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Transport Research Arena (TRA) Conference

The electric road system: technical, economic and environmental study carried out in France. Part 2. Economic and environmental aspects

Fabien Perdu^a, Pierre Chanot^b, Marc Raynal^{b*}, François Combes^c

^aUniversité de Grenoble Alpes; CEA/LITEN F-38402 Saint Martin d'Hères, France

^bCEREMA, 110 rue de Paris, 77171 Sourdun, France

^cUniversité Gustave Eiffel, Cité Descartes, F-77420 Champs-sur-Marne, France

Abstract

This paper evaluates the introduction of an Electric Road System on the French motorway network. The starting assumptions are the size of the network concerned, the size of the truck fleet and the truck traffic measured on this network from counting stations. The size of the necessary electrical infrastructure is calculated on the basis of peak traffic and an economic optimum is sought, including the costs of batteries and infrastructure. It follows that an ERS network applied to the French road network reaches the optimum for a size of about 8,700 km if it is limited to heavy goods vehicles and about 16,900 km if it is open to vans and private vehicles.

The results are as follows: (i) costs to carriers are similar to diesel, (ii) decarbonisation achieves 86% of current emissions, and (iii) the reduction in battery size significantly reduces pressure on critical materials such as nickel.

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Keywords: ERS; transport; decarbonisation; electrification.

Nomenclature

R	necessary range	HGV	heavy goods vehicle	ICE	internal combustion engine
L	length of the ERS network	LCV	light commercial vehicle	CNR	Comité National Routier
S	size of the country	(B)EV	(battery) electric vehicle	TCO	total cost of ownership
α	penalty factor	ICE	internal combustion engine	OEM	Original Equipment Manufacturer

* Corresponding author. Tel.: +33 6 64 02 04 99; fax: +33 1 45 36 81 00.

E-mail address: marc.raynal@cerema.fr

1. Introduction

The decarbonisation of road transportation is both a major priority for GHG emissions reduction, and a very difficult endeavor, considering the current competitiveness (in both cost and technical efficiency) of internal combustion engines and fossil fuels. One of the main directions currently worked on to achieve energy transition is to replace ICE cars and trucks with battery electric vehicles. The issue is that replacing an ICE vehicle with a BEV vehicle is a total cost of ownership tradeoff: while ICE are typically easier to purchase, they are more expensive to operate. However, vehicles need autonomy and/or fast reload capacity. Indeed, a vehicle is only as useful as the locations it allows its user to reach; and that is where BEV are, currently, not excellent. OEM faces the dilemma to compromise between vehicles with high autonomy, to satisfy customers needing to go anywhere, anytime, and keeping affordable prices but reducing the vehicles' ranges.

The concept of ERS (Electric Road Systems) enables to disconnect the vehicle range from the vehicle's purchasing cost (RGRA, 2022). On an ERS network, vehicles get electricity while moving at full speed, both propelling them and loading their batteries. Instead of carrying a heavy and expensive set of batteries, or stopping for long charging time or fast charging which reduces the battery lifetime and is quite costly, a pack giving a range of 200 to 250 km would be enough to travel everywhere, if using the ERS. The reduced battery pack (app. by two thirds) may ensure the remaining journey outside the ERS. (Jacob and al., 2022) presents the interest and the available technologies of ERS, which are assessed.

An ERS network is a costly infrastructure. Its design should reach an optimum between an over-sizing, beneficial in terms of accessibility, but very expensive, and a cheaper under-sizing, which may actually be useless. The economic system's uptake is crucial: carriers and drivers should find it competitive to equip their vehicles and use the network. It highly depends on the financing and pricing approach.

This paper pragmatically addresses these questions, in a quantified approach based on facts and figures, for an application in France. Therefore, a cost model of an ERS system is developed, based on simplified geometric assumptions (Section 2). The model provides an optimal extension of the ERS network in France, up to a size where the benefits of additional coverage reducing the vehicle range requirements more than compensate the increasing investment costs. Section 3 compares raw resources requirements of a transport system based solely on BEV versus a system combining a reduced BEVs range and ERS. The ERS will strongly reduce the environmental impact of the transport transition to carbon neutrality, in addition to the benefits of the transition itself. Section 4 examines the electric power design of ERS, based on the vehicle requirements and traffic flow. The cost of the ERS system is discussed in Section 5 and its financing in Section 6.

2. Optimization of the ERS network size

The required length of ERS infrastructure to deploy is the first question arising. A right sizing should allow significantly reducing the on-board capacity of batteries (gain of weight, space and cost) compared to a full battery solution, while avoiding unnecessary investment in the network. Our simplified model of the National road network links the required EV range, directly related to battery capacity, to the ERS network length.

Considering a regular square network in a territory (e.g. country), with square side of a , the total network length L is related to the surface of the territory S by: $a.L=2S$, under the assumption that the number of squares is large. The minimum required range R of a vehicle should allow reaching any point of the territory from the ERS network and coming back to it without recharging. Thus, $R=a$ and $R.L=2S$. Moreover, this relation remains valid for regular triangular or hexagonal networks.

For a real road network, the meshes are neither regular polygons, nor of the same size. The travel to a point inside a mesh is neither in a straight line nor at constant altitude. A penalty factor α is introduced to account for these various effects, leading to: $R.L=2 \alpha.S$

The penalty factor is tuned to represent the considered road network, e.g. $\alpha = 2$ in the case studied in this paper. This very simple model enables calculating a global cost including the cost of batteries (proportional to R) and the ERS network cost (proportional to L).

A numerical application is given for France. Table 1 summarizes all the considered inputs and figures.

Table 1. Numerical assumptions.

	Heavy Goods Vehicles	Light Commercial Vehicles	Passenger Cars
Country size (France)	550,000 km ²		
Battery cost	100 €/kWh		
Penalty factor	$\alpha = 2$		
ERS lifetime	20 years		
Number of vehicles using ERS	382,000	4,000,000	25,000,0000
Vehicle lifetime	8 years	15 years	15 years
Vehicle range without ERS	800 km	500 km	500 km
Vehicle consumption at battery outlet	143 kWh/100km	25 kWh/100km	16 kWh/100km
ERS cost, 2 directions	4 M€/km (1 lane)	2.2 M€/km (second lane)	

Source : Reports of 3 working groups, French Ministry of Ecology Transition, 2021

The HGVs’ number is estimated from the fleet composition (*SDES, 2020*) and given as an equivalent number of road tractor. We assume that only two thirds of the LCVs’ and cars’ fleets perform long distance trips, and would therefore benefit from the battery downsizing allowed by the ERS. The ERS cost given on the last line of Table 1, is split between the slow lane mainly used by HGVs (2 M€/km in each direction), and the extra cost to equip a second lane for lighter vehicles (in both directions).

The resulting total costs (batteries and ERS network) are calculated on a per year basis as not all components have the same lifetime. Figure 1 gives these total yearly investment costs, depending of the ERS length. When increasing the ERS length, it cost increases. When enough ERS is installed to reduce the required vehicle range, the battery cost decreases. Figure 1 left shows the case where only HGVs are using the ERS. Figure 1 right shows the case where HGVs, LCVs and passenger cars use the ERS. An optimum length of ERS clearly appears, reminded in Table 2.

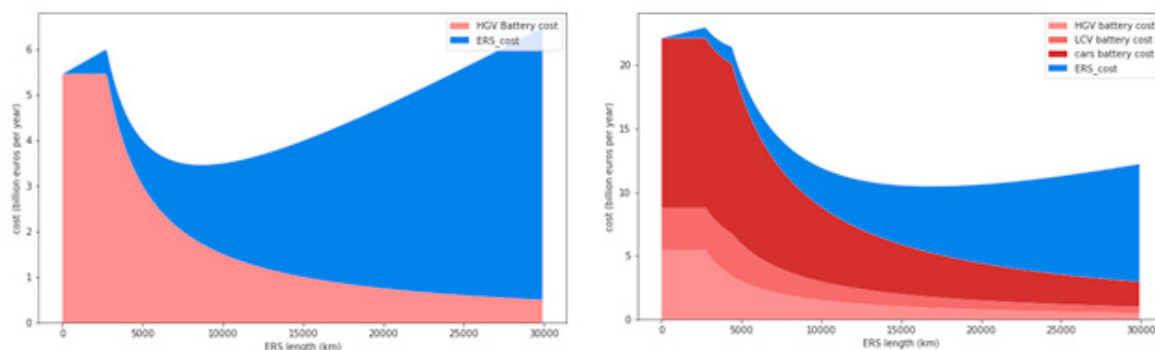


Fig. 1. Total yearly investment cost including batteries and ERS as a function of the ERS length.

Table 2. Optimal ERS size found by the model

	ERS length (<i>L</i>)	Required vehicle range (<i>R</i>)
ERS for HGVs only	8 666 km	254 km
ERS for all vehicles	16 882 km	130 km

Figure 1 provides also valuable information on the cost behaviour. The slope of the total cost curve is rather steep before the optimum, revealing a strong penalty if under-sizing the network. Reversely, the slope is much lower after the optimum, indicating that it is preferable to oversize the network than to undersize it. Furthermore, in the rather flat zone around (after) the optimum, the network size controls the cost split between the ERS and the batteries: for a similar total cost, a somewhat oversized ERS network shifts the cost burdens from the batteries to the infrastructure, freeing the road hauliers from an upfront cost that may be challenging for them.

The model has some limitations. The ERS cost and the number of lanes to be equipped should depend on the considered part of the road network. Expanding the ERS network to roads with less traffic, with a lower cost per km, should further flatten the curves after the optimum. Moreover, some costs are omitted, such as the cost of the pickups to be installed on the vehicles to connect to the ERS, and the savings of avoided charging stations thanks to the ERS. Altogether, these effects should tend towards expanding a bit the ERS network. However, various sensitivity calculations performed with the numerical inputs showed the robustness of the results, therefore, the optimal network length does not vary by more than 2,000 to 3,000 km.

3. Impact of ERS on mineral (raw material) resources

A shortage of raw materials could hinder the large production of batteries in the coming years. ERS could alleviate these constraints by substantially limiting the required amount of batteries. However, it is necessary to check that the material requirements of the ERS itself do not overcompensate the gain on battery raw materials.

Therefore, the mineral resource use was calculated for the two ERS network lengths described in Section 2 (for HGVs only and for all vehicles), and compared to the scenario with 100% batteries. All the assumptions of Section 2 still hold here, and are complemented by those given in Table 3.

Among the 35 million-car fleet, 25 million are assumed performing long distance trips and are eligible to the ERS if developed for all vehicles. If the ‘ERS for HGVs only’ is deployed, and if the technology is compatible with cars (induction or ground conduction), only 5 million cars would use the ERS installed on a single lane in each direction, among trucks traveling at 90 km/h. Similarly, among the 6 million LCVs fleet, 4 million are assumed performing long distance trips and would use the ‘ERS for all’, while only 1 million would use the ‘ERS for HGVs only’. The remaining cars and LCVs performing only short distance trips should have a range of 200 km on batteries. All these assumption would benefit from further validation before any technology adoption. They lead to the total amount of required batteries given in Table 3. The scenario ‘ERS for HGVs’ would reduce the amount of batteries for trucks by 2/3, and for cars and LCVs by 10% if using a technology compatible for these vehicles (induction or ground conduction). With the scenario ‘ERS for all’, the total amount of batteries HGVs would be divided by 6, and for cars and vans it would be reduced by 60%. Altogether, the first scenario would reduce the amount of batteries by 9% if the catenaries are used, and by 17% if a technology compatible for cars and LCVs is used. The second scenario would allow reducing the amount of batteries by 66%.

Table 3. Required battery total capacity per scenario and class of vehicles.

	100% batteries	ERS for HGVs (catenaries)	ERS for HGVs (induction or ground conduction)	ERS for all
HGVs	460 GWh	146 GWh	146 GWh	75 GWh
LCVs	600 GWh	600 GWh	539 GWh	230 GWh
Cars	2,320 GWh	2,320 GWh	2,123 GWh	840 GWh

The typical material content of a battery pack comprises, for 1 kWh: 550 g of Cu, 1650 g of Al, 717 g of Ni, 90 g of Co, and 106 g of Li. These values depend on the chemistry and on the pack design.

The technology providers indicated the materials required for each ERS solution (*French Ministry of Ecology Transition*, 2021). The most comprehensive data used here come from Siemens (catenaries), Alstom (ground conduction), and IPT Primove (induction, only providing the amount of copper of the coils embedded in the road). Fig. 2 gives the content of two representative critical materials (Ni and Cu) for the 3 scenarii, 100% batteries, ERS for HGVs and ERS for all. Nickel is a critical component for batteries and is foreseen to see a production bottleneck in the coming years (Roskill, 2021, and Rystadt Energy, 2021). Copper is an ubiquitous metal for which the energy transition will further increase the tensions.

The results show a very clear benefit, the mineral consumption for the ERS being much lower than the savings obtained thanks to battery downsizing. ERS for HDVs allows around 10-15% savings depending on technologies. The more ambitious ‘ERS for all’ is much more efficient with above 60% savings thanks to the downsizing of millions of car batteries. This underlines the importance of selecting a technology compatible with small vehicles and deploying a large network. Special attention must be paid to the significant copper consumption by induction technology.

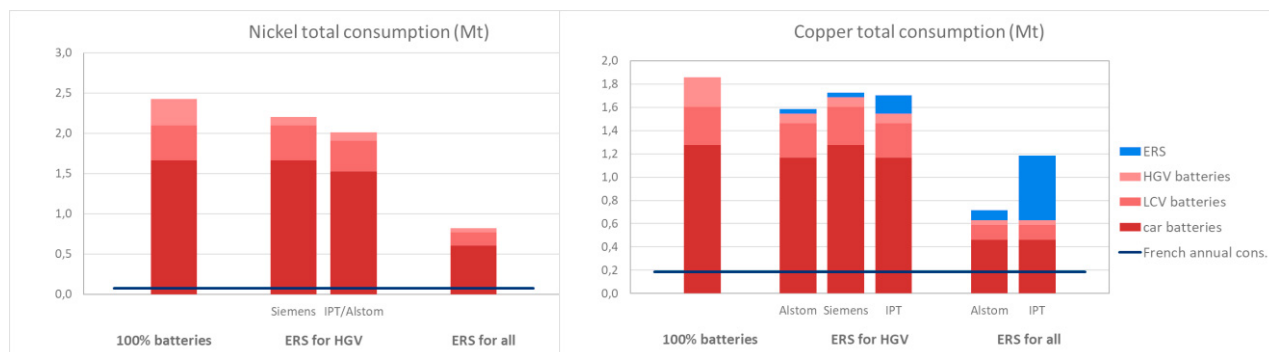


Fig. 2. Total consumption of nickel (on the left) and copper (on the right). The material present in batteries is represented by various level of red, and the material present in the ERS is in blue. For each metal, a horizontal line represents today annual consumption in France, showing that the quantities involved are very significant. ERS for HGVS already brings benefits, but the savings obtained thanks to the car batteries are much greater.

4. Sizing of the power to be supplied by the ERS

The electrical pre-sizing of the ERS network on a French scale was done in several steps. First, the capacity of the battery required for the trips outside the ERS was defined, then the power to be supplied to each truck and finally the linear power to be installed on each section of the ERS.

4.1. Battery capacity required for trucks

With the proposed ERS network, a truck would be within 125 km of the charging facility at any given time. Therefore, the selected range is 250 km, which allows a round trip from the ERS. The capacity of the battery (360 kWh) is directly derived from this range and from the real consumption data of the trucks as they are observed in France. This capacity allows to easily cross most of the steepest areas of the national road network, even in windy conditions (headwind at 40 km/h).

4.2. Power required per truck

The power required to recharge the battery of a 40 t truck to 70% while ensuring its propulsion has been calculated for 4 scenarios. These scenarios rely on realistic assumptions concerning the rate of equipment of the network in ERS and on the duration of a truck's journey on this network.

Table 4: Individual power to be supplied to each truck by the ERS according to the rate of linear network equipped and the desired charging time

	Charging time : 1 hour		Charging time : 2 hours	
	50%	80%	50%	80%
Rate of equipment of the ERS network	50%	80%	50%	80%
Power to deliver	816 kW	510 kW	568 kW	353 kW

Theoretical calculations have ensured that these powers are sufficient to prevent battery discharge on moderate slopes (<1.5%). Given these elements and considering the motorization powers proposed by the manufacturers, the power to be brought by truck was fixed at 400 kW. The chosen value for the rate of equipment of the road is 80%.

4.3. Sizing of the ERS power according to the peak traffic

For each section of the ERS, the electrical sizing aimed at satisfying the power supply of all the trucks during the peak traffic, associated with the 30th most loaded hour of the year. This assumption is based on an analogy with the sizing of static charging stations.

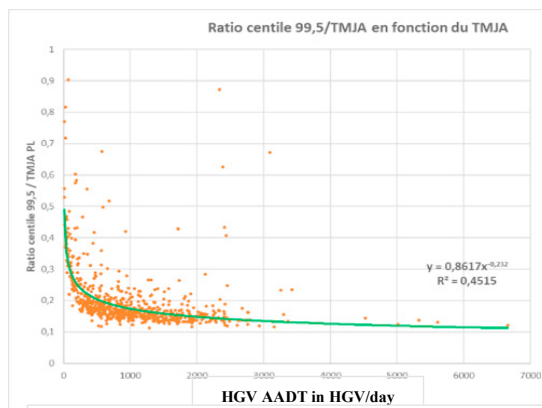


Fig. 3. ratio centile 99.5/AADT according to AADT

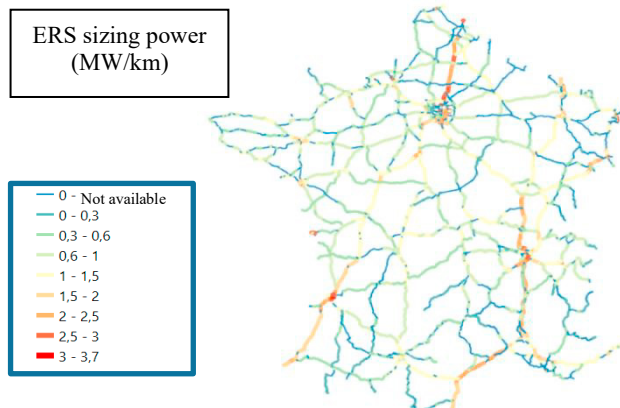


Fig. 4. ERS sizing power per network section for 250 kW/HGV

The 2017-2018 data from the WIM stations on the French road network allowed us to estimate the peak traffic for all sections of the non-concession network. On average, the flow at the 30th busiest hour of the year (ERS design flow) is 4 times the annual average daily traffic (AADT) on the non-concession network. Statistical processing of the 2017-2018 data yielded a power-law regression, expressing peak traffic as a function of AADT. This regression was used to extrapolate the peak traffic for all sections of the road network, under concession or not. The data used for this regression does not cover the concession road network and it is difficult at this stage to assess the bias induced by this deficiency.

Dividing the peak traffic by 80 km/h, enable obtaining an estimate of the rate of trucks per kilometer at the traffic peak. The sizing power by km of the ERS is then obtained by multiplying this concentration by 400 kW. To simulate the fact that not all vehicles will require 400 kW power all the time and that not all vehicles will be equipped with the ERS, we also considered the provision of 250 kW power for 100% of the trucks.

The average sizing of the 2035 network is 1.1 MW/km/direction considering a 250 kW contribution for 100% of the trucks. It is 1.7 MW/km considering an input of 400 kW for 100% of the trucks. Finally, if 100% of the trucks would draw an average power of 250 kW as soon as they are connected to the ERS network, the average power to be delivered on the whole network would be 4.6 GW in 2035.

5. Estimated cost of the infrastructure

The infrastructure costs have been studied on a declarative basis with the suppliers of ERS technology, the public works companies and the electricity companies.

The costs include: (i) the creation of 225 KV/ 20 kV - 100 MW source substations, every 50 km in average, to deliver app. 1 MW/way/km, (ii) the creation of 20 kV AC/750 V DC substations every 2 km in average, (iii) the power lines supplying the specific conductors for rail, catenary or electromagnetic induction technologies, (iv) roadway works, (v) miscellaneous safety works.

At this stage, the estimates only give a range of costs, as detailed studies could not be carried out in this framework.

Figure 5 shows the histogram of the ERS network by power class for the 2030 and 2035 horizons (defined in the Reports of the 3 Working Groups on ERS), and the estimated costs per kilometer of work by power class.

Multiplying the costs per kilometer by the number of kilometers of ERS in each power class (Fig. 5), gives a global estimate of all the work between 30 and 38 billion euros. The following section shows how this project could be financed.

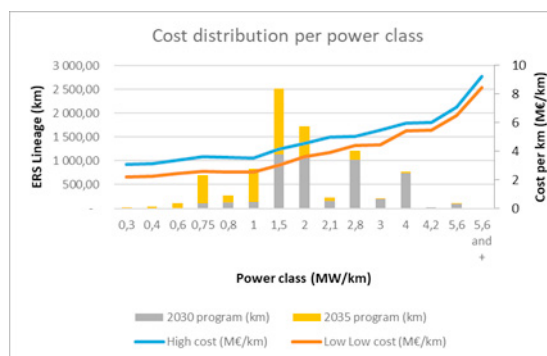


Fig. 5. ERS costs per power class

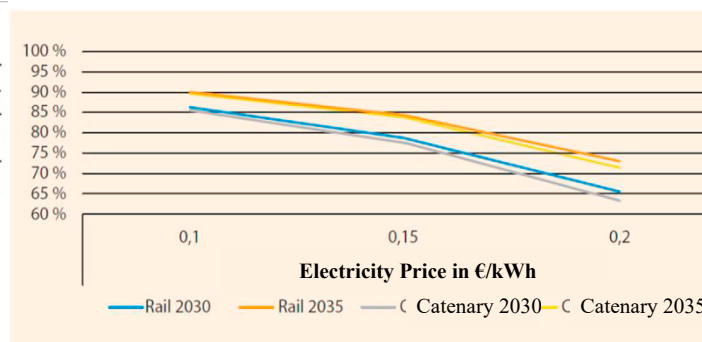


Fig. 6. Share of HGV traffic captured by the ERS by technology

6. Investment project by Stakeholder for Various Assumptions

The main actors in this project are (i) the ERS operators including energy suppliers, investors and managers in the road network, (ii) vehicle manufacturers, and (iii) freight carriers who are the end customers of the ERS, and (iv) the public authority.

A traffic study was conducted, determining the traffic shift to the ERS based on the cost of electricity versus diesel. The share of shift is presented in Fig. 6.

6.1. View from the operator perspective

The electricity fare for operators is assumed at about 0.07 €/kWh, and about: 0.10 €/kWh for end customers. Table 5 shows the investments benefiting from a concessional loan on the left part, and the revenues collected by the private ERS operator on the right part. The grey cells show a balanced account. The traffic share captured by the ERS is derived from Figure 6.

Table 5: Investment expenses and revenue for several ERS network

Detailed expenses	ERS network size	Linear investment costs (M€/km - 2 ways)	Total invest. M€	Annuity + M&O (2%) (in M€/year) – Loan:		HGV traffic 2019	Captured traffic		Infra cost rate €/km per HGV	Infra revenue M€/yr
				Rate	Duration (yr)		Share %	Total/yr HGV*km/yr * 10 ⁹		
Network	km		M€			HGV*km/yr * 10 ⁹	%	HGV*km/yr * 10 ⁹	€/km per HGV	M€/yr
High estimate										
2030+2035	9 673	3.88	37 573	1%	30	2 207	70%	11.235	0.196	2 207
ERS for all	14 962	4.12	61 675	1%	40	3 112	80%	19	0.164	3 112
Low estimate										
2030+2035	9 673	3.08	29 776	1%	30	1 750	70%	11.235	0.156	1 749
ERS for all	14 962	3.21	48 085	1%	40	2 426	80%	19	0.128	2 426

Compared with the average motorway toll currently charged to HGVs, about 0.228 €/km, the rates per HGV are slightly lower. The current rates, if maintained for the whole traffic (diesel or not), could finance the project. Moreover, with an electricity fare of 0.10 €/kWh and an average HGV consumption of 1.55 kWh/km, the energy revenue would reach 1,742 M€/yr for the 2030+2035 network and 2,946 M€/yr for the extended network. The income would represent around 30% of that revenue. It should be noted that the seven historical motorway concessions in France will expire between 2031 and 2037 as the investments will be fully paid back. It represents approximately 8,279 km. This would allow funding the ERS network without any change in the current highway rates.

6.2. View from the carrier's perspective

As the financing of the infrastructure leads to a relatively unchanged average cost of tolls, the change for carriers will be a cut off of the cost per km with electricity for HGVs, down to 0.155 €/km (1.55 kWh/km x 0.10 €/kWh) against 0.323 €/km for diesel (CNR, 2019). Such a cost difference could drain a significant number of HGVs from the secondary road network to the ERS network on motorways. A comprehensive study of the total cost of ownership of transport equipment, including fuel, electricity, 360 kWh batteries, tolls, etc., conducted with the French National Road Committee, results in the costs shown in Fig. 7.

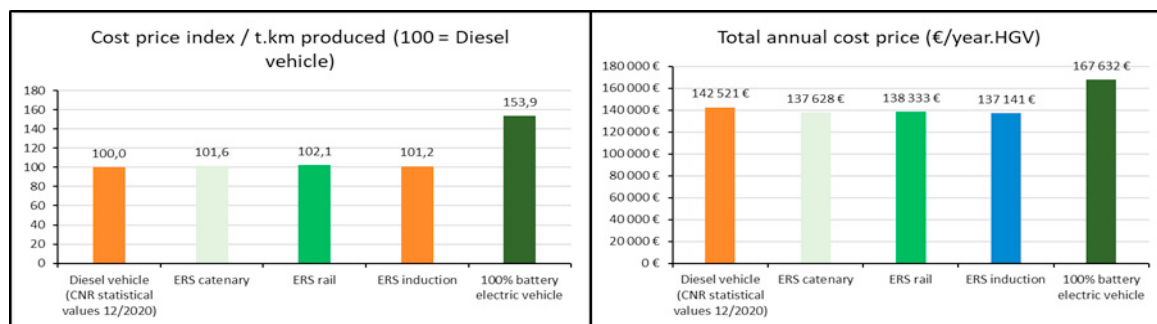


Fig. 7. TCO for diesel, ERS and battery

7. Conclusion

Several studies in Finland, Denmark and Sweden have concluded that ERS is collectively more cost-effective than battery-only solutions because it allows for large-scale battery downsizing (Connolly, 2016 and Trafikverket, 2017). ERS is particularly cost-effective for heavy trucks that follow well-defined routes, as opposed to individual traffic that follows diffuse routes that are difficult to make cost-effective for ERS (Finnish Transport Agency). The ERS system should be deployed with a financial benefit and a reduction of mineral resource consumptions. A bit less than 10,000 km of ERS on the French highway network makes it possible to rely on BEV with a range of about 250 km to go anywhere. The financial balance is also favorable: given reasonable pricing and cost assumptions, the cost of the ERS system can be covered with a very limited financial impact on road users. Moreover, the environmental impact is positive, with a substantial reduction in raw resources consumption, thanks to the highly reduced need for large batteries.

The business model, while pragmatic, is simplified, and future research should focus on improving it. Indeed, a number of questions remains: depending on the current annual activity of each vehicle, what will be the net benefit of equipping them to use the ERS? Depending on the toll rates and electricity fare, how many vehicles will actually use the network? These questions are important for refining the financing scheme to optimize the use of the system, and thus its social and environmental utility.

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