Revue générale des routes et de l'aménagement
RGRA
www.rgra.fr

ERS TO DECARBONIZE ROAD TRANSPORT

FOREWORD

The Electric Road System (ERS) is an innovative technology that could, if it reaches maturity, contribute to the decarbonization of road transport. After the publication of the reports of three working groups commissioned by the DGITM (General Directorate for Infrastructure, Transport and Mobility) to explore its potential, this has been confirmed, but there are still technological obstacles that only a demonstrator can overcome.

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In order to limit the extent of global warming to 1.5°C, France's objective is to be carbon neutral by 2050. For transport, this objective means complete decarbonization of land transport by that date.

For light vehicles (LDVs), passenger cars and light commercial vehicles (LCVs), electrification is the main pathway to decarbonization and has been widely implemented since 2020 following a European regulation adopted in 2009 and amended in 2014.

For heavy-duty vehicles (HGVs), European regulation 2019/1242 requires manufacturers to reduce CO_2 emissions from new trucks sold in 2030 by 30% compared to 2020, or face substantial penalties. The main solutions for decarbonization are biogas, biodiesel, battery electric, hydrogen or the Electric Road System (ERS).

The ERS consists in supplying electricity - continuously or in sections - to vehicles in motion on a road or highway. The objective is to improve the autonomy (increase the range) of the vehicles without making them heavier or more expensive due to an excessive battery volume. This is particularly important for heavy trucks, especially the larger and heavier ones, for which the battery mass required for reasonable ranges quickly becomes a deterrent.

Three main ERS technologies are currently being studied and proposed at industrial prototype or pre-industrialization stages: overhead conductivity (catenary and pantograph), ground conductivity (power rail in the pavement or at the trackside), and induction (inductive loops embedded in the pavement) (see article "Technological solutions and deployment conditions"). Vehicles must be equipped with an electricity collection system, depending on the technology (pantograph, skid or inductive system) and an electric motor.

While Germany and Sweden have ERS demonstrators on open roads and Sweden has decided to build the first permanent electric highway (25 km between Örebro and Hallsberg) by 2025 and must make its technological choice by the end of the year, France has long remained on the sidelines due to a lack of consensus among the players.

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In response to this observation, the General Directorate for Infrastructure, Transport and Mobility (DGITM) organized a seminar on October 15, 2020, bringing together all the players (solution providers, vehicle manufacturers, road managers, transporters, construction companies, energy providers), at the end of which it was agreed to launch three working groups to explore the potential of the ERS:

• one on socio-economic, energy and environmental issues, chaired by Patrick Pélata, former Deputy CEO of Renault, and co-chaired by Olivier Gavaud, DGITM;

• a second one on technical solutions, potentialities and obstacles, chaired by Stéphane Levesque, Director of the French Road Union (URF), and co-chaired by Bernard Jacob, Gustave Eiffel University;

• a third on the search for proof, with an update on experiments to date and the opportunity for a full-scale demonstrator in France, chaired by Marc Gohlke, director of the CARA cluster (European Cluster for mobility solutions, a cluster of the Auvergne-Rhône-Alpes region), and co-chaired by Nicolas Hautière, Gustave Eiffel University.

After more than 50 meetings, which gave all the players the opportunity to express and compare their points of view, the groups presented their conclusions to the Minister of Transport, Jean-Baptiste Djebbari, on October 20, 2021, during a ministerial committee for the development of innovation in transport (CMDIT).

The results show that ERS has great potential for achieving the objectives of decarbonization of road transport, but also that there are still technological obstacles, listed in the reports, that only a demonstrator in France can overcome.

This is why the Minister launched on the same day, within the framework of the PIA4, a call for projects "Automated road mobility, connected and low-carbon service infrastructures" in order to finance one or more ERS demonstrators. The next round is scheduled for June 15, 2022, and we hope to see some great projects in response to the challenges identified.

At the same time, the reports of the three groups have been translated and have aroused great interest among our German and Swedish partners. France has thus made a first contribution to the project, in a context where the choice of deploying the ERS could only be considered on a European scale, given the necessary investments and the interoperability issues. Exchanges are also planned with other European Union member states and with the European Commission. On a global scale, PIARC is also very interested in ERS and has formed a dedicated study group.

Thus, if no deployment decision has been made to date, the processes are underway to remove doubts and build the decision at the right scale. ■

REFERENCE

1. Ministry of Ecological Transition, "Reports from WG1, 2 and 3 on the Electric Road System," 2021: https://www.ecologie.gouv.fr/lautoroute-electrique.

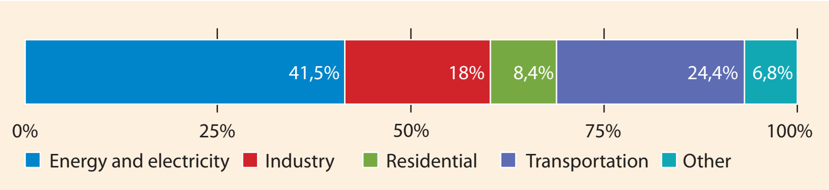
CONTEXT, ISSUES AND STRATEGY

Decarbonization of road transport is a major challenge for the coming decades. Various solutions are proposed (gas, biogas, battery electrification with charging stations, hydrogen), each with different degrees of maturity, advantages and limitations, and highly variable costs. Electric highways could allow both propulsion and recharging of vehicle batteries, thus a virtually unlimited range, a much lower battery mass and trucks cost. While it would be, by far, the best solution in life cycle decarbonization of road freight, it requires significant initial investments and the creation of a new business.

In order to respect the 1.5°C global warming limit set by the IPCC (Intergovernmental Panel on Climate Change), the global carbon credit - the admissible quantity of CO_2 -eq to be emitted world-wide - is 500 Gt. At the current rate, this credit will be exhausted in about 15 years. It is therefore urgent to strongly reduce the quantities of emissions and to move towards carbon neutrality in 2050. The later the massive decrease in emissions is implemented, the more difficult it will be to reach the goal, because the absolute credit will be exhausted, and it will be necessary to reduce emissions even more rapidly.

Globally, transportation is the second most emissive sector (24.4%) after energy production. Road traffic accounts for nearly three quarters of this sector (figure 1), or about 18% of total emissions, or 6.5 Gt/year.

–Figure 1–
Share of CO_2 emissions by sector of activity in the world.



In France, these figures are quite different due to the importance of the nuclear fleet, with a much smaller share of emissions related to electricity production. The share of road transport will reach 29% in 2019, i.e. 127 Mt CO_2 -eq in 2019[1]. This is the only sector, along with air and maritime transport, whose emissions have increased in absolute terms since 1990 (+10%) despite a slight decrease of 8% since 2003-2004 and despite major progress on vehicles and fuels. Heavy goods vehicles (HGVs), buses and coaches account for 24% of road emissions, and light commercial vehicles (LCVs) for 20%. The commitments of the COP21 (2016) and the National Low Carbon Strategy (SNBC) have set targets - a 30% reduction, revised to 40%, in emissions in 2030 compared to 1990, and then carbon neutrality in 2050 - but France's emissions have barely fallen since 2002-2003. Europe has further increased its requirements with the "Fit for 55" strategy (2021), which aims to reduce greenhouse gas (GHG) emissions by 55% by 2030.

Roads, which transport 83% of passengers and 88% of freight in France, must therefore make a very significant contribution to this effort and meet at least the overall objectives presented above. For freight, the modal shift does not meet expectations. Despite an investment effort in rail and a decrease of more than 50 percent in road investment since 1990, the modal share of rail freight has been halved since 1990, to 9 percent at present, to the benefit of road, which has demonstrated its efficiency and adaptability, including in the recent Covid period. Thus, the volume of rail freight has fallen by 25% since 2007 (Grenelle de l'Environnement). Even in the European countries that are the most rail-oriented, the share of road freight remains above 70-75%, except in the Alpine countries (Austria and Switzerland). Decarbonization of road freight is therefore essential, regardless of future progress in rail freight.

The French motorway network, with a total length of 11,600 km, including 9,100 km under concession, represents only 1.4% of the road network, but accounts for nearly one-third of the distances covered by all vehicles, and 66% of those covered by heavy goods vehicles (HGVs)[2] . Motorways must therefore be an important focus for decarbonizing road transport, particularly for long-distance freight.

"CLASSIC" DECARBONATION SOLUTIONS AND THEIR LIMITS

A. Bigo[3] mentions five decarbonization levers: moderation of transport demand (sobriety), modal shift, better vehicle load factors, energy efficiency and electrification. For freight in particular, but also partly for passengers, the first two levers have shown their limits and seem more like wishes than

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realities. The third and fourth levers are already widely used for economic reasons; increasing the capacity (weight and dimensions) of heavy goods vehicles could contribute (in a limited way) to the decarbonization of freight ton-kilometers. Finally, electrification (5e lever) seems to be the most promising way forward.

Given the challenges and the urgency, it is necessary to mobilize all available or emerging solutions and technologies as quickly as possible and to play on their complementarities and their areas of performance. Nevertheless, we must also be aware of their limitations.

GAS, BIOGAS, AND BIOFUELS

Compressed or liquefied natural gas (CNG and LNG) is, of course, an easy solution to implement in the short term, with suitable combustion engines. But it is still a carbon-based mode with a potential reduction of CO_2 emissions limited to 10 or 15% compared to diesel, far from what is required even for 2030.

Biogas (essentially methane) and liquid biofuels allow, still with thermal engines, a theoretical decarbonation more important:

- Biodiesel, unless produced from waste oil, which is available in limited quantities, provides only a limited benefit in terms of CO_2eq emissions, of the order of 45%. Moreover, these liquid biofuels from biomass will be used for aviation in the form of bio-kerosene.
- Biogas, on the other hand, has a greater decarbonization potential (up to 90% compared to diesel), but only if there are no leaks, because methane has a global warming power 81 times higher than CO_2 at 25 years. At 1% leakage, the reduction is only about 50%, and these leaks are difficult to control from production to combustion in the engine, through transportation, distribution and storage under pressure in the truck tank. At 3.5% leakage, there is no gain. In addition, the current production of biogas in France is 1 Mtoe (million tons of oil equivalent), far from the need to serve even 50% of the trucks and light vehicles (9 Mtoe). Finally, biogas will be needed for backup power plants (winter peaks) and heating networks (at least 10 Mtoe), and even for a significant part of the gas heating of buildings (≈ 27 Mtoe) for which heat pumps or geothermal cannot work.

Therefore, biogas could eventually contribute to decarbonization, but under multiple conditions.

ELECTRIFICATION WITH BATTERY AND CHARGING STATIONS

Partial electrification of vehicles, through hybridization, provides only a 15 to 20 percent gain, and much less, if any, for long-distance freight. To date, plug-in hybrids (PHEVs) and especially battery-only electric vehicles (BEVs) are the most studied and under development solutions for cars in most countries of the world. China and Europe are well ahead with, respectively, 3.4 and 2.3 million PHEVs+BEVs sold in 2021 and 0.7 million in the U.S. out of 6.75 million sold worldwide (8.3% of sales). France is now slightly below the European average, and Germany well ahead. As for Norway, 62% of BEVs plus 24% of PHEVs were sold there in 2021.

A necessary condition for the development of EVs is the installation of charging stations, which are still insufficient in France. For trucks, the situation is more complex. To guarantee a range equivalent to that obtained with a diesel tank, a 40 t truck would have to carry more than 8 t of Li-ion batteries. With quick charging possibilities every 400 km, the mass of batteries on board would still be around 5 t. In addition to the very high costs, at least 80,000 € at the 2025 cost, the battery life for the trucks will be limited to about 3 to 5 years (2,000 charge/discharge cycles), provided that the fast charge rate does not exceed 50%, i.e. two replacements of the battery pack over the operating life of the truck and a reinvestment each time higher than the cost of a thermal truck. This would increase the cost of ownership of the trucks by 15 to 20%, with a loss of 3 t (10%) of payload if additional measures are not taken to derogate from the maximum weight.

For LCVs, the situation is intermediate between that of light vehicles (LVs) and HGVs.

Finally, in order for each truck to find a fast-charging station during its compulsory breaks, without waiting or degrading its productivity or punctuality, it would be necessary to have a very high density of charging stations (every 100 km according to an ASFA estimate), distributed in sufficient numbers at all rest areas and guaranteeing that no truck will have to wait for a charging station to become available...

Charging times should not exceed 30 to 40 minutes for trucks. The necessary charging stations would then need a power of 1 to 1.5 MW. For long-range trucks (Tesla, Daimler), charging would take place at night with lower power requirements, in the order of 200kW. But each truck in a long stop would have to find a free charging point for the whole

To be noted

- Tesla is already installing 250 kW charging stations for its cars.
- For long-range trucks a 1.3 to 1.5 MWh battery is needed if it is recharged to 90% systematically. It recharges quickly to 80% (in 6 hours), the complement to go to 90 or 100% of charge being much slower. The necessary power is then about 200kW.

night. In both cases, taking into account the flow of each type of vehicle on the freeway, the power required to supply all the freeway parking lots will be considerable. They will require connecting these parking lots to high voltage lines under the responsibility of RTE with significant costs. Moreover, the profitability of such investments, necessarily sized for peak periods, will be difficult[4].

The mass of batteries to be produced and recycled at the end of their life would be considerable, with the associated high costs of ownership and the risk of depleting the necessary raw materials. Depending on the density of the charging station network and therefore the required vehicle autonomy, we can estimate the mass of individual batteries per type of vehicle and, taking into account the number of vehicles in service, we end up with a total mass of batteries between 16 and 26 million tons for France.

Estimated individual battery masses by vehicle type

Cars: between 400 and 600 kg per vehicle, with a fleet of approximately 30 million units.
LCV: 500 to 1,000 kg per vehicle, with a fleet of 6 million units.
HGVs: 5,000 to 8,000 kg for 40-tonne HGVs, with a number of approximately 200,000 equivalent units for the 600,000-strong HGV fleet (it is assumed that the capacity of the batteries should be proportional to the gross vehicle weight).

HYDROGEN

Hydrogen is often presented as the energy of the future and a way to get around the difficulties of storing large quantities of energy on board vehicles. Announcements of ambitious hydrogen production plans, combined with high expectations, contribute to the idea that this vector is THE solution of the future.

Without calling into question certain prospects and potentialities of this gas, it is nevertheless necessary to recall as a preamble certain laws of elementary physics, industrial and economic realities, and their consequences on the use of hydrogen for road transport.

Today, 96% of the world's hydrogen production comes from natural gas. It is therefore a major emitter of CO_2 -eq, almost as much as commercial aviation before Covid. Used directly by a thermal engine or a fuel cell, the hydrogen produced in this way does not bring any decarbonization benefit. To be decarbonized, hydrogen must be produced by water electrolysis, by steam reforming with CO capture and sequestration$_2$, by methane pyrolysis via a plasma torch and carbon separation, or by thermolysis and steam cracking of biomass. Finally, natural hydrogen, known as "white" hydrogen, emanating from the depths of the earth at various points on the planet, raises hopes, but we know neither its potential nor the means to industrialize its collection, transport and distribution. Only production by electrolysis is realistic at present and this is where all the investments are going.

But hydrogen from water electrolysis requires a lot of energy, currently above 50 kWh/kg with a hope to go down to 40 kWh/kg in the next decade. It must then be compressed, transported, distributed in the vehicle's tanks, and then either transformed into electricity by a fuel cell or burned as a fuel in a thermal engine. The efficiency, finally, between the initial electrical energy and the energy transmitted to the wheel is about 25-27%. Compared to the efficiency of a battery electric vehicle, this is about 3 times less.

To ensure 50% of truck travel in France with hydrogen, about 2 Mt of hydrogen would be needed. To produce it by electrolysis, 100 TWh of electricity would be needed, i.e. nearly 20% of the national production, and three times more than with a direct use of this electricity.

Therefore, the use of hydrogen in land transport would degrade energy efficiency and would amplify a demand for decarbonized electricity that is already difficult to satisfy in the next two decades, as demonstrated by the RTE report "Energy Futures 2050", without forgetting on the one hand the priority to be given to the sectors that have no other solution (steel, chemicals, maritime, even aeronautics), and on the other hand the difficulties of hydrogen distribution.

For HGVs, some specific limitations must be added, also applicable to LCVs. To travel 1,000 km at a steady speed on the flat, a 40 t electric truck would need about 120 kg of hydrogen. To store these 2,800 l of gas at 700 bars, high-tech steel and carbon fiber tanks occupying 4 m^3 and weighing about 3,000 kg are needed. For an LCV and 400 km of autonomy, 6 to 7 kg of hydrogen would be needed stored in 250 to 300 kg tanks, with architectural problems since modern LCVs have a flat and low floor, very useful for deliveries.

From an economic point of view, decarbonated hydrogen is currently expected to reach 2 to 2.5 times the price of equivalent diesel fuel, excluding high distribution costs. Finally, fuel cells are expensive and have a limited lifespan, which means that they will have to be replaced during the life of the truck. From this point of view too, the electric hydrogen truck remains expensive and reserved, perhaps, for niche markets if a distribution infrastructure were to be set up. Hydrogen makes sense for other mobility applications, such as railways, where electrification is not cost-effective, or shipping, probably in the form of ammonia. In the road sector, it may be useful for certain niche markets, such as the extension of autonomy for certain HGVs on the secondary network, long bus lines, cabs (Hype in Paris) or bicycles and three-wheelers for urban delivery.

THE ELECTRIC ROAD SYSTEM (ERS)

CONTEXT AND SITUATION IN FRANCE

In view of the difficulties and limitations mentioned for the various solutions for decarbonizing road transport and taking into account the fact that electricity is easy to transport but difficult to store, the idea was born to power vehicles while they are in motion. The concept is not new and has been applied to subways and tramways since the end of the 19th century. From the 1920s onwards, electrification of long-distance rail networks by catenaries became widespread.

Over the last ten years, the idea of electrifying high-traffic areas (freeways), especially for heavy goods vehicles, has emerged. The ERS *(Electric Road System)* has become a solution to be studied, allowing to ensure both the propulsion of vehicles and the recharging of their batteries while driving.

Three families of technologies are currently being studied, developed by various companies, with different levels of maturity (*Technology Readiness Level* - TRL) and their own advantages or disadvantages, and even different fields of application. They are :

- overhead power supply (catenaries and pantographs);
- ground power supply (APS, conduction on a "rail" consisting of two conductive lines in the roadway);
- Induction (contactless power transfer between transmitter loops in the road and receiver loops under the vehicles).

Various studies and publications present these technologies, which have been tested on tracks and on portions of open roads in Sweden, Germany, the United States and Korea. The World Road Association has completed a review study[5] and launched a working group (TF2.2) on the subject in late 2020.

The Ministry of Ecological Transition, under the aegis of the DGITM (General Directorate for Infrastructure, Transport and the Sea), has commissioned an analysis of the potential and prospects of ERS for France, involving all the players in the sector (public authorities and their representatives, research organizations, road infrastructure managers and manufacturers, vehicle manufacturers, transporters and shippers, and energy providers). Potential solution providers were also involved. Three working groups (WG) were set up in early 2021, which submitted their reports[6] to Minister Jean-Baptiste Djebbari in October 2021:

- WG1: Issues and strategy (moderator: Patrick Pélata, Meta Consulting, and Olivier Gavaud, DGITM);
- WG2: Technical solutions, potentialities and obstacles (moderator: Stéphane Levesque, URF, and Bernard Jacob, Gustave Eiffel University);
- WG3: Large-scale experimentation (moderator: Marc Gohlke, CARA cluster, and Nicolas Hautière, Gustave Eiffel University).

Following these reports, the Minister announced, at the end of a Committee for Development and Innovation in Transport (CMDIT) dedicated to roads, the launch of the PIA4 call for projects on "Automated road mobility, connected and low-carbon service infrastructures", for which ERS demonstrators are eligible.

The TRL

TRL (*Technology Readiness Level*) is a measurement system used to assess the level of maturity of a technology. First developed and used by NASA in the 1970s and 1980s, TRLs are now widely used.

The scale has 9 maturity levels (from 1 - weak - to 9 - strong). The higher the level, the more secure the technology is for market entry as a product (for example, a software application) or as a component to be integrated into a system.

ERS ISSUES AND STRATEGY

In addition to energy and environmental considerations and analyses of decarbonization solutions, WG1 studied the economic aspects of ERS and its deployment conditions in France.

The assumptions made in terms of power to be delivered for HGVs are: 350 to 400 kW per HGV, taking into account the peak power on a 2% gradient for a fully loaded HGV (44 t) and a battery recharge to 80% in 1 to 2 hours. This leads to deliverable powers of about 3 to 4 MW per km on the densest sections. It has been decided that 80% of the linear roadway should be equipped, thus avoiding certain critical sections (bridges, tunnels, interchange areas, etc.).

The scope of relevance of the ERS in France for a first phase of 4,900 km by 2030 was defined on the European TEN-R core network, where HGV flows are important, with a high rate of long-distance trips (figure 2). The Paris-Rennes route has been included to serve Brittany. In phase 2, an additional 3,950 km were added for 2035, including essential transnational links, routes with more than 1,500 HGVs per day and, above all, routes that could serve any point within 125 km of an equipped freeway.

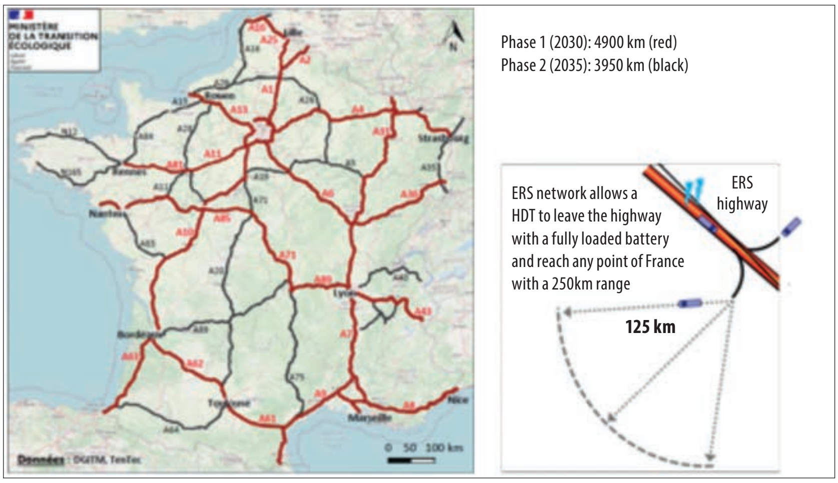
Three questions to Louis du Pasquier, Director in charge of decarbonization issues at Vinci Autoroutes

What opportunities and threats do ERSs present for Vinci Autoroutes?
In the face of the climate emergency, the ERS is an opportunity to decarbonize the road, which accounts for one-third of France's greenhouse gas emissions, 40% of which are generated by heavy goods vehicles (HGVs). In the coming years, with the development of battery-powered vehicles, decarbonization of long-distance trucks will be possible, but their need for autonomy will force them to carry 6 to 8 tons of batteries. The ERS will make it possible to considerably reduce the size of these batteries, thus limiting the environmental footprint of vehicles and their energy consumption.

Which ERS technology do you plan to focus on?
Catenaries are more technologically mature, but are incompatible with light vehicles (LV) and present safety and maintenance issues; rail is compatible with LV, but is less technologically advanced and poses questions of grip, winter conditions (frost, snow, etc.) and maintenance of the pavement interacting with the rail. The Vinci Group entities therefore have a preference for induction, which does not change the operating conditions of the road, both in terms of road safety and maintenance.

What changes does the ERS imply for Vinci Autoroutes' organization and skills?
The ERS transforms road infrastructure into an energy infrastructure: in addition to adapting the pavement, a high-voltage electrical network must be designed and built along the highways to power the infrastructure. This will be a revolution, as tomorrow's road infrastructure will necessarily be electrified to accommodate decarbonized vehicles, regardless of the decarbonization technologies (hydrogen, electric vehicle charging stations, ERS...).

–Figure 2–
Proposed deployment of ERS in France.



–Table 1–
ERS investment costs (8,850 km = 4,900 km + 3,950 km).

	Catenaries	APS HGV	APS with VL
Phase 1 (2030)	18.5 billion	21.8 billion	22.5 billion
Phase 2 (2035)	11.5 billion	14.2 billion	14.5 billion
Total	30 billion	36 billion	40 billion

This would reduce battery autonomy to 250 km and thus their capacity, for 40 and 44 t trucks, to 350 or 400 kWh against 1300 kWh (long autonomy and slow recharge) or 750 kWh (autonomy of 400 km but systematic fast recharge and premature wear of batteries at 600-800 000 km due to the high proportion of fast recharges). Most of the ERS would thus be on the concession network, with the exception of Brittany, the A75 (Massif Central), the A35 (Alsace) and a few connecting sections or urban bypasses such as the A87 (Île-de-France).

2030 is an important deadline because, under European regulations, truck manufacturers who do not meet the 30% reduction target for emissions from new vehicles sold by that date compared with 2020 (Directive 2019/1242) will face prohibitive penalties. Moreover, for users to equip themselves with EVs with ERS, the deployment of the infrastructure must already be massive in 2030.

For the economic analyses, WG1 has retained only the conductive solutions (aerial and ground), because it has not been demonstrated that induction will be able to reach the required power in a timeframe compatible with a massive deployment in 2030. In addition, the cost and copper consumption - critical - are significantly higher than for conductive solutions.

The total investment would reach 30 to 40 billion €, including the power supply from RTE high voltage lines, the necessary power electronics, transformers, rails or catenaries and installation works. Table 1 shows the breakdown of investment costs per phase and per conduction technology according to two scenarios for ground conduction: with or without a second track equipped for cars on the densest sections. The catenary power supply obviously does not allow the supply of cars or LCVs.

These costs, although high, can be borne by operators used to long payback periods, such as freeway concessionaires or major energy companies. In addition, the installation of the ERS would greatly reduce the number of fast charging stations on freeways, especially with the ground conduction solution, which can be used by cars and light trucks.

In both cases, the energy to be provided on the freeways is identical, since the energy required for trucks is the same, except for battery losses. However, the "peak" effect would have a greater impact for a network of charging stations than for the ERS.

Details of calculation assumptions

All calculations are made in 2040 as a proxy for 2050 and the fleets are therefore assumed to be stabilized.

- HGV and LCV traffic growth 2019-2040: 20%.
- Diesel truck efficiency improvements 2019-2040: 15%.
- CO_2 footprint -eq/kWh of electricity in 2040: 30 g.
- Catenary and rail efficiency (including power routing): 90%.
- Battery charge-discharge efficiency: 95 %.
- Average battery usage ratio versus live ERS: 40%.
- CO2 -eq footprint of biodiesel: 35 g CO_2 -eq /t.km (compared to 63 g/t.km for fossil diesel).
- CO_2 footprint -eq of biogas from 8 g/t.km to 20 g/t.km (excluding leaks) to be compared to 59 g/t.km in CNG.
- 1% biogas leakage would add about 20 g CO_2 -eq/t.km (30% of CNG emissions).
- LCA footprint of batteries: 50 kg CO_2 -eq/ kWh of capacity in 2040.
- The number of HGVs and LCVs (for the battery LCA calculation) has been reduced to 6 times the volumes sold in 2019 to take into account only vehicles that drive a lot.
- The LCA footprint of ERS infrastructure is negligible compared to that of vehicle fleets in the different scenarios.

The first estimates suggest that, on this criterion of infrastructure equipment alone, the ERS would be advantageous. Electricity could be sold directly to the consumer by the network operator at a forward price of less than €0.20/kWh, according to WG1 calculations, if the operator has access to the price granted to electro-intensives. Public support would nevertheless be necessary for the ramp-up phase.

For users (transporters and private individuals for cars with APS), the ERS would be easily profitable whatever the hypotheses compared to EVs on batteries alone: most of the additional investment cost is borne by the operator, and the additional cost of the HGV is quickly offset by a much lower operating cost which should, according to the simulations carried out by the DGITM, attract transporters to the ERS highway.

The ERS could thus capture at least 50% of national freight traffic, in vehicle-km or t-km. The cost of ownership of HGVs would be reduced by 3 to 4% compared to current diesel, instead of an increase of 15 to 20% with long-range batteries, and of 8 to 13% with a network of fast charging stations.

CONCLUSION

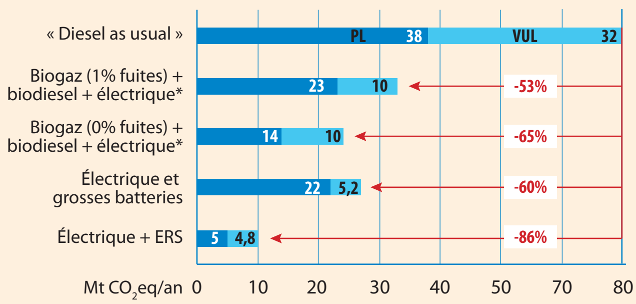
In order to better compare the different solutions mentioned with the ERS from the point of view of GHG emissions (the only reason for which this revolution is envisaged), it is interesting to look again at the complete assessment, in life cycle analysis, of the evolution of the fleet of HGVs and LCVs circulating in France at a horizon where the whole transformation would have been made, between 2040 and 2050 (figure 3).

This assessment is estimated for 5 scenarios, including the "diesel as usual" continuity scenario taken as reference:

- that of the National Low Carbon Strategy (SNBC2): electric trucks 50%, biogas 25% and biodiesel 25%; electric LCVs 82% or biodiesel 18%;
- the same scenario taking into account 1% biomethane leakage;
- a scenario where trucks and LCVs are all electric and therefore with very large batteries for long-distance trucks;
- a scenario where battery-powered HGVs and LCVs and ERS for 50% of the HGV t.km and 18% of the LCV t.km (those who do long distance regularly), battery-powered electric for the others.

The calculation takes into account the CO_2 -eq footprint of the production of the batteries and the infrastructure of the ERS, as well as that of the electricity production.

–Figure 3–
Decarbonization potential of the HGV+LCV fleet in France according to different scenarios by 2040.



* 25% biodiesel, 25% biogas and 50% electric for trucks, 18% biodiesel (long distance) and 72% electric for LCVs. LCVs are assumed to be battery electric or biodiesel because of their low floor and compactness, which are not compatible with a biogas LCV architecture.

Under these assumptions, we can see that the solution where trucks and LCVs are electric and where all those who regularly drive long distances can use an ERS-equipped highway is much more efficient to decarbonize road transport than the "all-battery" solution or the solutions mixing battery electric vehicles, biogas and biodiesel, as considered in the current National Low Carbon Strategy.

Finally, two other significant benefits must be mentioned, thanks to a possible reduction of two thirds in the mass and capacity of the on-board batteries:

- for the most critical resource, nickel, annual savings in Europe of 35,000 t for trucks and LCVs using ERS and 100,000 t for cars in the case of ERS by ground conduction, thus avoiding the purchase of a large battery (50 kWh instead of 100 kWh);

• significant reduction in the need for charging stations on highways, whose high cost could reach a significant proportion of that of the ERS, or even exceed it.

The deployment of the ERS will require a pan-European decision and a rapid arbitration on the choice of the technical solution. In France, it is recommended that actions be taken as soon as possible to bring the ground conductivity solution (with high potential) to a TRL level of 6 or 7 by the end of 2023.

Finally, it should be noted that the Vinci Autoroutes & Altermind report[4] also concludes that the ERS is the most powerful lever for decarbonization for trucks and cars (except for the overhead conductive solution which is only used for trucks) by 2035, with a positive balance for all actors. ■

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TECHNOLOGICAL SOLUTIONS

AND DEPLOYMENT CONDITIONS

Three families of technologies for electric road system (ERS) exist: overhead conduction by catenary, ground conduction by rail, and induction. They are briefly presented and then evaluated against a series of criteria by representatives of the various stakeholder groups involved. Performance, installation and maintenance issues are addressed. A synthesis is provided to identify the pros and cons, or points for attention, of each technology, as well as the locks that require further testing in addition to that already carried out on tracks or open roads. Finally, recommendations are made for policy makers.

Electricity is an energy that is easy to transport, but not easy to store. The traditional energies used for motorized transport since the 19th century (coal, fuel oil, kerosene, diesel or gasoline and gas) are easily stored in compartments or tanks and are therefore carried on board vehicles to ensure their autonomy between two refuelling stations. This concept has given a large autonomy and freedom to ships and aircrafts that used to depend on wind, and to motor vehicles that used to be powered by animal traction. Nevertheless, the autonomy of all these vehicles is limited by the carrying capacity of the fuel or energy source.

With the development of electricity at the end of the XIXth century, a new concept (a revolution?) appeared in rail transport. Energy was no longer carried on board the train, but was supplied to it throughout its journey by a power supply network. For guided transport (trains, subways, tramways and electrified trolleybuses), it was easy to electrify the network. The major advantage of this system, a century before environmental and climatic considerations, was to give unlimited autonomy to mobiles on the electrified network and to lighten them of the storage of the energy source (gain in payload and volume).

For two means of transport for which the supply of electricity was more complex, or even impossible, it was imagined to store or produce electricity on board: the first electric cars appeared at the beginning of the 20th^{e} century, with a very limited capacity storage on batteries, and, in the second half of the century, submarines and nuclear-powered ships.

Finally, the recent concept of hydrogen vehicles combines these two approaches, with on-board storage (hydrogen) and on-board electricity production (fuel cell). But the energy efficiency of this technology is very low (27%) and the hydrogen storage is complex.

With the development, since the 1960s, of motorway networks and high-traffic corridors, a large proportion of road vehicles travel mainly on these routes. Faced with the constraints of decarbonization of road transport, electrification is currently the only (main?) solution for large-scale decarbonization of road vehicles. Electrifying these busiest corridors to power vehicles continuously is an appropriate and physically realistic response, which is in line with the choices made for railways 100 years ago.

If batteries or other forms of on-board energy storage are a necessary complement to ensure the autonomy of vehicles outside the electrified roads, wanting to embark all the necessary electrical energy, with the constraints of mass, material resources and cost of batteries, seems to be a technological and economic mistake. Who would think of equipping his country house or his farm with tons of batteries to store his electricity for weeks or months, as it is done for domestic fuel or was done for coal?

Finally, the principle of limiting ourselves to batteries and recharging stations (slow or fast) is not an optimal solution and seems not very viable on a large scale. It is is derived from a conceptual conservatism that transposes the notion of refueling station, for easily storable fuels, to electricity. It is a necessary, but not sufficient, temporary measure.

The ERS *(Electric Road System) is* therefore a solution that should be considered as essential for the decarbonization of road transport, even if it must be combined with other solutions (batteries, some charging stations and hydrogen for niche markets).

ERS TECHNOLOGIES

To date, three families of ERS technologies have been proposed and partially developed, some at the prototype stage, others at the demonstrator or pilot stage, and some close to the industrial stage. Two families of systems use the principle of conductivity to transfer electricity from the grid to the vehicles: overhead conductivity (the current is

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brought in and returned by catenaries suspended above the road by pylons), and ground conductivity (the current arrives and leaves in "rails" or equipment installed in the roadway or along it). In the first case, the vehicles capture the current using deployable pantographs on the roof and, in the second, using retractable pads or pins located under the floor.

The third family of technologies uses the principle of induction, i.e. a contactless transfer of energy between transmitter coils buried in the roadway and receiver coils installed on board vehicles, via a magnetic field created between the two.

OVERHEAD CONDUCTION BY CATENARIES (SIEMENS)

This is the best known solution to date, as it is directly derived from the railways and developed by Siemens (eHighway). The main difference is that the overhead contact line has two catenaries per track and each vehicle has a double collector pantograph, because, contrary to the rail system, the current return cannot be made through the ground, as the tires and road surfaces are not conductive.

Pylons installed every 50 to 60 m, outside the traffic lane support the two catenary lines **(photos 1)**, consisting, as in railways, of carrying cables fixed to the pylons and of power cables with a straight longitudinal profile (constant altitude above the roadway, between 4.5 and 5.4 m, with a tolerance of 8 cm) in contact with the pantographs. The two catenaries must be spaced a little more than one meter apart to avoid any risk of electric arcing.

The direct current is injected at 1,200 V into the catenaries from substations installed outside the road and connected to the electrical network. The maximum power per vehicle can reach 450 kW. The sections supplied by each substation would be about one kilometer long, adaptable to the power requirements, between 400 m and 3.4 km.

The system allows the equipped heavy goods vehicles (HGVs) to travel at speeds of up to 100 km/h and to have a lateral clearance of up to 1.20 m.

The contact force of the pantographs on the catenary must remain between 30 and 300 N in dynamic.

Cenelec recommendations for the ERS solution with catenaries

- Pavement flatness: 7 mm maximum for a 4 m section (in the longitudinal and transverse directions).
- Longitudinal slope: 4.5% maximum.
- Cross slope: 6% maximum.
- Curve radius: 720 m minimum (Cenelec TS50712 and EN50119), but Siemens assures that its system can tolerate radii of 400 m.

The pantograph deploys automatically when the truck enters an equipped section and folds up when it leaves the track. In this case, the battery automatically takes over. The recommendations of the European Committee for Standardization in Electronics and Electrotechnics (Cenelec) also specify the tolerances for the flatness of the roadway, its longitudinal profile and the radii of curvature.

This system is at a *Technology Readiness* Level (TRL) of 8 to 9. Several demonstrators and pilots on open roads have been installed since 2010 **(photo 2)**, including three in Germany, one in Sweden and one in the United States (California, but dismantled after one year of testing).

–Photos 1–
ERS by overhead conduction (catenaries) - eHighway

© SIEMENS

–Photo 2–
Experimentation of ERS by overhead conduction on freeway.

© SIEMENS

GROUND AND LATERAL CONDUCTION

APS solution (Alstom)

This solution is derived from that of the Bordeaux tramway, developed to avoid the presence of catenaries and pylons in the city center: a third flat rail, made up of independent sections of up to 11 m in length, is laid between the two running rails. The sections are only powered when the tramway passes, which has two collector pads to ensure the

continuity of its power supply. Given the length of the trains (minimum 30 m), only the APS sections located under the tramway are powered, avoiding any risk of electrocution for pedestrians.
Alstom has adapted this technology to road vehicles. As for the catenary system, the return of the current cannot be done by the wheels and pavement, two supply segments (rails) are needed.

–Photos 3–
APS ground power system on a Volvo test track in Sweden.

© ALSTOM

© ALSTOM

–Photos 4–
APS rail grip tests on the test track of the Gustave Eiffel University in Nantes and winter tests in the Vosges.

They are parallel, flush and fixed on a structure of insulating material installed in a groove in the axis of the track, which constitutes the feeder track, also called "rail" for simplicity, of 0.50 m wide and 0.07 m high. The 11 m long segments (adaptable length) are automatically fed when the vehicles pass by, equipped with retractable collection pads, fixed at the end of an articulated arm, allowing a lateral movement of the vehicle of 0.50 m on either side of the median position (photos 3).
The conductive segments are made of steel. A bidirectional radio communication between the segment and the vehicle allows the activation of the power and the sharing of data. To avoid any risk of electrocution of other road users, if the powered segment goes a few meters ahead of the vehicle, the power is only activated above a threshold speed (30 to 60 km/h) and if no obstacle is detected by intelligent sensors such as lidar. When the ERS is off or without power, the vehicles are powered by their batteries.
The DC voltage is currently 750 V. The deliverable power per vehicle, up to a velocity of 90 km/h, is 400 kW, with a transfer efficiency of 97%. This power has been defined to make the propulsion and the recharging of the truck batteries possible. However, as the segments are independently powered, the power delivered per kilometer can reach 6 MW with an adapted dimensioning and density of the substations.
Tests carried out on the track by the Gustave Eiffel University validated the grip, the crossing and braking conditions on the rail by a motorcycle and a car (photos 4). In dry and wet conditions, the grip and braking distances were of the same order as on a usual roadway, thanks to an optimization of the rail structure by Alstom compared to the initial versions. Tests with a fatigue machine helped to optimize the bonding of the rail in the groove and to verify its fatigue resistance under repeated passages of truck wheels.
Finally, tests carried out in the Vosges in winter conditions with snow ploughs have shown that the use of salt did not cause any short-circuit between the two parts of the rail and that the rail resisted winter operation. The 5% current leakage observed should not hinder the use of the system under these conditions.

Single rail segmented solution (Elonroad)

It is characterized by the use of a single aluminum and stainless steel rail, segmented. The segments are very short (1 m), powered only when the vehicle is on top to avoid any risk of electrocution, and with alternating polarities (photos 5). Under the vehicle, at least three contacts (and up to 6 or 8 for buses or trucks), aligned one behind the other, alternately recover the positive and negative polarities, to limit the current of each contact and ensure redundancy.

The rail can be laid on top of the road, especially for static applications, or inserted in a 6 cm deep and 40 cm wide groove. It can be removed for road maintenance. Work has been carried out by the VTI (Swedish Road Research Institute) to optimize the skid resistance on the rail and its resistance to repeated passage of truck wheels.
The in-line arrangement offers a compact system with less material, but requires a larger number of power switches than with the dual rail. Bus charging at 160 kW has been demonstrated at 40 km/h, and the manufacturer is announcing up to 300 kW for HGVs by the end of 2022, with an efficiency of 97%. Trials have been conducted in Lund, Sweden, first with a 135-m surface section (2017) and then with two 300-m surface and 600-m road bleed sections.


© ELONROAD

–Photos 5–
Elonroad's ground conductive system (Sweden).

Solution with hollow rail (Elways/Evias)
The Swedish company Elways (now Evias) has developed a system of conduction by the ground comprising a hollow metal profile rail (photos 6). The system can have two parallel rails (current supply and return) or a single rail with conductive parts located on both sides of the profile on its inner vertical faces. In both cases, this profile prevents accidental touching of the conductors and avoids any risk of electrical leakage in the presence of water, subject to operational drainage of the rail. The powered segments can reach 50 m.
The current is collected by one or two pins located at the end of an articulated arm under the vehicle, which are inserted in the rail(s). The rail is made of plastic and aluminum conductors with a weight of 20 kg/m. It is imperative that the profile is free of any undesirable elements that may be in the grooves, and that the drainage is effective (one drainage nozzle every 50 m). Resistance heating prevents ice from forming in the grooves in winter. The system has been tested up to an individual power of 200 kW and 130 km/h.

–Photos 6–
Hollow rail ground conduction solution in Sweden.


© EVIAS

Lateral conductive solution (Honda)
The power is brought to the side by a rail inserted in the safety barrier (picture 7). The vehicle deploys a lateral articulated arm with two conductive wheels. The length of the arm in the presence of an emergency lane can become critical. The system is designed for very fast charging on short stretches. Therefore, it does not seem to be compatible with optimal Li-Ion battery life, unless a power-type chemistry is chosen, but with a lower energy density. It has been tested in Japan up to 450 kW and 150 km/h.

–Photos 7–
Lateral conductive solution in Japan.


© HONDAT2

INDUCTION

Inductive solution (Electreon)
With this technology developed in Israel by Electreon, passive transmitter coils, inserted in the road at a depth of 8 cm, are powered when vehicles pass by (photos 8). Each receiver coil receives 25 to 30 kW, with a passive cooling system (the next generation will be able to go to 45 kW, with an active cooling system). One cooling system is needed per vehicle for cars, at least four for trucks and up to seven to reach 200 kW. This solution implies equipping the trailers or semi-trailers of the road units.
The gap (distance between the transmitting and receiving coils) is 25 cm for cars and 60 to 80 cm for trucks.

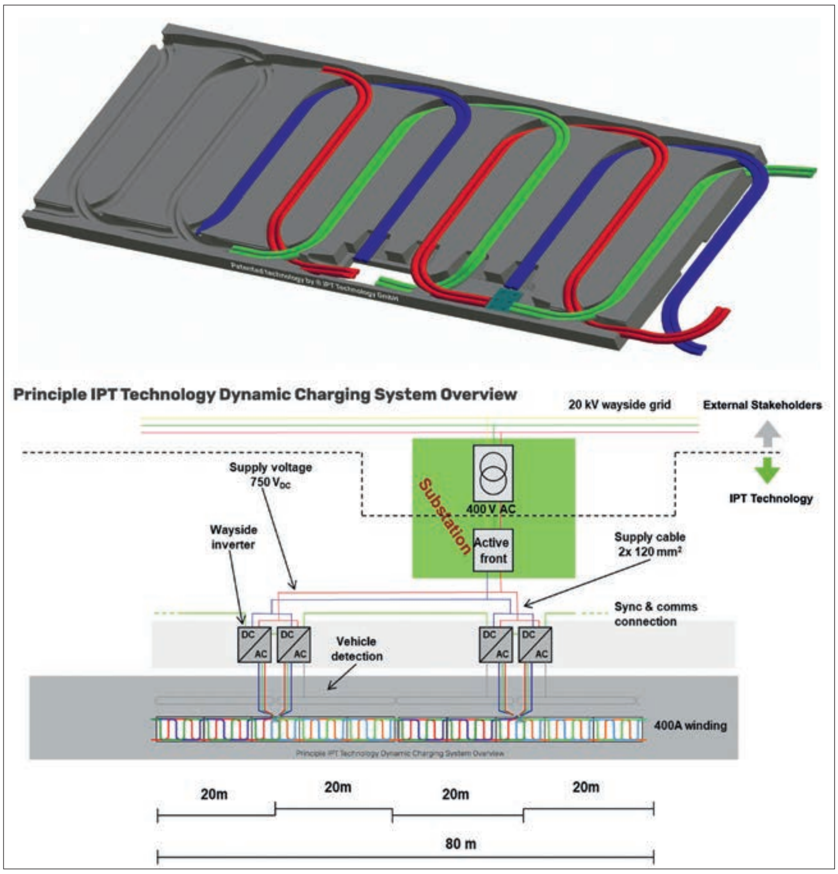
–Photos 8–
Electreon inductive system.

© ELECTREON

–Photo 9–
Olev inductive system.

© OLEV

–Figure 1–
Inductive solution developed in Germany by IPT Technology/Primove.



© IPT TECHNOLOGY

The power supply and management units, installed on the roadside, manage 60 segments of 1.65 m, i.e. approximately 100 m of road. Asphalt is not currently recommended for the installation of this device. The transfer rate for static recharge is 92%, and 87% for dynamic recharge.

The system is interoperable for all vehicles with a receiver. The transmitting coils do not heat up when a single vehicle passes, but when a large traffic flow passes.

WiPowerOne inductive solution (KAIST/Olev)

As with the previous system, the transmitting coils are powered as the vehicles pass by. The receiving coils can receive 75 kW. One coil is sufficient for a car (22 kW) or a light commercial vehicle (LCV); two are required for buses. The company KAIST/Olev (South Korea) has announced the possibility of increasing to 300 kW in one or two years with 4 receiver coils and to 400 kW with 6 coils for trucks. The system (photo 9) also works in static charging, with the same power as in dynamic charging.

The system is resilient to the climate (snow or rain) without altering performance. The gap is 0.27 m and the possible lateral wandering is 0.20 m. At 30 km/h, the energy transfer rate is 85% DC, but the speed can be higher. Current installations of the system are in concrete pavements.

The power is cut off if an object is on the track. For the moment, there is only a 60 m demonstration track in Dubai.

Inductive solution IPT Technology/Primove

German company IPT Technology has taken over Primove's technology from Bombardier for static bus charging. The system also works dynamically. The system, which is based on interleaved sinusoidal coils with three phases, allows the length of the segments, currently 20 m, to be varied easily (figure 1). A common electrical connection feeds two contiguous segments, i.e. 40 m of road.

The transfer rate is 90% for a power of 180 kW at 60 km/h, but with great sensitivity to the lateral position of the vehicle. Five projects have been carried out, on concrete (without reinforcement) or asphalt pavements, but doubts remain about the resilience of the system in this type of pavement.

ERS TECHNOLOGY ASSESSMENT

The WT Technical Solutions, Potential and Obstacles set up by the General Directorate for Infrastructure, Transport and Mobility (DGITM) has identified the available technologies, analyzed their characteristics, and made a multi-criteria evaluation, taking into account the points of view of all stakeholders. This should inform the choices and decisions of public authorities.

It established evaluation criteria and defined their weights, and then studied the satisfaction of these criteria for each group of stakeholders and each technology.

Finally, a multi-criteria and multi-actor synthesis has been established, with an eye to maintaining strict technological neutrality.

The conditions for the deployment of the ERS, the obstacles to be overcome and the outstanding issues were identified.

STAKEHOLDER GROUPS, EVALUATION CRITERIA AND TECHNOLOGIES EVALUATED

Some thirty participants representing the various stakeholders (public administrations, road infrastructure manufacturers and managers, vehicle manufacturers, transport and user federations, energy companies, researchers, etc.) took part in the evaluation. They were divided into 6 sub-groups, by profession:

- SG1: Government and regulators ;
- SG2: Infrastructure builders and managers;
- SG3: vehicle manufacturers ;
- SG4: Carriers and Users;
- SG5: energy specialists ;
- and, supporting these 5 subgroups, but without a direct evaluation mission, SGe: scientific and technical organizations and consultants.

An array of 63 criteria, organized by subject into 13 families, has been developed[1]:

A. Interoperability, scope of use, technological maturity
B. Decarbonation potential
C. Capacity and energy efficiency
D. Costs: investment, maintenance and operation
E. Intrusiveness (infrastructure, environment)
F. Integrability to vehicles
G. Health impact
H. Impact on road safety
I. Security
J. Sustainability and resilience
K. Technological and systemic risks
L. Environmental and social acceptability...
M. Other

Each subgroup first proposed a weighting of the criteria, on a scale of 0 (not important or not applicable criterion) to 4 (essential criterion), based on their importance to the sector and uncertainty about the assessment. Then, the satisfaction of the criteria by technology and by subgroup was scored on a scale of 0 (criterion not met) to 3 (criterion fully met).

The technologies evaluated are those presented above.

RESULTS BY STAKEHOLDER GROUP

Road Builders and Operators Group

This group, mainly composed of ASFA (Association of French Motorway Companies), its members and construction companies, was the one that filled in the most criteria and contributed the most to the evaluation.

It ranked Electreon and WiPowerOne/Olev inductive technologies first, with scores ranging from 7.2 to 7.6/10 for their low intrusiveness once installed and low impact on subsequent road operations. APS technology (Alstom) came second (6.2 to 6.8/10), with average intrusiveness and a lighter infrastructure than catenaries, but with some issues to be addressed.

Overhead conduction (Siemens) came in third place (around 6/10), with strong concerns about the operating constraints linked to pylons, the risks of falling catenaries and the fact that it cannot supply cars and LCVs, closely followed by ground conduction in the version proposed by Elonroad in 2021 (a surface rail with an extra thickness, which was deemed dangerous on freeways, since replaced by an embedded rail).

The Elways/Evais hollow rail technology, rated around 5.5, was deemed unsuitable for deployment on high-traffic highways.

Energy suppliers

For this group, which includes EDF, Enedis and Eiffage Energie Systèmes, ground-based conduction comes out on top, rated around 8/10, for its energy efficiency, cost and material balance, but also its deployment, which seems easier than that of other technologies.

The overhead conduction (Siemens), rated around 6.5/10, came in second place, with a sufficient power supply, but they were penalized by the heaviness of the infrastructure and the non-interoperability with cars and light commercial vehicles (LV).

Finally, induction (Electreon) is considered to be immature, expensive and with insufficient efficiency (rated between 4 and 5/10).

Other stakeholders

Carriers did not rate technologies, but rated importance by criterion.

The administrations and regulators and the vehicle manufacturers have expressed any opinion at this stage, the latter indicating that they could adapt to all technologies as far as vehicle equipment is concerned. To date, they are not very involved in ERS, except for Scania, which has supplied some trucks to Siemens for experiments with catenaries. OEMs are focusing more on batteries, charging stations and hydrogen, i.e. solutions that leave as much equipment on board as possible and make vehicles as independent as possible of the infrastructure.

INSTALLATION AND MAINTENANCE OF THE ERS

Roads and pavements experts analyzed the issues of installation of ERS systems, their maintenance and the maintenance of the supporting pavement. The presence of loops buried a few centimeters deep, for inductive solutions, could significantly alter the integrity and durability of the pavement, a complex multi-layer structure whose strength depends on a perfect bonding of all layers. A lack of bonding strongly alters the mechanical strength of the pavement, which could be degraded by the insertion of induction coils, boxes and power cables. This point should be checked for the different types of pavement (asphalt concrete, hydraulic concrete) and the most suitable material should be chosen. The majority of French pavements are bituminous and could be particularly sensitive.

Ground conductive solutions, with a rail (single or double) and the power supply device in the pavement, raise the same questions about the damage to the pavement, but to a lesser extent than for induction. Experimental verifications will therefore also have to be carried out here. In addition, it will be necessary to check whether the rail does not risk inducing altimetric differences between its surface and that of the pavement on either side, particularly for bituminous pavements (polishing, rutting, etc.). Finally, given that wearing courses must be renewed every 10 years or so, it will be necessary to develop machines and processes capable of doing so while preserving the integrity of the feeder rail, unless it is dismantled and reassembled for each operation, which would be cumbersome and costly.

Solutions that do not involve the pavement do not affect its integrity and therefore have little or no impact on their maintenance. The conductive solution with lateral rail at the roadside (Honda) is the least intrusive for the pavement, but poses other rather prohibitive operational problems for the traffic. The overhead catenary conductive solution does not require any direct work on the pavement, but the renovation of the pavement requires construction equipment with a high clearance, such as for the movement of trucks with lifted dumpsters. It would therefore be necessary to use the pavement renovation methods used in tunnels.

EVALUATION SUMMARY AND RECOMMENDATIONS

Overhead conduction by catenaries

This solution, which benefits from the know-how of the Siemens group, is the most mature to date, thanks to both railway experience and experiments carried out on tracks and open roads. It does not require any direct work on the pavements, which are thus preserved in their integrity.

On the other hand, many disadvantages or points of vigilance have been identified, in particular on the part of motorway operators and energy suppliers:

- The presence of pylons along the road every 50 to 60 m poses safety problems, both for vehicles and for the structure itself, in the event of impact following a track departure. In particular in case of impact by a truck, the risk of catenary falling on the track after destruction of a pylon is major. The proposed solution, consisting in protecting the pylons by a continuous concrete wall, is heavy and raises problems of access to the emergency services in case of accident. The catenaries also prohibit rescue by helicopter. Finally, the lifting of overturned trucks with a mobile crane, a fairly frequent operation, would be seriously complicated by the presence of the catenaries, even after the power has been cut.
- The risks of catenaries being caught by a machine (crane) deploying accidentally, or of catenaries falling due to mechanical failure, fatigue, lightning or violent weather have also been identified. The frequency of pantograph passage on a heavily trafficked freeway, with 5 to 8,000 HGVs per day and direction, would be almost 100 times greater than on a rail network. This would imply either a very heavy dimensioning or a very short life span of the infrastructure. The mechanical stresses applied by the pantographs would also be much greater than in the rail sector, given the much greater difference in roadway levels than for rails on a railroad line, and the deflection of the HGVs' tires and suspensions, with the added risk of disbonding and electric arcing. Finally, in case of high temperatures, the speed of the HGVs would be limited because of the expansion of the cables.
- The power deliverable by km of equipped lane would be limited by the acceptable amperage in the catenary, to about 1 to 1.5 MW/km, which would allow to supply only a part of the heaviest HGVs in case of high traffic density or on slopes, or would lead to suspend the batteries recharging during traffic peaks.
- Crossing overpasses and tunnels requires either the interruption of the catenary or switching to a rigid catenary fixed under the bridge deck or tunnel vault, because of the air draft limit.
- The wind load of the deployed pantographs and the possible overconsumption remain to be evaluated.
- The visual and environmental acceptability of the system on highways appears to be questionable and also remains to be more accurately assessed.
- Finally, one of the main reservations is that the system could only supply HGVs and coaches of a certain height (2.5 to 3 m minimum), but not LVs or LCVs, which strongly limits the decarbonization potential of the system and penalizes its economic profitability.

Three questions to Philippe Redoulez, General Manager of ATMB

What opportunities and threats do ERSs present for ATMB?

ATMB's Research and Innovation teams at the freeway and the Mont Blanc Tunnel are closely monitoring innovations related to the decarbonization of transport. It is even a major issue that ATMB has included in its statutes with its raison d'être, which aims to initiate tomorrow's mobility in a sustainable way, by reducing its environmental footprint, while remaining attractive for the territories served.

In fact, an electric transport route between the Arve Valley, which is exposed to air pollution because of its geography, and the Aosta Valley in Italy, is a real opportunity.

In order to advance the envisaged technologies, ATMB proposes to be a testing ground for ERS. The ATMB network (A40 and RN 205), between the Arve valley and the entrance to the Mont Blanc tunnel, would be of great interest for testing the different ERS technologies in mountain conditions (curves, difference in level and altitude of more than 1,000 m, rigorous winter service, with the use of salt and scraping blades).

The interest in testing these devices is above all to arrive at a common technical solution that can be adopted by all infrastructure managers. The idea is not to relive the different heterogeneous recharging modes that the first electric vehicles experienced, for example.

Given the investment required, it will be important to determine who will finance the project: motorway operators via tolls or third-party operators? The economic model must be found, as well as the electrical distribution capacity to be organized.

Which ERS technology do you plan to focus on?

Today, there are three types of technologies: overhead conduction, ground conduction and induction, each with its own advantages and disadvantages. At this stage, no solution is favored by ATMB, as a transportation infrastructure manager.

All these solutions imply profound changes for the future operation of the freeway, and even for the safety of drivers, in the case of rails in the roadway for example, but also for the cohabitation on the same roads of "conventional" vehicles and vehicles with electric charging. The catenary solution could also present constraints in terms of visual impact.

Work is currently underway to try to develop a technological model that will bring consensus among all the players: manufacturers, managers, energy and infrastructure suppliers. We are following this work closely!

What changes do the ERSs imply for ATMB's organization and skills?

As with the platooning experiments (connecting trucks together so that one of the vehicles "drives" for the other members of the group) currently underway in the Mont Blanc Tunnel, more than ever our job as infrastructure managers is evolving into that of "dynamic road switchers", with a more cadenced organization of traffic and open to different forms of mobility.

The freeway of the future requires us to develop our project engineering capabilities with growing expertise in dynamic vehicle powering. Our maintenance model must also evolve in order to be able to maintain these systems.

Ground or lateral conduction solutions

The side conduction solution developed by Honda was eliminated, both because of insufficient maturity and because the operational and road safety risks were considered too high. In addition, the complexity of the on-board arm and its deployment seems high and no tests have proven that the system can power the trucks.

The Elways/Evias hollow rail solution seemed unsuitable for high-traffic highways and high speeds, with the added risk of a sudden sideways swerve (risk of breakage and fall of the arm onto the road) and problems with the durability of the drainage.

The chosen solution is the flush flat rail (APS, Alstom, or even Elonroad, which was not presented in its current version with embedded rail in spring 2021). Its maturity is intermediate between that of catenaries and induction, and it has fewer blocking locks than the other technologies with respect to the essential criteria.

The constraints or points of vigilance in operation are clearly less than with catenaries, but greater than with induction (excluding installation). On the other hand, for the installation and the repair of the surface layers, the work seems less cumbersome than with induction. The rail installation should not take longer than the installation of the pylons and catenaries of the overhead conductor solution. All vehicles (except motorcycles) can be powered and there is practically no limitation of deliverable power.

This solution has the best material balance with respect to copper and critical metals (nickel and cobalt) and the highest decabonation potential (see article "Material balance of ERS technologies compared to the battery solution").

The points of vigilance concern maintenance and pavement repair solutions, and the long-term mechanical strength of the rail. The issues of risk of electrocution or loss of adhesion have been successfully studied on track, but will need to be the subject of additional large-scale studies, as well as operation in winter conditions (with chlorides). The safety and durability of the system in case of falling objects or liquids (conductive or flammable) and when snowploughs pass by will also have to be verified.

The standardization of this type of system is underway in Europe by CEN/Cenelec.

Inductive solutions

The main advantage of these solutions is that they are not intrusive once installed (and as long as there is no intervention on the buried transmitter coils), and therefore do not modify the operating conditions of the road. The absence of mechanical contact between vehicles and road is also an advantage in terms of durability and use. All types of vehicles can be powered.

The main obstacle, in terms of deployment deadlines, is the technological maturity, which is much less than for conductive solutions. There are still uncertainties regarding the implementation of this technology and the durability and reliability of its components. The power limitation, especially for trucks, could be prohibitive on highly-trafficked highways, which are the core target of the ERS. In addition, the required receiver loop surfaces seem difficult to fit into the dimensions of road tractors and the tolerance, still in terms of power, is low with respect to the lateral wandering of the trucks in their lane.

The risk of low resilience of loops in asphalt pavements (the most frequent in France) was mentioned and would require specific studies. The durability of these loops in the event of repair of the wearing course is not assured to date (still a point to be verified by experimentation). The question of the presence of water infiltrated in the pavement is also raised.

The energy efficiency is at least 5% lower than that of conductive solutions, which induces a very significant energy overcost over the operating period (several decades). The material balance (copper) of this solution is not good, with an additional consumption of a factor of 2 or 3 compared to catenaries. The cost of the system and its installation could also be quite higher than other technologies. Finally, the health risk for road users, linked to intense electromagnetic fields, which seem to be under control if the system respects the standards in force, has not yet been fully documented and may penalize the acceptability of these solutions by users.

Recommendations

The recommendations made by WG2 are as follows:

1. At this stage, reserve induction for urban use and static fast charging (LCVs, buses, cabs, etc.), until the degree of maturity and performance have reached the required levels and been demonstrated by full-scale tests.
2. The solution by ground conduction with flush rail seems to be the most suitable for the different requirements, in the current state of the art:

- for its interoperability (all types of vehicles);
- for its less intrusiveness in operation;
- for its reduced impact on road safety;
- for an a priori longer durability, especially in case of extreme climatic events and intense traffic.

It will be important to have a European consultation and to seek an interoperable solution within the European Union.

3. Experiment, on an open road and on a scale of 1 (over several km), with the ground power supply solution in order to remove the last identified locks.
4. Overhead line technology (catenaries) can meet the main requirements of the ERS. Although it presents greater operating constraints than the other two families of technologies, it could nevertheless be the solution to be retained if the following two hypotheses are proven:

- none of the ground conductivity solutions reach the required TRL level within the given time frame or overcome the residual locks;
- none of the inductive solutions achieves the required level of performance in the same time frame or comes in at costs comparable to the other two.

5. Restrict the use of ground conduction with hollow rail and pins to secondary networks (low traffic) and limited speeds.
6. Lateral conduction has not been analyzed in detail, as it is still in the prototype stage and poses serious safety and operational issues.

NEED FOR EXPERIMENTATION IN FRANCE AND PERSPECTIVES

Despite an ecosystem that is already largely in place and French industrial players across the entire value chain, it has not yet been possible to test ERS on open roads in France, unlike in other European countries, notably Sweden and Germany. In this context, the challenge of open road trials in France is twofold:

- to develop at least one charging technology that meets the needs identified by WG1 (350 to 400 kW per truck), ideally a technology that is interoperable between trucks and cars;
- Build and validate an ERS simulator on the scale of the whole of France, using real data from vehicle fleets, to identify the points of the electrical network that would need to be reinforced, and to provide the key elements of a future digital model of the electrical road.

DEVELOPMENT OF TECHNICAL SOLUTIONS FOR DYNAMIC CHARGING

The solution identified by WG2 as the most promising is the ground power technology with flush flat rail and on-board pad(s). A comparison between the solution proposed by Alstom, with a double rail and a single pad per vehicle, and the solution by Elonroad, with segmented single rail with alternating polarities and multiple pads, will be useful. It is advisable to help the manufacturers to test it on track, then on open road if the results on track are sufficiently convincing.

Among the points to be checked are the grip on the rail and its long-term behaviour in the pavement, the operation of the system in winter conditions in the presence of salts, the durability of the collecting pad and its integration in the vehicles. The speed of installation and the maintainability of the rail are also points to be specified. It is also interesting to study the interest of this technology

for the guidance of vehicles, in particular for truck platooning.
Induction technology is now mobilizing more players internationally, particularly in the United States, Germany, Italy and Israel. The U.S. Biden Plan is providing substantial funding for induction research, which could help push back the current power limits identified by the WG2. France has expertise in this area, developed within the European Incit-EV project (integration into the roadway, durability of solutions, etc.) or the Carapower project in Rhône-Alpes to develop a power electronics industry. The challenge of experimenting with inductive recharging is therefore to contribute to the development of a competitive offer, ideally sovereign, and to increase the power of this technology, while remaining acceptable to the road transport industry.
For overhead line and catenary technology, three main limitations have been identified, two of which could be the subject of research to inform public decision makers. The visual impact of overhead lines on existing highways is a potential regulatory issue and may be a barrier to acceptance by the population. The reliability and durability of overhead lines are also identified as issues, as overhead line falls can be more frequent and more problematic than in the rail sector. French know-how in cable monitoring, for engineering structures or high-voltage lines and, more recently, for offshore wind power, could be exploited in this respect. The idea would be to develop intelligent catenaries with predictive maintenance. This know-how could eventually be exploited in the railway sector.

MORE ACCURATE ESTIMATION OF DEMAND

The power levels required to enable the ERS to meet the demand for mobility over a large part of the territory from the equipped motorway network, particularly for HGVs, leads to individual power levels of 350 to 400 kW to ensure driving and battery recharging in the most difficult conditions (wind, ramp). The capacity of the batteries is then adapted, per vehicle, to the coverage of the targeted territory and its operating conditions. This level of power means that induction can not be currently used and catenaries are somewhat limited in the current state of technology.
It would be advisable to estimate the power requirements more precisely by developing a laboratory vehicle capable of validating the hypotheses, by analyzing the requirements with the carriers and by developing a simulator on the scale of the whole of France for the electric roads. The players in the French ecosystem have the skills to do this, as implemented in the Equilibre project. The challenge is to produce a BIM *(Building Information Model)* of the ERS for large-scale replication of the first demonstrators.
Smart control strategies, coupled with decentralized renewable energy production, would help optimize the potential need for grid reinforcement. This work on "smart grids" for the ERS has been undertaken within the VEDECOM Institute with the Grid4Mobility project financed by the new Auvergne-Rhône-Alpes State-Region contract. ■

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SIZING OF THE ERS: NETWORK LENGTH AND POWER

This article presents the main assumptions and results concerning the dimensioning of an ERS infrastructure at the French scale. These results have been established by the working groups initiated by the DGITM in 2021.

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SIZING OF THE ERS NETWORK TO BE DEPLOYED

USE OF A ROAD NETWORK MODEL

A simplified model of the national road network (NRN) and motorways was developed in order to determine the optimal length of road to be equipped with ERS. The cost of the ERS increases proportionally to its extent, but the required autonomy for the vehicles decreases and thus the mass and cost of the on-board batteries are reduced. Therefore, the working group sought to determine if there is an optimum that minimizes the total cost of the infrastructure and the batteries.

The model used is based on a regular mesh (square or triangular) which allows to demonstrate that the product (length of road to be equipped) x (required autonomy) is a constant, proportional to the surface of the territory. This constant has been estimated at about 2.2 million km^2 on the network described in figure 1. Using the network shown in figure 1, the following relationship was established: individual autonomy x length of the network = 4 x area.

With this very simple model, an optimal ERS network length can be proposed using the following data (table 1):

- heavy duty vehicles (HGVs): 382,000 HGVs eq. 40 t, with an average lifespan of 8 years and consuming 1.43 kWh/km ;
- light vehicles (LV): 25 million LVs, with an average life of 15 years and consuming 0.15 kWh/km;
- cost of the ERS in both directions: 4 M €/km for HGVs alone, 6.2 M €/km for HGVs + LVs, with a 20-year life span;
- vehicle equipment cost: 3 000 € for trucks, 2 000 € for cars (cost before industrialization);
- batteries : 100 €/kWh ;
- autonomy in a scenario without ERS: 800 km for trucks, 500 km for cars.

The gains over "all-battery" do not include savings on the network of charging stations, which would be significantly reduced with the ERS.

To be noted

Mesh analysis shows that we have this relationship: autonomy individual x length of the network = 4 x area.

–Table 1–
Optimal ERS network length, required autonomy and savings from ERS.

	Length to be equipped	Autonomy required	Savings versus "all batteries"
ERS for HGVs alone	8,700 km	250 km	1.9 Md €/an
ERS for HGV + LV	15,000 km	150 km	5.2 Md €/an

A relatively well-distributed network of about 8,700 km would therefore need to be equipped in the case of ERS for trucks alone, and about 15,000 km in the case where cars could also benefit from ERS.

Furthermore, these results are relatively insensitive to the assumptions already made. For example, the optimal ERS network length varies by 2,000 to 3,000 km at most. The proposed 2035 ERS network length is very close to the optimum for trucks only. This network length may be extended in a later phase to include light vehicles if they become eligible.

NETWORK SELECTED FOR THE 2030 AND 2035 PHASES

A study taking into account the main HGV flows on a national scale was carried out to define the axes to be equipped in priority.

Figure 1 shows the network selected, which would be equipped in two phases: in 2030, 4,900 km would be completed, and in 2035, the remainder of 3,950 km, for a total length of 8,850 km for France. This is mainly the TEN-T trans-European network, plus the Paris-Rennes axis. With this network, any point in the country would be closer than 125 km from an ERS section.

–Figure 1–
Proposed deployment of ERS in France, in two phases: 2030 in red, 2035 in black.

In 2018, traffic on the network to be equipped by 2030 represented 11.5 billion HGV.km/year and 16.5 billion HGV.km/year for the network by 2035.

This traffic is of the same order of magnitude as the HGV traffic on the entire motorway network under concession for the same year (13.4 billion HGV.km/year).

The two-phase sequencing takes into account the gradual uptake of electric powertrain and ERS power collection systems by the trucks fleets, and the duration of the construction sites. The average ownership of a truck is 8 years. The ERS 2030 network could be completed in 4 years of work, using 20 simultaneous workshops advancing at a rate of 500 to 800m per day.

SIZING OF THE POWER TO BE SUPPLIED BY THE ERS

To dimension the power delivered by the ERS network on a French scale, the following were considered

- the residual battery capacity required to make non-ERS trips;
- the power to be supplied to each truck for its propulsion and the recharge of its battery;
- and, consequently, the electrical power to be installed for each linear section of the road network equipped with ERS, according to the traffic assumptions.

Global indicators such as average power mobilized per year or per ERS section were then estimated.

BATTERY CAPACITY REQUIRED FOR TRUCKS

With the proposed ERS network, a truck would be within 125 km of an ERS section at any time. Therefore, the selected range is 250 km, allowing for a round trip from the charging facility.

Using the consumption data provided by the CNR (National Road Committee) for an articulated vehicle used for long-distance transport, i.e. 31.4 l/100 km of diesel, the battery capacity required is 360 kWh, compared with 1,200 kWh without ERS for a range of just over 800 km.

It was verified that this capacity allowed the majority of the steepest areas of the RRN to be crossed easily. For the few most complex cases identified on the RRN (Fau Pass - Grenoble via the A51N), the remaining range when leaving the ERS section would still be 193 km, even taking into account a 40 km/h headwind on the climb.

POWER REQUIREMENT PER HGV

The power supplied to each HGV must allow at least the propulsion of the vehicle, i.e. 131 kW (mean value calculated on the basis of the average consumption of an articulated unit of 40 t with an efficiency of the combustion engine of 39% and an efficiency of the electric motor of 90%). This propulsion power rises to 216 kW on a 0.5 % slope and 276 kW on a 1% slope.

The power supplied must also ensure the recharging of the battery on the road and take into account the fact that the linear equipment fraction of the recharging infrastructure would probably not exceed 80% (excluding areas with significant slopes, engineering structures, interchanges and other singular points). Considering an average HGV trip on a 73.1 km motorway section, the power required by the ERS to recharge 70% of the HGV battery in 1 h and 2 h has been estimated (table 2).

–Tableau 2–
Individual power to be supplied to each HGV by the ERS according to the fraction of the linear of equipped network and the recharging time of the batteries.

	Recharge time: 1 h		Recharge time: 2 h	
Network equipment fraction	50%	80%	50%	80%
Power to be delivered	816 kW	510 kW	568 kW	353 kW

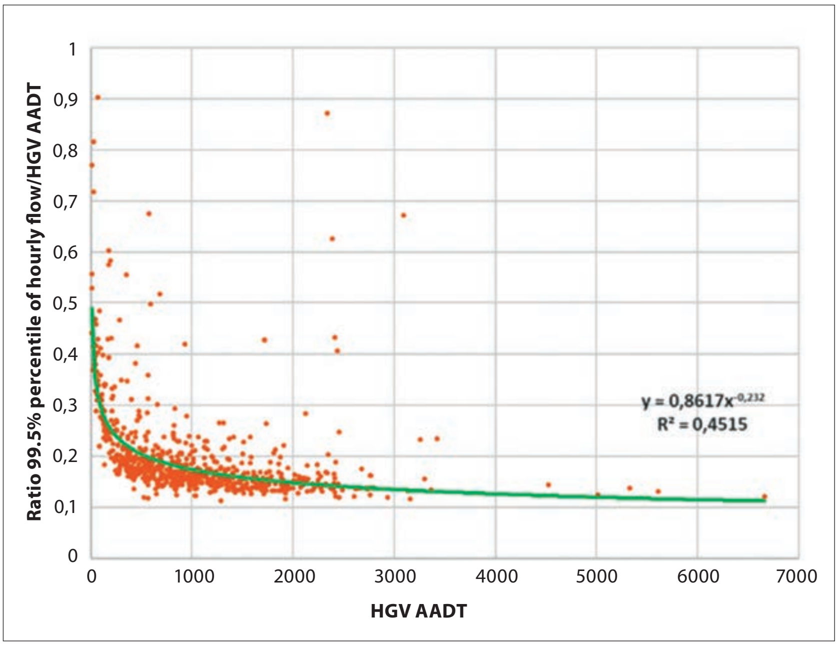
On the basis of these elements, and taking into account the motorization powers proposed by the manufacturers, a power of 400 kW available to each HGV and a linear equipment fraction of 80% were chosen.

SIZING THE POWER OF THE ERS ACCORDING TO THE PEAK TRAFFIC

The French road network is equipped with counting stations (Computerized Data Collection System - Siredo). These stations provide hourly vehicle flows, according to their classification by silhouette. Each year, Cerema centralizes the counts provided by the interdepartmental road directorates (DIR). The present work was based on data from 2017 and 2018.

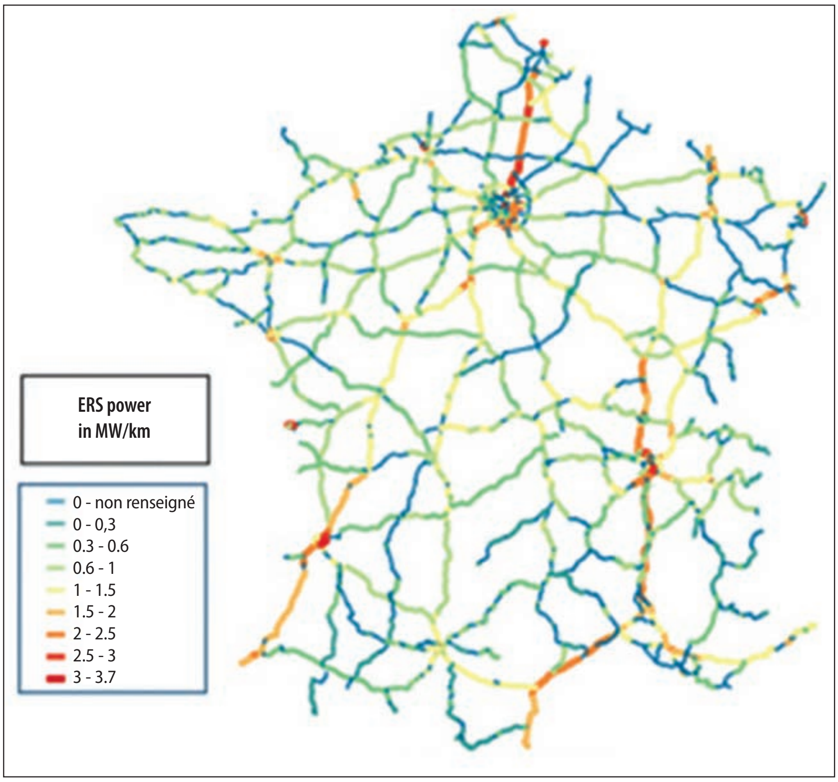
It should be noted that the Siredo stations are located on the National Road Network (NRN) and therefore do not concern the concessionary road network. It is difficult at this stage to assess the bias induced by the lack of data on the concession network.

–Figure 2–
99.5% percentile of annual hourly flows versus average annual daily traffic (AADT).



For each metering station, the 99.5% percentile of the hourly flows observed over a year was extracted. In fact, by analogy with electrical installations, the design power is approximated by the 30th busiest hour of the year, which amounts, in statistical terms, to considering the 99.5% percentile (approximately 30/8760) of the traffic peak. The results of these investigations at the scale of the NRN led to the relation between the peak traffic and the annual average daily traffic (AADT) presented in **figure 2**.

–Figure 3–
ERS sizing power per network section for 250 kW/HGV.



A power law regression was thus determined, allowing by extrapolation to obtain the peak traffic as a function of the AADT on all sections of the NRN and the concession network. It can be noted that, on average, the flow at the 30th busiest hour of the year (design flow of the ERS) is 4 times higher than the daily average flow on annual basis.

By dividing the peak flow rate by 80 km/h, an estimate of the maximum concentration of HGVs per km was obtained for each section of the NRN. Finally, by multiplying this concentration by 400 kW, the design power of the ERS infrastructure line was determined.

To simulate the fact that not all vehicles will call for 400 kW power all the time and that not all vehicles will be equipped with the ERS, the working group also looked at providing 250 kW power for 100% of the trucks **(figure 3)**.

The average capacity of the 2035 network is then 1.1 MW/km/direction considering an input of 250 kW for 100% of the trucks (1.7 MW/km considering an input of 400 kW for 100% of the trucks).

If 100% of the PLs called for an average power of 250 kW as soon as they are on the ERS, the average power to be delivered on the whole ERS network in 2035 would be 4.6 GW. ■

MATERIAL BALANCE OF ERS TECHNOLOGIES COMPARED TO THE BATTERY SOLUTION

The large-scale development of batteries may face issues of critical materials availability over the decade. If the electric road can reduce the amount of batteries to be produced, it is necessary to ensure that it will not shift these issues to the infrastructure. This paper aims to assess the critical materials consumption of different ERS technologies and compare them to current national consumption and avoided consumption in batteries.

ASSUMPTIONS

DEPLOYMENT SCENARIOS

As described in the article "Sizing the ERS: Linear and Power", two sizing assumptions were made:

- The "2035 Network" has 8,850 km of single-track ERSs; the required range is 250 km without ERSs;
- "ERS for all" is an optimal network for heavy goods vehicles (HGVs) and light vehicles (LVs), with 15,000 km of ERS on 2 lanes and a required range outside the ERS of 150 km.

For comparison, we add a scenario without an electric road: "100% batteries", which does not include an electric road and which requires a range of 800 km for trucks and 500 km for cars.

In all scenarios, the materials used for charging stations will be neglected. This assumption is unfavorable to the electric road.

COMPOSITION OF THE BATTERIES

The battery composition is assumed to be similar to the composition of a current NMC811 battery. For 1 kWh of cells, there are:

- 652 g of nickel;
- 82 g of cobalt;
- 96 g of lithium.

And, for 1 useful kWh, on a pack scale, we count :

- 1.1 kWh of cells;
- 600 to 2,700g of aluminum (value retained: 1,650g);
- 400 to 700g of copper (value retained: 550g).

The amounts of copper and especially aluminum are highly dependent on the design of the pack, but the average value chosen allows to see the trends. The results would be very different for an LFP (iron phosphate) battery, as it does not contain nickel or cobalt. On the other hand, the required amounts of lithium, copper and aluminum would not change much.

VEHICLE FLEET AND BATTERY QUANTITY

The truck fleet considered is that given by the SDES (Service de la donnée et des études statistiques). It is considered that for a 44 t truck, a battery capacity of 1300 kWh is necessary for a range of 800 km, and it is assumed that this capacity is proportional to the GVW (gross vehicle weight). This gives a total battery capacity of 460 GWh for the truck fleet in circulation without the ERS.

For cars, the consumption is assumed to be 15 kWh/100km. 25 million cars are assumed to perform in long distance travels with a range of 500 km in the absence of a ERS. The remaining 10 million cars are assumed to have a range of 200 km (30 kWh) in all cases.

In the case of the 2035 network, it is assumed that, if the solution is interoperable with cars, only 5 million cars will adopt it. This number is small because cars will have to share the 90 km/h truck lane. In the "ERS for all" case, it is assumed that all 25 million long-distance vehicles will adopt ERS.

These various assumptions depend on the cost of the equipment and batteries. They will have to be checked, for example, by means of a survey of stated preferences.

> **Truck fleet**
>
> Out of a total registered fleet of 601,000 HGVs in 2020, the distribution of GVW is as follows:
>
> - 5.9% to 7.5 t;
> - 10.4% to 12 t;
> - 25.4% to 19 t;
> - 15.2% to 26 t;
> - 6.5% to 32 t;
> - 36.6% to 40 t.
>
> Source: SDES, transport accounts 2020.

Table 1 summarizes the quantities of batteries required for each scenario. Battery materials will be directly proportional to these quantities.

ELECTRIC ROAD TECHNOLOGIES

Five technology vendors were consulted to develop the ERS material balance:

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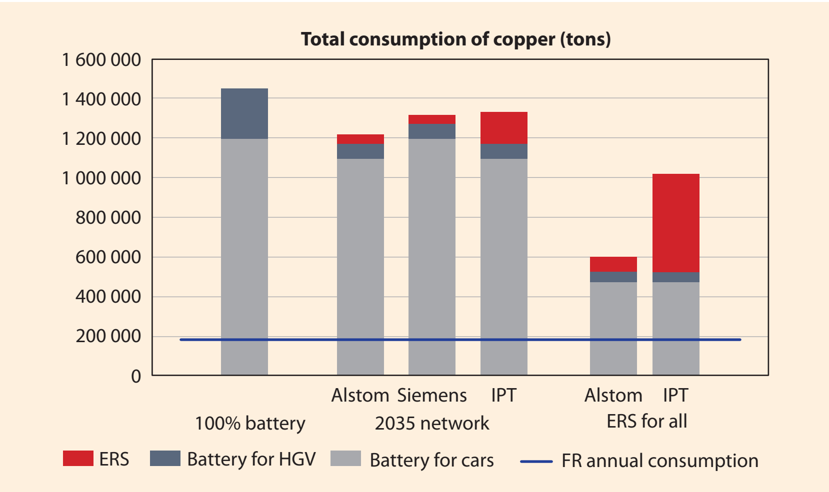
- Siemens for catenaries ;
- Alstom, Evias and Elonroad for the ground rails;
- Electreon and IPT for induction.

The WG1 report[1] details the data collected for 1 track, 1 direction, 1 km, and 2 MW/km. They are the most complete for Alstom and Siemens, and more fragmentary for the induction technologies. This is why the results shown below use Alstom data for ground rails, Siemens data for catenaries, and we will limit ourselves to the copper data provided by IPT for induction.

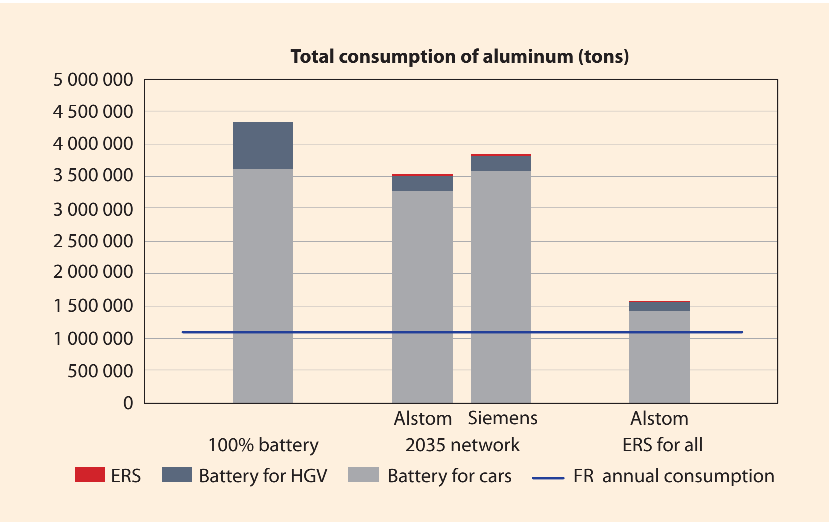
–Table 1–
Battery capacity to be mobilized according to the electrification scenarios.

	HGV	VL
100% batteries	460 GWh	2,175 GWh
Network 2035 without LV	143 GWh	2,175 GWh
Network 2035 - interoperable		1,862 GWh
ERS for all	86 GWh	862 GWh

–Figure 1–
Amount of copper embedded in batteries and infrastructure for the three scenarios and different technologies.



–Figure 2–
Amount of aluminum embedded in batteries and infrastructure for the three scenarios and different technologies.



Data are missing upstream of the substations, but as the voltages are much higher, the quantities of metal are much lower for the same power to be transmitted and are neglected here.

RESULTS

In all the results presented, the lifetime is not taken into account, as metals are assumed to be more than 90% recyclable. Therefore, we are only interested in the stock embedded in the infrastructure and in the vehicle fleet. Annual French consumption is shown in the graphs for comparison[2].

COPPER

Copper is a widely used metal, particularly in electrical generation and motors. The energy transition will contribute to future tensions on this metal from 2030[3].

The figure 1 shows that the quantities of copper involved correspond to several years of current consumption in France. The electric road, by reducing the size of the batteries, can reduce this need. For HGVs, the amount of copper consumed by the road itself is smaller than the amount saved on the batteries.

Choosing a technology that is interoperable with LVs can further reduce copper requirements by up to 60% in a scenario where ERS is highly developed. One point of attention concerns induction technology, whose copper consumption is significantly higher than others and could offset the savings obtained on batteries.

ALUMINIUM

Aluminum is not strictly speaking a critical metal, but its production is very energy intensive and can weigh on the CO_2 balance of a solution.

The figure 2 shows that the balance of the electric road is also favourable for aluminium, because the aluminium consumption of the considered technologies is very low. Indeed, they use mainly steel, which is not critical.

SPECIFIC BATTERY MATERIALS: NICKEL, LITHIUM AND COBALT

These three materials are identified as critical and their worldwide demand will increase significantly with the electrification of the automobile fleet:

- Cobalt, which is scarce and poorly distributed, has already been the subject of a major substitution effort in batteries.
- The changes in the price of lithium can already be seen in the price of batteries[4].
- As for nickel, a structural production deficit compared to demand is to be feared by 2027[5], or even 2024[6].

The reduction in requirements through the electric road is similar to those seen previously on copper and aluminum, on the order of 20% with the 2035 network and 64% with the ERS for all.

The **figure 3** illustrates the case of nickel. These reductions are particularly necessary, as the consumption of the 100% battery scenario represents about 25 years of the current French consumption. The savings obtained thanks to a scenario such as "ERS for all" at the scale of Europe can contribute significantly to reducing the foreseeable nickel deficit from the 2030s.

CONCLUSION

The amount of metals required for the ERS infrastructure is smaller than the metal savings from the reduction in size of the on-board batteries. The gain is greatly increased if an LV-compatible energy transfer technology is chosen and widely deployed.

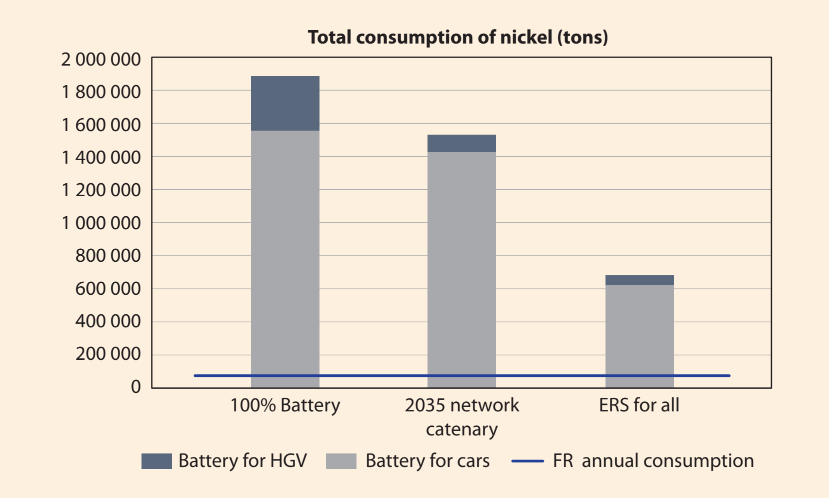
This is the case for all metals considered and for all three ERS technologies. This conclusion would be reinforced if the metal consumption for charging stations required in a 100% battery scenario were considered.

However, there is still a point of attention on the induction technology, whose copper consumption could counterbalance the gain obtained on the batteries.

This material saving could be crucial in the coming decades for metals such as nickel and even copper.

–Figure 3–

Amount of nickel embedded in batteries for the three scenarios.



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ECONOMIC ANALYSIS AND ATTRACTIVENESS OF THE ERS

FOR ACTORS AND USERS

This article examines the economic issues of the ERS (Electric Road System), based on the elements provided by the working groups set up by the DGITM and listed in reference.
The assumptions concern the road network used for the ERS, the investment costs including connections to the RTE high voltage or Enedis medium voltage networks, the economic balances by category of actor, and the specific balance for transporters.

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NETWORK AND INVESTMENT COSTS

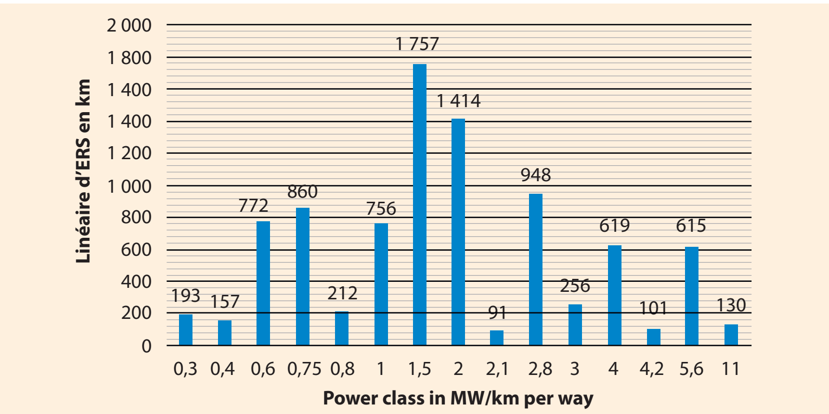
CHARACTERISTICS OF THE SELECTED NETWORK

The results provided are based on the work of the WG1 working group. In summary, an average power requirement of 250 kW per heavy vehicle (HV) on the ERS is used, with a 99.5% percentile of 400 kW over a year. These power requirements meet the needs of the haulers. 80% of the ERS eligible network would be equipped, avoiding singular points such as tunnels or engineering structures, while allowing vehicles to be recharged en route so that they can leave the ERS network with full batteries.

The ERS network retained for 2035 (see article "ERS sizing: linear and power"), includes 8,800 km of freeways and expressways, to be electrified in both directions. The total length of the ERS would therefore be 17,200 km, with one lane in each direction. The distribution of this line by power class is given in figure 1.

Power classes are defined for the construction of the ERS network, for questions of sizing and standardization of electrical substations, their number and distribution, and for the realization of electrification works to be distributed according to power levels. 80% of the network is in the classes between 0.6 and 3 MW/km/sense.

–Figure 1–
Distribution of ERS linear by power class.



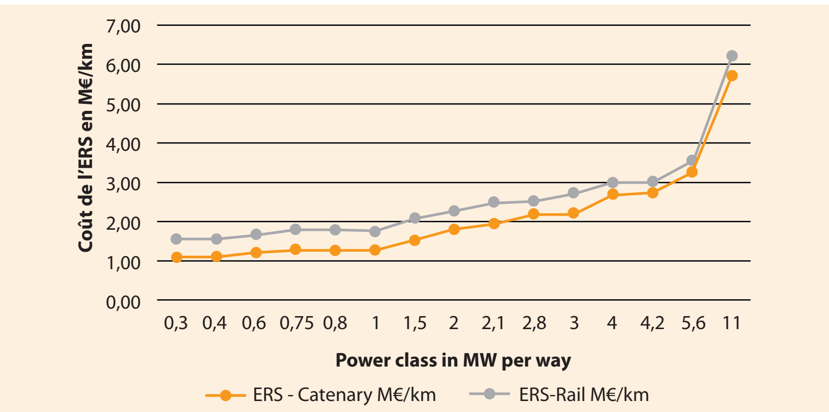
ESTIMATED INFRASTRUCTURE INVESTMENT COSTS

The orders of magnitude of ERS construction cost per kilometer by technology were discussed with the solution providers and construction companies in the working groups. For the two most mature technologies, overhead conduction by catenaries and ground-based conduction by rail in pavement, the variations in cost per kilometer as a function of power delivered are shown in figure 2. By multiplying the linear (Figure 1) by the cost per kilometer (figure 2) of a class, we obtain the share of the cost for this power class. The powers are given for one direction and are to be multiplied by 2 for the network.

Finally, by equipping 80% of the linear network eligible for ERS at a rate of one lane per direction over 8,800 km and adding a flat rate cost for connection to the Enedis medium voltage or RTE high voltage network, which depends on the geographical area, we end up with a total net investment cost of between €28 and €35 billion, of which approximately €2.5 billion is for connection to the electrical networks.

It should be noted, however, that these costs are estimates, for technologies still under development, and are not the result of a call for tenders or detailed costings based on complete specifications. They do not allow us to rank the two technologies in terms of cost. The cost for inductive technologies, whose maturity is less advanced and for which

–Figure 2–
Distribution of ERS cost per kilometer by power class.



the investigations could not be sufficiently deepened, is not presented. However, we can estimate that the order of magnitude of their cost should be significantly higher.

COST OF ELECTRICAL ENERGY, INFRASTRUCTURE CHARGES AND TRAFFIC SHARES THAT CAN BE CAPTURED BY THE ERS

Once the electrical infrastructure is financed, it was considered that the ERS operator could acquire electricity at the industrial rate, i.e. at a price of about 0.07 €/kWh TTC[1], for an annual quantity of between 20 and 70 GWh. A selling price of 0.10 €/kWh for the ERS user, excluding the infrastructure fee, was therefore retained.

The calculation of the individual infrastructure charge is complex because it is iterative. It depends on the volume of annual traffic that will use the ERS, which results from the extension of the network, which is more attractive the larger it is, and on the total cost charged to the user, including the fee and the energy price.

Using a simulation with the Marvell traffic model, the share of (now diesel) traffic captured could be estimated, neglecting the ERS-enhancing measures associated with the planned end of diesel. The results for the two conductive technologies are presented in figure 3 as a function of the total cost of electricity, including the infrastructure charge.

Two trends are emerging:

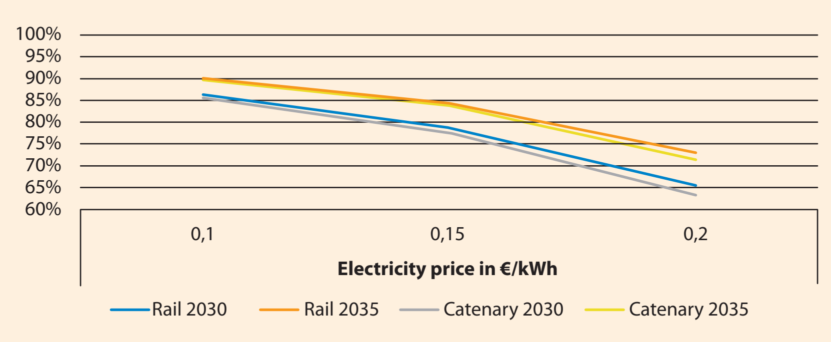
- the strong correlation between cost and attractiveness of ERS (cost elements and calculations are provided in the WG1 report);
- the attractiveness of the ERS, which increases with the size of the network.

To increase the attractiveness of the ERS, one can therefore either reduce the price of electricity sold to the user or increase the size of the ERS network.

The price of diesel taken as a reference is 1.33 €/l TTC. This level in 2020 is a conservative assumption, which has been largely exceeded since 2021 and even more so in 2022. In addition, public policies for the climate could maintain a higher diesel price and thus reinforce the relative attractiveness of electric energy. However, in the event of a massive shift in consumption from one energy source to another, the question arises of the transfer of specific taxation. The TICPE (domestic consumption tax on energy products: diesel, gasoline...) brought in € 32 billion in public revenue in 2019. The stakes are therefore considerable. As there are many unknown factors that may cause these factors to change in the years to come, the work has been carried out on a constant tax basis.

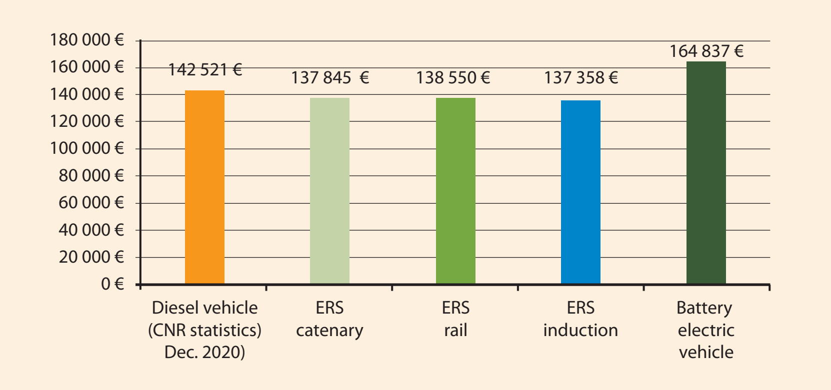
–Figure 3–

Share of HGV traffic captured by the ERS under the cost assumptions by technology.



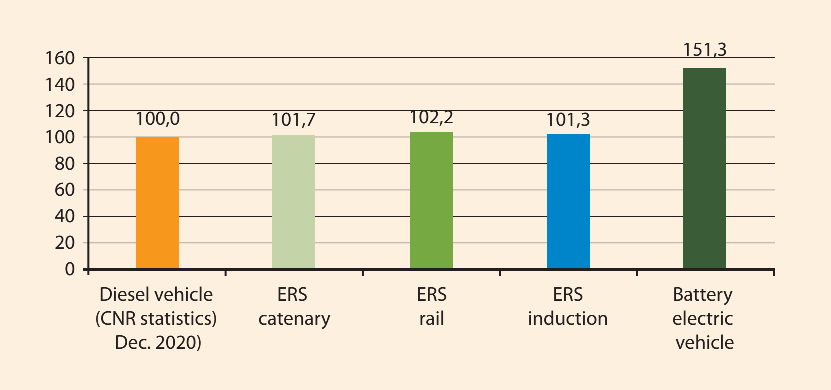
–Figure 4a–

Annual operating cost of a 44 t long-haul truck as a function of energy technologies.



–Figure 4b–

Relative cost price per t.km by energy technology (base 100 for diesel).



TOTAL OPERATING COSTS FOR CARRIERS

The National Road Committee (NRC) has a tool for calculating the total operating cost of an electric vehicle. The results of the calculations and statistics on the operating costs of diesel vehicles were also provided by the NRC. The main calculation assumptions are given in the WG1 report. The comparison between the technologies leads to the results shown in figures 4a and 4b.

The cost per ton-kilometer of freight is very close between diesel and ERS, but 50% higher with "all-battery", mainly because of the price of batteries and, to a lesser extent, because of the loss of

–Table 1–
Balance sheet for the ERS operator.

ERS tariff in €/kWh (electricity + infrastructure) for users	0,10	0,15	0,20
ERS solution	Balance sheet for the operator (in billions of euros over 31 years)		
HGV balance sheet for ERS rail only	-13,1	-4,7	-4,4
HGV balance sheet for ERS catenary only	-6,0	2,0	1,9
HGV balance for ERS rail without 2nd track	-9,8	5,2	12,4
HGV balance for ERS rail with 80% 2nd track	-22,2	-7,1	0
HGV balance for ERS rail with 15% 2nd track	-12,2	2,9	10,1

–Table 2–
Balance sheet for the state or community.

Electricity prices for ERS users		0,15	0,2
ERS solutions	Balance sheet for the State and the community (in billions of euros over 31 years)		
Balance sheet of ground rail heavy goods vehicles only	**Overall results**	**178,3**	**159,1**
	Infrastructure component	-0,9	-0,9
	Energy component	179,2	160,0
Balance sheet of catenaries for heavy goods vehicles only	**Overall results**	**176,0**	**155,5**
	Infrastructure component	-1,0	-1,0
	Energy component	177,0	156,5

payload. In addition, sensitivity calculations confirmed that:

- The operating cost of the different types of electric PLs is not discriminated by the price of electricity, but their attractiveness depends mainly on the relative cost of electricity compared to diesel.
- This operating cost depends heavily on the quantity and unit price of batteries. The assumption used, which is very optimistic, foresees a fourfold reduction in the cost of batteries compared to 2021, but this could be jeopardized by the shortage and increase in the price of raw materials, which would further penalize the "all-battery" solution.
- The investment in loaders at the depot, although very heavy, does not have a major impact on these operating costs because of the length of time they are depreciated.

A major issue for shippers is the flexibility of truck operation, i.e. productivity excluding operating costs. With diesel, the range can reach up to 4,000 km, with almost no time to refuel. Battery-powered electric solutions allow for a range of 750 km, or a day's driving with a safety margin. This would make long-distance transport totally dependent on charging stations on the routes, their availability, the price of the energy delivered there, etc., with a strong impact on the organization and optimization of transport services.

With an HGV connected to the ERS and equipped with a battery reduced from 2/3 to 3/4, the loss of productivity would be much less. The truck would carry more freight and fewer batteries, without being subject to local failures of the charging infrastructure. They could continue to take their rest periods in any parking lot or depot. Finally, the investment for transporters would remain limited, whereas with "all batteries", the additional cost of the truck at the time of purchase is more than 100%, not counting the purchase and maintenance of very high capacity chargers and the electrification of the depot with medium voltage.

GAIN FOR ERS OPERATORS AND FOR THE STATE

The operator of the ERS is a concessionaire, public or private, who will finance the electrical infrastructure and ensure its construction, maintenance and operation. Various arrangements are possible, not detailed in this article.

The calculation of the socio-economic net present value was done by comparing:

- ERS to diesel ;
- the ERS to "all batteries", with a diesel price of 1.5 €/l.

The results are from the Marvell model discussed above. Only the results of the comparison between ERS and diesel are presented here; those of the comparison between ERS and "all-battery" are even more favorable to ERS.

Tables 1 and 2 show the balances for the ERS operator and the state or community with various ERS alternatives, compared to diesel, based on the costs of using the ERS or selling the electricity. This helps to assess the attractiveness and acceptability of the ERS solutions. Carbon footprint, fuel taxes and pollution costs are taken into account. The ton of CO_2 (or CO_2 -eq) is set at €246 in 2030, €491 in 2040 and €763 in 2050, at 2015 euro value. Electricity is purchased at a price of €0.07/kWh.

The ERS solutions considered are overhead conduction by catenary reserved for HGVs only, for a total investment of €30 billion, and trackside conduction (rail) on one lane per direction, for a total investment of €36 billion, applied to HGVs only or also to light vehicles (LVs). Ground conductivity solutions were also considered by equipping a second lane for light vehicles, over 15 or 80% of its length. The calculations were made for the two deployment phases (2030 and 2035) over a 31-year period.

For the ERS operator, the bottom line:

- is always negative for the ground conductive solution applied to HGVs only, whereas with the catenary solution, 20% cheaper, it becomes positive as soon as the electricity price exceeds 0.15 €/kWh;
- is positive with the ground conduction solution from 0,15 €/kWh if light commercial vehicles (LCV) and cars are eligible, with a better balance than the catenary solution;

• is still positive with ground power and by equipping a second lane on 15% of the route. This option would allow LCVs and LGVs to recharge in often congested suburban areas, thus increasing the attractiveness of the ERS. On the other hand, equipping 80% of the second track would not be cost-effective under the assumptions of carry-over.

The balance sheet for the State has been merged with that for the community, as it is difficult to distinguish one from the other. It has been carried out on a constant tax basis, in particular with regard to fuel taxes.

The overall balance sheet of the ERS for the State and the community is largely positive, with close figures for both technologies. The balances on the infrastructure component alone are slightly negative, but largely offset by the energy gains, which will involve rebalancing and transfers.

CONCLUSION

These results show that all players (transporters, ERS operators and the state or local authorities) could benefit substantially from ERS technology compared to diesel, with room to maneuver on the price of electricity.

REFERENCE

1. Electricity prices in France and the European Union in 2017, Datalab, CGDD, October 2018: https://www.statistiques.developpement-durable.gouv.fr/sites/default/files/2018-10/datalab-essentiel-153-prix-de-l-electricite-en-france-et-dans-l-union-europeenne-en-2017-octobre2018.pdf

Avec le soutien et la participation du ministère de la Transition écologique représenté par la Direction Générale des Infrastructures, des Transports et des Mobilités (General Directorate for Infrastructure, Transport and Mobility)