VIL
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LOGISTICS

LOGIBAT

WP2 CHAPTER:

ECONOMIC IMPACTS OF THE CATENARY ELECTRIC ROAD SYSTEM IMPLEMENTATION IN FLANDERS

Authors: Raimonds Aronietis and Thierry Vanelslander

PROJECT PARTNER:

Universiteit Antwerpen

Inhoudsopgave

FLANDERS
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1 INTRODUCTION

Logibat is a VIL project, financially supported by Flanders Innovation & Entrepreneurship, that investigates what the operational and economic conditions are to make battery-electric transport feasible and what the requirements are to roll out a nationwide charging network.

In the WP2 of the Logibat project, the economic impacts of developing a catenary ERS[1] network in Flanders to use it for road freight transport are investigated. The aim is to identify what the economic impacts of such a system would be for the involved stakeholders and society, what is the best way of building it and what it would mean for the international freight traffic.

ERS is a general term that refers to technologies that enable vehicles to be propelled and charged from the infrastructure while they are moving. The three ERS approaches are: overhead catenary, rail in the road surface, and contactless induction system embedded in the road surface. In this research we focus on the catenary ERS because it is the system with the highest Technology Readiness Level and market maturity[2], existing field trials show promising results, and the system implementation, compared to other two ERS approaches, will likely face less economic, technological, supply chain and other barriers.

Catenary ERS is a technology that enables powering pantograph-equipped road freight vehicles with electricity from overhead catenary while in motorway traffic, and using another energy source (hybrid diesel, natural gas, hydrogen or battery electric) for the final leg between the electrified portion of the road and the customer.

The catenary network is similar to that of the traditional trolleybus network in cities with DC power supply through positive and negative wires. While under the catenary the truck that is equipped with pantograph can connect to the network and use the supplied power for propulsion, and also for charging the battery, should that be required. After disconnecting from the catenary network, another energy source is used for propulsion – diesel, natural gas, hydrogen or electricity from the battery.

Leveraging the catenary network provides a distinct advantage for battery electric trucks. The battery size can be significantly reduced, from a range of 800-1200 kWh of usable energy to 100-400 kWh, while allowing to perform the same transport operations and also having the benefit of not having to allow time for battery fast charging, because the battery of the truck is recharged while driving in motorway traffic. The lower battery size allows significantly reducing the required investment in vehicles and improves the return on investment, while maintaining the flexibility in operational pattern and suitability for different logistics business models. For fuel-propelled vehicles, this benefit does not exist, because off the catenary network they use fuel for propulsion.

In this report we describe the research questions, the approach that is taken in this investigation and the findings.

Concretely, in section 2 we show how the Flemish road network and the impact of catenary ERS implementation is modelled. And how we use the inputs covering Flanders geography, traffic, industrial site locations, vehicles, their performance and cost parameters, and a number of technology adoption scenarios for simulating the impacts for the various stakeholders.

In section 3.1, we discover that the development of the catenary ERS network in Flanders can be logically structured in five implementation stages. We show what those stages are and where the network could most rationally be built in each of those stages. As the simulated network grows, we

[1] Electric Road System
[2] Movares (2020)

observe that the international road freight traffic starts using it, which brings additional synergies that ensure economic sustainability of the ERS network operator, as described in 3.2.

For the trucking sector, described in section 3.3, we observe how the catenary network, which allows minimising investment in vehicle batteries, allows cost-efficient decarbonisation of road freight. The return on investment for the road hauliers improves, especially in the short run for the first-movers before the prices have managed to adapt due to supply pressures. We also conclude that once the catenary network is fully built, even the truck of smallest battery size of only 100 kWh usable energy can serve almost any industrial site in Flanders.

In this research, we simulated the catenary network operator who is not subsidised and invests rationally in developing the network to maximise his profitability. In section 3.4 we show that the operator can successfully reach a modest level of profitability at reasonable technology adoption levels and is capable of covering all investment and operation costs.

Given the importance of decarbonising, we simulate the impact on emission costs that society has to cover. Our calculations described in section 3.5 show how the use of catenary ERS in Flanders can radically reduce the costs to society, which amount to approximately € 1 billion every year. The emission cost reduction can reach 77% in monetary terms, which in volume terms corresponds to 69% of CO_2 and complete local pollutant reduction.

Last, in section 4 we propose some policy statements resulting from this research. We offer statements which could be used for both, supporting and countering implementation of the catenary ERS system. The statements relate to the implementation of the system, achievement of emission targets and the various impacts of the system which have been investigated in this research. We believe there is value in seeing both sides of the argument.

2 METHODOLOGY

In this sub-chapter, the approach for modelling the implementation of catenary ERS in Flanders is described. We first show the research questions that guided our work, then we describe the taken modelling approach, and last, we focus in detail on specific data, inputs and assumptions that were used as inputs in this work.

2.1 Research questions

The work on this work package, as defined in the project terms of reference, was guided by the following four research questions:

1. **What are the economic impacts** of the catenary ERS implementation in Flanders for the road haulage industry, their clients and wider society?
2. **What is the most optimal way for building-out the catenary ERS network** in Flanders for maximising the economic benefits and minimising externalities for all the relevant stakeholders?
3. **What are the synergies** that could come from the implementation of the catenary ERS system in the countries that are main trading partners of Flanders and/or in the transit countries that are used for this trade? What are the requirements for capitalising on those synergies?

4. **What are the** main impacts of the catenary ERS system that can (and will) be simplified to become **arguments for the policymakers** to support (or counter) implementation of the system?

2.2 Approach

To answer the research questions we developed a model that allows quantifying the impacts of catenary ERS implementation on Flemish roads to answer the above research questions.

Figure 1 – Modelling approach

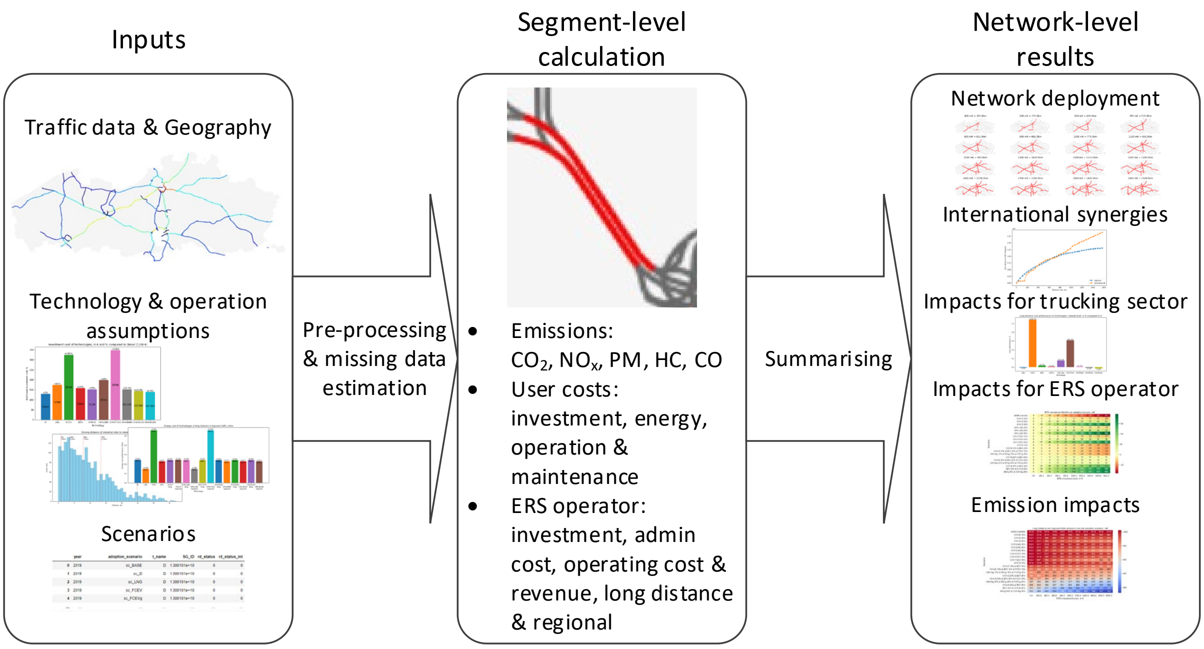


Figure 1, starts with collecting input data. The input data, described in detail in section 2.3 below, describe Flemish geography and roads, road freight traffic volumes on those roads, industrial site locations in Flanders, vehicle and technology performance characteristics, infrastructure cost assumptions, emission cost assumptions, etc. Also, a number of technology adoption scenarios are developed to test the performance of each of the investigated vehicle types separately and in a mix with other vehicle types.

The raw data that we were able to obtain is incomplete, therefore in the next step of the modelling approach, first arrow from the left in Figure 1, pre-processing of data to prepare it to be used in the model was done. Where the data was incomplete missing data is estimated. The methods that are used for this are described in section 2.3 below together with the relevant data inputs.

Then, the segment[3]-level calculation for the entire Flemish road network is done. This means that for every segment on the road network the level of emissions (and their costs), user costs and ERS operator costs and revenues are calculated.

[3] A road segment is a section of the road network which the vehicles cannot enter or leave in the middle. Entering or leaving a segment is possible only at the ends of any segment.

Next, second arrow in Figure 1, summarising of the segment-level results is done. This is needed to translate the local impacts that any modelled technology scenario might have from local segment level to Flanders level. The impacts on the regional off-motorway traffic is also calculated in this and the above step, in a similar manner.

Last, having the result summaries allows producing network-level outputs that describe the catenary ERS network deployment, potential synergies that would come from international traffic use of catenary network in Flanders, economic impacts for trucking sector and ERS network operator and emission cost impacts for society. Those network-level results are presented in detail in section 3 below.

2.3 Modelling inputs

To do the required calculations inputs that describe the geography of the modelled region, the spatial layout of the origins/destinations of the cargo, cost and performance characteristics of the vehicle technologies and infrastructure are required. Here we describe the details and sources of the used input data.

2.3.1 Geography

The geographical location of roads and their shape that is used in this work is obtained from Web Web Map Service (WMS) of Vlaams Verkeerscentrum[4] that provides georeferenced maps and data over the internet. Each road in the data is divided into segments – streches of road between two successive points where traffic can join or leave the road – and data is provided on segment level. We also use use the outline shape of Flanders from the same source.

2.3.2 Traffic data

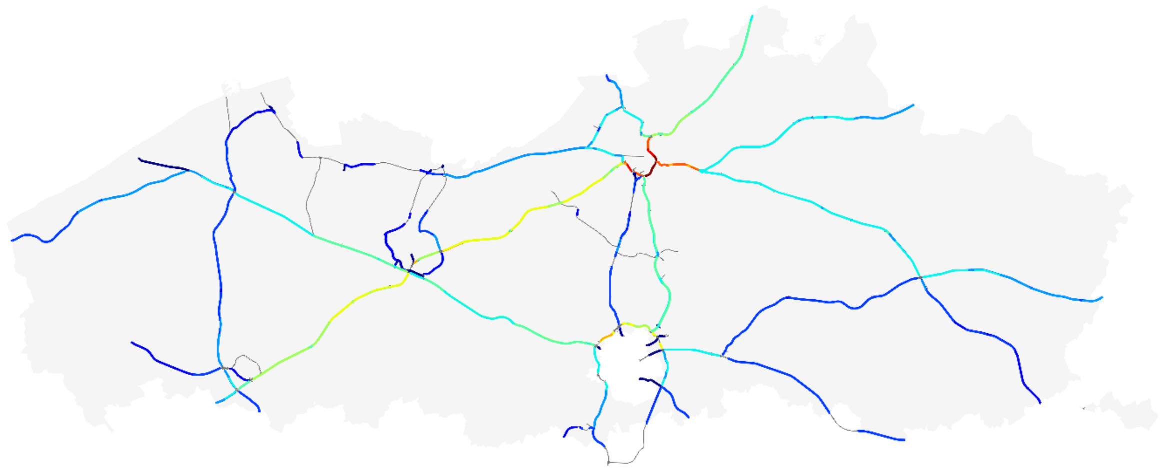
The truck traffic data from Verkeerscentrum are also obtained from their WMS and linked to the geography information. We use the provided data for an average day and for modeling purposes convert it to yearly volume for each road segment.

The traffic data is available in split by vehicle type in which heavy goods vehicles are defined as those vehicles longer than 6.9 m and include all rigid or articulated vehicles.

Recorded heavy goods vehicle traffic volumes are shown in Figure 2. Darker blue show lower, yellow shows medium and red shows high recorded traffic volumes. Motorways with fine dark grey lines have no recorded data available.

[4] A technical description of the used WMS is available from Stuyts (2021).

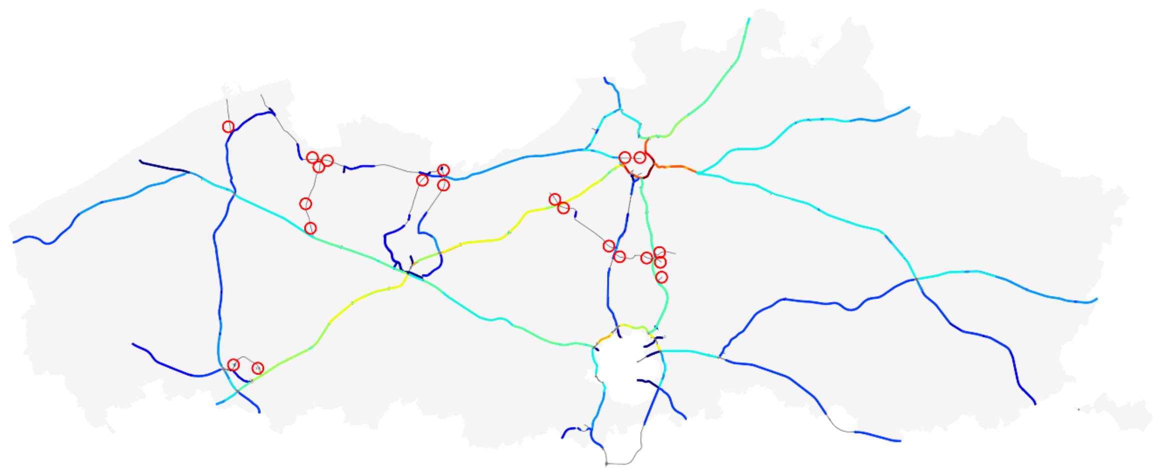
Figure 2 - HGV motorway traffic intensity in Flanders



There are two areas where the above traffic data is lacking. First, there are the roads where traffic volumes are not recorded, shown fine grey roads in Figure 2. And, second, there is no split in the data of the traffic volumes into national and international traffic.

For roads with missing data, a machine learning approach using KNeighborsRegressor is used from scikit-learn learn package in Python. In simple terms it is an approach that allows estimating the missing traffic volume on a specific road segment based on the available data of neighbouring road sections. To improve the estimation results in some places in the road network in the training dataset the traffic volumes were provided manually, marked with red circles on the road network in Figure 3.

Figure 3 – Locations with manually provided data for traffic estimation model



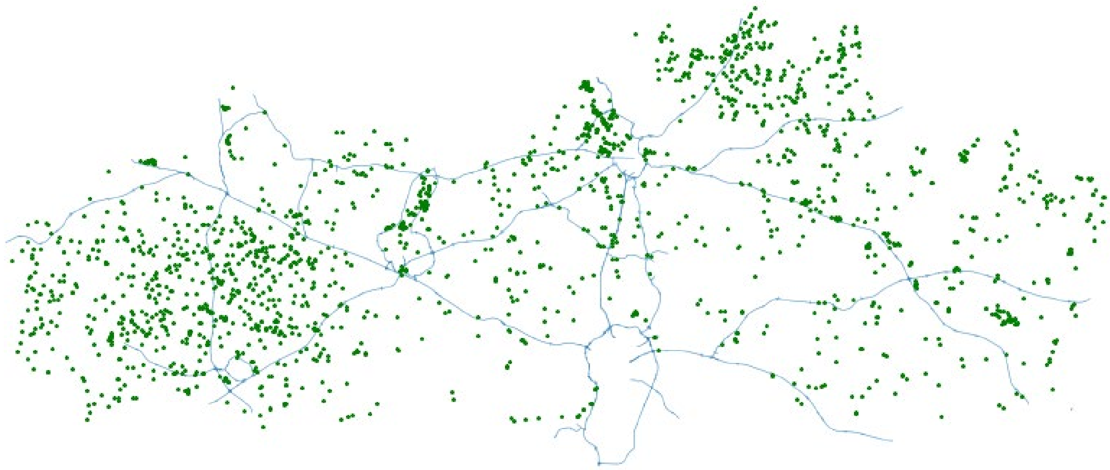
Other algorithms were also tested for this, including classic neural net and random forest for which hyperparameter optimisation was attempted, but that yielded worse results on a test set than the chosen approach.

to obtain access to big data containing GPS routing of all trucks in operation in Belgium, but unfortunately this was not possible before writing of this chapter of the report. Nevertheless, we think that our estimation provides a reasonable traffic split and does not introduce substantial calculation error.

2.3.3 Industrial sites in Flanders and battery sizing

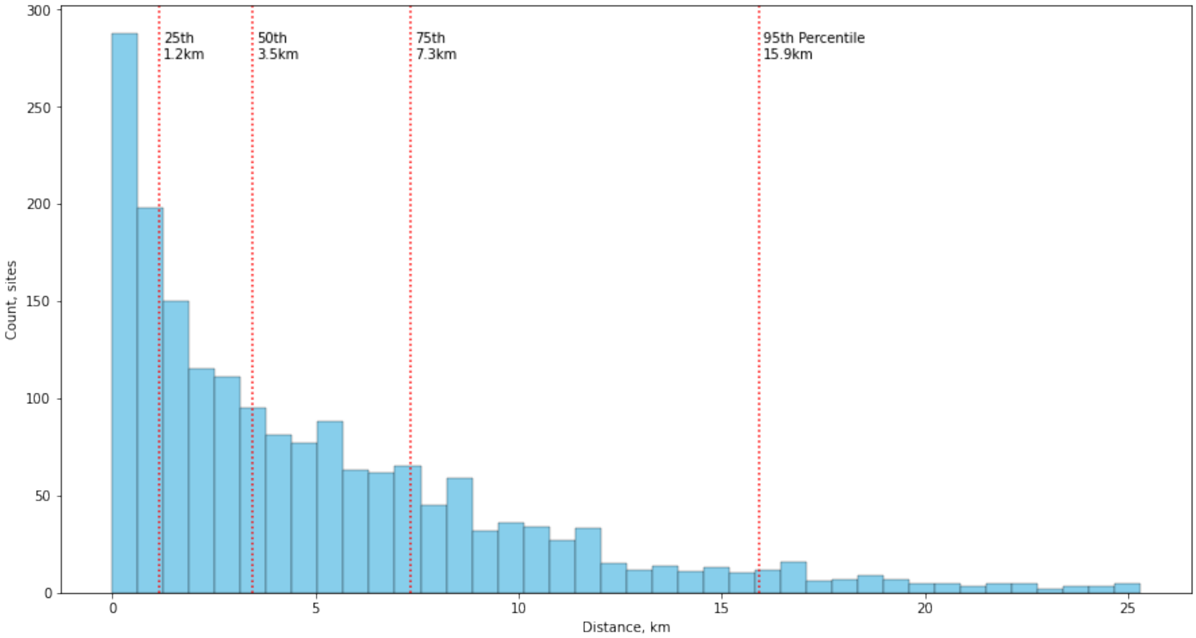
The region of Flanders was one of the first areas of continental Europe to undergo industrial revolution in the 19th century. Initially the industry developed in food processing and textiles, but after the second world war petrochemical and other industries expanded. Despite the current structure of economy that is mainly service-oriented, the tradition of port activity and industrialisation has resulted in the region having a network of industrial sites that are well connected with the motorway network, see Figure 4. The data on industrial site GPS locations is available from Vlaamse Milieumaatschappij (2020).

Figure 4 - Locations of industrial sites in relation to motorway network in Flanders



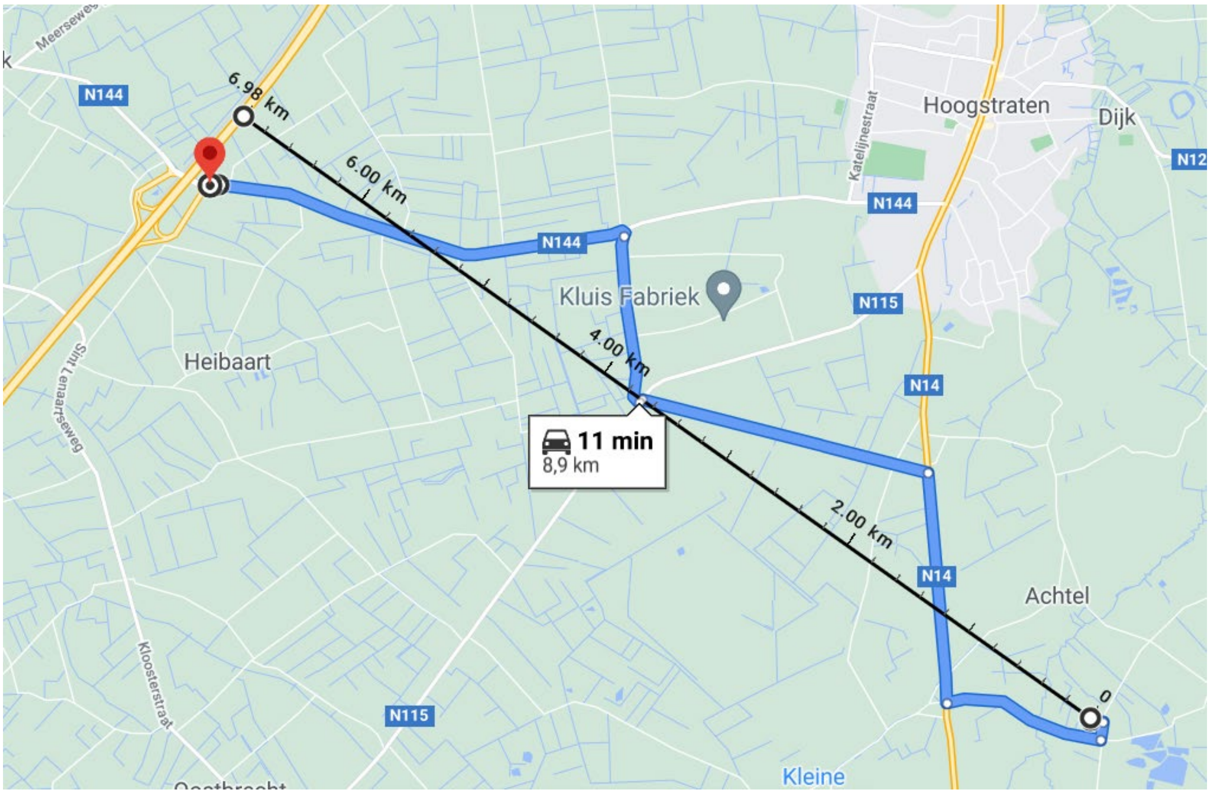
For assessing the appropriate technologies, e.g. battery size for catenary heavy goods transport operations, it is useful to understand where industrial sites are located in relation to the nearest motorway. In order to understand that, using motorway network data and industrial sites registry, we measured the distance to the nearest motorway for each industrial location in straight line. The results of this are shown in Figure 5. We see that 50% of the industrial sites are less than 3.5km away from the motorway, and 95% are within 15.9km.

Figure 5 – Distance of industrial sites to nearest motorway, Flanders



Although representative to a certain degree, the measurement in direct line is not very useful for understanding the actual distance the vehicle has to travel through the road network from an industrial site to the closest off- or on-ramp of the motorway. As shown in Figure 6 for one of the industrial sites, the distance through the road network will be longer, like in this example 9 km instead of 7 km.

Figure 6 – Routing example: Distance as the crow flies vs. routed distance



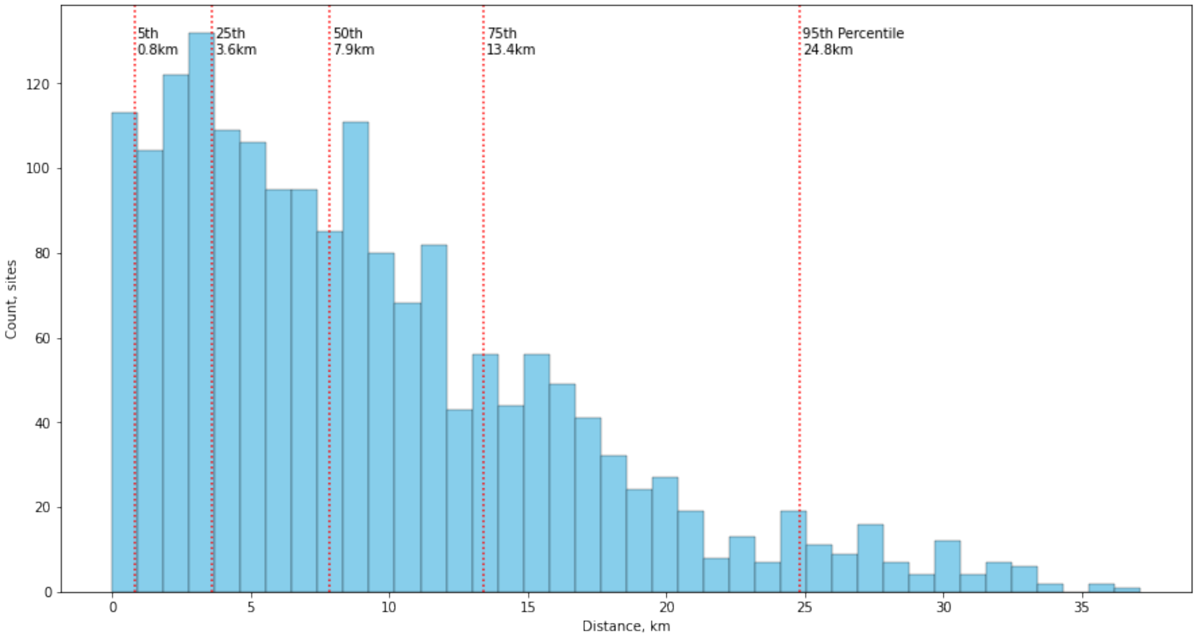
In order to gain a more useful assessment of the distance that a heavy goods vehicle has to travel to/from the motorway from the industrial sites in Flanders, a routing exercise was conducted. Using Python and Open Source Routing Machine[5] we routed the shortest distance to the closest motorway for each of the registered 1827 industrial sites in Flanders.

This gives us a more accurate assessment of the actual locations of the industrial sites in relation to motorway network. As shown in Figure 7, 25% of the industrial locations are less than 3.6 km away, 50% are less than 7.9 km away, 75% are less than 13.4 km away and 95% are less than 24.8 km away from the motorway network.

We conclude that, due to the compact geography of industrial sites to be served and the dense motorway network in Flanders, there the use of catenary hybrid road freight vehicles even with small batteries seems very promising, especially in the later stages of catenary network development.

[5] https://github.com/Project-OSRM/

Figure 7 – Driving distance of industrial sites to nearest motorway, Flanders



2.3.4 Vehicles

For modelling it is assumed that heavy goods transport in the developed scenarios can use diesel, LNG, hydrogen, electricity from batteries and electricity from overhead catenary for propulsion. Also, hybrid combinations of all the fuels with electricity can be used. In this section, we describe our assumptions on vehicle emissions for each propulsion type and list the assumptions for each vehicle type that we model.

Forecasting of vehicle technology developments that relate to fuel efficiency improvements for different tested technologies falls out of the scope of this research. Also, it seems that no substantial efficiency improvements in the currently mature technologies can be achieved in daily operations. Therefore, the future performance of technologies is not assumed, estimated or modelled.

2.3.4.1 Vehicle emissions

The emissions from heavy goods vehicles are of five major categories: carbon dioxide CO_2, nitrogen oxides NO_x, particulate matter PM, hydrocarbons HC and carbon monoxide CO are taken into account. Those are related to the energy that the vehicle uses during operation on a specific road segment. For example, for hybrid vehicles a combination of the emissions would be used in calculation depending on the defined operational pattern for a specific road segment.

The vehicle emissions by specific power sources are shown in Table 1. The power sources are D – diesel, LNG – liquified natural gas, H_2 – hydrogen, CAT – catenary electric road system, EL – battery-electric with electricity supplied from catenary, GEL – battery electric with grid electricity supplied from grid without the use of catenary electric network.

For trucks using diesel [D] for propulsion, the emissions assumption is done based on data provided by Gnann et al. (2017), which is recalculated to our needs based on Aronietis (2015). For LNG we use the emission values provided in Gnann et al. (2017). For trucks using hydrogen [H_2] we rely on Gnann et al. (2017), although acknowledge that currently hydrogen is in practice produced in an inefficient process from fossil fuels and the emissions may vary greatly depending on what hydrogen generation process is used at that time if it actually starts being used for road freight propulsion. For battery electric [EL] and [GEL] we also rely on values used in the study of Gnann et al. (2017), while for catenary electric [CAT] we assume that the emissions are those of power generation in Belgium in 2019. The split of CO_2 emissions into tank-to-wheel and well-to-tank is introduced based on Movares (2020) study.

Table 1 – Emissions in g per kWh of generated power by fuel type

	CO_2	CO_2 TTW	CO_2 WTT	NOx	PM	HC	CO	*Source*
D	324	256	68	1.620	0.012	0.005	0.125	*(1)(2)(5)*
LNG	307	247	60	0.25	0.0013	0.25	0.341	*(4)(5)*
H_2	306	0	306	0	0	0	0	*(1)*
EL	119	0	119	0	0	0	0	*(3)(6)*
CAT	119	0	119	0	0	0	0	*(3)(7)*
GEL	119		119					*(3)(6)*

Sources: (1) Recalculation of Gnann et al. (2017), (2) Gnann et al. (2017), (3) European Environment Agency (2021) for Belgium, (4) Estimate based on Verbeek and Verbeek (2015), Vermeulen (2019) and Gis, Pielecha and Gis (2021), (5) Movares (2020), (6) assuming battery 80% charge-discharge efficiency and 90% motor efficiency, (7) assuming 80% catenary efficiency and 90% motor efficiency

When interpreting the modelling results it must be taken into account that diesel and LNG vehicle emissions cannot be substantially reduced further by any means. At the same time, hydrogen vehicle emissions can be reduced using technical solutions, the economic viability for which has not yet been proven. The electricity grid used for battery electric and hybrid catenary propulsion is gradually reducing its emissions because of existing economic incentives, making zero emissions achievable. Also, it is possible to use green Power Purchase Agreements to ensure emission-free operation of the ERS catenary.

2.3.4.2 Vehicle performance

In the model, we introduce vehicle types that are powered from a single power source, like diesel [D], LNG, hydrogen [FCEV] or battery electric [BEV], and hybrid vehicles that can use catenary, like catenary-diesel [CHV-D], catenary-LNG [CHV-LNG], catenary-hydrogen [CHV-FCEV] and catenary-battery electric vehicles [CHV-Bxxx] with different usable battery capacities (denoted in index in kWh of usable battery capacity).

As inputs for the model, we use a number of other parameters that describe the energy and economic performance characteristics of each vehicle type, shown in Table 2.

Table 2 – Energy and economic performance of modelled vehicle types

Vehicle type	Energy		Investment, €	Energy consumption[1]		Operation & maintenance[1]	
	long distance	regional		long distance, kWh/km	regional, kWh/km	long distance, €/km	regional, €/km
D	D	D	129000[1]	2.46[1]	2.46[1]	0.143	0.143
LNG	LNG	LNG	174000[1,6,7]	2.78[1]	2.78[1]	0.143	0.143
FCEV	H2	H2	324000[3]	2.25[1]	2.25[1]	0.137	0.137
BEV800	GEL	GEL	148400[2]	1.42[4]	1.42[4]	0.126	0.126
BEV1200	GEL	GEL	167600[2]	1.42[4]	1.42[4]	0.126	0.126
CHV-D	CAT	D	152000[1]	1.51[4]	2.46[1]	0.107	0.143
CHV-LNG	CAT	LNG	197000[1&2]	1.51[4]	2.78[1]	0.107	0.143
CHV-FCEV	CAT	H2	347000[1&2]	1.51[4]	2.25[1]	0.107	0.137
CHV-B400	CAT	EL	152200[2]	1.51[4]	1.42[4]	0.107	0.126
CHV-B200	CAT	EL	142600[2]	1.51[4]	1.42[4]	0.107	0.126
CHV-B100	CAT	EL	137800[2]	1.51[4]	1.42[4]	0.107	0.126

Sources: (1) Gnann et al. (2017), excludes driver wage and administrative overheads, (2) Estimation based on the following: 1) a hybrid truck without battery and pantograph costs € 110 thousand; 2) pantograph system costs additional € 23 thousand; 3) battery costs 48 €/kWh in 2030 based on Bloomberg NEF (2020), (3) Gnann et al. (2017) and Transport & Environment (2020), (4) Movares (2020), (5) Smajla et al. (2019) (6) Moritz Mottschall, Peter Kasten, and Felipe Rodríguez (2020).

2.3.5 Infrastructure cost

Building out catenary ERS infrastructure requires a number of components to be built. Starting from the electricity grid side, there should be a power grid connection that is provided by the regional/national grid operator usually at 10-20 kV. Next, in a substation a transformer and a rectifier is required to reduce the medium voltage to an acceptable level for overhead catenary and a rectifier to convert the three-phase AC into DC. The number and density of substations on an electrified road will depend on the power requirements that are determined by the traffic flow and the voltage level. Last, an overhead catenary with two messenger wires and two contact wires is required.

An example of catenary infrastructure currently operational near Frankfurt Airport on motorway A5 in Germany is shown in Figure 8. Circled is a 20-foot container housing one of the substations.

Figure 8 – Catenary ERS infrastructure on motorway A5, near Frankfurt, Germany

Source: photo from field trip to A5 motorway, 07.10.2021

In practice, the infrastructure can be built out either in a “continuous line” with minimal interruptions for more complex road stretches or skipping tunnels to reduce construction costs, or in “dashed line” pattern where on a motorway stretch gaps would be left to reduce costs, while higher charge rates would need to be required on the covered stretches to compensate for the lacking network in other places. We think that “dashed line” approach is promising for early stages of catenary network implementation in specific situations, but in the development of our model we do not investigate it due to the technological unknowns and complexity that it would introduce.

Based on construction costs in Germany and Sweden, it can be estimated that 1 km of infrastructure in Belgium could cost € 1.15 to € 1.4 million for a continuous catenary lane in one direction, depending on the density of sub-stations, which are determined by the expected traffic level. In modelling ERS infrastructure, the investment cost per km is estimated depending on the freight traffic volume as show in Table 3.

Table 3 – ERS infrastructure cost depending on freight traffic volume per road segment

Total freight traffic volume, vehicles / day			ERS infrastructure cost, million €/km
0	-	1000	1.15
1000	-	6000	1.2
6000	-	12000	1.3
12000	-	999999	1.4

2.3.6 Energy cost and price

In Table 4, the energy cost and price that are used in the model are shown. The cost column contains the electricity price that the ERS network operator would have to pay, estimated based on Eurostat (2021) data. The sale price of electricity by the network operator is set with 87.5% markup, which was calculated to balance the requirement to cover investment costs of the network operator with economic sustainability of the catenary users. The price of diesel is estimated based on GlobalPetrolPrices (2021) and Dats24 (2021) and taking into account excise return system for professional diesel users. The hydrogen price was determined by visiting a hydrogen filling station in Zaventem and confirmed on Carbu.com (2021).

Table 4 – Energy cost and price, €/kWh excluding VAT

Energy	Cost	Price
D	-	0.124
LNG	-	0.053
H_2	-	0.248
EL	0.08	0.15
CAT	0.08	0.15
GEL	-	0.14

Sources: Eurostat (2021), GlobalPetrolPrices (2021), Dats24 (2021), Carbu.com (2021), Wartsila
Energy type abbreviations: D – diesel, LNG – Liquified/compressed natural gas, H2 – hydrogen, EL – electricity supplied by ERS operator for use in regional traffic, CAT – electricity supplied by ERS operator for direct use on motorway, GEL – grid electricity

2.3.7 Adoption scenarios

A number of technology adoption scenarios were made for testing what the impacts of the introduction of those technologies would be in Flanders. Each of the scenarios is developed based on vehicle stock data on 1st January 2021, Statbel (2021), and by substituting diesel vehicles with the tested market share of the particular tested technology.

There are two types of scenarios introduced in the model. The first type are scenarios where a single technology adoption is simulated, and the second type is where a technology mix is introduced. This allows testing both the performance of a single technology and also more realistic situations where a number of alternative technologies would be adopted. This is important to specifically understand the initial decarbonisation stages, where possibly no winning technology would be apparent and a technology adoption mix is more likely.

A summary of technology adoption scenarios is shown in Table 5. The scenarios are listed in rows of the column and the technology shares of each technology are shown in the columns. To have a reference, a base scenario of the current situation is created that describes the current situation where almost all trucks use diesel and only 1.35% use CNG/LNG and 0.17% are battery electric, shown in the first row of the table. Next in the table, a number of pure technology adoption scenarios are listed in rows D to CHV-B100.

Table 5 – Technology adoption scenarios

	Tecnology adoption, %										
Adoption scenario	D	LNG	FCEV	BEV800	BEV1200	CHV-D	CHV-LNG	CHV-FCEV	CHV-B400	CHV-B200	CHV-B100
BASE	98.48	1.35	0	0.17	0	0	0	0	0	0	0
D	100	0	0	0	0	0	0	0	0	0	0
LNG	0	100	0	0	0	0	0	0	0	0	0
FCEV	0	0	100	0	0	0	0	0	0	0	0
BEV	0	0	0	50	50	0	0	0	0	0	0
CHV-D	0	0	0	0	0	100	0	0	0	0	0
CHV-LNG	0	0	0	0	0	0	100	0	0	0	0
CHV-FCEV	0	0	0	0	0	0	0	100	0	0	0
CHV-B400	0	0	0	0	0	0	0	0	100	0	0
CHV-B200	0	0	0	0	0	0	0	0	0	100	0
CHV-B100	0	0	0	0	0	0	0	0	0	0	100
CHV-B-mix	0	0	0	0	0	0	0	0	33.33	33.33	33.33
CHV-D10	88.48	1.35	0	0.17	0	10	0	0	0	0	0
CHV-D20	78.48	1.35	0	0.17	0	20	0	0	0	0	0
CHV-D40	58.48	1.35	0	0.17	0	40	0	0	0	0	0
CHV-LNG10	88.48	1.35	0	0.17	0	0	10	0	0	0	0
CHV-LNG20	78.48	1.35	0	0.17	0	0	20	0	0	0	0
CHV-LNG40	58.48	1.35	0	0.17	0	0	40	0	0	0	0
CHV-FCEV10	88.48	1.35	0	0.17	0	0	0	10	0	0	0
CHV-FCEV20	78.48	1.35	0	0.17	0	0	0	20	0	0	0
CHV-FCEV40	58.48	1.35	0	0.17	0	0	0	40	0	0	0
CHV-B10	88.48	1.35	0	0.17	0	0	0	0	3.33	3.33	3.33
CHV-B20	78.48	1.35	0	0.17	0	0	0	0	6.67	6.67	6.67
CHV-B40	58.48	1.35	0	0.17	0	0	0	0	13.33	13.33	13.33
CHV-B10-BEV10	78.65	1.35	0	5	5	0	0	0	3.33	3.33	3.33
CHV-B10-BEV10-FCEV10	68.65	1.35	10	5	5	0	0	0	3.33	3.33	3.33
CHV-B20-BEV20	58.65	1.35	0	10	10	0	0	0	6.67	6.67	6.67
CHV-B20-BEV20-FCEV20	38.65	1.35	20	10	10	0	0	0	6.67	6.67	6.67
CHV-B40-BEV40	18.65	1.35	0	20	20	0	0	0	13.33	13.33	13.33
BEV50-CHV-B50	0	0	0	25	25	0	0	0	16.67	16.67	16.67

Abbreviations for heavy goods vehicle technologies: D – diesel, LNG – Liquefied/compressed natural gas, FCEV – fuel cell electric, BEVxxxx – battery electric (index xxxx shows battery usable size in kWh), CHV-D – diesel catenary hybrid, CHV-LNG – LNG catenary hybrid, CHV-FCEV – FCEV catenary hybrid, CHV-Bxxx – battery catenary hybrid (index xxx shows battery usable size in kWh).

Adoption scenario abbreviations: based on technology name, number after technology name corresponds to technology adoption percentage.

2.3.8 Emission costs

For calculating the emission costs that Flanders as a society is bearing because of road freight transport, we base ourself on "Handbook on the external costs of transport", CE Delft et al. (2020) and "Environmental Prices Handbook EU28", CE Delft (2018). We adjust the emission cost values for inflation. A summary of model input values is shown in Table 6.

Table 6 – Emission costs

	€/kg*
CO2	0.106
NOx	15.968
PM	120.550
HC	3.807
CO	0.057

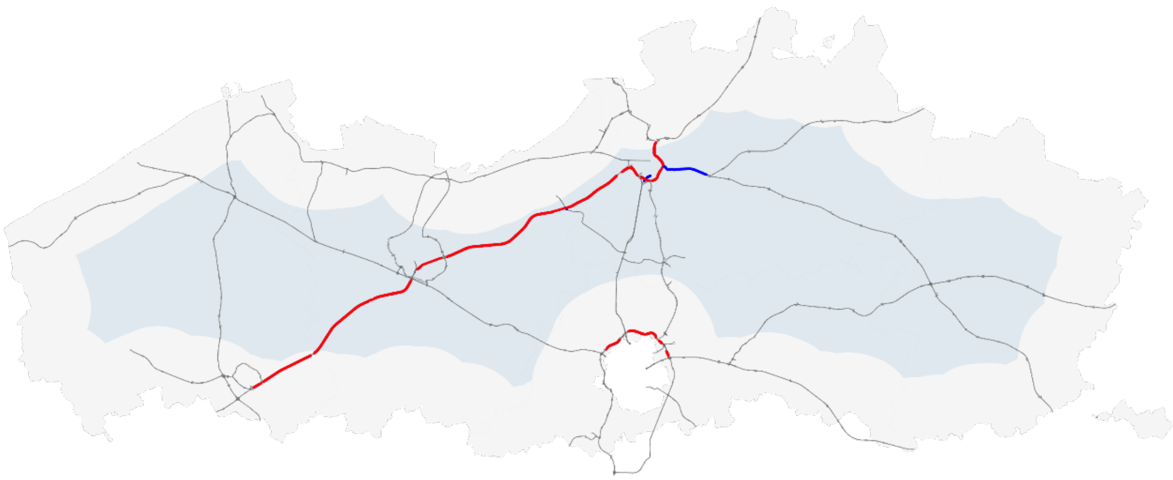
*in 2020 prices, rounded to 3 digits

2.3.9 Assumptions on international road freight transport

For determining if the international traffic on a specific road will use the catenary in Flanders, it is assumed that this will happen only if the infrastructure is sufficiently developed – ERS is built sufficiently close to the border so that a truck from abroad could reach the ERS network. The cut-off distance used is 12km.

An example for investment level of € 300 million, which corresponds to a network length of 224 km, is shown in Figure 9. It can be seen that the ERS catenary network on the E17 from Antwerp in the direction of Lille is built out sufficiently close to French border for the international traffic to use ERS on this road (road marked in red). At the same time, the first section of motorway E313 to the East from Antwerp does not reach into the border zone, therefore the catenary on this road will not be used by international traffic, unless built out further.

Figure 9 – Selection of ERS-equipped roads used in international traffic



3 FINDINGS

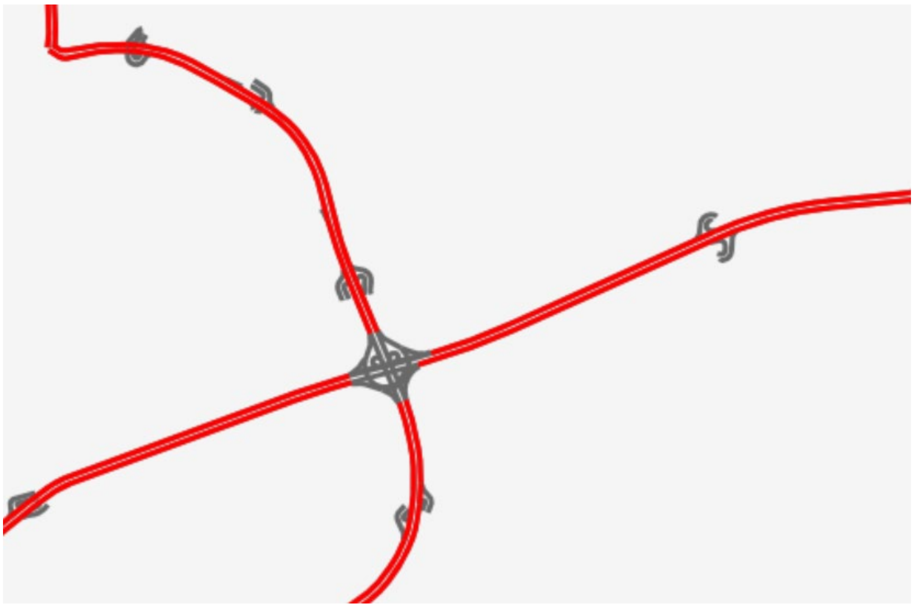
In this sub-chapter we describe the findings from modelling of ERS catenary network in Flanders.

First, we describe the development of the network and the stages that this could take. Then come the impacts that we saw for the trucking sector, specifically focussing on the cost implications for road freight transport operators. Third, the impacts of the technology adoption for the ERS network operator are summarised. Fourth, the emission cost impacts are shown. Last, synergies that come from international freight traffic are assessed.

3.1 Development of ERS catenary network

In modelling the network development, we have assumed that the ERS network operator is rational and would want to invest and build out the catenary on the road network stretches with the highest transport intensity. This is because on those stretches there would be most demand for catenary power supply. Also, we assumed that the network could be built only on straight, relatively simple sections of the motorway and would not be built on complex junctions and on/off ramps, as shown in Figure 10, where with red the roads are marked where catenary could potentially be built.

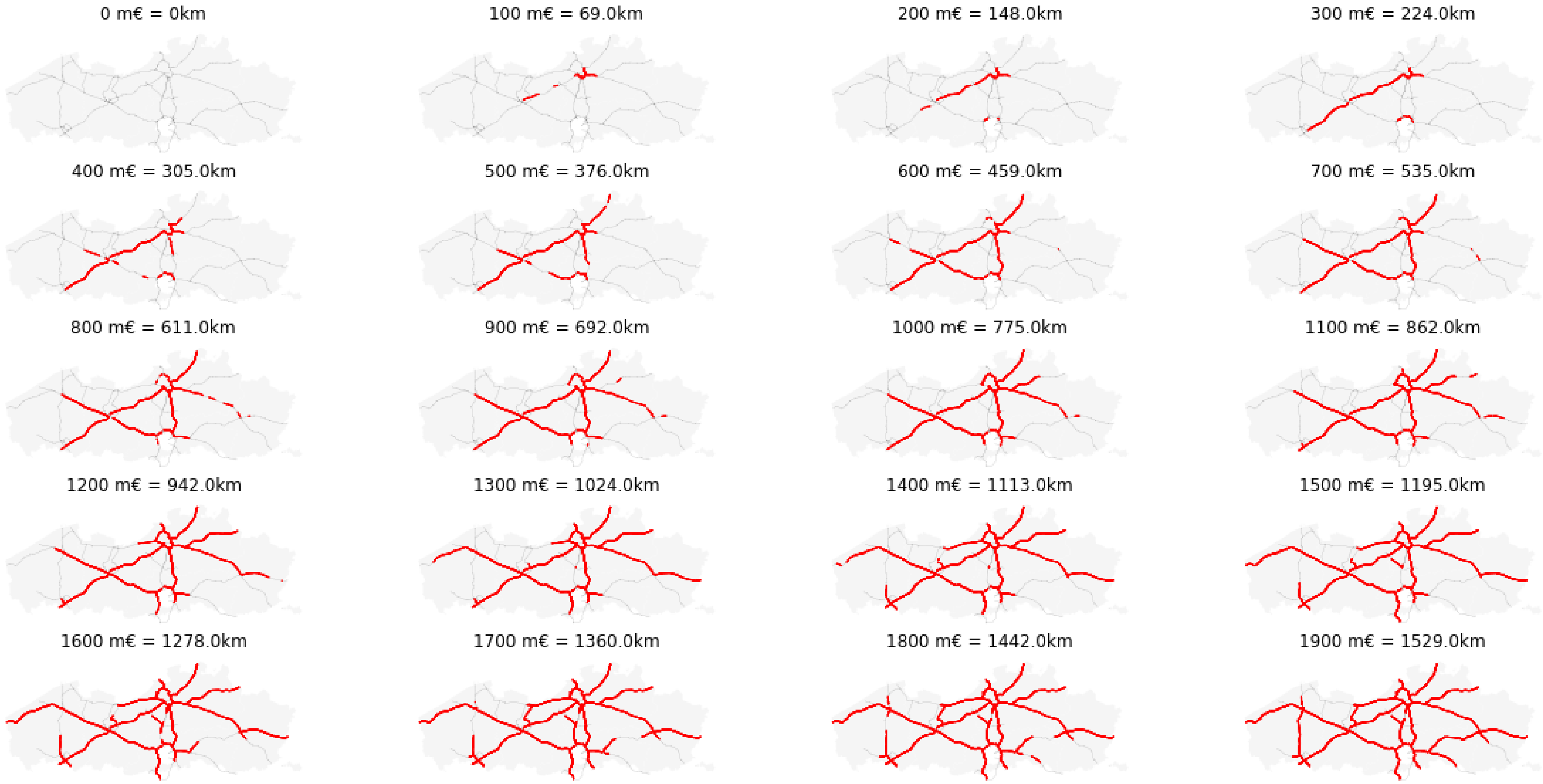
Figure 10 – Example of road stretches where ERS could be deployed (red)



When modelling the ERS network growth, we took into account the cost of building the network, which would be slightly lower for roads with lower traffic intensity, and higher for roads with high traffic intensity, as shown above in Table 3 on page 15. This is because with increased traffic volume that uses the network, additional electricity sub-stations have to be foreseen to provide the additional power that is needed by these additional trucks. In practice, a smart investor would probably want to grow the catenary power supply capacity gradually by initially deploying only a part of the sub-stations. And as the power demand grows he would increase the number of sub-stations to match it.

Subject to the above constraints of the network selection, and taking into account the non-linear relationship of infrastructure cost to traffic volumes, we model the likely deployment geography of the ERS network in Flanders depending on the investment level, as shown in Figure 11. It shows maps of ERS networks that the operator would likely build depending on the investment level.

Figure 11 – ERS network size depending on investment level, million €



We see that with a relatively modest investment of less than € 2 billion in the infrastructure, which is less than 0.8 % of Flanders GDP, extensive coverage of more than 1.5 thousand km of the whole network could be achieved.

In practice, the network development could be done in stages, as described in the following sub-sections. It is possible that priorities could be different, and some other routes are prioritised because of specific business interests of large shippers or ports. This could be interesting in the context of the planned merger of the ports of Antwerp and Zeebrugge, therefore influencing the network development proposed here. These developments are outside the scope of this research as they require investigation on a more detailed level for specific road sections that one would be interested in.

3.1.1 Stage 1: Demonstration deployment

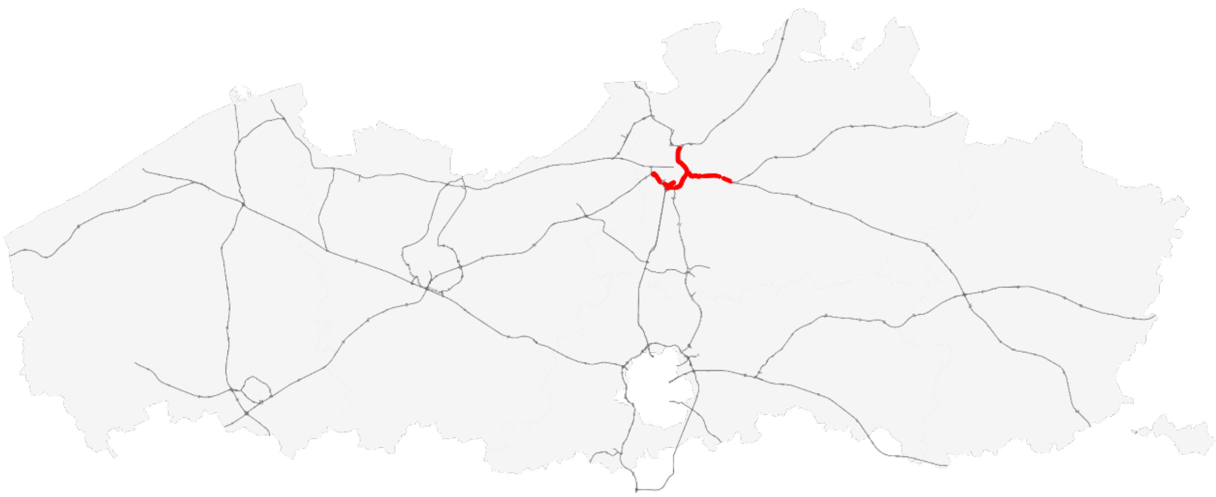
In the demonstration stage, the goal of ERS deployment is to demonstrate the feasibility of the technology for implementation in Flanders.

Due to the small scale, the exact location should be determined based on non-economic factors: engagement and commitment are more important. It could be rational to choose a motorway stretch of high complexity with high road freight traffic volumes like it has been done in Germany, where implementation in a complex high traffic environment allowed testing the system under the most extreme circumstances. This provided reassurance that implementation in less challenging traffic environments is easily possible. In case of such implementation in a suitable high-traffic area, it facilitates trucking/logistics operations for first-movers.

A part of the motorway network that meets the criteria of a complex high-traffic flow area is the Antwerp ring road R1 and the initial stretch of the E313 motorway in the East direction, as shown in Figure 12, but it could also be E17 motorway in the direction of Ghent. It should be possible to find several road freight transport operators that work daily on this road stretch.

The infrastructure investment budget for the demonstration stage could be up to € 50 million.

Figure 12 – Possible Demonstration stage location



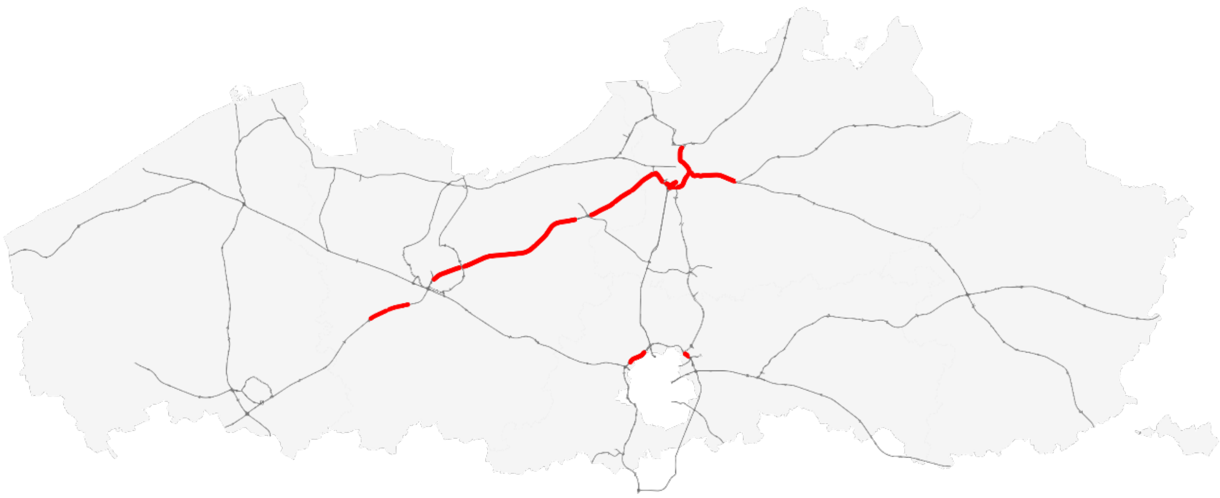
For initial demonstration also other locations must be considered, possibly, because of decarbonisation strategy of ports or specific business cases of operators that are more adapted to the use of ERS in those areas. As there are benefits to growing the system out from the initial demonstration stage, the areas of the next stage, described below, should be preferred.

3.1.2 Stage 2: Local deployment

In the second stage a regional traffic-oriented deployment on a high-priority axis should be electrified. The implementation would allow limited use of ERS in specific business cases. The motorway E17 from Antwerp to Gent is a good candidate for this because of its high freight traffic volume serving businesses between the two largest cities in Flanders, see Figure 13. Also, in parts of Brussels ring road R0 the implementation of ERS could be considered at this stage, subject to demand from logistics/trucking operators.

The investment at this stage of project, including the previous demonstration stage, could reach € 200 million.

Figure 13 – Proposed Local deployment stage location

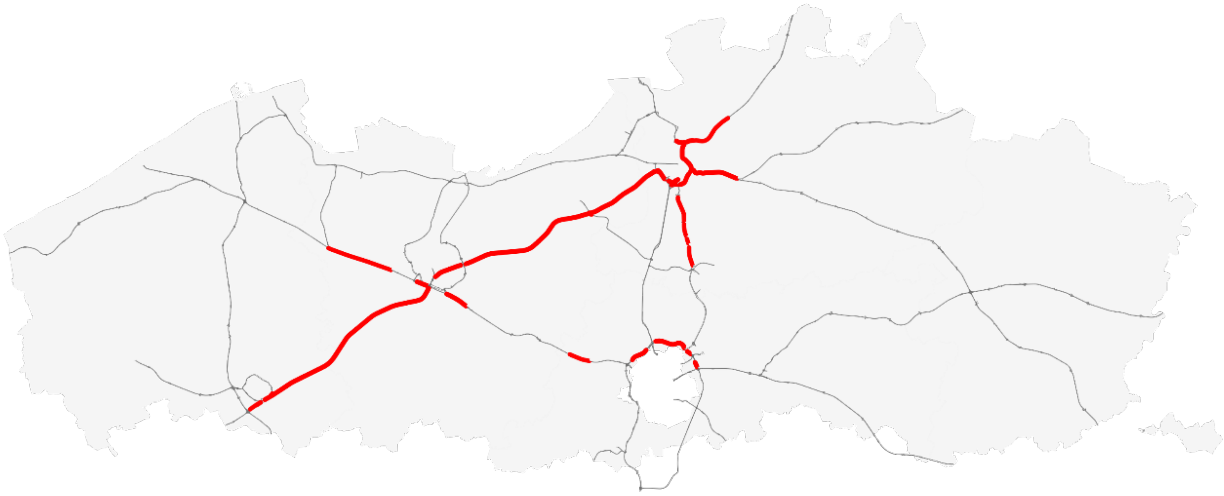


In the third stage of deployment, it seems rational for the ERS operator to extend the system to cover North-South axis on E17 on the route Antwerp-Lille, possibly starting from the border of Netherlands on E19 to Breda. Also, sections of E19 between Antwerp and Mechelen, the northern part of the Brussels ring road R0 and E40 could also be electrified.

At this stage of implementation, the total investment including the two previous stages of deployment, could reach € 400 million.

In this stage of development of the system, the first substantial benefits from international synergies appear. Those are described in detail in section 3.2 on International synergies on page 24.

Figure 14 – Proposed High-priority international axis stage location

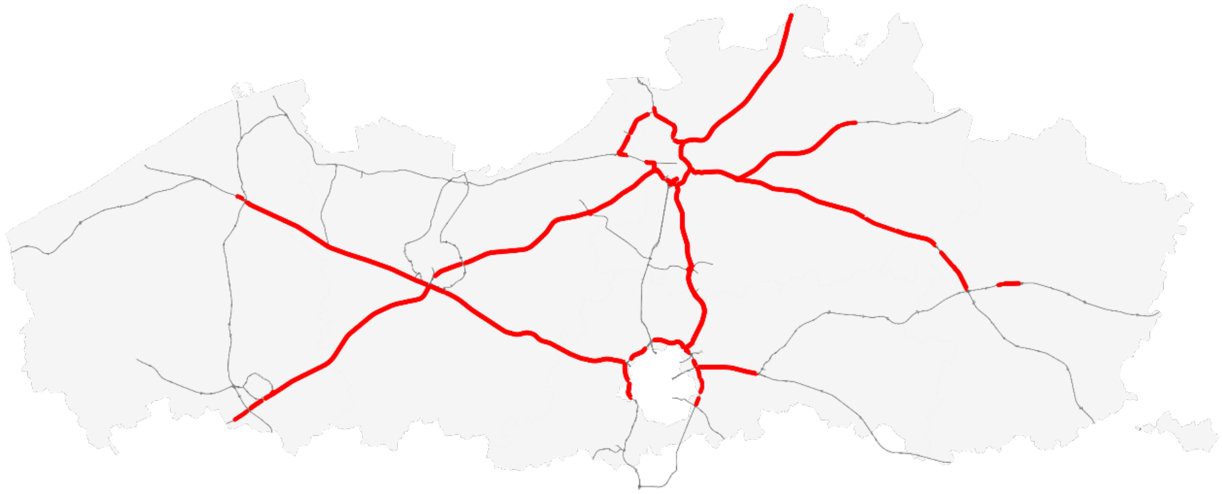


3.1.4 Stage 4: Major national & international route deployment

In the fourth stage of ERS development with the total investment of approximately € 1 billion, a substantial coverage of major axes can be reached. This allows wider operation of the ERS network in different business models in national and international traffic.

With this network size, it can be expected that international traffic starts widely using the ERS network, because it allows not only delivering freight to/from Belgium, but also using the ERS system for transiting Flanders on North-South and East-South axes.

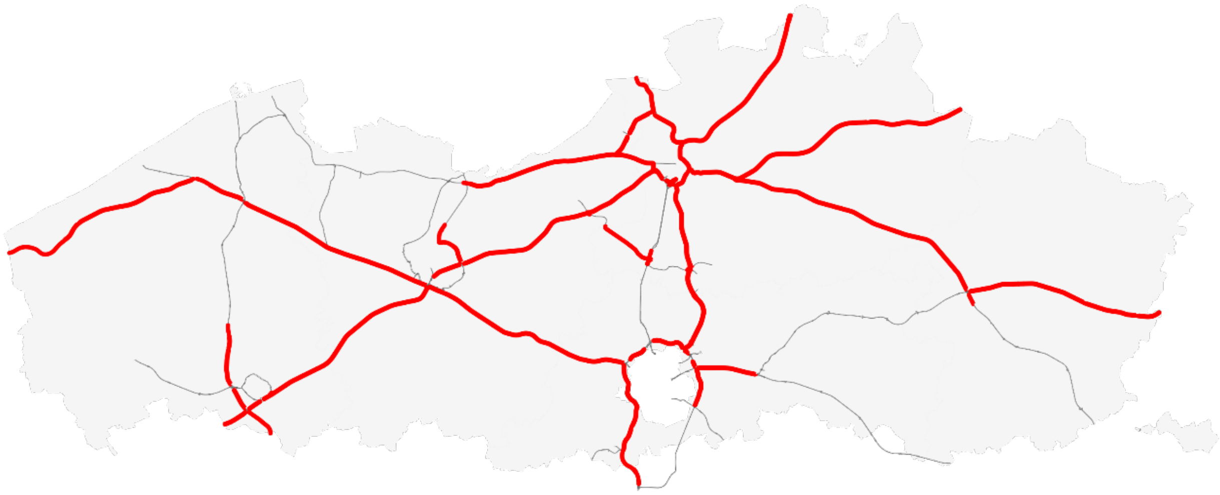
Figure 15 – Proposed Major national & international route deployment



In the fifth stage, with a total investment across previous stages of € 1.5 billion or more, the ERS catenary network will have grown extensively, covering approximately 1200 km of Flanders motorway length.

At this stage, the ERS network is mature and allows wide national and international use in a way that is suitable for most logistics business models. The possible network layout that the ERS operator might choose is shown in Figure 16.

Figure 16 – Proposed Extensive network stage



The cost of the development of the system of up to approximately € 2 billion may seem large at the first glance, but it must be viewed in the context of other transport policies that have been introduced in Belgium. For example, according to calculations of the FPS Finance and FPS Health, Food Chain Safety and Environment (2021), Belgium granted more than € 13 billion in subsidies to fossil fuels in 2019, which includes a subsidy for employee company car use of € 1.9 billion. Coincidentally, one year of company car subsidy could cover the whole required investment cost for ERS network development, which could be used for at least 20 years. The investment of less than € 2 billion is also modest in Flemish context, which is less than 0.8 % of Flanders GDP.

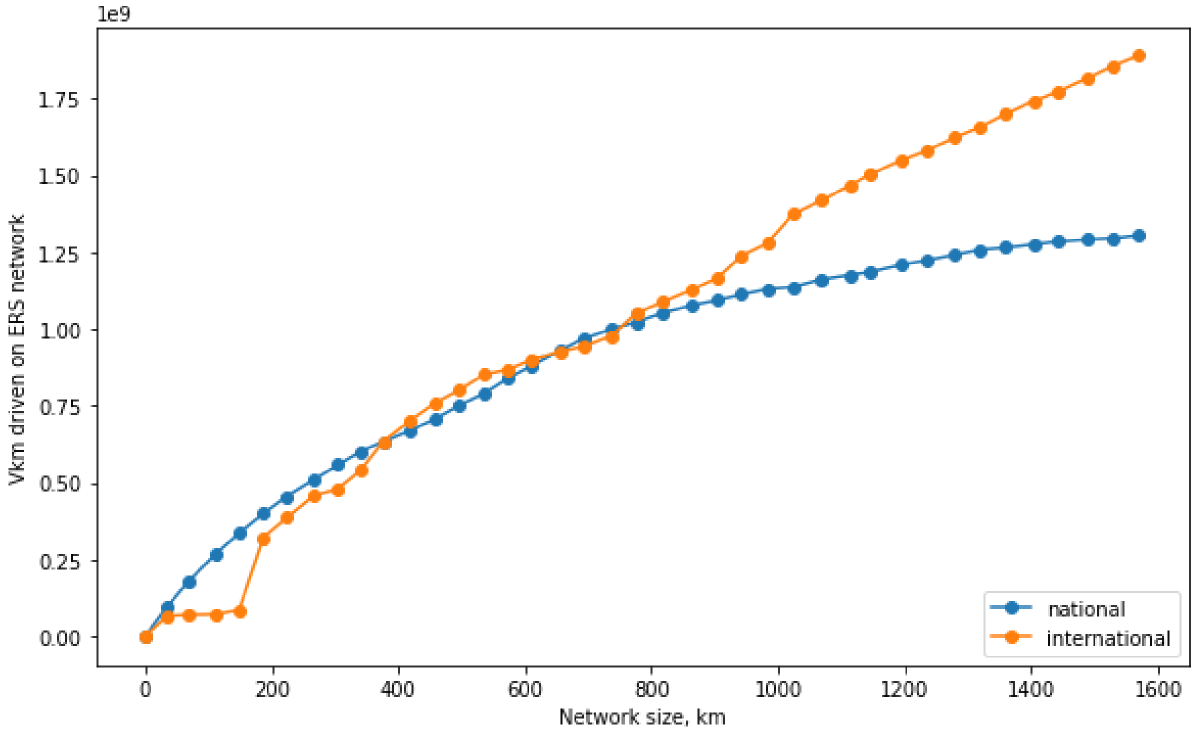
We therefore conclude that the investment required for decarbonisation of road freight transport by constructing an extensive ERS catenary network of more than 1.5 thousand km is modest in the context of Belgian mobility policies and GDP of Flanders.

3.2 International synergies

Simulation of the development of the ERS network to determine the synergies was done based on assumptions described above in section 2.3.9 on page 18. In summary, it is assumed that interoperable catenary ERS systems are available in the neighbouring countries and international traffic will start using a particular road only if ERS is built sufficiently close to the border so that a truck from abroad can reach the ERS network.

With building out of the ERS network the national traffic is the first one to use and benefit from the system, and only at the network length reaches approximately 200 km the international traffic starts using the network. As the network size grows further the proportion of national and international traffic levels out up until 900 km in length. At that point, the national traffic that uses the network starts to reach saturation, while the international traffic share on the network keeps growing, see Figure 17.

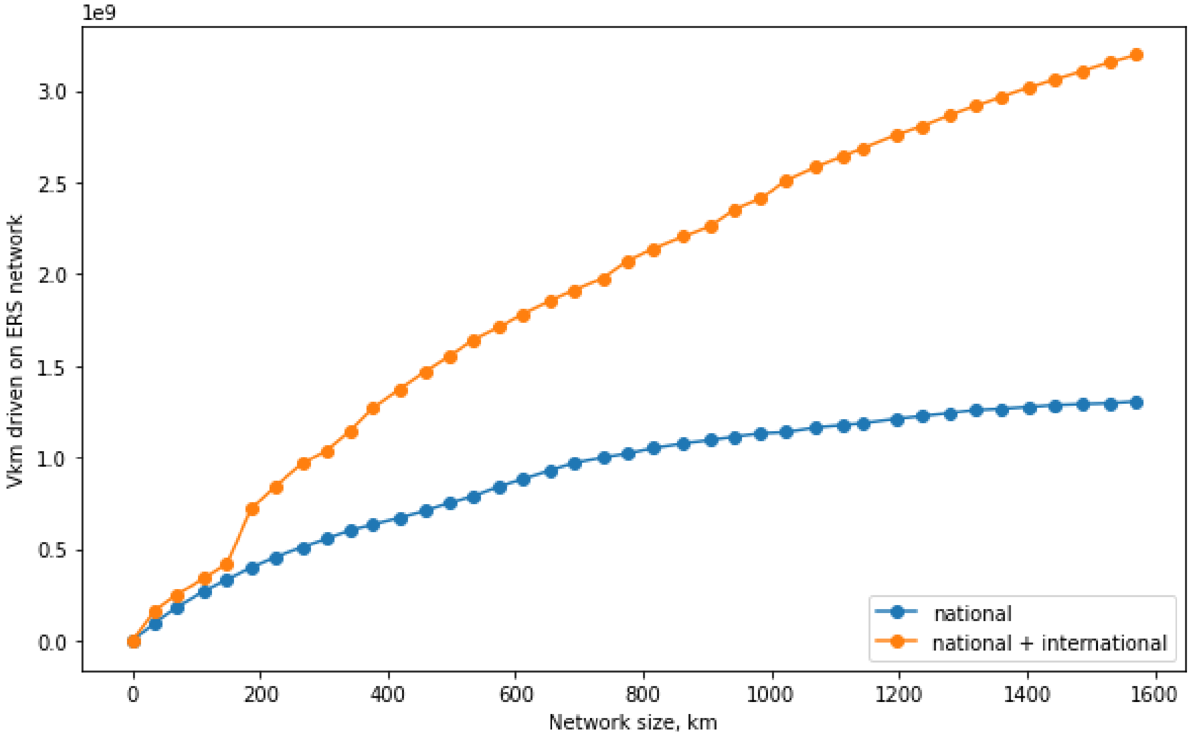
Figure 17 – ERS network use depending on the network size, billion vkm



We therefore conclude that in the initial stages of the ERS deployment the use of the network for international traffic will be limited. As the network grows it becomes possible to use it in international operations, which almost doubles the vkm driven on the catenary network. At a certain network size the national use of the network starts reaching saturation, while the international use still keeps or even slightly accelerates its growth rate. The cumulative effect of this for national and international traffic is shown in Figure 18.

For Flemish ports and logistics operators to remain competitive and relevant, in a situation where the neighbouring countries have developed their interoperable catenary ERS systems, having such a system is a must.

Figure 18 - ERS network use depending on the network size, national + international, billion vkm



3.3 Impacts on trucking sector

This sub-section compares the economic performance of the investigated technologies in motorway and regional traffic. The comparison is done for investment cost, energy cost, and operation and maintenance cost. We also compare the total cost performance of technologies.

For the purposes of comparison, it is assumed that the ERS catenary network is fully built out and the catenary trucks use catenary network whenever on the motorway. The comparison is done on the cost per vkm basis and presented as a cost percentage change from the current cost level of road freight operators for each particular cost category and in total.

Comparing the investment cost in vehicles, in Figure 19, we see that all modelled technologies require higher investment per vkm driven than currently. The investment is particularly high for hydrogen fuel cell vehicles and even higher if those vehicles are equipped with pantograph system. Investment in LNG trucks is 45% higher than currently, while the additional pantograph system naturally requires even higher investment cost. Battery electric vehicles[6] increase the investment cost per km by 22%, but the lower size of batteries for catenary versions of battery trucks allow limiting the additional investment costs in those vehicles to a range of +9 to +23%. Of particular interest, due to the fact that this technology at the time of writing is tested in field

[6] Assumed a 50:50% battery size mix between 800 kWh and 1200 kWh.

trials in Germany and Sweden, is the diesel catenary hybrid vehicle, which requires 23% of additional investment.

Figure 19 – Investment cost comparison, in € and % change compared to Diesel

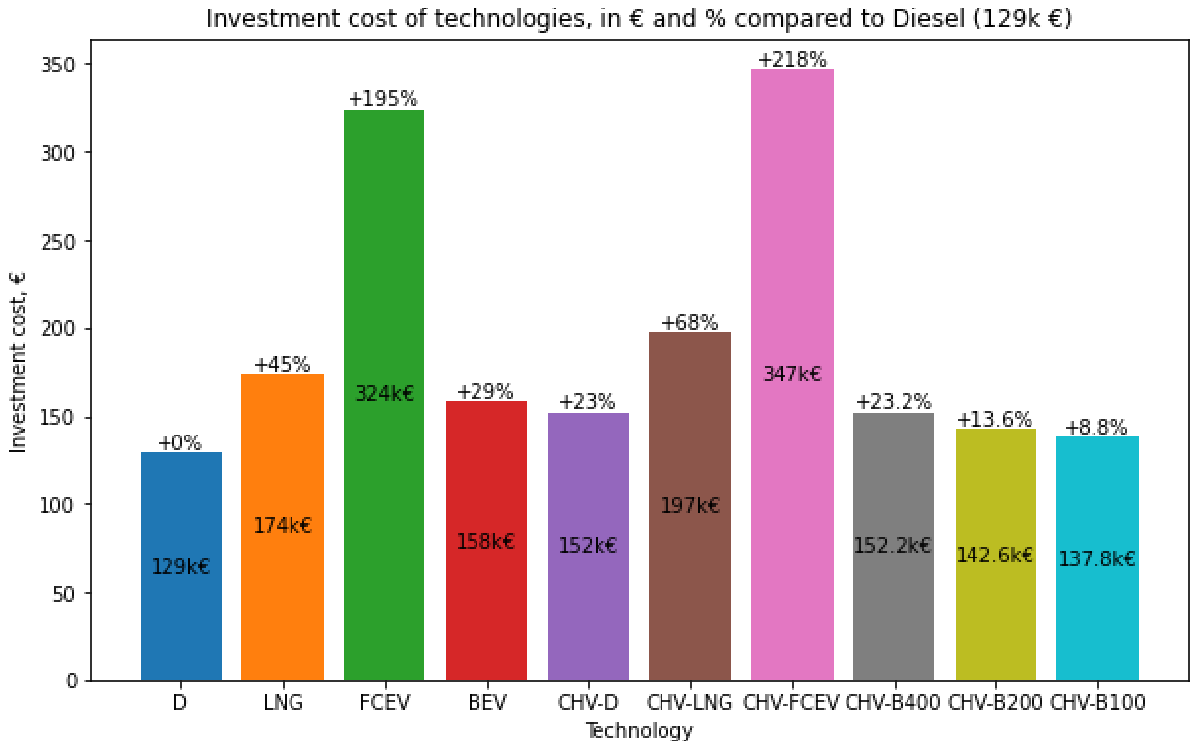
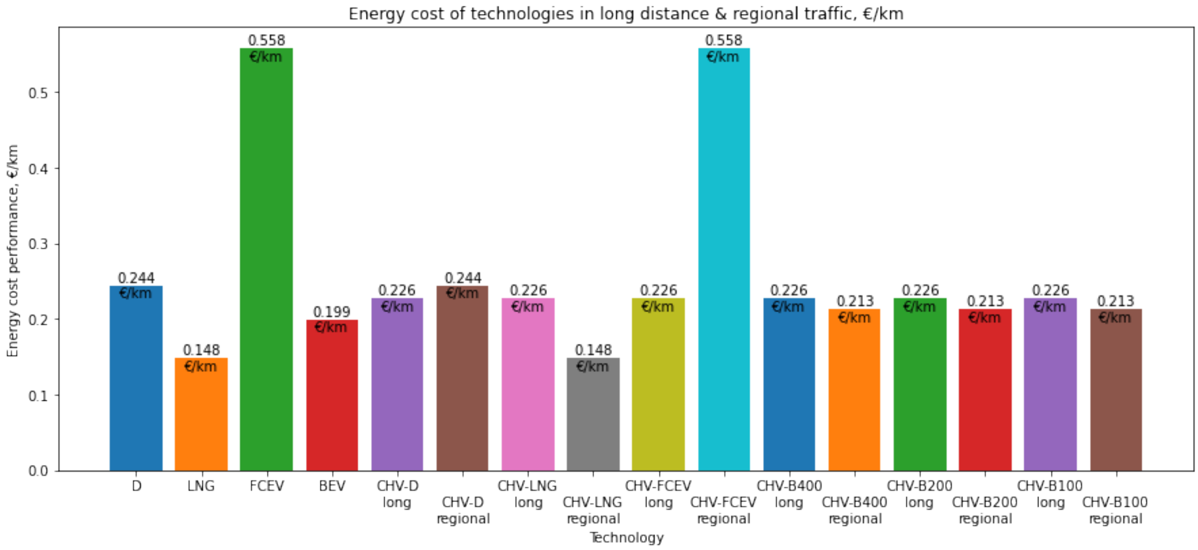


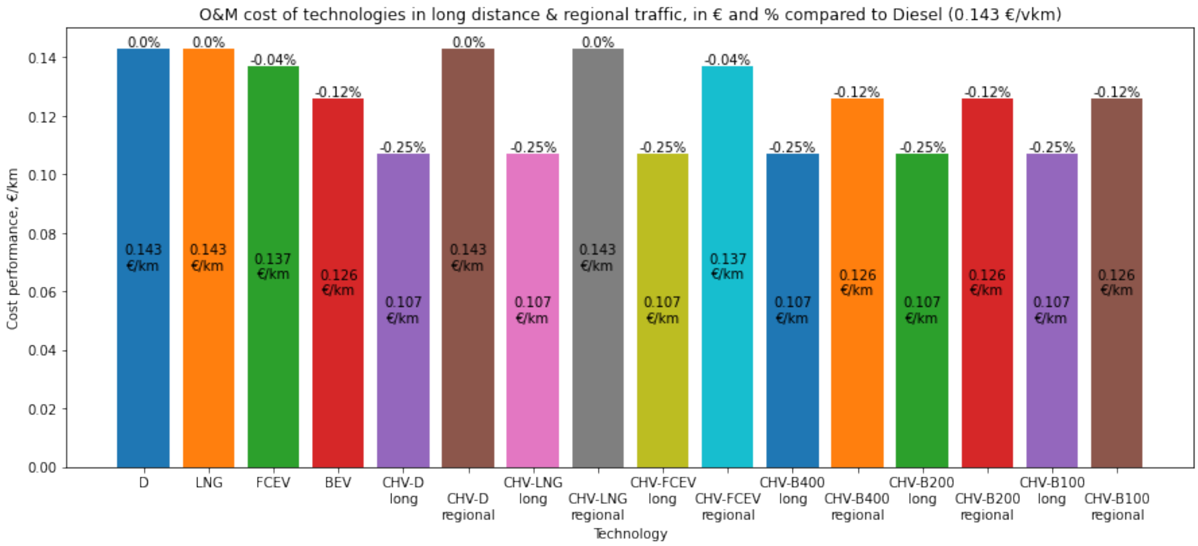
Figure 20 shows the energy cost comparison of the different technologies. For technologies that are capable of using the ERS catenary network, the cost performance is split for long distance motorway use with catenary and regional traffic, which uses the corresponding other propulsion technology. The higher investment of all the technologies allows for energy cost savings for all except hydrogen fuel cell vehicles. Hydrogen fuel cell vehicles incur 129% higher energy cost per vkm driven. Vehicles on catenary allow saving 7% of the energy costs compared to diesel in long distance traffic and slightly more in regional traffic. Battery electric vehicles allow reducing energy cost by approximately 18%, because they can charge on cheaper electricity than is supplied by the catenary, while the best performing technology on energy cost is LNG, which allows saving up 39% of energy cost compared to diesel.

Figure 20 – Energy cost comparison in long distance and regional traffic, €/km



Operation and maintenance performance of each of the vehicle types in motorway and regional traffic, where applicable, is show in Figure 21.

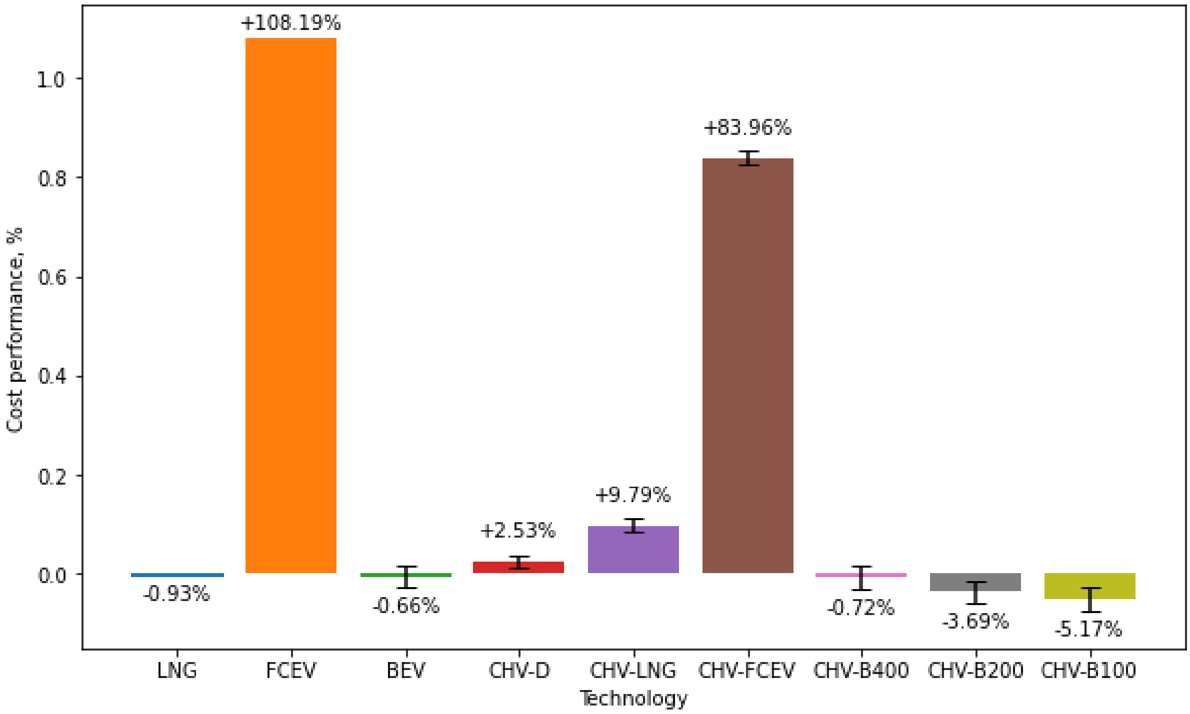
Figure 21 – Operation and maintenance cost comparison, motorway traffic, % change from current cost level



Above, the technology cost components are compared separately, while in real life circumstances the road freight operator is comparing total cost per vkm driven. The results of total cost calculation per vkm are shown in Figure 22.

We observe that both hydrogen fuel cell vehicle types (FCEV and CHV-FCEV) use is associated with substantial increase in cost per vkm driven. This is the result of the high energy and investment cost, which are not outweighed by the operation and maintenance savings compared to conventional diesel vehicles. The investment in LNG-fuelled vehicles is justified by other savings, while catenary LNG vehicles, despite having the lower energy costs, still produce increased vkm costs because of the required investment in a pantograph system. BEV use results in a slight vkm decrease, which is mainly due to the availability of cheaper electricity than from catenary ERS, while impacted negatively mainly by the costs[7] related to large battery size. The smaller batteries of the catenary battery hybrid vehicles (CHV-B400, CHV-B200 and CHV-B100) have the best cost performance, with the vehicle with the smallest battery providing the highest cost savings.

Figure 22 – Total technology vkm cost comparison, motorway traffic, % change from current, whiskers: sensitivity to electricity price: +/- 0.01 €/kWh



Changes compared to the assumptions on inputs of our model may come from either the electricity cost and by how much more expensive it is in comparison with the price of kWh of diesel, or from the investment cost which is required for buying vehicles of each type. Therefore, in Figure 22 we are showing what the impact of € 1 cent/kWh (or 6.6%) of electricity price difference would mean. Clearly, for technologies where electricity is used in conjunction with fuel, the impact is smaller, while for BEV and CHV-B the impact is bigger.

In the longer term, according to IEA (2021) World Energy Outlook, it is likely that the oil prices will be "rising slowly over time and then plateauing", but also will experience price volatility due to sustainable investing trends that result in underinvestment in oil production capacities. On the other hand, they estimate that substantial electricity generation capacity can and will be added without change in average retail prices and historically electricity price has had a tendency to be

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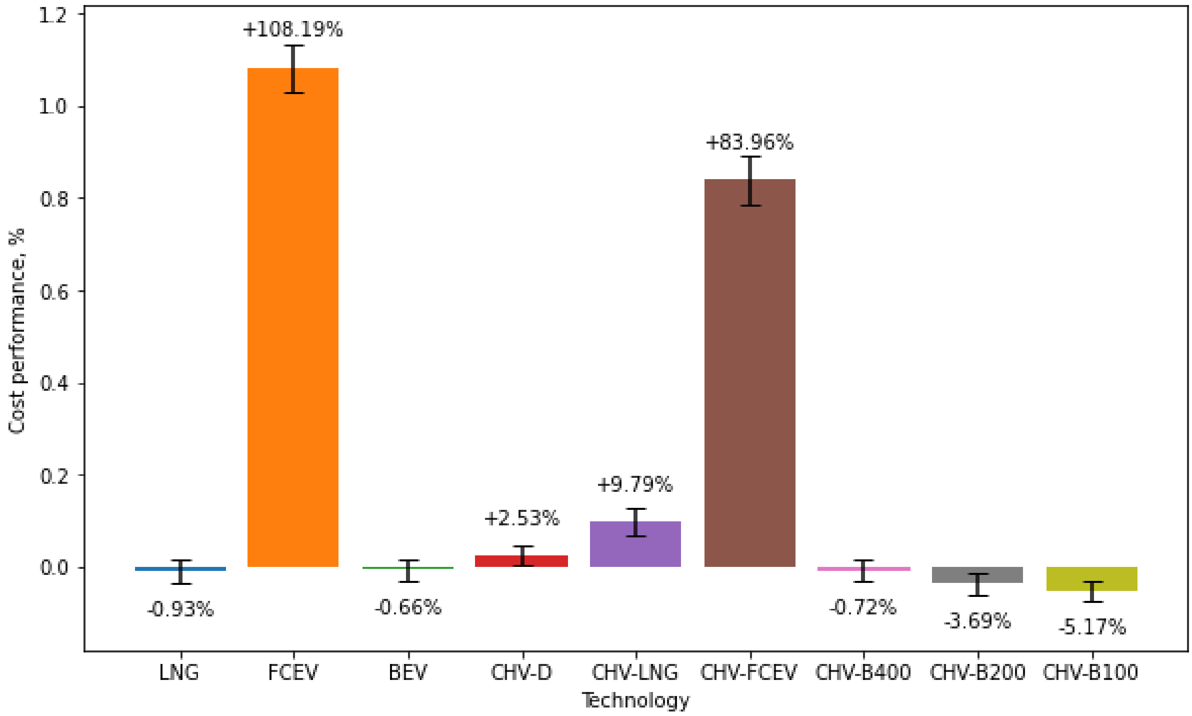
[7] Battery costs in 2030 based on Bloomberg NEF (2020)

less volatile. This leads us to believe that in the longer run the spread between diesel and electricity will narrow and may reverse, improving the economic performance of BEV and CHV vehicles.

It could also be that we are over- or underestimating the investment costs in the technologies. The technology developments may diverge from our expectations and result in lower or higher purchase prices of trucks than we currently expect. In Figure 23 we show what the vkm cost impacts could be from a potential 5% investment cost variability. For technologies with higher share of investment costs in the total cost mix, the impacts are bigger.

Figure 23 - Total technology vkm cost comparison, motorway traffic, % change from current, whiskers: sensitivity to investment cost: +/- 5%



Seeing the sensitivity of the results to the inputs, we conclude that the economic performance of LNG, BEV, CHV-D and CHV-B400 could stay at a comparable level to D in real life applications. CHV-LNG will perform a little worse, while the catenary vehicles with smaller batteries will tend to perform better in adequate operation. The use of bigger batteries in CHV vehicles might not be justifiable, unless operational patterns require those bigger batteries. We do not see economic grounds for use of hydrogen fuel cell vehicles in road freight transport.

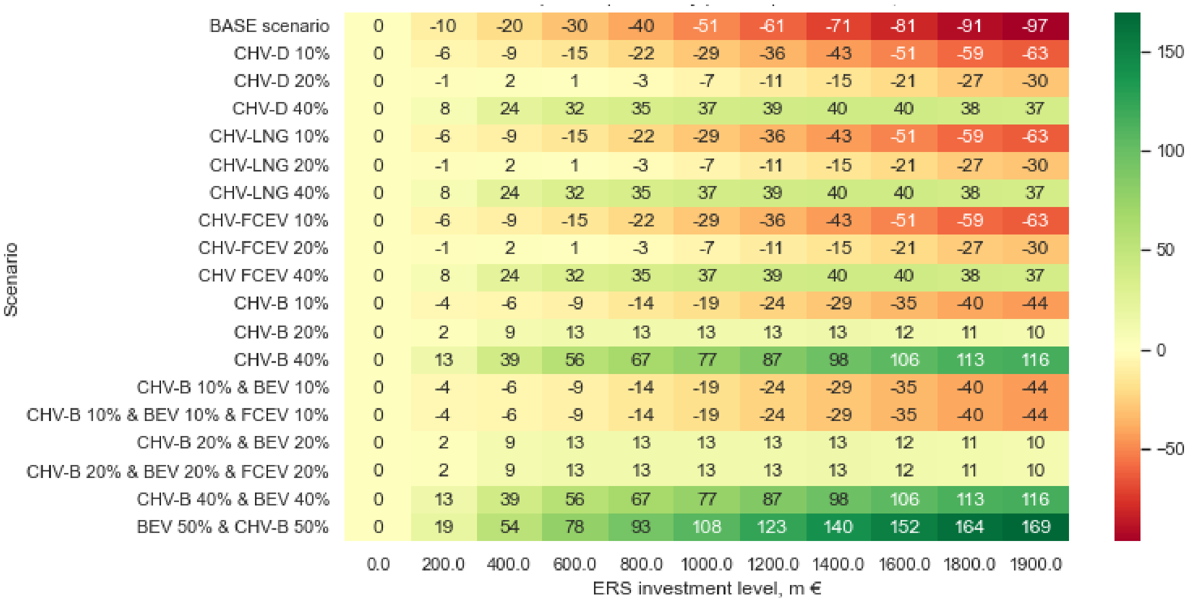
3.4 Impacts for ERS network operator

The revenue of the ERS network operator comes from energy sales to the network users. The energy is then used either directly for vehicle propulsion on the motorway network, or for charging of the catenary battery electric vehicles for use when not on the motorway network or on the motorway stretches that are not electrified.

The costs that the network operator has to cover consist of investment costs for building out the network, costs for purchasing electricity and administrative costs. The assumptions for infrastructure costs are described in detail in section 2.3.5 and energy costs are covered in section 2.3.6. Administrative costs are fixed at € 2000 per year per road segment that the network is built on. The revenues of the operator as mentioned in section 2.3.6 are from the sale of electricity with 87.5% markup at 0.15 €/kWh.

A heatmap of ERS operator profitability depending on the adoption scenario and developed network size is shown in Figure 24. The scenarios are listed on the vertical axis and the investment in the ERS network is shown on the horizontal axis. Red colour shows when the operator is losing money, e.g. in the BASE scenario where there is no catenary vehicle adoption, the development of the network will lead to large annual losses because of lack of revenue, and the bigger the network, the bigger the losses. Green colour shows where the operator is making profit.

Figure 24 – ERS operator profitability, heatmap, million €



We observe that higher catenary usage leads to better financial performance of the operator. Not only the CHV adoption rate matters, but also the type of technology plays a role: the scenarios where the CHV vehicle is based on a fuel consuming vehicle (D, LNG, FCEV) tend to lead to lower profitability of the operator in comparison with CHV battery trucks. This is because trucks with battery use the catenary network not only for propulsion while under the catenary, but also for charging the battery for regional trips away from the motorway network.

Calculations also show that there is an optimal network size for the operator. This means that for a specific technology adoption mix the ERS operator has an optimal network size that he will aim to build in order to maximise the profitability.

Profitable operation of both the trucking fleet and infrastructure operator is possible. This requires balancing of the energy sale price so that the both the road freight hauliers and the network operator share the benefits. In the beginning stages of the network development a government support might be beneficial to improve the profitability of the catenary network operator, which is not possible at low technology adoption levels.

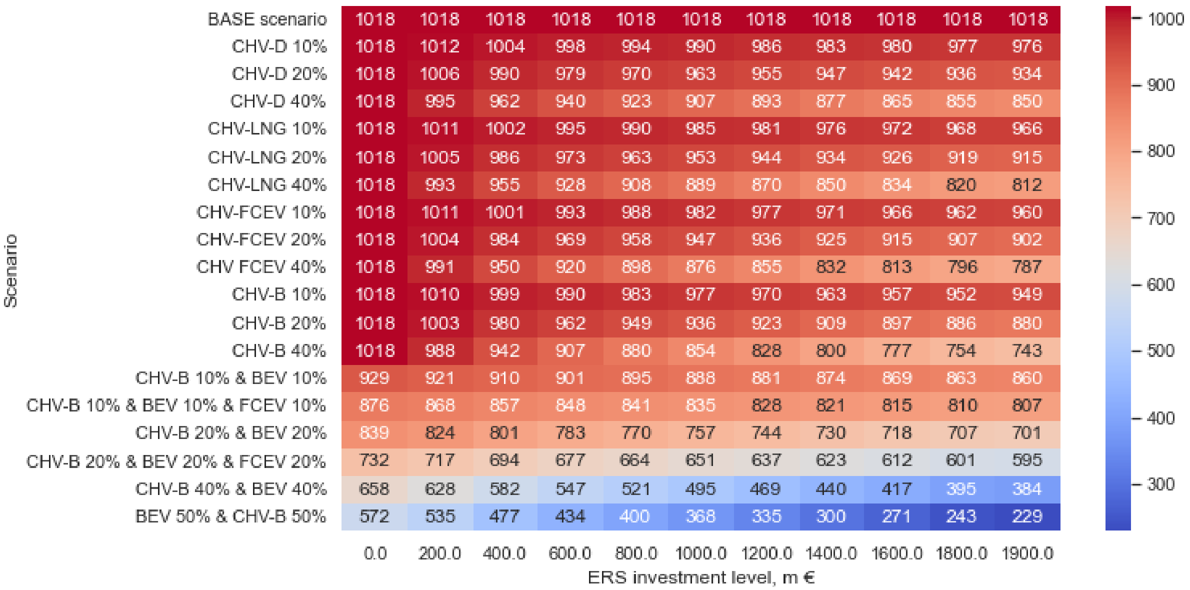
In our modelling approach, we assumed that the operator has to earn back all the investment, which is possible with relatively modest technology adoption. In other European countries, e.g. Sweden, at the time of writing the government is considering the possibility to build a nation-wide network and passing it on to private operator for free to operate. This changes the economics for the network operator, and those cost savings would also be passed on the network users, which is a good way of accelerating the technology adoption by improving the return on investment for the users.

3.5 Emission cost

Society faces different costs related to the activity of road freight transport. In this analysis, due to the political importance, we take into account the emission costs that are associated with CO_2 emissions, as well as the costs of local pollutants such as NO_x, PM, HC and CO. The input values for assessing the impacts of these pollutants are listed in Table 6 on page 18 of this report. We use the adoption scenarios, described in section 2.3.7 on page 16.

For each of the technology adoption scenarios, the heatmap in Figure 25 shows the annual societal cost level in million €. The societal costs for each of the adoption scenarios are shown in relation to the investment level in ERS. It can be observed that with increasing investment in the ERS catenary system, the societal costs are reduced. The scenarios that assume higher use of technologies with lower emissions perform better.

Figure 25 – Emission costs for scenarios at different ERS investment levels, heatmap, million €



In the BASE scenario, we see that currently the annual emission cost that society absorbs in Flanders is approximately € 1 billion. The use of catenary hybrid vehicles allows reducing this cost, in some scenarios radically. For example for BEV 50% & CHV-B 50% scenario at investment of € 1.9 billion the cost savings can reach 77%. This corresponds with 69% CO_2 reduction and complete local pollution reduction. The remaining CO_2 emissions and the corresponding costs come from electricity generation and the solution for reducing those emissions should be sought outside the transportation system.

The above heatmap illustrates that catenary ERS is a very cheap way to reduce emissions in Flanders. With a required investment of € 1.9 billion the annual cost savings can be up to € 0.789 billion. This corresponds to 42% annual return on investment for the government. In simple terms, € 1 invested in ERS infrastructure will return emission savings for the society of € 8.3 over the following 20 years. This is the reason why the development of the ERS network using public money is justifiable and should be considered.

4 POLICY STATEMENTS

In this sub-chapter we present statements for policymakers that can be used to support or counter the implementation of the catenary ERS. Here we do not aim to suggest a course of action, but rather focus on developing the argumentation, which should help the policymaker in supporting his or her position. With positive statements we help justify why introduction of catenary ERS is beneficial, but to help with preparing adequate counterarguments, we also present negative statements which we think will be brought up by the opponents.

Implementation

There are certain implementation risks that should be taken into account during each of the ERS deployment stages. Those can be used as arguments by the policymakers.

Positive statements:

+ Technology is in use today in Germany and in Sweden. The field-testing and fine-tuning of the technology is in the finishing stages. The technology readiness level is high.
+ With a modest investment of less than € 2 billion an extensive coverage of more than 1.5 thousand km of the whole Flanders motorway network could be achieved. The investment cost in context:
    - € 2 billion is less than 0.8% of Flanders yearly GDP.
    - Belgium granted more than € 13 billion in subsidies to fossil fuels in 2019, which included a subsidy for employee company car use of € 1.9 billion.
+ Operational patterns matter. Initially the ERS network would be able to serve only the users that happened to work on the early stages developed network. The network in those early stages, however has a tendency to cover a bigger share of traffic per km than in later stages.
+ Due to the small scale initially the costs are limited, and that reduces the monetary impacts if it turns out that the technology is not suitable for implementation in Flanders due to local industry characteristics.

Negative statements

- Implementation of the demonstration deployment stage is risky, because, if further implementation of the catenary ERS does not follow, the investment is wasted. When developing a demonstration deployment of the catenary network in Flanders the main benefit is the practical demonstration, but such testing has already been done in Germany and Sweden.

- Development of an extra demonstration and testing phase is of little use because sufficient information has already been obtained / can be obtained from existing test sites in Germany and Sweden.
- Operational patterns matter. To maximise the return on investment transport operator should maximise ERS network use. Those benefits are not achievable for all operators, especially in early network development stages. And substantial investments are required to achieve a higher network coverage.

Reaching emission targets

Reduction of emissions to reach the targets set out by the national and regional commitments is an important motivation for introducing catenary ERS. Positive and negative arguments can be formed based on this.

Positive statements

+ Introduction of catenary ERS has the potential 69% CO_2 reduction and complete local pollution reduction. The remaining CO_2 emissions are from electricity generation and the emission performance of the grid has been improving.
+ Use of green Power Purchase Agreements can ensure zero-emission operation of the ERS catenary system from the start.

Negative statements

- If the catenary ERS adoption is low, a substantial part of the emissions will still be emitted. Another technology, although further in the future, has the potential of reaching higher emission reduction without relying on the electricity grid becoming greener.
- The grid electricity, which catenary ERS uses, will have a substantial carbon footprint in the future. This is a result of the policy to increase the number of gas-powered electricity production plants in Belgium by subsidising them. We should therefore consider other alternatives.

Societal benefits

Consideration of costs and benefits for society is important. Examples of statements based on societal impacts are proposed below.

Positive statements

+ Catenary ERS is a very cheap way of reaching emission targets in road freight transport. It allows reducing emission-related costs to the society radically. E.g. at an investment of € 1.9 billion, the savings can reach 77%. In such way, 69% of CO_2 and complete local pollutant reduction can be achieved, with remaining emissions being the result of electricity generation.
+ If a subsidy is given for the development of the catenary ERS, there is a very good return on investment. € 1 invested in ERS infrastructure will return emission savings for the society of € 8.3 over the following 20 years.

Negative statements

- Public funds have a better use elsewhere. Supporting business activities and contributing to the profits of private companies is not the task of the government.

- The visual appearance of the catenary on the road network is not pleasing. It is a distraction to the drivers and may cause additional accidents. Therefore, introduction should be postponed until sufficient evidence on safety impacts is available.

Impacts on the trucking industry

Concerning the economic impacts on trucking industry, we propose the following statements.

Positive statements

+ Field trials with CHV-D vehicles show that road freight transport operators do not have to change the operational pattern because of ERS. As the catenary network grows undisrupted operation is possible with CHV-B vehicles with all battery sizes.
+ It is possible to cost-effectively decarbonise road freight transport. Catenary ERS ensures an improved economic performance of vehicles, which is crucial for economic sustainability of trucking.
+ Use of catenary ERS allows using smaller batteries, which minimises the required investment in vehicles and improves the return on investment for road hauliers.
+ Compared with the traditional battery-electric trucks the smaller battery size of catenary trucks allows carrying more payload before reaching the legal weight and axle load limits.

Negative statements

- Improved economic performance of road freight transport threatens the shares of other modes of transport like rail and inland shipping. This is contrary to the long-standing policies on modal shift.
- Breakthrough in battery technology that greatly increases their energy density and reduces cost would be disruptive to the catenary ERS business model.

Economic performance of the ERS operator and government support

The proposed statements on economic performance of the ERS network operator and provision of subsidies are the following.

Positive statements

+ Profitable operation of infrastructure operation is possible. This requires reasonable technology adoption rates and network size that is both, optimised for the traffic level and operational pattern of the road users.
+ If the government helps with the initial investment, which is rational to do from socio-economic cost-benefit perspective, the sustainability of ERS operator can be guaranteed.

Negative statements

- Initially the catenary ERS network will be loss-making. Given the risks related to the take-up of the technology, the investment of public funding is risky and therefore should be directed elsewhere.

International impacts

The positive and negative statements on international impacts are the following.

Positive statements

+ Strong synergies from international traffic can be expected. The larger the catenary network size, the more these synergies intensify. This ensures:
  - financially sustainable operation of ERS network operator,
  - decarbonisation of international road freight transport that is passing Flanders.

Negative statements

- ERS network operator is a rational economic actor. It cannot be ensured that the optimal network size for the operator will be sufficient for the industry and match Flanders transport policy objectives.

5 CONCLUSIONS

This research was started to answer the four research questions described in section 2.1. We wanted to determine: (1) what the economic impacts of the catenary ERS implementation in Flanders could be for the different stakeholders, (2) what the most optimal way of building out the catenary network would be, (3) what synergies could come from international road freight transport, and (4) what are the main arguments for policymakers to support or counter the introduction of such a system.

To answer the research questions we developed a model of Flanders that takes into account a range of inputs. As shown in detail in section 2.3, some of those were: Flanders geography, data on traffic volumes on motorways, performance of different vehicle technologies and their economic characteristics, catenary ERS infrastructure building costs, energy prices, costs of emissions to the society, and other more general assumptions on rationality of the ERS system operator and freight transport operators.

For running the model and determining the impacts of the technologies we chose to introduce two types of scenarios in the model: single technology scenarios and technology mix scenarios. This allowed us testing both, the performance of a single technology and also situations where a mix of alternative technologies would be adopted.

Running the scenarios allowed us to produce quantitative results for assessing the development of the catenary ERS in Flanders, identifying potential synergies from international traffic and when those synergies would occur, determining the economic impacts for the trucking sector and catenary network operator and determining what the impacts for the society would be.

This work allowed us drawing a number of conclusions on the implementation of the system and the implications that a catenary ERS system would have for the involved stakeholders.

The investment required for the system development is relatively modest. An extensive network coverage in Flanders could be obtained with an investment of less than € 2 billion, which is less than 0.8% of Flanders GDP, and small in comparison with the annual € 13 billion fossil fuel subsidies that Belgium provides.

The catenary ERS network, especially in the later development stages, will strongly benefit from its use by the international road freight transport. There will be two main benefits that this will bring. First, with more than half of the traffic on catenary network in international transport, this traffic will ensure economically sustainable operation of the network operator. Second, as the international traffic switches to using catenary, substantial benefits from that will come as emission savings across emission categories for Flanders.

The catenary network can ensure a profitable way of decarbonising road freight transport. It allows both the network operator and trucking industry to work with profit, while working towards decarbonisation. This comes as a result of lower energy and investment cost requirements in comparison with diesel and also with other alternative technologies. The lower investment cost is related to smaller batteries that catenary trucks require to achieve the same operational performance as traditional battery-electric trucks.

We see that investment in some of the alternative technologies is not economically justifiable. For example, our calculations show no economic grounds for use of hydrogen fuel cell vehicles in road freight transport. We foresee this technology will not be adopted, unless radical technological breakthroughs can reduce the required investment costs, increase the energy performance of those vehicles and reduce the hydrogen fuel price. However, the relatively poor performance of hydrogen in road freight is dictated by physics and currently does not seem surmountable.

We also foresee that catenary ERS will allow reducing the required battery size of regular battery-electric vehicles, therefore the required investment costs for an average truck will be lower, and their economic performance will improve. Also, once the catenary network will be built, the operational pattern of catenary hybrid vehicles will be unrestricted by their battery size. Our calculations show that even the smallest battery size that we modelled of 100 kWh allows serving almost any industrial location in Flanders.

Adoption of catenary ERS would also reduce the need for fast charging infrastructure and lower required investments because a part of the vehicle fleet would be using the catenary for propulsion and charging. Constantly having a large battery capacity connected to the catenary ERS offers flexibility to the electricity grid to shift power demand when needed. Various smart energy management and pricing approaches could be investigated for this.

Further research could also investigate the use of the catenary ERS for bus and coach passenger transport on local and international routes.

In this research we have shown that catenary ERS has the potential to be developed into an economically sustainable and cheap way of decarbonising road freight transport. It offers considerable economic incentives for all involved stakeholders and is beneficial to the society as a whole.

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VIL

EMPOWERING LOGISTICS

Koninklijkelaan 76 – B-2600 Berchem
T: +32 (0)3 229 05 00

WWW.VIL.BE
info@vil.be