vehicles or 31% of heavy goods vehicles worldwide;
- 900 million 2-3 wheelers or 90% of 2-3 wheelers worldwide.

Figure 6: Market penetration of electric engines in the road transport market by 2060



Source: Mirova / (IEA, 2017)

In all the IEA scenarios, the market penetration of electric motors is very low in the heavy goods vehicles segment especially because the fuel cell vehicle sector still has many (mostly economic) challenges to be met before being included in projections (IEA, 2017). We are more optimistic regarding the heavy good vehicles segment of the market because we feel that the autonomy of fuel cell vehicles meets the needs of this type of transport.

Electric motors in other modes of transport

Greenhouse gas emissions from air, marine, and rail transport account for nearly one-quarter of total transportation emissions or 2.2 $GtCO_2$ (ICCT, 2018). It should be noted that this is only a partial estimation given that the impact of contrails can double the overall impact of air transport.

However, it should be noted that potential traffic growth, along with the still weak regulations compared to those applied to the automotive sector, makes it likely that greenhouse gas emissions will increase in the upcoming years. Electrification will also be a major challenge for these modes of transport with regard to the ecological transition.

However, switching to electric engines may be more complicated in the sea and air transport sectors over the short term (see Outlook: Uses and market growth). The International Energy Agency only predicts the first market developments from 2030 onwards, which does not allow us to establish projections for 2060 at this stage.

Electric rail transport has already existed for many years, mostly in Europe and in Japan. As of 2015, one in every three railroads worldwide had already made the switch to electricity (ICCT, 2018). However, the tracks which have been electrified are generally among the most profitable and therefore the most used lines. This means that almost 70% of all rail journeys are electrically powered, compared to about 40% of freight transportation (in ton-miles).

Three primary solutions are available for electrifying rail transport. The initial solution will be electrifying the lines, but in certain cases battery and hydrogen-powered trains are also feasible solutions. In order to stay on track with the 2°C scenario, greenhouse gas emissions must be reduced by 87%. This necessitates that most, or even all, rail transport switches to electricity.

This is the reason why transition models include all types of transportation switching to electricity, although this might occur at different rates and in different proportions.

B. The transportation energy transition

FREEING TRANSPORTATION FROM OIL DEPENDENCY

The transportation sector is responsible for 28% of all primary energy consumption. Transportation energy sources are also not very diverse: nearly all of the energy consumed (92%) comes from petroleum derivatives (IEA, 2017).

Electric vehicles help to end oil dependency by diversifying energy sources:

- Battery electric vehicles run solely on electricity. Therefore, their primary energy consumption depends on the energy mix of the country in which the vehicle is charged;
- Plug-in electric vehicles are powered by both electricity and fossil fuels;
- Fuel cell vehicles are powered by hydrogen. The hydrogen is produced either by electrolysis of water, which consumes electricity, or by steam methane reforming.

In order for us to reach a 2°C scenario, in 2040, only 60% of transportation can still be running on oil. Moreover, electric vehicles also generate gains in energy efficiency (see Energy efficiency).

CO-BENEFITS FOR THE ENERGY AND TRANSPORTATION SECTORS

In addition to reducing our dependence on fossil fuels, electric transport helps to accelerate the transition towards a low-carbon energy mix by investing in:

- New tools for storing energy (in both batteries and fuel cells) from renewable energy sources, which often suffer from intermittent production;
- Computer intelligence which can optimize energy consumption across the grid.

C. Improving the quality of urban life

In order to accommodate projected urban population growth, traffic patterns must adapt. By 2050, nearly 66% of the world's population is expected to live in urban areas (United Nations, 2014). This would amount to nearly 6.5 billion city dwellers (United Nations, 2017). If these projections become a reality, the cities of tomorrow will face many challenges related to the environment, spatial planning, accessing and sharing resources, urban pollution, and safety. Electrically-powered transportation and all the associated transportation services (car sharing, electric delivery vehicles, electric bikes and scooters) will have a role to play.

Electric transportation does not produce exhaust emissions, and the reverse electrolysis reaction that takes place in fuel cells only produces water molecules. In contrast, conventional vehicles continue to release several different pollutants which have a negative impact on both the environment and human health despite increasingly strict emission standards.

Nitrogen oxides (NO et NO_2) contribute to the acidification and eutrophication of natural ecosystems. Along with Sulphur dioxide (SO_2), they create tropospheric ozone when exposed to solar radiation combined with volatile organic compounds (VOCs) and carbon monoxide (CO), which are also byproducts of combustion.

These gases are responsible for irritating eyes and respiratory tract, among other things. Altogether, air pollution causes 7 million deaths per year (through heart attacks, pneumonia, strokes, cancers, etc.) (WHO, 2018). Electric vehicles are a way of diminishing air pollution and the associated health issues. Electric transport has also been linked to an improvement in the quality of life in urban areas due to a drop-in noise pollution, less smog, and diminished health problems, initially caused by conventional vehicles.

Electric vehicles appear to be an indispensable part of the ecological transition: they provide clear solutions to issues related to energy, climate change, and local pollution. This is why understanding electric vehicle's value chain and its externalities and challenges is so important.

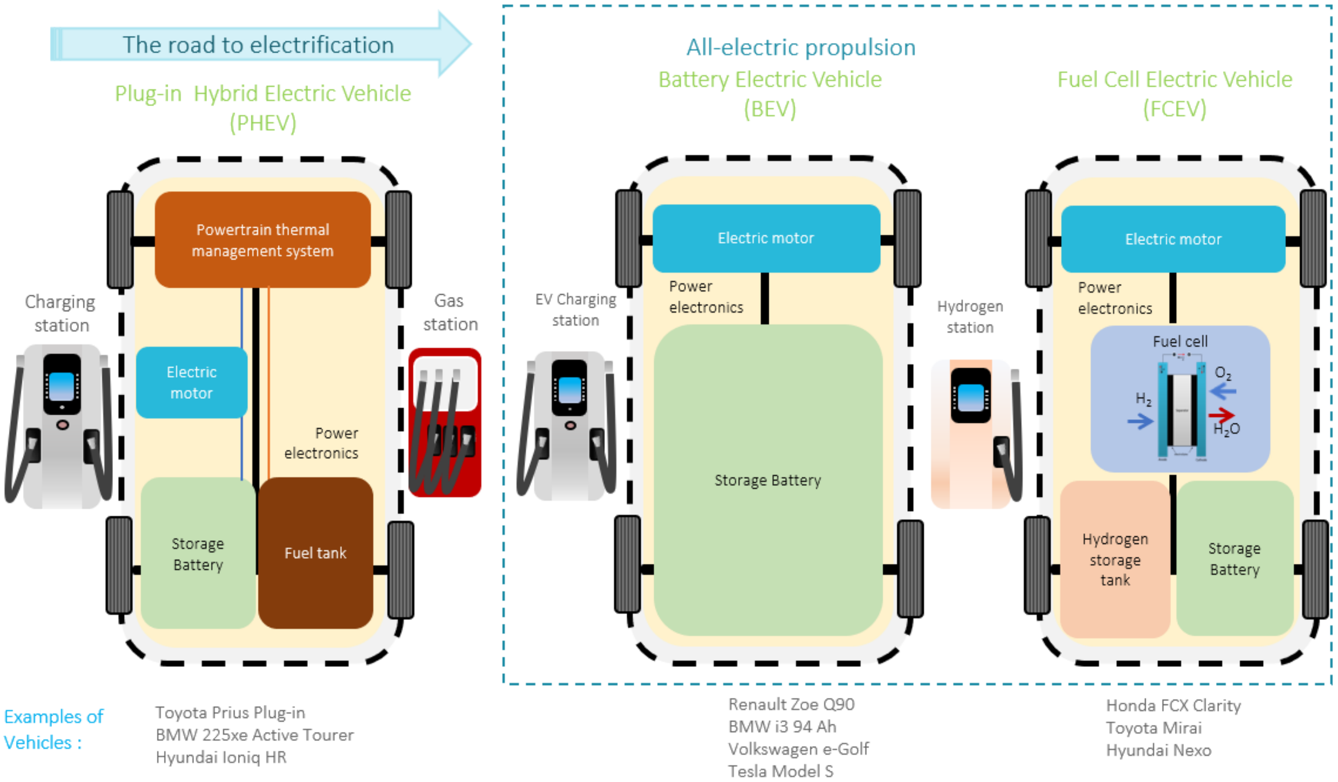
II. Technologies

The keystone to the electric vehicle value chain, in terms of both cost and technical challenge, is energy storage, whether thanks to electric batteries or by transforming hydrogen. Apart from this central element, electric vehicles have a relatively simple make-up.

A. Vehicle make-up

The architecture of battery electric vehicles radically differs from the architecture of conventional vehicles.

Figure 7: The architecture of electric vehicles



Sources: Mirova

Because there are fewer elements and no complicated powertrain, the operation of electric vehicles is much easier than that of conventional vehicles. Electric vehicles contain three main elements:

- A battery which allows to store electricity on board the vehicle;
- The powertrain including the electric motor, which powers the vehicle, and the speed reducer which transmits energy from the engine;
- Power electronics which is used throughout the vehicle and which relies on semiconductors to ensure the optimized operation of the vehicle.

In fuel cell vehicles, there are two additional elements which are necessary for storing energy in the form of hydrogen:

- The fuel cell which converts hydrogen into electricity;
- The hydrogen tank which can store hydrogen at a pressure of up to 700 bars.

In plug-in hybrid electric vehicles, sometimes considered a “transitional technology,” elements from both conventional vehicles and battery electric vehicles are present.

B. Energy storage

In an electric vehicle, electricity can be stored either in a device called a storage battery, of in the form of hydrogen. Electricity and hydrogen do not occur naturally on Earth: they are produced by converting primary energy. Electricity and hydrogen are energy vectors which are used to transfer primary energy to the electric motor.

Energy storage and distribution are key parts of electrical traction, which means that the added value of technology mastered before in the automotive sector is being replaced by emerging technologies from the chemical, energy management, and semiconductor sectors. Today, the development of the electric vehicle industry is faced with the obstacles that all developing markets must overcome: cost, efficiency and reliability. Regarding battery electric vehicles, there are repeated technological breakthroughs, particularly on storage batteries, which have made these technologies more attractive and have allowed manufacturers to reduce the cost, facilitate the charging process, and increase the range and the lifespan of electric vehicles, thus offering consumers a product which is comparable to a conventional vehicle.

For fuel cell vehicles, this development process will take place over a longer period. Over the short term, fuel cell technology is expected to be adapted for use in heavy-duty, long-haul vehicles. In order for fuel cell vehicles to be widely adopted as an environmentally friendly solution for the transportation transition, problems related to the cost of producing, storing, and converting hydrogen into electricity as well as their carbon performance and reliability (safety and charging issues), must be resolved.

STORAGE BATTERIES

Electric vehicles must be able to store energy in the form of upstream electricity.

Description of the system

A storage battery is composed of hundreds of basic units called cells. These electrochemical cells are grouped into modules which together make up the battery pack. A cooling system (aluminum tubes, coolant, and a pump) and a battery management system (BMS) which is made up of an electronic component linked to sensors, insure that the battery’s operation is optimal.

Illustration 1: Architecture of an electric vehicle (Tesla model S 85)

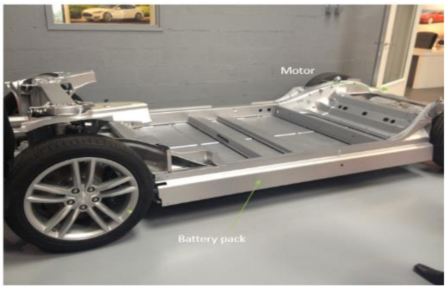
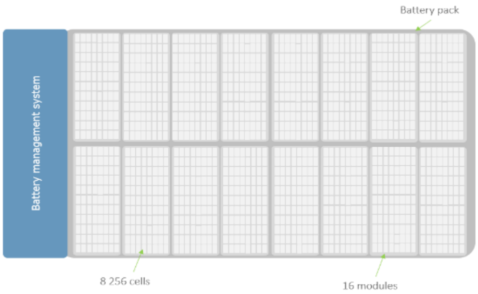


Figure 8: Architecture of an electric vehicle (Tesla model S 100)

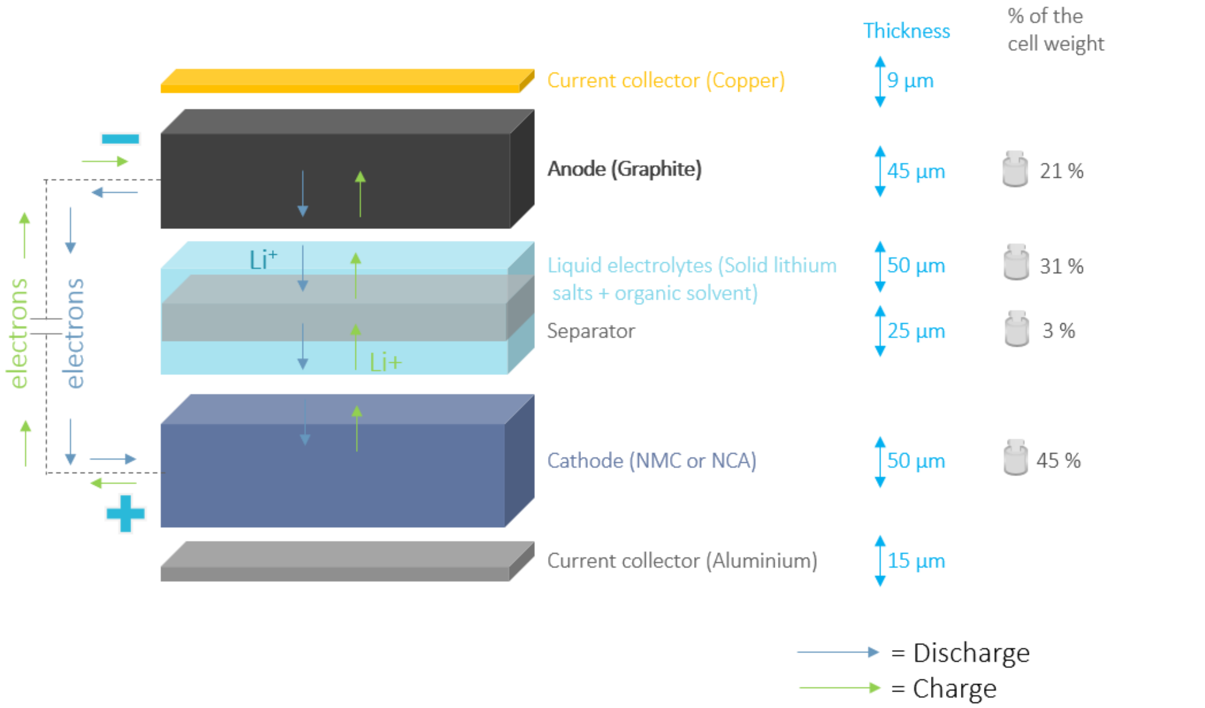


Sources: Mirova

A cell is made up of:

- Two electrodes − a cathode, which is the positive active material and an anode, which is the negative active material;
- A liquid electrolyte solution;
- A separator and copper foils.

Figure 9: Diagram of a cell in a lithium-ion battery



Sources: Mirova / (Ulvestad, 2018)

During discharge, lithium ions (Li+) move from the cathode to the anode, generating an electric current which powers the motor. During charging, the ions move in the opposite direction.

Today's storage batteries

The first lead-acid batteries of the 19th century were soon followed by a series of technological advances, particularly rapid over the last few decades (Mirova, 2012). Lithium-ion batteries, which first appeared in the 1990s, have now become standard technology, and their capabilities have allowed the growth of electric mobility. Today, four main types of lithium-ion batteries are used in electric vehicles currently on the market. Each of them draws its name from the components of its cathode:

- The most common type is the NMC (lithium nickel manganese cobalt oxide) battery, which actually covers several subgroups of batteries (NMC 111, NMC 532, NMC 622) all of which have varying energy densities depending on the proportion of nickel in the cathode. The NMC 111 was used widely in the early 2010s, and the NMC 532 and the NMC 622 were used in many of the models which entered the market in 2018;
- NCA type (lithium nickel cobalt aluminium oxide) batteries are mainly used by Tesla and their performance is close to that of an NMC 622 battery;
- LFP (lithium ferro phosphate) batteries are mainly used in China and have a lower specific energy. This type is perfect for buses which can charge at each station, but is of limited use in private vehicles;
- LMO (lithium manganese oxide) batteries, in which cobalt is replaced with manganese, are more cost-efficient than other batteries, but also have a lower specific energy (see focus 1) and are prone to premature aging when exposed to high temperatures. LMO batteries were paired with NMC 111 batteries in the early generations of electric vehicles.
- LMP (lithium metal polymer) batteries are another type of battery which are frequently used in the framework of car sharing. They were first marketed by Bolloré. This battery offers advantages in terms of lifespan (200,000 to 400,000 km) and range (about 200 km), but must constantly be either used or plugged in, in order to maintain a constant temperature of 80°C so as not to lose its charge. This drawback limits use of the LMP to car sharing and commercial fleet vehicles.

Focus 1: Specific energy and range

Specific energy has become a key indicator of performance because it plays a large part in defining a vehicle’s range: the amount of energy stored on board a vehicle divided by the amount of fuel consumed during operation.

To determine the amount of energy stored on board a vehicle, we must consider the specific energy (the energy density per unit mass). All vehicles, regardless of whether they are powered by electricity or combustion, have a specific energy. For conventional vehicles, this value depends on the capacity of the fuel tank; for battery electric vehicles, it depends on the storage capacity of the battery; and for fuel cell vehicles, it depends on the volume of hydrogen which can be stored on board.

For battery electric vehicles, the specific energy of a cell is around 200 to 250 Wh/kg. By increasing the number of cells and the size of the batteries, battery electric vehicles can now store up to 100 kWh, giving certain vehicles, such as the Tesla S 100, a range of over 600 kilometers. Most of the new generation of electric vehicles have a capacity of ~40 kWh and a range of ~300 kilometers.

Fuel cell vehicle models currently on the market have reservoirs which can hold ~140 liters of hydrogen gas for an energy capacity of ~200 kWh and a range of 600 kilometers.

Early models included anodes made from graphite, which usually came from coal mines. Today, the graphite used is make from coke[3], which improves the specific energy. There is one exception on the market: Toshiba’s SciB Rechargeable lithium-ion Battery which uses a LMO or NMC cathode and lithium titanium oxide (LTO) in its anode instead of graphite. It has a lower specific energy (~100 Wh/kg) but greater thermal stability which gives it a very short

[3] Coke is produced by heating coking coals (a variety of coal) in a coke oven in a reducing atmosphere.

charging time and a long lifespan (over 10,000 cycles). These characteristics make it a good solution for both two-wheeled vehicles and buses.

Finally, the electrolytes undergo changes, passing from lithium iron phosphate salts (LiPF6) dissolved in organic solvents, to fluorinated electrolytes in order to improve the specific energy, voltage, and lifespan of the battery while regulating thermal stability. Eventually, electrolytes will likely become solid (see Anticipated innovations); in the meantime, the separators in the electrolyte solution play an essential role: they guarantee thermal stability between the cathode and the anode, and are thin enough not to lower the specific energy of the cell.

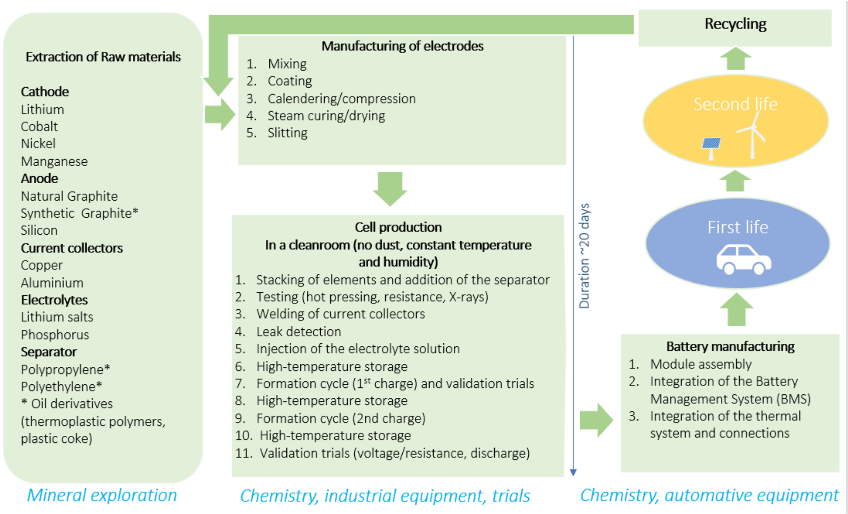
Despite considerable technological advances over the past ten years, these types of batteries still have certain weaknesses in terms of cost, specific energy, and charging time. Manufacturers are improving the manufacturing process while chemists are testing new chemical compositions in cells in order to achieve a better cost-efficiency-reliability compromise and to provide a service which is equal or superior to that of a conventional vehicle.

Manufacturing process

Similar manufacturing processes are used to create different types of lithium-ion batteries. These processes include:

- Extracting raw materials,
- Fabricating electrodes (cathodes and anodes),
- Forming cells,
- Assembling cells,
- Finally, assembling the whole battery adding the BMS, an electronic battery management system which controls the charging and discharging processes, and the thermal management system.

Figure 10: Lithium-ion battery production process



Sources: Mirova / (Dougher, 2018), (Berckmans, Vanhaverbeke, Messagie, Smekens, & Omar, 2017), (Patry, 2015), (Nussbaumer, 2014)

The raw materials needed to manufacture the batteries are extracted from processed ores or recovered through recycling systems. In order to make electrodes, the materials then undergo several long and demanding treatments to form rolls of electrodes which, once cut, will become anodes and cathodes. Then, another complex series of operations take place. These steps are carried out in clean rooms under optimal conditions in order to limit contamination and changes in temperature and humidity. These operations include multiple testing phases, charging, and ageing to obtain cells. This roll-to-roll compression manufacturing process has not evolved much since the first lithium-ion batteries marketed by Sony in 1991, and it is:

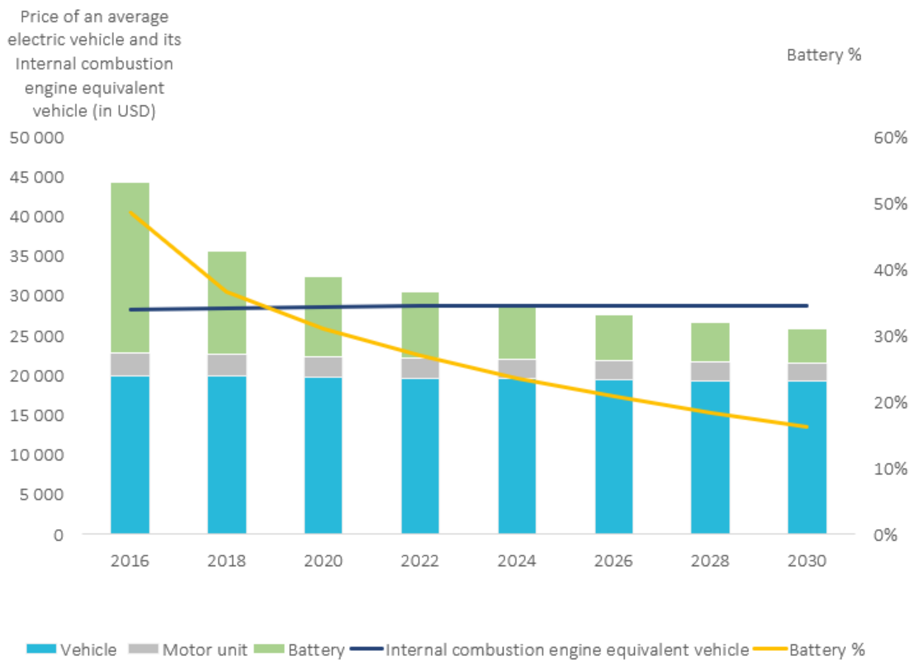
- Time consuming, which makes it difficult to adapt to the rhythm of automobile manufacturing;
- Costly in terms of both money and energy per each kWh of cells produced because clean rooms must be used to produce even small quantities of batteries. This will change to match production volumes as they increase;
- Consuming resources, which are more or less critical resources (see Resource Issues).

Battery manufacturing involves players in the mining, metallurgy, chemistry and automotive industries. In order to reduce the disadvantages of the current manufacturing process, innovation factors depend on chemical advances regarding the composition of electrodes and the assembly of various components, on the performance of the industrial equipment used at each manufacturing stage and on the pertinence of the tests performed.

Cost

In 2018, the cost of an average electric vehicle (segment C) was still higher than the cost of an equivalent conventional vehicle (see Total Cost of Ownership). However, the breakdown of the value is completely different: in a conventional vehicle, around 30% of the price is from the engine. In an electric vehicle the engine costs 10 times less than the storage battery which represents ~50% of a vehicle's total value. This data offers a partial explanation as to why innovation and added value are linked to batteries.

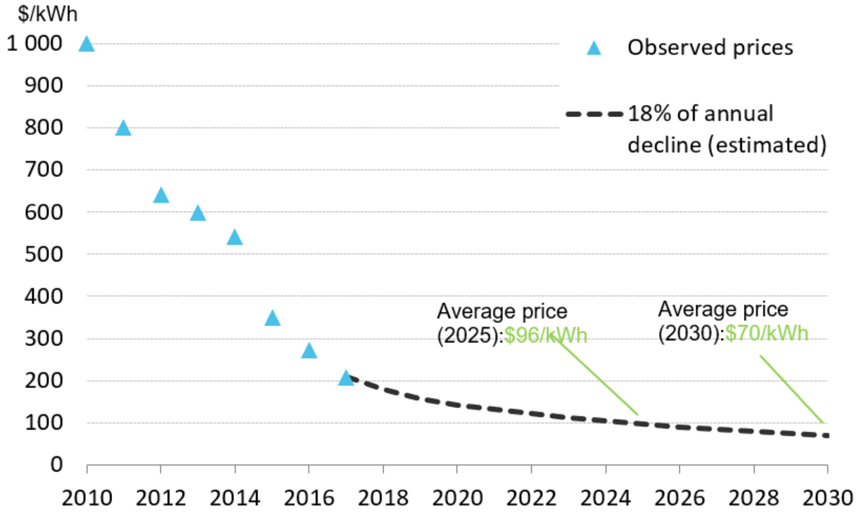
Figure 11: Current and estimated future prices of an average electric vehicle



Source: Mirova/ (BNEF, 2018)

The cost of lithium-ion batteries has decreased by almost 80% in 8 years, from ~1,000 USD/kWh to ~200 USD/kWh in 2018. This trend is expected to continue in the coming years, as prices benefit from increased production capacity and the introduction of new battery technologies.

Figure 12: Evolution of the cost of lithium-ion batteries



Source: Mirova/ (BNEF, 2018)

Today, the two batteries which offer the highest specific energy and greatest opportunities are the NCA and NMC 622 batteries. Each of these batteries costs about 200 USD/kWh. The bulk of the cost comes from the cell and, more specifically, from the cathode which accounts for about half the cell's cost.

Cost of NCA batteries

Figure 13: Breakdown of the cost of NCA batteries - at the battery level

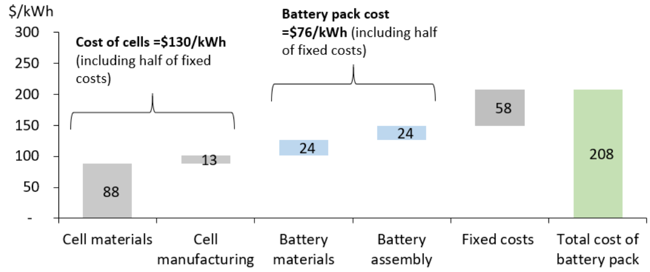
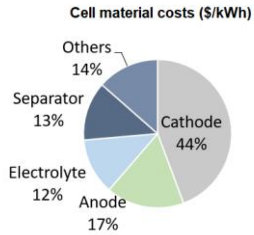


Figure 14: Breakdown of the cost of NCA batteries - at the cell level

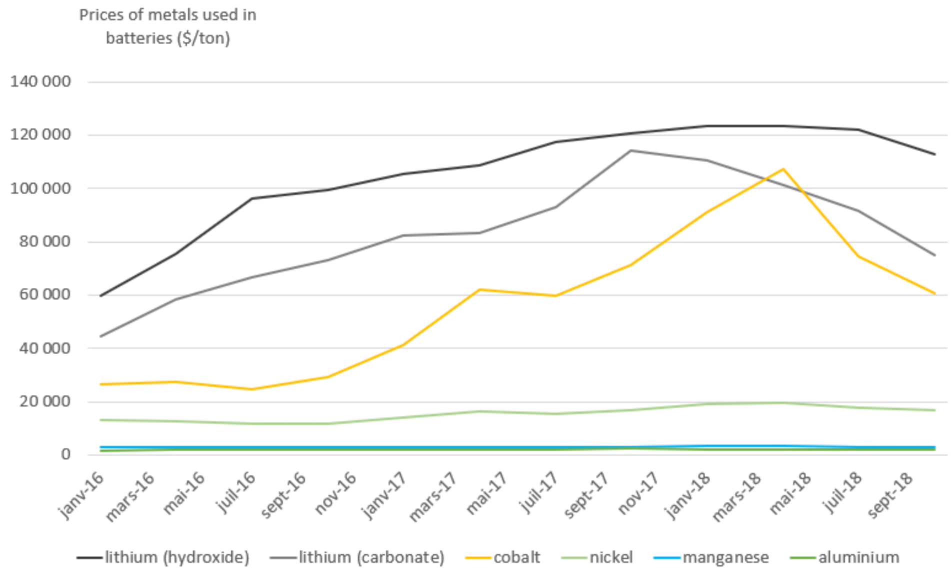


Source: Mirova/ (Argonne National Laboratory, 2018)/ (Berenberg, 2018)

This explains why the chemical composition of electrodes, and especially cathodes, has changed with time. The cathodes currently being developed and marketed for use in NCA battery technologies contain lithium, manganese, nickel, cobalt, and aluminum in varying proportions.

While the prices of aluminum and nickel are relatively low and stable, ranging from 1.5 USD/kg to 2.2 USD/kg and from 12 USD/kg to 20 USD/kg respectively, prices for lithium and cobalt are more volatile and significantly higher, rising from 26 USD/kg in January 2016 to 115 USD/kg in December 2018.

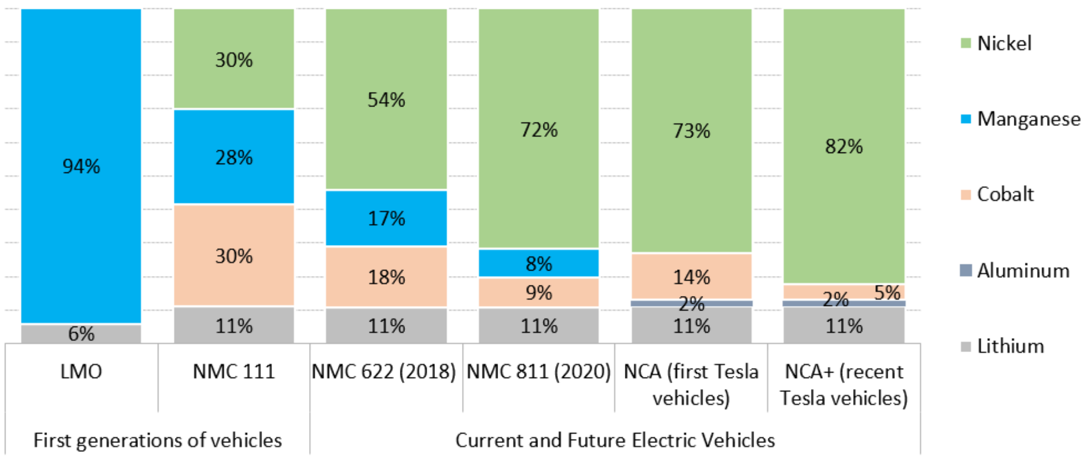
Figure 15: Evolution of the price of raw materials used in cathodes



Sources: Mirova/BNEF

The current short-term goal is to increase the proportion of nickel and aluminum and decrease the proportion of cobalt, thereby reducing the cost of raw materials. Over the long term, the goal is to reduce the proportion of heavy metals in order to reach cost parity with conventional vehicles, without the fear that the decline in the price of electric cars, due to the increase in production volumes, could be reversed if the prices of raw materials rise.

Figure 16: Compositions of different types of batteries (kWh)



Source: Mirova/BNEF

With each generation, the proportion of expensive and volatile materials used in NMC batteries is reduced. “NMC” refers to nickel, manganese, and cobalt, the three primary components of NMC batteries. Lithium, a compact element that stores a lot of energy as lithium ion, accounts for ~10% of the cathode, and then the remaining 90% is roughly distributed according to the name of the technology. For example, NMC 811 batteries contain approximately 8 times more nickel than manganese and cobalt.

Cost is not the only area where improvements can be made. Performance is also a determining factor for the development of electric vehicles. Performance refers to the range, lifespan, and thermal stability of a vehicle.

Current Performances

Besides the cost, the use of different materials in the cathode (and soon in the anode and the electrolyte) can improve the energy density (range), the recyclability (lifespan), the thermal stability (safety), and the charging time.

RANGE

Thanks to the increased size and advances in the chemical composition of batteries used in electric vehicles, their range has doubled. Early generations had a range of ~100/150 km whereas electric vehicles on the market today can travel ~300 km before they need to be charged.

However, increasing the size of the battery packs is only a superficial solution which would increase a vehicle's range, but which would also increase the cost of vehicles with more kWh on board. (A 30-kWh electric vehicle would reach cost parity with a conventional vehicle at 100 USD/kWh whereas a 60-kWh electric vehicle would reach cost parity at 60 USD/kWh.) Larger battery packs would also have a negative environmental impact because battery production produces most of the CO_2 emissions and consumes most of the energy used in the manufacturing process (see Carbon footprint over the life cycle).

LIFESPAN

The lifespan of a battery ends when a battery has lost 20% of its initial capacity. The degradation rate depends on the technology used, as well as charging conditions and how the battery is used, particularly the depth of discharge. Newer batteries (NMC 622, NCA) generally offer 1,000 to 1,500 charge cycles under optimal conditions, which corresponds to about 200,000 km. Actually, the degradation rate varies greatly depending on the technology used and the vehicle. The type of cooling system plays an especially important role in determining the degradation rate of a vehicle. Today, the degradation rate is between 5 and 8 years. The widespread use of nickel-rich cathodes, the development of ultra-fast charging, and the increase in discharge depth will likely keep battery lifespans from lengthening in the short term. However, battery lifespans are important because the battery represents most of the value in an electric vehicle and the battery's lifespan plays an important role in determining the vehicle's overall environmental impact. The length of a battery's lifespan also affects the development of second-life battery applications (stationary energy storage) and recycling programs which would allow used batteries to be collected and recycled, thus reducing the cost of a new battery by half.

FAST CHARGING CAPACITY

Innovations relating to charging infrastructure are essential if we wish to shorten the charging period (see Infrastructure). However, other elements can also contribute. For example, batteries have a role to play: the anode must have the capacity to handle fast charging. Today's graphite anodes struggle to withstand too sudden of a charge.

THERMAL STABILITY

A battery's thermal runaway determines how quickly it heats up while charging and discharging. The cooling system is responsible for controlling the runaway and preventing the electrolyte from igniting. Early NMC111 technologies, and especially LFP and LTO, offer better thermal stability, which makes them more secure and better suited to applications where thermal stability is important, such as buses. The trend of increasing nickel quantity reduces the thermal stability and therefore represents a technical challenge to ensuring optimal safety. Better thermal stability also allows batteries to withstand higher voltages and therefore to charge more quickly. The development of solid batteries, in which the liquid electrolyte is replaced with a polymer membrane, will be decisive in ensuring better thermal stability which will in turn decrease the charging time, making it easier for electric cars to compete with conventional vehicles. More broadly, the optimal operating range of batteries is expected to increase in the coming years and reduce the performance losses currently observed in winter conditions (negative temperatures).

Anticipated innovations

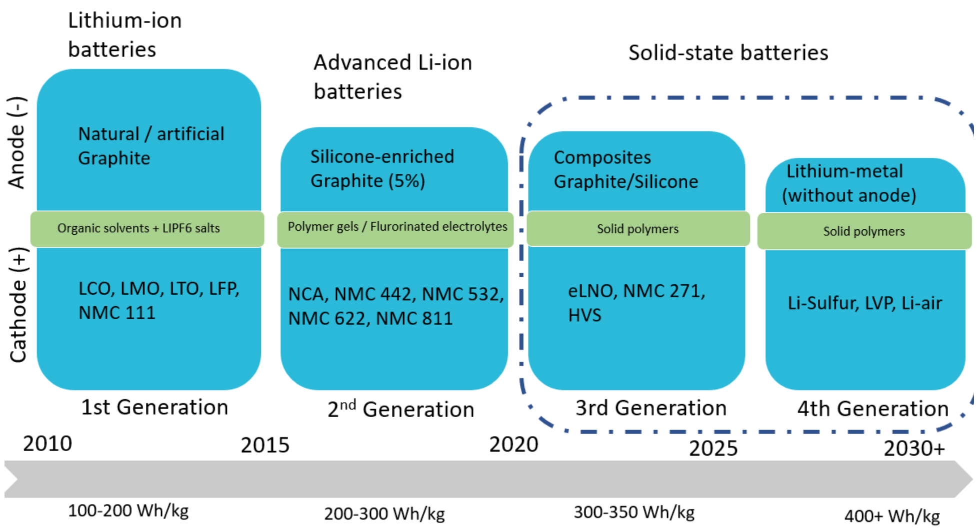
Progress in terms of cost and range will depend on innovations in storage batteries. However, even the best cost/range compromises cannot come at the expense of the lifespan (number of charging cycles) or thermal stability.

Cobalt improves specific energy, but is expensive, causes supply problems, and is subject to risks related to thermal runaway.[4]. Therefore, the amount of cobalt in batteries should be reduced. Nickel oxide, which has tended to be cobalt's primary replacement, has an excellent specific energy (see Focus 1) but is not stable, while manganese, which is less expensive and thermally stable, generally has a lower specific energy and begins to age more quickly. In order to obtain adequate thermal stability together with a good specific energy and a reasonable cost, cathodes are composed of mixed oxides.

Batteries can be divided into 4 generations:

- Generation 1 (2010-2015): low energy density and high cost;
- Generation 2 (2015-2020): NCA and NMC batteries, gradually increasing proportions of nickel to replace cobalt in order to reduce the cost and improve the specific energy;
- Generation 3 (2020-2030): varying cathode compositions, increasing proportions of silicon in the anode, and introduction of solid polymer electrolytes;
- Generation 4 (2030 onwards): solid state batteries with a solid anode, a solid electrolyte, and three possible cathode compositions (as of now).

Figure 17: Evolution of battery technologies



Sources: Mirova / (IEA, 2018)

Since cobalt is expensive and its supply is subject to problems, the industry's first priority is to reduce the proportion of cobalt used by increasing the proportion of nickel and thus improving the battery's specific energy and therefore the range of the vehicle. However, nickel also decreases the number of charging cycles and is slightly more expensive than manganese and aluminum. Therefore, the industry is also working to cut down on the amount of nickel.

[4] Cobalt oxide is reactive. If the battery fails, the rise in temperature will cause the oxide decomposition. This will release oxygen which will react with other combustible materials.

The main advances expected between now and 2030 are:

- **eLNO**, an improved lithium nickel oxide battery developed by Johnson Matthey which is expected to contain 90% nickel, 5% manganese and 5% cobalt, and to go into production in 2021. This technology would improve the specific energy (+15% compared to NCA technology), lower the cost by further reducing the use of cobalt, and increase the number of charging cycles;
- **NMC 271**, a battery developed by BASF which is expected to go into production in 2021, and which will replace a significant proportion of the nickel in the battery with manganese (slightly less expensive). However, the ability of manganese oxide to deliver a specific high energy given the limited specific energy of LMO (lithium manganese oxide) technology is questionable;
- **The HVS cathode** (LNMO) which is composed of lithium, nickel and manganese, and which does not contain any cobalt. This technology is in the preliminary phase of experimental research;
- Increasing integration of fluorinated electrolytes which will raise charging voltage capacities and increase the battery's lifespan;
- Incorporating silicon into the synthetic graphite which forms the anode. Today, silicon represents less than 5% of the anode, but this proportion is expected to increase because the integration of more silicon could significantly improve the specific energy.

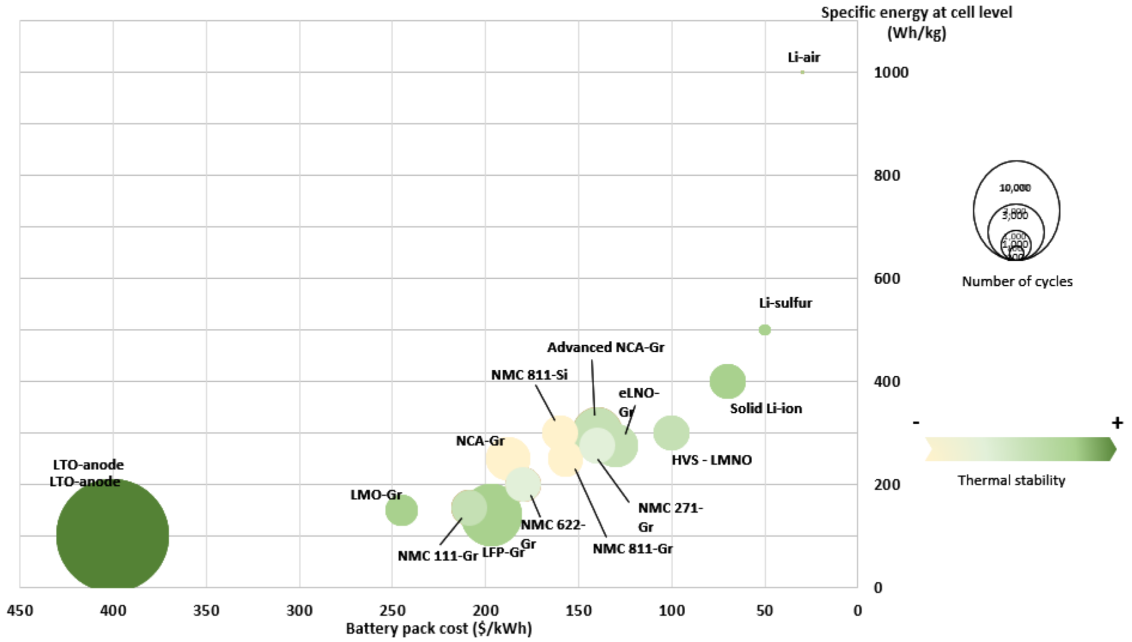
After 2030, batteries are expected to enter a "solid" battery age. Several things are necessary in order for this to happen:

- **Solid electrolytes** which can replace liquid electrolytes. Solid electrolytes (glass or ceramic plates) are safer and have a longer lifespan (~1,200 charging cycles). They also have a specific energy of 800 to 1,000 Wh/kg[5] and take only a few minutes to charge which allows them to compete with conventional vehicles in terms of range;
- **Anodes** made of an ultra-thin layer of **lithium metal** or **pure silicon.** In theory, an anode made entirely from silicon could increase the specific energy by a factor of 10, but the cost of production is currently too high. However, lithium metal anodes are even more expensive, and using lithium anodes would lead to a dependency on lithium which also has a volatile price;
- **Lithium-Sulfur** or **Lithium-Air cathodes** with a specific energy of 500 Wh/kg and 750 to 1,500 Wh/kg respectively. Significant research is being done into both types, but there are still many technical challenges to overcome — flawed stability and a short life cycle for lithium-sulfur and inability to discharge for lithium-air.

In solid battery technologies, there is no longer a separator at the center of the electrolyte. Dates are hypothetical and may be subject to change depending on electrochemical research efforts currently underway. The "all-solid-state" battery, which is expected to hit the market by 2030, could arrive much earlier (2025), if we go by the increasingly accurate announcements made by producers.

[5] Gasoline has a specific energy of 13,138 Wh/kg

Figure 18: Summary of existing and anticipated technologies



Sources: Mirova

Over the past ten years, the automotive industry has experienced a technological breakthrough. Although it started small, it has continued to gain momentum and today it is viewed as a threat by traditional car and equipment manufacturers who have lost their technological advantage.

HYDROGEN

In fuel cell vehicles, electrical energy is stored in the form of hydrogen which acts as a vector. This means that there are several steps separating the primary source of energy from the energy which is consumed by the car.

The range that fuel cell vehicles offer is comparable to conventional vehicles: approximately 600 km. More generally, if we ignore the current lack of charging stations, the experience offered by a fuel cell vehicle is similar to a conventional vehicle, particularly in terms of the time it takes to charge/refuel the vehicle. Therefore, the first challenge facing fuel vehicles is to be ecologically attractive at an equivalent cost to that of a conventional vehicle. These two parameters - cost and environmental benefit - are based on the life cycle of hydrogen, from its production to its conversion into electricity inside the vehicle. Today, the production of hydrogen depends largely on fossil fuels, which means hydrogen has a mixed carbon footprint (see Hydrogen). This also makes fuel cell vehicles very expensive.

The hydrogen sector

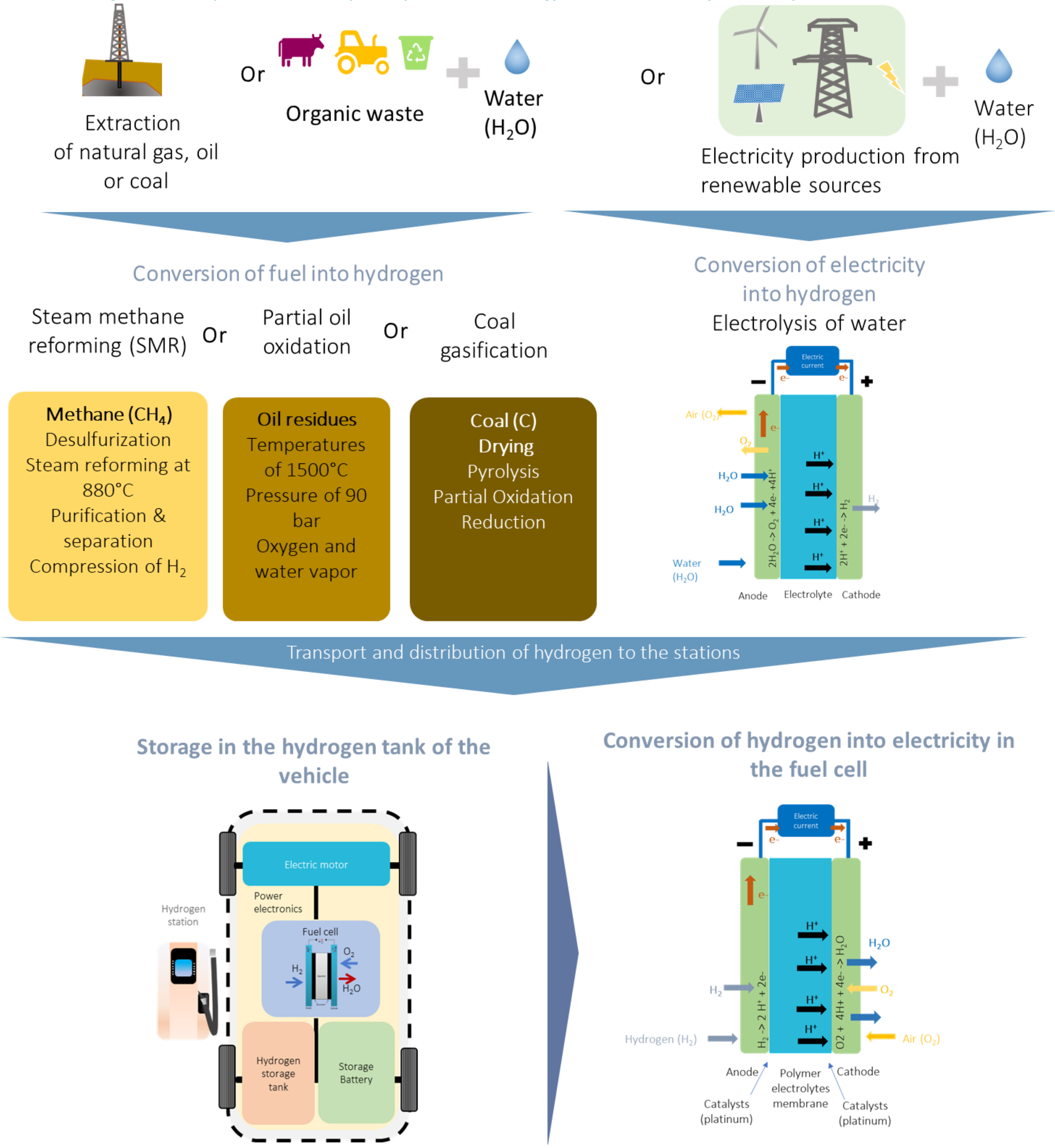
The market for hydrogen is already significant even if we do not factor in transportation applications. Around 70 million tons are produced each year and used for applications such as: oil recovery and refinery (46%), ammonia production (44%), methanol production (4%), metal production and manufacturing (2%), electronics (1%), the food industry (1%). Hydrogen is already being produced and distributed for all of these applications.

HYDROGEN PRODUCTION

Hydrogen does not occur naturally on Earth. To store energy in the form of hydrogen, hydrogen must first be produced. To do so, the four main methods used today, from the most common to the least common, are:

- Steam reforming or steam methane reforming (SMR) of natural gas or biogas. This method involves very hot steam reacting with methane;
- Partial oxidation of oil fractions. This method uses heavy oil fractions and coal. Reactions take place under very high pressure and temperature and in the presence of oxygen and steam;
- Coal or biomass gasification. This method relies on coal pyrolysis which, under high temperature and pressure, decomposes to form carbon monoxide, hydrogen, and by-products;
- Water electrolysis. This method consists of passing an electric current through an aqueous electrolyte between two electrodes in order to break the bonds that hold hydrogen and oxygen together in water.

Figure 19: Steps between the primary source of energy and the electricity used to power fuel cell vehicles



Source: Mirova

Today, 96% of hydrogen is produced using fossil fuels: 49% by steam methane reforming, 29% by the partial oxidation of oil fractions, and 18% by the gasification of coal. The remaining 4% is produced by water electrolysis (OECD/IEA, 2015).

Steam methane reforming is the most widespread industrial production process. This process is well-known and inexpensive (< €2/kg of hydrogen vs. ~€3 from biogas), but does not yield low-carbon hydrogen, (~10 kg of CO_2 per kg of H_2 produced), nor does it break the dependence on fossil fuels. Partial oxidation of oil is used mainly because of the low cost of oil fractioning. And lastly, the gasification of coal, a method which is only used in China and

South Africa, is limited due to its large carbon footprint. Biomass gasification presents complications related to competitiveness due to the lack of supply chains near gasification units. However, in 2018, Japan announced plans to source liquid hydrogen produced from Australian lignite. Following Fukushima, countries such as Japan which do not have fossil fuel deposits must either develop their renewable energy sector or import energy. This plan will provide Japan with a reliable source of continuous energy but will also transfer the CO_2 emissions to Australia. This sort of plan, unless it includes provisions for carbon capture and storage facilities, completely cancels out the environmental benefits associated with hydrogen. Unfortunately, providing for carbon capture and storage does not make much sense from an economic point of view (>€10/kg of hydrogen produced).

Lastly, although water electrolysis has existed for nearly a century and offers a good carbon footprint when low-carbon electricity is used, the high cost of electricity and electrolyzers make it expensive (4 to €10/kg) and it has remained a marginal production method.

Table 1 lists the advantages and limitations of the production processes most widely used today.

Table 1: Comparison of the two main methods of hydrogen production

	Steam reforming	Electrolysis of water from renewable energy sources
Price (€/kg of H_2)	1.5-2	4-10
Well-to-tank carbon balance ($kgCO_2$/kg d'H_2)	13.8	0.5
Advantages	Mature technology Price	Carbon balance : close to zero Independence from fossil fuels
Challenges	Dependence on liquid hydrocarbons, gas or coal resources Limited carbon benefits during the life cycle (approximately 20% less than diesel vehicles)	Energy-intensive process with carbon benefits if the electricity used comes from renewable or nuclear energy Lower yield than steam reforming (taking into account the electricity used to split water molecules) Costly production because of the price of the electrolyzer and the energy-intesive aspect of the process Great amount of energy needed all year long (issue of the lack of continuity when it comes to renewable energy sources)
Solutions	Developement of biogas solutions which are able to capture methane Installation of new devices which are able to capture and store carbon near steam reforming plants in order to capture CO_2 (which would recude the advantage regarding the cost)	Development of electrolysis at high temperatures to improve the yield and reduce the costs Although the yield is average (approximately 50%, if it involves renewable energy sources the impact is low Using hydraulic and nuclear energy allows for a low carbon balance, an affordable cost and the issue regarding the irregular basis of renewable energy is compensated by small decentralized electrolysis falicities

Sources: Mirova

At this stage, hydrogen as a whole is dependent on fossil fuels and is a carbon energy vector. In order to become a valid solution for the transportation energy transition, hydrogen production must become low-carbon while remaining economically competitive.

TRANSPORTATION AND DISTRIBUTION OF HYDROGEN

Hydrogen logistics and distribution infrastructure can be more closely compared to the refueling infrastructure for conventional vehicles (see Infrastructure: Refueling fuel cell vehicles). There do not seem to be any major challenges in this regard.

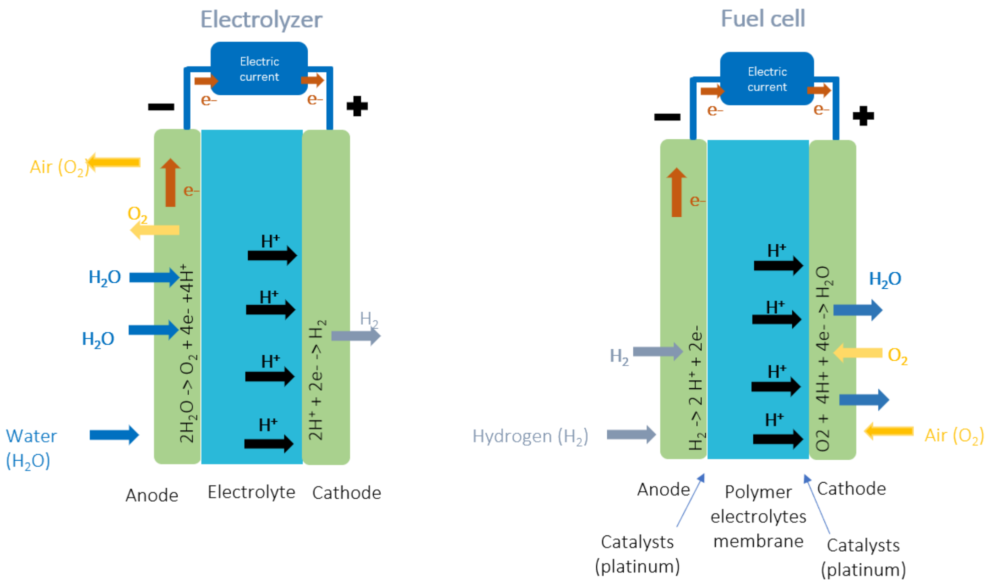
However, storing the hydrogen once it is on-board the vehicle is complicated and expensive: hydrogen tanks are subject to stricter standards than traditional gasoline or diesel fuel tanks. Hydrogen is most often stored in type IV tanks, made from carbon fiber reinforced polymers which can withstand an internal pressure of 700 bar, allowing them to carry between 5 and 6.5 kg of hydrogen. 700 bar of pressure decreases the energy efficiency of hydrogen by about 15%. Because of this, 350 bar of pressure is commonly used in buses where there is more storage space.

CONVERTING HYDROGEN INTO ELECTRICITY

In order to be used as an energy vector in transportation, hydrogen must be transformed into electricity by the fuel cell on board fuel cell vehicles.

The fuel cell uses electricity to perform reverse electrolysis: transforming hydrogen and oxygen into electricity and water.

Figure 20: Diagram of cells in an electrolyzer and a fuel cell



Sources: Mirova

The proton exchange membrane fuel cell (PEMFC) is the technology used in today's transportation applications. A fuel cell system consists of a fuel cell and auxiliary components which are necessary to support the chemical reactions taking place within the cell. These auxiliary components include the air compressor which supplies oxygen to the battery, a cooling system and humidifiers. In the cell, the anode and cathode are separated by a polymer electrolyte membrane which is surrounded by two catalytic layers that accelerate reactions. These layers are usually made of platinum because platinum greatly accelerates reactions.

These hydrogen oxidation reactions (at the anode), which produce H+ protons, and oxygen reduction reactions (at the cathode), occur at the electrode-electrolyte interface in the presence of a catalyst, usually platinum.

Using hydrogen in transportation applications involves many steps and relies on the expertise of chemists. Today, these steps raise questions about costs, energy consumption, and CO_2 emissions. They also raise safety questions which complicate introducing hydrogen into transportation systems.

Economic and ecological costs

The economic data on fuel cell vehicles is based on the integration of the costs of all the components needed in order to use hydrogen as a transportation energy vector, such as:

- Fuel cell systems and tanks for vehicle manufacture,
- Electrolyzers necessary for producing low-carbon hydrogen.

Figure 21: Fuel Cell Vehicle Cost Breakdown – Sedan type

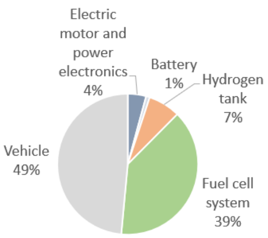
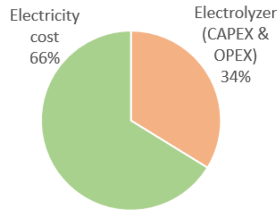


Figure 22: Breakdown of the production costs of one kg of hydrogen from water electrolysis



Hypotheses: Initial capex of 2,600 USD/kW, opex equal to 6% of the capex, 15-year lifespan with 5,000 operating hours per year, 500 kW of power, median electricity price of €7/MWh

Source: Mirova / (OECD / IEA, 2015)/ (Ministry of Ecology, Sustainable Development and Energy, 2015)

To be accepted as a viable ecological solution, the production of hydrogen must become low-carbon and accessible thanks to the solutions found regarding key steps, in terms of costs and ecological balance: hydrogen production, on-board storage and the transformation of hydrogen into electricity.

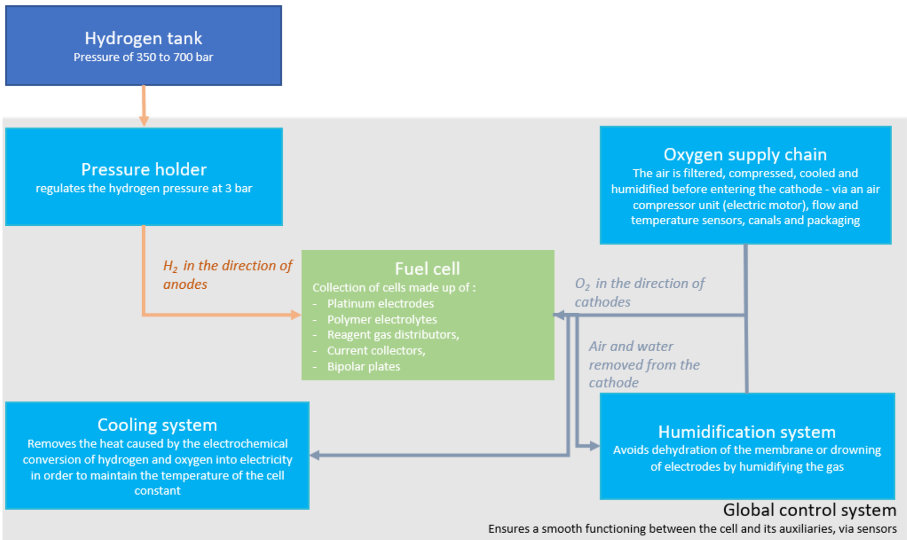
VEHICLE MANUFACTURING COST

The fuel cell system accounts for almost 40% of the cost of a sedan-type vehicle, which remains significantly more expensive than a conventional vehicle of the same type. On-board hydrogen storage alone represents ~7% of the cost.

(a) Fuel cell systems

The transformation of hydrogen into electricity is carried out by the fuel cell system which connects the fuel cell to other elements. These elements supply the reagents (hydrogen and air), control them (pressure, flow rate) and manage the reaction products (water, heat, electricity). An electric motor is used to compress air.

Figure 23: Simplified diagram of a fuel cell system

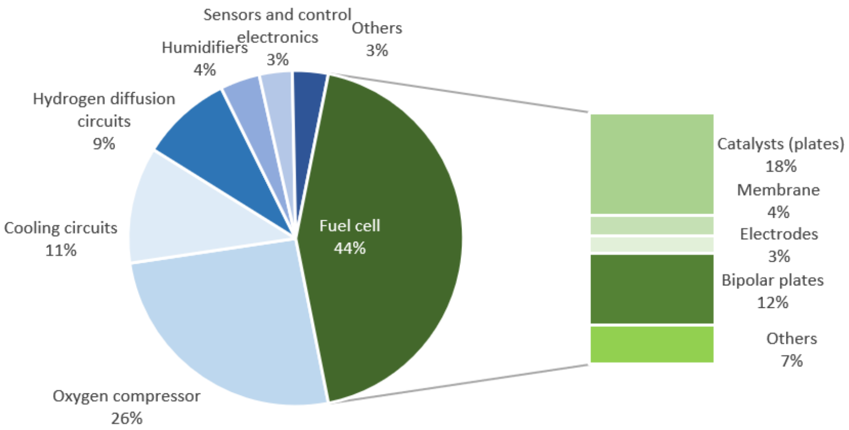


Sources: Mirova/ (Thompson, et al., 2018)

As of 2018, fuel cell systems installed in vehicles offer 80 kW at a cost of 230 USD/kW – excluding hydrogen tanks. In less than five years, the cost has been halved by massive investments, including Toyota's.

Estimated cost parity with conventional vehicles is around 30 USD/kW and may be reached in 2030 thanks to larger-scale productions and electrochemical progress.

Figure 24: Fuel cell system cost breakdown – excluding the hydrogen tank



Sources: Mirova/ (Thompson, et al., 2018)

The items which cost most are:

- The oxygen diffusion circuit, and especially the oxygen compressor (the electric motor requires permanent magnets),
- Catalysts (generally, platinum) perform the best, but the cost of platinum is high and volatile,
- Bipolar plates, made of aluminium or composite materials, which help to maintain the system, distribute gas, and cool the fuel cell.

Like electolyzers, mobile fuel cell systems are still at the experimental stage and are produced in very small quantities, which explains their high cost. We can therefore expect technical developments in the coming years, which will reduce energy loss and costs. The US Department of Energy estimates that increasing production to 500,000 units could lower the cost of the system to 50 USD/kW. The aim is to lower it to 40 USD/kW by 2025 and eventually to 30 USD/kWh which is considered cost parity (US Department of Energy, 2018).

Experimental work is also being done on solid oxide fuel cells (SOFC), which operate at high temperatures (650 to 1,000°C) and do not use catalysts.

Table 2: Portable fuel cell characteristics

Fuel-cells	Alkaline fuel cell	Proton-exchange membrane (PEM)	Solid oxide fuel cell
Maturity	On the market	New on the market	Being developed
Operating temperature	80-90°C	<120°C	~500-1000°C
Useful output energy	60-70% (62%)	50-70% (45%)	60-65% (55%)
Power	10-100 kW	0.1 à 500 kW	1kW – 2MW
Useful life	5,000-8,000 hours	<8,000 hours (Ballard)	Up until 90,000 hours
Advantages	+Cheaper components +Low temperature: starts quickly	+ High energy density + Low temperature ~80°C : starts quickly + Solid electrolytes means higher durability	+High energy output +Various Fuels +Solid electrolytes
Disadvantages	-Sensitive to CO2 -Electrolyte	- Cost of platinum catalysts - Sensitive to hydrogen purity	-High operating temperature - Starts slowly - Can only be restarted a limited amount of times
Applications	Movable, Transport, Military, Aerospace	Movable, Transport (90%), Stationary, Commercial vehicles	Stationary storage
Maturity	On the market	New on the market	Being developed
Cost (2015)	~200-700 USD/kW	~300 USD/kW	3,000-6,000 USD /kW
Concerned companies	AFC Energy GenCell	Toyota, Hyundai, Honda Toshiba	Bloom Energy Aisin

Sources: Mirova / (OECD/IEA, 2015)/ (U.S. Department of Energy, 2016)

(b) Hydrogen tanks

The characteristics of hydrogen – low bulk density (0.089 kg/m^3), lightweight, disperses easily – make on-board storage tricky.

Storing 1 kg of hydrogen under normal temperature and pressure conditions would require about 11 m^3, a family-sized sedan only offers ~0.4 m^3. This gap explains the need to compress hydrogen and to find solutions which allow it to be stored safely in normal-sized vehicles.

Today, hydrogen is most commonly stored under pressure. For on-board vehicle applications, hydrogen is compressed under around 700 bar of pressure (density of 42 kg/m^3) for cars and 350 bar for buses. Compression requires a certain amount of energy, which lowers the energy efficiency of hydrogen, but is nevertheless indispensable for transportation applications. With 6 kg of hydrogen compressed under 700 bars, a fuel cell car's range is 600 kilometers, comparable to the range of a conventional vehicle. The refueling time is also similar: around 1.5 to 2 kg H_2/min.

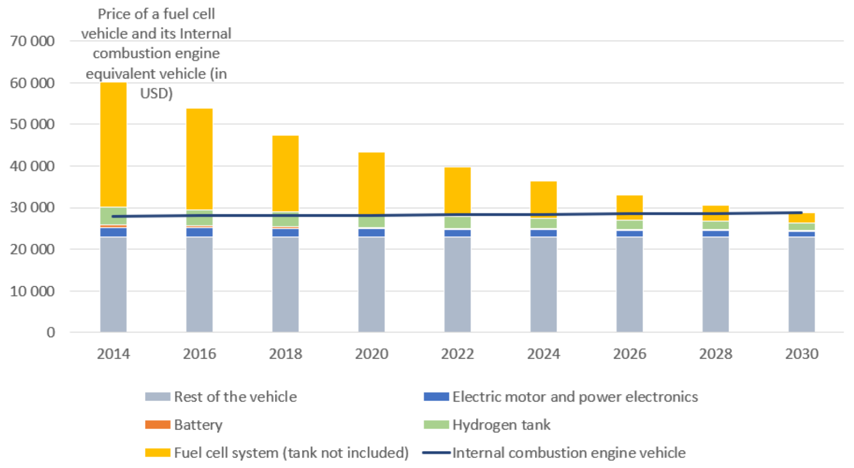
However, storing hydrogen requires a tank that is both light and durable. This is made possible by the characteristics of carbon fiber-reinforced composite materials. Tanks made of these materials do exist and meet all requirements in terms of impermeability and resistance to pressure and shocks, but they remain very expensive to develop.

The current cost of a 6 kg tank is approximately 3,000 USD (US DOE, 2018) (Azzaro-Pantel, 2018). Composite materials make up a large part of the cost of the tank. The goal of the U.S. Department of Energy is to reduce the cost to 333 USD/kg by 2020, and eventually, to cut the current price by half thanks to scale effect and lower costs of composite materials (Mirova, 2013).

Solid storage via metals (magnesium-based alloys) which act as sponges, absorbing hydrogen at a certain temperature and returning it to another temperature threshold, is also being studied. This process would allow large storage volumes (106 kg/m^3 density) to be achieved by eliminating pressure constraints (energy loss and cost), however prohibitive mass density limits its use in mobile applications.

The fuel cell vehicle industry suffers from the number of expensive and energy-intensive steps between the primary energy source and the use of electricity in the vehicle. Certain technologies, which improve performance and reduce costs, exist or are in development. By 2030, technological progress should have made it possible to achieve cost parity with conventional vehicles, at least in the case of private vehicles.

Figure 25: Current and anticipated price of a family sedan-type fuel cell vehicle



Sources: Mirova/ (IEA, 2015) (Thompson, et al., 2018) (US DOE, 2018)

The fuel cell vehicle sector seems only a little behind the "pure" electric vehicle industry; the costliest items – the electrolyzer/fuel cell and the on-board hydrogen tank – are only produced on a small scale and remain experimental. This suggests that there is no technical barrier to obtaining/producing affordable fuel cell vehicles, but that significant investment is required, and that this type of vehicle will be integrated into the transportation sector more slowly. However, in terms of range and fueling speed, fuel cell vehicles remain a fairly logical solution for heavy-duty vehicles – which cannot handle the addition of heavy batteries – and are designed to travel long distances.

PRODUCTION OF LOW-CARBON HYDROGEN

Three main solutions for producing low-carbon hydrogen dominate projections:

- Water electrolysis using renewable energy,
- Steam methane reforming using biogas or biogas gasification,
- Developing carbon capture and storage.

All three solutions are theoretically possible but costly. In order for these technologies to be developed, the cost will be close to the cost of hydrogen produced from steam methane reforming: ~400 USD/kWh (OECD/IEA, 2015).

(c) Water electrolysis

The cost of water electrolysis depends mostly on the cost of electricity (today, ~50-60 kWh are required to produce 1 kg H_2) and the type of electrolyzers used. Thus, the production of electrolyzers represents a compromise between energy efficiency and cost of capital. Figure 22 shows that the cost of investing in and maintaining the electrolyzer accounts for more than a third of the production cost for 1 kilogram of hydrogen. However, this proportion can increase greatly depending on the estimated lifespan of the electrolyzer and the energy efficiency.

Because electrolyzers and fuel cells carry out the same reaction in reverse, their composition, the principles behind how they function, and the knowledge required to produce them are similar. Two different technologies are used in electrolyzers and fuel cells, depending on the pH level of the electrolyte:

- Alkaline (basic) electrolyzers and fuel cells use sodium hydroxide (NAOH) or potassium hydroxide (KOH) electrolytes:
- Acidic electrolyzers with a polymer electrolyte membrane (PEM).

To date, alkaline electrolyzers are the most widely used. PEMs are preferred by almost all of the world's automotive programs because of their compactness, how simple they are to manufacture and operate, their lack of corrosion-related problems, and their performance (higher theoretical efficiency, better adapted to receive intermittent renewable energy due to their capacity to withstand variations in electrical power). However, the cost of a PEM electrolyzer is about 2,600 USD/kW vs. 1,150 USD/kW for an alkaline electrolyzer. This is largely due to the cost of the polymer membrane and the use of metal-based catalysts which have a shorter lifespan (40,000 hours versus 75,000 hours for alkaline electrolyzers) (OECD/IEA, 2015).

Today, only very low volumes of electrolyzers are produced. Most of the assembly process is still done by hand. Low production volumes leave manufacturers with little bargaining power to negotiate prices with suppliers, especially the prices of raw materials. Highly complex specialized manufacturing systems must be both simplified and industrialized before costs can come down. The following two factors in combination will reduce prices:

- Economy of scale as production capacities increase;
- Technological synergies from investments in the PEM fuel cell which will reduce costs and improve technology.

According to the International Energy Agency, PEM electrolyzers are expected to achieve a yield of 82% and a lifespan of 75,000 hours at a cost of 800 USD/kW by 2030. The cost per installed kW is expected to be 640 USD/kW by 2050 (OECD/IEA, 2015).

In addition to developments in storage batteries, funds are being invested to make electrolytes solid, both in fuel cells or in electrolyzers. Solid electrolyte (SO) electrolyzers would increase efficiency to 90% vs. 75 % for polymer electrolyte (PEM) electrolyzers.

(d) Steam methane reforming using biogas or biogas gasification

Biomass can reduce the carbon footprint of steam methane reforming and gasification processes.

Steam methane reforming can use biomethane, which comes from biogas which is produced by organic waste such as agricultural, municipal, or coastal agroindustrial waste (green algae).

Gasification, which consists of decomposing a solid carbon fuel using heat to obtain a gaseous mixture, can also be done using coal or biomass.

The process of producing hydrogen from biomass is virtually unexploited. The chemical and biochemical technology which would need to be implemented is relatively complex and would require a significant investment to the tune of 1,250 USD/kW (OECD/IEA, 2015) and expensive operations, whereas the process for producing hydrogen through natural gas reformation is already in place and is inexpensive.

(e) Developing carbon capture and storage

Carbon capture and storage is another solution for recovering CO_2 emissions issued by steam methane reforming plants. This process involves trapping CO_2 molecules to prevent their release. The CO_2 is then transported, either by pipeline, by ship, or by truck, to be stored in geological formations in the subsoil allowing for its long-term sequestration. This solution is expensive and would increase the initial capital cost of methane reforming plants from 550 to 1,370 USD/kW. Moreover, it only makes economic sense for large plants.

(f) Other solutions

Other resources and production methods, such as using bioreactors to produce hydrogen from algae, are also being studied. Algae dissociate water into hydrogen and oxygen during photosynthesis, using only solar radiation and water. However, at this stage yields are too low to justify the type of investment necessary to develop bioreactors.

Even if we disregard further progress related to biogas/biomass and the development of carbon capture and storage, producing hydrogen from water electrolysis using renewable energies is a major asset in positioning hydrogen as a form of energy storage and a catalyst for developing intermittent renewable energies. In addition to its uses in the mobility sector, hydrogen can be used as a tool for storing energy and could help to meet the challenges of intermittent renewable energies such as solar and wind, especially because hydrogen production can be either centralized or decentralized. When decentralized, the production facility is located near sites where renewable energy is produced or consumed. The flexibility offered by catalysts allows for energy consumption to be adjusted to match energy production or the energy demands of sites. This link between hydrogen and renewable energy is crucial for future progress in the sector.

Safety

Hydrogen gas is highly flammable, therefore, storing it under high pressure pose a significant risk. However, the low density and high volatility of hydrogen make it relatively easy to handle it safely, especially since its autoignition point is higher than other fuels.

Moreover, both hydrogen and the residues from its combustion are not toxic, so leaks do not pose environmental or health problems.

Finally, certified pressurized storage technologies and fuel cells ensure that hydrogen is reliable and no more dangerous than other fuels.

C. Electric motors

The electric motor converts electrical energy into mechanical energy. The powertrain also consists of a gearbox, which provides the transmission, and power electronics (inverter and converter), which transform the electric current between the battery and the motor.

Electric motors are less complex and less expensive than internal combustion engines. In all electric motors, torque is produced by the electromagnetic interaction between a static part, the stator, and a moving part, the rotor. There are three main types of AC electric motors on the automotive market today:

- The permanent magnet synchronous motor improves maintenance, performance and weight by using magnets to generate a magnetic field. The drawback is that these magnets contain rare earth elements such as neodymium, praseodymium and samarium (see Resource Issues). These engines are the most common on the market today. The Chevrolet Volt, the Nissan Leaf, the BMW i3 and the VW e-Golf are all equipped with them;
- The wound-rotor synchronous motor is larger and often more unstable which means that it requires more maintenance. It is used in the Zoe, the Fluence, and the Kangoo by Renault, as well as in the Smart electric drive Mehari;
- The asynchronous (or induction) motor is adapted from heavy industry where it is very widely used. It is considered robust, compact and reliable; however, it suffers from inefficient performance. It is well suited to hybrid vehicles, due to its cost and reliability, and it is also used in the Renault Twizzy, as well as in the Tesla Model S and the Tesla Model X.

The production process does not pose any specific problems in terms of cost or duration. The challenge is to find a technology which performs efficiently, and which requires limited maintenance, without depending on rare earth elements.

Generally, engines are produced internally within the automotive sector or by equipment manufacturers. Sometimes they are also made by manufacturers with an interest in electric motorization for different applications.

D. Power electronics

Power electronics are based on semiconductor technologies. Necessary for ensuring that onboard energy is managed optimally, power electronics are more and more present in the automotive market. In electric vehicles, semiconductors are scattered throughout the vehicle and they fulfill a variety of functions, such as:

- Ensuring that the battery receives a constant supply of power using AC-DC rectifiers that convert AC current from the grid to DC power, which is compatible with the battery;
- Managing the electric motor using DC/AC inverters which reduce switching losses and maximize efficiency;
- Recovering energy released by braking using the main inverter;
- Transferring energy from the storage battery to the 12 V low voltage battery used for powering the headlights and the computer via DC/DC converters;
- And lastly, ensuring that the battery management system which controls the charging and discharging of the battery is functional.

Semiconductors used in electric vehicles must be able to withstand high voltages. They are generally based on silicon diodes and IGBTs (insulated gate bipolar transistors). Innovations regarding semiconductors for electric vehicles aim to improve their electrical efficiency for an increased range and faster charging. Two wide bandgap technologies[6] are being studied: Gallium Nitride (Gan) semiconductor technologies and silicon carbide (SiC) semiconductor technologies. These technologies would replace standard silicon. Silicon carbide (SiC) is a wide bandgap technology that enables the production of smaller components capable of operating clearly far above the voltage range of 400 V. SiC components react faster than silicon integrated circuits which minimizes energy loss and reduces the size of the components. The second semiconductor technology which contributes to vehicle performance is gallium nitride (Gan), which performs well and is robust and resistant to high temperatures.

E. Infrastructure

In order for an automotive technology to be reliable, a user must be able to recharge their vehicle quickly and easily. The change in the propulsion method will result in changes in energy vectors and changes to the recharging infrastructure. Thus, the development of electric vehicles requires the implementation of an efficient and well-connected electrical grid.

REFUELING BATTERY ELECTRIC VEHICLES

There are two major challenges facing the charging infrastructure sector when it comes to battery electric vehicles:

- Reduce the charging time to that required to refuel, ~2 minutes;
- Build a network of charging stations and meet user needs by installing “slow,” “accelerated,” “fast,” and “ultrafast” charging stations based on geographic location and projected demand.

Charging time

The duration of a charge depends on the characteristics of the vehicle’s battery (size and the charge that the anode can withstand) and on the amount of power delivered by the charging station.

Today, charging an electric vehicle with a compact battery (50 kWh) takes about fifteen hours with a standard charge (3 kW), or about one hour with a fast charge (43 kW). The charge rate is not linear, which means that in just over 30 minutes the battery will be at 80%. Still long charging times mean two things:

- It is doubtful that this long charging time will decrease naturally, because vehicles’ onboard capacity in kWh continues to increase in order to meet consumer demand for range. Therefore, in order to reduce charging time, it is necessary to find innovative solutions for charging stations which will reduce charging times (and to ensure that the batteries used can withstand such high voltages);
- There is not a single charging mode, but several charging modes to match consumers’ needs (standard "slow" charging at night may be used most of the time and ultrafast charging may be used occasionally on long journeys) and the vehicle’s charging capacity.

[6] A wide bandgap semiconductor is a semiconductor whose band gap, the space between the valence band and the conduction band, is significantly wider than the bandgap in silicon. This characteristic is what makes wide bandgap semiconducters able to exceed the functional limitations of silicon, allowing devices to operate at much higher voltages.

Creating a network of charging stations

Unlike fuel stations for conventional vehicles, charging stations are not standardized. Several different types of charging stations with different charging speeds and price points currently exist and must find ways to respond to consumer demand.

WAYS OF CHARGING ELECTRIC VEHICLES

Different ways of charging electric vehicles exist:

- Charging via a cable is still the only option available today for passenger vehicles;
- Induction charging via an electromagnetic field generated under the vehicle is another charging option. This option is more practical but less efficient. This technology is still in the early experimental phase. Widespread use of this technology outside of fleets of autonomous or shared vehicles is not expected to be made available for at least ten years for regulatory and safety reasons.
- Dynamic charging, where a vehicle is charged while on the road is viewed as a long-term charging solution;
- Battery swapping, which was initially considered an interesting option for reducing charging time now seems to have fallen by the wayside due to a lack of standardization and the rapid evolution of battery technologies.

In the case of electric buses, solutions differ depending on whether the bus is charged at the terminus or during the journey. A bus equipped with a battery with a large range can charge at night using a charging station located at the bus terminal. For buses with smaller ranges, various charging methods are possible, such as:

- A telescopic arm, mounted on the roof of the bus, that connects to a storage battery in the bus stop shelter;
- A pantograph, fixed to the bus stop shelter which connects to the bus when it arrives at the stop;
- An underground induction charging system at the bus stop.

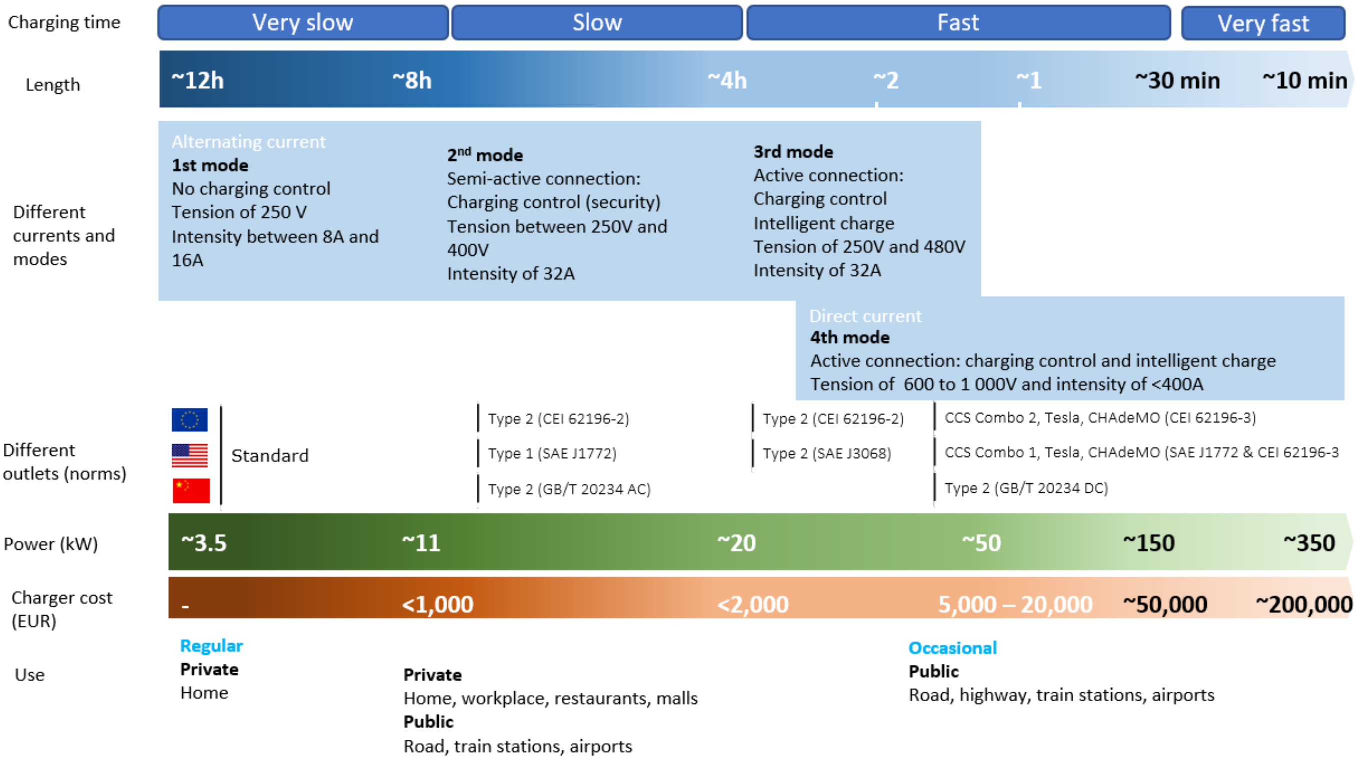
Numerous innovative solutions to the needs of urban bus use are currently being explored. However, when it comes to passenger vehicles, cable charging seems to be the preferred option. Cable charging includes:

- Private infrastructure, which includes home chargers, chargers at the workplace for charging employees' cars and company cars, as well as chargers at restaurants, shopping centers, hotels, stores, and throughout the commercial and service industries;
- Public infrastructure, which is accessible to road users (highways, airports, roads, parking lots, train and bus stations).

Multiple technologies coexist, using either alternating current for slow charging or direct current for fast to ultrafast charging. These different charging technologies can be divided into:

- 4 modes which are defined by the charging time, the power, the voltage, and the type of connection;
- Several types of connectors (sockets) which are adapted to the type of current (alternating or continuous), the charging speed, and the geographical areas where they will be used. These connectors must conform to local standards in order to be placed on the market.

Figure 26: Charging solutions



Sources: Mirova / (Spöttle, 2018) (IEA, 2018)

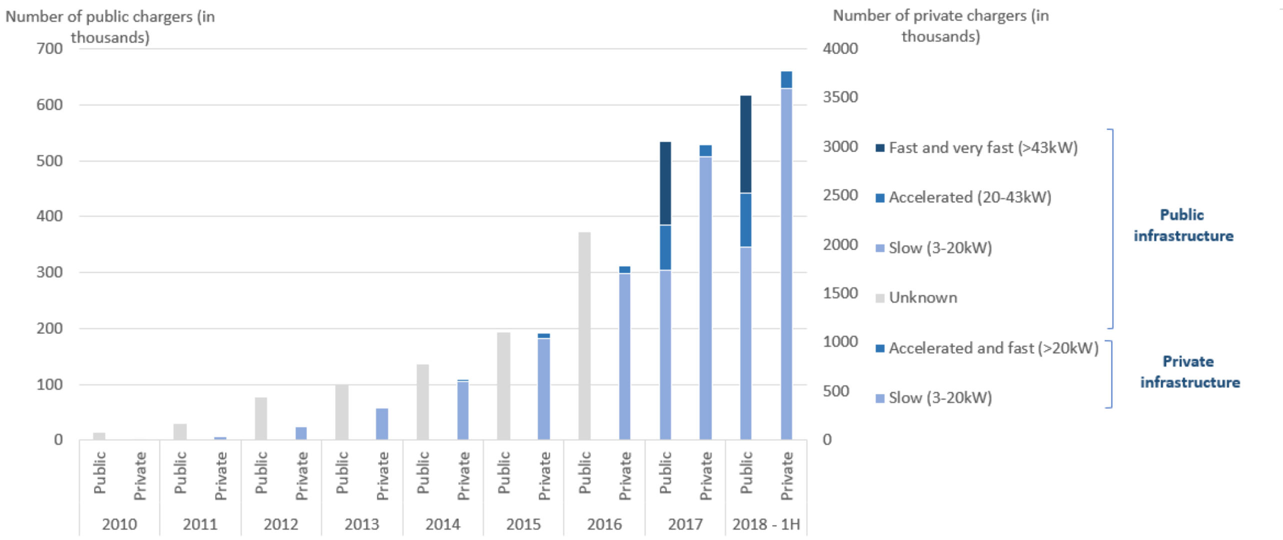
Private charging could be done simply by using an outlet in a garage. However, often a charger is supplied by the manufacturer when the vehicle is purchased. Other electrical equipment can be used in combination with the charger to secure and accelerate charging. In order to reach 22 kW of power (~2.5 hours of charging time for an onboard battery of 60 kWh), additional charging stations and investment are required. Among companies, the charging speed available depends on whether the future user is an employee or a client.

Finally, in the case of public infrastructure, it is also necessary to think about the intended use of stations in order to install the more expensive fast and ultrafast charging stations in areas where demand will be high (highways). Some ultrafast chargers have already been installed, however, most electric vehicles do not yet have the technical capacity to withstand such a high charge. Today, ultrafast chargers calibrate the charging speed to find the best compromise between the charging speed and each vehicle's charging ceiling.

CURRENT CHARGING STATION INSTALLATION

An electrical outlet in a garage can function as a charging station. However, when the number of private charging stations is counted, only outlets equipped with a special device for electric vehicles are included. Globally, without counting China and Japan, there is roughly one private charging station, in the home or at the workplace, for each electric vehicle. In China and Japan, the ratio shrinks to 0.8 chargers per vehicle (IEA, 2018). The relatively high proportion of chargers per vehicle can be explained by the fact that the decision to purchase electric vehicles is primarily based on the ease of recharging the vehicle daily. However, this data is only based on estimates given the lack of information available on the number of private charging points (lack of data collection, limited market).

Figure 27: Number of charging stations available globally



Sources: Mirova/ (IEA, 2018)/ (BNEF, 2018)

In 2018, more than 600,000 public charging stations (and ~3.5 million private charging stations) were available globally: 50% of these stations are slow (3-20 kW), 15% are accelerated (20-43 kW) and 30% are fast (>43 kW). More than half of these charging stations are located in China.

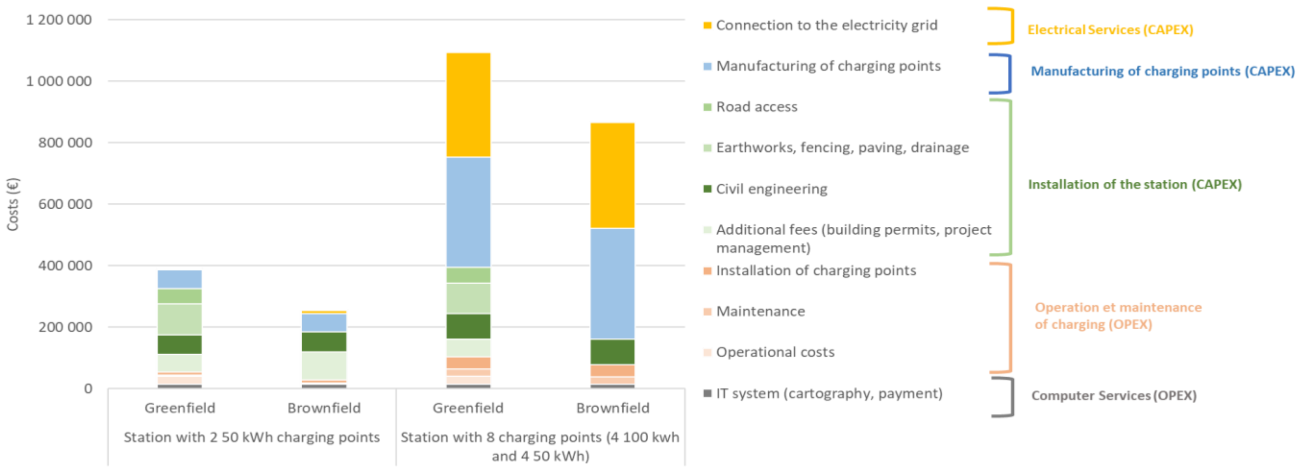
Today, there is ~1 charging station for every 5 vehicles globally. Distribution varies from country to country, from 3.5 vehicles (Netherlands) to 15 vehicles (Norway) for each charging station. The International Energy Agency estimates that a ratio of 8 vehicles per charging station would be enough to support electric vehicle development. Available charging points leads to user acceptance of electric vehicles and positively impacts other elements such as the number of models available, tax incentives, and urban density.

Based on projections from Bloomberg New Energy Finance (see Outlook: Uses and market growth), electric vehicles are expected to account for one third of all vehicles in use by 2040 — ~500 million electric vehicle, or more than 60 million public charging points. To support the development of electric vehicles, the charging infrastructure must grow by nearly 25% each year.

FINANCING

Most of the operators/owners of public charging infrastructures must make unprofitable investments at this stage in the hopes that their strategic positions will become monetizable later on. Other segments of the market: equipment supply, civil and electrical engineering, and maintenance can be profitable in some cases. The charging infrastructure's lack of profitability is primarily due to the low number of users and the fact that the price that users pay for electricity is calibrated to integrate financing costs. In Europe, half of this infrastructure is financed by public funding. The majority of costs come from connecting to the grid, improving the electricity grid, civil engineering, and manufacturing charging stations.

Figure 28: Costs of charging stations in the European Union



Sources: Mirova/ (European Commission, 2018)

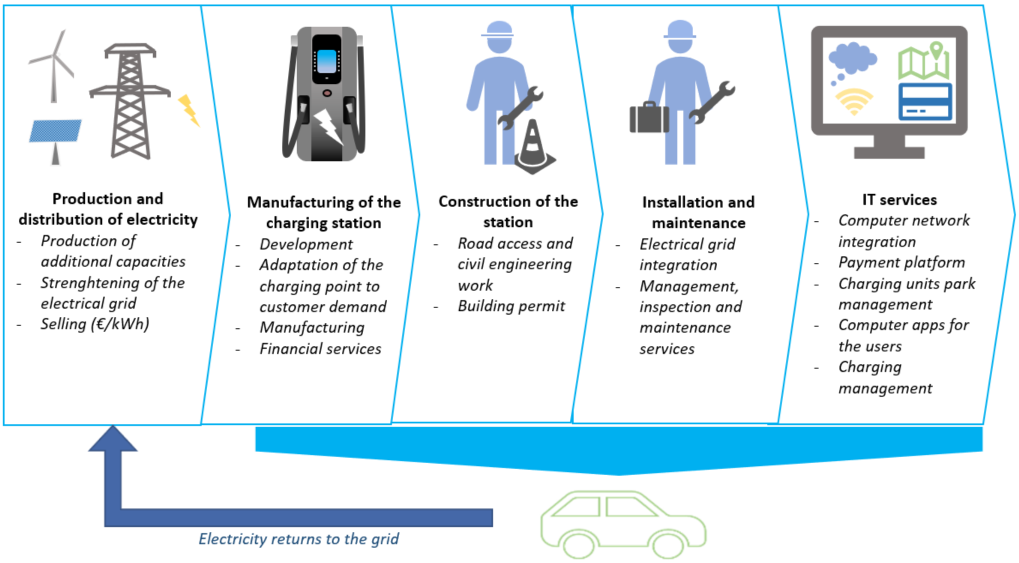
The costs of charging stations can vary depending on whether the station is part of an existing charging point (Brownfield) or a new site (Greenfield) as well as on the load capacity available. These costs do not include the production of the additional electrical capacity required to deploy electric vehicles.

The infrastructure value chain which combines members of the industry (electricity providers, charging station manufacturers and operators, the public buildings and works sector, and information services providers) with investors and takes the need for public financing into account early on is relatively well adapted to public-private partnership models. Most of the networks operating today started with public funding. Initially, services were free, but they transitioned to become paid services as the number of electric vehicles in use grew. This approach makes it possible to include areas which might have been neglected by private investors. The challenge is for communities to justify these investments with non-economic criteria. Reducing investment costs allows networks to become profitable more quickly.

ELECTRIC INFRASTRUCTURE VALUE CHAIN

Four main sectors are involved in ensuring that electric vehicles demonstrate sustainable growth: electricity production and supply (lines and transformers), charging station manufacturing, charging station installation/operation and maintenance, and digital systems which facilitate use and payment.

Figure 29: Electric Infrastructure Value Chain



Sources: Mirova

(a) Electricity production and supply

Electricity providers must adapt the volume of electricity generated to match the growing demand for electric vehicles. This demand can be evaluated:

- If we assume an average distance of 15,000 km/year and an average consumption of 0.2 kWh/km, the total electricity consumed per household is approximately double the average amount of electricity consumed per household in 2014 which was 3,000 kWh (OECD/IEA, 2017);
- More generally, if we include passenger vehicles, buses, and two-wheeled electric vehicles, estimated demand was around 54 TWh in 2017 (IEA, 2018); 90% of this demand came from China. According to Bloomberg New Energy Finance, the demand for electricity to power electric vehicles will reach 2,000 TWh by 2040, which will represent only 5-10% of the global demand for electricity (OECD/IEA, 2017). These projections assume an increase in generation capacity, but that does not seem to be a major problem.

The real challenge lies in managing demand to avoid simultaneously charging a large number of electric vehicles as this would cause local overloads and risk of voltage drops. Electricity providers have a role to play in optimizing charging times and adjusting their rates in order to increase the charging load outside of peak hours (night or midday), spans which also correspond to peak production times for certain renewable energies.

Electric vehicles, and storage batteries in particular, can also help to improve energy management and to integrate intermittent renewables through vehicle-to-grid (V2G) technology because they are able to recover, store, and return electricity to the grid. This technology makes it easier to manage charging demand by distributing electricity through a price signal to avoid peaks in demand. This allows for the charging process to be optimized, both economically and in terms of its carbon footprint. Furthermore, V2G technology can be used to return energy to the grid to smooth peaks in consumption and to provide a useful source of energy for household consumption. In order to be implemented, V2G technology requires a system for compensating storage services, which could ultimately also reduce the costs associated with charging infrastructure.

(b) Manufacturing charging stations

The fast to ultrafast charging stations, ranging from 50 kW to 350 kW, which will be distributed according to projected local demand, do not seem to pose any major technical difficulties. In fact, most major manufacturers are already starting to market ultrafast charging stations. The priority now is to win calls for tenders from large operators in order to continue moving forward by working on large-scale projects.

(c) Charging station providers

The economic analysis of charging infrastructure highlights significant costs which represent development opportunities for private operators, largely in energy services and the manufacture of charging stations. Moreover, the value chain shows that different segments of the market are involved in charging station installation projects. These two factors together explain the large number of companies looking to position themselves in charging infrastructure installation and operation. Operators may be:

- Companies that specialize in the sector, such as Chargepoint, Allego, FLO, Blink, Fastned, Evgo, etc., which primarily run of the fees users pay to access their stations and which could potentially diversify their revenue streams through partnerships with charging station manufacturers and electricity providers. These companies attract many of the largest investor groups, as evidenced by recent acquisitions (Shell acquiring Newmotion, Meridiam acquiring Allego). Some of these companies, like Allego, are launching large-scale initiatives such as the Mega-E (Metropolitan Greater Areas Electrified) project which is subsidized by the European Commission and which aims to deploy more than 320 ultrafast charging stations and about 40 multimodal charging stations in urban areas across Europe;
- Car manufacturers such as
    - Tesla, which has developed its own ultrafast charging network: a move which has strengthened its brand image and increased its sales but has not been profitable;
    - Porsche, who wants to roll out 500 ultrafast charging stations in the USA by the end of 2019
    - Ionity, a European initiative which brings together German manufacturers with Ford, Shell, OMV, Tank & Rast and Circle K and aims to provide a network of 400 ultrafast chargers (350 kW) every 120 km in Europe by 2020. This collaboration makes it possible to obtain public aid which reduces initial investment needs (estimated to ~3 billion euros) and increases profitability;
- Electricity producers and providers for whom the main challenge lies in managing the grid load. For example, Sodetrel (a subsidiary of EDF), Evbox (Engie), Incharge (Vattenfall), E.On, Charge & Drive (Fortum), Innogy, Enel;
- Highway operators such as Tank & Rast in Germany and oil tankers who are taking advantage of the gas stations already in place by joining forces with specialized operators such as Newmotion (Shell), Chargemaster (BP).

Certain hybrid approaches are beginning to materialize, such as Ubitricity’s approach, which allows users to connect their vehicles to the public grid using a small portable charger, or the partnership between BYD and China Southern Power which connects key points in the infrastructure value chain, and which has allowed electric vehicles to penetrate the Chinese market more rapidly. For each purchase of an electric vehicle, 2 charging stations (home and work) are paid for and installed by the partnership. This development comes after the development of vehicle sales which limits profitability problems. This mechanism is supported by public funding.

Operators such as these rely on the skills of manufacturers who make charging stations, building and construction companies, and digital companies in order to implement their projects.

(d) Information technology services

Digital services come into play because users connect to charging stations, use them, and pay for their use via communication systems. Because there are still relatively few electric vehicles on the road at this point, payments have not yet been standardized, either in terms of systems of payment (subscriptions, pay-as-you-go, card-based) or in terms of price. Currently, different pricing systems coexist, including: price per kWh, price per minute, price per hour, and combinations of these factors. As a result, many different charging options are available which can complicate things for users. Users often have to rely on a combination of providers in order to have access to a decent number of charging stations which means users must keep track of multiple cards, applications, and subscriptions. This diversity also raises questions about data security: one of the major challenges associated with standardization. All this means that interoperability is a major goal. Many providers have chosen to use Open Clearing House Protocol. OCHP could become standard across Europe.

At this stage of development, the main challenges facing charging infrastructure are:

- High initial investment needs which may dissuade investors;
- The lack of vehicles and charging infrastructure which allow for charging to be completed in under 10 minutes;
- Potential difficulties associated with overloading the power grid;
- A lack of interoperability between payment systems and a lack of consistent pricing.

All these challenges could be resolved thanks to already existing or developing technologies such as:

- The V2G technology, which provides electricity suppliers with solutions to handle the electric vehicle load on the grid, simplifies the integration of intermittent renewable energy sources to the grid, and allows to reduce the overall costs by using the batteries’ capacity to return electricity to the grid in order to smooth consumption peaks;
- Ultrafast charging units (350 kw) which go hand in hand with the development of anode technologies (use of graphene, niobium-titanium oxide, solid batteries) that can handle the charging speed;
- The Ionity project, MEGA-E, or any other large-scale approach that implies prices harmonization, economies of scale, shared costs between various players and the implementation of a single IT system for geo-tracking and simplified payments.

REFUELING FUEL CELL VEHICLES

There is no standard supply chain since hydrogen distribution depends on:

- The production location - decentralized or on-site - using a renewable energy supplied electrolyzer;
- The targeted use (on which depends the amount of hydrogen stored and compressed on-site).

When the production of hydrogen does not take place on-site, the following modes of transportation are available:

- Pipelines, in which hydrogen can travel alone or with other gases, are mainly implemented in Europe and the USA,
- Road or rail transportation in the form of compressed gas or in cooled-liquid form,
- Maritime transport in liquid form, as Japan wishes to develop.

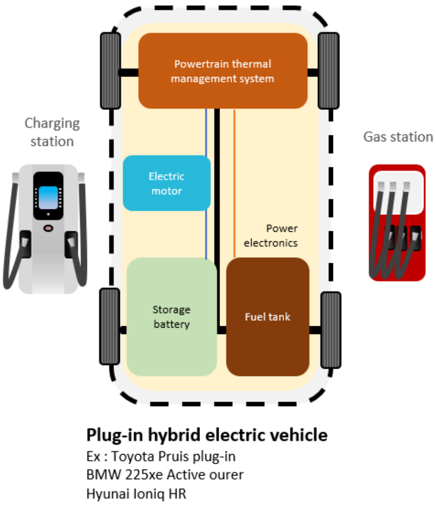
During transportation, hydrogen gas is stored in units of several connected bottles which are unloaded and dropped off at the gas stations, or in form of tubes on a trailer which can support up to 500 kilos of hydrogen. The hydrogen is then distributed to the stations before supplying the hydrogen tanks aboard the vehicles. Several hydrogen stations have already been implanted, mainly in Germany and Japan.

The reduction of the supply chain costs will stem from the adjustment of distribution modes and stations to the final needs as well as progress regarding on-site hydrogen compression. However, the distribution process in itself does not seem to be facing any technical issues, whether on the grid or at the stations.

F. Plug-in hybrid vehicles

Plug-in hybrid electric vehicles are defined as electric vehicles which can function thanks to an pure electric propulsion and offer a 50 km autonomy.

Figure 30: Structure of a plug-in electric vehicle



Sources: Mirova

In such vehicles, the electric motor can either be used to propel the vehicle or in assistance to the combustion engine, which helps reduce fuel consumption. Traditional hybrid vehicles, which only use regenerative braking and assist the internal combustion engine, are not considered as electric vehicles but only as solutions to improve vehicle propulsion.

The environmental benefit of a plug-in electric vehicle depends on its user's habits. If the driver only uses it for short trips and recharges the batteries daily, the advantages will be similar to those of a battery electric vehicle, but if the car is used for long trips, the environmental benefit will be equivalent to the one of a classic hybrid vehicle. Storage batteries in plug-in vehicles tend to have a capacity of <10 kWh, which is four times lower than the capacity of a compact electric vehicle and ten times lower than a Tesla Model S. This weaker capacity has an impact on various parameters:

- The added weight from the batteries cannot be compared to the one of pure electric vehicle's batteries and does not compensate the benefit of the electric drive. In other words, although a plug-in electric vehicle is heavier than its conventional counterpart, it still consummates more energy in mixed use;
- The carbon balance caused by battery production is reduced (see Carbon footprint over the life cycle);
- The autonomy is limited.

From a technical perspective, a plug-in electric vehicle gathers both components from a conventional vehicle and from an electric vehicle, which means that the complexity of the two propulsion modes is contained in one vehicle.

Although a plug-in electric vehicle allows a smooth transition to the complete electrification of the car for the consumer who can choose the electric-only mode for short rides and the hybrid mode for longer ones, the complexity of its structure which combines two propulsion modes and various types of components appears to be an obstacle to its development. When battery electric vehicles will represent a mature sector in terms of costs, performance and reliability, which should happen over a 10-year period, plug-in hybrid electric vehicles will become a costly option for both the manufacturer and the user because of the rise of oil prices, of environmental norms on combustion engines, difficult to make and to maintain and of limited environmental interest.

However, in the short term, plug-in hybrid electric vehicles represent a significant part of electric vehicles (more than 1/3 in 2018).

III. Challenges for the users

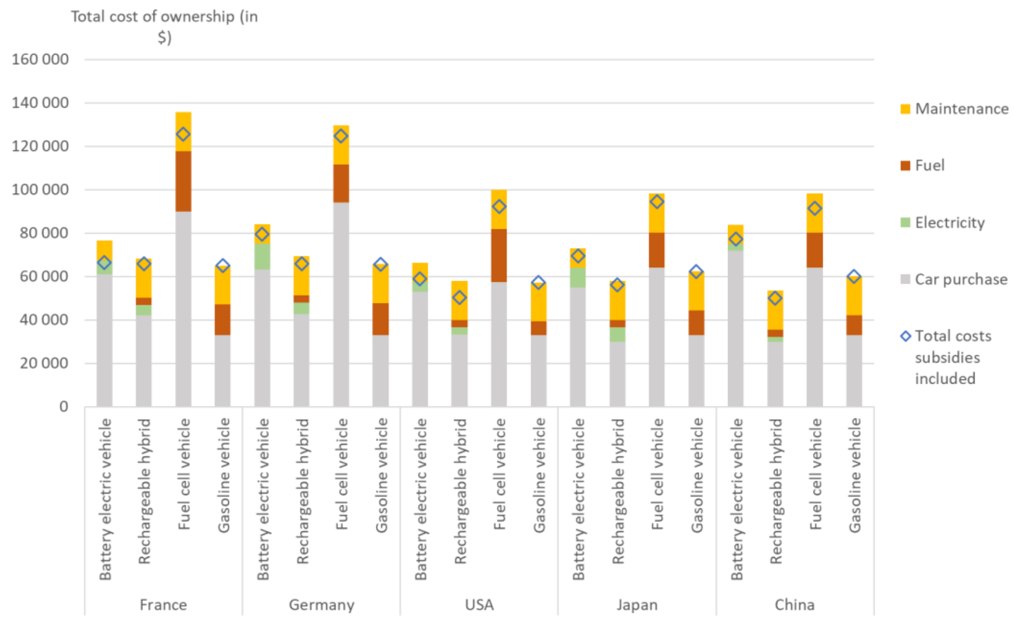
Although the gap between electric and conventional vehicles has been greatly reduced over the last years, the situation on both technical and economic fronts did not lead to a massive adoption of the electric vehicle and many drivers do not seem ready to take this step. This can be explained by three main factors: the cost, the availability of charging options and the novelty of this technology.

A. Total cost of ownership

The total cost of ownership of a vehicle accounts for the total costs at the expense of the driver for his vehicle and therefore includes, in addition to the purchase price, the recurring costs linked to maintenance, oil (or electricity) and insurance. It also takes into account the residual value at the end of the considered period, as well as benefits such as subsidies.

The cost parity of battery electric vehicle with conventional vehicle is expected between 2021 and 2024 depending on segments and technologies. It is typically associated with a battery cost of less than ~100 USD/kWh (depending on battery size). Considering the total cost of ownership of the vehicle, cost parity has already been achieved in some markets, notably thanks to subsidies.

Figure 31: Current total cost of ownership of electric and conventional vehicles (sedan car) over 180,000 km.



Source: Mirova

While electric vehicles are generally more expensive to buy (excluding subsidies), overall the use cost is lower. Electric motors require fewer components, which reduces vehicle maintenance costs (up to a factor 2). Despite some differences between countries, electricity is 2 or 3 times cheaper than gasoline per kilometer, especially in case of home charging which accounts for 90% of charging types. The costs of insurance and financing (interests) are generally the same.

It is different for plug-in hybrid electric vehicles when compared to conventional vehicles: their respective initial costs are close, but lower fuel costs and subsidies for the former offset some of this benefit. Maintenance costs for both engines are also higher.

For fuel cell vehicles, parity cost is not expected before 10 years, and this technology remains more expensive because of the absence of incentives on all markets. The expected technological and industrial benefits, as well as benefits from hydrogen production, should make this technology competitive over the next 10 years in certain segments (large vehicles and commercial vehicles).

In the meantime, the role of incentives and regulations is essential to the development of electric vehicles. The leading markets (Norway, China, California...) have ambitious development objectives helped by numerous mechanisms to support electric mobility at the local, regional and national scales: direct incentives (subsidies for purchase, registration, access to parking, exemption from tolls, access to priority lanes) or through the development of electric car-sharing fleets or public vehicles. Public sector policies for electric mobility also target infrastructure development.

B. Availability of charging facilities

Another major obstacle to the adoption of electric vehicles is linked to the change in practices needed for switching to this technology.

Car drivers consider that the lack of available infrastructure for battery electric vehicles is a major obstacle to the purchase of such a vehicle. It is worth noticing that for all users who have a private place, this obstacle in mainly psychological because most of the time, an electric vehicle driver charges his vehicle at home and only occasionally uses public charging facilities. This different approach concerning refueling supposes that we have to change our habits, which is not necessarily easy nor appreciated by everyone. From a charging operator perspective, the expansion of fast charging stations has not been easy because of the lack of electric vehicles on the road which does not ensure the profitability of charging points. Today, the situation is evolving following the statements in favor of electric vehicles from most car manufacturers. Both industrials and public authorities are rallying around the expansion of fast and ultrafast charging stations on a large scale (see Infrastructure: creating a network of charging stations). That way, this fear, although disproportionate considering the observed needs, should quickly clear up thanks to fast charging points which will provide users with a safety net.

The infrastructure needed to develop fuel cell vehicles has not been spread out enough, hence the lack of this type of vehicle in the offer. However, hydrogen stations are more easily developed to meet the needs of commercial fleets, road freights and public transportation.

Plug-in hybrid electric vehicles provide a solution to this problem by allowing the democratization of electric propulsion minus the fear concerning the autonomy, but they can also prove counterproductive when their electric potential is not used to full capacity and the vehicle is not plugged in.

C. Confidence in technology

The adoption of electric vehicles is also slowed down by the constant innovation in this field. Progress made in battery electric vehicles are so fast that on a 2- to 3-year period a new and cheaper generation can emerge and offer twice as much autonomy than the previous one. But the average holding period for a vehicle is of approximately 5 years which explains why drivers who would be interested in buying an electric vehicle could be tempted to wait a few extra months or years to take this step, in order to be sure that the acquired technology will not be outdated in a couple of years. Knowing that technology is becoming more and more mature, this phenomenon should also regulate itself in the next 5 years.

IV. Control of environmental and social impacts

Although electrifying the transportation system seems like an efficient solution to reduce the impact of transportation on the environment, it is still necessary to monitor this development to ensure that it does not lead to other negative consequences on ecosystems or human beings. The first point is the climate benefit, and then from a life cycle prospect, to assess the impact on resources.

A. Carbon footprint over the life cycle

Electro-mobility technologies allow a significant (plug-in hybrid electric vehicles), sometimes even total (battery electric vehicle and fuel cell electric vehicle) reduction of exhaust emissions. However, in order to determine the carbon footprint of an electric vehicle, one must take into account greenhouse gas emissions linked to:

- The life cycle of the vehicle, from its construction to the end-of-life phase, including its use-phase;
- The life cycle of the energy vector, from the primary energy source (from the well) to the mechanical energy, i.e. the vehicle's driving force (to the wheel).

All of the information presented on the carbon footprint of vehicles is linked to their energy efficiency (see Appendix III).

LIFE CYCLE OF THE VEHICLE

The carbon footprint from the production of electric vehicles is currently more significant than the one of conventional vehicles. Although a conventional vehicle requires more components than its electric counterpart in order to ensure its proper functioning, these components are mass produced and controlled by the automotive industry. On the other hand, electric vehicles include new components whose production on an industrial scale and at a high rate is still new.

For a family sedan, the order of magnitude will be of 20 tons of CO_2 for a battery electric vehicle, 17 tons for a fuel cell electric vehicle and 12 tons for a plug-in hybrid electric vehicle, in comparison to 11 tons for a conventional vehicle. These numbers only refer to an order of magnitude. Indeed, there are not enough electric vehicles on the road to constitute a reliable database on life cycle analysis related to the production of vehicles. The carbon footprint from the production of an electric vehicle is mainly caused by battery manufacturing. The literature review on this subject shows that the results change significantly depending on the approach and the retained hypotheses such as the amount of energy needed to produce one kWh of battery, the share of electricity used, the production site of the different components, the battery's lifespan as well as the inclusion or not of the inputs from the batteries' second life (see Appendix II).

Plug-in hybrid vehicles are conventional vehicles with an electric motor and enough battery capacity to travel about 50 kilometers in pure electric operating state. This battery capacity is much lower than the one of electric-only propulsion battery electric vehicles. This way, the carbon footprint linked to production is lower.

When it comes to fuel cell vehicles manufacturing, other elements should be taken into account. The power of the battery is very low compared to battery electric vehicles, and in the case of the Toyota Mirai model which is one of the most popular at the moment, it is not a lithium-ion battery, but a Ni-mh battery commonly used for hybrid vehicles, which is not as complex. Therefore, in the case of fuel cell vehicles, the carbon footprint is linked to:

- The manufacturing of the fuel cell which notably contains platinum,
- The portable hydrogen storage system in tanks made of composite materials based on carbon fiber and whose manufacturing process has a significant carbon footprint (Mirova, 2013).

Even more so than for battery electric vehicles - only 3 models on the market in 2018[7], the lack of maturity of the market and the experimental scale of manufacturing weigh on the quality of this data and makes the carbon balance heavier. For example, if the fuel cell used for a mobile app was produced on a larger scale, the carbon balance would be much lower with a better use of the production chain.

LIFE CYCLE OF THE ENERGY VECTOR

Electric vehicles and fuel cell vehicles do not emit CO_2 in use-phase (tank-to-wheel). However, CO_2 emissions are generated from the well to the plug:

- To produce electricity for battery electric vehicles;
- To produce hydrogen for fuel cell vehicles.

The carbon footprint of power generation differs from one country to another depending on the electricity mix. In France, where nuclear energy represents 77% of the electricity mix, the carbon factor is of 55 gCO_2/kWh, whereas in China, where coal makes up for 70% of the mix, the carbon factor reaches 717 gCO_2/kWh (IEA 2015)/(IPCC). From one country to another, electric vehicles do not contribute the same way to climate-related aspects.

For conventional vehicles, two stages of the carbon balance can be identified:

- Well-to-tank: hydrocarbon extraction, oil refining, storage, transportation, distribution;
- Tank-to-wheel: CO_2 emissions caused by combustion [8].

Finally, plug-in hybrid electric vehicles can be powered by electricity, oil and electricity or oil only, depending on the use of the vehicle:

- Electricity exclusively, on short rides (power consumption with CO_2emissions only during the well-to-plug phase),
- Oil/electricity mix with a charged battery on long rides (lower energy use than for a conventional vehicle)
- Electricity exclusively followed by oil exclusively with an empty battery on long rides (energy use similar to a conventional vehicle of the same category).

Over a life cycle of 180,000 km, there is a need to determine the number of kilometers corresponding to each mode. This distribution varies significantly depending on the user. In order to establish a consumption standard for this type of vehicles, a coefficient named utility factor based on electric autonomy was defined by the NEDC and now WLTP European norms. Although it could still be improved by 2020 thanks to statistical surveys about actual use in Europe (EU WLTP, 2014), this coefficiesnt allows an estimation of CO_2 emissions over the whole life cycle of the fuel for specific type of use.

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[7]Toyota Mirai, Honda FCX Clarity and Hyundai Nexo

[8]In order to determine each vehicle's energy consumption, performances in terms of mixed use come from WLTP norms (Worldwide Harmonised Light Vehicle Test Procedure) or EPA (Environmental Protection Agency), judged more realistic than NEDC norms (New European Driving Cycle).

Finally, for fuel cell vehicles, the carbon footprint depends greatly on the selected hydrogen production process: by electrolysis of water from renewable energy sources or by steam methane reforming (SMR).

OVERVIEW OF THE CARBON BALANCE OVER THE COMPLETE LIFE CYCLE

Regardless of the automotive segments, we evaluate that electric vehicles emit less CO_2 during the whole life cycle, of the vehicle and the fuel, than conventional vehicles. Other studies confirm these results, for instance the Carbon 4 one (Carbon 4, 2018).

In order to provide customers with an adequate autonomy, the industry has been increasing battery capacity, until now in the absence of a sufficient specific energy per conventional vehicle cell. This rise in battery size, which is both economically and environmentally costly, should quickly be slowed down by ongoing electrochemical progress. Furthermore, the heavier a vehicle gets, the higher battery capacity it requires in order to ensure its autonomy on a long period. Finally, the more expensive a vehicle range is, the more demanding the customer. All of these factors explain why the carbon balance of battery electric vehicles suffers more from the production of batteries for upper ranges of vehicles.

In some geographic areas with a very carbonaceous electricity mix, the carbon balance of electric vehicles from sedan and luxury car segments can equal or even exceed its diesel counterpart. This statement could still be balanced by two elements:

- The development and maintenance of diesel vehicles are challenged by other aspects such as city pollution;
- Electricity mixes which tend to use less carbon thanks to national agreements;
- Progress made on storage battery manufacturing, whether regarding production pace or the chemical composition of the batteries, should result in twice as less CO_2 emissions.

Figure 32: Carbon balance of a city vehicle by propulsion type, life cycle assessment (180,000 km)

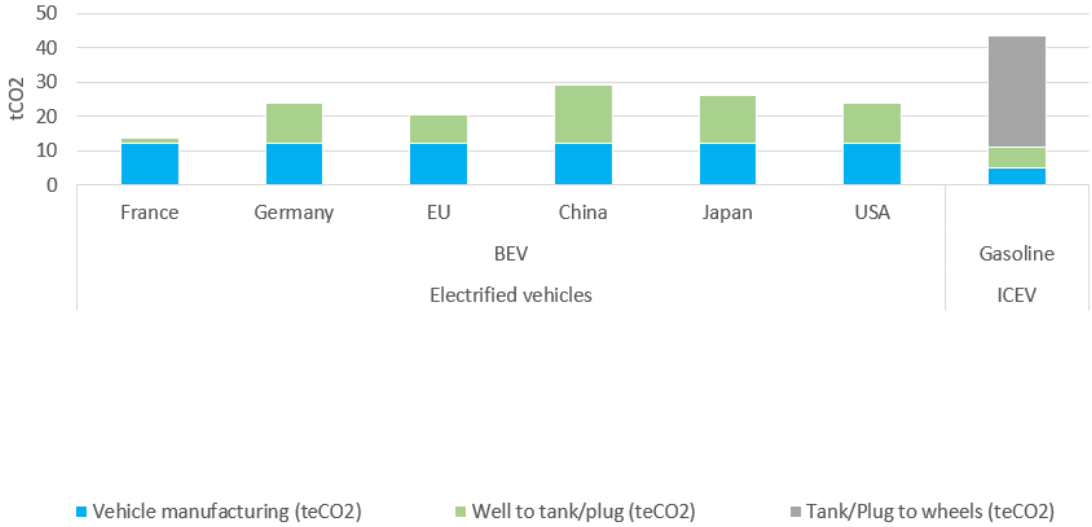


Figure 33: Carbon balance of a compact vehicle by propulsion type, life cycle assessment (180,000 km)

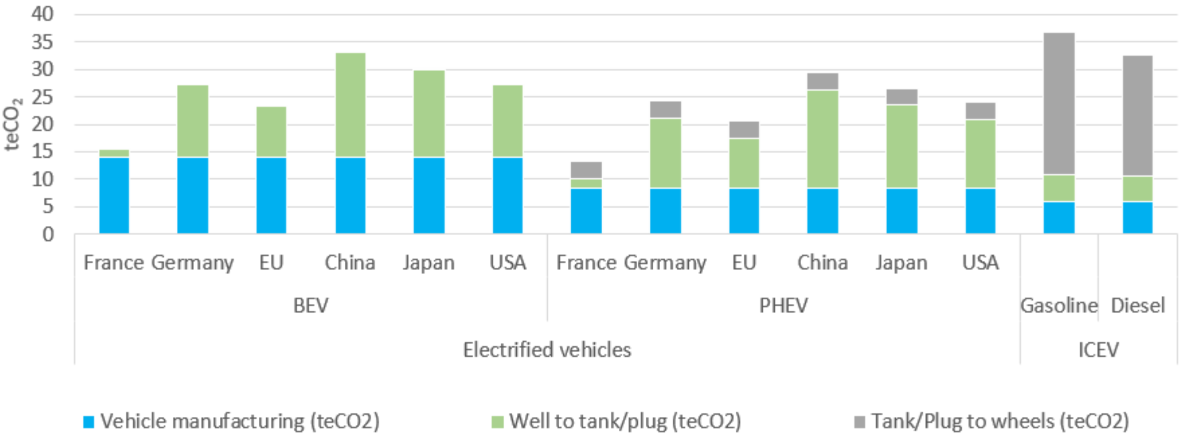


Figure 34: Carbon balance of a sedan by propulsion type, life cycle assessment (180,000 km)

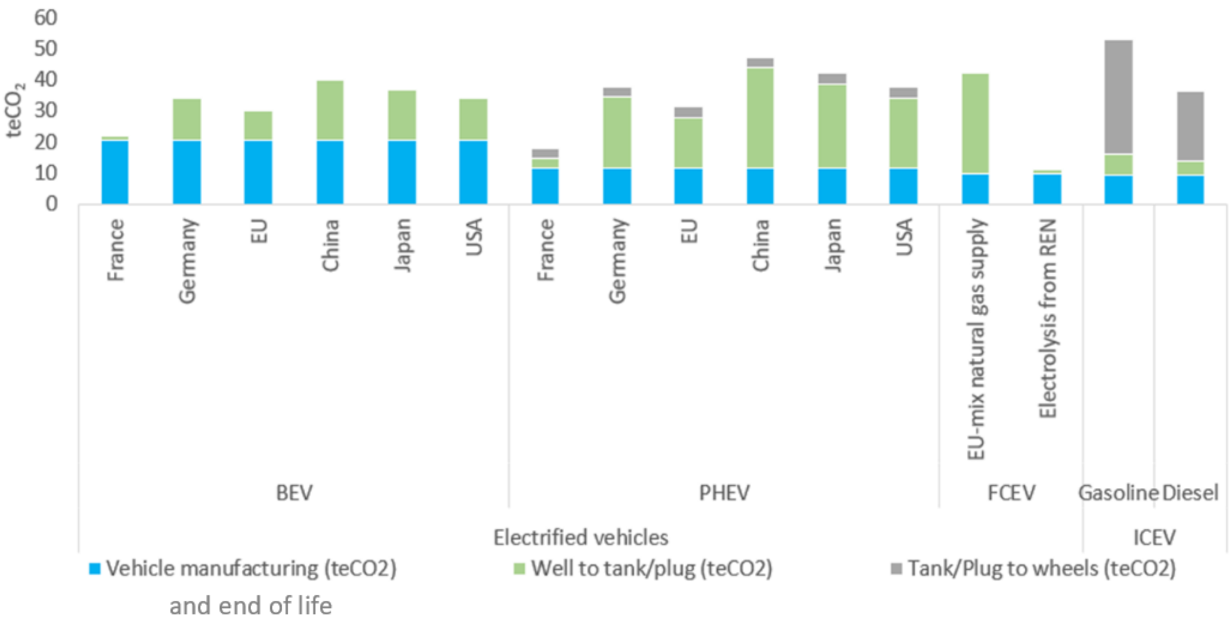
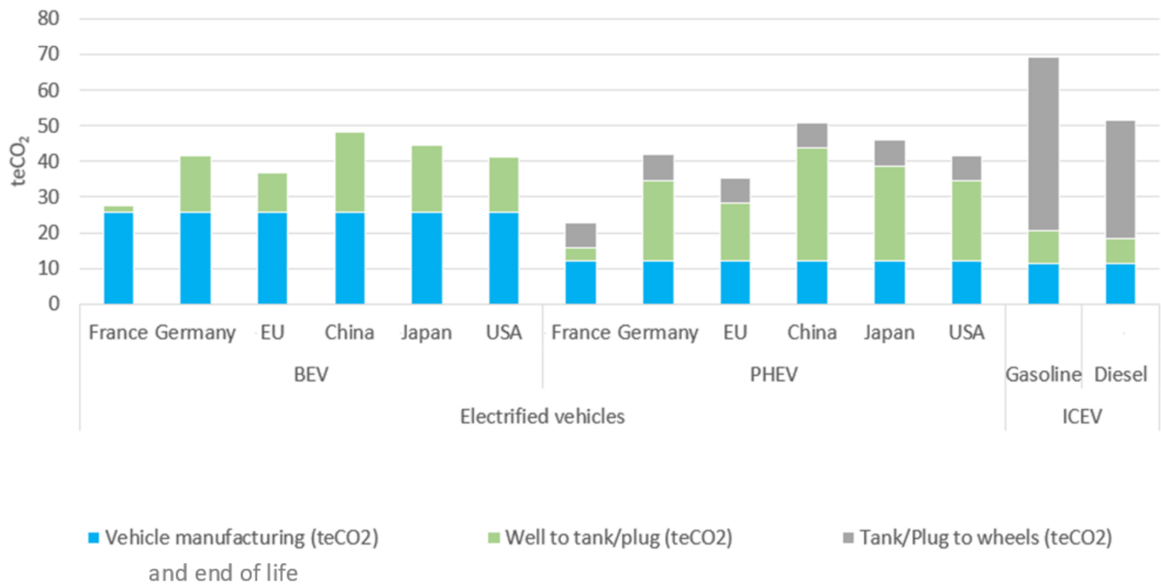


Figure 35: Carbon balance of a luxury vehicle by propulsion type, life cycle assessment (180,000 km)



Sources: Mirova/ (Zubi, Carvalho, Dufo-Lopez, & Pasaoglu, 2018) and (Ager-Wick Ellingsen, Singh, & Hammer Strømman, 2016) on manufacturing of electric and conventional vehicles,(GREET, 2017) on manufacturing of a fuel-cell vehicle/(OECD/IEA, 2015) on carbon electricity factors by country/ (JEC - Joint Research Centre-EUCAR-CONCAWE collaboration, 2014)on well-to-wheel and tank-to-wheel emissions from thermal and fuel-cell vehicles/(US DOE, 2018) on EPA consumptions from models in circulation in 2018

Although the carbon footprint linked to the production of vehicles is bound to be reduced and the climate benefit is already real today, the expansion of electric vehicles on a large scale as a solution only makes sense if it goes hand in hand with the development of low-carbon energies. This way, the benefit in terms of greenhouse gas emissions reduction, that is expected from the electrification of the global vehicle fleet, goes with the effective implementation of the energy transition on a global scale. All of the data used can be found in Appendix I: Key figures and orders of magnitude.

B. Resources issues

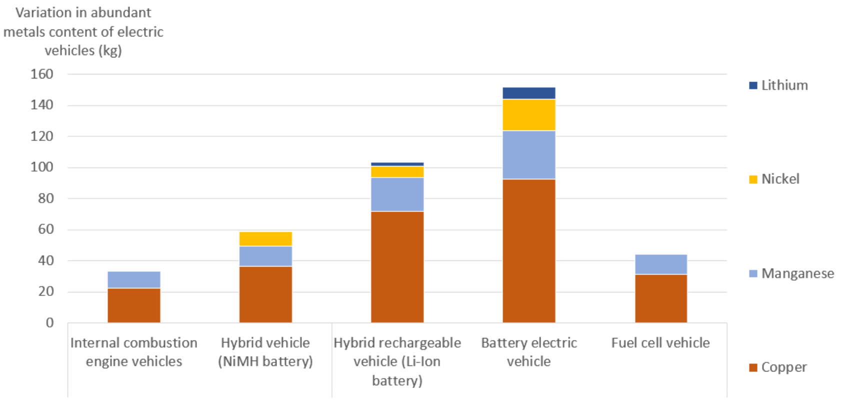
Battery electric vehicles or fuel cell vehicles and their components constitute a radical change from the classic structure and composition of a vehicle; as some materials disappear and others become essential.

Regarding the composition of a vehicle, two types of metals can be found: abundant and critical metals, defined by the European Commission as presenting a high risk of shortage of supply and being of great economic importance for green technologies and new technologies (European Commission, 2017). Electric vehicles increase the need for critical metals. However, progress made regarding the chemical composition of batteries, motors and fuel cells allows us to nuance and put this current observation into perspective.

ABUNDANT METALS

The composition in terms of iron, aluminium, zinc, lead, rubber, plastics, chromium and glass does not vary much from a conventional to an electric vehicle. There is approximately one ton of iron, 100 kg of aluminium, 100 grams of zinc and 300 grams of load in an average vehicle of 1,200 kg. Three abundant metals can be identified in battery electric vehicles: copper, which is present four times as much (~ 90 kg per battery electric vehicle), manganese, nickel and lithium which make an appearance and represent respectively ~30 kg, ~20 kg and ~8 kg. Fuel cell vehicles do not differ much from conventional vehicles in terms of abundant metals proportions.

Figure 36: Differences in terms of abundant metals composition between electric and conventional vehicles - for metals representing a significant change only.



Sources: Mirova/ (Fishman, Myers, Rios, & Graedel, 2018)/(Yano, Muroi, & Sakai, 2015)/(Hawkins, Singh, Majeau-Bettez, & Stromman, Comparative Environmental Life Cycle Assessment of Covnentional and Electric Vehicles, 2013)/(Hawkings, Singh, Majeau-Bettez, & Stromman, Comparative environmental life cycle assessment of conventional and electric vehicles, 2012)

Copper

Copper can be found in many components of a battery electric vehicle, from batteries to the motor and the cables. Copper is also needed for the development of charging stations. Consequently, the growth of electric vehicles will have an impact on copper demand.

Reserves of copper can be found worldwide, mainly in Latin America (21% in Chile, 10% in Peru) and Australia (11%), and reach ~790 million tons. The annual production represents ~20 million tons (USGS, 2018) which equals a 40-year reserve at the current production pace. Although this metal is considered “abundant”, our economy already greatly depends on it (copper alloys, electricity and electronics, health, agriculture). The increasing demand will cause tension regarding the production/demand balance, price volatility and eventually affect the reserves. Hardly substitutable in its use for electric vehicles, copper can still be recycled and re-used indefinitely. These recycling solutions exist and could be developed on a global scale. Today, ~15% of the copper used worldwide has been recycled.

Manganese

Manganese can mainly be found in lithium-ion batteries (NMC type).

Manganese reserves reach ~680 million tons with an annual production of ~16 million tons, which equals a 40-year reserve at the current production rate. South Africa handles 33% of the production, Australia 16%, and China 14%. There is no particular issue regarding this metal except that most reserves can be found in South Africa. Furthermore, this metal can be recycled quite easily.

Nickel

Nickel can be found in storage batteries cathodes.

A quarter of nickel reserves are located in Australia and the rest is quite well distributed. These reserves reach ~74 million tons. The annual production is of ~2 million tons which equals a 35-year reserve at the current production rate (USGS, 2018). Nickel reserves do not seem to be a challenge. However, the nickel used in batteries is very pure (class 1). This type of nickel represents half of the overall production, so ~1 million tons. Furthermore, apart from the purity of the nickel, batteries also require specific forms (granulated, briquettes, powder) which reduces the production amount by half: so ~500,000 tons. Although the amount of nickel used in electric vehicles is rather low, the narrowing of production for certain very specific types of nickel could cause tension regarding prices.

Recent battery technologies increased the proportion of nickel in order to improve the specific energy. However, looking further ahead, nickel could disappear from batteries following the development of solid battery technologies. Moreover, nickel can also be recycled. Today, ~40% of the nickel used worldwide has been recycled.

Lithium

Lithium can also be found in storage batteries cathodes. Lithium resources are abundant, approximately 53 million tons, which can be found in salt deserts in Latin America, China, the United States, Canada and Australia, in several minerals such as aluminium silicate or pegmatite, in a variety of clay (hectorite), in oilfields or geothermal salt deposits. The proven reserves reach ~16 million tons (47% in Chile, 20% in China, 17% in Australia and 13% in Argentina) and are mainly exploited in Australia (43% of the production) and in Chile (33%). The annual production is of ~43,000 tons which equals a ~372-year reserve at the current production rate (USGS, 2018). Like nickel, the lithium used in batteries is very pure but still represents 80% of the production. The issue with lithium is more related to responsible production, in order to reduce water consumption and potential social inequalities in countries suffering from hydric stress. Indeed, the process of collecting lithium is a major water-consumer: 2,000 m^3 needed to produce a ton of lithium. This issue creates tension between mining companies and local communities, particularly in Argentina and Chile. In order to limit the impact of lithium extraction and refining, actions can be taken to improve the production process, and recycling could be a solution to satisfy part of the demand.

Table 3: Characteristics of abundant metals in electric vehicles

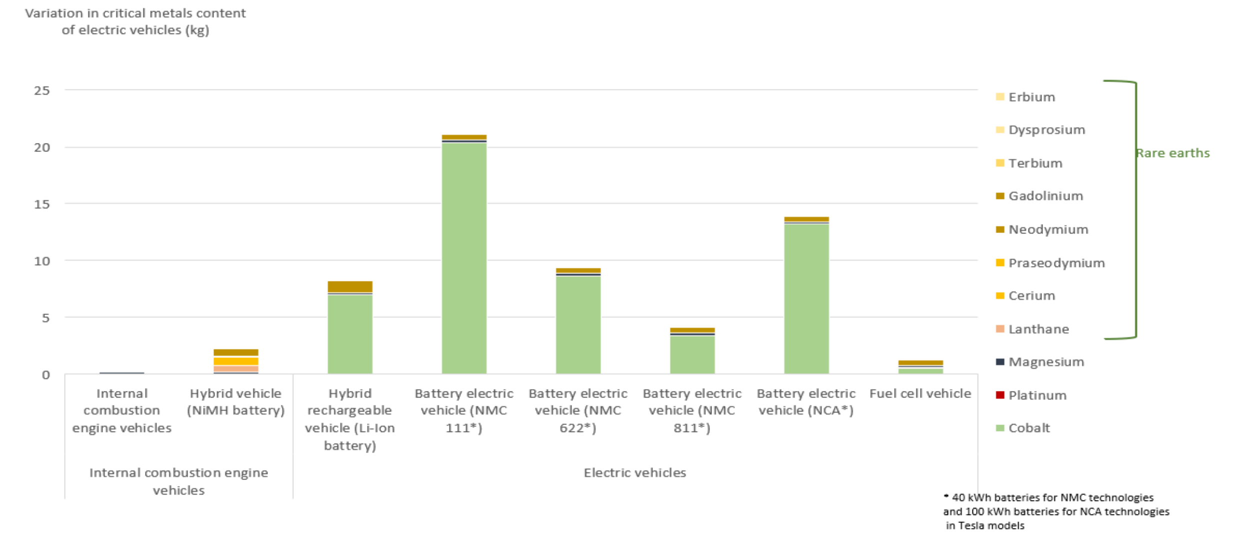
	Contained in a battery electric vehicle (kg)	Contained in a battery fuel cell vehicle (kg)	Reserves volumes (in millions of tons)	Annual production (in millions of tons)	Reserves at current production rate (years)	Issues	Solutions
Copper	90	30	790	20	40	Tensions regarding the production/demand balance Reserves	Recycling
Manganese	30	10	680	16	43	Significant reserves in South Africa	Recycling
Nickel	20	1	74	2	35	Tensions regarding the production of the nickel specifically used in batteries	Recycling / substitution
Lithium	8	<1	16	0	372	Water intensive production process in areas suffering from hydric stress	Improvement of the process / Recycling

Sources: Mirova / (USGS, 2018)

CRITICAL METALS

The European Commission (European Commission, 2017) defined critical metals as metals presenting supplying issues in the context of the rise of energy transition (electric vehicles, renewable energy) and of the digital technologies (where they are used as semiconductors). Critical metals used in electric vehicles include cobalt, platinum and rare earth elements.

Figure 37: Differences between electric and conventional vehicles in terms of critical metals composition



Sources: Mirova/ (Fishman, Myers, Rios, & Graedel, 2018)/ (Yano, Muroi, & Sakai, 2015)/ (Hawkins, Singh, Majeau-Bettez, & Stromman, Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles, 2013)/ (Hawkins, Singh, Majeau-Bettez, & Stromman, Comparative environmental life cycle assessment of conventional and electric vehicles, 2012)

These metals present common features:

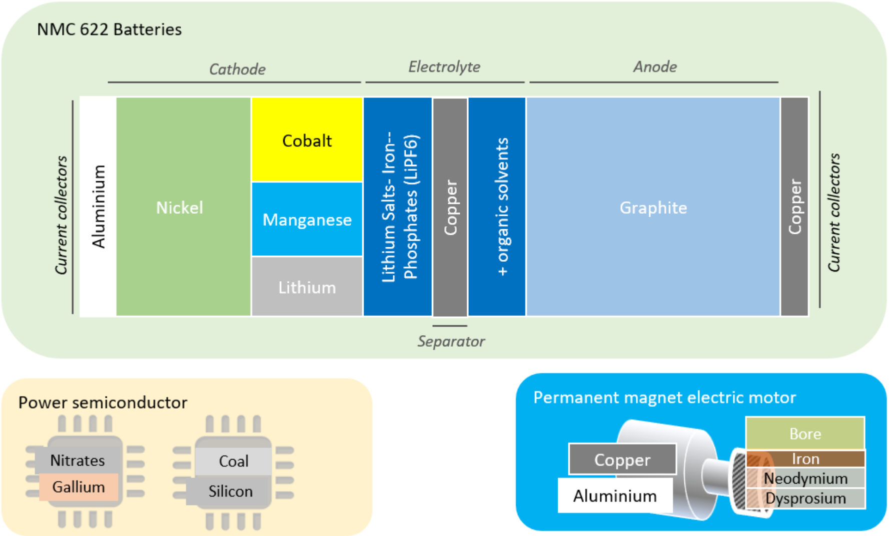
- Coproducts of abundant metals, their production depends on abundant metals production as well;
- Cannot be found in great proportions in ore, meaning that you need to extract a lot to collect a little;
- Extraction and transformation issues, as rare earth elements are found in very small amounts hidden in very large amounts of abundant ores;
- Production sites are concentrated, mainly in China.

These features explain the issues related to cost and geopolitical problems. Moreover, most of the critical metals used in electric vehicles present extraction conditions-related issues, and environmental and/or social challenges.

For electric vehicles, critical metals can be found in:

- Storage batteries for battery electric vehicles (cobalt),
- The electric motor (neodymium, dysprosium and praseodymium),
- Power semiconductors whose penetration in electric vehicles will increase, to increase the performance of electric vehicles (especially the GAN technology which requires gallium),
- Fuel cells used in fuel cell vehicles (platinum).

Figure 38: Critical metals in battery electric vehicles



Sources: Mirova

Cobalt

Cobalt can be found in most lithium-ion batteries used in the development of electric vehicles (NMC and NCA). Lithium-ion batteries, all uses included, represent ~40% of cobalt consumption.

Cobalt is mainly a by-product of nickel (48%) and copper (37%) extraction, as well as of lead and zinc, to a lesser extent. The proportion of cobalt varies from one ore to another. The reserves reach ~7 million tons and the annual production is of ~110,000 tons which equals a 65-year reserve at the current production rate. Although the notion of exploitable reserve remains unclear for a coproduct of abundant metals, the issue regarding cobalt is not related to the reserves, but rather the production. Firstly, the production of cobalt depends on the production of abundant metals. Secondly, almost 60% of the production takes place in the Democratic Republic of Congo (DRC) and the rest is divided between Australia, Russia, Canada, Cuba and the Philippines in an order of magnitude inferior to 5% of the total production.

Today, cobalt supply from the DRC violates rules from the International Labour Organization (ILO) on child labour, health and security, and probably fuels armed conflicts in this country. Finally, mining activity in DRC is a source of violation of local communities' rights (they are not consulted) and biodiversity loss. ILO violations are mainly related to handmade mining operations which are not regulated by the DRC Mining Code. In a context of poverty, conflict and weak governance from the State, these artisanal mines provide a lot of people, adults and children, with means of subsistence. Contrary to industrial mining which involves machines, minors working in artisanal mines use rudimentary tools to dig and excavate the rock. Afterwards, these minors negotiate with mediators in order for the cobalt to be bought by bigger operators in charge of processing and selling the ore to cathode manufacturers. The complexity of the supply chain and the number of mediators makes it difficult to hold the battery manufacturers accountable. Pointed out by more and more studies (Amnesty International, 2017), the issue of cobalt is now taken into account by car manufacturers who became conscious of the great risk weighing on the electrical industry. As for taking actions, manufacturers are increasingly investigating upstream the supply chain, conducting audits regarding traceability and trying to find new production locations.

Moreover, given these production issues, cobalt is quite expensive, and the price is volatile, which explains the technological advances to reduce its amount in electric vehicles. The new generations of NMC and NCA batteries, which offer a similar capacity, have divided the amount of cobalt in battery electric vehicles by 10, which means that in new generation vehicles NMC 811, cobalt represents ~3 kg of a 1-ton vehicle. Total substitution could be achieved thanks to the emergence of solid batteries by 2030. Finally, cobalt can be recycled: its recycling rate is of 70% at the end of life (UNEP, 2011). However, reusing it in new batteries implies a lot of new treatments in order to improve the quality of the metal (Battery University, 2018).

Rare earth elements

There are three main types of electric motors: the asynchronous, or induction motor, the wound-rotor synchronous motor and the permanent-magnet synchronous motor (see Electric motors). The latter is more common as he offers the best compromise in terms of performance, reduced size and low maintenance. However, high quality permanent-magnets are required. They are obtained thanks to 3 rare earth elements: neodymium, dysprosium and praseodymium, which offer outstanding mechanical properties. Rare earth magnets performance is linked to their composition, which combines a rare earth metal (neodymium or praseodymium) and a transition metal (iron or cobalt), which makes it possible to obtain an anisotropic structure[9], able to keep its magnetic properties permanently thanks to the transition metal, and to gather high magnetization in a small volume thanks to the rare earth metal (BRGM, 2015). The addition of dysprosium allows to increase the magnetic resistance to demagnetization at high temperatures. When they encounter an electrical load, these magnets rotate in a joint movement and thus transform the electrical power into mechanical energy able to propel the vehicle.

This is why most electric vehicles use rare earth elements for propulsion. However, rare earth elements can also be used in conventional and hybrid vehicles: for the last fifty years, rare earth elements have been used in a lot of components because of their electronic, magnetic, optical and catalytic properties. Thus, electrifying the secondary functions and the global mechanism has led to an increase of rare earth elements contained in the whole vehicle (lanthanum, cerium, praseodymium, neodymium, gadolinium, terbium, dysprosium and erbium) to ensure the functioning of the windows, the windshield wiper or the sensors. Moreover, the catalytic converter contains cerium. It is quite interesting to notice that a hybrid vehicle with a NiMH battery contains more rare earth elements than an electric vehicle, including the catalytic converter, the electric micromotors (automatic window openers, windshield wipers, seats, etc.) and the NiMH battery with lanthanum in its anode or fuel additive[10] (Fishman, Myers, Rios, & Graedel, 2018) / (Pitron, 2018).

Rare earth elements include 17 elements which, contrary to what their name indicates, are more frequently encountered on the Earth's crust than gold or silver. Thus, the issue regarding these metals is not related to their rarity, but to the extraction and refining conditions, as well as the concentration of production sites in China. The small proportion of rare earth elements in ore, which aggregated over billions of years, explains the issues related to extraction and refining.

Discovered at the end of the 19th century, neodymium and praseodymium are ceric rare earth elements, so-called light metals - found in greater amounts at the surface of the ore - while dysprosium is an yttric rare earth element, so-called heavy metal - less abundant and in deeper layers of the ore. Never found in pure form, rare earth elements are mainly found in bastnaesite and monazite ores, and in ionic clay in Southern China.

Bastnaesite, with a high proportion of ceric earths, is exploited in China, in the Bayan Obo deposit, and in the United States, in Mountain Pass. Monazite can also be found in China in

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[9] Dependent on the direction

[10] Adding to diesel fuel an additive containing cerium allows the improvement of polycyclic aromatic hydrocarbons combustion.

the Bayan Obo deposit and in the heavy minerals from beach sand, exploited for titanium and zircon in India, Brazil, Malaysia and formerly in Australia.

The production process includes:

- Mineral extraction (open sky, underground, in situ leaching);
- Mineral processing (flotation, magnetism, gravimetry);
- Chemical treatment (acid attack, basic attack);
- Separation (solvent extraction, ion exchange);
- Reduction and refining.

Refining requires ore grinding, tens of operations using polluting chemical reagents (sulfuric and nitric acids), great water consumption, ~200 m^3 for one ton of rare earth elements (which also load up in pollutants) in order to obtain a small proportion of rare earth elements. Thus, the refining process is very long, expensive and polluting. Moreover, some of these rare earth deposits, such as monazite and bastnaesite, can cause radioactive pollution.

The disadvantages of this refining process explain why, even though rare earth elements can be found in many geographical areas, most of the former deposit mines in the USA and in France have been abandoned. Today, China holds more than 80% of the global production, as it is the only country willing to carry out this complex and polluting process at a low cost. Bringing back the exploitation of old deposits or developing new ones which would comply with social and environmental obligations will take between 15 and 20 years and will inevitably lead to an increase in costs. So far, by keeping rather low prices, China has been able to prevent any external development attempt.

Rare earth elements can also be recycled, although, similarly to refining, it is a complex process in terms of separating rather small amounts of rare earth metals from impurities in final products. Therefore, recycling is still a more expensive process than the extraction in China, but it is technically possible. In 2015, recycling equals 1% of the consumption.

Beyond these options of developing recycling or moving the extraction process to new areas, there are ways to substitute the use of rare earth elements in electric vehicles. Today, the amount of rare earth elements in an electric vehicle equals ~500 grams. Among the three existing electric motors, two of them do not include rare earth elements and are used in models such as the Renault Zoé (wound-rotor synchronous motor) or the Tesla Model S (asynchronous motor). Other electric motors such as the variable reluctance synchronous motor could be used in cars if the equipment manufacturers would succeed in reducing vibrations and making the production process easier. This motor combines sturdiness, low cost, performance and lack of rare earth elements. Thereby, as it is the case for most technologies linked to the electrical industry, innovation can still make the current findings outdated.

Platinum

Overall, 50% of platinum is used in catalytic converters, 25% in jeweler's craft, 6% in electronics, 5% in chemistry, 5% in glass and 9% in others. In a fuel cell vehicle, platinum is used as a catalytic converter in the fuel cell (~20 grams/vehicle). It is also used in catalytic converters in conventional and hybrid vehicles (~2 grams/vehicle).

Platinum is either the main resource (South Africa, Zimbabwe) or a coproduct of copper, nickel and palladium (Russia, Canada). Once extracted, the ore is crushed, plunged in water with reagents, decanted, dried, melted and purified. Platinum and palladium reserves reach ~69 million tons which equals a 345-year reserve at the current production rate and are concentrated in South Africa (91%), which reflects on the production sites: 70% in South Africa, 10% in Russia, 8% in Zimbabwe and 6% in Canada for the main areas (USGS, 2018). Consequently, platinum represents a high geopolitical risk as well as potential pressure on prices caused by a limited production and the supply/demand imbalance in case of the expansion of fuel cell vehicles.

We could still get around these issues thanks to potential changes: the catalytic converter in a fuel cell could be another metal, and recycling could also be a solution with catalysts recovery (which is already well developed).

Gallium

Gallium is not found a lot in electric vehicles, but it could gradually be integrated with the introduction of power semiconductors, via gallium nitride (GaN) technologies, which will improve the energy efficiency of the electric vehicle and its ability to handle a greater charge power.

Gallium is a very rare metal, coproduct of aluminium. The total amount of gallium in the world equals 1 million tons. Gallium used for electronic purposes requires an advanced purification in order to reach 99.999999% purity. Besides, the complexity and high cost of recycling are linked to the difficulty of collecting very small quantities used as scattered alloys in a multitude of electronic devices. However, at this stage, gallium is not really of concern when it comes to electric vehicles.

Chart 4: Characteristics of critical metals in electric vehicles

	Contained in a battery electric vehicle (kg)	Contained in a battery fuel cell vehicle (kg)	Co-product	Reserve volumes (in millions of tons)	Annual production (in millions of tons)	Reserves at current production rate (years)	Issues	Solutions
Cobalt	3-20 depending on the technologies	<1	Copper Nickel Zinc Lead	7	0.11	64	- Concentration of the production in DRC - High price	Recycling
Rare earths	1	1	Iron Copper Gold	120	0.13	923	- Complex, expensive and polluting refining - Concentration of the production in China	- Development of new deposits or reinstatement of old ones, respectful of social and environmental requirements - Deployment of recycling - Resort to technologies of motors without rare earths
Platinum	20	1	Principal substance or co-product of copper, nickel or palladium	69	0.20	345	- Concentration of the production in South Africa and Russia - Limited production	Recycling / substitution

Sources: Mirova / (USGS, 2018)

By listing all the main abundant and critical metals needed for electric vehicles and the issues related to them, it does not appear, at this stage, that any major technical, environmental, social or economic barrier would call into question the development of these sectors. In most cases, substitution is an option, especially as electric vehicles still rely on emerging technologies which are evolving constantly. Finally, recycling offers a new horizon when substitution is not an option.

RECYCLING AND SECOND LIFE

Both second life and recycling come up when battery lifespan is discussed. Until now, batteries deteriorate with each charging and discharging cycle. They reach the end of their first life after 20% of deterioration which equals ~7/8 years depending on the use.

However, this rate of degradation could accelerate given:

- The development of ultrafast charging points, which make charging twice as fast, but the effect on the batteries four times as damaging;
- The development of nickel-rich cathodes, which improve the specific energy but degrade the lifespan (NMC 811 deteriorates 3 times faster than LFP);

- The reduction of battery size and the increase of the depth of discharge.

After the first life, two options are usually considered: using the battery for stationary storage during its second life (~8/10 years) or recycling the elements without waiting for the end of the second life. Second life mitigates the environmental and economic cost of lithium-ion batteries by storing renewable energy.

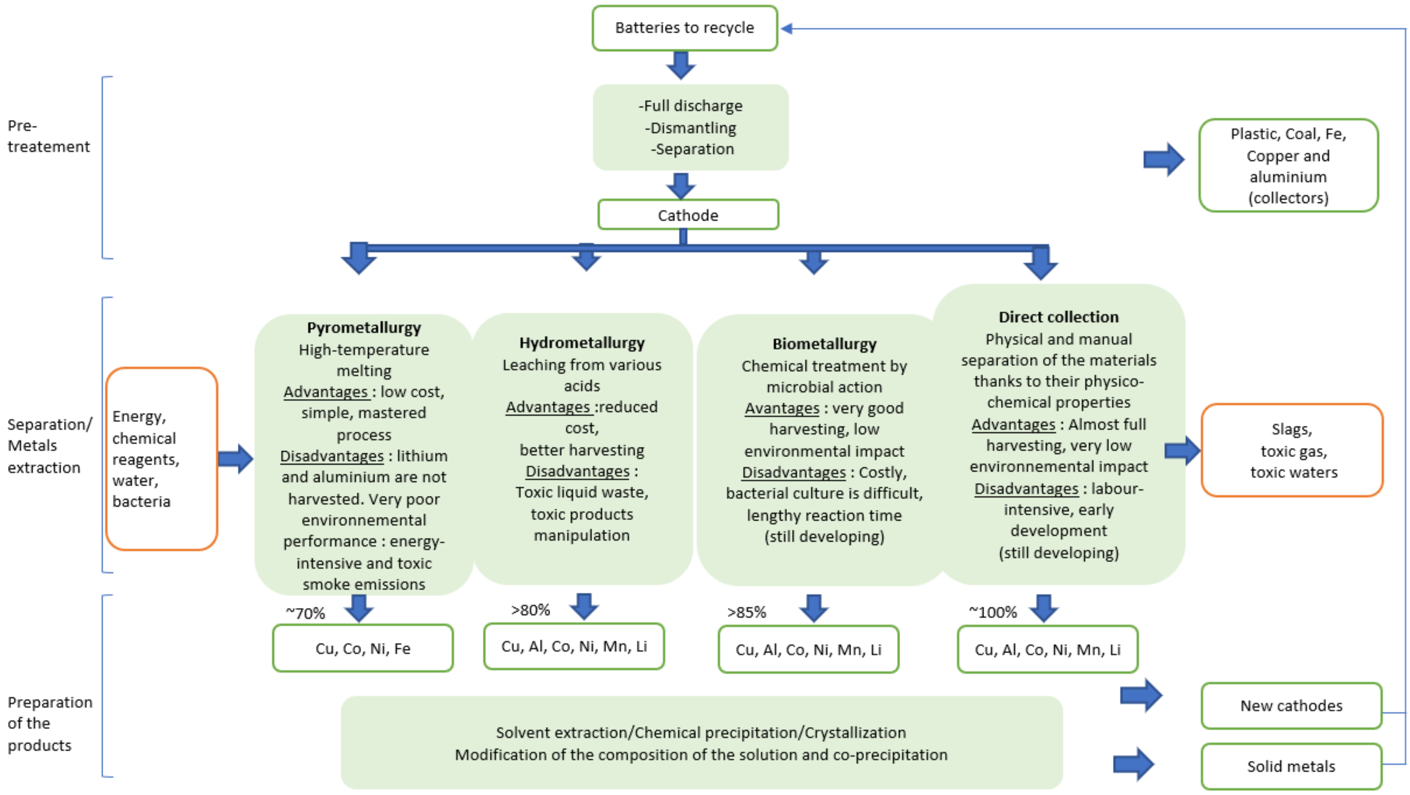
In any case, given the metals present in batteries and a lifespan that can be reduced to improve performance and cost, a rapid increase in recycling seems to be essential in order to meet resource challenges, to control the carbon footprint associated with the production of the vehicle, and also to improve the economic equation of the electric vehicle.

In 2018, approximately 40% of lithium-ion batteries reaching their end of life were recycled. A great amount of the remaining 60% are stored, mainly in China, waiting for more favorable economic conditions to be recycled.

Different recycling methods can be used jointly or successively in order to increase the collection rate:

- Pyrometallurgy, although it is a mastered and low-cost process, remains very energy-intensive, polluting, and offers a limited result;
- Hydrometallurgy is more expensive but offers better results although toxicants are also used;
- Biometallurgy and direct collection: very high costs, but with a very high success rate and a low environmental impact.

Figure 39: Recycling process



Sources: Mirova

Pyrometallurgy is traditionally used by recycling specialists. However, the diversification towards hydrometallurgy has already started. The mining sector also takes part in the recycling process, as well as cathode and battery manufacturers, and, to a lesser extent, car manufacturers.

Lithium-ion batteries recycling is still not profitable at this stage. The lack of standardization, the rapid development of chemical industry and the absence of collecting infrastructure and visibility on the evolution of volumes make it difficult and limit and complicate the setting up of recycling facilities. Nevertheless, the reinforcement of regulations, the development of recycling credit systems, the pressure on resources or the security of supply policies of companies could all contribute to the rapid development of recycling systems as batteries will reach the end of their lifespan.

V. Outlook

A. Uses and market growth

ROAD TRANSPORTATION

The expansion of electric vehicles for road transportation depends on various fiscal instruments, regulations and public investments. In addition to national measures, big cities are asserting themselves as the main defenders of low-carbon mobility. In 2018, 25 metropolises [11] were home to 44% of the electric vehicles on the road (versus 12% of sold vehicles and 4% of the world population) (ICCT 2018). The different actions taken by public authorities on a national, regional and municipal level can be divided into 4 categories:

- Direct support through:
    - Purchase subsidies (tax credit, VAT exemption, scrapping premium, direct grants, assistance with vehicle registration). These subsidies can go up to USD 12,000 in South Korea and USD 16,000 at a local level in Seoul;
    - Day-to-day use assistance (access to paid parking, priority roads, exemptions from tolls, access to zero-emission zones, reduced insurance costs, V2G credits, preferential electricity prices);
- Development of the charging facilities (in cooperation with electricity suppliers, direct construction of stations, financial incentives, implementation of construction standards which impose charging points in collective habitat);
- Electric fleets and new means of transportation (measures to initiate the transition for taxis and VFH - vehicles for hire, electrification of buses and public fleets, implementation of vehicle fleets for car sharing and zero-emission zones, prohibition to sell conventional vehicles from 2030 in some countries);
- Strategies and communication (restrictive emission standards for the manufacturers, R&D public funding, public-private partnerships, educational measures, promotion and exhibitions).

These mechanisms are bound to evolve along with the increase of electric vehicles sales. In any case, these public policy choices guide the growth prospects of different vehicles in different markets and segments, with technological developments.

Private vehicles

In 2017, more than one million electric vehicles were sold. The take-off of the electric vehicle is observed in a small number of leading markets:

- China, which has accounted for nearly half of the global electric vehicle sales in the last two years,
- Scandinavia, where the market share of electric vehicles has become significant (respectively 6% and 39% of the sales in Sweden and Norway);
- Germany and Japan, where the biggest sales growth was recorded in 2017.

[11] Beijing, Changsha, Chongqing, Guangzhou, Hangzhou, Qingdao, Shanghai, Shenzhen, Tianjin, Wuhan and Zhengzhou in China, London in England, Paris in France, Tokyo and Kyoto in Japan; Amsterdam in the Netherlands; Bergen and Oslo in Norway, Stockholm in Sweden and Los Angeles, New York, Sand Diego, San Francisco, San José and Seattle in the United States.

Although relying on recent technologies, electric and plug-in hybrid vehicles seem mature enough to be developed on a large scale in the private vehicles sector in the years to come regarding charging infrastructure as well as battery technologies which have passed the important milestone of the early generations. The same cannot be said of fuel cell vehicles which remain too expensive and not mature enough to be introduced in the private vehicles sector in the short term.

Bloomberg New Energy Finance believes that electric and plug-in hybrid electric vehicles sales could reach respectively 53 million and 7.3 million of vehicles sold, which equals 34% of all vehicles on the road. This would mean that more than 50% of private vehicles sold would be electric or plug-in hybrid electric vehicles.

Figure 40: Evolution of private vehicles annual sales

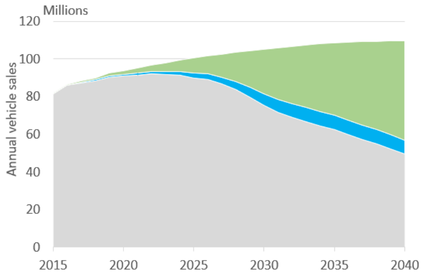
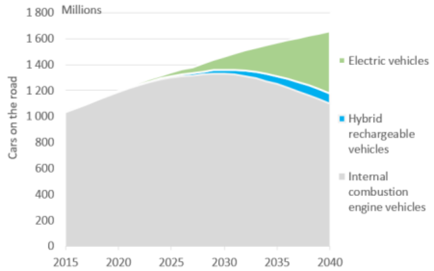


Figure 41: Evolution of the vehicle fleet on the road



Sources: Mirova / (BNEF, 2018)

In the framework of these prospects, electric and plug-in hybrid electric vehicles would represent 34% of the vehicle fleet on the road.

Two-wheeled vehicles and low-speed electric vehicles

Two-wheeled vehicles are already well on track in terms of electrification. Their technical features (low weight and energetical needs) and their use (mainly urban and on short rides) make them suitable for conversion to battery-powered electricity. In addition, it is also possible to change the battery or to charge it in only a few hours on a household socket.

Driven by significant urban pollution rates, China almost makes up for the whole market with nearly 300 million two- and three-wheeled electric vehicles on the road and ~30 million sold each year (IEA, 2018). In other Asian countries, which use up to ~900 million two-wheeled vehicles, electrification is still marginal. In Europe, electric two-wheeled vehicles represent 4% of overall two-wheeled vehicles sales in mid-2018, which still represents a +49% growth compared to the previous year (ACEM, 2018).

In Europe and the United States, electric two-wheeled vehicles are in competition with electric bikes which do not require a driver's license or insurance on the one hand, and with low-speed electric vehicles on the other hand. Low-speed electric vehicles (LSEV) are an intermediate category between two-wheeled vehicles and cars, which provide a solution to the imperatives of sustainable mobility. They are subject to different regulations than classic vehicles, their speed and weight are limited, and they are particularly well suited for urban areas. There has been rapid growth in China where sales reached 1.75 million vehicles in 2017, and makes up for ~5 million of these vehicles on the road in 2018 (IEA, 2018) (The Wall Street Journal 2018).

Buses

Public road transportation, from minibuses to buses, is also experiencing a boom in low-carbon solutions. In 2017, almost 400,000 electric buses and plug-in hybrid buses were on the road in China, ~4,000 in OECD countries. This represents 12% of the global fleet, and it should rise to 40% in 2025 (1.2 million in China and 120,000 in the rest of the world).

After 2025, electric options should become less expensive than their conventional counterparts and dominate in most countries, reaching 90% of the sales between 2030 and 2035.

Moreover, ~250 fuel cell buses were on the road in 2017 (IEA, 2017). Urban buses, and mainly interurban buses, have several features that make them good candidates for this technology: critical size, fixed roadmap, less weight constraints. The Hydrogen Council[12] believes that 35% to 40% buses could run on hydrogen by 2050.

Overall, the electrification of this segment, which can adjust to hydrogen as well as batteries, first depends on public authorities.

Commercial vehicles and heavy trucks

Heavy trucks are more suited for fuel cell solutions than battery solutions because of the power and range they require. The Hydrogen Council believes that the implementation of hydrogen will reach 20% in 2050, which equals 15 to 20 million vehicles.

The first battery electric heavy trucks are reaching the market (Daimler, Volkswagen and Tesla), but this technology should become widespread among light freight and commercial vehicles.

Overall, this segment should experience the slowest electrification process, and hybrid and plug-in hybrid options should make up for most of the sales.

AIR TRANSPORT

Air transport presents significant obstacles to the use of electric propulsion. At this stage, storage technologies do not allow to consider such a transition. The hybridization of some aircrafts, mostly short-haul ones, could occur by 2030 and electrification could be developed for short-haul flights in the following decade. The first projects of battery-powered aircrafts are still at a very early development stage (EasyJet is developing an airplane that would offer a 500 km range with Wright Electric for 2030). As for fuel cell vehicles, the issue is mainly linked to the current hydrogen storage conditions. We will have to wait for technological progress regarding solid storage solutions to be able to consider a change for airplane propulsion.

MARITIME TRANSPORT

Maritime transport also presents significant obstacles to electrification, mainly due to the required range. Battery-powered and fuel cell electric ferries are already in service in Europe and offer a real opportunity. For river navigation and short distance maritime transport, these technologies could also offer substantial gains in emissions and air quality, but their development would require regulatory and financial support as well as infrastructure in the absence of cost competitiveness in the medium term. As for container ships and transoceanic transport, the transition to alternative propulsion seems more uncertain due to the length of the distances covered. It should become more of a long-term solution in the absence of a technological break.

[12] The Hydrogen Council is a global initiative of energy and transportation companies, launched during the 2017 World Energy Forum in Davos, to define the development focus of the hydrogen sector. This initiative gathers 39 companies (http://hydrogencouncil.com/).

RAIL TRANSPORT

Railways electrification has been mainstreamed for a few decades in Europe and in Japan, and made up for 30% of the worldwide railways in 2015. Considering that railways electrification requires high investments, the implementation of battery electric trains could be a solution for the lines with less traffic. The two first fuel cell trains were designed by Alstom and put into service in Germany in 2018.

B. Key players

The electric vehicle implies big changes in terms of the distribution of added value: while traditional automotive manufacturers and suppliers are struggling to find their spot in the value chain, opportunities are arising in other sectors, particularly electrochemistry, electricity supply and metal treatment.

In order to rationalize the amount of companies referred to, only the most evident segments of the value chain are mentioned in this study. However, many other subsectors add value to the chain, such as: the companies in charge of battery testing during industrial production, which play a key role in improving the efficiency of production; those in charge of battery packs who are in a position to upgrade cellular organization; the solution providers regarding different segments of the fuel cell; companies specialized in polymers, etc. The list could be very long and is difficult to establish due to the emulation in all the activities related directly or indirectly to the development of electric vehicles.

To support this ecological transition solution, the search for new investment ideas is ongoing and relies on the meeting of specialized industrial partners to identify all the links in the chain.

BATTERY ELECTRIC VEHICLES

Battery manufacturing

CELLS

Battery manufacturing is not extremely concentrated: along with Korean historical manufacturers, a multitude of small manufacturers have developed in China. Due to the conditions of subvention attributions which hardened in 2018, and to the increasing complexity of the technologies, the concentration of the market should accelerate, as European manufacturers are emerging.

Apart from Tesla, BYD and Daimer (to a lesser extent), car manufacturers have not expressed their wish to integrate cell manufacturing. The required electrochemistry expertise is an obstacle to this implementation for car manufacturers, especially as these technologies could potentially be replaced by solid batteries in the next decade.

Some stakeholders are present on the cell as well as the cathode chemistry front, such as BYD, Panasonic, Samsung SDI and LG Chem Ltd to name a few, but most cell manufacturers rely on other cathode specialists.

The companies involved in solid batteries are also present on various subsegments of the value chain, particularly anodes and electrolytes.

Table 5: Battery manufacturing

Companies	Countries	Public / private	Cells & battery packs	Cathode	Anode	Electrolyte	Separator
Tesla Inc., Panasonic Corp	USA	Public	- NCA, NMC : 105,000 MWh (USA) by 2023 - 7 % of market in 2017	NCA, NMC			
Contemporary Amperex Technology Co Ltd	China	Private	- Battery manufacturing: 100% of storage battery revenues, 16% of the 2017 global battery market; capacity: 17,000 MWh available, 53,260 MWh under construction, 104,260 MWh announced; expertise on NMC and LFP cathodes; main clients (excluding China): Volkswagen - Recycling: via its subsidiary Brunp; capacity of 6 kt in 2017				
BYD Co Ltd	China	Public	- Battery manufacturing: NMC batteries for automobiles (53% of 2017 revenues) and solar storage batteries (8%); 10% of the 2017 world battery market; expertise on NMC cathodes; capacity: 26,000 MWh available, 34,000 in construction - Recycling : recycling plant in Shenzen - 100% electric vehicle manufacturer	NMC			
LG Chem Ltd.	South Korea	Public	- Battery manufacturing: 6% of 2017 revenues; 7% of the world market 2017 in batteries; expertise in NMC and LMO cathodes; capacity: 23,400 MWh available; main clients: Volkswagen, PSA	NMC			
NorthVolt AB	Sweden	Private	- NMC: 32,125 MWh (Sweden) by 2023 - Objective: to design a gigafoctory in Europe in partnership with ABB;				
SK Innovation Co Ltd	South Korea	Public	- Battery manufacturing: 0.3% of 2017 revenues related to storage batteries for electric vehicles; expertise on NMC cathodes; capacity: 1,200 MWh available, 17,800 MWh under construction, 800 MWh announced; main clients: Volkswagen				6% of market in 2017
Microvast Inc	USA	Private	- NMC, LTO: 15,000 MWh (China) by 2023 - 6 % of the market in 2017				
Samsung SDI	South Korea	Public	- NMC: 8,650 MWh (South Korea, China, Hungary) by 2023 - 11% of the market in 2017 - R&D on solid batteries - Partnership(s): Volkswagen	NMC			
Beijing Pride Power Battery Technology Co. Ltd.	China	Private	- LFP Batteries - Partnership(s): BAIC				
Tianjin Lishen Battery Joint-Stock Co Ltd	China	Private	LFP Batteries for light electric vehicles and buses				
Guoxuan High-Tech Co., Ltd	China	Public	- LFP Batteries - Partnership(s): JAC, Zoyte	LFP			
Deutsche Accumotive GmbH & Co.	Germany	Private	Subsidiary of Daimler AG for NMC				
Blue solutions	France	Public	- LMP batteries for carsharing and storage solutions			Polymer electrolyte	
Front Edge Technology Inc	USA	Private	- R&D on solid batteries - Partnership(s)/Investor(s) : STMicroelectronics			Polymer electrolyte	
Ilika PLC	United Kingdom	Public	- R&D on solid batteries - Partnership(s)/Investor(s) : Toyota		Silicon	Polymer electrolyte	
Prieto Battery Inc	USA	Private	- R&D on solid batteries - Partnership(s): Intel/Stanley, Black & Decker			Polymer electrolyte	
QuantumScape Corp	USA	Private	- R&D on solid batteries - Partnership(s): Volkswagen			Polymer electrolyte	
Solid Power Inc	USA	Private	- R&D on solid batteries - Partnership(s)/Investor(s) : Solvay		Li-metal	Polymer electrolyte	
SolidEnergy Systems Corp	USA	Private	- R&D on solid batteries - Partnership(s)/Investor(s) : GM		Li-metal	Polymer electrolyte	
Fisker Inc	USA	Private	- R&D on solid batteries - Partnership(s)/Investor(s) : Caterpillar			Polymer electrolyte	
Ionic Materials Inc	USA	Private	- R&D on solid batteries - Partnership(s)/Investor(s) : Hyundai, Renault, Nissan			Polymer electrolyte	
Sakti3 Inc	USA	Private	- R&D on solid batteries - Partnership(s)/Investor(s) : Dyson			Polymer electrolyte	
Seeo Inc	USA	Private	- R&D on solid batteries - Partnership(s)/Investor(s) : Bosch			Polymer electrolyte	

Sources: Mirova/ BNEF/ (BMO Capital Markets, 2018)

CATHODES

The innovation in cathode chemistry is ongoing to optimize the specific energy and to reduce the costs. The concentration of this industry is rather low but the obstacles to its implementation are numerous due to the increasing complexity of the technologies. NMC and NCA technologies should remain at the top in the next decades, and potentially be substituted by solid batteries.

Table 6: Cathode manufacturers

Companies	Countries	Public / private	Cathode	Anode	Electrolyte
Shanghai Shanshan Tech Co., Ltd.	China	Private	LCO/NMC/LFP with 11% of the NMC market in 2017	Graphite (50 kt announced) with 5% of the market in 2017	LiPF6 (5% of the market in 2017)
Umicore SA	Belgium	Public	LCO/NMC: 8 kt in 2016 (120 kt announced) with 15% of the NMC market in 2017		
Nichia Corportation	Japan	Private	LCO/NMC/LMO/LFP : 13 kt in 2016 (32 kt announced) with 9% of the NMC market in 2017		
Ningbo Jinhe New Materials Co Ltd	China	Private	LCO/NMC: 15 kt announced) with 9% of the NMC market in 2017		
L&F Co Ltd	South Korea	Public	NMC : 9 kt in 2016 (18 kt announced) with 11% of the NMC market in 2017		
Sumitomo Corporation	Japan	Public	- Cathodes : NCA; 43 kt capacity in 2017; supplier for Tesla/Panasonic Inc - Recycling: partnership with Nissan		
Toda Kogyo Corp	Japan	Public	NMC/NCA : 22 kt with 16% of NCA market in 2017		
BASF SE	Germany	Public	- NMC Cathodes: <10% of BASF 2017 revenues; 54 kt capacity 54 kt in 2017 ; partnership with TODA Battery Materials LLC		
Nihon Kagaku Sangyo Co., Ltd.	Japan	Private	- Fluorinated Electrolytes		
Ecopro Co Ltd	South Korea	Public	NCA : 9 kt in 2016 with 5% of the NCA market in 2017		
Pulead Technology Industry Co Ltd	China	Private	LFP : 10 kt in 2016 with 9% of the LFP market in 2017		
Johnson Matthey	United Kingdom	Public	- LFP : 5 kt in 2016 with 8% of the LFP market in 2017 - Innovation cathodes eLNO		
Beijing Easpring Material Technology Co., Ltd	China	Private	LCO/NMC/NCA : 4 kt in 2016 with 4% of the NMC market in 2017		
Xiamen Tungsten Co., Ltd. (XTC)	China	Public	NMC : 3 kt in 2016 (27 kt announced)		

Sources: Mirova/ BNEF/ (BMO Capital Markets, 2018)

ANODES

The anode market is more concentrated than the cathode market. Today, it mainly consists of natural or synthetic graphite. The incremental enhancement followed by the substitution by pure silicon and, eventually, lithium-iron anodes could disrupt the market and mobilize new players.

Table 7: Anode manufacturers

Companies	Countries	Public / private	Cells & battery packs	Cathode	Anode	Electrolyte
Shanghai Shanshan Tech Co., Ltd.	China	Private		LCO/NMC/LFP with 11% of NMC market in 2017	Graphite : 50 kt announced) with 5% of market in 2017	LiPF6 (5% of the market in 2017)
Mitsubishi Chemical Corporation	Japan	Public			Graphite : 15 kt announced	LiPF6 (17% of the market in 2017)
BTR New Energy Materials Inc	China	Private			Graphite : 57 kt announced	
Jiangxi Zichen Technology Co Ltd	China	Private			Graphite : 40 kt announced	
Pyrotek Inc	USA	Private			Graphite : 40 kt announced	
Shenzhen Sinuo Industrial Development Co Ltd	China	Private			Graphite : 34 kt announced	
Hitachi Chemical Company, Ltd.	Japan	Public			Graphite : 28 kt announced	
JFE Chemical Corp	Japan	Private			Graphite : 28 kt announced	
Huzhou Chuangya Power Battery Materials Co Ltd	China	Private			Graphite : 15 kt announced	
Hunan Shinzoom Technology Co Ltd	China	Private			Graphite : 15 kt announced	
Jiangxi Zhengtuo New Energy Technology Co Ltd	China	Private			Graphite : 13 kt announced	
Altair Nanotechnologies Inc	USA	Private			Anode LTO	
Hunan Shinzoom Technology Co Ltd	China	Private			Graphite : 15 kt announced	
Toyo Tanso	Japan	Public			Graphite	
Enevate	USA	Private			Silicon	
Ilika (Toyota)	United Kingdom	Public			Silicon	
Paraclete	USA	Private			Silicon	
Solid Power Inc	USA	Private	- R&D on solid batteries - Partnership(s)/Investor(s) : Solvay		Li-metal	Polymer electrolyte
SolidEnergy Systems	USA	Private	- R&D on solid batteries - Partnership(s)/Investor(s) : GM		Li-metal	Polymer electrolyte
Hitachi Chemical Co Ltd	Japan	Public			Graphite anode (5% of revenues in 2017)	
Mitsubishi Chemical Holdings Corp	Japan	Public			Graphite anode; LIPF6 electrolyte ; Gallium nitride (GaN) for power semiconductors.The segment linked to lithium-ion batteries is included in MC Ionic Solutions US, Inc.	

Sources: Mirova/ BNEF/ (BMO Capital Markets, 2018)

Most players specialize in one segment, but some companies are present on the anode, cathode and electrolytes markets, such as Shanshan Technology Group co, Ltd.

ELECTROLYTES

From an industrial point of view, electrolytes manufacturing is not very complex, but the implementation of this market faces many obstacles. The evolution towards fluorinated electrolytes, able to reach higher voltage, and then towards more complex solid and semi-solid electrolytes, polymer or ceramic, will probably mobilize new players.

Table 8: Electrolyte manufacturers

Companies	Countries	Public / private	Cathode	Anode	Electrolyte
Mitsubishi Chemical Corp	Japan	Public		Graphite	LiPF6 (17% of the market in 2017)
Tinci Materials Technology Co., Ltd.	China	Private			LiPF6 (15% of the market in 2017)
Shenzhen Capchem Technology Co Ltd	China	Public			LiPF6 (10% of the market in 2017)
Panax E-tec Co., Ltd	South Korea	Private			LiPF6 (8% of the market in 2017)
Guotai-Huarong Chemical New Material Co., Ltd	China	Private			LiPF6 (6% of the market in 2017)
Ube Industries, Ltd.	Japan	Public			LiPF6 (5% of the market in 2017)
Shanghai Shanshan Tech Co., Ltd.	China	Private	LCO/NMC/LFP	Graphite	LiPF6 (5% of the market in 2017)
Solvay SA	Belgium	Public			Fluorinated electrolytes
Daikin Industries Ltd.	China	Public			Fluorinated electrolytes
Arkema	France	Public			Fluorinated electrolytes
BASF SE	Germany	Public			Fluorinated electrolytes

Source: Mirova/ BNEF/ (BMO Capital Markets, 2018)

SEPARATOR

The separators market is gradually becoming concentrated. Although technical obstacles are not very common at this stage, financial obstacles are present. Moreover, the change to solid batteries which do not include separators should happen at the cost of these players. However, short-term innovation lies in the search of the best thermal security/specific energy compromise which relies on the discovery of the thinnest separator possible.

Table 9: Electrolyte manufacturers

Companies	Countries	Sector	Cells & battery packs	Separator
Celgard, LLC	USA	Chemical		15% of the market in 2017 (Asahi Kasei Corporation acquisition)
Shanghai Energy New Materials Technology Co., Ltd.	China	Chemical		12% of the market in 2017
Toray Battery Separator Film Co., Ltd	Japan	Chemical		7% of the market in 2017 (acquisition of LG Chem separator activities)
Hunan Zhongli	China	Chemical		7% of the market in 2017
SK Innovation Co Ltd	South Korea	Chemical	- NMC: 104,260 MWh (USA, China, Hungary, South Korea) by 2023 - Partnership: Volkswagen	6% of the market in 2017

Sources: Mirova/ BNEF/ (BMO Capital Markets, 2018)

Automotive manufacturers and suppliers

In the automotive sector, some companies historically stand out from the others in the electricity segment, such as Tesla and BYD. Today, most car manufacturers are investing and setting high goals when it comes to electric, battery electric or plug-in hybrid vehicles.

Table10: Manufacturers from the electricity sector

Companies	Countries	Public / private	Economic indicators / comments
Tesla	USA	Public	100% electric vehicles
BYD	China	Public	100% electric vehicles
BMW	Germany	Public	Objective: offer 25 electrified models (12 electric with battery) in 2025
Renault	France	Public	Objective: offer 12 electrified models in 2022
Nissan	Japan	Public	Objective: sell 1 million electrified vehicles per year after 2022
Daimler	Germany	Public	Acquisitions and investments in EV charging solutions and the development of battery technology
Volkswagen	Germany	Public	- Objective: offer 80 electrified models (50 electric with battery) in 2025 - 50 billion euros investment in battery supply
PSA	France	Public	Objective: offer an electrified version (EV, PHEV) of all flagship models in 2025
GM	USA	Public	Objective: offer 20 electrified models in 2023
Ford	USA	Public	Objective: offer 40 electrified models in 2025
Toyota	Japan	Public	Investment in solid batteries, pioneer in hybrid and plug-in hybrid vehicles

Source: Mirova

Automotive suppliers are also investing in order to provide solutions for electric propulsion (motorization, semiconductors, optimizing efficiency). However, the competition and the technological advances regarding traditional vehicles no longer constitute an advantage.

Electric motorization is commonly integrated by automotive manufacturers and suppliers and represents less technical challenges. However, players are trying to reach new markets. Some industrial players, not familiar with the automotive sector until now, are developing partnerships to create opportunities for development, such as Nidec Motor and PSA, Toshiba and Ford, or Hitachi and Honda. Regarding other means of transportation, other partnerships have emerged such as Siemens and Airbus and Rolls Royce, who are working on electric propulsion for commercial aviation.

Power semiconductors technologies also entered the race for the development of electric vehicles. The main expected players are those from the silicon carbide and gallium nitride sectors. Semiconductors segments also include various subsegments with their own features and added values: substrate provision, product conception, processor, semiconductor packaging and integration of the operating system. Many companies are present at various stages of the value chain, such as: Infineon, Bosch, Denso, STMicroelectronics, Wolfspeed or ON Semiconductors.

Metals chain

The required metals for battery and electric vehicles manufacturing include lithium, cobalt, nickel or copper. The market of lithium is distributed between five main players. As for other metals, extraction and refining is better shared out between two major players.

Table 11: Metals producers

Companies	Countries	Public / private	Economic indicators / comments
Lithium			
Albemarle	USA	Public	18% of the world's lithium reserves
Jiangxi Ganfeng	China	Private	17% of the world's lithium reserves
SQM	Chile	Public	14% of the world's lithium reserves
Tianqi	China	Public	12% of the world's lithium reserves
FMC	USA	Public	5% of the world's lithium reserves
Galaxy Resources	Australia	Public	Lower reserves of resources
Mineral Resources	Australia	Public	Lower reserves of resources
Neometals	Australia	Public	Lower reserves of resources
Orocobre	Australia	Public	Lower reserves of resources
Cobalt			
Glencore	USA	Public	Production in 2017: 27,400 tons of cobalt
Freeport Cobalt	China	Private	Production in 2017: 25,000 tons of cobalt
Vale SA	Brazil	Public	Production in 2017: 5,811 tons of cobalt
Jinchuan Group Int. Resources Co. Ltd.	China	Public	Production in 2017: 5,500 tons of cobalt
Nornickel	Russia	Public	Production in 2017: 4,800 tons of cobalt
Sumitomo MM	Japan	Public	Production in 2017: 4,800 tons of cobalt
Nickel			
Vale SA	Brazil	Public	Share of world refined production (2017): 13%
Norilsk Nickel	Russia	Public	Share of world refined production (2017): 10%
Tsingshan Group	China	Private	Share of world refined production (2017): 9%
Jinchuan	China	Private	Share of world refined production (2017): 7%
Glencore	Switzerland	Public	Share of world refined production (2017): 7%
Sumitomo MM	Japan	Public	Share of world refined production (2017): 5%
Copper			
Coldeco	Chile	Private	Share of world refined production (2017): 9%
Freeport-Mcmoran	USA	Public	Share of world refined production (2017): 9%
BHP Billiton	Australia	Public	Share of world refined production (2017): 7%
Glencore	Switzerland	Public	Share of world refined production (2017): 6%
Southern Copper	USA	Public	Share of world refined production (2017): 4%
Rare earths			
Molycorp	Poland	Private	Rare earths
Inner Mongolia Baotou Steel Rare Earth Hi-Tech Co.	China	Private	Rare earths
Lynas Corporation Limited	Malaysia	Public	Rare earths
China Rare Earth Holdings	China	Public	Rare earths
Great Western Mineral Group	Canada	Public	Rare earths
Indian Rare Earths Ltd	India	Private	Rare earths
Chinalco Yunnan Copper Resources Ltd.	Australia	Public	Rare earths
Alkane Resources	Australia	Public	Rare earths
Platinum			
Anglo Platinum	South Africa	Public	Share of world refined production (2017): 40%
Impala Platinum	South Africa	Public	Share of world refined production (2017): 25%
Lonmin	United Kingdom	Public	Share of world refined production (2017): 11%
Norilsk Nickel	Russia	Public	Share of world refined production (2017): 11%
Northam Platinum	South Africa	Public	Share of world refined production (2017): 4%

Sources: Mirova / (Cobalt Institute, 2017) (5 Top Cobalt-mining Companies, 2018)/ (Norilsk Nickel, 2017) / (BRGM, 2015)

Regarding fuel cell vehicles, other players must be added such as the companies using the platinum as a catalytic converter in fuel cells. Besides extraction and treatment, the recycling sector is also bound to be developed.

Table 12: Metal recycling companies

Companies	Countries	Public / private	Economic indicators / comments
Retriev Technologies Inc	USA	Private	Hydrometallurgy: 4.5 tons capacity in 2017 (9 t announced)
Accurec	Germany	Private	Pyrometallurgy, hydrometallurgy, collect: 4 t in 2017 (15 tons announced)
AkkuSer	Finland	Private	Pyrometallurgy, hydrometallurgy, collect: 1 t in 2017
American Manganese Inc	Canada	Public	Hydrometallurgy: 1 t announced
Guangdong Brunp recycling Technology Co., Ltd	China	Public	Hydrometallurgy, collect: 4 t in 2017 (100 announced)
BYD	China	Public	Recycling plant in Shenzen
Glencore	Switzerland	Public	Pyrometallurgy, hydrometallurgy: 7 t in 2017
Jx Nippon Mining	Japan	Public	Pyrometallurgy: 5 t in 2017
Li-cycle	Canada	Private	Hydrometallurgy, collect: 5 t announced
Neometals Inc.	Australia	Public	Hydrometallurgy: 4 t announced
Redux	Germany	Private	Collect: 10 t in 2017
Umicore	Belgium	Public	Pyrometallurgy, hydrometallurgy: 7 t in 2017
Valdi/Eramet	France	Public	Pyrometallurgy: 20 t in 2017
Recupyl SAS	France	Private	Hydrometallurgy: 0.11 t announced
Aurubis AG	Germany	Public	Copper recycling
Boliden AB.	Sweden	Public	Copper recycling

Source: Mirova

Charging infrastructure

Until recently, the installation of charging stations infrastructure was not very profitable due to the small number of electric vehicles on the road. Today, the impulse of the automotive sector towards electrification is leading to a significant development of the market and the introduction of different players: oil tankers, electricity suppliers, charging infrastructure specialists, investors (see Charging points operators).

Table 13: Electric vehicles charging points

Companies	Countries	Public / private	Economic indicators / comments
Charging points manufacturing			
Alfen Beheer BV	Netherlands	Public	Home / public charging point
WiTricity Corp	USA	Private	Wirelss charging
QUALCOMM Inc	USA	Public	Wirelss charging
Clippercreek Inc	USA	Private	Home / public charging point
Infineon Technologies AG	Germany	Public	AURIX/ XMC microcontroller for fast charging
Denso Corp	Japan	Public	Charging points
Toshiba	Japan	Public	Wirelss charging
Sensata Technologies Holding PLC	United Kingdom	Public	Point components
Webasto AG	Germany	Private	Home / public charging point
Siemens	Germany	Public	Home / public charging point
EVBox (Engie)	Netherlands	Private	Home / public charging point
Electric Motor Werks Inc	Germany	Private	Home / public charging point
Broadband TelCom Power Inc	USA	Private	Home / public charging point
ZTE Corp	China	Public	Charging point components
DBT SACA	France	Public	Home / public charging point
ABB Ltd	Switzerland	Public	Home / public charging point
Elix Wireless Inc	Canada	Private	Wirelss charging
Leviton Manufacturing Co Inc	USA	Private	Home / public charging point
Hella GmbH & Co KGaA	Germany	Public	Wirelss charging
Schneider Electric SE	France	Public	Home / public charging point
Charging points operation & maintenance			
Qingdao TGOOD Electric Co Ltd	China	Public	Number of charging points: 168,100
State Grid Corp of China	China	Private	Number of charging points: 84,900
Star Charge	China	Private	Number of charging points: 66,100
New Motion Ltd	Europe	Private	Number of charging points: 64,000; acquired by Shell
Xcharge Inc.	China	Private	Number of charging points: 45,000
ChargePoint Inc	USA	Private	Number of charging points: 26,000
Shanghai Potevio Co Ltd	China	Private	Number of charging points: 21,700
EVBox	Netherlands	Private	Number of charging points: 20,000; acquired by Engie
Tesla	USA	Public	Number of charging points: 12,200
Incharge	Sweden	Private	Number of charging points: 9,000; acquired by Vattenfall AB
Allego BV	Netherlands	Private	Number of charging points: 8,000; acquired by Meridiam
Chargemaster PLC	United Kingdom	Private	Number of charging points: 6,500; acquired by BP
E.ON SE	Germany	Public	Number of charging points: 6,000
Charge & Drive	Finland	Public	Number of charging points: 4,612; acquired by Fortum
Innogy SE	Germany	Public	Number of charging points: 4600
Blink Charging Co	USA	Public	Number of charging points: 3,500
EVgo Services LLC	USA	Public	Number of charging points: 2,400
Electric Circuit	USA	Public	Number of charging points: 2,200
Enel SpA	Italy	Public	Number of charging points: 2,000
Tellus Power Inc	USA	Private	Number of charging points: 1 800
Greenlots Global	Singapore	Private	Number of charging points: 1,100
Fastned BV	Netherlands	Private	Number of charging points: 500
Izivia (ex Sodetrel)	France	Private	Number of charging points: 5,000
IT systems			
PlugSurfing GmbH	Finland	Private	Charging points maps and softwares
Trialog	France	Private	Charging points maps and softwares
Pod Point Ltd	United Kingdom	Private	Charging points maps and softwares
Recargo Inc	USA	Private	Charging points maps and softwares

Sources: MIROVA/ BNEF

FUEL CELL VEHICLES

The fuel cell vehicles sector is still new. Some players take part in the production and distribution of hydrogen, but at this stage, hydrogen is barely used in transportation.

Hydrogen production

Hydrogen is mainly produced from steam methane reforming. This industrial process includes two main players: Air Liquide and Linde. These players are the ones who would be able to develop the biogas and the CO_2 capture and storage sectors which are necessary to make the hydrogen from steam methane reforming more respectful of the environment and the climate. They are also the ones, alongside oil tankers, whose investments are needed in order to develop hydrogen stations.

Hydrogen production from water electrolysis relies on companies who sell electrolyzers.

Table 14: Electrolyzers manufacturers

Companies	Countries	Private / Public	Technology
Electrolyzers			
AccaGen SA	Switzerland	Private	Alkaline
Acta Spa	Italy	Private	Alkaline
ELB Elektrolyse Technik	Germany	Private	Alkaline
Erredue	Italy	Private	Alkaline
Asahi Kasei Europe	Germany	Private	Alkaline
Hydrogen Pro	Norway	Private	Alkaline
NEL ASA	Norway	Public	Alkaline
Tianjin Mainland Hydrogen Equipment	China	Private	Allkaline
AVL List	Austria	Private	Solid oxide
Enapter	Germany	Private	Proton exchange membrane
Giner Inc	USA	Private	Proton exchange membrane
GreenHydrogen.dk ApS	Denmark	Private	Proton exchange membrane
H2 Nitidor	Italy	Private	Proton exchange membrane
H2BZ Wasserstoff und Brennstoffzellen-Initiative	Germany	Private	Proton exchange membrane
H2Gen Innovations Inc	France	Public	Proton exchange membrane
H-TEC Systems	Germany	Private	Proton exchange membrane
Hydrogenics Corp	Canada	Public	Proton exchange membrane
iGas Energy	Germany	Private	Proton exchange membrane
IHT	Switzerland	Private	Proton exchange membrane
ITM Power PLC	United Kingdom	Public	Proton exchange membrane
McPhy Energy SA	France	Public	Proton exchange membrane
Nilsson Energy	Sweden	Private	Proton exchange membrane
Rouge H2 Engineering	Austria	Private	Proton exchange membrane
Siemens	Germany	Public	Proton exchange membrane

Sources: MIROVA/ BNEF

Portable hydrogen storage system

The portable hydrogen storage subsector involves few companies at this stage.

Table 15: Storage tanks

Companies	Countries	Private / Public	Segment
Faber	Italy	Private	Pressurized storage system
Hexagon Composites	Norway	Public	Pressurized storage system
Hydrogen Power Storage and Solutions	Germany	Private	Pressurized storage system
Hydrogenious Technologies	Germany	Private	Pressurized storage system
NPROXXX Jülich	Germany	Private	Pressurized storage system
Steelhead Composites	USA	Private	Pressurized storage system
Vopak	Netherlands	Public	Pressurized storage system
Kawazaki	Japan	Public	Pressurized storage system
Faurecia	France	Public	Pressurized storage system
Plastic Omnium	France	Public	Pressurized storage system

Sources: MIROVA/ BNEF

Hydrogen conversion into electricity

Once again, the field of electrochemistry is the solution provider. Just as for batteries, the fuel cell sector could experience major technological changes in order to make the technology more mature.

Table 16: Fuel cell manufacturers

Companies	Countries	Private / Public	Technology
Fuel cell components			
HyPlat	South Africa	Private	Electrode membrane assembly
WL Gore & Associates Inc	USA	Private	Electrode membrane assembly
Borit	Belgium	Private	Bipolar plates
IHI Hauzer Techno Coating	Netherlands	Private	Bipolar plates
Impact Coatings	Sweden	Private	Bipolar plates
Celeroton	Switzerland	Private	Hydrogen compressor
Howden	Netherlands	Private	Hydrogen compressor
Mehrer Compression	Germany	Private	Hydrogen compressor
Ventos Compressors	Italy	Private	Hydrogen compressor
Takaiski Industry Co	Japan	Private	Hydrogen compressor
Johnson Matthey	United Kingdom	Public	Catalysts
Pressure Tech	United Kingdom	Private	Gas diffusion system
Vairex air systems	USA	Private	Gas diffusion system
Piles à combustibles			
Palcan Power Systems Inc	Canada	Private	Mobile PEM
Plastic Omnium	France	Public	Mobile PEM
Plug Power Inc	USA	Public	Mobile PEM
PowerCell Sweden AB	Sweden	Private	Mobile PEM
Refire	China	Private	Mobile PEM
Cummins	USA	Public	Mobile PEM
Efoy Investering AS	Germany	Private	Mobile PEM
First Element Fuel	USA	Private	Mobile PEM
Proton Motor Fuel Cell	Germany	Private	Mobile PEM
Faurecia	France	Public	Mobile PEM
Mcphy	France	Public	PEM
Hydrogenics	Canada	Public	PEM
Horizon	Singapore	Private	PEM
Ceramic Fuel Cells Ltd	Australia	Private	PEM
FuelCell Energy Inc	USA	Public	PEM
Intelligent Energy Ltd	United Kingdom	Private	PEM
Ballard	Canada	Public	PEM
Nel	Norway	Public	PEM
N2telligence GmbH	Germany	Private	PEM / Alkaline
AFC Energy	United Kingdom	Public	Alkaline
Bloom Energy Corp	USA	Private	SOFC
Bosch	Germany	Public	SOFC
Watt Fuel Cell	USA	Private	SOFC

Sources: MIROVA/ BNEF

Car manufacturers

Some manufacturers are historically present in the fuel cell vehicles sector such as Toyota, Honda and Hyundai.

Some suppliers are also trying to enter the market, such as Michelin which started working with Symbio to sell fuel cell systems, or Faurecia and Plastic Omnim, involved in fuel cell components and on-board tanks. Beyond the automotive industry, Alstom is also investing in locomotive propulsion systems in Germany, and Safran is looking into using this energy source to reduce the carbon footprint in the air sector.

Conclusion

Nowadays, the shift towards the electrification of transportation seems inevitable. Innovations are still expected regarding energy storage, whether in batteries or hydrogen, to make the electric vehicles sector mature. However, the foundations seem well rooted.

As a responsible investor convinced that sustainable development is the key to long-term economic performance, Mirova wants to take part in this technological break by supporting the players who could meet the technological challenges of this transition.

This choice does not exclude the investments in other ecological transition solutions such as the efficiency of conventional vehicles that should remain in the next fifty years, the change to environmentally-friendly means of transportation, or new mobility solutions that allow the reduction of energy consumption, such as car sharing.

Appendixes

Appendix I: Key data and orders of magnitude

	Internal combustion engine vehicle (ICEV)	Plug-in hybrid vehicle (PHEV)	Battery electric vehicle (BEV)	Fuel cell electric vehicle (FCEV)
Carbon balance on 180,000 km (including the well-to-wheel fuel cycle and the vehicle's LCA)	**43 and 70 teCO_2** o Manufacturing of the vehicle between 8 and 12 teCO_2 depending on the segments o Consumption: in pure electric mode, from 19 to 48 kWh at 100 km depending on the model and in hybrid mode (empty battery), from 41 to 80 kWh at 100 km.	**19 and 57 teCO_2** o Manufacturing of the vehicle between 8 and 12 teCO2 depending on the segments o Consumption: in pure electric mode, from 19 to 48 kWh at 100 km depending on the model and in hybrid mode (empty battery), from 41 to 80 kWh at 100 km.	**13 and 48 teCO_2** o Manufacturing of the vehicle: between 8 and 19 teCO2 depending on the segments This carbon balance is quite significant, mainly because of the carbon footprint of the battery. In this study, the reference value used is: 170 kgCO2e/kWh for the battery. o Consumption: From 13.5 to 18 kWh at 100 km depending on the models	**17 (electrolysis of water) and 42 teCO_2 (SMR)** o Manufacturing of the vehicle: ~16 teCO_2 for a D segment, mainly due to the manufacturing of the fuel cell and the hydrogen tank in CFRP[13] o Consumption: ~1 kg at 100 km, which equals 33.33 kWh at 100 km These results are only based on a D segment vehicle.
Energy efficiency	**~21%** o Oil production: 83% Average losses of ~7% and ~8% linked respectively to hydrocarbon extraction and oil refining o Vehicle performance: ~26% o Motor average performance: 30%	**~30%** o Utility factor= 0.005*AER+0.4 WLTP with AER (All electric range): autonomy of the vehicle in pure electric mode. For the estimation of energy efficiency, we used a 60% coefficient. o Energy production (oil and electricity): 54% o Vehicle performance: 55% (72% in electric mode and 25% in hybrid mode with a better performance of the motor thanks to the harvesting of energy allowed by the hybrid)	**~25%.** o Electricity manufacturing: 34% including ~5% loss due to the extraction of uranium or the manufacturing of equipment (solar panels, wind turbines, etc.), an average performance of 38% for the electricity plants and an average of ~5% loss due to grid distribution o Vehicle performance: ~72% including a battery charging/discharging performance of ~90% and an electric motor performance between 80% and 85%	**Between ~10% (electrolysis of water) and ~16% (SMR)** o Hydrogen manufacturing: 20% (electrolysis) to 33% (SMR) The electrolysis of water requires 1L of water and 5 kWh of electricity to obtain 1,000 L of H2. The electrolysis of water offers a 70% performance. Using natural gas, SMR [14] offers a 46% performance o Regarding storage and compression at 700 bars, performance reaches 80% with a 15% loss during compression. o Vehicle performance: ~50% including a vehicle performance between 43% and 60% with a PEMFC fuel cell performance (~60%) and an electric motor performance (~85%)
Economic record on 180,000 km of an average sedan	**From USD 57,000 to 66,000** o Vehicle cost: USD 35,000-45,000 o Maintenance cost: 5-15 USD/100 km o Depreciation: 50% in 3 years o Global average cost of oil: 1.09 USD/liter	**From USD 54,000 to 69,000** o Vehicle cost: USD 40,000-51,000 o Maintenance cost: 5-20 USD/100 km o Depreciation: 50% in 3 years o Fuel cost: 3 à 6 USD/100 km	**From USD 65,000 to 85,000** o Vehicle cost: USD 45,000-57,000 o Maintenance cost: 3-10 USD/100 km o Depreciation: 50% in 3 years o Fuel cost: 1.5 à 6.5 USD/100 km	**From USD 98,000 to 136,000** o Vehicle cost: USD 68,000-102,000 o Maintenance cost: 5-15 USD/100 km o Depreciation: 50% in 3 years o Fuel cost: 9 à 15 USD/100 km.
Technical data	Data and consumption of the vehicles sold in 2017 and 2018	o Battery capacity: from 8.8 to 11.6 kWh depending on the models (Li-ion or LiPo technologies) o Autonomy in pure electric mode: from 25 to 50 km depending on the models o Mainly equipped with Atkinson cycle thermal motors [15]	o Battery capacity: from 20 to 100 kWh depending on the models o Autonomy in pure electric mode: from 150 to 570 km depending on the models	o Only the D segments and SUV on the market o Hydrogen compression at 70 MPa o On-board hydrogen tanks: volume between 122 and 155 liters which equals a mass between 5 and 6.5 kg and an amount of energy between 171 and 219 kWh depending on the models, with a hydrogen density of 0.04 kg/liters and a lower heating value (LHV) of the hydrogen of 120 MJ/kg.

Sources: Mirova / (OECD/IEA, 2015) / (U.S. Department of Energy, 2018)/ (JEC - Joint Research Centre-EUCAR-CONCAWE collaboration, 2014)/ (GREET, 2017) pour le bilan carbone de la fabrication des véhicules à pile à combustible/ (BP , 2017)/ (IEA, 2015)/ (Zubi, Carvalho, Dufo-Lopez, & Pasaoglu, 2018)/ (Ager-Wick Ellingsen, Singh, & Hammer Strømman, The size and range effect: lifecycle greenhouse gas, 2016)/ (Globalpetrolprices.com, 2019)

[13] CFRP: Carbon fiber reinforced polymer

[14] SMR: steam methane reforming

[15] Atkinson cycle is a variation from the classic cycle named "Four-stroke engine". This type of motor allows better performance by ~10%.

Appendix II: Carbon footprint of electric vehicles

The carbon footprint from the production of an electric vehicle is mainly caused by battery manufacturing. The literature review on this subject shows that the results differ significantly depending on the angle and the hypothesis adopted such as the required amount of energy to produce a kWh of battery, the electricity share used, the manufacturing location of the different components, the battery lifespan or the inclusion of the inputs from the second life of the battery. Moreover, production volumes are increasing, and the production processes are evolving fast in order to support the deployment of the sector, which allows a fast economic and energy cost reduction regarding battery manufacturing. This means that data based on today's assessments could be proven false in the next five years in light of the improvement regarding technological maturity and knowledge on the subject. In this study, the carbon footprint reference is of 170gCO_2/kWh which corresponds to the average value frequently used in scientific journals and consistent with the life cycle analysis provided by the industry. This number can seem quite high in light of the significant progress referred to before, however the differences of opinion regarding this data encourage to be more careful and conservative. The manufacturing of one battery is based on the whole life cycle when two cycles might be needed. However, not taking the contributions linked to the recycling or second life of the battery into account makes up for the fact that only one battery is considered, to a certain extent.

Appendix III: Energy efficiency

Electric motors offer energy efficiency that amount to 85%, which is far superior to gasoline-powered vehicles (36%) or diesel vehicles (42%).

However, in order to get the real efficiency, we must consider the average energy efficiency, in mixed cycle, and integrate the losses caused by:

- Energy production (electricity for battery electric vehicles, gasoline for conventional vehicles and hydrogen for fuel cell vehicles);
- The operation of the vehicle

For battery electric vehicles, the losses caused by electricity production come from power plants performance and from the preparation of uranium for the nuclear.

For fuel cell vehicles, hydrogen is produced by electrolysis of water, the primary energy is turned into electricity and then into hydrogen by the electrolyzer and then turned back into electricity by the fuel cell: these transformations cause losses. If the hydrogen is produced by gas reformation, the losses come from the extraction of hydrocarbon and from the reforming industrial process.

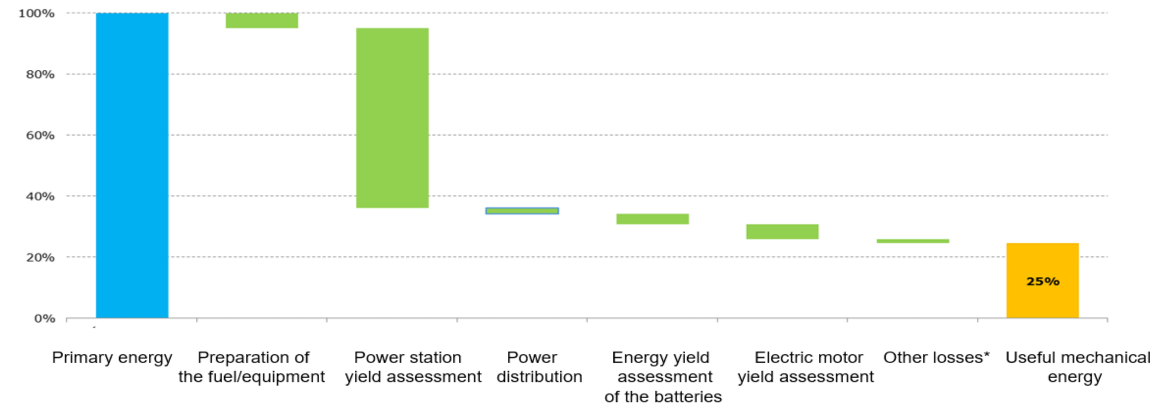
For conventional vehicles and fuel cell vehicles, whose propulsion is based on hydrogen obtained by steam methane reforming, the losses are caused by the production of gasoline, diesel or hydrogen, or linked to the extraction of hydrocarbon and the production process (oil refining or steam methane reforming).

For plug-in hybrid electric vehicles, we have to determine what are the average real uses of this type of vehicle. European regulations refer to a coefficient named Utility factor (see Life cycle of the energy vector) which defines the percentage of kilometers travelled in pure electric mode over the whole life cycle of the vehicle. In this study, we used an average value of 60% for this coefficient, which seems realistic regarding the efficiency of the vehicles on the market in 2018.

To these energy chains can be added the losses caused by transportation, storage and energy distribution.

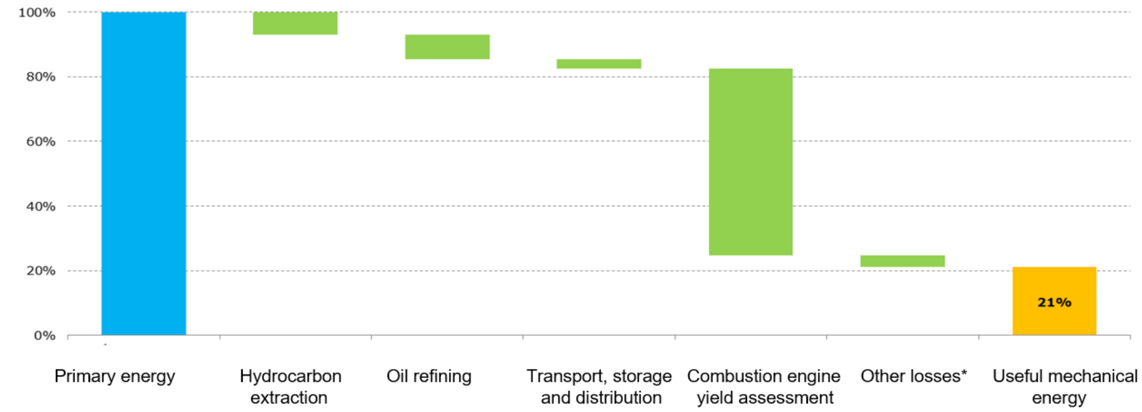
Finally, the use of the vehicle also causes new losses linked to the electrical auxiliaries on board, to the transmission in the case of conventional vehicles and to parasitic losses.

Figure 42: Energy chain of an electric vehicle



*Other losses: use of auxiliaries and parasitic losses

Figure 43: Energy chain of a conventional vehicle



*Other losses: transmission, use of auxiliaries, idling and parasitic losses

Figure 44: Energy chain of a plug-in hybrid vehicle

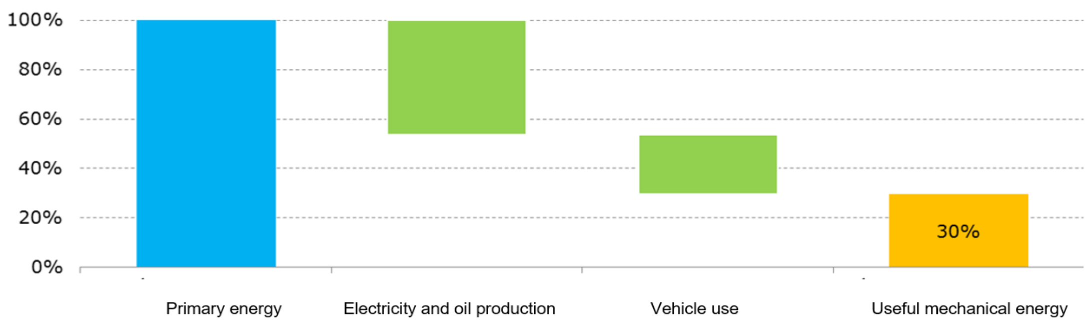
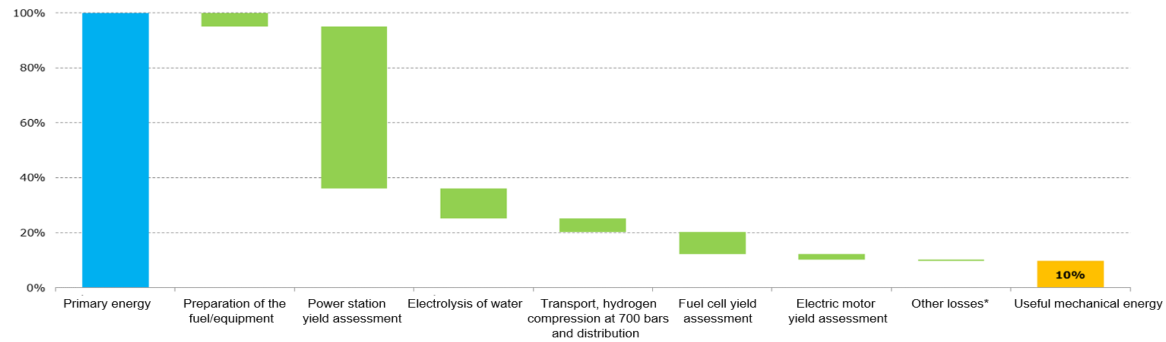
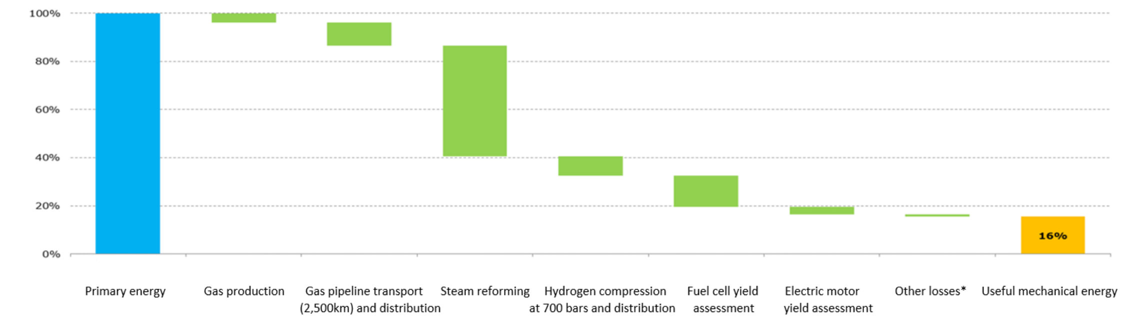


Figure 45: Energy chain of the fuel cell vehicle - hydrogen production by electrolysis



*Other losses: use of auxiliaries and parasitic losses

Figure 46: Energy chain of the fuel cell vehicle - hydrogen production by steam methane reforming



*Other losses: use of auxiliaries and parasitic losses

Sources: Mirova / (JEC - Joint Research Centre-EUCAR-CONCAWE collaboration, 2014)/ (U.S. Department of Energy, 2018) for the energy loss due to use of the vehicle / (IFP Energies Nouvelles, 2018) for the energy efficiency of the engine / (BP , 2017), (IEA, 2015) et (OECD/IEA, 2015) for the energy efficiency of the plants.

Battery electric vehicles maintain a higher energy efficiency than conventional vehicles. Fuel cell vehicles face difficulties regarding energy efficiency because of hydrogen production which involves two conversions: production of electricity and then hydrogen in the case of water electrolysis; or gas production and then hydrogen production in the case of steam reforming.

All of the data used can be found in Appendix I: key figures and orders of magnitude.

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