Energy Transition Monitor - Critical Metals

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No easy road to greening road transportation

- **There are three options for greening road transportation, namely full or partial electrification, more efficient fuel combustion and the rollout of fuel cell infrastructure.**
- **Every option will lead to the scarcity of some metals and a geopolitical dependency**
- **But a combination of these options would ease the scarcity and criticality of these metals**
- **We think demand and prices will rise substantially for lithium, some rare earth metals and platinum group metals**

1. Introduction

Greening road mobility has been on most governments' minds for a long while e.g. in the form of fuel efficiency standards for vehicles. Now the shift is to move away from combustion engines. Transportation (shipping, aviation and road transport) accounts for more than a quarter of global energy-related carbon emissions. Road travel accounts for roughly three-quarters of the transport emissions.

Lower emissions by vehicles would therefore help these governments to reach their targets of the Paris Climate Agreement. Paris Agreement's main goal of 'holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels.

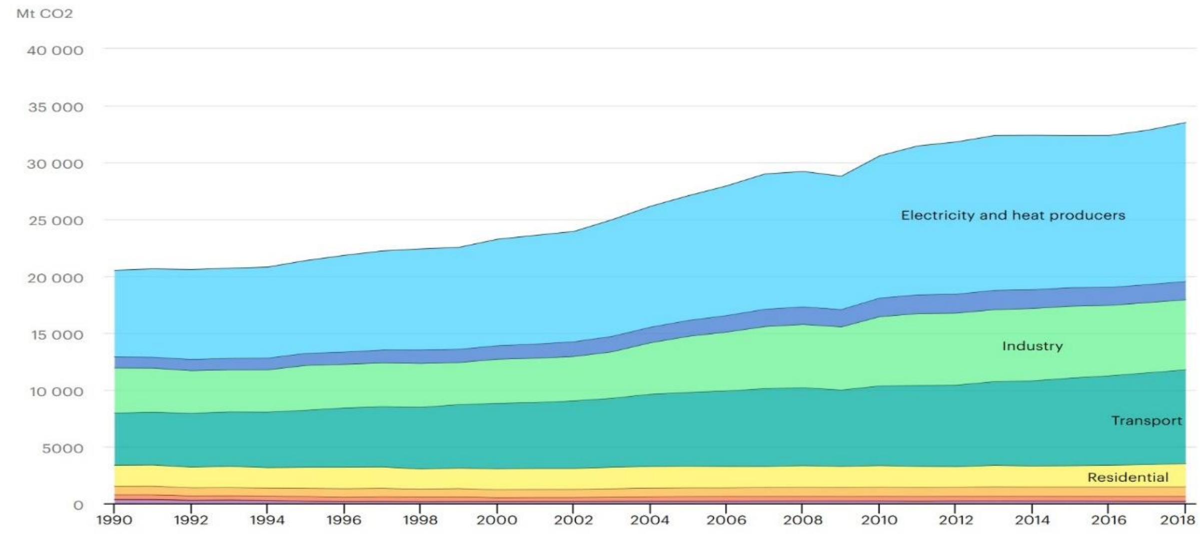
As ABN AMRO we hope to help to combat climate change and promote the energy transition. We focus on reducing the emissions of our clients active in mobility. Together with our clients active in shipping, road transport and mobility we seek for solutions to decrease the carbon footprint of their activities. This report focuses on road mobility.

In order to help our clients, we will answer the following questions in this report:

- What are the consequences of greening road transportation?
- What are the implications of future road vehicle scenarios (electrification, more efficient fuel combustion, fuel cell).
  - Which metals will become critical under the three competing vehicle scenarios?
  - What are the geographical concentration risks surrounding these critical metals?
  - How do these geographical concentration risks compare to the emission reduction benefits?

We start with an overview of the global transportation sector. Then we show some recent reports on critical metals. Later in our report we explain what scarce and critical mean and what rare earth elements are. We show what critical metals are use in internal combustion engine vehicles (ICEV), in electric vehicles (EV) and fuel cell electric vehicles (FCEV). Then we make the point that technology could dramatically alter the results and that there is no easy road to greening transportation.

Energy-related CO2 emissions by sector, World 1990-2018



Source: IEA. All rights reserves

2. While total production and sales of vehicles decreases, electric vehicles sales is growing

According to WardsAuto, 65 million vehicles were produced globally in 2020. This was sharply lower than the 90 million vehicles that were produced in 2019. Data from the International Organization of Motor Vehicle Manufacturers or OICA show that 73% of this were passenger cars, 22% light duty vehicles, 0.3% heavy busses and 4.5% heavy trucks. Global vehicle sales totalled 72 million vehicles in 2020 according to WardsAuto. The total vehicle fleet in 2018 amounted to 1,42 billion. Car registrations accounted for 72% of this and commercial vehicles for 27%. Car registrations increased on average by 3.1% a year from 1990 to 2018 and commercial vehicles by 3.8%. We estimate that the global registered car fleet was around 1.5bn vehicles at the end of 2020.

Global vehicle production, sales and registrations

In volume, 95% of Electric vehicles sales is passenger cars and light duty vehicles.

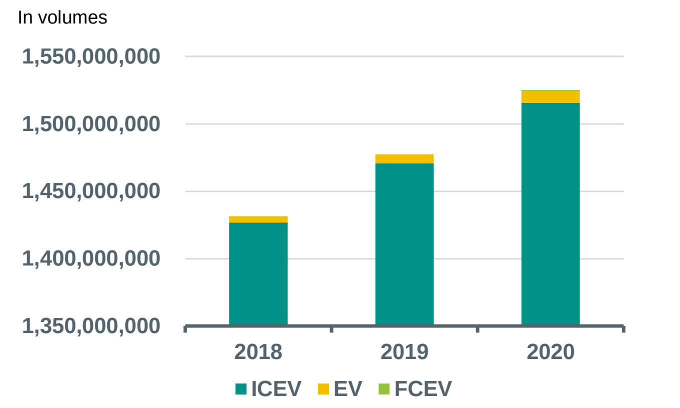
	Global production			Global sales			Global registrations/fleet				
	Total	PC ****	CV ****	Total *	EV **	FCEV **	Total ***	PC ***	CV ***	EV **	FCEV **
2018	94,469,019	69,907,074	24,561,945	64,318,996	2,037,716		1,431,448,000	1,042,274,000	389,174,000	4,659,368	
2019	89,564,146	65,381,827	24,182,319	61,615,569	2,246,679		1,477,504,832	1,073,542,220	403,962,612	6,672,332	
2020	63,408,585	46,288,267	17,120,318	50,423,327	3,226,798	12,000	1,525,061,678	1,105,748,487	419,313,191	9,535,766	50,000

Source: * Wardsauto, ** Rhomotion, *** Wards and own calculations, **** OICA and own calculations

Source: Wards autos, OICA, RhoMotion, ABN AMRO Group Economics. PC = Passenger Cars, CV = Commercial Vehicles, EV = Electric Vehicles, FCEV = Fuel Cell Electric Vehicles

Electric vehicles have become increasingly popular in some countries/regions but they still account for a very small proportion of the global vehicle sales and global fleet. In 2020 global electric vehicle sales were 3.2 million vehicles and 95% were passenger cars and light duty vehicles. So roughly 6.3% of the global vehicle sales were electric cars, a sharp increase from the 3.5% in 2019 but still a relatively low number. However, these trends are changing fast. While global vehicle sales dropped by 18% in crisis pandemic year 2020, electric vehicle (EV) sales rose by 44%. The strong sales in EV in 2020 could be the result of higher generic demand and/or the result of ending lease-contracts. The fact is that in the countries were EV is popular, governments offer extensive financial programs to support the growth in EV. In the global fleet or car registrations electric cars account for less than 1% of the total. Details about the different types of vehicles and how they work can be found in the appendix at the end of this report.

Market share of the vehicle types in the global fleet



Source: WardsAuto, RhoMotion, ABN AMRO Group Economics

There are three options in greening road transportation namely full or partial electrification, more efficient fuel combustion, the rollout of fuel cell infrastructure or a combination of these three. Each option would result in a certain geopolitical dependency and a number of raw materials becoming critical in a wider context of increasing pressure on resources. We start with the geopolitical dependency.

3. Geopolitical dependency

Geopolitical dependency is not a new phenomenon in dealing with raw materials. Some countries/companies have access to raw materials (have the deposits or hold the rights to these deposits) while other countries don't have sufficient access to raw materials. This creates a power struggle between countries and results in a geopolitical dependency from the buyer on the seller. For example, the EU does not have sufficient oil reserves. Therefore, it imports oil from other countries such as Russia (30%), Iraq (9%) and Saudi Arabia (7%). As long as there is enough supply on the world market and there are more suppliers to choose from this geopolitical dependency is lower.

The same holds for metals used in road transportation. What metals are used depends on the option of greening road transportation. To produce conventional vehicles a large number of metals are used such as copper, aluminium, steel, iron, titanium, platinum (diesel), palladium and rhodium (gasoline cars). For the battery and the motor of electric vehicles lithium, nickel, cobalt, manganese, aluminium and rare earth metals are needed. For fuel cell electric vehicles platinum and rare earth metals are needed among other metals. The geopolitical dependency closely relates to the scarcity and criticality of these metals. We focus on this in our next chapters.

4. Scarce and critical metals

In this part of the report we focus on recent reports from the EC and the IEA and define scarce, critical and rare earth elements (REE). After this we focus on what metals are critical in greening road transportation followed by the consequence of this for geopolitical dependency and transition.

Critical raw materials according to EC and IEA

Last year the European Commission (EC) published a study on the EU's list of Critical Raw Materials (link to the background report). According to the EC pressure on resources will increase - due to increasing global population, industrialisation, digitalisation and increasing demand from countries. Furthermore, pressure comes from the transition to climate neutrality with metals, minerals and biotic materials used in low-emission technologies and products. The OECD forecasts that global materials demand will more than double from 79 billion tonnes today to 167 billion tonnes in 2060. Global competition for resources will become fierce in the coming decade. Dependence on critical raw materials may soon replace today's dependence on oil according to the EC. The EC identified the following raw materials as being critical.

EU's list of Critical Raw Materials

2020 Critical Raw Materials (30)			
Antimony	Fluorspar	Magnesium	Silicon Metal
Baryte	Gallium	Natural Graphite	Tantalum
Bauxite	Germanium	Natural Rubber	Titanium
Beryllium	Hafnium	Niobium	Vanadium
Bismuth	HREEs	PGMs	Tungsten
Borates	Indium	Phosphate rock	Strontium
Cobalt	Lithium	Phosphorus	
Coking Coal	LREEs	Scandium	

Source: EC

Last week the IEA also published a report on this topic with the title: The role of Critical Minerals in Clean Energy Transitions (link to the report). Part of this report covers electric vehicles. According to IEA minerals used in clean energy technologies for transport are copper, lithium, nickel, manganese, cobalt, graphite, rare earth elements, aluminium. The technical information about electric vehicles as well as the developments overlap our report. However, we take a different approach to critical metals in greening road transportation. We focus on all three options of greening road transportation and compare them. And we focus on the consequences of choosing of these options or the combination of the three.

What is scarce?

A metal is scarce if the abundancy is low in the Earth's crust. This is measured by percentage or parts per million (ppm) in mass. Oxygen is the most abundant element followed by silicon in the crust while osmium and rhodium are very scarce.

What is critical?

Next to being scarce, a metal can also be defined as critical. Critical minerals are metals and non-metals that are considered vital for the economic well-being of the world's major and emerging economies, yet whose supply may be at risk due to geopolitical scarcity, geopolitical issues, trade policy or other factors[1]. In this report we focus on critical metals for road transportation. For example, lithium and cobalt are currently critical metals for greening road transportation. A metal could be scarce, meaning a low abundance in the Earth's crust such as the platinum group metals and a metal could also be critical meaning it can be found only in a few countries or a country that you don't have a good relationship with. For example, cobalt is mainly found in DR Congo and can therefore be seen as critical.

What are rare earth elements?

Rare earth elements are known as rare because it is very unusual to find them in a pure form. They are grouped together as a family because of their incredible chemical similarities. They are difficult to mine, difficult to separate and difficult to process. They are mostly mined in the China. Some rare earth elements are not scarce, but they are generally critical.

[1] https://www.ga.gov.au/about/projects/resources/critical-minerals#:~:text=Critical%20minerals%20are%20metals%20and,trade%20policy%20or%20other%20factors.

5. Critical metals used in vehicles

In this section we focus on answering the first sub-question of the introduction: which metals will become critical under the three vehicle scenarios (more efficient internal combustion engines, electrification and fuel cell electric vehicles)?

As mentioned above to produce vehicles a large number of metals are used. Some metals are relatively easy to obtain such as aluminium, steel, iron, titanium, copper and nickel. These metals are neither scarce nor critical. Some other metals are far more difficult to obtain because they are scarce, or they are mined in a small number of countries. For example, platinum group metals, lithium, cobalt and rare earth elements.

Critical metals used in vehicles

A higher abundance number is scarcer.

	Mobility/automotive	Abundance	Supply: source US Geological Survey
Metals			
Cobalt	Lithium-ion batteries	31	71% Congo
Lithium	Rechargable batteries *	33	55% Australia, 23% Chile, 10% China
Niobium	Fast-charging battery cells **	34	88% Brazil, 10% Canada
Rare earth elements			63% China, 12% US, 10% Australia
Cerium	Cerium-based catalists in cars ***	26	
Dysprosium	To increase the operating temperature of magnets in electric cars ****	42	
Lanthanum	Used in Solid Oxide Fuel Cell *****	28	
Neodymium	In magnets for traction motors electric cars ****	27	
Praseodymium	In magnets for traction motors electric cars ****	39	
Yttrium	Used in Solid Oxide Fuel Cell *****	29	
Platinum Group metals			
Platinum	Catalyst in ICE, Catalyst in Fuel Cell Electric Vehicle	74	72% South Africa, 8% Russia
Palladium	Catalyst ICE	70	42% Russia, 38% South Africa, 10% Canada
Rhodium	Catalyst ICE	80	80% South Africa

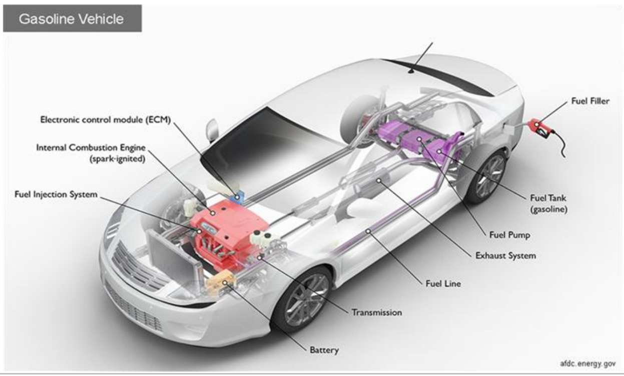
* Johnson Matthey
** https://www.mes-insights.com/the-current-state-of-ev-battery-development-a-938833/?cmp=go-ta-art-trf-MES_DSA-20200217&gclid=EAIaIQobChMI76vNvPTh7QIVEdN3Ch1-pwt9EAMYASAAEgKk1PD_BwE
*** Potential for Recovery of Cerium Oxide Contained in Automotive Catalytic Converters - By Donald I. Bleiwas
**** RhoMotion
***** IEA

Source: US Geological Survey, Abundance of elements of the Earth's crust table, ABN AMRO Group Economics, RhoMotion, Johnson Matthey, IEA

Critical metals used in vehicles with internal combustion engines

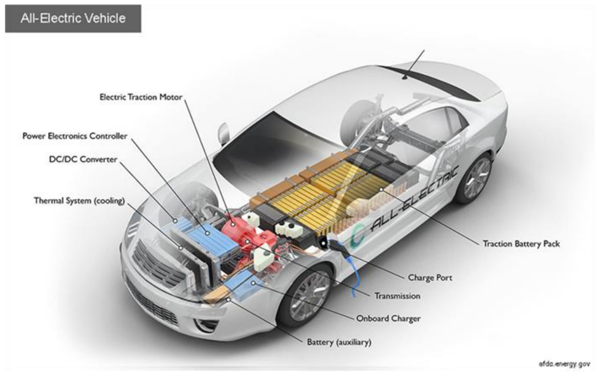
Platinum group metals such as palladium, platinum and rhodium are used as catalysts in vehicles with internal combustion engines. These metals are responsible for lowering the harmful emissions and thereby the are critical for the greening of road mobility. Emission regulations in many countries have become stricter. This means that new vehicles with internal combustion engines should emit less and less harmful emissions. This is only possible if higher loadings of palladium, platinum and rhodium are used in catalysts. Catalysts in gasoline vehicles mainly contain palladium and rhodium. Catalysts in diesel vehicles mainly contain platinum (see appendix). These metals are critical metals and mainly mined in South Africa and Russia.

Gasoline vehicle versus



Source: US Energy Department

All-Battery vehicle

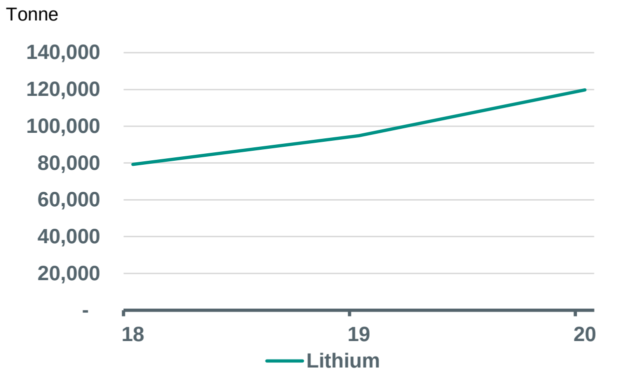


Source: US Energy Department

Critical metals used in electric vehicles

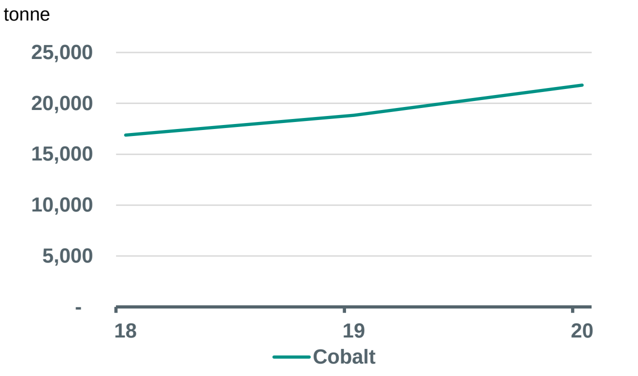
To further reduce harmful emissions, electric vehicles have gained popularity. Electric vehicles may not emit harmful emissions, but the mining of the metals used in these vehicles is often not CO2 neutral. There are also critical metals used in electric vehicles. There are different parts of electric vehicles that contain critical metals: the battery and the motor. To start with the battery of an electric vehicle. For the battery lithium and cobalt are the critical metals. In 2020 the annual lithium demand to produce electric vehicles was 120,000 tonnes compared to an annual mine supply of around 360,000 tonnes. Lithium is mined in Australia, Chile and China. In 2020 the annual cobalt demand for the production of electric vehicles was 22,000 tonnes; annual mine supply according to USGS was 144,000 tonnes. Cobalt supply comes for more than 70% from DR Congo. So, mine supply is still enough to cover the demand for electric vehicles at this point in time.

Annual EV lithium demand in tonne



Source: Based on data from RhoMotion, ABN AMRO Group Economics

Annual EV Cobalt demand in tonne



Source: Based on data from RhoMotion, ABN AMRO Group Economics

There is a drive to increase the energy density of the battery. This is the measure of how much energy a battery contains in proportion to its weight. It is typically presented in Watt-hours per kilogram. A higher energy density means that vehicles can travel further without the need to recharge. There are several ways to increase the energy density of a battery. First more lithium, cobalt and other components are used. Second, the composition of the battery and the materials used change (battery chemistry). So, for example a lower use of cobalt and a higher use of nickel. According to the IEA, a Lithium Cobalt Oxide (LCO) battery has the greatest energy density, a Lithium Manganese Oxide (LMO) battery has a high specific power, a longer cycle life and much better thermal stability than an LCO. The Lithium Iron

Phosphate (LFP) battery offers thermal stability at even high temperatures, low cost and high durability. The Lithium Nickel Cobalt Aluminium Oxide (NCA) battery has the highest specific energy range in the current class of technologies as well as a specific power. Finally, the Lithium Nickel Manganese Cobalt Oxide (NMC) battery has a longer life cycle compared to NCA, but a lower energy density.

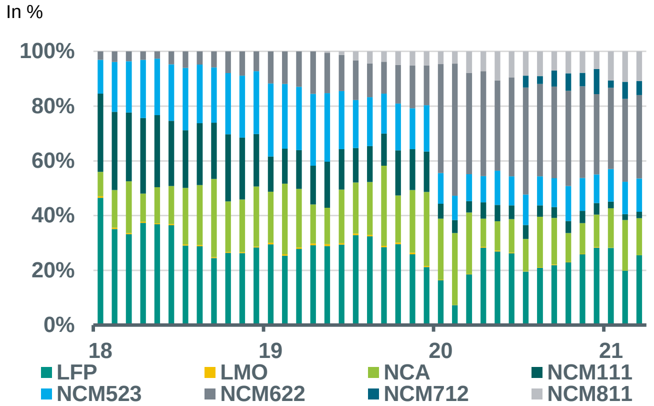
The technology is moving fast forward and there is a tendency to use a lower cobalt content or no cobalt at all. The two graphs below show what metals are used in a lithium-ion battery and what the market share is of these batteries. Batteries with lower cobalt have gained market share. For example, NCM 622, NCM 712 and NCM811 have a lower ratio of cobalt than earlier batteries. LFP has no cobalt content at all.

Types of lithium-ion batteries

	Cathode	Anode	Use
LCO	Lithium Cobalt Oxide (60% Cobalt)	Graphite	Mobile phones, tablets, laptops, cameras
LFP	Lithium Iron Phospate	Graphite	Portable and stationary needing high load current and endurance
LMO	Lithium Manganese Oxide	Graphite	EV, Electric powertrains
NCA	Lithium Nickel Cobalt Aluminium Oxide (9% Cobalt)	Graphite	Medical devices, industrial, electric powertrain (Tesla)
NCM111	Lithium Nickel Manganese Cobalt Oxide (ratio NMC 1:1:1)	Graphite	E-bikes, EV, medical devices
NCM523	Lithium Nickel Manganese Cobalt Oxide (ratio NMC 5:2:3)	Graphite	E-bikes, EV, medical devices
NCM622	Lithium Nickel Manganese Cobalt Oxide (ratio NMC 6:2:2)	Graphite	E-bikes, EV, medical devices
NCM712	Lithium Nickel Manganese Cobalt Oxide (ratio NMC 7:1:2)	Graphite	E-bikes, EV, medical devices
NCM811	Lithium Nickel Manganese Cobalt Oxide (ratio NMC 8:1:1)	Graphite	E-bikes, EV, medical devices
LTO	LMO or NMC	Lithium Titanate	Electric powertrain (Mitsubishi i-MiEV, Honda Fit EV)

Source: https://batteryuniversity.com/learn/article/types_of_lithium_ion

Market share of the battery types



Source: RhoMotion

For the motor other critical metals are used. In the motor there are permanent magnets, which contain rare earth elements dysprosium, neodymium and praseodymium (see appendix). These metals have very high magnetic strength at low temperatures. China is the big producer/miner of these rare-earth elements.

Critical metals used in fuel cell electric vehicles

An alternative to vehicles with internal combustion engines and/or electric vehicles is the fuel cell electric vehicle. Fuel cell electric vehicles use a fuel cell instead of a battery. They are rarely used because the fuelling infrastructure still needs to be built (see appendix). As with internal combustion engines, most fuel cells used in vehicles also use a catalyst. The catalyst is made of platinum, but the loadings are around double of what is used in internal combustion engines. However, there are some fuel cells used in vehicles that don't need a catalyst because they operate at much higher temperatures. This is the Solid Oxide Fuel Cell (for explanation see appendix). This fuel cell doesn't use platinum but is does contain lanthanum and yttrium. Platinum, lanthanum and yttrium are critical metals for fuel cells used in vehicles. Platinum comes for 70% from South Africa and lanthanum and yttrium are mainly mined in China.

6. Technology could increase the competition between the transportation options

Technology is a crucial driver in greening road transportation. This could increase the competition between the three options of transportation – internal combustion engine, electric vehicle, fuel cell electric vehicle. There are several reasons for this. First if technology finds ways to largely reduce the harmful emissions that internal combustion engines emit than there is a lower need to switch to electric vehicles.

Second, the improved technology has also made working from home more possible resulting in lower home-work travel and less business travel. A lower demand for travel would also lessen the criticality on raw materials.

Third, there is a tendency to lower the content of cobalt in the cathode of the battery of the electric vehicle by increasing the nickel content. The result is a lower geopolitical dependency on DR Congo. The table below shows some future technologies in the batteries of electric vehicles.

A number of future technologies

	Description	Pros	Cons
NCM 9.5.5 *	Lithium Nickel Managese Cobalt Oxide	Higher range Lower Cobalt content	
Solid state	Solid electrolyte, not a liquid. Anode free	Higher energy density than Li-ion battery with liquid electrolyte Safer than liquid electrolyte	Technology under development But can crack
Silicon in anode	High end EV use 6-8% silicon oxide in the anode Could increase to15% Silicon dominant anodes (80%)	Increase capacity	Silicon grows and shrinks with charge and discharge Mechanical stress, shorter life cycle
Li-S	Lithium Sulfur	Higher energy density of around 500Wh/kg Reduced costs because of Sulfur	Leakage of active material Low life cycle
Lithium-air	Oxidation of lithium at anode , reduction of oxygen at cathode => current flow	High energy density	Stability electrlyte
Battery swapping *	To swap a battery when being on the road	Larger ranges	Conditions and limitations of swapping a battery

Source:* RhoMotion, https://batteryuniversity.com/learn/article/types_of_lithium_ion

Fourth, the content of the anode of the battery could be adjusted to extend the battery lifespan. Graphite is the most commonly used anode material, followed by silicon. Silicon offers 10 times higher energy density than graphite and high charging/discharging speeds. But silicon has a larger expansion than graphite and the silicon structure need to be improved. Both graphite and silicon are abundant and non-critical materials.

Fifth, currently permanent magnets are used in the motor of electric vehicles. These could become more efficient but also another motor could be used that don't contain rare earth metals. For example, an induction motor, but this one is less efficient (-4 to -5%). A switch to a motor with no rare earth elements would largely reduce the supplier power of China.

Different motors in electric vehicles

	Permanent Magnet Synchronous Motors	AC Induction Motor	Switched Reluctance Motor	Permanent Magnet Switched Reluctance Motors
Pros	High efficiency	No real earth elements	Very robust	Reduction of requited magnetic material
	Power density	Simple to construct	Simple to manufacture	Improve efficiency
	Compactness			
	Easy to control			
Cons	High dependency on rare earth elements	Asynchronous rotor and stator	Noisy	
		Lower efficiency than PMSM	Less efficient	
		Higher copper intensity	Difficult to control	

Source: IDTechEx

Finally, the idea of battery swapping has entered the market. A battery swapping station allows vehicles to exchange a discharged battery pack for a charged one, eliminating the charge interval. This is a novel idea and a lot still needs to be figured out. The idea of swapping a battery for commercial road mobility is great as it substantially lowers the time to recharge. If this is implemented in the future, electric vehicles could become a more serious competitor for vehicles with internal combustion engines, especially in more remote areas.

7. No easy road to greening road transportation

Currently internal combustion engines have the dominant position in the sector, but they have harmful emissions. Electric vehicles have no emissions at use but have a small range and a high dependency on critical metals (lithium, cobalt and rare earth elements). Fuel cell electric vehicles are less efficient than electric vehicles and currently lack the infrastructure. In the perfect world there would be no harmful emissions, a large range and no high dependency on critical metals.

Based on our analysis, we think that there is no easy road to greening road transportation and it comes at a price. Suppliers (countries that supply critical metals) have a lot of power and buyers (countries that need critical metals) have low power. Countries that need critical metals have the option to choose the way of greening road transportation and therefore also decide on their geopolitical dependence. They will remain geopolitical dependent regardless the way of greening road transportation they choose, but they can at least determine the country they want to depend on. Technology is in favour of the countries that need critical metals, because road transportation could become more efficient or the way of road transportation could change. This would have a direct impact on the power balance between countries that supply critical metals and countries that need critical metals.

Comparison of internal combustion engine, electric vehicle and fuel cell electric vehicle

	Internal Combustion Engine (ICEV)	Electric Vehicle (EV)	Fuel Cell Electric Vehicle (FCEV)
Energy density *	Diesel has 13,000 Wh/kg	Current battery technology 280 Wh/kg	FCEV 3,000 Wh/kg
Pros	Largest range (diesel) *	No harmful emissions	Large range *
	Easy refilling	95% efficiency	No/lower harmfull emissions
			Refilling similar than ICEV
Cons	Harmful emissions	Small range *	Refilling infrastructure
	More platinum, palladium and rodium needed	High dependency on critical metals	60% efficiency
		Can't use while charging	
		Charging time	
		Electricity net expansion	

Source: ABN AMRO Group Economics, * RhoMotion

By favouring electric vehicles, the geopolitical dependency on China, Chile, Australia and DR Congo also increases. The question which we should ask ourselves here in Europe (and/or the US) if this is the desired outcome. There are more roads to Rome and the geopolitical dependence/independence also has a crucial role to play. The greening of road transportation could also be reached by making internal combustion engines more efficient, investing in fuel cell electric vehicles and infrastructure or a combination of the three options. But if only one road is favoured this will result in a shortage of the critical metals used in that option of transportation. By only favouring electric vehicles there will be a shortage of lithium, cobalt (depending on the technology) and rare earth metals over time. If internal combustion engine vehicles or fuel cell electric vehicles are favoured there will be a serious supply shortage of platinum.

To add to this equation is that the pandemic has resulted in a change of behaviour in mobility, at least in the western world. Going forward working more from home and less (business) travelling is expected to be the new normal. As a result, it is likely that the need for transport by road will decline or at least dampen some of the extra kilometres driven by small trucks because of packages delivery.

Finally, we should not underestimate the adoptability of mankind. If there is a substantial shortage of a critical metal, exploration in other parts of the world will increase. There will be more effort in finding deposits in locations where there is a possibility to find the critical metal. Moreover, technology will be focussed on finding a way around this shortage. For these reasons we think that there could be a shortage for a number of years, but we doubt if there will a shortage in the long run. Technology is moving fast forward and what is now in demand doesn't mean it is also in demand in ten or twenty years from now. Therefore, it is not realistic to calculate with scenario's that will not change over time.

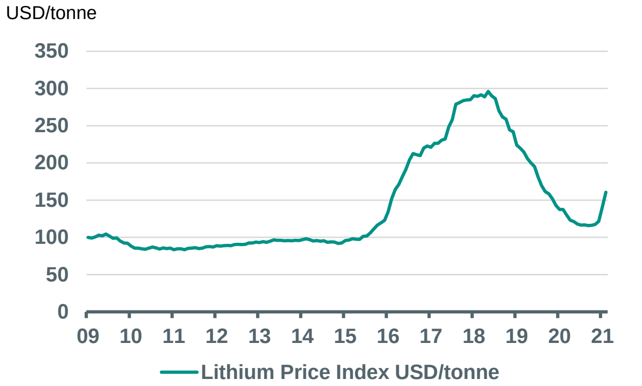
8. A combination of the options eases the scarcity and criticality of metals

We think that the most desirable outcome is to use the strengths of all three ways of greening road transportation. What does this mean? First the use of electric vehicles for short distance ranges and in cities. Electric vehicles can't currently compete with the long-distance ranges with diesel. Even if they would be able to compete, this would mean a higher use of critical metals and a higher dependence on the countries that supply these metals. Second, as long as the fuel cell electric vehicle infrastructure is not up and running, internal combustion engines complying with more stringent emission regulations or a hybrid vehicle (combination of internal combustion engine with electric vehicle) will be needed for the long-distance ranges. So, persons and companies that regularly travel longer distances will opt for a hybrid vehicle or a vehicle with an internal combustion engine. As soon as the fuel cell electric vehicle infrastructure is rolled out, we think that internal combustion engines will be phased out at a faster pace.

What are the results of this combination of outcomes? There will be a less dramatic increase in demand for the critical metals used in electric vehicles. Despite this we think that demand for electric vehicles will increase considerably from this very low level. This will lead to higher demand for lithium and rare earth elements. With this Australia, Chile and China will increase their strong supplier power. We think that battery technology will result in lower cobalt demand going forward so the DR Congo should slowly but surely lose its supplier power. Demand for electric vehicles will mainly be for the use in the city or for short distances as Norway and Oslo have shown. In the coming years, demand for platinum, palladium and rhodium will also increase. The more stringent emission regulations for internal combustion engines will demand higher loadings of these platinum group metals. Moreover, vehicles with internal combustion engines are still needed for longer distance travel as long as the fuel cell infrastructure is not rolled out. Demand for fuel cell vehicles will also result in higher demand for platinum. There is already a supply shortage in these metals, and this will only increase resulting in higher prices.

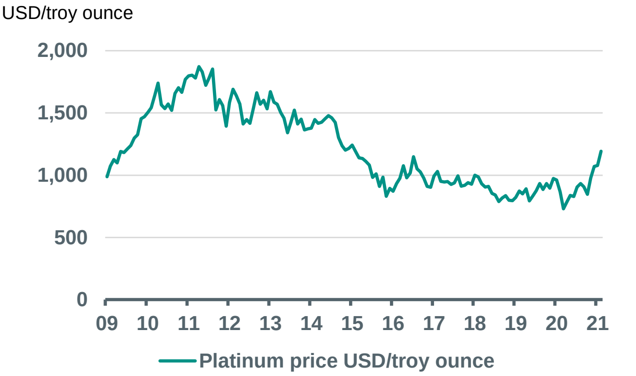
So, in the coming years critical metals lithium, dysprosium, neodymium, praseodymium, platinum, palladium and rhodium will see high demand, while in the longer run fuel cell electric vehicles could replace vehicles with internal combustion engines leading to even more platinum demand.

Lithium price index



Source: Benchmark Minerals, Bloomberg

Platinum price



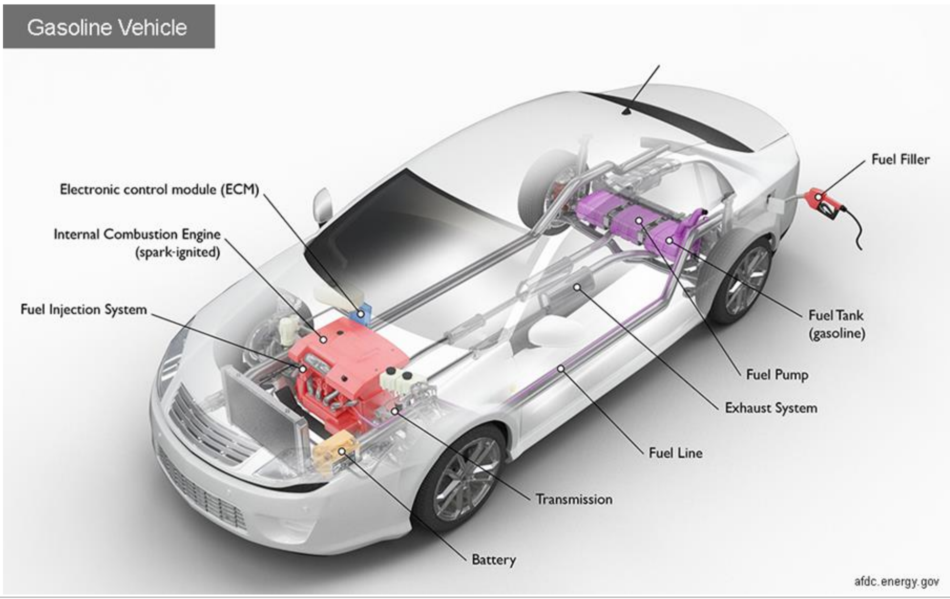
Source: Bloomberg

Appendix

Internal combustion engine vehicles (ICEV)

The large majority of the global vehicle fleet consists of vehicles with internal combustion engines of ICEV. These engines burn fossil fuel. In this process ICEV emit unburned hydrocarbons, carbon monoxide (CO) and nitrogen oxygen (NOx), particulate matter (PM) and Sulphur oxide (SOx). These have a negative impact on air quality, human life and global warming. Globally governments have set emission standards. They are designed to achieve better air quality and protect human life. Platinum, palladium and rhodium are used in car catalysts of internal combustion engines to limit these emissions. Catalysts in diesel cars contains for a large part platinum while catalysts in gasoline cars contain mostly palladium and rhodium. Rhodium is the best catalyst for after treatment of gasoline NOx emissions. Governments make the emission standards stricter and as a result more platinum, palladium and rhodium are used to limit the harmful emissions. So ICEV will become less pollutive over time but it there will always be some pollution. With the global focus on reducing harmful emissions and limit global warming under the Paris Climate Agreement other forms of mobility by road have entered the market such as electric vehicles (EV), hybrid vehicles and fuel cell electric vehicles (FCEV).

Graph 1: How do gasoline cars work?

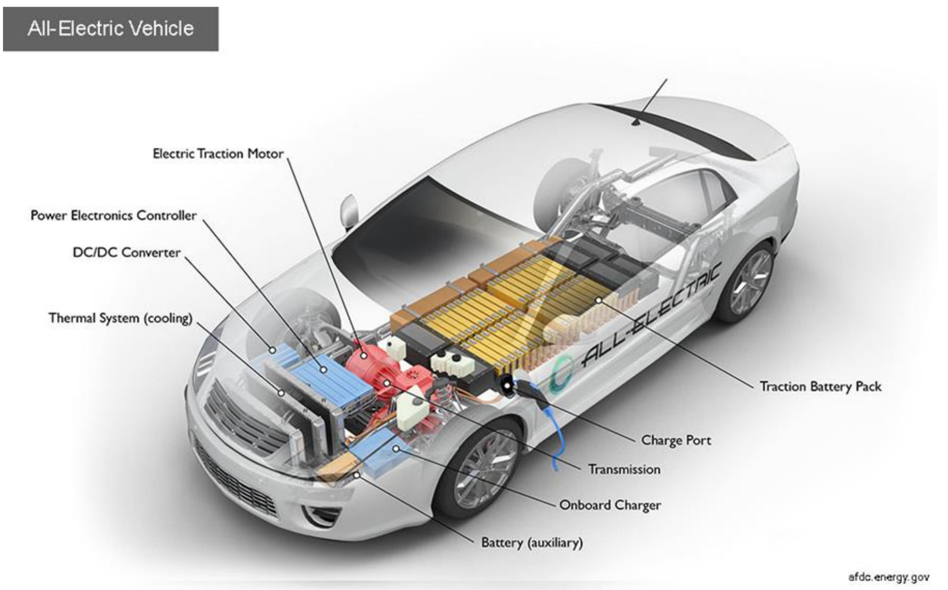


Source: US Energy Department

Electric vehicles

Electric vehicles have gained popularity because they don't emit harmful emission. But the range how far the car can drive is far less than that of a diesel or gasoline car. Moreover, an electric vehicle needs to be charged from time to time and then the vehicle can't be used. There are two types of electric vehicles: battery electric vehicles (BEV) and plug-in hybrids (PHEV).

Graph 2: How do all-electric cars work?



Source: US Energy Department

An electric car has a battery pack and an electric traction motor (instead of internal combustion engine). A battery can be packed in various ways: cylindrical, prismatic or pouch. Every way of packing has a different system of thermal management. The battery has a cathode, anode, electrolyte and a separator. The cathode is responsible for the capacity and the power. The anode is responsible for the lifespan. The electrolyte and separator determine the safety of a battery. When a battery is charged lithium-ions are stored in the anode. When a battery is discharged lithium-ion move to the cathode[2]. During a discharge cycle, lithium atoms in the anode are ionized and separated from their electrons. The lithium ions move from the anode and pass through the electrolyte until they reach the cathode, where they recombine with their electrons and electrically neutralize[3]. The electrolyte doesn't let the electrons pass. Electrons move through the wire. The capacity and the voltage are determined by the active material type of the cathode[4]. Most cathodes contain nickel, lithium, cobalt and manganese but in different quantities. Some batteries contain aluminium. Nickel has high capacity, manganese and cobalt have high safety and aluminium increases the power of the battery[5].

The anode is mostly made of natural or synthetic graphite. In the graphs below the chemistry of the different cathodes and market share. The main focus is how to improve the range and to increase the energy density. If the energy density is higher, it can be loaded with lighter weight and smaller size onto the EV. Another focus is how to minimize cobalt in the battery.

The majority of electric vehicles has permanent magnets in their motors. These motors are called permanent magnet synchronous motors or PMSM. Permanent means that the magnet is rotating even with no electrical current applied, magnetic flux will still be present. Magnets have a high efficiency. Neodymium is the primary Rare Earth Element present in these magnets in an alloy of Neodymium-Iron-Born (NdFeB). The alloy is then doped with other rare earth elements

2 The Four Components of a Li-ion Battery (samsungsdi.com)
3 https://www.cei.washington.edu/education/science-of-solar/battery-technology/
4 https://batteryuniversity.com/learn/article/types_of_lithium_ion
5 Samsung

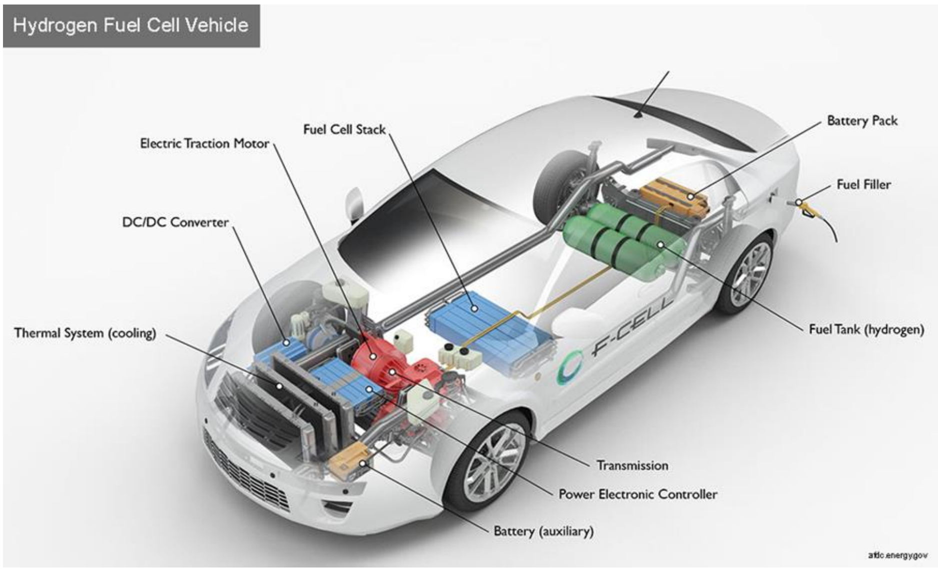
such as Praseodymium and Dysprosium to improve the operating characteristics of the magnet like to increase the operating temperature of the magnet without becoming demagnetised (RhoMotion).

Fuel cell electric vehicles (FCEV)

Next to electric vehicles there are also fuel cell electric vehicles (FCEV). Fuel cell electric vehicles use a fuel cell instead of a battery. They are rarely used because the fuelling infrastructure still needs to be built.

There are different forms of fuel cells but not every form is suitable to be placed in a vehicle. The fuel cell that is mostly used is the Polymer Electrolyte Membrane (PEM) fuel cell also called a proton exchange membrane fuel cell. They use solid polymer as an electrolyte and porous carbon electrodes containing platinum or platinum alloy catalyst. They need only hydrogen, oxygen from the air and water to operate. They are typically fuelled with pure hydrogen supplied at storage tanks or reformers. Power is generated from the movement of hydrogen ions (protons) in an electrolyte solution. PEMs operate at relatively low temperatures, 80 degrees Celsius. Low-temperature operation allows them to start quickly (less warm-up time) and results in less wear on system components. It requires that platinum catalyst be used to separate the hydrogen's electrons and protons [6]. The efficiency of a PEM fuel cell is 50% compared to 95% of an EV.

Graph 5: How do fuel cell electric vehicles work using hydrogen?



Source: US Energy Department

Another fuel cell that is used in vehicles is the solid oxide fuel cell. Solid oxide fuel cells (SOFC) have also been used in vehicles for example in the e-biofuel cell. They use a hard non-porous ceramic compound as electrolyte. It has ethanol or ethanol blended water as fuel source. This fuel cell vehicle can use the existing infrastructure of biofuel. A reformer produces hydrogen from bioethanol and a SOFC stack generates electricity from a reaction between the hydrogen and oxygen (air) in the stack. Power is generated from the movement of oxygen ions in an electrolyte solution. The generated electricity is stored in the on-board battery. The heat that is generated during the power generation is reused in the generation of hydrogen[7]. It has a higher efficiency than PEMs and the electrolyte will not leak (but can crack). But

[6] www.energy.gov – office of energy efficiency & renewable energy

[7] https://www.nissan-global.com/EN/TECHNOLOGY/OVERVIEW/e_bio_fuel_cell.html

SOFCs operate at very high temperatures – as high as 1,000 degrees Celsius. So, it requires significant thermal shielding but there is no need for a catalyst. High temperatures have large wear on the system components. The SOFC has an efficiency of around 65%[8].

8 www.energy.gov – office of energy efficiency & renewable energy