ELinGO

Electric Infrastructure for Goods Transport

Estimations of climate mitigation potential and costs of electric roads in Norway

Work Package 4.1/4.2

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1 Background and Scope

Heavy Duty Vehicles (HDV) has 12% of the traffic volume and close to 50% of greenhouse gas emissions from land based transport in Norway (NTP 2017). Transportation contributes to 60% of the land based emissions from non-ETS sectors in Norway.

According to the Paris agreement, the Norwegian Government has a binding target to cut emissions in Norwegian territory by at least 40% below 1990 levels by 2030 (KMD 2015) In pursuing this target, large reductions in emissions from land based transport, and HDVs especially, is necessary.

Electrification is the most promising technology towards reducing emissions from transportation, for small vehicles there has been good results for some years already. In principle, there are two ways to electrify vehicles, direct electric propulsion or indirect.

In direct electrification, the propulsion of the vehicle is done by an electric motor, which is fed from a battery or by a continuous conductive or inductive feed of electricity from the grid.

By indirect electrification, the electricity is converted to a suitable energy carrier (fuel), and this energy carrier is then used to fuel a suitable engine. Hydrogen is reckoned as one of the most promising technologies for indirect electrification of transport systems.

But, the introduction of indirect electrification has met significant opposition due to two reasons:

- Low efficiency due to significant loss of energy in the production of hydrogen
- Difficulties in safe and cost effective transport and storage of hydrogen.

There has been continuous progress related to both of these issues, and the technology will be available in a not so distant future. However, there will still be a significant loss of energy with indirect electrification, and a 66% efficiency loss is expected.

For direct electrification of transport, conductive transmission of electricity to vehicles has been a proven technology for almost a century, used by trams, busses and trains. Mostly the vehicles have been using rails, but in some cases busses on fixed routes with rubber wheels (trolley busses) has used electricity. The disadvantage of direct transmission is the lack of flexibility, since the vehicles are dependent on a continuous conductive supply of electricity, and thus has to be in the immediate proximity of a supply system. Solutions for inductive transfer of electricity has made progress over the last years, but the technology readiness is low, and is only feasible for stationary charging, not for propelling or charging moving vehicles.

For small vehicles, temporary storage of electricity in the vehicles by batteries is a solution to the flexibility problem. However, the current batteries have limitations in a relatively low storage capacity per kilogram battery, and a corresponding low driving range. The effect on emission reduction has been questionable due to large emissions in battery production and in production of electricity. Nevertheless, with the latest production technologies, battery electric vehicles emit less greenhouse gases over the lifetime of the vehicle even with coal-fired electricity. A shift towards solid-state batteries is expected to further improve the power to weight ratio of batteries (IEA 2017).

Battery electric propulsion has not been a viable option for heavy-duty vehicles due to the power to weight ratio of batteries, with a corresponding low payload, low range and time consumption for charging. Recently, new vehicles have been presented that eliminates these concerns, but the availability of these (batteries) in the near future is uncertain (IEA 2017).

This uncertainty is due to the availability and production capacity of the necessary minerals needed for battery electric vehicles. One solution to this is electric roads, with a significant lower demand for batteries. In addition, a large portion of the landbased transport by heavy-duty vehicles follows regular transport routes along the main roads, and has a lower need for flexibility. Thus, a solution with conductive or inductive electric roads can facilitate the need for electrification of land-based transport, and at the same time circumvent the low availability of essential minerals.

This report investigates the possible reduction in greenhouse gas emissions from road transport by introducing conductive electric roads in Norway. The analysis has used the parts of the E39 coastal highway between Bergen and Stavanger as a case, but the assumptions used for the calculations is general for Norway, and the traffic scenarios provided. The results is thus applicable for all major roads in Norway.

Finally, this report estimates the costs of greenhouse gas reductions from electric roads.

2 Methods

The life cycle assessment in this report was conducted as a master thesis at the department of Civil and Environmental Engineering, NTNU, by stud.tech Erlend Brenna Raabe under the supervision of Professor Rolf André Bohne (Raabe 2017).

The LCA calculation has followed ISO 14040 (2006).

In order for the LCA calculations to be comparable to the other calculations within the ELINGO project, the project group agreed upon the following parameter values:

- CO_2 emissions from the combustion of diesel, including extraction, distillation and transport to fueling station:
    - 2,9 kg CO_{2eq}/L
- CO_2 emissions from production and delivery of electricity:
    - 0,03 kg CO_{2eq}/kWh
- Service life of infrastructure
    - 40 years

For the estimation of the associated costs of greenhouse gas emissions by electric roads, we have however modified our parameters and system boarders to be comparable with "tiltakskostnader" (cost of actions) developed by Norwegian Environment Agency (Miljødirektoratet 2015). In the instructions for official studies and reports for Norway, the Norwegian Environment Agency sets the system borders and parameters. These inputs are set in such way that only direct emissions within Norway is counted, i.e.:

- Emissions from production of vehicles produced outside of Norway is not part of the calculations.
- Emissions from production of materials produced outside of Norway is not part of the calculations.
- Emissions from consumption of electricity is defined as 0 kg CO_{2eq}/kWh
- Emissions from combustion of diesel is 2,66 kg CO_{2eq}/L

Thus, during the construction of infrastructure, the emissions from diesel combustions from construction machines is accounted for, whereas the emissions from materials i.e. asphalt is not counted. All changes in CO2 emissions are summarized as changes in emissions, and all additional costs are summarized. The "cost of actions" is then the additional costs divided on changes in CO2 emissions.

Lost governmental income, i.e. lost consumption or carbon tax on diesel due to lowered consumption of diesel, is not accounted for.

Also on all expenses payed for by the government, an additional financing cost of 20% is added. This will be applied to all costs of infrastructure.

3 Assumptions used in the analysis

As a basis for the analysis on the possible reduction of greenhouse gases by electrification of the heavy-duty vehicles on E39, we have the following three assumptions.

1 **Traffic**
We are using the 200 kilometer stretch from Bergen to Stavanger as case. In the case we have an averge of 100 HDVs on a daily basis.

2 **Traffic growth**
Traffic volumes are expected to increase steadily in the forthcoming years. According to the National Transport plan (2017), an average annual growth of 2,0% is to be expected towards 2050. We have a low growth (1,5%) and high growth (2,5%) scenarios in our analysis, Figure 1.

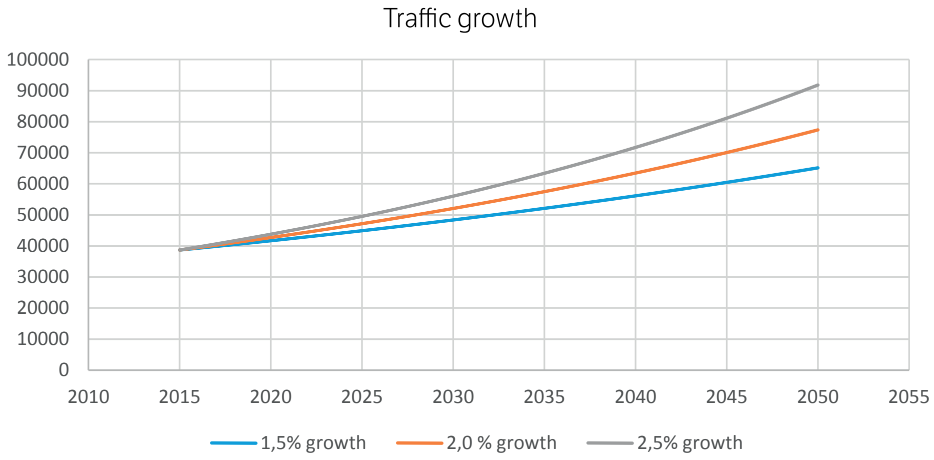

Figure 1 Estimated traffic growth

3 **Introduction of electric HDVs**
The last assumption is on the introduction of electric HDVs on the electric road. In our calculation, we assume that there will be a rapid introduction. The rationale behind our assumptions is as follows. The average service life of HDVs traveling long haul on the E39 is 4,5 years. The operational cost of driving electric is significantly lower than for conventional internal combustion engines (ICE). Thus, after the opening of an electric road, a majority of HDV owners will choose an electric HDV when replacing their vehicle. Therefore, we assume that 98% of HDVs will be electric within 10 years after the opening of the electric road, Figure 2.

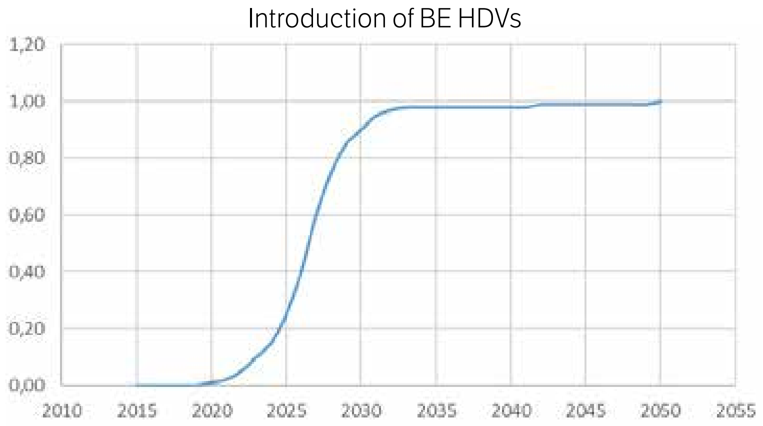

Figure 2 Introduction of electric HDVs.

4 System descriptions

In principle, there are six different ways of constructing an electric road, where electricity is transferred to a vehicle in motion, Figure 3.

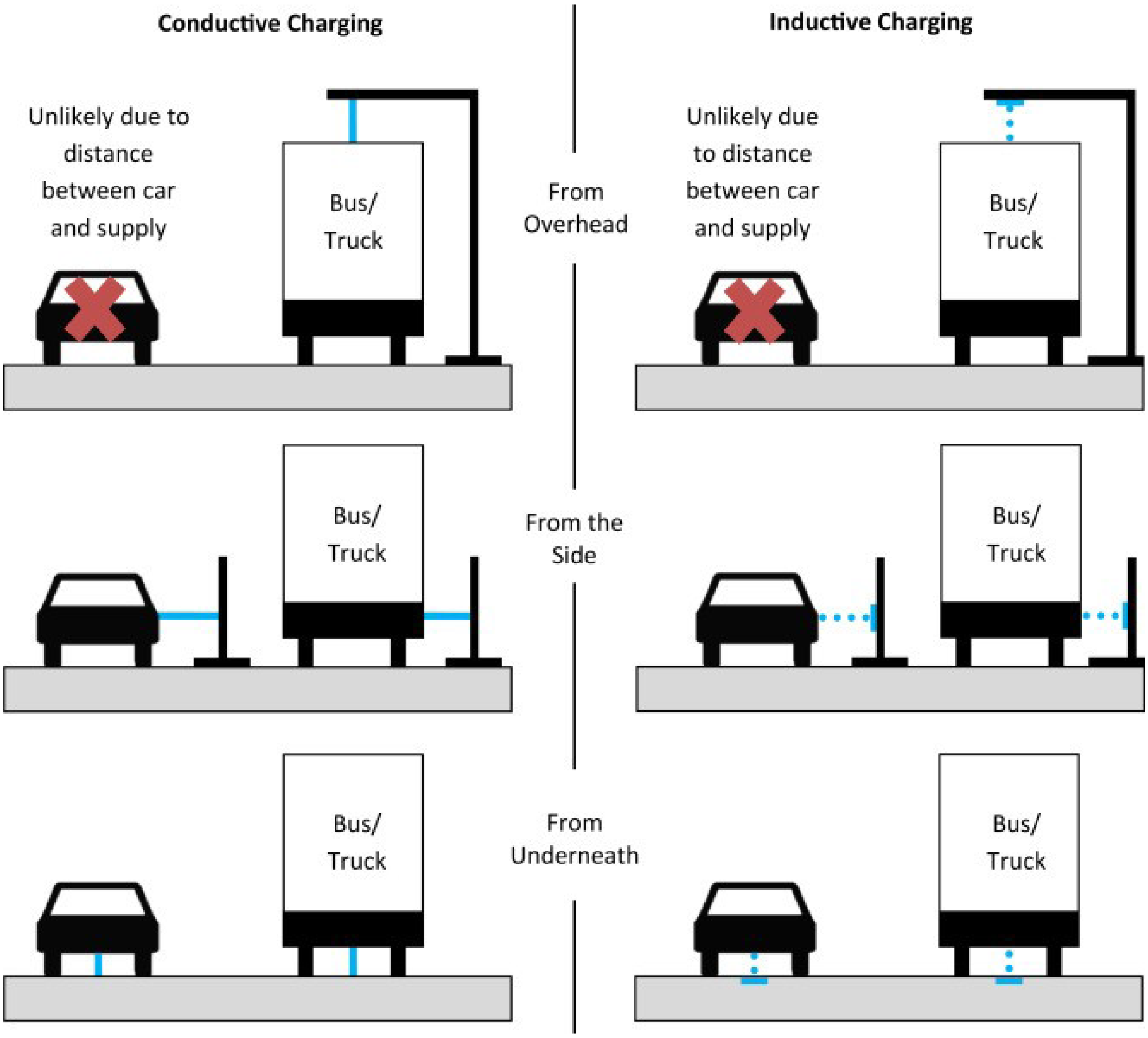

Figure 3 Principles for transfer of electricity to vehicles, after Conolly 2017.

Our initial plan was to study both conductive and inductive solutions for electric roads, but as the technology readiness level for inductive solutions was low, we decided to focus on conductive solutions. We decided to focus on two different approaches - Overhead Conductive Systems (OCS) and Ground Level Supply system (GLS).

In this chapter, a summary of the respective inventories will be described. First, will the inventory development related to the ICE HDV, and the BE HDV be presented. Then, will the two different electrical systems related to the BE HDVs be described. Further details can be found in the master thesis of Erlend Brenna Raabe (2017)

4.1 Heavy Duty vehicles (HDV)

Heavy duty vehicles (HDVs) exist in many different variations, designs, and sizes. The different sizes of the vehicles are classified based on their weight distribution and their carrying capacity (also called Gross Vehicle Weight Rating (GVWR)). The different classes consist of 1-8, where 4-8 is classified as medium duty vehicles (MDVs) and HDVs (Table 1).

Table 1 Classification of Duty Vehicles (Bennet, 2010)

Class	Type	Ca Weight [kg]
4	MDV	6 350–7 300
5	MDV	7 300–8 500
6	MDV	8 500–12 000
7	HDV	12 000–15 000
8	HDV	>15 000

The different MDV and HDV have in principle many of the same main characterizations and configurations, both with respect to the powertrain, the engine, and the main components. They will be explained in the following sub-chapter, with a main focus on the different powertrains such as the internal combustion engine (ICE) powertrain, and the battery electric vehicle (BEV) powertrain.

The main components, in a HDV are wheels and tires, chassis/frame, suspension, miscellaneous accessories, the truck body structure, and the powertrain. The weight distribution of HDVs, are 48% powertrain, 31% chassis/suspension, and 18% body/cab (U.S. DoE, 2013).

4.1.1 Conventional Heavy duty vehicle (ICE)

The internal combustion engine, is the conventional engine technology mostly used on HDVs today, which is transferring power from the engine directly to the vehicle powertrain and further to the wheels (Husain, 2011).

The power input required for the engine depends on several factors, such as rolling resistance, air resistance, and speed requirement. In addition, the amount of fuel necessary for the engine to create sufficient power, depends on the efficiency of the system. This is one of the main disadvantages with the ICE, where the maximum efficiency is 45% (due to several factors, i.e. mechanical losses) (Husain, 2003).

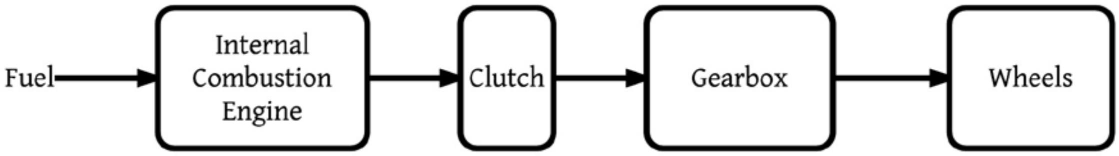

Figure 4 Internal combustion engine powertrain. Modified from Husain (2011)

4.1.2. Battery Electric Heavy Duty Vehicle

The battery electric vehicle (BEV), is different from the system described above in the way that the vehicle is completely powered by the electrical power stored in the battery (Figure 5.

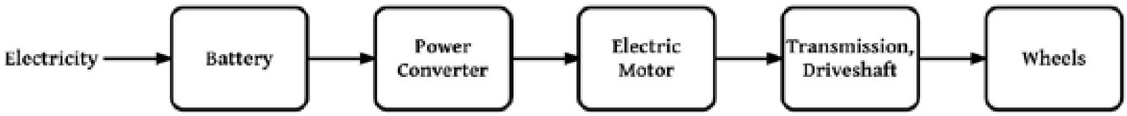

Figure 5 Battery electric powertrain. Modified from Husain (2001)

4.1.3 System description

As described earlier with respect to the OCL- and the GLS system, the HDV operating on these systems are diesel-hybrid electric configurations, specifically as HEVs. However, as further expansion of this system may potentially take place, the more relevant it will be to utilize the systems based on BEVs, with a larger on-board battery scaled for reasonable range when the HDVs are not powered by the dynamic power supply system (Suul & Guidi, 2016). Due to this potential development, it has been decided to model with a comparison of a BE HDV and an ICE HDV, in order to make way for a best case comparison between two independent systems (Figure 6).

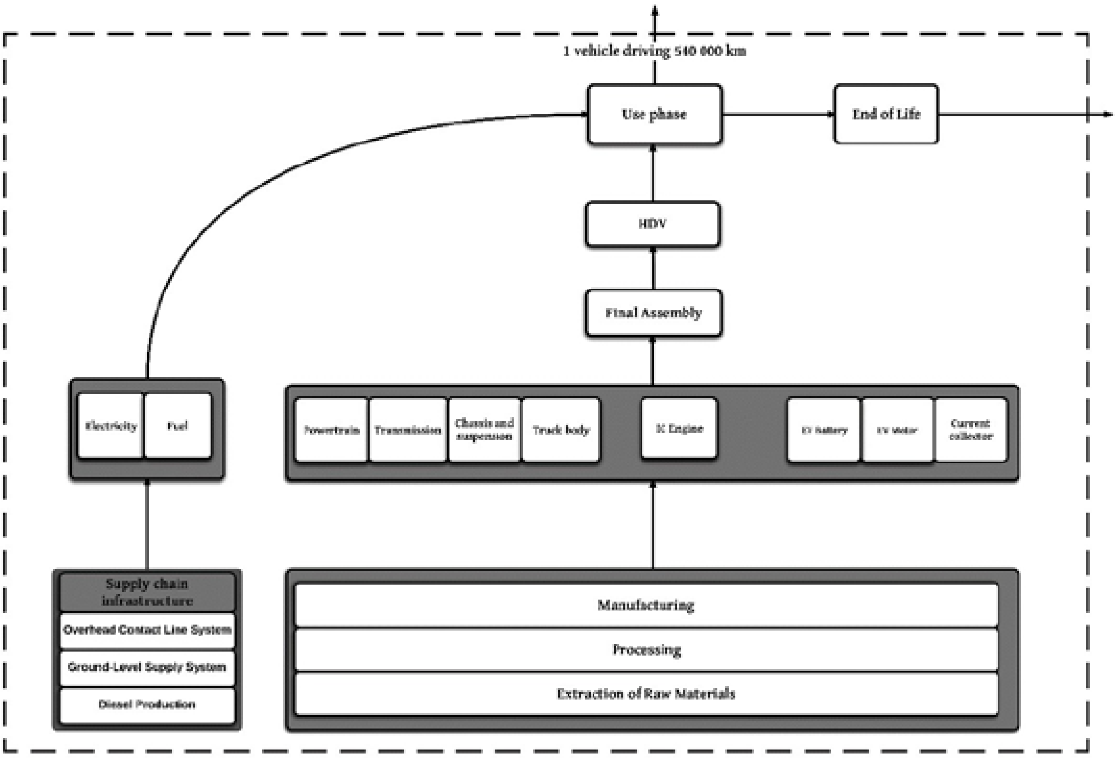

Figure 6 Simple flowchart and system boundary of the related components with additional supply chain infrastructure

During the vehicle manufacturing, several processes are required, i.e. stamping processes, metal part- and wiring harness manufacturing, the production of the engine, final assembly and testing of the vehicle. This demands energy from natural gas, electricity, light fuel oil, and diesel. The inventory data for producing a vehicle in this thesis, is mainly based on data from Spielmann et al. (2007), which is further assembled from a Volvo Environmental Product Declaration (EPD). That EPD covers all life cycles of the system for a Volvo FH12 and a Volvo FM12, with Euro class 3 (Spielmann et al., 2007; Volvo, 2004). This data is used as a basis, and further modified for the development of the BE HDV.

With respect to the estimated material composition for the truck, average data has been employed for a HDV of 40 tons, with Euro Standard 5. Even though, this in most cases are sufficient with respect to data quality, some materials i.e. plastics and "other metals", are general. For the case of plastics, it has been assumed to model all plastic in the vehicle production as polyethylene (Spielmann et al., 2007).

Table 2 Driving performance for ICE HDV and BE HDV (Raabe 2017)

Description	ICE HDV	BE HDV	Unit	Source
Total km performance	540,000	540,000	km/vehicle	(Spielmann et al., 2007)
Average load	9.68	9.68	ton/vehicle	(Spielmann et al., 2007)
Transport performance	5,227,200	5,22,7200	tkm/vehicle	(Spielmann et al., 2007)
Annual km performance	120,000	120,000	km/year	(Scania, 2016; Volvo, 2016)
Diesel consumption	32*		litre/100 km	(Scania, 2016; Volvo, 2016)
Electricity consumption		1.2*	kWh/km	Dalløkken, 2016)
Lifetime	4.5	4.5	years	(Spielmann et al., 2007)
Maintenance	120,000	120,000	km	(Scania, 2016; Volvo, 2016)

* After discussions with the project group, it was decided to increase fuel and energy consumption for both ICE HDV and BE HDV to 40 L/100km and 1,8 kWh/km respectively.

4.2 Electric Road Systems

4.2.1 Power Supply

The following chapter, will describe relevant parts of the power distribution system for both ERS. The reason for this, is because only minor differences are required between the GLS- and OCL systems (Suul & Guidi, 2016).

The power distribution system is the link between the existing grid, substations, catenaries and other equipment. In that way, high voltage is converted to low voltage in the substations according to the design requirements of the OCL- and GLS system (Figure 7). The main components in the power distribution system are the switchgear-SF6, substations, positive current cables, and return cables (functioning as grounding), and respective isolators (Ovedal et al., 2012; Tingos & Raposa, 1996).

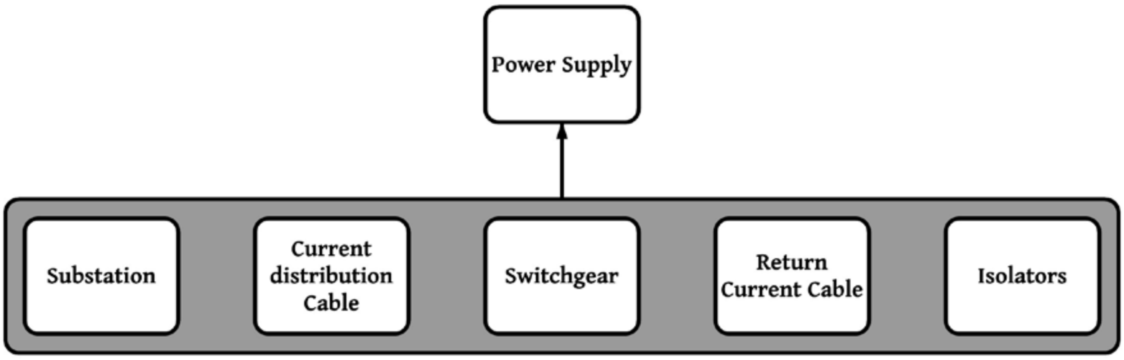

Figure 7 General flowchart of power supply. Modified from Ovedal et al. (2012); Tingos & Raposa (1996)

According to Siemens, the power distribution system used for the OCL system is adapted from light rail technology, trolley bus power supply, and long-distance passenger service (Siemens, 2012). The additional power box included in the power distribution system, is the main difference between the GLS- and OCL system.

4.2.2 Overhead Conductive system (OCS)

OCL systems are the physical construction necessary for distributing electrical power to create movement on the vehicle. The OCLs can be designed with respect both to the vehicle design, operation speed of the vehicle, and climatic variabilities, and due to this many different configurations exists. Generally the OCLs are built up from catenary, cantilever, support structure and tensioning section, in addition to the respective power distribution system (Kiessling et al., 2001; Ovedal et al., 2012; Tingos & Raposa, 1996). In addition, the OCL system has subcomponents included in the system, such as insulators, droppers, and masts.

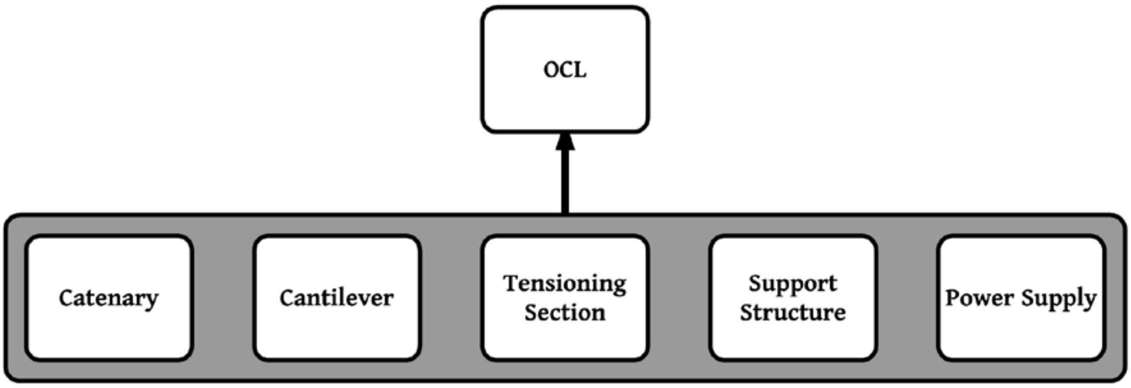

Figure 8 Simplified flowchart of the overhead contact line system

According to Kiessling et al. (2001), a variety of requirements exist for contact lines, such as distributing reliable electrical energy through lines over a specific distance, and ensuring that the sliding contacts function under all conditions.

By considering the design requirements and operating speeds linked to these OCLs, it is decided to continue with the base line design of Re100. This is due to the constraints in operating speed for the HDVs with a maximum of 90 km/h (Suul & Guidi, 2016).

4.2.3 Ground Level Supply System (GLS)

The tramway principle of dynamic power transfer from conductive infrastructure built in the ground has been constructed as a way of avoiding the use of overhead contact line infrastructure above the ground (Suul & Guidi, 2016). As already mentioned (In 4.1.3 System description), different solutions and designs exist with respect to the ground-level supply (GLS) systems (i.e. Alstom, Elways, Elon-Road), and the following chapter will describe and discuss essential components and sub-components related to the Alstom system design (Alstom, 2016 and 2017). This is mainly due to the technology readiness level (TRL), but also due to the information available in literature during the project period (Alstom, 2017; Suul & Guidi, 2016). In Figure 9, the related components for the GLS system, is presented.

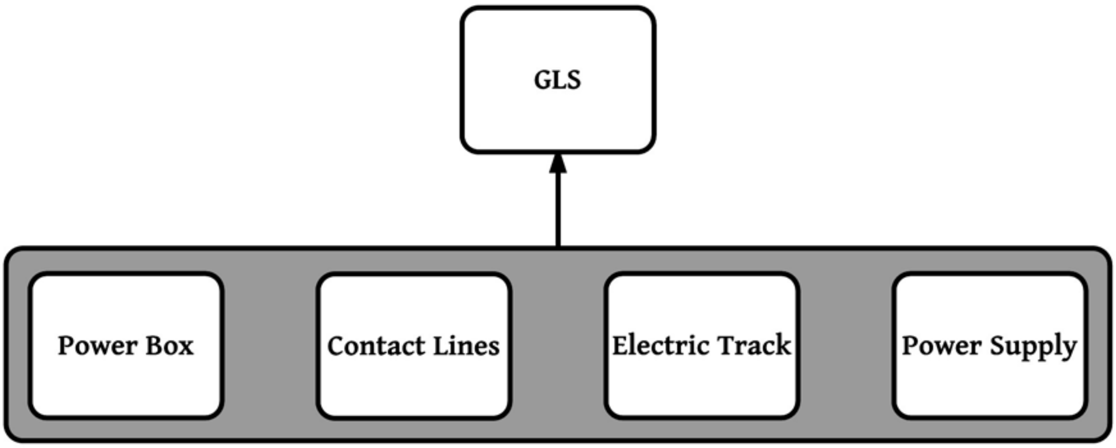

Figure 9 Simplified flowchart of the GLS system

4.4 Costs

During the project period, the cost estimates for conductive electric roads have decreased, especially for the ground level systems. There are several reasons for this, but different technology readiness and maturity, as well as reduced price of manufacturing are believed to be the main causes . However, there is still a huge variation in cost estimates, and few sources of information.

One reason for this is the lack of transparency between stakeholders, and what costs are included in the cost estimates.

In Table 3, we have shown the lowest and highest cost estimate, that we have found in publicly available sources.

Table 3 Cost of electric road infrastructure

	Lowest cost estimate	Highest cost estimate
OCL	13 mill[1]	41 mill[1]
GLS	18 mill[2]	54 mill[5]

However, the numbers for GLS are criticized by eRoadArlanda/Elways for being too high. eRoadArlanda/Elways (2018) claims that the for their system cost will start at 25 mill, and as system matures - cost less than 10 mill NOK/km (see Appendix). These calculations will be publically available ultimo 2018.

In their report for the German Transport Ministry (BMVI), Fraunhofer (2017) present different scenarios for implementations, showing best case and worst case studies from a minimum installation of selected roads to a full coverage of the entire Autobahn system. We find do not find the full scale implementation relevant for our studies, and have in discussion with stakeholders selected to use the following three different cost estimates in our studies.

-Low cost of 13 mill NOK/km

-Medium cost of 18 mill NOK/km

-High cost of 26 mill NOK/km

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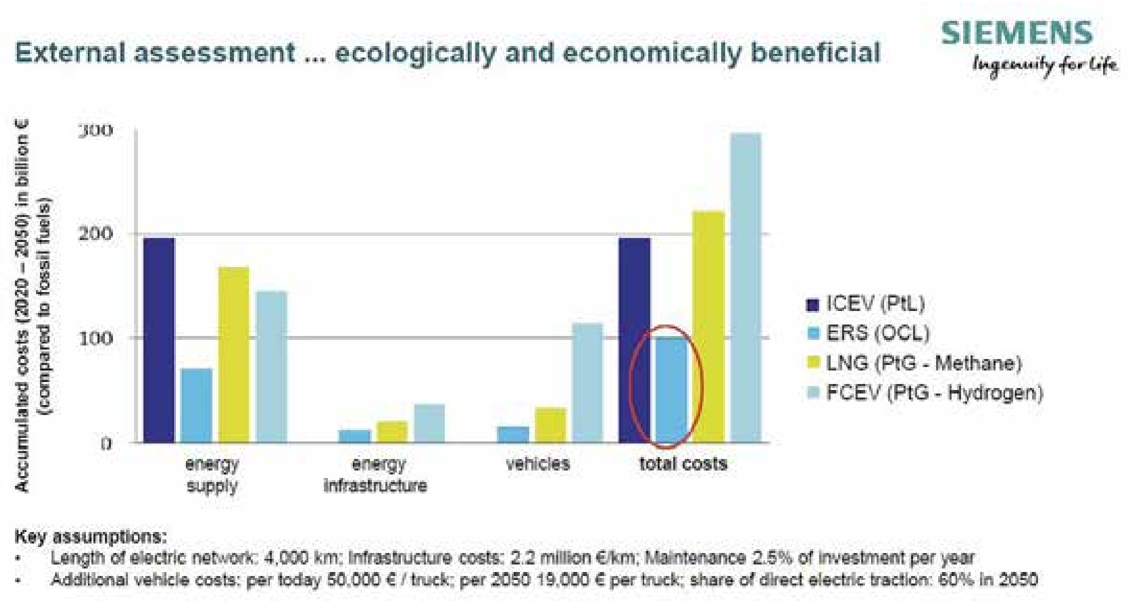
[1] Fraunhofer (2017)
[2] Olsson (2014

But, the Fraunhofer report is very useful, since it separates the costs from the various subcomponents and subsystems in the estimates, so that the calculations easily can be updated. In California USA, Ceravolo et al (2016) claims a cost of approx. 17 mill NOK/km, (1 mill USD per lane), a little higher than the lowest estimate in the German study.

It is also worth noting that while the OCL system consists of well know, proven and available technology on the infrastructure side, the GLS system is still under development, and there are at least three competing technologies; Alstom, Elways and ElOnRoad. The German study examines the Alstom technology, the technically most advanced of these (and possibly the costliest).

Other studies, have tried to estimate the future costs of different technologies. Öko Institut (2017) compared costs between an OCL system and alternative technologies for Germany in 2050. According to their work, electric roads (OCL) are by far the cheapest alternative, Figur 1



External assessment ... ecologically and economically beneficial

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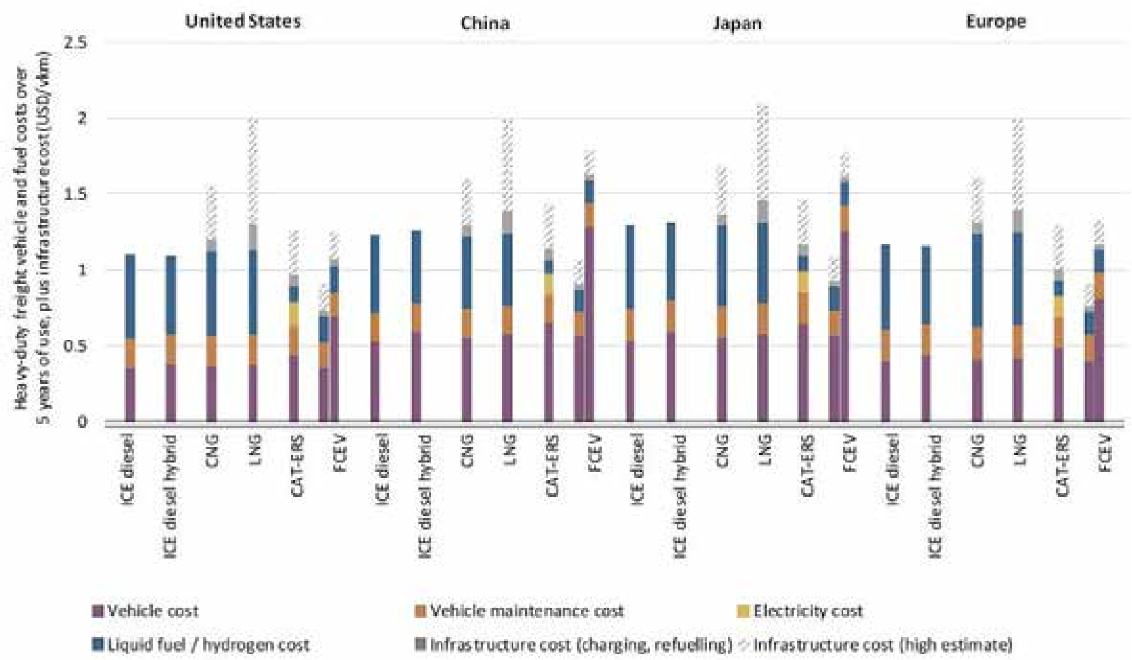
Key assumptions:

- Length of electric network: 4,000 km; Infrastructure costs: 2.2 million €/km; Maintenance 2.5% of investment per year
- Additional vehicle costs: per today 50,000 € / truck; per 2050 19,000 € per truck; share of direct electric traction: 60% in 2050

Figur 1 Comparison of energy supply, energy infrastructure, vehicles and total cost for combustion engines (ICEV), Siemens ERS, natural gas engines and hydrogen based fuel cells. (Siemens 2017).

In another study, The International Energy Agency (IEA) has studied "The Future of Trucks" (2017). Besides identifying reduced fuel costs and modernization of roads as most important for future costs, they conclude that cost of infrastructure is far less than the potential savings of constructing electric roads, Figur 2.



Figur 2 Heavy-duty freight vehicle and fuel costs over five years of usage in 2050 in the Modern Truck Scenario, including infrastructure costs (with high and low infrastructure utilization assumptions) (IEA, 2017).

Thus the given cost of electric roads is estimated between 13-18 mill NOK for OCL and 18-26mill NOK for GLS. The huge difference between the estimates for GLS, reflects the technology readiness level, and also the technological development during the project period.

In the end, we expect GLS system to have costs closer to OCL systems. From our investigation and discussions with stakeholders we find 13-18 mill NOK per km a reasonable cost estimate for both OCL and GLS. Thus with a need of conductive systems along 33% of road, or maximum 44% of the open road, hen the average cost of conductive electric roads should be around 6-8 mill NOK per km in Norway.

4.5 Action costs

Another way of evaluating costs, is by what the Norwegian Environment Agency called “Action Costs” (Miljødirektoratet 2015).

The rationale behind these calculations is simple. Actions needs to be taken to cut emissions, where can we get the largest emissions cuts per NOK ”. I.e. the calculations are used to prioritize between alternative technologies.

		Unit
Interest rate	4 %	
Design as % of investment	10 %	
Annual maintenance as % of investment	2 %	
Tax costs	20 %	
Investments grid and transformers – low cost	3 000 000	NOK/km
Investments grid and transformers – high cost	6 000 000	NOK/km
Service life grid and transformers	40	year
Electric road infrastructure, low cost	10 000 000	NOk/km
Electric road infrastructure, high cost	20 000 000	NOK/km
Service life of road	40	Years
% of open road	75 %	
% of open road electrified	44 %	
% road driven electric	100 %	
Length of road	200	km
Cost reduction new vs old (retrofit) road	20 %	
Fuel consumption ICE HDV	0,4	liter/km
Electricity demand BE HDV	1,8	kWh/km
CO2-emission per L diesel	2,66	kg CO2/liter
CO2-emissions per kWh	0,00	kg CO2/kWh
Cost of diesel ex tax	5,80	NOK/liter
Price of electricity ex tax	0,34	NOK/kWh
Grid rental ex tax	0,28	NOK/kWh
Maintenance + oil/tires diesel ex VAT	3,02	NOK/km
Maintenance + tires BE HDV ex VAT	2,92	NOK/km
Annual driving distance	120 000	NOK/year
Battery size	300	kWh
Cost of engine ICE	500 000	NOK/vehicle
Cost of motor and battery BE HDV	800 000	NOK/vehicle
Service life engine/motor and battery	4,5	Year

The action cost is calculated as the “societal cost divided by the annual emission reductions”.

The Norwegian Environment Agency sets the system boundary, and does only calculate emissions within Norway. Thus only emissions from production within Norway is accounted for.

5 Results

In these estimations, we have calculated the green-house-gas emissions from the production, maintenance and use of the vehicles:

Table 5 Co2 emissions from production of HDVs

	ICE	BE GLS	BE OCL
Vehicle	3,79E+04	3,79E+04	3,79E+04
Motor	5,05E+03	0,00E+00	0,00E+00
EV Motor	0,00E+00	2,48E+03	2,48E+03
Battery	0,00E+00	4,48E+04	4,48E+04
Pantograf	0,00E+00	2,55E+02	0,00E+00
Collector shoe	0,00E+00	0,00E+00	6,03E+02
Maintenance	4,55E+04	4,41E+04	4,41E+04
Maintenace motor ICE	1,77E+03	0,00E+00	0,00E+00
Maintenace ICE+EV	4,37E+04	4,37E+04	4,37E+04
Maintenance EV only	0,00E+00	3,85E+02	3,85E+02
Disposal	1,68E+03	1,68E+03	1,68E+03
Sum	**1,36E+05**	**1,75E+05**	**1,76E+05**

But for this estimation we are interested in the emissions on a per km basis. So according to the input parameters in Table 2, we estimated the carbon emissions on a per km basis for different service life expectations:

Table 6 CO2 emissions form production of HDVs per km based on average driving distance and service life

	4,5 year	7,75 year	9 year
ICE	2,51E-01	-	-
GLS/OCL	3,25E-01	2,57E-01	2,44E-01

In addition to the production of the vehicles, the use of the vehicles causes green-house as-emissions. The amount depends on source of energy and energy demand. The energy demand is determined by the vehicles weight, engine, payload and the road gradient. We have tested the sensitivity of varying the energy need for the BE HDV,

Table 7 CO2 emission from HDV use

	ICE 40L/100km	BE HDV 1,2 kWh/km	BE HDV 1,8 kWh/km	BE HDV 2,4 kWh/km
ICE	1,16	-	-	-
GLS/OCL	-	0,036	0,054	0,072

And finally we estimated the emissions from the electric roads.

The OCL system is based on mature railroad technology. We do not expect the technology to change much, but simpler support systems might be implemented.

Table 8 Total contribution of the OCL System with FU of 1 km

Impact Category	Unit	Catenary	Cantilever	Tensioning section	Support structure	Power supply
GWP_{100}	kg CO_2-eq	1,91E+04	1,53E+04	1,92E+04	5,77E+04	3,27E+04
FDP_{100}	kg oil-eq	3,99E+03	3,78E+03	3,16E+03	1,54E+04	1,88E+04
$FETP_H$	kg 1,4-DB-eq	9,25E+03	1,93E+02	2,16E+03	7,46E+02	1,24E+03
FEP_{100}	kg P-eq	2,73E+02	7,20E+00	6,40E+01	2,70E+01	3,63E+01
HTP_H	kg 1,4-DB-eq	5,71E+05	6,84E+03	1,32E+05	3,33E+04	6,63E+04
$METP_H$	kg 1,4-DB eq	9,91E+03	1,97E+02	2,30E+03	7,59E+02	1,29E+03
MEP_{100}	kg N-eq	2,58E+01	2,51E+00	7,65E+00	9,76E+00	6,34E+00
MDP_{100}	kg Fe-eq	1,58E+05	7,43E+02	3,71E+04	2,76E+04	2,40E+04
ODP_{100}	kg CFC-11-eq	1,12E-03	1,01E-03	9,83E-04	2,50E-03	7,13E-04
$PMFP_{100}$	kg PM_{10}-eq	2,35E+02	2,96E+01	7,14E+01	1,50E+02	7,20E+01
$POFP_{100}$	kg NMVOC	1,99E+02	3,88E+01	8,73E+01	1,90E+02	1,34E+02
TAP_{100}	kg SO_2-eq	6,38E+02	6,22E+01	1,82E+02	1,73E+02	1,70E+02
$TETP_H$	kg 1,4-DB-eq	2,57E+01	1,41E+00	6,56E+00	5,93E+00	4,00E+00

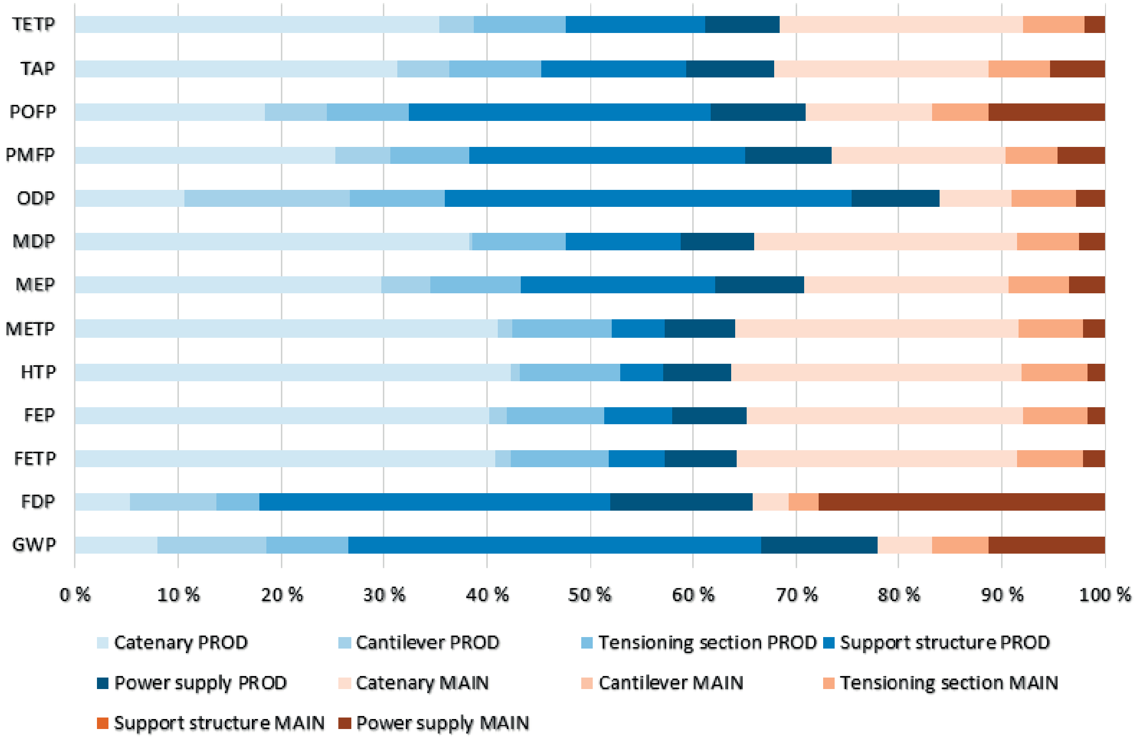


Figure 10 Advanced contribution analysis of the OCL System, with FU of 1 km. PROD, describes the production phase. MAIN, describes the maintenance phase

The GLS system is at a lower technology readiness level, and our calculations is based on an early version of the Alstom system. We know there has been changes in our system during the project time, but we have not been able to verify these. We expect a more mature GLS system with a simpler technology to have lower environmental impact, due to less material consumption.

Table 9 Total environmental impacts for the main components related to GLS, with FU of 1 km

Impact category	Unit	Electric track	Power box	Return cable	Switchgear SF6	Current distribution cable	Substation
GWP_{100}	kg CO_2-eq	2,53E+05	6,07E+02	1,25E+04	7,20E+03	4,90E+04	2,37E+03
FDP_{100}	kg oil-eq	6,84E+04	1,88E+02	3,47E+03	1,66E+03	3,99E+04	8,54E+02
FETP_{H}	kg 1,4-DB-eq	1,46E+04	4,70E+01	3,02E+02	6,72E+02	7,14E+01	4,08E+02
FEP_{100}	kg P-eq	4,70E+02	1,41E+00	1,45E+01	2,00E+01	1,51E+00	9,62E+00
HTP_{H}	kg 1,4-DB-eq	8,34E+05	2,77E+03	1,55E+04	3,90E+04	1,93E+03	1,94E+04
METP_{H}	kg 1,4-DB eq	1,52E+04	5,23E+01	3,06E+02	7,01E+02	6,20E+01	4,26E+02
MEP_{100}	kg N-eq	7,43E+01	2,07E-01	3,47E+00	2,46E+00	3,47E+00	1,20E+00
MDP_{100}	kg Fe-eq	2,45E+05	7,02E+02	2,63E+03	1,31E+04	3,79E+02	9,37E+03
ODP_{100}	kg CFC-11-eq	1,53E-02	5,73E-05	5,92E-04	2,28E-04	6,77E-05	2,26E-04
PMFP_{100}	kg PM_{10}-eq	7,57E+02	1,69E+00	1,93E+01	2,99E+01	5,11E+01	1,50E+01
POFP_{100}	kg NMVOC	8,70E+02	2,43E+00	2,85E+01	2,85E+01	2,18E+02	1,22E+01
TAP_{100}	kg SO_2-eq	1,77E+03	4,66E+00	5,83E+01	6,03E+01	1,52E+02	2,95E+01
TETP_{H}	kg 1,4-DB-eq	5,52E+01	1,45E-01	1,69E+00	2,03E+00	2,79E-01	1,16E+00

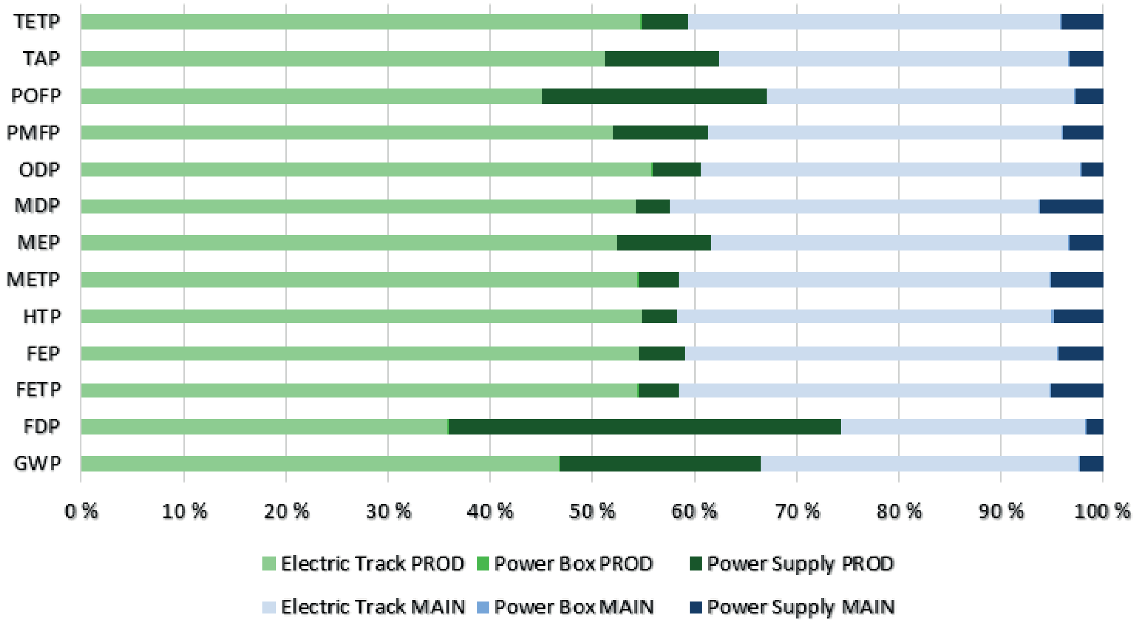


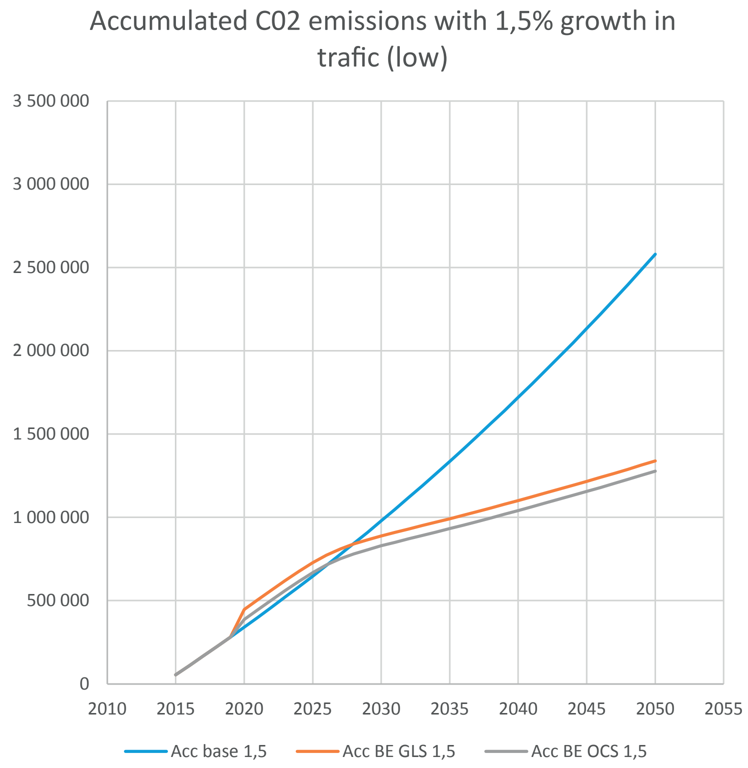
Figure 11 Advanced contribution analysis for the GLS System, with FU of 1 km. PROD describes the production phase, MAIN describes the maintenance phase.

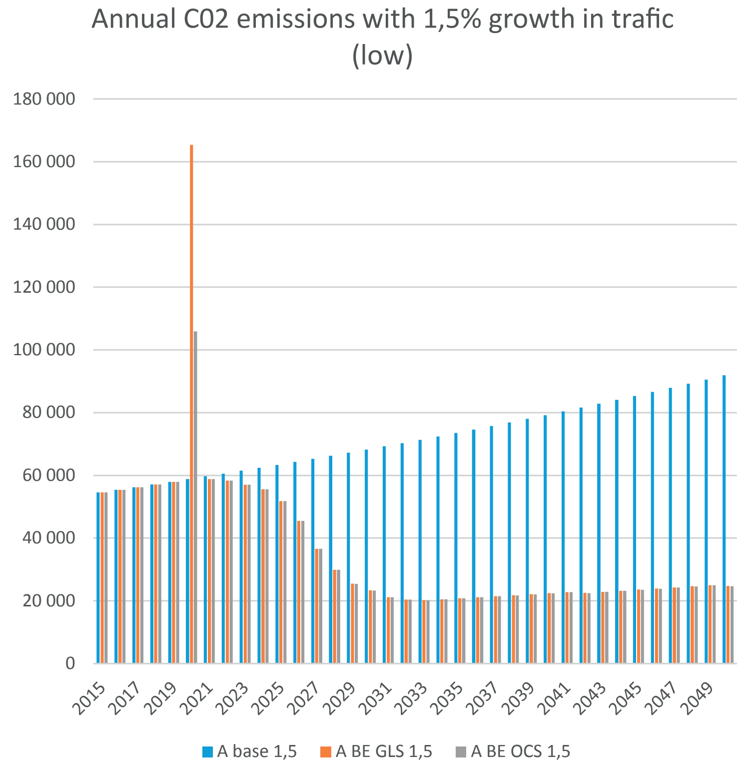
If we compare the two infrastructure systems as is, we get the following contributions from the infrastructure:

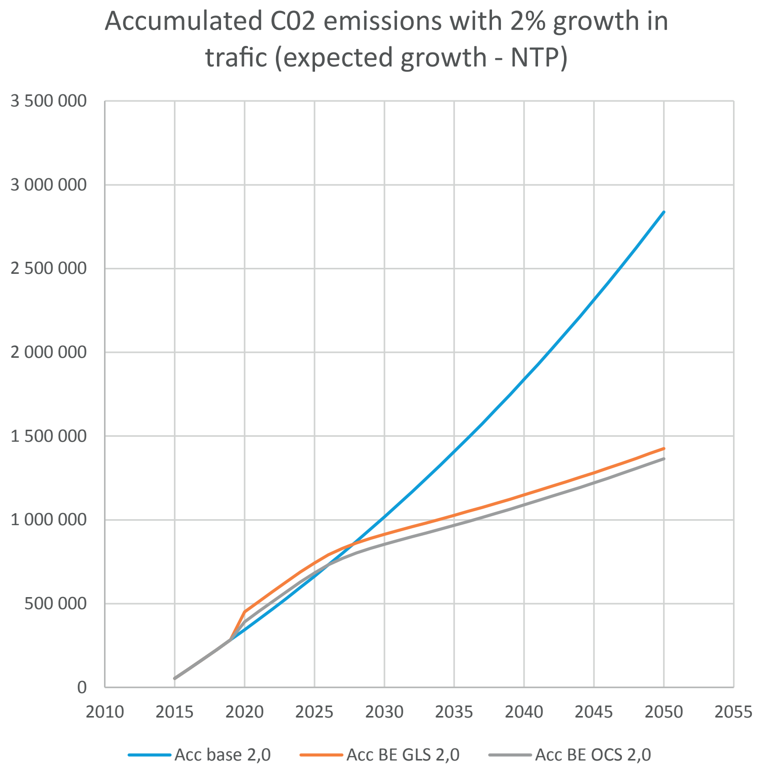
Table 10 Absolute values for the Electric Road Systems, with different functional units

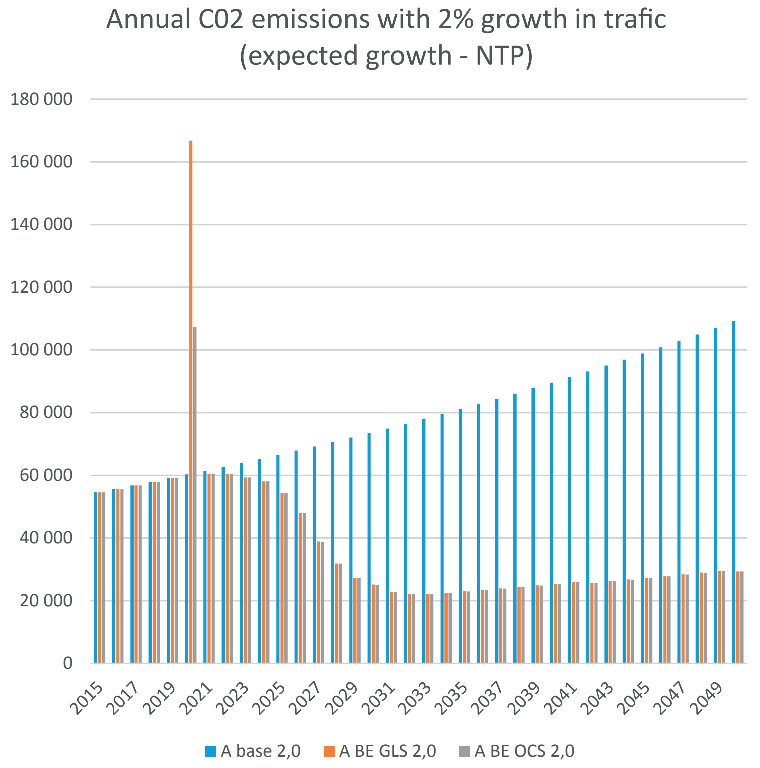
Impact category	Unit	Functional unit One km infrastructure		Alternative functional unit Distance Stavanger–Bergen One direction	
GWP$_{100}$	kg CO$_2$-eq	1,44E+05	3,24E+05	2,47E+07	5,56E+07
FDP$_{100}$	kg oil-eq	4,51E+04	1,15E+05	7,74E+06	1,97E+07
FETP$_H$	kg 1,4-DB-eq	1,36E+04	1,61E+04	2,33E+06	2,76E+06
FEP$_{100}$	kg P-eq	4,07E+02	5,17E+02	6,98E+04	8,87E+04
HTP$_H$	kg 1,4-DB-eq	8,09E+05	9,13E+05	1,39E+08	1,57E+08
METP$_H$	kg 1,4-DB eq	1,45E+04	1,68E+04	2,48E+06	2,88E+06
MEP$_{100}$	kg N-eq	5,20E+01	8,51E+01	8,93E+03	1,46E+04
MDP$_{100}$	kg Fe-eq	2,47E+05	2,71E+05	4,24E+07	4,65E+07
ODP$_{100}$	kg CFC-11-eq	6,33E-03	1,65E-02	1,09E+00	2,83E+00
PMFP$_{100}$	kg PM$_{10}$-eq	5,58E+02	8,74E+02	9,58E+04	1,50E+05
POFP$_{100}$	kg NMVOC	6,50E+02	1,16E+03	1,11E+05	1,99E+05
TAP$_{100}$	kg SO$_2$-eq	1,23E+03	2,08E+03	2,10E+05	3,56E+05
TETP$_H$	kg 1,4-DB-eq	4,36E+01	6,05E+01	7,49E+03	1,04E+04

If we combine the results, we get the following emissions from the heavy duty vehicles n an electric road between Bergen and Stavanger:






Accumulated C02 emissions with 2% growth in trafic (expected growth - NTP)
3 500 000
3 000 000
2 500 000
2 000 000
1 500 000
1 000 000
500 000
0
2010
2015
2020
2025
2030
2035
2040
2045
2050
2055
Acc base 2,0
Acc BE GLS 2,0
Acc BE OCS 2,0


Annual C02 emissions with 2% growth in trafic (expected growth - NTP)
180 000
160 000
140 000
120 000
100 000
80 000
60 000
40 000
20 000
0
2015
2017
2019
2021
2023
2025
2027
2029
2031
2033
2035
2037
2039
2041
2043
2045
2047
2049
A base 2,0
A BE GLS 2,0
A BE OCS 2,0

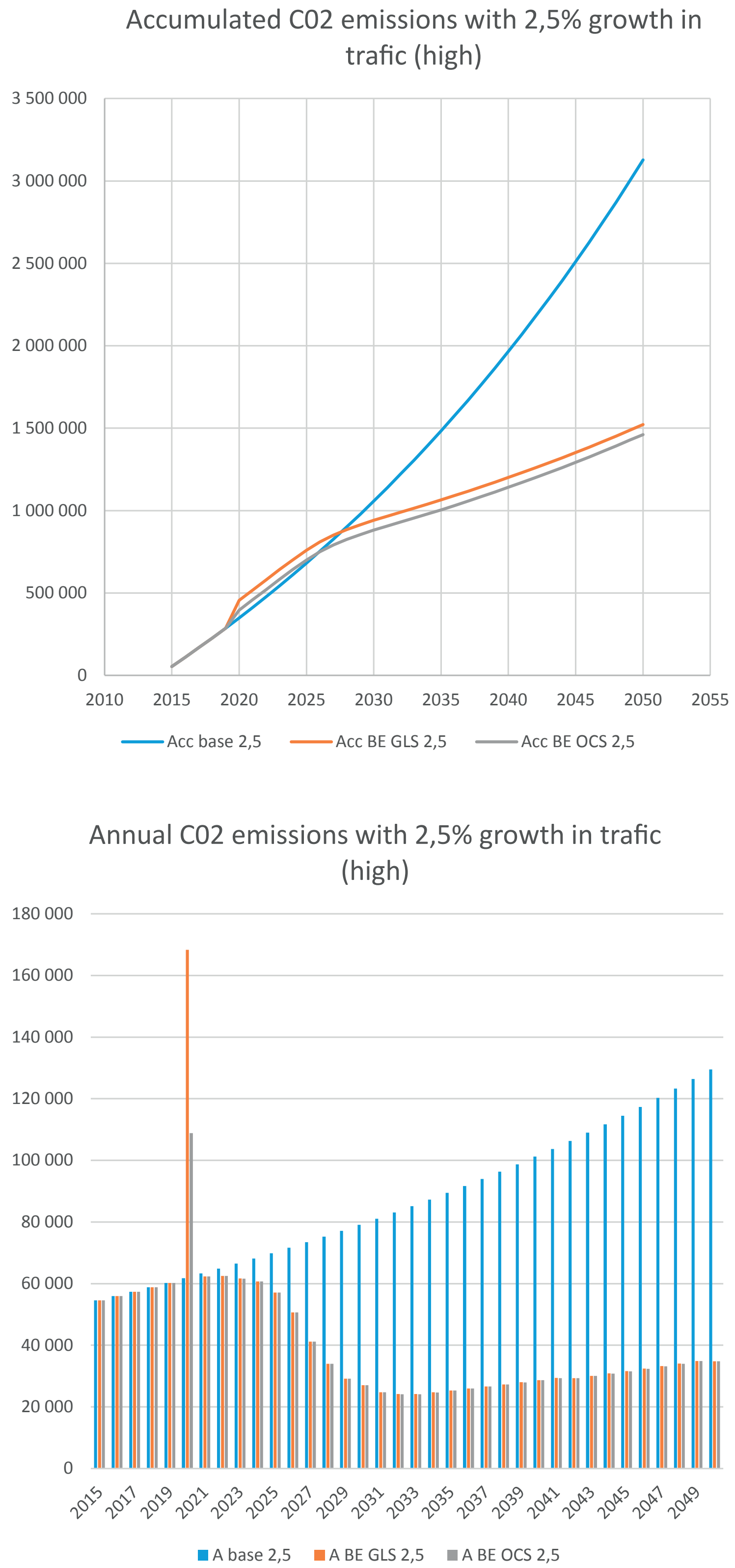


Figure 12 **Accumulated and year by year emissions from E39 Bergen Stavanger, with business as usual vs OCL and GLS systems.**

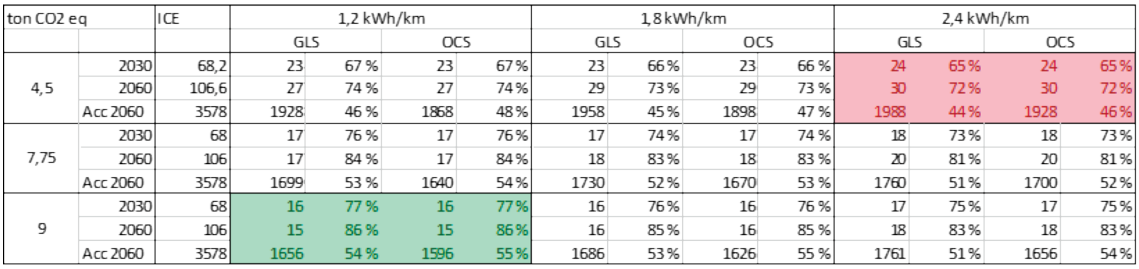
From our estimations, we can conclude the following:

- OCL is better than GLS if we look only at HDV, but GLS has the possibility to also be used by small and medium sized vehicles, and could possibly change the results.
- An electric road will have an environmental payback time of less than 10 years. And is better for the environment than continued use of ICEs in all scenarios.
- An annual CO2 reduction of 65% before 2030.
- An annual CO2 reduction of 75% before 2030, and growing with time.
- An accumulated reduction of CO2 of more than 50% with a service life of 40 years.

In order to test the robustness of the calculations, we also conducted a sensitivity analysis:

- We variated the electricity demand per km for the BE HDV
    - From 1,8 kWh/km, to low demand of 1,2 kWh/km and high demand of 2,4 kWh/km.
    - This will influence the results both positively and negatively
- We have variated the service life of the BE HDVs:
    - From 4,5 years to 7,75 years and 9 years.
    - This will influence the results for electric roads positively.

Table 11 Sensitivity analysis



ton CO2 eq		ICE	1,2 kWh/km				1,8 kWh/km				2,4 kWh/km			
			GLS		OCS		GLS		OCS		GLS		OCS	
4,5	2030	68,2	23	67 %	23	67 %	23	66 %	23	66 %	24	65 %	24	65 %
	2060	106,6	27	74 %	27	74 %	29	73 %	29	73 %	30	72 %	30	72 %
	Acc 2060	3578	1928	46 %	1868	48 %	1958	45 %	1898	47 %	1988	44 %	1928	46 %
7,75	2030	68	17	76 %	17	76 %	17	74 %	17	74 %	18	73 %	18	73 %
	2060	106	17	84 %	17	84 %	18	83 %	18	83 %	20	81 %	20	81 %
	Acc 2060	3578	1699	53 %	1640	54 %	1730	52 %	1670	53 %	1760	51 %	1700	52 %
9	2030	68	16	77 %	16	77 %	16	76 %	16	76 %	17	75 %	17	75 %
	2060	106	15	86 %	15	86 %	16	85 %	16	85 %	18	83 %	18	83 %
	Acc 2060	3578	1656	54 %	1596	55 %	1686	53 %	1626	55 %	1761	51 %	1656	54 %

From the results we see some sensitivity towards higher energy consumption. But this sensitivity may change if we had investigated the sensitivity towards the electricity mix (production). But we decided not to investigate the production of electricity, since we expect the future electricity production to be cleaner than today's electricity mix.

Our estimates predict an annual reduction of 40 ton CO2eq per km lane electric road between Bergen and Stavanger with a 33% coverage of conductive infrastructure and a traffic of 100 HDVs daily. Over a lifetime of 40 years this will accumulate to 1600-1800 tons.

By using the calculation rules set forth by the Norwegian Environment Agency (2015), using the parameters from Table 4, we have estimated the action cost for mitigating 1 ton of CO2eq by electric roads with various traffic loads. We have estimated the action cost for constructing the necessary infrastructure (44% of open road) at low, medium and high cost; 13 mill NOK/km, 18 mill NOK/km and 26 mill NOK/km, for both construction of new roads and retrofitting existing roadsThis is presented in figure 13, 14 and 15.

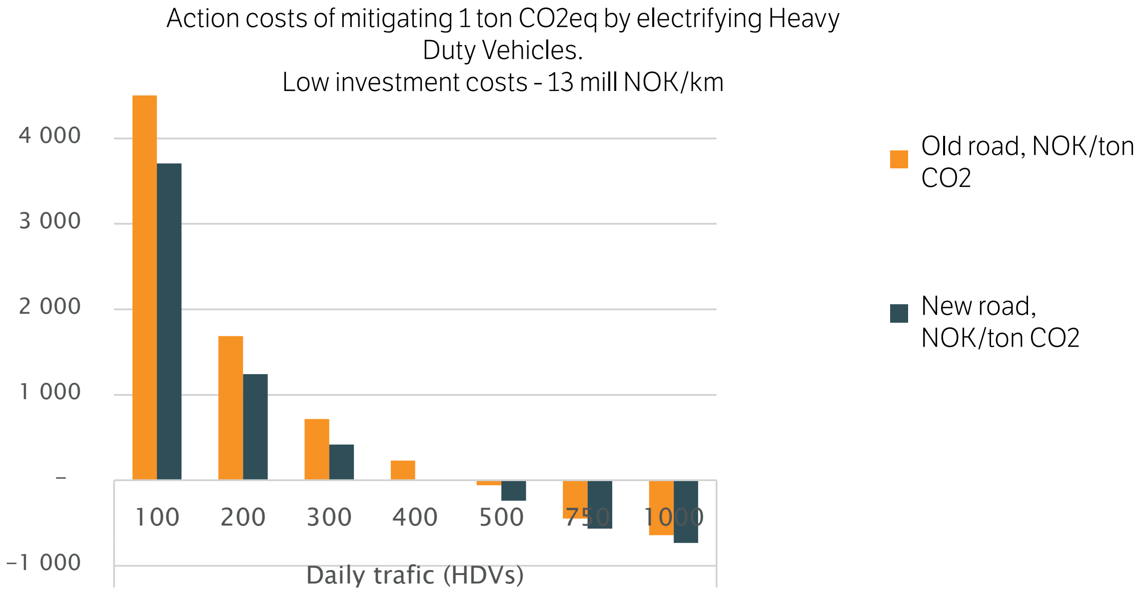


Figure 13 **Action cost of electric roads vs traffic, low cost of infrastructure**

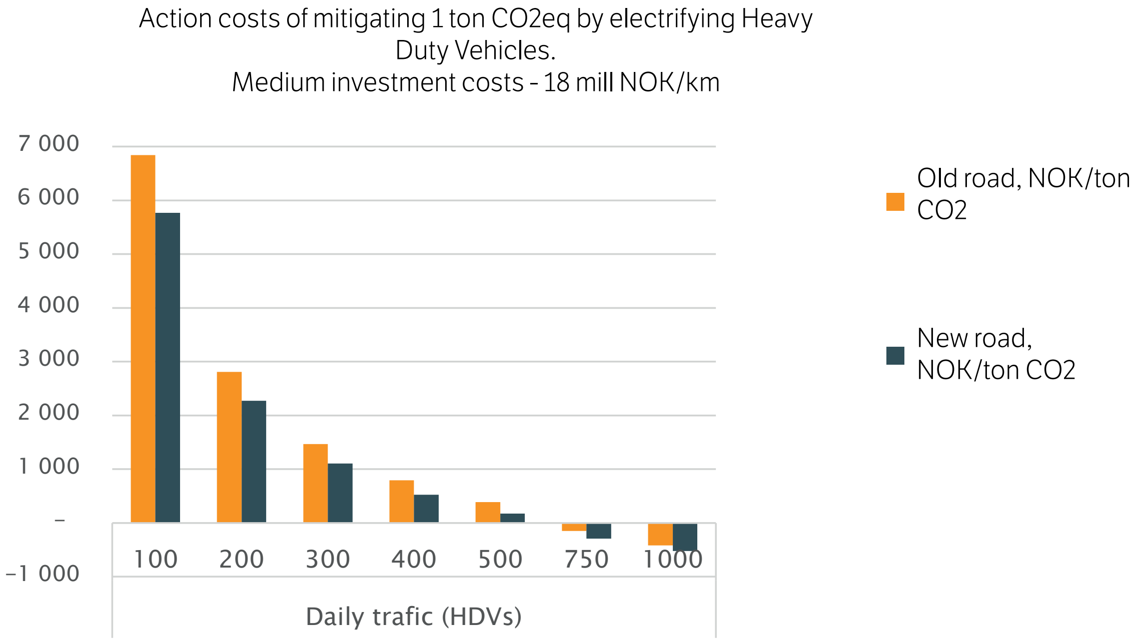


Figure 14 **Action cost of electric roads vs traffic, high cost of OCL infrastructure**

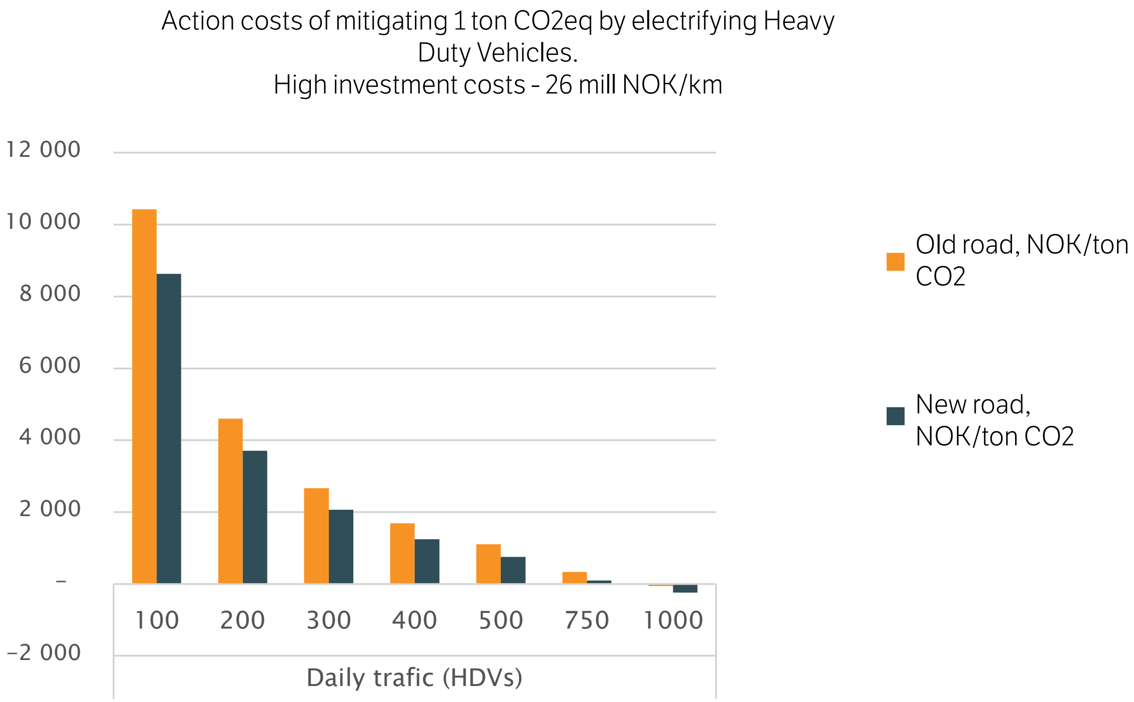


Figure 15 Action cost of electric roads vs traffic, high cost of GLS infrastructure

As Figure 13, Figure 14 and Figure 15 shows, the cost of mitigating 1 ton of CO2eq by electric roads is highly sensitive to investment costs and traffic.

This should suggest that E39 south of Bergen, E6 south of Trondheim and E18 all could achieve significant CO2 reductions at a reasonable cost.

6 Discussion and conclusion

The results show that implementing electric roads could cut the carbon emissions from road-based transport (HDVs) by over 66%, possibly more, even if we do the calculations for immature technologies. A ground-level-system has the benefit of also allowing small and medium sized vehicles to connect, and thus allowing for a larger reduction in carbon emissions.

The cost of action by implementing electric roads as a climate mitigation technology, is also low, when compared with other technologies.

But it seems clear that some sort of electrification of road transport is the future. The discourse is more on which technology and when.

Thus other technologies such as inductive electric roads should be investigated, although the technology readiness level of inductive electric roads is currently low.

Other technologies to consider is battery electric HDVs and /or hydrogen HDVs, which both has the potential to mitigate carbon emissions from road based transport significantly. Therefore, a feasibility study should be conducted.

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Appendix:

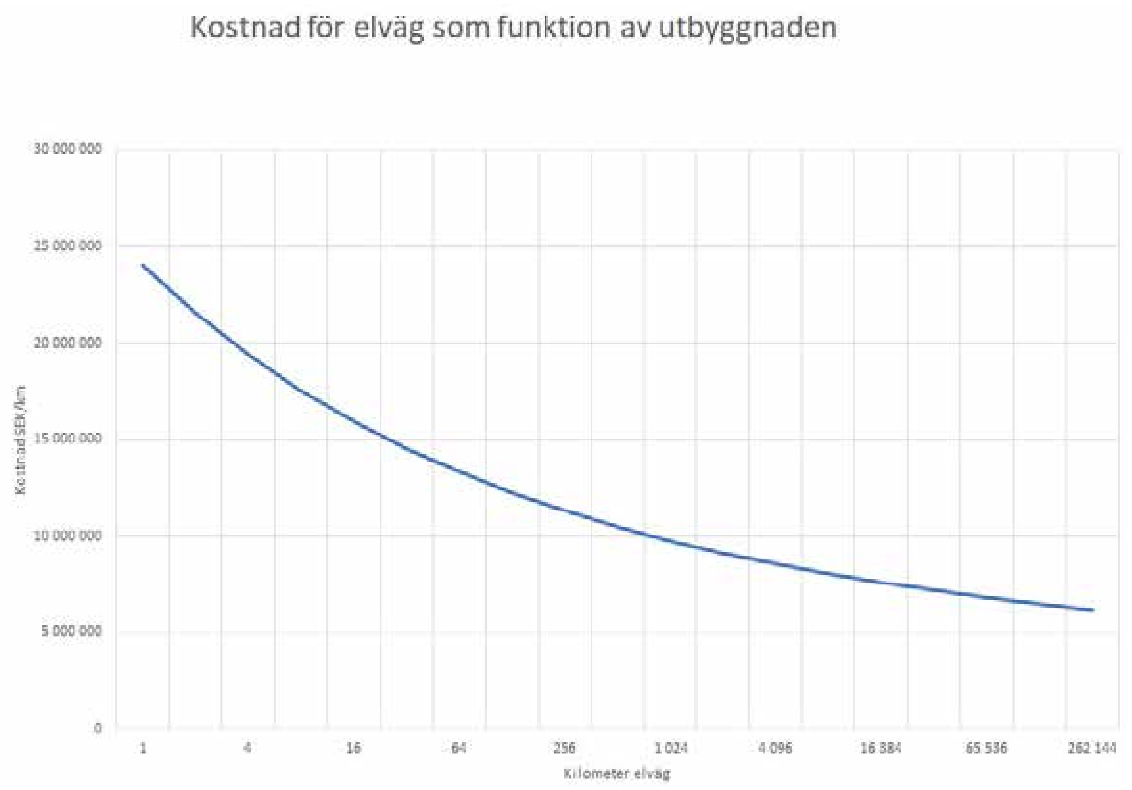
Kostnadsestimat, eRoadArlanda (Elways)

Nedanstående kurva visar en totalbild över kostnaderna för en kilometer dubbelfilig elväg baserat på teknik från Elways och anläggningsarbeten utförda av NCC inom ramen för projekt eRoadArlanda.

Startpunkten på kurvan är verkliga kostnader med ett pålägg på 15%. Fortsättningen på kurvan utgår från den ”learning curve” som normalt används i vetenskapliga sammanhang för att visa hur kostnader förändras för en produkt/teknik i takt med utveckling, industrialisering av produktion och ökad mognadsgrad mm. I denna kurva har en kostnadssänkning på 15% vid varje fördubbling av elvägen använts. För ingående material har en kostnadssänkning på 3% vid varje fördubbling av elvägens längd använts.

I vetenskaplig litteratur är det vanligt att man för helt nya och mycket innovativa lösningar räknar med kostnadssänkningar på 30% vid fördubblad volym medan äldre teknik och innovationer som utvecklats under många år brukar ha 5% kostnadssänkning vid en fördubbling.

Mot denna bakgrund anser vi att den av oss tillämpade procentsatsen på 15% är mycket konservativ och försiktig.



Källor: Gunnar Asplund (Elways) och Stefan Hörnfeldt (NCC)

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