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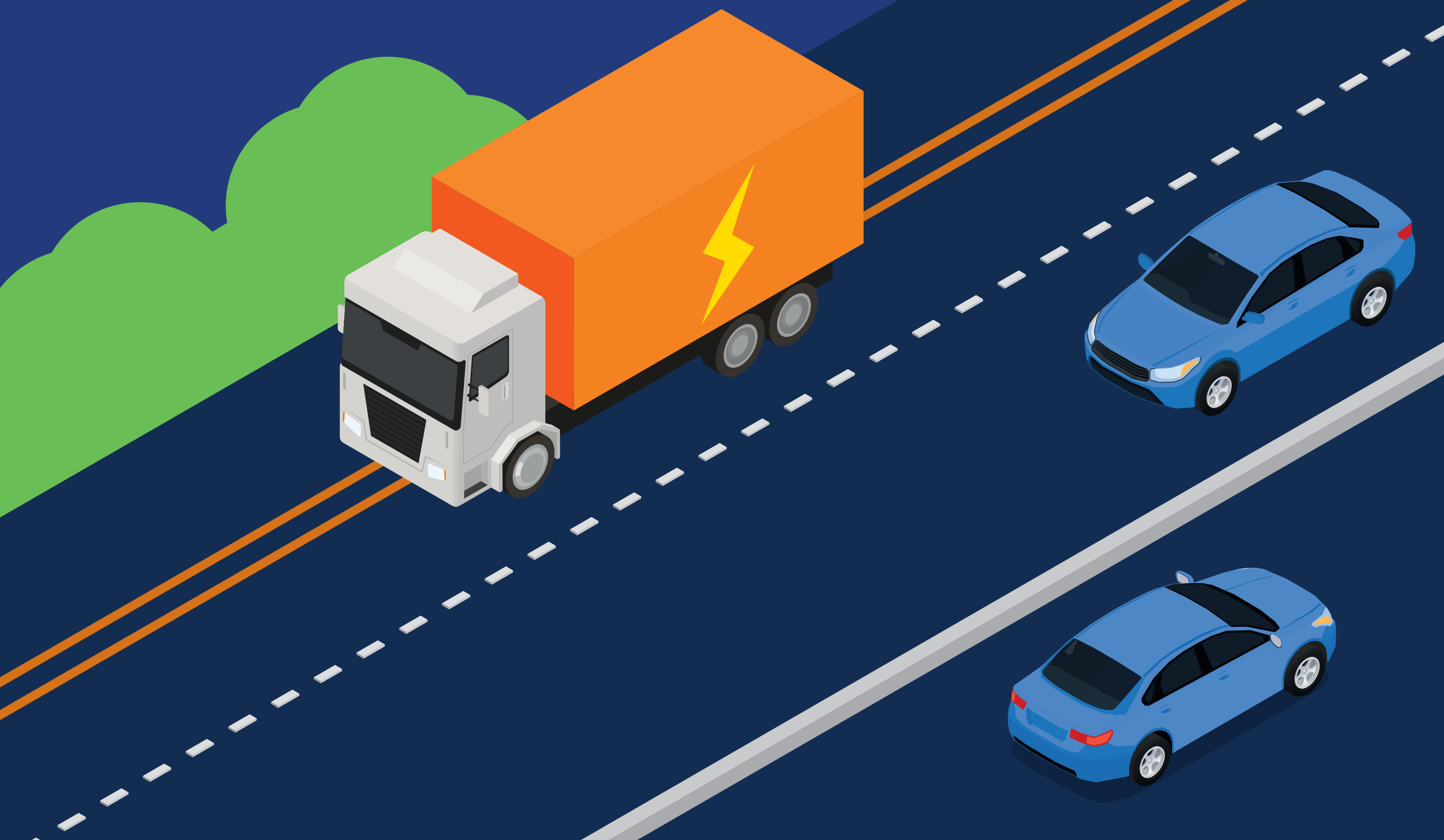
Electric road

It's time to get ready

November 2023



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Summary

The electric mobility sector is evolving rapidly, driven by both technological advances and regulatory pressure to decarbonise the transport sector. The electric vehicle, which was merely a promise ten years ago, has now become a reality and is being extended to all road transport. The industry is on the move and, at the same time as giant battery factories are being built, manufacturers are bringing new electric vehicle models to the market every month.

That said, not everything has yet been resolved, and there are still uncertainties over the long-term availability of battery materials, the roll-out of a sufficiently large and available infrastructure of charging stations, and the ability of research and development to deliver on the promises of battery development in terms of cost, durability, capacity and recharging speed.

The stakes are high, not only in terms of the possibility of converting the entire fleet of private vehicles in the medium term, but also in terms of transforming road haulage, which is currently a major emitter of CO_2, for which the electric solution, with its still limited range, its costs and its charging times, means that operating conditions will have to be adapted, which can be complex to put in place.

After a detailed study of the use of hydrogen to decarbonise road haulage[1], EdEn looked at an alternative to the battery solution: charging the vehicle while driving, in other words, the electric road system or ERS *(Electric Road System)*.

More than ten years ago, a number of research groups, universities and other economic players began promoting the electric road as an alternative to the 100% battery or hydrogen solution. ERS technologies were still at a very early stage of development at the time, and were of greater relevance to R&D departments and academia than to operations management.

Since then, ERS technologies have matured and have been the subject of numerous unit system experiments. A major study was carried out in 2021 by a working group under led by the French Directorate-General for Infrastructure, Transport and Mobility (DGITM), which concluded that this solution was worthwhile.

The principles of the electric road

The basic idea behind the electric road is to transpose to road haulage vehicles the systems that power certain vehicles while they are moving: trains, trams and trolleybuses. Three solutions are in the running, with varying degrees of maturity: power supply via catenaries, power supply via a rail flush with the track, and the transfer of electrical energy by induction from coils housed in the surface course.

Under such a system, however, heavy-duty vehicles (HDVs) would still be equipped with a minimum number of batteries to cover journeys outside the charging zone, whether on sections not equipped with batteries or on parts of the journey outside the motorway.

The costs involved and the need to coexist with other road users mean that these solutions are more likely to be found on motorways and expressways, with or without a concession, rather than on national or departmental roads. As HDVs are expected to have a range of 250 km, the absence of an Electric Road System over several kilometres, or even several dozen kilometres, is acceptable. Even in a long-term vision, the

1. *L'hydrogène dans le secteur du transport routier de marchandises (Hydrogen in the road haulage sector) - EdEn (October 2021).*

rate of equipment should not exceed 70-80% to avoid singular points such as bridges, tunnels, interchanges or areas too far from electricity distribution networks.

Compared with the all-battery solution, the main benefit of the ERS is that it significantly reduces the size of the batteries fitted to HDVs, while necessitating a limited quantity of copper or aluminium. This is particularly true for long-distance national and international traffic on motorways, but less so for regional and local traffic, which is less likely to use expressways.

In addition, rail and induction solutions could be made accessible to private vehicles, eliminating the need for either hybrid vehicles or vehicles with very large batteries, thereby increasing the benefits for the community, especially as HDVs do not operate on peak days for private vehicles.

Three solutions with advantages and drawbacks

Each of the three technologies has its advantages and drawbacks, which are analysed in this report. They are at different levels of maturity and the fact that they each have variants, especially for rail and induction solutions, means that they are families of solutions.

Catenary power supply has been a tried and tested solution on trains and trams for many years. From a purely technological point of view, it is the most mature solution and has been tested in Germany, Sweden and the United States. However, operating in the open environment of a road or motorway, with a heterogeneous fleet of heavy-duty vehicles, makes relying on this solution considerably more complex.

The experience with railways cannot be directly transposed to the ERS, because train and tram traffic is one or two orders of magnitude lower than traffic on a busy motorway, and HDVs are not all maintained with the same care, nor are they as well calibrated as trains. There will be significant wear and tear, with a corresponding risk of equipment being wrenched off and the motorway being more or less partially cut off for several hours.

Furthermore, it seems impossible, unless very complex systems are devised, for civil protection helicopters to land on the motorway to evacuate seriously injured people in the event of an accident. Similarly, the catenaries will make it very difficult to lift lorries that have been involved in accidents and are lying on their sides with cranes. This last point, which is part of everyday operations on the motorway, is seen as essential by motorway operators.

The system will be reserved for HDVs over 26 t, those with a gauge that allows them to reach the catenary located between 4.6 and 5.4 m, and the installation of a double pantograph will require the cabs to be reinforced.

The catenary poles will be installed along the tracks. They will have to be protected by concrete guardrails, which will significantly increase CapEx, with a potentially negative impact on the acceptability of the system in the motorway environment.

Ultimately, the problem with the catenary solution is that it has not yet been tested in a real operating environment, and it is difficult to know whether or not the points mentioned above will prove to be blocking factors.

In rail solutions, vehicles are powered from a rail cut into segments measuring between one and ten metres. This requires either two rails (Alstom solution) or one rail cut into one-metre segments (Elonroad solution), alternately positive and negative, so that the vehicle's collectors are always connected to both supply tracks. The segments are only powered up when a vehicle drives over them.

Rail can be used to transfer large amounts of power, in the range of several hundred kW, relatively easily. It is compatible with the operation of heavy-duty vehicles, even when fully loaded. The system can be used in static mode to charge stationary vehicles at delivery bays or depots. It could also be used by light vehicles.

Motorway operators are raising the issue of repairing the motorway's surface course. This maintenance takes place every 15 years or so, and could become more complex: the road would have to be planed on both sides of the rail, or else the feeder rail would have to be removed.

The risk to users, particularly motorcyclists, needs to be assessed. The rail can be slippery and will necessarily be relatively wide (8 to 10 cm). The link with the rest of the road may deteriorate over time, resulting in differences in levels that would be dangerous for two-wheelers.

Alstom believes it can provide solutions to these issues, including the system's resistance to winter or extreme conditions. The tramway experience is useful, but the motorway system tests carried out in France are on-track tests. The forthcoming tests following the call for projects launched in 2022 in France should make it possible to verify the viability of the rail solution in commercial operation, under real conditions.

The principle of the induction road (*In-Road Inductive Charging System*) consists of transferring power in the form of a variable electromagnetic field emitted from coils inserted in the ground to one or more coils located under the vehicle chassis.

Several manufacturers are developing their own solutions, which are mutually incompatible at this stage, in particular the Israeli company Electreon.

The first application of induction is static charging. The technology is well mastered and presents no particular difficulties apart from the electromagnetic risk, which should not be overlooked.

Induction charging on the road has major advantages: the coils do not interfere with traffic and can even be buried deep enough not to interfere with the renovation of the surface course.

The system is complex, however, because the vehicle remains above the buried coil for very little time (40 ms for a coil 1 m in diameter at 90 km/h). The problem is to develop ultra-fast switching systems and to ensure, with a good degree of efficiency, a power transfer that should reach 80 kW per coil at 90 km/h. Current trials are reporting 25 or 35 kW, which is not enough.

We also have to take into account the problems that can arise when the surface course heats up due to the heat generated by the windings, and the difficulties of inserting the coils into existing concrete motorways.

Tests have been carried out or are under way in Sweden, under normal traffic conditions on open roads, in France, Dubai, Germany, Israel, Italy, the United States and South Korea, but using different technologies (Electreon, VEDECOM, OLEV/KAIST).

These trials demonstrated the technical feasibility of the solution. However, the issue of power transmission has not been resolved and substantial progress is needed. The induction solution has potential comparative advantages over the other solutions, but its level of maturity is less advanced and we are still a long way from having a marketable solution.

Economic aspects

EdEn has calculated the cost price of an Electric Road System using traffic data available on the A7/A9 motorway sections, based on information gathered from solution designers and information provided by other companies in the ecosystem (road builders, energy utilities).

The elements on which this study is based show lower costs than those retained in the DGITM report. This information was provided to us by the manufacturers of the solutions. A commercial bias cannot be ruled out in a situation of intense competition.

The costs of peripheral equipment, such as the electricity distribution network or the presence or absence of concrete safety barriers, are of the same order of magnitude as for the main system. Some players insist on the need for these barriers, while others consider that they are not essential. Experimentation and the regulations specific to each country will decide.

Costs are set to fall as systems mature and competition between players increases, while full-scale trials may bring to light elements that have not yet been considered.

At this stage, it is the order of magnitude that should be taken into account when assessing the feasibility of solutions.

Infrastructure and maintenance costs

Table 1 summarises the infrastructure costs (CapEx) required by each solution, in millions of euros per km equipped, for one direction of traffic and with a motorway equipment rate (ratio of km equipped to total km) of 70%.

These investment costs, for a lane equipped for both directions of traffic, represent approximately 25% of the average cost of a motorway in France.

The financing costs were calculated on this basis, in accordance with standard motorway practice.

Heavy-duty vehicle equipment

The cost of the equipment has been estimated at €20k per HDV for the catenary and €15k for the other two technologies, for a lifespan of 8 years. The difference takes account of comments made by HDV manufacturers.

Application to the A7/A9 motorways

Applying the model to known traffic on the A7/A9 motorways gives the results shown in Table 2.

The selling price of the service provided and the total cost of ownership (TCO) over the lifetime of the vehicle can thus be compared with EdEn's estimates in its study on the use of hydrogen by heavy-duty vehicles.

Table 1: Infrastructure costs per km of motorway, for one direction of traffic and for each technology.

in €k/km	Induction		Catenaries		Rail	
	CapEx	Maintenance	CapEx	Maintenance	CapEx	Maintenance
Passive infrastructure (induction loops - catenary - rail)	150	5%	250	15%	150	10%
Electronics/Active equipment	500	5%	50	5%	150	10%
Installation work (including concrete guardrails)	150	-	425	-	150	-
Medium-voltage network	250	5%	250	5%	250	5%
Total (€k/km)	**1,050**		**1,025**		**700**	

Table 2: Estimate of the price of the service provided in 2030 and the TCO, in €/km, for long-distance journeys (> 500 km).

in €/km travelled	Hydrogen (by 2030)	Batteries (by 2030)	Induction	Catenaries	Rail
Estimated selling price of the service (including margin and excluding additional vehicle costs)	0.475	0.466	0.48	0.41	0.28
Total cost of ownership (TCO)	0.793	0.783	0.78	0.70	0.67

Note 1: These figures do not include toll fees, which can be estimated at €0.26/km on average and which have to be added in all cases.

TCO analysis gives an advantage to the electric road and more specifically to the rail solution

ERS solutions benefit from the low cost of vehicle equipment: batteries are limited in size and the equipment on the vehicle itself remains relatively affordable. What's more, the vehicle's carrying capacity is identical to that of a diesel vehicle, and the vehicle's structure does not have to be reinforced to support the weight of the batteries.

Compared with rail, induction is penalised by the cost of maintaining/replacing the electronics and by the lower rate of electricity transfer.

Catenary systems are penalised by the cost of passive infrastructure, which may require concrete safety barriers, and by the cost of maintenance.

Other motorway configurations are considered in the report. Of course, the results are very sensitive to the price of electricity. The above calculations have been carried out assuming an electricity price of €93/MWh, which takes into account the fact that the connection points are far apart and that HDVs only drive at peak times, but the relative positioning of the results is not affected by the assumptions made.

Deployment challenges

A number of considerations need to be taken into account when drawing up a strategy for rolling out the ERS.

Validation of technological choices

We have seen that each of these systems has a different level of maturity. The catenary solution is the most advanced, followed by the rail solution and, further down the line, the induction solution, which has not yet demonstrated its ability to transfer sufficient power.

Each of these solutions still needs to be tested to validate the basic techniques in conditions close to operational conditions. This will be the aim of the calls for projects launched by various European countries, including France, in 2022.

These tests might make it possible to rule out one or other of the solutions or simply to make progress in the choice of technical options specific to each of the solutions. For example: grooved or solid rail, frequencies or type of coils for induction, vehicle/infrastructure communication, etc. But it is unlikely that these tests will be sufficient to validate any of the solutions operationally, under real traffic conditions.

The next stage, which is necessary for such a validation, appears more delicate as it implies a change of scale and major investments. The cost of equipping a section of road of around one hundred kilometres would be in the region of €1 million to €2 million per kilometre per direction of traffic, to which must be added the cost of adapting a significant fleet of heavy-duty vehicles. Adapting 500 HDVs to one or other of the solutions will cost between €7.5 million and €10 million.

Infrastructure roll-out

In its study on hydrogen, EdEn showed that infrastructure could be rolled out gradually, with refuelling stations initially widely spaced, then a densification of the distribution network coupled with a replacement of simple distribution points by production stations.

Rolling out the Electric Road System will not be as gradual a process, although some flexibility will be possible. Once HDV batteries have been made smaller to take advantage of the ERS, the spacing between equipped sections will have to be relatively short. However, a deployment scenario by section (and by local and captive fleets) seems possible, starting with the priority sections.

Planning outline

In view of the above, the shortest possible time frame does not point to the start of a large-scale roll-out before 2029/2030, provided that the necessary impetus is given at both national and European level to speed up full-scale tests and bring to the fore those technologies that deserve to be rolled out across the board.

The sequence could be as follows:

- continue unit tests and experiments over limited distances (a few kilometres) at national level, with the support of European R&D funds (Horizon Europe). These will be launched in France following the call for proposals launched in 2022, the results of which were published in July 2023;
- set up working groups at European level, including equipment manufacturers, HDV manufacturers, hauliers and motorway operators, to specify the preselected technologies and facilitate standardisation. This phase may lead to certain options being set aside but does not imply any definitive technological choices;
- organise and carry out pilot test operations over significant lengths (100 or 200 km sections), with the participation of partner users in the test operations. These operations can only be envisaged as part of a European programme. The *Innovation Fund*, which will benefit from resources from the new ETS dedicated to the building and transport sectors, should include the ERS among its future calls for proposals;
- large-scale deployment can only reasonably begin once mature, standardised technologies have emerged, bearing in mind that there will still be a considerable time lag between the decision to roll out and operational deployment: calls for tender, industrialisation by suppliers, etc.

The above-mentioned pilot operations could:

- either correspond to a trailer transport service on a given route, using unmarked and shared tractors: the trailers would be picked up at a suitable area, hitched to a tractor using the Electric Road System and driven to a drop-off area where they would again be hitched to conventional tractors. Such a solution could be implemented to reduce pollution on specific, particularly polluted segments, such as the Arve Valley in Haute Savoie;
- or be based on a limited segment, long enough to be significant, by inviting interested hauliers to adapt part of their tractor or trailer fleets. A segment such as Paris-Orléans would be a good candidate.

Conclusion

Today, the ERS is of undeniable interest in achieving the decarbonisation of freight transport. That said, it will probably only come to the fore once the first phase of battery-equipped HDVs has been rolled out. This second phase could fit in with the timetable for the draft regulation amending Regulation (EU) 2019/1242 setting CO_2 emission performance standards for new heavy-duty vehicles, with the aim of achieving a minimum decarbonisation rate of 90% by 2040.

Of course, nothing can be taken for granted: we live in a rapidly changing world, and a technological breakthrough in batteries could call into question the entirety of this report's conclusions. Nevertheless, it is vital for Europe to anticipate and prepare now for a virtuous alternative to the all-battery model and an alternative to the hydrogen or bioNGV models. The timescales for testing, validation and adoption are too long to wait for any given model to fail.

EdEn recommends raising awareness at national and European level of the importance of the ERS in the light of the new regulation currently under discussion. It is advisable:

- at the national level in France, to push ahead with the tests already planned as part of the call for projects launched in 2022. The efforts made by ADEME, the French Environment and Energy Management Agency, and the consortia that responded to the call for projects must be maintained and, if possible, accelerated;
- at European level, to prepare without delay for full-scale tests with a significant fleet of heavy-duty vehicles and a range of around 100 to 200 km with each of the technologies that will have passed the first stage. We see the introduction of the Building/Road transport ETS and the resulting extension of the scope of the *Innovation Fund* as appropriate levers for setting up such projects.

With a proactive strategy, the ERS could begin to be deployed on a large scale from 2030 onwards and thus contribute to achieving the objectives set for 2040.

1

Introduction

Batteries and hydrogen: two possible solutions for decarbonising freight transport

In 2021, EdEn published a study on the possibilities for decarbonising road freight transport[2], which is a key issue in order to achieve carbon neutrality by 2050 and to reduce pollution in sensitive areas.

Several solutions were considered, two of which were selected for further analysis: battery-based electrification and the use of hydrogen in fuel cells. These solutions were considered to be the most mature and the most appropriate for a fast roll-out. It was not considered that synthetic fuels and liquid biofuels would be developed on a large scale, as they are considered a priority for modes of transport such as air transport, for which there is no alternative. However, the compressed biogas (BioGNV) segment remains a possibility that should be further explored.

The 2021 study showed, first of all, that no solution was competitive with diesel and that it was therefore essential for the French and European public authorities to provide strong incentives for decarbonisation. The draft regulation, amending Regulation (EU) 2019/1242 setting CO_2 emission performance standards for new heavy-duty vehicles, is likely to generate strong regulatory pressure by requiring a 90% reduction in heavy-duty vehicle emissions by 2040. With this in mind, battery electrification will be the preferred solution for short and medium-distance road haulage, mainly for regional transport or transport between neighbouring regions, while hydrogen could have a competitive advantage for long-distance, international or inter-regional transport.

However, none of these solutions is ideal, and none of them can easily replace diesel.

The "all-battery" solution is a natural extension of the development of electric vehicles, but has a number of drawbacks in the case of heavy-duty vehicles:

- the weight of on-board batteries for long-distance transport is very high, even taking into account expected technological progress. This extra weight, in the range of 1 to 3 tonnes (see below), increases the vehicle's fuel consumption, even when empty, and partly limits the payload[3];
- operating conditions and regulations on driving times for lorry drivers mean that charging times are relatively short compared with the quantities of electricity to be charged;
- charging technology for the very large capacities – up to 750 kWh or even 1 MWh – required for long-distance transport is still being developed, with a number of issues still to be addressed, such as battery cooling, charging cables and HV (1,000 V) cable connections;
- Batteries are expensive, consume resources that can become limited, such as lithium, cobalt, nickel, graphite and copper, and their supply pollutes or is unevenly distributed across the planet.

However, manufacturers are investing heavily in all-battery solutions, and Tesla in particular has just announced the launch of its 36-tonne truck with a real-world range of up to 800 km on a charge, well ahead of rivals such as the Mercedes-Benz eActros, which currently states a range of 400 km on a 420 kWh battery.

In addition, standardisation of high-capacity battery charging has been introduced at European level by the CharIN consortium. The consortium is first working on MCS (Megawatt Charging System) connectors, for static charging stations compatible with long distances, i.e. a heavyweight pair of 800 kWh batteries with a charging power of at least 750 kW to be compatible with charging during the regulatory 45-minute breaks.

Finally, lithium iron phosphate (LFP) batteries offer advantages that have made them a priority in China, for both light and heavy vehicles.

2. *L'hydrogène dans le secteur du transport routier de marchandises (Hydrogen in the road haulage sector) - EdEn (October 2021).*
3. *The road hauliers interviewed said that in most cases they were more concerned about the volume they could carry than the maximum permissible weight. Furthermore, legislation may authorise an increase in the maximum permissible weight in order to limit this impact. On the other hand, the weight of on-board batteries will always be present, even when the HDV is travelling empty.*

The hydrogen solution has a number of significant advantages:

- Its use is similar to that of diesel, at least in terms of filling time and mileage on a full tank;
- it can be stored, which means that its production can be decoupled from its use and the electrolysers can be removed from the grid during peak periods;
- It can be rolled out gradually, as the number of users increases.

That said, carbon-free hydrogen is likely to remain an expensive solution.

The EdEn study showed that, because of the 1 to 8 ratio between the energy density of hydrogen at 700 bars and that of diesel, it would be impossible to envisage refuelling motorway service stations by truck during the industrial deployment phase. Hydrogen will either have to be produced on site by electrolysis, using relatively expensive electricity[4], or a network of ad hoc pipelines will have to be created along the motorways to meet demand. In both cases, the solution will come up against the unfavourable efficiency of the complete chain (electrolysis/compression to 700 bars/fuel cell), which will not exceed 40%, even in the most optimistic assumptions of reusing the waste heat generated by the electrolysers. The yield is currently closer to 30%.

The production of green hydrogen in massive hubs backed by cheap renewable energies, or blue hydrogen by steam methane reforming (SMR) accompanied by CO_2 capture and storage (CCS), will primarily be of interest to the chemical and steel industries, which will have priority in the absence of alternative carbon-free solutions.

The hydrogen used will only make sense for large-scale deployment beyond a trial period if it is carbon-free.

The emergence of the electric road concept

Alongside these solutions, a number of manufacturers and research bodies have been studying and experimenting with the possibilities of continuous charging, even outside the laboratory. This is the electric road concept or ERS (*Electric Road System*).

Several solutions are currently being considered, but none has yet won out over the others:

- feeder rails;
- catenaries;
- induction.

These solutions are discussed later in this document and the advantages and drawbacks of each one are analysed in detail. What they all have in common is the idea that distributing electricity as it is consumed is at least as efficient as storing it in batteries or producing hydrogen, and that it reduces the pressure on rare materials:

- efficiency is improved, since virtually 100% of the electricity drawn from the system is fed into the vehicle's engine (perhaps a little less for induction[5]);
- the size of the vehicle batteries can be greatly reduced, since the range required is reduced to the distance travelled off the motorway, i.e. around 200 to 300 km, or even less[6];
- batteries also provide the additional power needed for steep gradients;
- charging on the move would avoid the need for more MCS chargers and night chargers in HDV car parks, and would also avoid the need to increase the surface area of car parks, as HDV spaces would have to be separated by islands to accommodate the charging stations, with HDVs plugging in on the left-hand side.

The stakes are high, with major potential savings in terms of rare materials for batteries, electricity consumption and constraints on the distribution network.

4. *Local hydrogen production at service stations will come up against a number of problems: regulatory constraints (large-capacity electrolysers are Seveso installations) and constraints on the amount of electricity used, which will compete with the needs of many other consumers.*
5. *The efficiency of converting electricity from the distribution network to the transmitting coils is likely to be similar to that of the other technologies, but the efficiency of induction will also be sensitive to the alignment of the HDV with the coils and to the passage from one coil to another while the HDV is moving. Tests under operational conditions will make it possible to confirm or refute this point.*
6. *Some manufacturers are even envisaging HDVs with virtually no batteries, designed for motorway use only.*

In addition, induction technology and, to a lesser extent, rail technology, which requires retractable collectors, could be used by light vehicles. There would be many benefits:

- increased range with batteries that would remain limited in size, without having to resort to hybrid technologies;
- convenience of use for static charging;
- accelerated return on investment for electric road infrastructure;
- reducing the need for fast-charging stations for light vehicles. This is a particularly sensitive point, as major holiday or long weekend departures are too infrequent for fast-charging infrastructures to be sized for these events alone.

These studies and experiments are not recent: KAIST (Korean Advanced Institute of Technology) has been testing an induction solution in Seoul's Grand Park since 2011, and tests on catenary systems in Germany go back several years. Technologies have matured and are also benefiting from advances in driving aids, such as adaptive cruise control and lane-keeping assist. These improvements make it much easier to deploy an ERS solution operationally, because they make it easier to comply with the "charging corridor", whatever ERS option is chosen.

There are currently a dozen pilot projects around the world, and larger projects are at the specification and even tender stage in Sweden and the United States (see Appendix 1). The ERS can therefore no longer be considered as a fiction and could be an industrial reality by 2030.

In France, the Ministry of Transport (DGITM) led a study in 2021, in the form of three working groups, each of which produced a report with the participation of numerous stakeholders. This study, which the Ministry of Transport has published on its website, has confirmed the benefits of this type of solution.

The three working groups were as follows:

- WG1: **Decarbonising road freight transport through ERS**, issues and strategy, chaired by Patrick Pélata, former Deputy CEO of the Renault Group[7];
- WG2: **Technical solutions, potential and obstacles**, chaired by Stéphane Levesque, Director of Union Routière de France (URF);
- WG3: **Large-scale experimentation with electric road systems (ERS)**, chaired by Marc Gohlke, CEO of CARA, the European Cluster for Mobility Solutions[8].

In conclusion, the study tends to recommend rail as the technical solution for the electric road, even though some of the participants, in particular motorway operators, have not yet all come round to this solution.

EdEn believes it is necessary to revise certain assumptions, in particular those relating to the minimum instantaneous power to be delivered to each HDV, estimated at 400 kW. This assumption is crucial. However, the choice of the 400 KW threshold does not take into account the contribution of the internal battery to climb gradients or the fact that the ERS will be used mainly for long-distance transport and that the distance covered on the motorway will therefore be much greater than the 76 km used by WG1:

- The average motorway journey used by WG1 is that published by ASFA[9] and corresponds to 76 km, or 50 minutes. It covers all forms of transport, whether local, regional or long-distance. WG1 estimates that the battery of an international HDV needs to be recharged in these 50 minutes, hence the 400 kW required, whereas the power required by the engine of a 44-tonne truck at a steady speed of 90 km/h on a flat road is less than 150 kW;
- EdEn' vision is that the ERS will be used mainly by long-distance road vehicles, which stay on the motorway much longer. The additional power required to charge the battery will be much lower and is estimated at between 200 and 250 kW;
- It should be noted that the power transmitted in experiments on catenaries in Germany is between 200 and 250 kW, while in Sweden it is between 110 and 250 kW.

7. *https://www.ecologie.gouv.fr/sites/default/files/GT1%20rapport%20final.pdf*
8. *https://www.ecologie.gouv.fr/sites/default/files/GT3%20rapport%20final.pdf*
9. *Association des Sociétés Françaises d'Autoroutes et d'ouvrages à péage (Association of French Motorway and Toll Facility Companies)*

In a number of countries, these technologies are currently benefiting from substantial R&D investment, and their deployment in the medium term would be of undoubted socio-economic interest, particularly if, while focusing primarily on heavy-duty vehicles, they were to provide a response to the need for very long-distance autonomy for private vehicles and to the risk of congestion at charging areas on very busy days.

The economic benefits for the community look positive on paper. However, such a system can only be developed if all the players – hauliers, distribution networks, energy suppliers, motorway operators, HDV manufacturers – are prepared to support it.

The prospects offered by these systems have therefore led EdEn to analyse in more detail the maturity, advantages and drawbacks of each solution and the conditions for their development.

2

Technologies being considered: rail, catenaries, induction

General systems architecture

General overview

Three technologies are currently being studied or tested by various organisations: rail power, catenary power and induction power. The common feature of all these technologies is that they provide an almost continuous supply of power to HDVs on the road to cover their journey and recharge their batteries.

The power is supplied to the truck by relatively short cells: one to two metres for induction, around ten metres for rail and a few kilometres for catenaries[10] (*Figures 1 and 2*). The voltages used to power vehicles are relatively low: from 800 V to 1 kV maximum, for safety reasons[11].

The cells are installed in the right-hand or central lane of the motorway or road, and when the truck is charging, it travels in the equipped lane. In all three cases, the truck must remain aligned with the centre of the lane, with a maximum lateral tolerance of a few dozen centimetres. The recent development of driving aids and lane-keeping assist systems will be major assets in meeting this requirement.

Power supply

The cells themselves are powered by low voltage. The length of the cables powering the cells is limited by the voltage of the network and the power used, which depends on the number of HDVs equipped and travelling on the section. It can be measured in hundreds of metres or kilometres at most.

The power is drawn from connection points on the distribution (ENEDIS) or transmission (RTE) networks located close to the motorway.

ENEDIS and RTE networks are not systematically close to the motorway. The cost and time required to create a new link between the public network (transmission or distribution) and the motorway every kilometre or so could be prohibitive. It may be worth deploying an underground MV (medium voltage) network within the motorway right-of-way, enabling the necessary power to be distributed over a distance of a few dozen kilometres.

As it will be a distribution network deployed in a public domain under concession, the status of this network and the regulatory aspects will have to be studied: it will have to be decided whether it is public or private and which entity will be authorised to operate it.

ERS technologies generate both transients on the upstream network, which are much more difficult to manage than with stationary charging, and harmonics, due to the conversion to direct current, which need to be filtered to prevent them from disturbing the upstream network.

These disruptions exist on the SNCF (French rail) network, but are partly filtered out by the length of the cables.

HDVs need to be powered in both directions, so the supply infrastructure has to be duplicated on the other side of the motorway. A possibility is for one side to be powered by the other by running the medium-voltage network under the motorway.

As vehicle tyres are insulating, rail and catenary solutions require a return path for electricity.

Power requirements

The power consumed by a fully loaded HDV travelling on a flat stretch of motorway is around 150 kW, to which must be added around 100 kW[12] to charge the battery and cover conversion/transport losses. Traffic density can reach 11 HDVs per kilometre[13]. With a target equipment rate of 80%, this means a

10. Two catenaries are needed to ensure the flow of electric current, because HDV tyres are insulating, whereas for trains and trams the return is via the rail.

11. By way of comparison, the rail network is powered with 25 kV alternating current for the part built in the post-war period and 1,500 V direct current for the oldest part. The Paris Regional Express Network (RER) is powered with 1,500 V, while the metro and trams are powered with 750 V DC.

12. Taking into account an internal battery capacity of 250 kWh, 100 kW corresponds to charging half of this capacity in 1¼ hours, which is acceptable for a heavy-duty vehicle making long-distance journeys. This also leaves capacity for negotiating slightly longer gradients or crossing areas not equipped with the ERS.

13. Respecting safety distances allows up to 15 HDVs per kilometre. This is a maximum figure once the technology has been fully deployed and used.

Figure 1: Schematic diagram of an ERS catenary power supply network.

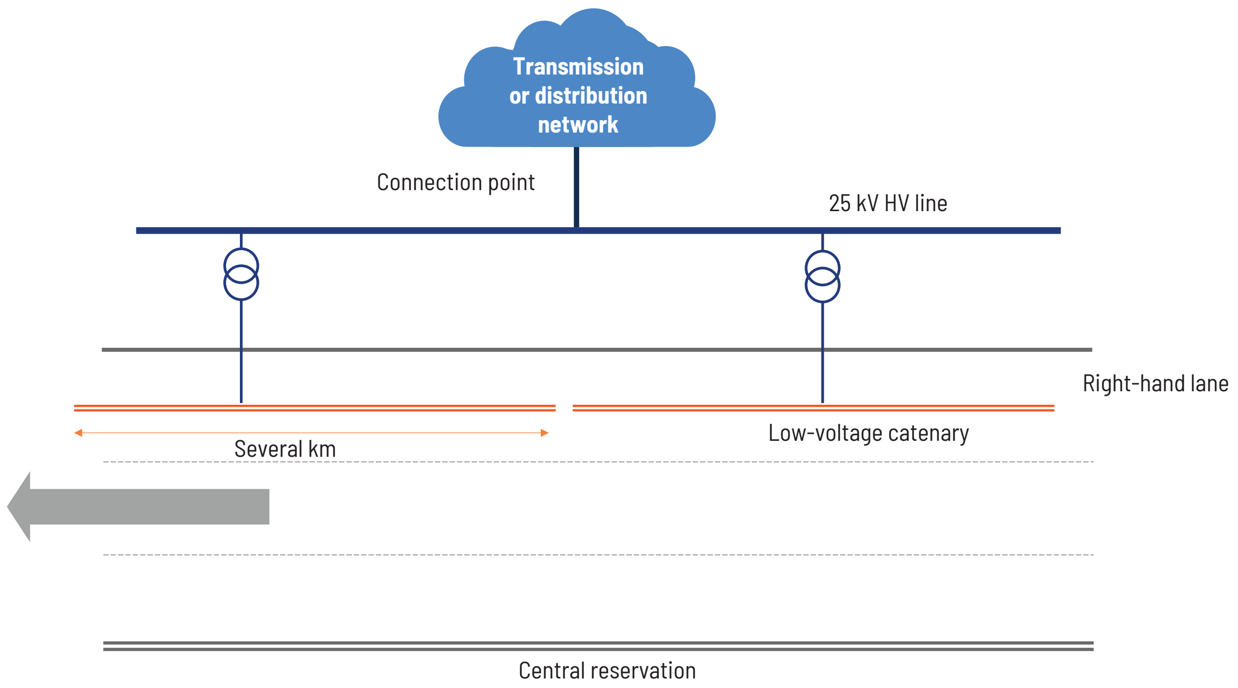
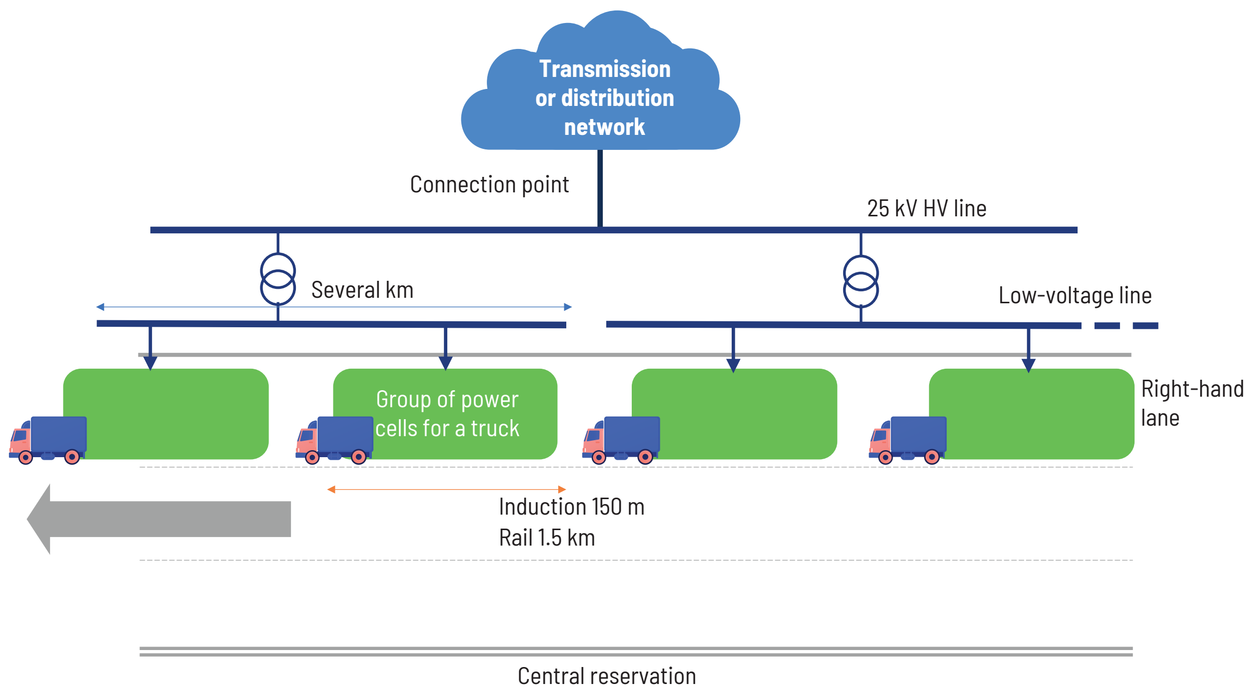


Figure 2: Schematic diagram of a power supply network for an Electric Road System by induction or rail.



power consumption of 2.2 MW/km for the busiest areas, once the system has been fully rolled out at hauliers.

A medium-voltage network (HV - 25 kV - three-phase) has a maximum capacity of around 13 MW. This means that 65 HDVs can be charged simultaneously at full power per connection point. This power cannot be supplied by connecting to extraction points on the ENEDIS network serving other users. It will therefore be necessary either to create other substations or to connect directly to the RTE network.

Based on traffic on the A7/A9 motorways, the distance between HDVs at rush hour varies between 90 metres and 300 metres, with a weighted average of 210 metres. The average length of the section between two connections to the electricity grid will therefore be 13.5 km, ranging from 8 km for the busiest sections to 20 km for the others. It will be much greater for less busy stretches of motorway.

These are constraints that will have to be met once the ERS has been fully rolled out at hauliers. Clearly, there will be a gradual ramp-up of capacity, with the network and extraction points gradually being reinforced. The ramp-up plan will have to be based on the results of experiments. The length of the segments will have to be adapted progressively according to actual traffic and the availability of network connection points.

As HDVs have a range of 250 km, the absence of an Electric Road System over several kilometres, or even a few dozen kilometres, is acceptable, as the batteries will be charged when the HDV picks up the next section. Even in a long-term vision, the rate of equipment should not exceed 70-80% to avoid singular points such as bridges, tunnels or interchanges.

The intensities transmitted are significant but not prohibitive: 200 kW at 800 V corresponds to a current of 250 A.

Protection against over-consumption and limitation of power demand

Limitations linked to battery technology

A mechanism linked to current battery technology means that the power required by the battery when charging is not constant, but decreases as the charge progresses: for a completely empty 100 kWh battery charging on a system capable of delivering 100 kW, charging will take well over an hour; the first 80 kWh will be charged in almost 50 minutes, but the last 20 will take almost as long.

Figure 3 shows that on most current vehicles, charging power decreases very quickly and that, for all batteries, it falls above 80%[14].

If a margin of 100 kW is allowed for charging batteries in excess of the 150 kW required, the total power of 250 kW will only be drawn from the ERS when the battery is partially discharged, the HDV is climbing a gradient or charging after a long climb. In other cases, the power demand will be lower.

Over-consumption

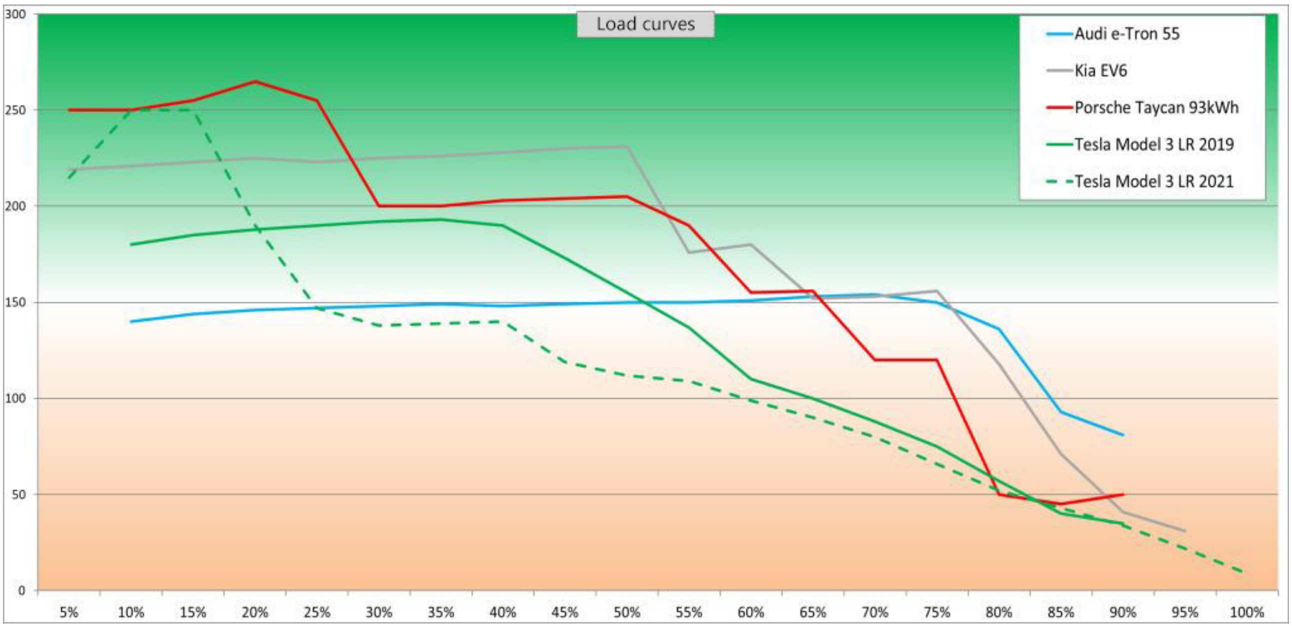
In an electricity system, the power demand is defined by the consumer (the load). If the power demand exceeds that authorised by the supplier's system, the system will overheat and the protective circuit breakers may shut it down.

There may be many reasons for such over-consumption: a technical fault in the HDV's power electronics, a steep incline (power demand could reach 400 kW on the steepest gradients for a loaded HDV), or an excessive number of HDVs in a segment.

The source will therefore need to be able to protect itself against over-consumption by the load(s), either by communicating with them, as is already the case for charging stations, or by providing protection against overvoltage or oversizing.

14. New technologies, other than the current Li-ion, look promising, such as solid electrolyte technologies, which could change the game in terms of charging time and linearity.

Figure 3: Load curves for different EV battery models. *Source: VW France.*



The induction system seems naturally well protected: the HDV spends little time on a loop or a set of loops sharing a common chopper.

Rail also appears to be protected for the same reasons. However, if power is supplied every 1.5 to 2 km, a protection system will have to be put in place to avoid the risk of over-consumption if the HDVs are too close together.

The catenary is the most open system: all HDVs present on the same segment will be able to draw as much power as they need, without any dialogue between source and consumers limiting the power demanded. The experiments will provide information on how to limit these risks.

This situation of over-consumption exists on trains or trams (power demand at start-up or excessive restitution to the network when the train or tram brakes and reinjects electricity), but the risk is reduced because the number of trains or trams on the same segment is limited by procedures linked to trainset operation. This will not be the case for heavy-duty vehicles.

Communication between HDVs and the infrastructure

As well as supplying electricity, the HDVs need to communicate with the infrastructure in order to fulfil two functions:

- identifying the HDV for billing purposes if billing is based on consumption. In the case of toll-related billing, this function is no longer important;
- for both rail and induction, ensuring that each segment or group of segments is powered up just before the vehicle arrives on it, leaving switching delays of a few tens of milliseconds.
  For reasons of safety and power consumption, it is not possible to keep the entire rail or the coils of the induction system permanently powered up.
  To give a few orders of magnitude, a vehicle travelling at 90 km/h will cover one metre in 40 ms. On the other hand, it can remain paired on the same cell for several minutes if there is a traffic jam. If the system powers up several cells simultaneously to be compatible with the speed of traffic, in the event of a traffic jam, it will have to adapt to reduced speeds and intervals between vehicles, so as not to power cells that would not be used or could present a risk to people or other vehicles above them.

Vehicle identification and vehicle-infrastructure dialogue are provided for in ISO 15118. However, this standard does not specify the physical communication channel (it provides for Wi-Fi, but it will be necessary to specify a variant or another protocol). In addition, it was designed, at least in the first versions, for contactless static charging (by induction); it will therefore be necessary to check that the authentication dialogue is possible at vehicle speed, taking into account the number of communications generated by heavy traffic.

Contractual and regulatory aspects of an open system

As long as the infrastructure is not reserved for a captive fleet (see chapter on deployment), free and fair access to this infrastructure must be ensured for the various national and foreign hauliers. The charging infrastructure operator, whether or not it is the motorway concession holder, will enjoy a de facto monopoly. The price of the service (distribution, billing) and the conditions under which it can be revised must be set out in the contract authorising operation.

Electricity will therefore form part of the service provided by the operator and will normally be included in the overall price of the service. Article L. 334-4 of the French Energy Code will have to be adapted to this service. This article currently states:
"*Electric and plug-in hybrid vehicle charging operators who source all their power, for the needs of their activity, from one or more suppliers of their choice who hold the authorisation provided for in article L. 333-1 are not carrying out the activity of purchasing electricity for resale to end consumers within the meaning of the same article L. 333-1, but rather the activity of providing a service.*"

This will be a global service, with the ERS operator responsible for finding the best electricity supplier to meet its obligations: overall cost of the service, energy from renewable sources, etc. In this case, the concession grantor will have to include in the concession contract the conditions for revising the prices of the service provided, based in particular on changes in electricity costs.

It will also be necessary to set up a roaming system enabling an HDV to use routes operated by several operators, with the latter ensuring that the HDV is effectively recognised and that they are paid for the service rendered, via a system of intermediary agents performing this function.

This is a system similar to the inter-company electronic toll system (TIS-PL). International telepayment operators are already well used to the system. Solutions to the problem of roaming charging therefore exist, but none have yet been defined. An organisation such as GIREVE[15] or equivalent could provide a good basis.

Alternatively, the electricity itself could be purchased by the haulier operating the HDV from the supplier of his choice. The operator would find itself in a situation similar to that of a distribution network operator, ensuring the distribution, metering and billing of electricity on behalf of the supplier, as ENEDIS does today in France.

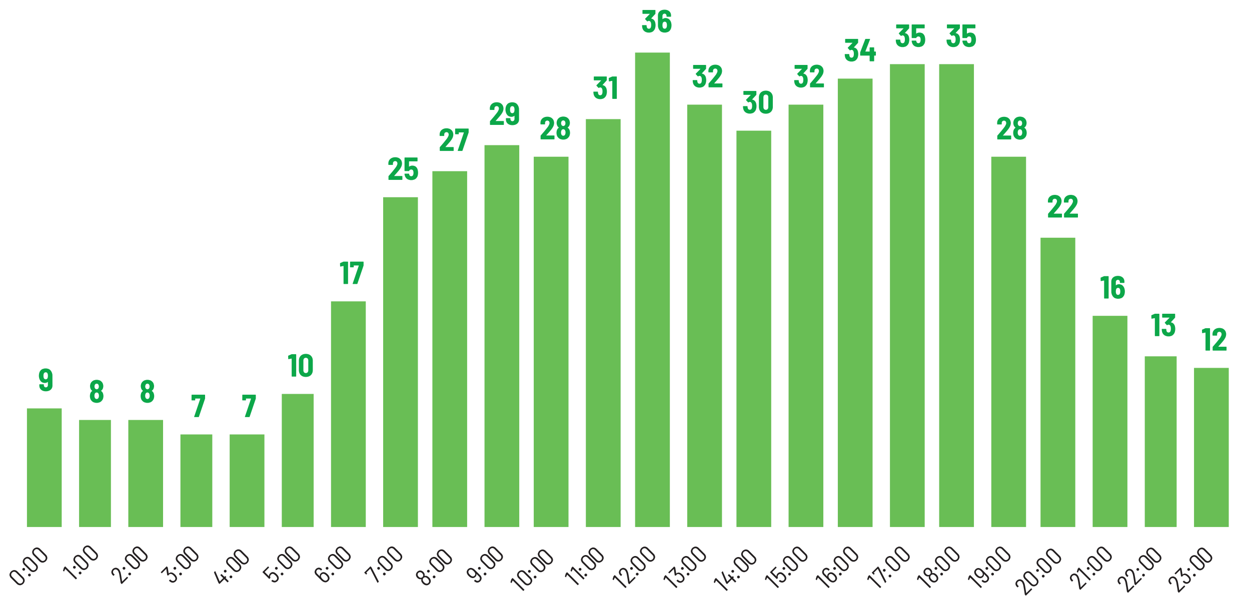
However, this solution seems more complex to implement:

- the operator would not know the subscriber directly but through the supplier, just as currently motorway companies do not know the HDVs directly but the suppliers of TIS-PL[16] subscriptions;
- it would require either the installation of an approved meter on the HDV, with the complexity associated with the supply and maintenance of an approved meter communicating with all the existing infrastructures and integrated into the electrical architecture of each HDV, or a meter for each segment or coil to measure the exact quantity of electricity consumed by each HDV. In the latter case, generating and processing millions of tickets is likely to be an expensive process compared to the value of each one;
- the infrastructure operator would become an electricity distributor in the same way as other distribution network operators (DNOs). This would require a change in regulations.

15. GIREVE is a digital platform bringing together a wide range of mobility players in Europe.
16. TIS-PL: "Télépéage inter-société poids lourds", inter-company electronic toll collection for HDVs.

Figure 4: HDVs entering a service area - Monday to Friday averages.

Source: Vinci Autoroutes.



Extraction profiles and impact on the network

Electricity is drawn from the grid throughout the day at the same time as the trucks are on the road.

It will not necessarily be more evenly spread than battery charging: figure 4 shows that HDV arrivals at motorway service areas are fairly evenly spread throughout the day. This does not necessarily mean that charging at the stations will be as evenly distributed, but it does give an indication of what it could be.

For the ERS, in the event of a critical situation, conceivable solutions include localised load shedding, temporarily limiting the speed of HDVs or reducing the amount of power supplied for a few tens of kilometres or a few tens of minutes by relying on battery capacity, but beyond that, it seems difficult without running the risk of HDVs running out of battery power along the motorway and at rest areas.

It should be noted that:

- for battery-powered HDVs, reducing the electricity supply would have an immediate impact on journey times and could be unpopular with hauliers;
- on the other hand, electrolysis for hydrogen production can be interrupted to meet peak demand, with a storage system ensuring continuity of distribution.

Extra cost of equipping vehicles

Each of the three technologies requires vehicles to be fitted with a number of items of equipment:

- a collection system (pantographs, collectors or induction coils). This equipment also includes an insertion/retraction mechanism that must be particularly reliable to retract when approaching any obstacle for catenaries or when there is no more rail for the collectors;
- a sufficiently precise lane-holding system;
- a power electronics system.

Assessment of the additional costs is still approximate, especially as no economies of scale have been evaluated at this stage. The figures provided by the companies designing the infrastructure range from €20-30k per vehicle. These values are probably overestimates: the cost of equipment for certain prototypes is already lower for induction. Rail will undoubtedly be cheaper as soon as it becomes industrialised. In the section on the economic aspects of the ERS, we assume an additional cost of €15k per vehicle for rail and induction and €20k for catenary, for the strengthening of the cab that is required.

The issue of HDV equipment is crucial to the deployment of the ERS in Europe. HDV roaming throughout Europe will be a key factor in guiding the decisions of the European Commission and investors alike.

Equipping HDVs with two systems would allow two technologies to be deployed in Europe, avoiding the need to choose a single option. In principle, catenary and rail solutions could share the same power electronics.

Savings on batteries and material requirements

The main promise of the electric road is that vehicles can be charged while on the road, saving on battery costs.

Assuming a minimum range of 250 km, compared with 700 km for international HDVs, based on the assumptions made in the EdEn study on hydrogen, the battery capacity required falls from 750[17] kWh to 375 kWh, representing a weight saving of 1,500 kg by 2030 and CapEx saving of around €31k[18]. The net saving is therefore at least €11k to €16k, depending on the range of HDV equipment costs for the ERS. This does not take into account the additional weight savings on the structure of the HDV, which no longer needs to support the extra 1.5 tonnes, nor the associated savings in fuel consumption.

Similarly, the quantity of materials (copper, lithium, nickel) would be reduced by 50%, i.e. a saving of 26,000 tonnes of copper on the French HDV fleet, taking into account a penetration rate of 80% in 2050, a quantity of copper of 9% per battery and a French long-distance HDV fleet of 243,000 units.

Compare this figure with the 60,000 to 100,000 tonnes of copper needed to equip 80% of France's 12,500 km of motorways with the induction system, which uses the most copper. Although the savings on batteries do not fully cover requirements, they are not negligible and the total quantity of copper required remains relatively modest compared with the 170,000 tonnes of copper consumed in France each year (see below).

Rail solutions

General overview

The principle of the rail-based solution is to power the vehicle from a conductive rail cut into small segments that are individually powered as the vehicle passes over them.

Several solutions are currently being developed: one with power supply on the side of the track, promoted by Honda in Japan, and solutions with one or two rails at road level. This study only considers the solution at road level, as the authors felt that the lateral power supply solution posed too many safety and complexity problems: distance from the hard shoulder, presence of an obstacle on the hard shoulder, etc.

Several variants are currently being tested:

1 **A solution developed by Elways has been tested in the eRoadArlanda project[19].** The main feature is that the rail has two grooves corresponding to the electrical plus and minus (Figure 5 and photo 1). There is no need to segment the rail as in the Elonroad solution described below. However, the system is sensitive to the presence of foreign bodies (gravel, etc.) in the grooves. This means the rail needs regular cleaning, and this difficulty does not seem to have been overcome. Furthermore, the shape of the grooves probably makes the system fairly sensitive to sudden changes in direction.

2 **The solution developed by Alstom** is derived from its experience in tramways, but modernised with the use of electronic switching to power the rails. This is done using two parallel conductive rails cut into 11-metre segments. The rails are installed flush with the road so as not to create any raised areas or ruts, however slight (photo 2).

The Alstom solution is based on an electrical substation every kilometre with a 20 kV loop, a 750 VDC power supply and distributed power of up to 6 MW.

17. The initial study on hydrogen took into account 1 MWh of batteries for long-distance HDVs. The roll-out of charging stations along motorways will lead to a reduction in this capacity as soon as the ERS starts to be rolled out.
18. The assumptions used in the EdEn study are a capacity of 750 kWh for the batteries of a long-distance HDV, with a cost of €82/kWh in 2030. Energy density is estimated at 250 Wh/kg by this date (source: Wikipedia).
19. https://www.ncc.com/about-ncc/about-the-group/other-brands/e-road-arlanda/

Figure 5: Cross-section of a road equipped with Elways double rail. These rails are powered from low-voltage cables that ensure rapid switching between segments. The low-voltage cables are themselves powered from the high-voltage cable. *Source: Elways.*

Photo 1: Elways rail fitted to the Arlanda e-Road pilot project in Sweden. *Source: Elways.*

Photo 2: Alstom system with double rail integrated into the road. *Source: Alstom*

Monitoring the effects of climate | Monitoring the effects of winter maintenance operations | Snow clearing and salting operation

Photo 3: Tests in winter conditions. *Source: Alstom*

Tests were carried out on a 50-metre track at the French Institute for Transport, Planning and Networks Science and Technology (Ifsttar)[20] for tests on dry and wet tracks and on a 20-metre test track in the Vosges at an altitude of 850 m to test winter conditions, including the impact of current leakage when the road has been salted (photo 3).

Power is supplied every 22 metres to the 11-metre segments.

Each segment is powered only when the vehicle runs over it, via radio communication between the vehicle and the infrastructure. Power is only supplied above 30 km/h. Below this speed, the truck is powered by its batteries.

The rail is 5 cm wide and the cast-iron collector is guided to stay on it.

The Alstom solution is currently being standardised by CEN/CENELEC in TC 9X, whose WG 30 is working on standardisation for ground power systems.

A Technical Specification (TS 50717)[21] has been published for collectors and there will shortly be a "*new work item proposal*" for infrastructure standardisation.

3 **In the solution developed by Elonroad**[22], the rail is single, flat and made up of consecutive one-metre-long segments separated by an insulating joint (photo 4). The rail is installed at road level. The power electronics are fitted into the rail. At each segment, a radio system detects the arrival of the vehicle to power up the rail and collect the information needed for billing.

For safety reasons, the segment is powered only when the vehicle passes, which requires real-time vehicle/rail communication and fast switching times: at 90 km/h, a vehicle takes 40 milliseconds to cover one metre.

The supply voltage is between 800 and 1,000 V.

The vehicle is fitted with at least three collectors. The three collectors ensure an uninterrupted feed even when one of the collectors is on the non-powered zone between two segments. The first collector is also used to sweep the rail. The conductive segments are spaced one metre apart and located one behind the other on the rail. To ensure the return path, the segments are alternately supplied with + and -. At all times, one of the collector collectors is in contact with a segment supplied with positive current, while the other collector is in contact with a segment supplied with negative current (Figure 6).

20. *Ifsttar: Institut français des sciences et technologies des transports, de l'aménagement et des réseaux (French Institute for Transport, Planning and Networks Science and Technology)*
21. *TS 50717:2022 Technical Requirements for Current Collectors for ground-level feeding system on road vehicles in operation. It should be remembered that a TS is a normative document which is not binding on the Member States. A TS can coexist with other solutions and does not prevent the existence of national standards. A TS may evolve into a European Standard (EN) that is binding on the Member States.*
22. *Elonroad is a Swedish start-up which has been chosen by the Swedish government to develop a pilot project in the city of Lund (photo 5). https://elonroad.com/*

A vehicle requiring more power than a segment pair can deliver, such as a tractor, will have several sets of two collectors spread over a greater length.

The manufacturer has announced a power output of 200 kW per segment pair, with plans to increase this to 300 kW and then 350/400 kW for a truck.

The segments are assembled in 10-metre-long modules laid in a trench in the middle of the track. The modules are clipped together, ensuring that the power supply is transmitted from one module to another over a distance of 1.5 km. Every 1.5 km, a lateral feeder supplies low voltage from a transformer located alongside the motorway. Elonroad says it should be possible to increase this distance to 3 km at a later date.

This point will have to be checked as traffic increases, because the cable in the rail will be low voltage and will not carry 2 or 3 MW (see above) over 2 or 3 km.

Maintenance will be carried out on systems positioned along the road (transformers and DC power supply systems) and on those positioned in the rail. Elonroad points out that the 10-metre modules can be dismantled relatively easily, so that only the faulty module needs to be serviced. This will still be an onerous operation, however, and identifying the faulty module over sections of 1.5 km can be complex

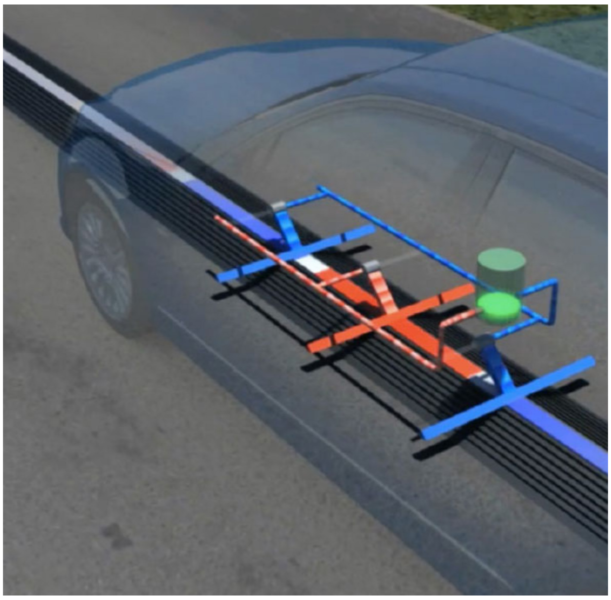


Figure 6: Schematic diagram of the Elonroad system. Two collectors alternately take the plus and minus on the rail.

© Elonroad.

if the appropriate tools have not been developed in advance. It should be noted that, in this solution, active elements are included in the rail and are therefore difficult to access. This category includes power switches for each pair of 1-metre segments and beacons for detecting and communicating with heavy-duty vehicles.

One of the issues to be monitored will be the system's tolerance to the failure of one of the segments, as well as the ease of identifying the equipment that has failed. A breakdown of a few segments between two maintenance operations, requiring traffic to be interrupted, would be acceptable, but a breakdown over a kilometre and a half would be less so.

Note: the solution developed by Elonroad is part of one of the projects proposed in response to the call for projects issued in 2022 by ADEME.

The advantages of the rail solution

- Rail can be used to transfer large amounts of power, in the range of several hundred kW, relatively easily. It is compatible with the operation of heavy-duty vehicles, even when fully loaded.
- Wear is relatively low, limited to the rail itself, which can be replaced, in the case of the Elonroad solution, without having to change the entire system. However, the choice of material (aluminium for Elonroad, steel for Alstom) will require long-term testing in real-life conditions to ensure its durability.
- Collector wear will also have to be measured in real-life conditions, even though they will be easier to replace.
- The system can be used in static mode to charge stationary vehicles at delivery bays or depots. This means that light commercial vehicles and delivery lorries can also be fitted. Even if they only use motorway charging occasionally, this would lead to a fall in equipment prices and contribute to the system's widespread adoption.
- It can also be used on light vehicles: the level of power transmitted far exceeds the needs of an SUV. When driving in the same lane as trucks (i.e. at 90 km/h), the 200 or 300 kW available are far in excess of the 20 to 30 kW required at that speed. Private vehicles that are equipped could therefore recharge by occasionally driving on the HDV lane.

Photo 5: A 1 km trial of the Elonroad solution in Lund (Sweden).

Source: Elonroad.

- On the other hand, home charging with two live bare conductors would require particular attention to safety and feasibility remains uncertain.

The drawbacks of the rail solution

- Laying the rail is "fairly easy" on asphalt roads. The solution developed by Elonroad and others can be installed by simply digging a trench of the width of the rail in the road, with transverse trenches every 1.5 km to power the system. On existing concrete roads, as is the case in some European countries, installation will require digging a trench. The complexity will depend on the width of the system and the depth to be cut, but the problem, which is often mentioned, does not seem insurmountable.
- Refurbishing the motorway's surface course, a process carried out every 15 years or so, is complex: the road has to be planed on both sides of the rail, or else the feeder rail would have to be removed. This is considered to be a major point in terms of

the cost of maintaining the motorway with rail, and could account for a significant proportion of the investment required each time the road is resurfaced. Another point to be considered is the layers below the surface course, as these are also periodically resurfaced, but over a longer period (around 30 years).

- **The risk for users, particularly motorbikes**: the rail can be slippery and will necessarily be relatively wide (8 to 10 cm). Its link with the rest of the road will not be perfectly flush. It will deteriorate over time and local differences in levels may appear, presenting an accident risk, depending on the performance of the road and the sealing materials for all users and even more so for two-wheelers.
- **The rail will not work in snowy conditions**, at least not until the road has been completely cleared. However, HDVs should have sufficient range to pass through a snow-covered area, especially as they will be travelling well below 90 km/h in these snowy conditions.
- The system's resistance to winter conditions, and in particular its resistance to salting, needs to be validated: current leaks when the snow turns to brine, but also chemical corrosion of the rail over the long term.
- Another unknown factor is resistance to extreme weather conditions, such as flooding, especially as, in the Elonroad solution, the sections between two feeders are 1.5 km long and made up of 10-metre rails laid end to end. The system's resistance to flooding remains to be tested over time, and a fault detection system will be needed to quickly identify which rail is faulty in the event of an incident.
- As with other Electric Road Systems, the tolerance of lateral positioning deviations needs to be checked. Both collectors must remain in contact with a flat rail at road level, around 8 to 10 cm wide. The geometry of the system lowering the collector must allow for some lateral positioning deviations. Some manufacturers claim a tolerance of around twenty centimetres. This system will benefit from driver assistance equipment, with precise automatic lane-keeping due to arrive in the near future on new vehicles.

These reservations are significant, but there are solutions, although they still need validation.

Readiness level of rail solution

Tests were carried out in Sweden over several years with the Elonroad solution, in parallel with tests on the Elways solution. At the time of writing, this is the only solution incorporating a flat rail that has been tested under real conditions on an open road. On 15 November 2022, the Swedish government launched a call for tenders to equip 21 km of the E20 motorway between Hallsberg, Kumla and Örebro with an ERS solution. This call for tenders is not specific to rail.

In France, track tests have been carried out. A number of applications have been submitted by consortia bringing together different types of manufacturers, including motorway operators, as part of a call for projects that is not specific to rail but to all ERS solutions. The projects selected in July 2023 are described in the appendix.

Another version of Elonroad's system is also being marketed for static charging.

The trials carried out to date have demonstrated the technical feasibility of the system. The power transmitted for the Elonroad solution is currently 200 kW for trucks travelling at 80 km/h. Tests scheduled for 2023 should enable trucks to reach 100 km/h with 300 kW of power.

The forthcoming tests should make it possible to verify the viability of commercial operation, under real conditions, over a period of several years: road performance, resistance of the rail to wear, flooding and extreme weather conditions, validation of the level of power to be delivered, performance of the collection systems, vehicle grip and road safety, etc.

Particular attention will be paid to the tests planned by French motorway operators on the danger to motorbikes.

On the TRL scale (see appendix 4), the rail system can be assessed at level 7: "*Demonstration of the prototype system in an operational environment*". Open road and real-life tests have enabled this level to be qualified, in particular for the Elonroad solution, but the results of experiments with a significant number of heavy-duty vehicles over time are still needed to qualify the system for level 8.

The catenary solution

In this solution, often called OCL (*Overhead Contact Line*), power is supplied by two parallel catenaries suspended above the HDVs. A double pantograph provides the electrical connection. The spacing of the catenaries is chosen to avoid any risk of short-circuit (photo 6).

The system is quite similar to that of a tramway, with supply voltages of between 600 and 800 V.

The length of each segment is determined by the number of HDVs that can feed into it (beyond that, there would be a drop in voltage) and also by the resistance of the cables and the expected voltage drop. It can reach several kilometres.

Unlike a tramway, the HDV does not have to be started up, and it also has built-in batteries, so there is no need to draw starting current. For the record, this can be up to six times the rated current. In the event of a traffic jam or circuit failure, the HDV is powered by its battery, which is also used to restart the vehicle. The pantograph has to retract automatically, so that it can pass through tunnels or under low bridges.

The cost of equipping the truck is around €30k. In this study, we have assumed that it could be reduced to €20k.

The advantages of the catenary solution

- The solution is simple, requiring no complex electronics or dialogue between the infrastructure and the vehicle, just powering up the system as the HDV passes, with rapid switching. The catenary presents no danger to anyone walking on the motorway.
- A system with catenaries enables the transfer of significant power, limited by the electrical voltage on the cable and the length of the sections, which can be several kilometres long. The spacing between substations depends solely on the number of HDVs that will be following each other on the same stretch of road.
- From a technical point of view, the solution is virtually mature and has been tested for many years in Germany, Sweden and the United States. Trains and tramways have been using catenaries for decades.
- As all the equipment is overhead, the system is compatible with existing roads, including concrete ones. In addition, repairs and interventions will be simpler than with systems integrated into the road, at least at road level. There will be no impact on the road surface and less disruption to road repair, provided that the machines can pass underneath.

The drawbacks of the catenary solution

- **The rail experience cannot be directly transposed to the ERS**: train or tramway traffic is one or two orders of magnitude lower than traffic on a busy motorway. For instance, on the Vienne-Valence section, there are more than 5,000 long-distance HDVs a day, far more than the hundred or so high-speed trains or even suburban trains that operate daily. Wear and maintenance will be much more important.
- **HDVs are not all maintained with the same care, nor are they as calibrated as trains, and the road is not as flat as a railway.** The risk of catenary wrenching will be greater than on rail, and given the volume of traffic, this will happen at regular intervals. If a catenary is wrenched off, the track or even the direction of traffic will have to be closed for at least several hours.
- It will be impossible to refuse electricity to an unidentified HDV: you can't cut power to the catenary because an unidentified HDV connects to it without also cutting power to the other HDVs. A flat-rate charge therefore needs to be considered for all HDVs equipped and/or included in the toll fee.
- The system is sensitive to bad weather: snow and storms. The Enedis and SNCF networks are good examples of how sensitive networks are to regular storms and snowfalls. Almost every year, sections of motorway will be unusable for several days for HDVs equipped with the system, because the system will have been wrenched away by a storm or will have collapsed under snow.
- It will be impossible for civil protection helicopters to land on the motorway to evacuate the seriously injured. Similarly, the catenaries will make it very difficult to lift lorries lying on their sides with cranes. **This last point is considered as a major blocking factor by motorway operators** who have to deal

Photo 6: Hybrid HDV on the eHighway near Darmstadt (Germany). *Source: Siemens.*

with this type of situation around once a week. The first point is also critical: evacuation by helicopter happens several times a year on the motorways, due to motorway and secondary network congestion, preventing evacuation by road. **With the catenary solution not allowing this type of evacuation, it may have to be ruled out as an option.**

- The system will be reserved exclusively for HDVs over 26 tonnes, which can connect to a catenary that is 4.6 to 5.4 m above the road. For height reasons, it will obviously not be possible to install the system on vans or small lorries, and even less so on private vehicles.
- Installing a pantograph requires the cab to be reinforced and lengthened: it has to impose a certain amount of pressure on the catenary, and existing cabs are not sufficiently reinforced to withstand this pressure.
- The poles supporting the catenaries are located along the tracks, whereas for safety purposes, the aim is to clear the road verges of any obstacles that might increase the risk in the event of an accident. They will have to be protected by concrete guardrails, which will increase CapEx by around €225k per kilometre and per direction of traffic.
- Lastly, another objection that could be raised is that catenaries damage the landscape and birdlife.

Readiness level of catenary solution

The catenary system is the most mature from a purely technological perspective. It is the system that has been tested the most, and for several years: in Germany with six different tests, in Los Angeles (SoCal) and in Sweden. But these tests are unit tests and do not provide information on how the system will behave in commercial operation. The system still needs to be qualified in real traffic, with vehicles of very different configurations. That said, the tests carried out showed that it was compatible with weather conditions and with a motorway's operation.

On the TRL scale (see appendix 4), the catenary system can be assessed at level 7: "*Demonstration of the prototype system in an operational environment*". Open road and real-life tests have made it possible to confirm the system has reached this level, but only over time, with experiments with a significant number of heavy-duty vehicles using this system, can it be confirmed as having reached level 8.

The induction solution

The principle of the induction road (*In-Road Inductive Charging System*) consists of transferring energy in the form of a variable electromagnetic field emitted from one or several coils inserted in the ground to one or more coils located under the vehicle chassis.

The concept and experiments are not new: KAIST (*Korea Advanced Institute of Science and Technology*), for example, has been running a full-scale experiment in a park in Seoul since 2011, as well as using buses on a specific route (Figure 7). The development of this technology is accelerating, however, both for static vehicle charging and for charging while on the move, because of the advantages it offers, first and foremost the fact that the charging device, catenaries and pantographs or collectors, are no longer needed.

Static induction and dynamic induction

The first application of induction is static charging of vehicles (private or commercial) at home, at the depot or at stops during journeys (red lights, bus stops), to do away with the need to connect a cable.

It works much like wireless mobile phone charging: the vehicle is fitted with a coil that acts as a receiving antenna and is parked on another coil that acts as a transmitting antenna. This antenna does not have to be buried and can be inserted into a special pad placed on the ground. The two antennae are tuned to the same resonance frequency and power is transmitted in the so-called "near field", where the magnetic field is dominant, giving good transmission efficiency if the transmitter and receiver remain close together.

This technology is attracting a lot of attention, and companies such as WiTricity[23] are offering pilot induction charging solutions that can be retrofitted to existing vehicles, whether passenger cars, buses or delivery fleets.

The technology is well mastered in a static environment and presents no particular difficulties apart from the electromagnetic risk (see below). The main benefit is that a cable is no longer needed for charging, and this is a feature much appreciated by users.

Charging while driving is a more complex problem, as the vehicle has to be charged while it is in motion. The difficulty is much greater, if only because the vehicle remains above the buried coil for very little time (40 ms for a coil 1 m in diameter at 90 km/h).

Figure 7: Tourist train charged by induction while running in a park in Seoul – KAIST.

23. Witricity (www.witricity.com) is an MIT spin-off created by Professor Marin Soljačić, author of a wireless energy transmission experiment in 2007 demonstrating the ability to light a 60 W light bulb, from an electrical source approximately two metres away, with 40% efficiency. See: https://www.science.org/doi/10.1126/science.1143254?cookieSet=1

Dynamic induction: general principles

Several solutions are currently being developed: the solution developed by KAIST, the one developed by the VEDECOM institute for energy transition, the solution developed by Electreon[24], not forgetting the work being done by ASPIRE and the Oak Ridge National Lab. In the remainder of this study, we will concentrate on Electreon's solution, but the other solutions are based on similar principles (Figure 8).

Power transferred: frequencies used

The system developed by Electreon uses a frequency of 85 kHz with a 400 V power supply, which is due to be upgraded to 1 kV in the near future. The transmission rate indicated by Electreon is 90% for static charging and 85% for dynamic charging, in good alignment conditions. To these values must be added losses in electronic systems.

The power transmitted by each coil is 25 kW, rising to 35 kW in the near future. This could rise to 80 kW by around 2024.

This is the main weakness of this technology: in order to comfortably reach 200 kW or even 250 kW, at least six or seven 35 kW coils or three 80 kW coils are needed, assuming optimal alignment and a transfer rate of 100% or close to 100%.

The coils have to be installed under the tractor unit, which limits their number to four or five. Equipping trailers should not be ruled out, but this would pose a number of difficulties: a significant additional cost, as all trailers likely to be hooked up to a tractor unit using the ERS would have to be equipped, and also risks in terms of operation with a cut-off point between the tractor unit and the trailer.

Induction system architecture

Operating at 85 kHz means that the distance between the chopper producing the high-frequency current and the transmitting antenna is relatively short, a maximum of a few dozen metres.

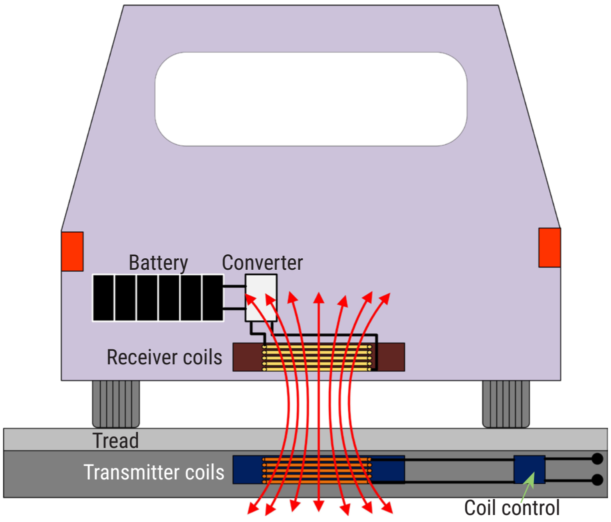


Figure 8: Schematic diagram of an induction charging system for electric vehicles.

Source: Authors.

The Electreon solution uses 1.70 m coils and management units at 40 metre intervals.

The solutions studied combine a chopper with around sixty coils. The chopper is supplied with low voltage. Power is transferred to the coils as the truck moves forward.

Risks specific to the induction system

The main risk is that of electromagnetic waves, for passengers in the vehicle or people in the vicinity, in a traffic jam or during static charging, but it is important to remember that transmission takes place in the near electromagnetic field, where the dominant magnetic component remains strongly directional. The vehicle's metal floor is deemed to be sufficient to prevent excessive exposure of passengers to the magnetic field.

The data supplied by the various manufacturers indicates a residual value right next to the vehicle of around one microtesla, well below the limit value of 6.25 microteslas set as the reference level by French decree no. 2002-775 of 3 May 2002 for the frequency range from 3 to 150 kHz. However, the thresholds set by this decree, which are consistent with European rules and WHO recommendations, are considered too lax by some organisations, meaning that great attention should be paid to this issue.

24. Electreon (https://electreon.com/) is an Israeli company founded in 2013.

Another point to be checked is possible interference with on-board vehicle systems.

Development areas

The main area for development is to increase the power transmitted, while respecting public health rules: if there is no significant progress in this area, the power transmitted will be insufficient for long-haul HDVs.

The second area for development could be to replace copper by aluminium for underground coils. Some players have indicated that they are working on this development, but without giving any further details. Considering the very specific properties of aluminium, this possibility seems rather unlikely.

The advantages of the induction system

- A solution suitable for all types of vehicles: the system can be adapted to light commercial vehicles and private cars, which will accelerate the amortisation of the infrastructure and increase the range of electric vehicles. The induction road would therefore offer a low-carbon alternative to rechargeable hybrid vehicles and enable any electric vehicle, including small urban vehicles with small batteries and limited charging power, to cover long distances.
- The momentum is positive, with a great deal of research and development taking place around the world, particularly in the United States, where several laboratories are working with start-ups and manufacturers and are receiving support under Biden's Inflation Reduction Act.
- Equipping private vehicles would go hand in hand with the development of static, wireless charging at home, at companies or at specially equipped sites.
- Relatively easy maintenance: in the solutions studied, the active equipment is accessible and located off the road. Only passive antennas are buried.
- No impact for non-equipped vehicles and no risk for other motorway users. As no equipment is visible on the road or installed overhead, this solution will not change anything for motorway users.
- The antennae are integrated under the surface course and therefore present no obstacle to its refurbishment. However, when the surface course is renewed every 24 years or so, the antennae will be removed when the layer is planed and the copper recycled.

The drawbacks of the induction solution

- This technology uses a lot of copper, and currently the part used in the coils cannot be replaced by aluminium or any other conductor. For the DGITM study, Electreon reported a consumption of 5.1 tonnes of copper per kilometre of motorway and per direction of traffic, broken down as follows:
  - 600 kg for substations;
  - 2,500 kg for the side power supply, much of which could probably be replaced by aluminium;
  - 2,000 kg for induction coils, for which there is currently no substitute material.

  This would require around 100,000 tonnes of copper to equip 80% of the 12,500 km of motorway in France, or 5,000 t/year if the equipment is installed over 20 years. By way of comparison, 172,400 tonnes of copper was consumed in France in 2020[25]. This is therefore not a major problem, especially as the copper would not disappear and would be recycled when the road is repaved. To this consumption must be subtracted the savings in copper, nickel and other materials under tension that could be saved in batteries. Copper savings are estimated at 26,000 t for copper alone (see above).
- Impact on road structure. The transmitter windings are buried under the surface course. They will give off heat that will be dissipated in the road itself. The long-term performance of the road remains to be verified, particularly in the context of global warming and increasingly frequent heatwaves: a road exposed to full sun in summer, in which the induction coils heat up due to heavy-duty vehicle traffic and which is at the same time subjected to the impact of wheels, could deteriorate rapidly. Experiments will shed more light on this issue.

25. Source: https://lelementarium.fr/element-fiche/cuivre/

- This technology does not seem very compatible with existing concrete roads, and its installation involves major roadworks, more so than for rail: lateral connections to the power electronics installed along the road, on the other side of the safety barriers, are required every 100 metres or less.
- However, it seems easier to implement on concrete roads under construction, which would lock the coil in place and better dissipate the heat released.
- The power transmitted is still too limited and, furthermore, losses in energy transfer have to be taken into account. Data, which is probably optimistic, gives an energy transfer rate of between 80 and 90%. At 35 kW per coil, six or seven receiver antennae are needed to recover the 200 or 250 kW considered necessary to ensure the system's viability. This could mean having to equip the trailer as well, adding a new level of complexity and cost to the system, and insofar as it is possible.

  Work is under way to address this issue.
- The vehicle must remain well in line for the cells to be superimposed. The constraint is estimated to be intermediate between that of catenary and that of rail. Electreon specifies a lateral tolerance of ± 25 cm.
- Finally, the problem of public health and electromagnetic compatibility (EMC) with on-board equipment must be anticipated, as it is likely that the technology's development will raise questions that could lead to rejection.

Readiness level of induction solution

Tests have been carried out or are under way in Sweden, under normal traffic conditions on open roads, in France, Dubai, Germany, Israel, Italy, the United States and South Korea, but using different technologies (Electreon, VEDECOM, OLEV/KAIST, etc.).

These trials demonstrated the technical feasibility of the solution. **However, the issue of power transmission has not been resolved and progress is needed.**

Forthcoming trials should make it possible to verify its performance in real-life conditions: impact on the road, real transfer rate, validation of the power required, etc.

On the TRL scale (see appendix 4), the induction system can be assessed at level 6: "*Demonstration of the system/sub-system model or prototype in a significant environment*".

Real-life operational tests on open roads are still needed to take the system to a higher level. A marketable solution is therefore still a long way off.

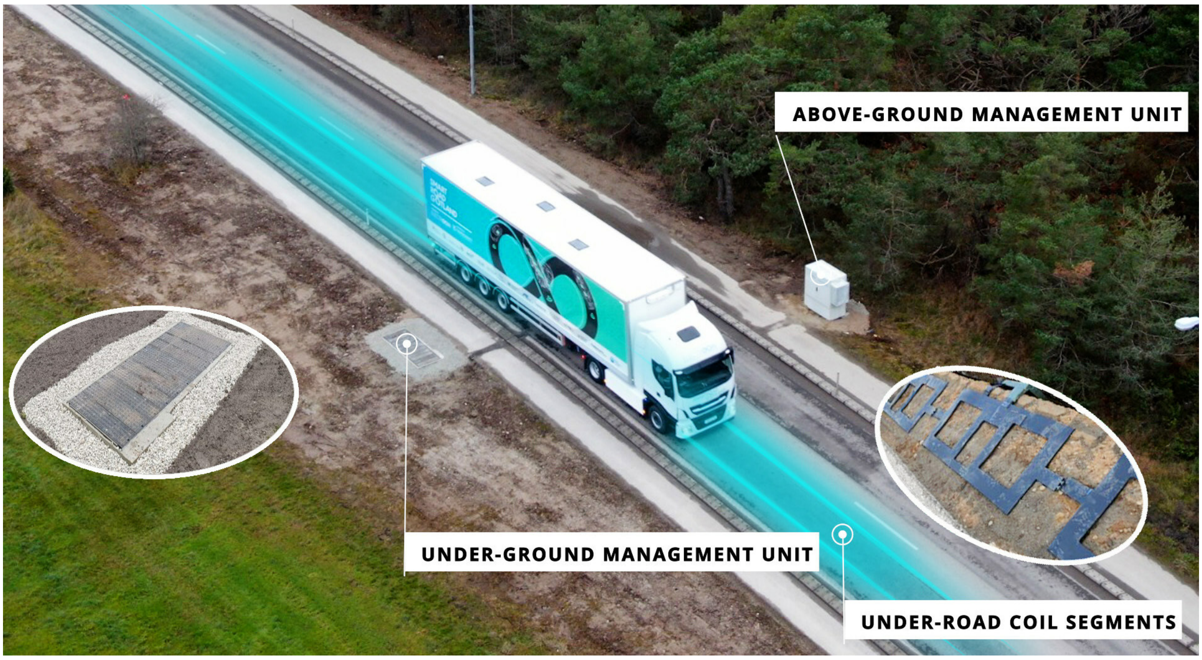


Photo 7: Overview of the Electreon system. This system will be tested as part of a trial conducted with Vinci with the support of BPI France (see appendix 3). *Source: Electreon.*

3

Economic aspects: comparisons with battery and hydrogen solutions

Based on information gathered from solution designers and information provided by other companies in the ecosystem (road builders, energy utilities, etc.), EdEn has calculated the cost price of an Electric Road System using traffic data available on the A7/A9 motorway sections and already used in its October 2021 study on the use of hydrogen by heavy-duty vehicles.

In this study, EdEn showed that hydrogen infrastructure could be rolled out gradually, with refuelling stations initially widely spaced, then a densification of the distribution network coupled with a replacement of simple distribution points by production stations.

Rolling out the Electric Road System will not be as gradual a process, although some flexibility will be possible. Once HDV batteries have been designed to adapt to the ERS, the spacing between equipped sections will have to be limited. However, a deployment scenario by section (and by local and captive fleets) seems possible, starting with the priority sections.

Economic assumptions on initial costs and maintenance costs

Table 3 summarises the infrastructure costs (CapEx) required by each solution, in millions of euros per km equipped for one direction of traffic and using the following set of assumptions.

Rail

The system is a mixed one, with a large passive infrastructure that is subject to wear and tear, but also substantial power electronics to power the segments as the HDV arrives.

Maintenance is estimated at 10% to take account of the additional cost of resurfacing the road every 15 years.

Catenaries

The cost of maintaining the passive infrastructure represents the largest part, both because of wear and tear on the catenaries caused by traffic and also to take account of damage caused by poorly maintained or badly adjusted lorries, an uneven road and climatic variations.

The cost of the installation work includes the creation of concrete safety barriers all along the poles supporting the catenaries, i.e. €225k/km for each direction, as well as secure access areas estimated at €50k every 2 km.

Induction

The power electronics include the choppers, estimated at €85k, the switching system for transmitting power to the coils and the vehicle/infrastructure communication system for detecting vehicles when they arrive at the coil or group of coils. The passive infrastructure includes the induction coils, ferrite and connection cables. Maintenance only covers the electronics, as the loss of a coil or group of coils for one reason or another will not compromise the service and there is no economic interest in opening up the road to replace it.

Motorway equipment rate

The motorway equipment rate (ratio of km equipped/ total km) was set at 70%. This reflects the fact that in some places, the cost or time required to connect to the distribution network would be prohibitive, and it would be better not to equip this section.

Assuming that the maximum power transmitted in equipped areas is 300 kW, when the vehicle is on an equipped section – the feasibility for induction not yet being certain – this means that, given the 70% equipment rate, the average power transmitted over the whole route is 210 kW, or just 60 kW more than the consumption of a heavy-duty vehicle at 90 km/h on a flat road. This ensures that batteries are charged over long distances, but not for vehicles making regional journeys.

Ramping up

The model chosen is based on a single traffic lane in each direction. On the sections where traffic will be heaviest, it will undoubtedly be necessary to equip two sections in the second part of the concession, especially if the ERS also equips regional vehicles and light vehicles: on the Valence-Orange section, at rush hour, there will be more than ten long-haul HDVs per km.

Connection to the electricity grid

To simplify the calculations, the model assumes a standard distance between two connections, independent of traffic, so as to ensure an average peak-hour withdrawal of 20 MW per connection point. The average distance between two connection points is therefore 11 km, but would vary in practice between 6 km and 50 km depending on the section, and the density of connections would be adjusted progressively in line with traffic growth.

These costs are significantly lower than those in the DIGTM report. They were provided to the authors by the manufacturers who designed the solutions.

The costs of peripheral equipment, such as the electricity distribution network or the presence or absence of concrete safety barriers, are of the same order of magnitude as for the main system. For example, concrete safety barriers are considered essential in France if the motorway is equipped with catenaries, but this is not the case everywhere. Experimentation and the regulations specific to each country will decide.

Costs are set to fall as systems mature and competition between players increases, while full-scale trials may bring to light elements that have not yet been considered.

At this stage, it is the order of magnitude that is of interest in assessing the feasibility of solutions.

Table 3: Infrastructure costs per km of motorway, for one direction of traffic and for each technology.

in €k/km	Induction		Catenaries		Rail	
	CapEx	Maintenance	CapEx	Maintenance	CapEx	Maintenance
Passive infrastructure (induction loops - catenary - rail)	150	5%	250	15%	150	10%
Electronics/Active equipment	500	5%	50	5%	150	10%
Installation work (including concrete guardrails)	150	-	425	-	150	-
Medium-voltage network	250	5%	250	5%	250	5%
Total (€k/km)	**1,050**		**1,025**		**700**	

Financing assumptions

General conditions

The financing calculation was based on the assumption of a concession-type financial structure with private financing.

The risk associated with uncertainties over the ramp-up of traffic and the technology's readiness means that the internal rate of return (IRR) demanded by investors is estimated at around 15%. The cost of debt, excluding inflation, is estimated at 5% and the split between equity and debt at 50% each. As a result, an average financing rate of 10% has been used in the depreciation calculations.

These values do not include any subsidies that may be granted by the public authorities to speed up deployment of the technology. A mix of installation subsidies and subsidies for HDV equipment would not only reduce the cost of the infrastructure but also reduce the uncertainty surrounding the increase in HDV traffic.

In the EdEn study on hydrogen, the financing rate was set at 4.5%, given the greater maturity of this solution, the action taken by the public authorities to facilitate the deployment of hydrogen and the announced obligation to install a hydrogen station every 150 km on the Trans-European Transport Network (TEN-T).

The financial model remains an approximation. No account has been taken of investors' demands for dividend payments in the early years or of the equity/quasi-equity/debt structure.

Public-private partnership (PPP) financing would greatly reduce the cost per kilometre.

Depreciation period

The model uses two accounting depreciation periods, aligned with the useful life of the equipment:

- 15 years for active equipment and road surface equipment.

  This duration corresponds roughly to that of the electronics and the road's surface course. The cost of replacing the electronics was assumed to be the same as the initial cost. With a constant function, the cost of electronics falls, but it is generally observed that new functions lead to costs being stable.
- 30 years for the structural layer of the road, such as induction coils, catenaries or rail power supplies. In the case of induction, as the coils are installed under the surface course, they will only be replaced when the structural layer is repaired. This includes equipment and networks located on the road shoulder: concrete safety barriers to protect catenary poles, concrete blocks for catenary poles, HV power supply network, etc.

  For rail, the question remains open, as it depends on whether the surface course can be refurbished without removing the rail, or whether it can be planed and the new surface course poured alongside it. The rail may have to be removed and reinstalled each time the surface course is refurbished.

  Extending the depreciation period to 50 years for equipment that will not be affected by the resurfacing of the road's structural layer has little impact on the cost price, given the financial model chosen.

Maintenance and servicing

Maintenance rates are applied to the initial capital. These rates depend on both the key nature of the equipment and the risk of premature wear.

Passive infrastructure is essential for catenaries and is also subject to significant wear and tear, while induction loops will not be repaired if they are damaged during the term of the concession.

Similarly, if a chopper fails in an induction system, the operator will wait for the right moment to repair it. On the other hand, if a switch fails in a rail system, it may have to be repaired relatively quickly.

Maintenance of the electronics has been set at 5% of the initial investment, as the sensitive part is not buried under the road but installed on its side.

Heavy-duty vehicle equipment

Not all HDVs will be equipped on day one. The ramp-up will depend on the rate of fitting of new HDVs and the active life of HDVs.

The cost of the equipment has been estimated at €20k per HDV. This is probably an overestimate for rail and induction, but correct for the catenary solution, which will require reinforcement of the cab to bear the weight of the double pantograph, as well as elements to raise and lower the pantograph automatically.

Lifespan of heavy-duty vehicles

The lifespan of heavy-duty vehicles in their long-distance transport function has been set at 8 years. Beyond that point, combustion-powered HDVs are expected to shift to shorter distances. The lifespan of electric HDVs is expected to be longer than that of internal combustion HDVs, with batteries being replaced halfway through their life. This will lead to a more rapid ramp-up in the rate of equipment, since the first HDVs to be equipped will not be taken off the road until much later. Nevertheless, the impact is very small and has not been taken into account.

Equipment rate for new heavy-duty vehicles

The rate at which new HDVs are equipped will depend on both manufacturers and the appetite of hauliers. It will be all the greater if confidence in the installation of the electric road is strong and vehicle manufacturers take account of the existence of the ERS by reducing the size of batteries in heavy-duty vehicles.

The model is based on a final equipment rate of 80% for HDVs making long-distance journeys, with a gradual ramp-up of new HDVs over 10 years: in the first year, only 8% of new vehicles will be adapted to the ERS, rising to 16% in the second year.

In the first year, only 1% of the vehicle fleet will be equipped, and it will not be until year 17 that 80% of the vehicle fleet will be equipped.

A 10% increase in traffic between 2001 and today has been taken into account.

Cost of electricity

The electricity costs used are those corresponding to 3 MW connections with a weighted winter/summer peak rate, i.e. €13k monthly subscription per connection and €93.5/MWh.

At this stage, the study has not included the hypothesis of global negotiations that an ERS infrastructure operator could conduct with an electricity producer.

The commercial margin rate is also applied to electricity supplies, insofar as this is a global service provided to the user and not a sale of energy.

Application to the A7/A9 motorways

Applying the model to known traffic on the A7/A9 motorways gives the results shown in Table 4.

The induction solution is penalised by the cost of maintaining/replacing the electronics and by the lower rate of electricity transfer.

The catenary solution is penalised by the cost of passive infrastructure, which requires concrete safety barriers, for example, and by the cost of maintenance.

The selling price of the service provided can be compared with the estimates arrived at by EdEn in its study on the use of hydrogen by heavy-duty vehicles (Table 5).

Based on these elements, and adding the costs specific to the vehicles, it is possible to establish a total cost of ownership (TCO) over the lifetime of the vehicle for each of the solutions considered (Table 6).

The TCO analysis gives an advantage to the electric road, which benefits from the low cost of the vehicle's equipment: the batteries are limited in size and the equipment on the vehicle itself remains relatively affordable. In addition, the vehicle's carrying capacity is identical to that of a diesel vehicle.

Table 4: Basic data relating to motorway segments A7/A9[26].

in €/km travelled	Cost of infrastructure	Cost of electricity supplies	Estimated selling price of the service (including margin)
Induction	0.19	0.20	0.48
Catenaries	0.16	0.17	0.41
Rail	0.11	0.17	0.35

Table 5: Estimated price of the service provided in 2030, in €/km, for long-distance journeys (> 500 km).

in €/km travelled	Hydrogen (by 2030)	Batteries (by 2030)	Induction	Catenaries	Rail
Estimated selling price of the service (including margin and excluding additional vehicle costs)	0.475	0.466	0.48	0.41	0.35

Note 1: These figures can be compared with the equivalent cost of diesel, i.e. €0.33/km according to the hydrogen study by EdEn. They do not include toll fees, which can be estimated at €0.26/km on average and which have to be added in all cases.
Note 2: Looking beyond the first depreciation period, when the motorway is completely refurbished, the costs will fall significantly: only the electronics and passive structure need to be replaced, and the financing rate falls to the level used in the EdEn hydrogen study.

Table 6: Total cost of ownership for each solution (€/km travelled) for long distances (> 500 km).

in €/km travelled	Hydrogen (by 2030)	Batteries (by 2030)	Induction	Catenaries	Rail
Total cost of ownership	0.793	0.783	0.78	0.71	0.64

26. All calculations were based on energy costs and interest rates prior to the war in Ukraine. Values are given in constant euros.

Notes on deployment speed

The speed of deploying ERS solutions in the HDV fleet can be considered high, compared with the speed of deployment for electric vehicles, for which it took around ten years to reach 1% of the number of cars on the road.

The deployment of electric mobility in private vehicles took off late because it required investing in R&D and industrialisation, which took time. Furthermore, we had to wait for strong pressure from the European Commission on the average CO_2 emission rate of vehicles. Since then, however, the rate of deployment has risen sharply (Figure 9).

In the case of the ERS, HDVs will benefit from R&D of private vehicles and will already be equipped with batteries when the ERS begins to be rolled out. It's a matter of fitting an HDV with a different collection system, not designing an HDV from scratch.

Setting aside the catenary solution, the first HDVs will simply be fitted with an additional collection device, with no reduction in battery mass. It is only in the second phase that they will be designed based on the ERS, with smaller batteries.

It could be argued that the roll-out of electric vehicles has been much slower, but at the time we were starting from scratch, with the range limited to the Renault Zoe and the first Tesla, an embryonic network of charging stations and low regulatory pressure on carmakers.

The deployment of electric vehicles really accelerated once these conditions improved, as shown by the AVERE France figures.

Heavy-duty vehicles will benefit from a "flying start", with already substantial penetration of electricity from battery-powered HDVs.

The cost of the service will hinge greatly on how quickly hauliers adopt the solution. This is partly due to the fact that deployment cannot be as gradual as that of charging stations or hydrogen charging stations. The ramp-up will involve reinforcing the electricity grid and increasing the density of connection points to RTE, but the HDV power supply system will have to be deployed for the most part from the outset. Most of the CapEx will therefore be spent in the first few years.

It should be noted that the induction and rail systems could benefit from additional income from private vehicles using the technology.

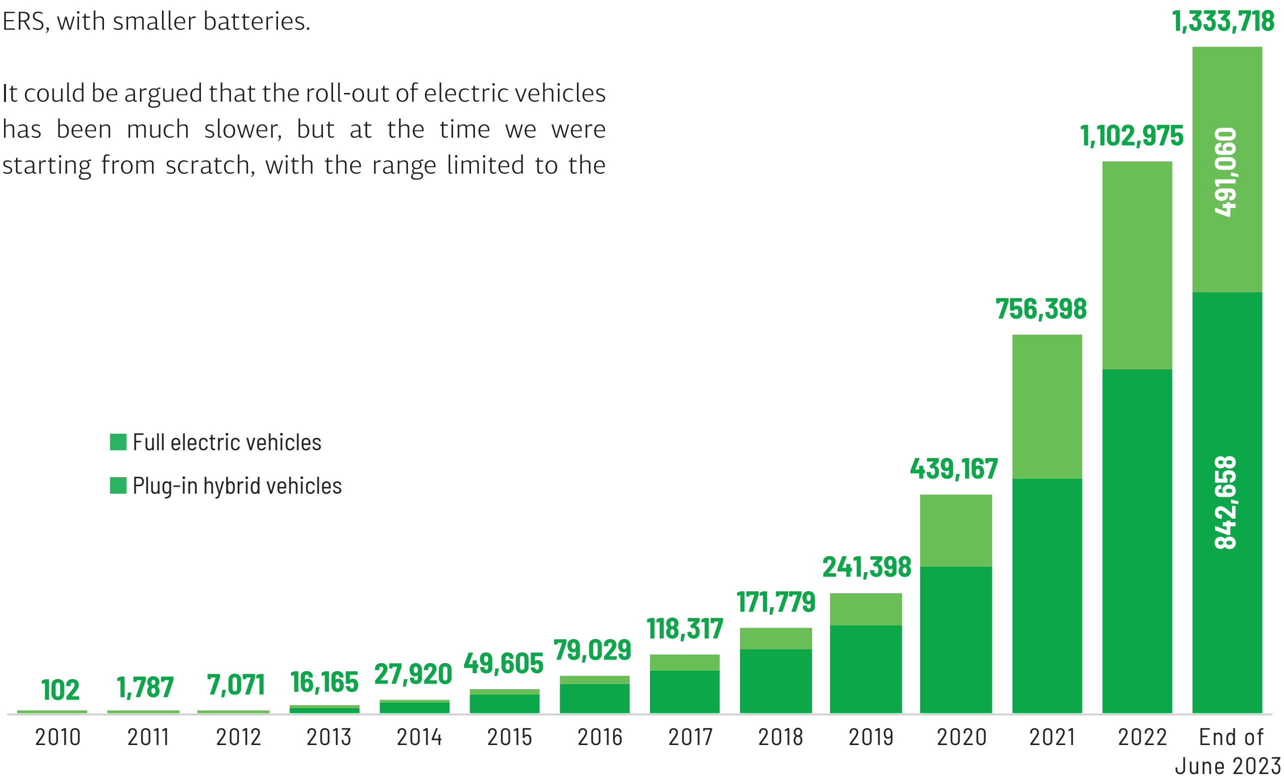


Figure 9: Change in the number of cars on the road since January 2010. *Source: AVERE France.*

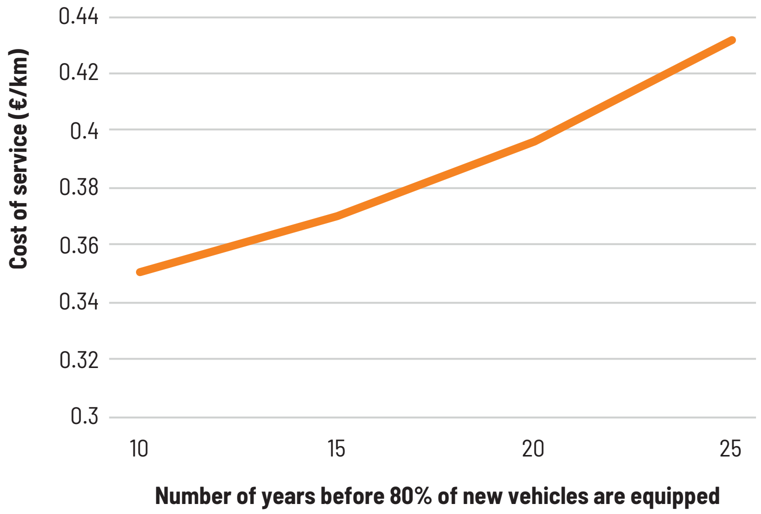


Figure 10: Sensitivity of the service to the speed of deployment – The case of rail.

By way of example, Table 7 shows, for the rail solution, the differences between the various segments of the A7/A9 sector according to the traffic they carry.

Table 7 shows a ratio of 2.3 between the average of the sections and the non-concession section. This is one of the drawbacks of the ERS compared with hydrogen or 100% battery-powered HDV solutions: if the section is not sufficiently equipped for transit, the HDV will not be able to use it, whatever the traffic, whereas hydrogen and charging stations can be rolled out more gradually.

Extending calculations to other motorway configurations

The above calculations were based on traffic data from the A7/A9 motorways, which present a favourable case because the traffic is particularly heavy. Obviously, on less busy routes, the equation will be less favourable because, even if it is possible to space out the connection points to the distribution or transmission network, these savings will not extend to the medium-voltage distribution network or to the infrastructure. The same level of equipment will be needed on the motorway, because this depends on the capacity of the HDV's battery, not on the amount of traffic.

In the context of a real-world deployment, it is obvious that the 82 km Lançon-Nîmes section, which is not very busy, would not be equipped. To make up for this, the adjacent sections would be slightly better equipped to allow HDVs to charge their batteries.

On the other hand, some expressways, particularly in Brittany, will have to be equipped, even though the traffic is moderate compared with the A7/A9 motorways. The cost of the service will increase accordingly.

TCO calculations are based on HDVs being equipped with a single technology. If we consider that there could be more than one, the cost of equipping HDVs will increase accordingly.

Table 7: Comparison of costs and selling prices between the A7/A9 segments as a function of traffic.

Section	HDV traffic (per day)	Cost of infrastructure (in €/km)	Cost of electricity supplies (in €/km)	Estimated selling price of the service (including margin) (in €/km)	Reminder of toll amount (in €/km)
Busiest section	13,017	0.062	0.17	0.29	0.22
Medium traffic	8,120	0.11	0.17	0.35	0.24
Light traffic	4,840	0.17	0.17	0.42	0.33
Lançon-Nîmes	1,625	0.50	0.17	0.83	Non-concession

Sensitivity to the cost of electricity

The events of 2022 have shown that energy tariffs are not as stable as they may have been in years gone by. The cost of historical nuclear power, which is supposed to be reflected in the ARENH tariff, is much lower than the cost of electricity that will be produced by the EPRs whose construction is now being considered, and the price of gas, which has a major impact on the electricity market, will continue to fluctuate depending on unforeseeable events.

The technologies used have very different sensitivities to the cost of electricity. In particular, hydrogen can be produced in hubs powered by nuclear or renewable electricity. However, the EdEn study showed that the bulk of production for long-distance road transport will probably soon be provided by electrolysers installed locally in distribution centres. The basic cost of electricity for producing hydrogen or charging batteries at service stations will not be very different from that for the ERS.

The induction solution is penalised by its lower transfer rate.

However, it should be borne in mind that these transfer rates are those declared by the manufacturers. Trials will provide a better measure of this.

Whatever the price of electricity, Figure 11 shows that the rail solution retains its competitive advantage and that the higher the price per kWh, the greater the gap with the hydrogen solution.

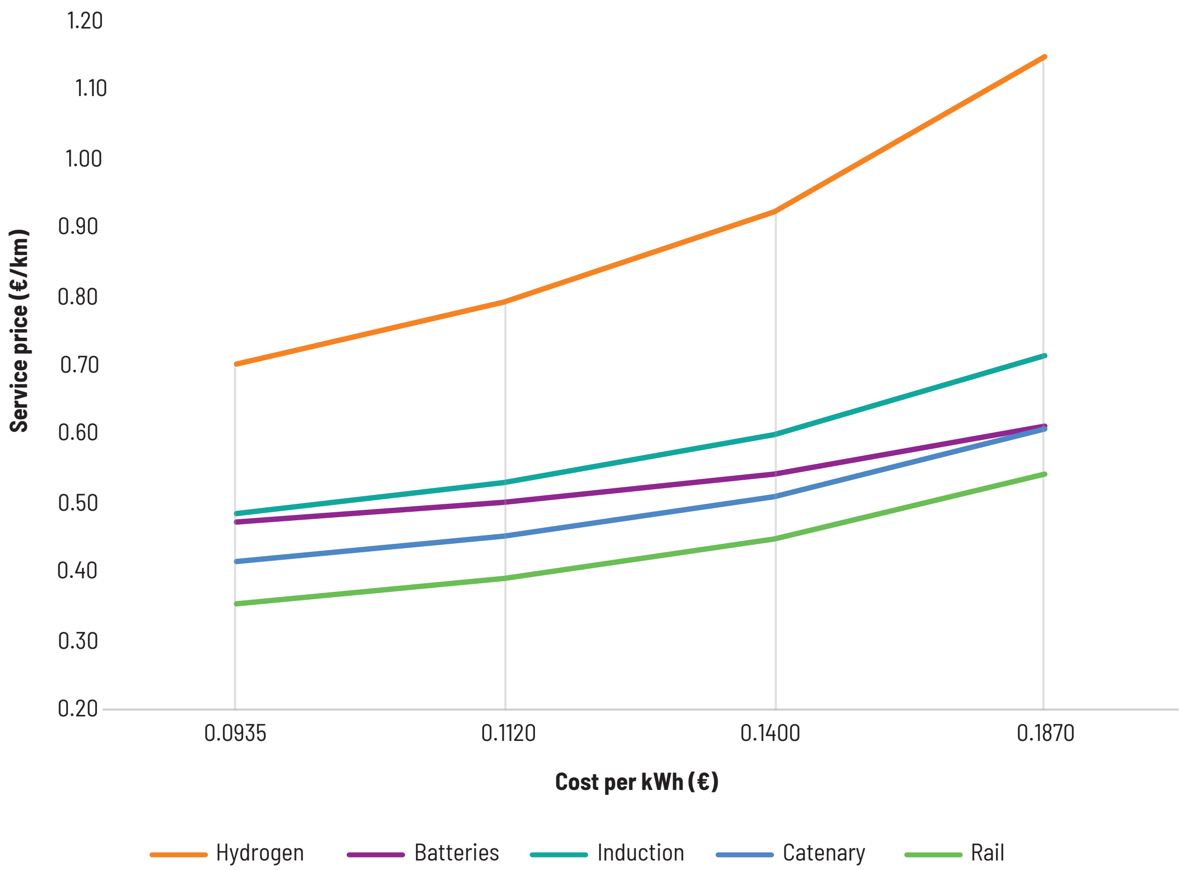


Figure 11: Sensitivity of cost price of service provided by different technologies to the price of electricity.

4

ERS deployment strategies

Deployment challenges

Validation and scaling up

The EdEn study on the use of hydrogen by heavy-duty vehicles showed that 100% battery-powered vehicles would be a satisfactory solution for regional and local road transport, both operationally and economically. Deploying the ERS could bring them environmental benefits by reducing battery size. That said, the cost of deploying such systems on national or secondary roads is likely to be much higher than the cost of deploying them on motorways, and the rate of acceptance by hauliers is likely to be even longer than for long-distance transport, delaying profitability even further. Consequently, the provision of ERS-type infrastructure on national or secondary roads does not appear to be an area for consideration.

The electric road mainly concerns long-distance goods and passenger transport on motorways. In the case of rail and induction solutions, private vehicle movements can also be taken into consideration.

Each of these systems has a different level of maturity. Based on experience in related fields, such as railways, tramways and metros, the catenary solution can be considered to be the most technically advanced, followed by the rail solution and the induction solution. For the catenary solution, proof of concept seems almost achieved, but there is still the major problem of incident management and safety (access for emergency services and the risks posed by the poles supporting the catenaries). The rail solution is close to maturity. Maturity is further off for the induction solution because its feasibility depends on the possibility of operationally transferring power of at least 50 kW from each coil. The induction solution is at TRL 6, while the other two solutions are at TRL 7.

Clearly, each of these solutions still requires experimental testing, which can be carried out on limited-scale sections without commercial deployment. These tests are essential to validate the solution under operational conditions. Assuming that these tests are positive, the next stage is more delicate, as it involves a change of scale and major investments. The cost of equipping a section of road of around one hundred kilometres would be in the region of €1 million to €2 million per kilometre per direction of traffic, to which must be added the cost of adapting a significant fleet of heavy-duty vehicles. Adapting 500 HDVs to one or other of the solutions will cost around €10 million.

So there is a problem of scaling up, made more complex by the fact that there are three competing technologies, none of which stands out clearly today. In addition, for each of these technologies, several manufacturers or institutes are developing competing systems that are not interoperable: grooved or solid rails, frequencies and types of induction coils, vehicle/infrastructure communication, etc.

The technical choice issue

The bare minimum for large-scale deployment in Europe will be that, eventually, the technologies deployed must enable a heavy-duty vehicle to cross the whole of the EU without having to change tractor units en route. The technologies deployed must therefore be neither too numerous nor mutually incompatible so that a heavy-duty vehicle can, if necessary, be equipped with several collection systems if no single technology has been adopted. We could, for example, imagine a tractor equipped with collectors to collect electricity on the rail and pantographs to collect it on the catenaries. But the feasibility of such coexistence remains to be demonstrated, just as the existence of several rail systems would be problematic and reminiscent of the not-so-distant past when rail gauges could vary from one country to another.

These issues of technical choice and interoperability, should there be more than one system, will be essential to provide reassurance to the investors who will finance the infrastructure, and to provide security to the transport companies who will have to equip their fleets and ensure deployment at a reasonable cost.

The solutions chosen will each have to be supported by an ecosystem of companies to ensure that there is a broad range of suppliers for both HDV equipment and infrastructure. They must therefore emerge from industrial consortia which will then take them to a standardisation body, probably CEN and CENELEC in Europe.

This standardisation must cover both aspects linked to charging, such as the height of catenaries, tolerances on dimensions, frequency for induction, voltage, etc., and aspects linked to vehicle/infrastructure dialogue and billing, so as to guarantee interoperability.

The role of Europe

In view of the European Commission's policy and decision-making rules, it is hard to see Europe imposing a single technology on European territory right now, through standardisation for example. On the one hand, the technical uncertainties have not been resolved, and on the other, the divergent industrial interests of the various countries will hamper attempts to make a single choice.

In addition, discussions with the various equipment manufacturers on which this study was based showed that it will probably be difficult to impose a single technology.

If no impetus is given, it is likely that a single technology per family (rail, induction, catenary) will eventually prevail, but this will be largely due to market pressure. Given the competition between companies working on these issues and the lack of dialogue, this will take a considerable amount of time and will spread industrial efforts too thinly. Previous experiences, such as the competition between HD DVD and Blue Ray or BetaMax and VHS, show that battles between two technologies can last several years before one of the two consortia finally gives up.

Today, however, there are not even any industrial consortia yet, but essentially start-ups fighting to impose their technology with national support.

The only way of organising and speeding up the process is for Europe to take up the issue, take over from national initiatives and impose a sequence that will allow the best technology(ies) to emerge.

Implementing a funding strategy based on the financial vehicles set up by Europe to support industrial initiatives, in particular through the *Innovation Fund*, can have a decisive effect. In line with the method used to develop carbon capture

and storage technologies, one solution could be for Europe to fund full-scale pilot operations over a sufficient distance, typically 100 to 200 km, built in consultation with the transport companies involved in the tests. These tests will have to take place in several countries representative of different transport and motorway operating conditions. They would be selected on the basis of calls for tender and would necessarily include a preliminary design phase to guarantee the feasibility of the solutions.

Planning outline

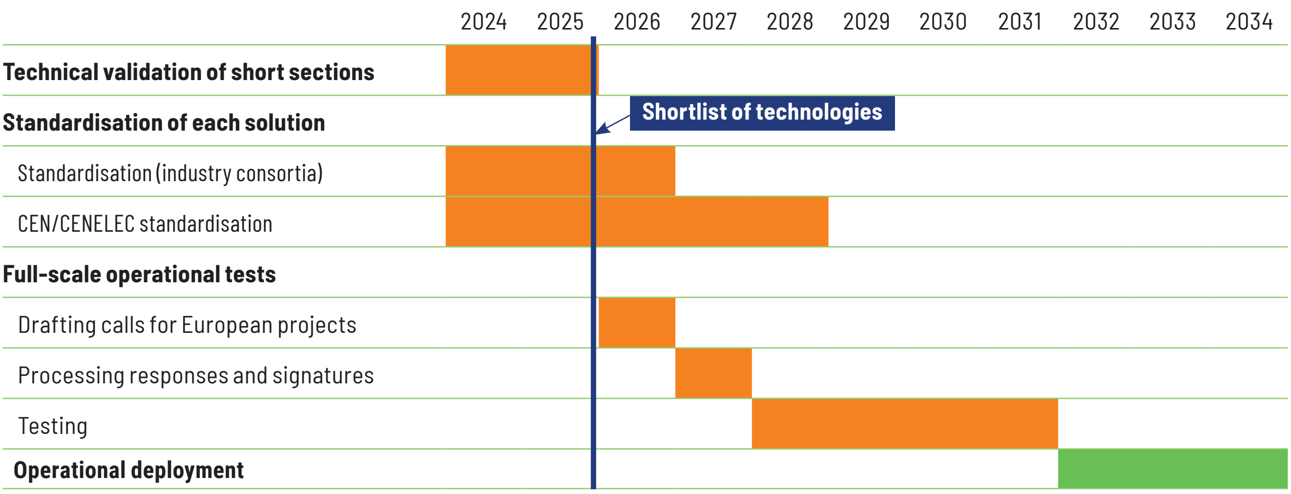
In view of the progress made with each of the technologies and the above factors, the shortest possible time frame does not point to the start of a large-scale roll-out before 2030/2031 at the earliest, provided that the necessary impetus is given at both national and European level to speed up full-scale tests and bring to the fore those technologies that deserve to be rolled out across the board.

The sequence could be as follows (Figure 12):

- continue unit tests and experiments over limited distances (a few kilometres) at national level, but with the support of European funds earmarked for R&D (Horizon Europe);
- set up working groups at European level, including equipment manufacturers, HDV manufacturers, hauliers and motorway operators, to specify the preselected technologies and propose them for standardisation. This phase may lead to certain options being set aside but does not imply any definitive technological choices;
- organise and carry out pilot test operations over significant distances (100 or 200 km sections), with the participation of partner users in the test operations, in order to validate the technology(ies) intended for widespread use:
  - check the technical feasibility of a certain volume of HDVs and a great length;
  - validate the impact on the road (in the case of rail and induction);
  - validate the impact on motorway operations in real-life situations: accidents, traffic jams, rain or snow.

  These pilot operations should be part of a European framework and be supported, as mentioned above, by the *Innovation Fund* which will be fed by the revenues from the new ETS applicable to transport and buildings. Germany is known to be particularly interested in the catenary solution. France could put forward two projects: one based on rail, the other on induction, but could also, if necessary, test catenaries if industrial operators wish to do so;
- large-scale deployment can only reasonably begin once mature, standardised technologies have emerged, bearing in mind that there will still be a considerable time lag between the decision to roll out and operational roll-out: calls for tender, industrialisation by suppliers, etc.

Figure 12: Outline of a schedule for the development of ERS technologies at European level.



Choosing pilot operations

Against a backdrop of uncertainty about the future of the ERS and the technology or technologies that will prevail, setting up pilot operations on 100 or 200 km stretches, involving a sufficient number of users, will not be easy. There are two possible targets for the emergence of projects: piggybacking on motorways or deployment on a high-traffic line.

Piggybacking on the motorway

The idea developed by several motorway operators would be to develop a trailer transport service on their motorway, or on a segment of it, using unmarked, shared tractors: the trailers would be picked up at a suitable area, hitched to a tractor using the Electric Road System and driven to a drop-off area where they would again be hitched to conventional tractors.

The advantage of such a system is that it enables an ERS solution to be deployed in a restricted area without waiting for a standard to emerge. Certain technologies (catenaries and rail) are sufficiently close to the level of maturity required for this idea to be feasible in the coming years and for the equipment of a fleet of tractor units to create the beginnings of industrialisation as part of the call for tenders that would be launched.

Such a solution could be implemented to reduce pollution on specific, particularly polluted segments, such as the Arve Valley in Haute Savoie, but other regions are also possible, notably on the A7/A9.

Motorway operators have indicated that they have received genuine interest from the hauliers they have contacted, and their initial models show that they are truly feasible.

The main drawback of this solution is its durability: if the technologies that emerge at European level prove to be incompatible with the chosen technology, the installed system will be marginalised in terms of cost and reinvestment will be required to enable it to operate with the others. However, this drawback is mitigated by the fact that the tractor units could continue to be used to service the equipped sections, even if the technology is not expected to become widespread.

The second drawback is the necessary investment to be made by the motorway concessionaire: deployment of the infrastructure, purchase of the tractor fleet, recruitment and training of drivers. Support at European or national level will be essential.

Deployment on a high-traffic route

Transport companies operate partly on the basis of routes. This opens up the possibility of rolling out the ERS on a limited segment, long enough to be significant, and inviting interested hauliers to adapt part of their tractor or trailer fleets.

In France, a segment such as Paris-Orléans would be a good candidate: reasonable length, existence of customers for hauliers at both ends of the segment, presence of transport companies operating on this specific route. Here too, motorway operators have received expressions of genuine interest.

5

Conclusions

The ERS is of undeniable interest in achieving the decarbonisation of freight transport. However, it is clear that this technology will only emerge in a second phase, after the deployment of 100% battery-powered HDVs in the first phase. This second phase could coincide with the timetable for the draft regulation amending Regulation (EU) 2019/1242 setting CO_2 emission performance standards for new heavy-duty vehicles, with the aim of achieving a minimum decarbonisation rate of 90% by 2040.

The technical feasibility of the ERS is not very far from being demonstrated. Of the three technologies, the catenary and rail solutions are the most advanced, but the induction solution offers attractive potential benefits, in particular transparency for other road users. At this stage, no solution can be ruled out.

The next stage for each of them is to check that they work under operational conditions, initially on a smaller scale and then on a larger one, in order to verify that they live up to their promise and validate their viability in real-life conditions. It will also be a way of deciding between these technologies.

The economic and financial equations for the electric road look rather better than those for the alternative long-distance solutions that EdEn has previously studied, the 100% battery solution and the hydrogen solution.

Admittedly, these competing technologies are more mature than ERS technologies and are more scalable. They will therefore have a significant period of time in which to be rolled out.

That said, another advantage of the ERS is that European players are in a good position to become leaders in its development. It also offers major potential benefits in terms of savings on scarce resources (cobalt and other critical metals for batteries, platinum for fuel cells and electrolysers), a reduced impact on the electricity grid due to the withdrawal profile, and a chain efficiency that is almost as high as that of batteries, and therefore reduced electricity consumption.

It's a technology that complements battery technology, and can expand the ecosystem of electric mobility solutions.

EdEn therefore recommends to pursue efforts on the ERS at both national and European level.

At national level

EdEn recommends that France gets involved in the development of the ERS sector and that tests should be continued or set up to remove the uncertainties that still weigh on functioning in operational conditions, to acquire know-how and to participate in the qualification of one or more technologies under the operating conditions encountered in the country (climate, financial model, etc.).

Initially, the aim should be to set up two or three tests on operational sections, with a few dozen HDVs equipped on at least two motorways with or without concessions, and to test rails, induction and possibly catenaries. The call for projects launched in 2022, the results of which were unveiled in 2023, meets this objective. It will be used to carry out three experiments (Appendix 3).

At European level

It is at European level that the final choices will have to be made in order to achieve a coherent European ERS infrastructure, based on a single technology or, failing that, on technologies that are sufficiently interoperable to allow the free movement of lorries in the European area.

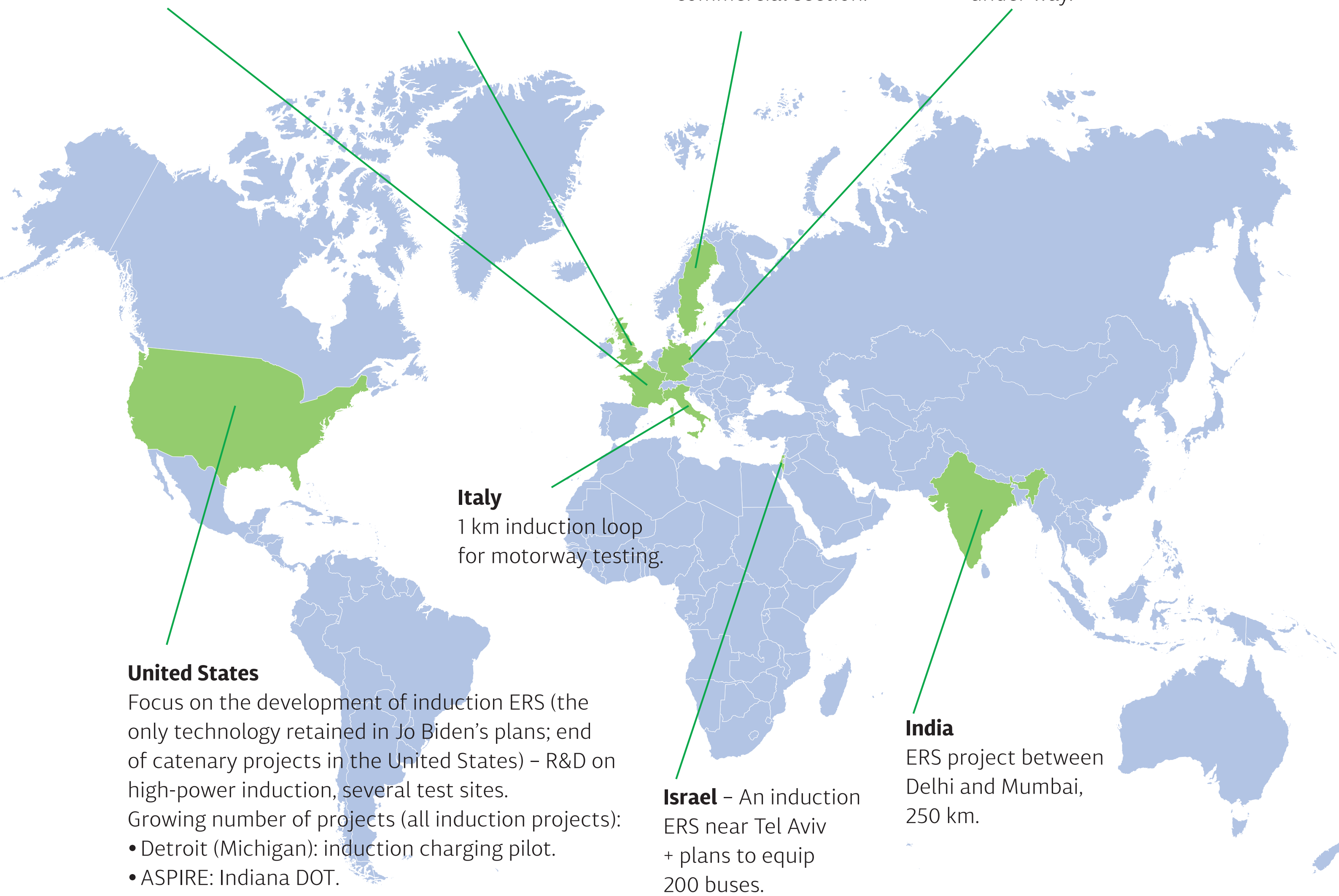
EdEn recommends taking to the European Commission the idea of launching, from 2026 onwards, as part of the *Innovation Fund*, calls for projects aimed at carrying out pilot operations on 100 to 200 km sections in areas where sufficient traffic of equipped heavy-duty vehicles can be mobilised. Each project would be preceded by a detailed preliminary design to ensure its validity, and would involve infrastructure suppliers and HDV manufacturers. The sections equipped should be spread across a number of countries representative of the European Union, with long-distance transport companies using these lines.

The amount of European subsidies would be in the region of €100 to €150 million per project, with a tenth to be allocated to a detailed preliminary design phase.

At the same time, and without waiting for the conclusions that will emerge around 2030 from these large-scale pilot operations, standardisation work on each of these solutions should be accelerated to avoid a dispersal of specifications within each technology.

6
Appendices

Appendix 1
ERS projects around the world



France
A national roadmap + calls for tender under way to test technologies.

United Kingdom
An ERS with catenaries near Glasgow + wider development plans.

Sweden
Two demonstration projects + a call for tenders for the first 21 km commercial section.

Germany
Two clusters with catenaries, several induction projects under way.

Italy
1 km induction loop for motorway testing.

United States
Focus on the development of induction ERS (the only technology retained in Jo Biden's plans; end of catenary projects in the United States) – R&D on high-power induction, several test sites.
Growing number of projects (all induction projects):
- Detroit (Michigan): induction charging pilot.
- ASPIRE: Indiana DOT.
- ASPIRE: Utah Inland Port, Utah.
- ASPIRE: Florida Turnpike, Florida.
- SunTrax Facility ERS Pilot, Central Florida Expressway (CFX).

Israel – An induction ERS near Tel Aviv + plans to equip 200 buses.

India
ERS project between Delhi and Mumbai, 250 km.

Details of US projects

Detroit In-Road Electric Charging Pilot in Detroit, Michigan

- Static and dynamic use cases.
- One mile road of dynamic charging.
- Agreement between Electreon and Michigan DOT to develop and implement a publicly accessible wireless charging system scalable beyond the one-mile project.
- Phase 1: Q3 2023; Phase 2: Q3 2024.

ASPIRE[27], Indiana DOT, Michigan

- 400 m test bench in West Lafayette (Indiana), with Purdue University.
- 220 kW, three-phase dynamic charging test.
- Construction to start in spring 2023.

ASPIRE Utah Inland Port Authority, Utah

- Salt Lake City, UT with the University of Utah.
- The technology suppliers have not yet been selected.
- $15 million grant from the State of Utah to demonstrate the potential of electric mobility applied to freight to improve air quality.
- The project will focus on transporting containers from the Union Pacific Project station in Salt Lake City to local warehouses.

ASPIRE, Florida Turnpike, Florida

SunTrax Facility ERS Pilot, Central Florida Expressway (CFX)

- Variable power from 11 kW to 200 kW.
- Cost: $10 million - New 5-mile stretch of motorway with 1,200 metres of electrified road.
- Construction of the road with installation of the slabs in 2025.
- The road is scheduled to open in early 2026.

27. ASPIRE: Advanced Sustainability through Powered Infrastructure for Roadway Electrification.

Appendix 2
Investment costs for ERS

	Depreciation period (years)	Induction		Catenaries		Rail	
		CapEx	Maintenance	CapEx	Maintenance	CapEx	Maintenance
Passive infrastructure cost/km in one direction	30	€150,000	5%	€250,000	15%	€150,000	5%
Ancillary costs (safety barriers, etc.).	30			€225,000			
Cost of works + asphalt/km for one direction of traffic	30	€150,000		€250,000		€150,000	
Power electronics cost one €1,000 box for two antennae of 1 m each	15	€500,000	10%	€50,000	5%	€150,000	10%
Cost of medium-voltage network and substations	30	€250,000	5%	€250,000	5%	€250,000	5%
Equipment rate (km equipped/ total km)		70%		70%		70%	
Electricity transfer rate		80%		95%		95%	
Total		**€1,050,000**	**€0**	**€1,025,000**	**€0**	**€700,000**	**€0**

Appendix 3

Projects selected in 2023

as part of the French government's call for projects and selected by BPI France

	Charge as you drive	RED4Fret Equans	E-Road Mont Blanc
Partners	• Vinci Autoroutes • Vinci Construction • Université Gustave Eiffel • Cerema • Hutchinson • Elonroad • Electreon		• Alstom • GREENMOT-Drive Innovation • FAAR-PRONERGY • Mersen • Université Gustave Eiffel • ATMB (Autoroutes et Tunnel du Mont Blanc)
Objective	Testing dynamic conductive rail charging (Elonroad) and dynamic induction charging on a motorway open to traffic	• Testing dynamic catenary charging on a motorway open to traffic • Test planned in eastern France	• Testing dynamic conductive rail charging (Alstom) on a motorway open to traffic
Tests	• Preliminary tests on a closed track at CEREMA • Two 2 km sections on the A10 • An Electreon induction section (a 40 t HDV and a bus) • A section of Elonroad track	• Test planned in eastern France • 2 km equipped with two hybrid catenary/battery vehicles	• Tests from mid-2024 on a closed track at Transpolis (500 m) • Installation of a 1 km section on the RN 205 (mid 2025) • LCV, a coach and a 40 t truck
Duration	3 years	The dossier is currently in the contracting phase (expected in Q4 2023) as the project was submitted in January 2023.	
Budget	€26m		

Appendix 4

Reminder of the definition of TRL

	Description
1	**Basic principles observed and reported** Lowest level of technological readiness. Scientific research begins to be translated into applied research and development. Examples might include paper studies of a technology's basic properties.
2	**Technology concept and/or application formulated** Invention begins. Once basic principles are observed, practical applications can be invented. The application is speculative and there is no proof or detailed analysis to support the assumption. Examples are still limited to paper studies.
3	**Analytical and experimental critical function or characteristic proof-of-concept** Active research and development are initiated. These include analytical studies and laboratory studies to physically validate analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.
4	**Component or breadboard validation in laboratory environment** Basic technology components are integrated to establish that the pieces will work together. This is relatively "low fidelity" compared with the eventual system. Examples include integration of ad hoc hardware in a laboratory.
5	**Component or breadboard validation in a relevant environment** Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so that the technology can be tested in a simulated environment. Examples include high-fidelity laboratory integration of components.
6	**System/sub-system model or prototype demonstration in a relevant environment** Representative model or prototype system (well beyond the breadboard tested for TRL 5) is tested in a relevant environment. This level represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high-fidelity laboratory environment or in a simulated operational environment.
7	**System prototype demonstration in an operational environment** Prototype near or at planned operational system. This represents a major step up from TRL 6, requiring the demonstration of an actual system prototype in an operational environment, such as in an aircraft or vehicle. Examples include testing the prototype in a testbed aircraft.
8	**Actual system completed and flight-qualified through test and demonstration** Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation of the system to determine if it meets design specifications.
9	**Actual system flight-proven through successful mission operations** Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation. In almost all cases, this is the end of the last bug-fixing aspects of true system development. Examples include using the system under operational mission conditions.

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