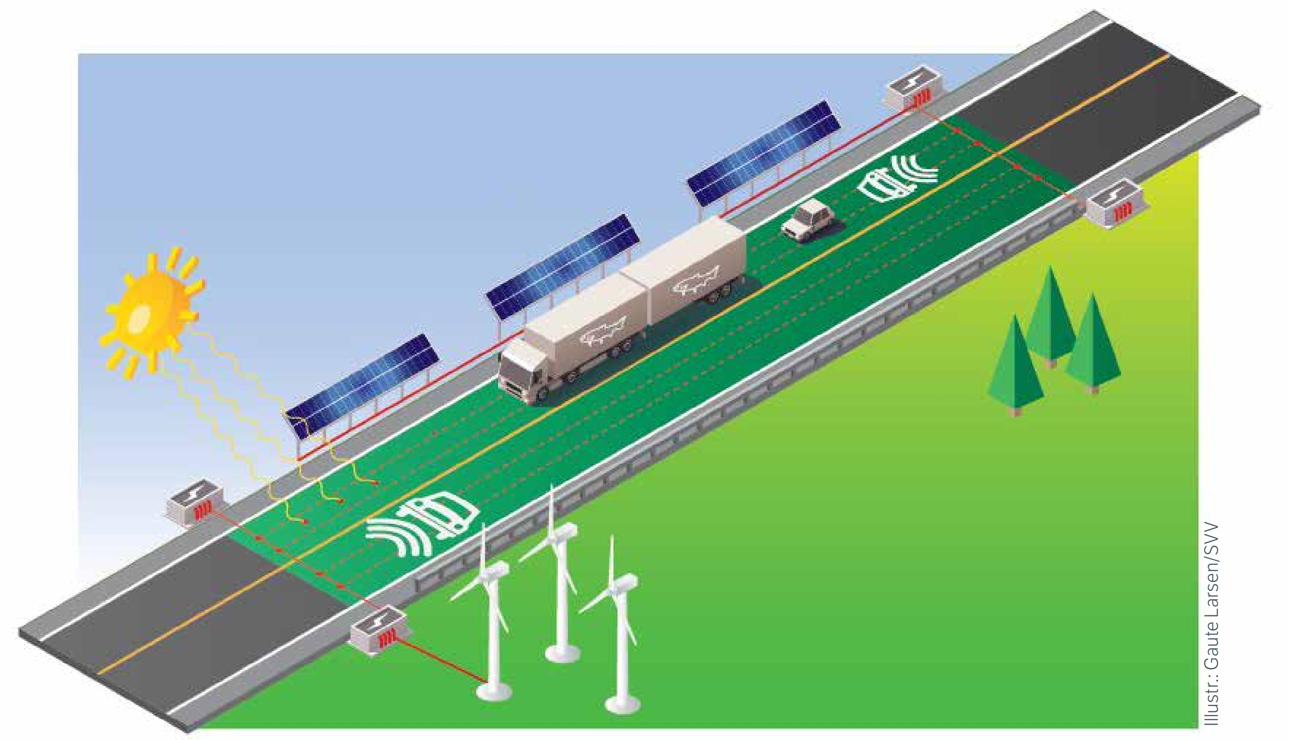
ELinGO

Electric Infrastructure for Goods Transport

Electric roads in Norway?

Summary of a concept analysis



Illustr.: Gaute Larsen/SVV

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Summary and main conclusions

- ELinGO focuses on the major x-factor in the green shift to sustainable transport – goods transport by road. ELinGO's aim has been to give a broad conceptual analysis for the electrification of heavy goods transport on Norwegian roads.
- The project has explored various technological solutions for electric roads (overhead lines, road rail and inductive charging) as well as various aspects of the economic, societal and climate impact associated with the realization of such solutions.
- As a starting point, the project has used the E39 as a case study, but the concept has relevance for roads all across the country.
- The starting point for ELinGO is: 1) Norway has set ambitious climate targets for the transport sector in that greenhouse gas emissions are to be rapidly reduced within 2030, and 2) that dramatic growth with the doubling of goods transport is expected to occur within 2050.
- Although battery and hydrogen fuel cell solutions for heavy transport are now being developed, electric roads have clear advantages over hydrogen and pure battery solutions. Hydrogen requires three times as much energy, and pure battery solutions will be large, heavy and expensive.
- Electric roads can be an effective way of reducing emissions from goods transport by road:
  - Overhead lines are a relatively developed technology that can be implemented relatively quickly and provide a considerable reduction in emissions.
  - Electric roads reduce the need for large batteries, a stationary charging infrastructure and eliminates queuing problems when charging.
  - Electric roads are adapted to an automated future.
- Electric roads can be a cheap way of reducing goods transport emissions:
  - The life cycle analysis indicates that greenhouse gas reductions will be obtained by building electric roads in Norway.
  - The cost-benefit analysis indicates that the socio-economic benefits can increase along with the traffic figures we expect for the decades to come.
  - The action costs indicate that electric roads can be a very favourable alternative compared to other options for reducing greenhouse gas emissions from heavy goods transport.
- On several stretches of road in Norway, the action costs fall under what the Norwegian Environment Agency designates as action category 1, with action costs ”below NOK 500/tonne”, which is the lowest action cost category. Among other relevant factors:
  - The southernmost part of E39 from Stavanger to Kristiansand has a good traffic basis and is already within the scope of action class 1.
  - Oslo-Trondheim also has a good traffic basis and is already in action class 1.
- Demonstration projects have been launched in both Sweden and Germany, which are now also working together to raise promote electric roads up at the at the European level. Against this background, establishing one or more demonstration projects in Norway with electric roads under Norwegian climatic conditions should be considered.

Contents

Why ELinGO?

Norway has set ambitious climate targets. By 2050, we are to be a low-emission economy. By 2030, Norway is to be climate neutral and have cut at least 40% of its emissions. In line with the EU, commitments include a large proportion of emission cuts to be made within non-quota sectors. This means in practice that in the years ahead Norway must be prepared to make major cuts in domestic greenhouse gas emissions. Major cuts in the transport sector are unavoidable. At the same time, the National Transport Plan 2018-2029 (NTP) shows that we expect to almost double the amount of goods transport by road within 2050.

In order for the growth in traffic not to get in the way of achieving climate goals, the government has signalled that it wishes to stimulate a change of pace for phasing in zero-emission technology more rapidly. According to the NTP, the development of Norwegian goods transport is to be facilitated so that it can contribute to the green shift, and the concrete goal set is that by 2030 all new all new distribution vehicles and 50 percent of heavy duty trucks are to be zero emission.

Technological solutions for zero-emission light vehicles are now ready, and Norway is at the forefront of the fleet conversion through strong incentives for the purchase of zero-emission passenger cars. However, a significant and considerable challenge remains, and the solution is still down the road in a manner of speaking: how to remove greenhouse gas emissions from long-distance goods transport by road? This has been called the major x-factor in the green shift towards sustainable transport, where there is great uncertainty about technological breakthroughs that can be rolled out on a large scale. Until now, we have focused on various alternatives with one thing in common, that the vehicle carries the energy it consumes on board. Hydrogen and the various varieties of biofuels have been considered the most appropriate alternatives.

This project, ”Electrical Infrastructure for Goods Transport” abbreviated as ”ELinGO”, is aimed at this major x-factor in the green shift towards sustainable transport. As the title indicates, we have focused on electrical solutions for heavy goods transport over longer distances. More specifically, we have focused on electric roads, where the road infrastructure supplies power to vehicles while in transit. This alternative solution has received relatively little attention and has hardly been researched in connection with Norway.

Here we have followed three main technology trails:

- overhead lines over the roadway.
- rail in the roadway.
- wireless transmission.

The study has been a conceptual analysis, which has mainly analysed technology, climate impact, costs and the societal framework conditions for making electric road concepts a reality in Norway. ELinGO has not conducted any concrete demonstration activities (with the exception of a small experiment, see Appendix II).

Figure 1. E39 from Trondheim to Kristiansand

E39 was chosen as a case study for the analyses. Many new stretches of road are to be built here over the next few years, providing a good opportunity for implementing new innovative solutions for power transfer to goods transport. Much of Norwegian value creation takes place along this corridor, in terms of farming, production and the shipbuilding industry. The possibility of railway transport is absent for most of this stretch. However, even though E39 is the starting point for the analyses, the results are nevertheless applicable for all of Norway.

Other countries are now investing in electric roads. Sweden and Germany have entered into an agreement to work together to promote electric road solutions at the European level and have several demonstration projects in progress. This may affect important transport corridors for the export of Norwegian goods and for Norwegian goods transport.

Photo: Scania.com (Creative Commons Liscense 3.0)

Why electric roads?

The dynamics for change towards electrification are currently in high gear. Several major car manufacturers, such as Volvo, BYD and Tesla have displayed electric HDV's that they are working towards bringing to market. Currently, it is mainly about vehicles that are at the conceptual stage. With the exception of Tesla Semi (battery-driven) and Nikola One (using hydrogen fuel cells), these are vehicles intended for use over relatively short distances. Only Tesla and Nikola have shown clear ambitions to solve the challenges for electric HDV's not just transporting heavy goods, but over long distances.

However, there are several factors that make the long-distance electric transport of heavy goods difficult. If one were to drive a long distance on a winter day with batteries, for example from Trondheim to Oslo, it would require batteries that were very:

- heavy
- large
- expensive.

Battery technology is currently under intense development, but whether the development of batteries for long-distance goods transport that are neither heavy nor large nor expensive will be successful is not yet clear.

Even if there is success, there may be other challenges related to climate, environment or access to resources. Authorities are targeting electric road transport because it is presumably sustainable, as well as having other possible benefits. In practice, this means that the solutions chosen should be sustainable in the sense that most road transport must be able to use such a solution. Thus, an important question is the sustainability of using batteries to power all heavy road transport, and all other road transport. In that case, there are three issues related to batteries that we need to get more knowledge about:

- Are there enough material resources for all the road transport in the world to be powered by batteries?
- Can these material resources be extracted in a way that does not break the assumption of battery powered transport as a gain to sustainability?
- Can these material resources be extracted quickly enough to avoid dangerous climate change? It takes about 10 years from deciding to open a mine until it is actually opened.

Illustr.: Colourbox

Even if the answer were yes to all three of these questions, batteries will probably have a high value in the years to come. A possible strategy for electrification not being too expensive may be to minimize the use of batteries wherever possible. If it is possible to find solutions not requiring batteries the size of a Tesla Semi, it would free up capacity in a market that is likely to be quite tight if climate goals are to be reached-

With electric roads, you can drive long distances without needing a lot of battery capacity and still be able to leave the electric road network and drive quite a distance on your own power. Energy consumption going to vehicles always transporting large batteries that are not necessarily needed, is avoided. Electric roads not only solve the technological challenges of batteries in connection with the heavy weight per unit of energy ratio, but also the practical disadvantages associated with charging times and queues. With wireless charging in transit, it will be possible to charge an "unlimited" number of heavy vehicles, thus avoiding charging stations becoming bottlenecks for heavy goods transport. Electric roads are therefore a suitable solution in the future for automated vehicles, in that you not only avoid maximum driving time and mandatory rest provisions, but you are able to maintain nearly 100% time on the road since there is no charging or refuelling to consider.

Compared with hydrogen fuel cells, electric roads have clear advantages as well:

> *A hydrogen-electric passenger car typically uses about 1 kg of hydrogen per 100 kilometres. Given the efficiency of the conversion processes from electricity to motion is between 30 and 35 percent, a hydrogen car requires 0.6 kWh of electricity per km. The equivalent for an electric car is about 0.2 kWh/km. Full electrification of today's passenger car fleet would under these assumptions require about 7 TWh of electricity annually, while the corresponding transition to hydrogen cars with hydrogen-based production based on water electrolysis would require about 20 TWh of electricity.*[1]

In other words, batteries are three times as energy efficient as hydrogen and fuel cells. Hydrogen-based goods transport will thus use three times as much energy as electric goods transport. With a sufficient amount of traffic, electric roads are more efficient than both battery and diesel operation (Connolly 2017).[2] As we will see, there are several places in Norway with an adequate traffic basis, which means that electric roads appears to be a relatively affordable way of reducing greenhouse gas emissions.

The three different E-road technologies

The most basic distinction when it comes to various electric road concepts is whether they are inductive or conductive. Inductive charging means the transmission of power without direct contact, i.e. wireless transmission. Conductive charging means charging using sliding contacts, either over or underneath the vehicle.

In work package 2, "Technology Development", three different technologies have been evaluated: overhead lines over the roadway, rail in the roadway and wireless transmission from the roadway. Thus two of the technologies are conductive, and one is inductive.

Table 1. Electric road technologies

	Conductive – with direct contact	Inductive – without direct contact
Over the roadway	Contact wire	
In the roadway	Rail	Wireless transmission

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[1] Norwegian Government White Paper 25 (2015-2016). *Power to Change - Energy Policy Towards 2030*. Oslo: Ministry of Petroleum and Energy

[2] Connolly, D. 2017. Economic Viability of Electric Roads Compared to Oil and Batteries for All Forms of Road Transport. *Energy Strategy Reviews (18)*, pp. 235-249.

Overhead lines

Photo: Region Gavleborg

The technology based on an overhead lines is definitely the most developed. Here you can draw on a hundred years of experience with trains, trams and trolley coaches. The first public demonstration was opened under the auspices of the Swedish Transport Administration in 2016. The technology is mainly marketed by Siemens, and several demonstrations are underway or in planning stages in Sweden, Germany and the United States. The obvious benefit of this solution is that it can be quickly brought into use, and can then swiftly help to reduce greenhouse gas emissions. One disadvantage compared to the other two relevant technologies is that it cannot be used by passenger cars.

Rail

Photo: eRoad Arlanda

Work is being done on several different variants of technology for conductive transmission of power from roadway to vehicle. In Sweden, the two start-up companies, Elways and Elonroad, are working with different rail concepts. In collaboration with Volvo, the French company Alstom is working on adapting technology in operation for urban railways to use with HDVs. All of these technologies have been tested at the level of power required by large HDVs. In Sweden, Elways' concept is now being tested on a two-kilometre stretch from the Arlanda cargo terminal.

The obvious benefit of rail solutions in the roadway is that they can serve vehicles of different sizes and different power requirements. The biggest drawback is challenges associated with operation and maintenance of a rail that entails separations in the asphalt and the introduction of a foreign element to the construction. These challenges are largely linked to winter conditions and the challenges created by frost, snow, ice and salt.

Inductive

Illustr.: Sustainable Electrified Transportation Center – SELECT

Technologies for inductive dynamic vehicle charging are significantly less developed than overhead lines and rail. Currently, different concepts and designs are under development, but only two projects have carried out demonstrations with the capacity levels required for long-distance, heavy goods transport, the Canadian company Bombardier and researchers at KAIST (Korea Advanced Institute of Science and Technology). In all likelihood, the potential also exists that many demonstrated systems with lower outputs can be further developed to deliver higher outputs. However, development is most certainly in too premature a phase to see signs of winners and losers among the technologies. The cost level appears to be significantly higher than for rail and contact wire. As always when it concerns technology development in general, cost reductions can be expected throughout the course of development, but it seems very difficult to say how much. Moreover, the industry has not been willing to publish either cost figures or technological specifications that would make it possible to estimate costs. We have therefore not been able to provide accounts relating to either the economic or climate impact of inductive solutions.[3]

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[3] In fact, there is a fourth variant of sliding contact in the form of an arm extending out to a side rail. This is being tested at high speeds in Japan by Honda. However, it is unclear whether there is any significant scope to this venture and there is little available documentation. We have therefore not gone into this to any extent other than referring to it in the technology report.

Basic advantages, disadvantages and common features of the different technologies

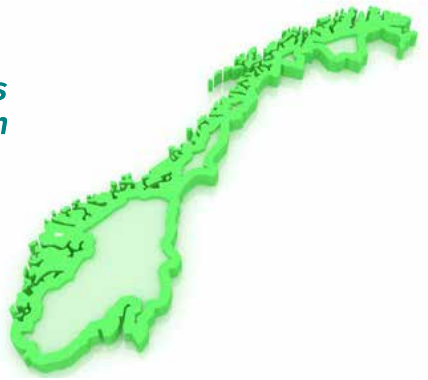
An advantage of power transfer from under the vehicle, as in rail and inductive, is that they can also work for smaller vehicles. Whereas, overhead lines can only work for large vehicles, as the wire is hanging too high for smaller vehicles. Overhead lines on the other hand, have the advantage of being by far the most developed technology. Since about half of the costs are related to the propagation of electricity along the roadside, the choice of this technology does not bear a sunk cost if another technology emerges as the clear winner. Half of the investment is considered to be long-term, as it is possible to replace the technology in the roadway without changing the power infrastructure along the roadside.

In terms of constructionability, there are no significant problems with any of the technologies. The use of overhead lines is a well-known technology, and can be easily installed on both old and new roads, provided there is space on the side of the road. A overhead lines is also a relatively proven technology in relation to winter operation. However, a rural coastal climate along the E39 can pose new operational challenges, but it's hard to imagine that it would be prohibitive.

Power transfer under the vehicle will be easy to install in the roadway, both in old and new roads. However, as this technology involves separations in the asphalt deck, and with the introduction of materials with physical properties other than asphalt, it is uncertain how such a solution will be affected by operation in winter. This can be problematic and drive up the costs. Test stretches should therefore be built to test this solution in various winter conditions before any large scale development. In particular, these technologies should be tested against frost heave and freeze/thaw cycles. Experiences from the Swedish rail project eRoadArlanda will provide valuable information.

Inductive power transfer under the vehicle will be more expensive to build than a rail solution, but is believed to eliminate most of the problems of operation in winter. Inductive solutions are built underneath the asphalt, thus no separation of the top layer of the road. However, there is some uncertainty about how robust inductive solutions are against moisture and frost heave. Test stretches should be built for this solution as well in frost-exposed areas before large-scale development.

Electrification of 5% of Norwegian roads will cut almost half of the emissions from heavy duty vehicles



Taljegård et al. (2017). Electric road systems in Norway and Sweden: Using ERS on 40% of the Norwegian E- and N-roads with the highest emissions will save 44% and 46% of the total Norwegian emissions from light vehicles and heacy vehicles, respectively.

Illustr.: colourbox

Figure 2. Research result from a different project (The E39 coastal highway route)

Power and energy requirements

In work package 3, "System Development", a model is developed for calculating power and energy requirements. This varies by type of vehicle, fuel and the characteristics of the stretch being driven. Topography and speed affect results considerably when it comes to electric vehicles. So in this way, the E39 is a good case study. It has varied topography with flat areas, hills, bridges and undersea tunnels. As the analyses were about to be carried out, a further delineation was considered appropriate, so the stretch between Bergen and Stavanger was taken as a starting point, which also offers a quite varied topography.

GENERAL ASSUMPTIONS

Vehicle

- Only electric drive trains
- 300 kWh battery
- Energy consumption of 1.8 kWh per km

Infrastructure

- Dynamic charging infrastructure along 33% of the stretch
- 300 kW power

The proper dimensioning of power and energy requirements is particularly important for electric vehicles. It is expensive to increase battery capacity, and the weight of additional batteries results in a constant higher energy consumption. On the other hand, underinvestment in battery capacity can make a vehicle useless. Good estimates of the necessary power and energy requirements are important when planning electrical support infrastructure. You need not only good estimates for how much energy is needed in total, but also for where the additional requirement for energy and power will exist.

The calculations have been based on a vehicle with a total weight of 42 tonnes. It is assumed that this is representative of an average weight while driving. In practice, the weight will vary between an empty vehicle of 22 tonnes and a fully loaded vehicle with a maximum total weight of 50 tonnes. The total distance of the route that has been chosen – from Bergen to Stavanger – is 183 kilometres. It was assumed that the electric infrastructure transmits electric power with an output of 300 kW.

Here we have calculated four scenarios, which we choose to call:

- Zero scenario
- 8% scenario
- 14% scenario
- 33% scenario

The percentage refers to how much of the driving time along the route energy is provided by the electrical infrastructure.

Table 2. Various electrification options on the route Bergen – Stavanger. 183 kilometres. Transmission power 300 kw.

Title	Portion of dynamic charging infrastructure	Percentage of route	Percentage of travel time	Need for own energy	Battery requirement (starting point in that only 70% is used)
Zero scenario	None, battery only	0% of the route	0% of travel time	337 kWh	480 kWh
8% scenario	15 km on flat road	8% of the route	8% of travel time	286 kWh	408 kWh
14% scenario	15 km up out of tunnels	8% of the route	14% of travel time (due to lower speed)	226 kWh	320 kWh
33% scenario	60 km average road	33% of the route	33% of travel time	110 kWh	160 kWh

Zero scenario

To drive the entire route on battery power only, you need a 337 kWh battery. However, it would not be expedient to assume that you need no more than what is required to reach your destination on that route under perfect climatic conditions. Temperature and rolling resistance vary with weather and seasons, and extra capacity is needed to be able to drive different routes. Also, batteries are unnecessarily worn out if they are constantly discharged. Under normal conditions, no more than 70% of total capacity should be used. Taking this as the starting point, a vehicle that is going to drive the Bergen – Stavanger route without being supplied electricity will need a 480 kWh battery.

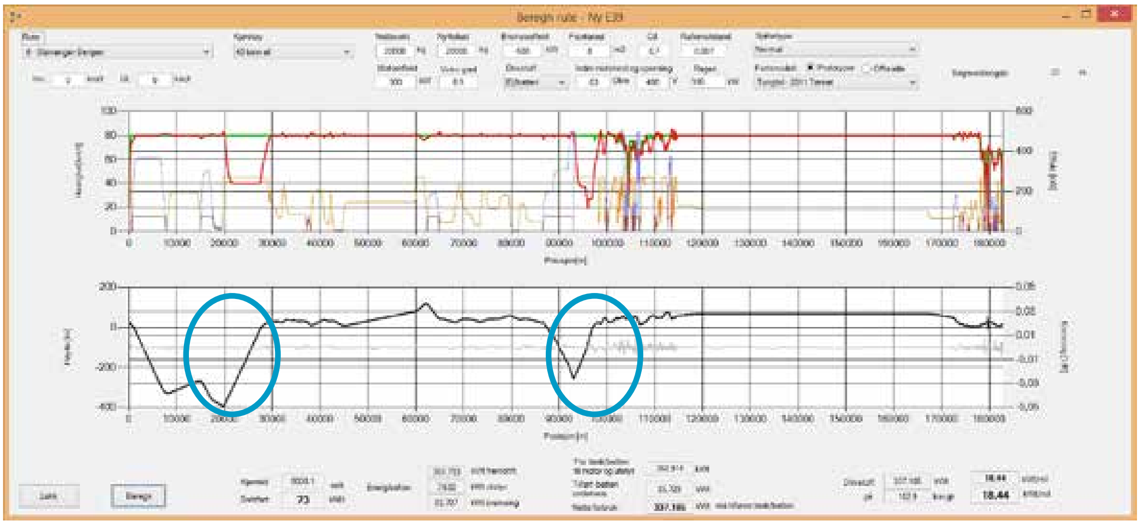
The Tesla Model S is sold with battery dimensions of 75 kWh and 100 kWh. Photo: Tesla Motors

8% scenario

In this scenario, 15 kilometres of charging have been placed on a fairly horizontal stretch between 125 and 140 kilometres from Stavanger in the direction of Bergen. Of 300 kW received, 115 kWh goes to propulsion (the vehicle requires 102 kWh for the wheels to hold 80 km/h). The other 185 kW goes to charging the battery. This will last for 0.188 hour. As a result, power consumption is reduced from 337 kWh in the zero scenario to 286 kWh. Thus a reduction of 51 kWh or about 15%. The required battery size is reduced from 480 kWh to a little more than 400 kWh.

14% scenario

Once the E39 is completed, there will be two deep tunnels in the area. In this example we have taken the starting point of electrifying when travelling up out of the tunnels, with two stretches of 10 and 5 kilometres, i.e. 15 kilometres in total. This corresponds to 8% of the distance in kilometres on the stretch from Stavanger to Bergen, but due to the reduced speed in the ascents, it will take 14% of the travel time. This reduces the energy consumption by one third compared with the battery-only solution in the zero scenario, i.e. from 337 to 226 kWh. Based on the rule that you should have a 30% buffer of total battery capacity, the requirement for the battery on board a vehicle is reduced to approximately 320 kWh. Almost all external power is transferred directly from the infrastructure to the engine here and does not pass through the battery.



Blue circle: Direct use of the energy up two tunnel ascents can reduce the required battery capacity by a third.

Figure 3. Illustration of energy model calculation.

33% scenario

This is the scenario that is in line with the general assumptions in the other relevant work packages in the project. The socio-economic calculations in the cost-benefit analysis, life cycle analysis and action cost-benefit analyses all have a starting point with the infrastructure being built along one third of the total stretch and that the vehicles have 300 kWh batteries, so there are ample opportunities to drive alongside the electrified roadway sections.

In this scenario, 60 km of the Stavanger – Bergen stretch, which corresponds to 33% of the route and travel time, are electrified. This translates to an energy requirement for the vehicle's battery of only 110 kWh. Taking the 70% battery discharging rule as a starting point, this battery requirement corresponds to only 160 kWh. As we have assumed the use of a 300 kWh battery in all calculations, the consumption of only 110 kWh on the stretch will provide ample flexibility in terms of climatic variations, maximum loads and driving outside of the electrical infrastructure. A residual capacity of 190 kWh in the battery provides the opportunity to drive approx. 100 kilometres on battery outside of the electrified road network.[4]

The analyses from work package 3 show that the optimal location for the charging infrastructure is on inclines. Not because the greatest power is required here, which it is obviously, but because this is where the lowest speeds are driven. Time-related charging infrastructure is the deciding factor for how much power you can transfer. Loss from internal resistance in the battery is of less importance. In addition, the analysis shows that maximum loads and winter conditions drain a lot of energy:

- If the load increases from 42 tonnes to a maximum of 50 tonnes, a 15% increase in electricity consumption occurs.
- With 50% increased rolling resistance in winter, a 20% increase in electricity consumption occurs.
- A maximum load of 50 tonnes and 50% increased rolling resistance due to winter conditions means a 38% increase in electricity consumption.

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[4] 300 kWh – 110 kWh = 190 kWh. 190 kWh/1,8 kWh per km = 105 km.

On the other hand, a lot can be gained through new types of vehicle design that have lower air resistance than those used today. Our analyses have assumed that the vehicles have a consumption of 1.8 kWh per km. However, based on knowledge acquired through the project, it is believed likely improvements on this can range anywhere from 0.5 kW to 1.3 kWh per km. If that is the case, it comes very close to approaching the consumption given for a Tesla Semi (1.2 kWh). This means that the combination of 300 kWh storage capacity in the battery and 33% electrification of the road distance probably will be well suited for longer distances such as Oslo-Trondheim, in the sense that the route can be driven without stops for stationary charging.

The question of available power along the road is also dealt with in work package 3. There are major local variations here along the stretch. Among the 17 power companies that own electrical grids along the E39, nine of them have provided the cost estimates we requested for fitting or upgrading the grid sufficiently for roadway electrification. The estimated cost for upgrading along the E39 is in the range of NOK 900–1,200 million. However, the ELinGO project has a general starting point of only 33% of the stretch of road being electrified. In practice, the actual location of stretches will be a balance between two factors:

- Where power grids are already available, which is an important factor today for the selection of charging station locations for buses and passenger cars.
- Where appropriate in relation to topography (ascents).

In addition, it should be mentioned that both the technology and costs are relatively independent of whether you are intending to provide overhead lines , rail or inductive charging. This also means that you can change the technology in the roadway at a later date without everything losing its value. The main service life of the power grid is approx. 60-70 years.

Accounts – Climate effects, socio-economics and action costs

In work package 4, several different ”accounts” were formulated, which answer various questions relating to electric roads in a Norwegian frame of reference:

- In the life cycle analysis, the question is whether electric roads are an adequate action against climate change, without regard to economic considerations.
- In the cost/benefit analysis, the question is whether electric roads are socio-economically profitable.
- In the action/cost analysis where it is a given that emissions are to disappear, the question is whether electric roads are a more or less expensive option than other alternatives for reducing emissions.

Electric roads require significant infrastructure development. The various accounts are largely influenced by the number of road infrastructure users. How much traffic there is on a road will therefore be important for whether it will be worthwhile to build electric roads.

Life cycle analysis

In a life cycle analysis, all emissions are taken into account. The life cycle analysis is a purely physical account, which as far as possible, takes the total of all emissions from all sub-processes in the value chain, regardless of country of origin. In practice, the analysis is limited to a set of indicators, each representative of a type of environmental impact. In our analysis, we have looked at greenhouse gas emissions or CO_2 equivalents. Our account describes how much greenhouse gas emissions are reduced by replacing today’s technology (diesel) with electric roads.

The starting point in the life cycle analysis is a case study with a transport volume of E39 between Stavanger and Bergen of 40,000 vehicles a year, corresponding to an annual average daily traffic (AADT) of 100. Furthermore, an annual growth rate of 2% is assumed for the period up to 2050. Furthermore, it is assumed that the electrified road stretch will be fully operational by 2020 and that all heavy vehicles driving the stretch will be electric by 2030 (given that heavy vehicles are usually replaced after approx. 4.5 years, and that there are financial incentives to choose electric).

Figure 4 shows how emissions will be spread over the various years in such a scenario.

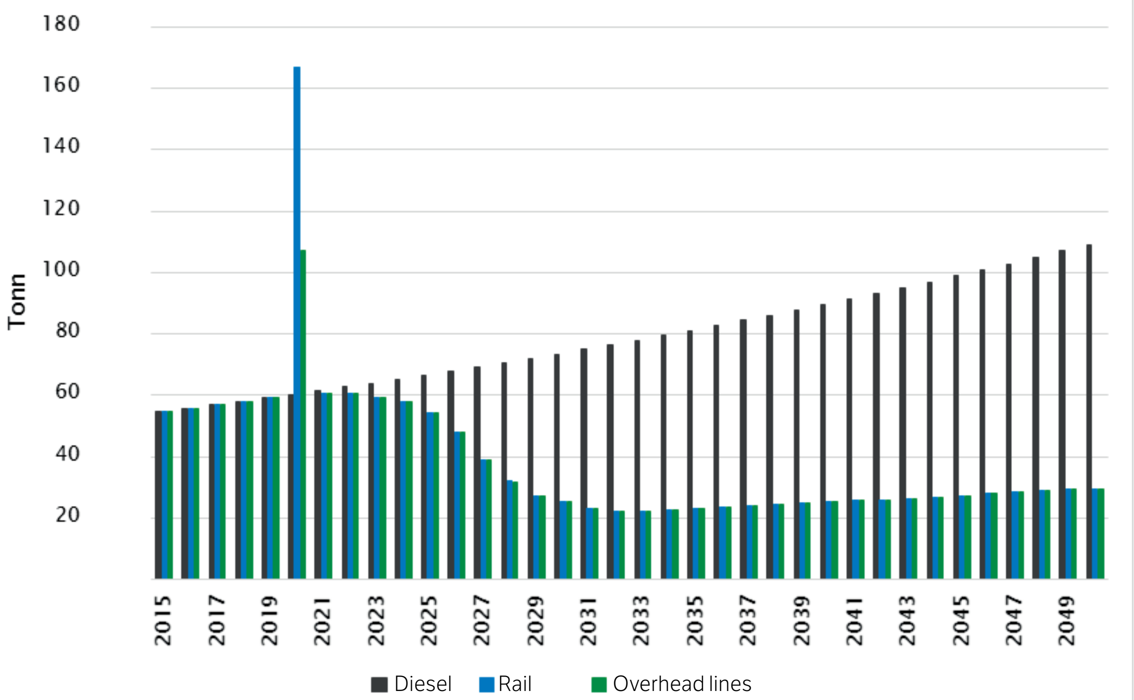

Figure 4. Annual CO_2 emissions with diesel and electric roads with 2% annual traffic growth

The figure shows the emissions from the reference case study (diesel) in black. Emissions from a system with a overhead lines are shown in green, emissions from a system with a rail are shown in blue. As shown here, considerable emissions will be generated during the year of installation, and then lower emissions as more electric vehicles are phased in. But the most interesting finding here is the total emissions account. This is illustrated in the figure below:

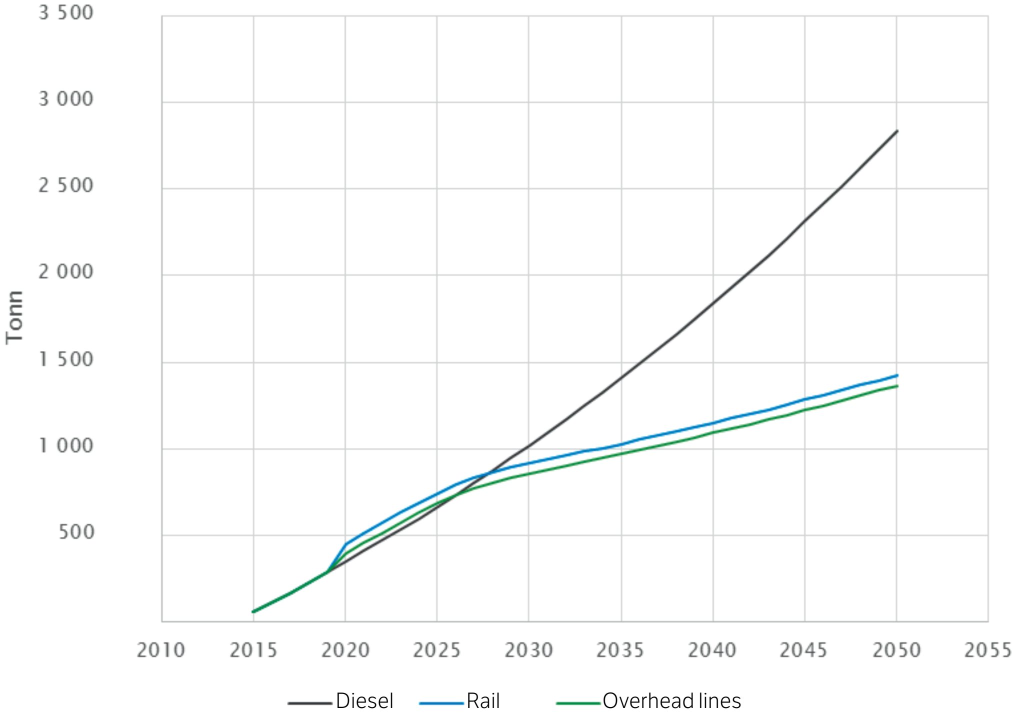

Figure 5. Total CO2 emissions with diesel and electric roads with 2% annual traffic growth.

The black line shows emissions with the continued use of diesel. The blue line shows emissions with a rail installed in the roadway. The green line shows emissions with overhead lines installed.

As shown here, emissions in connection with road infrastructure construction will be retrieved before 10 years, whether rail or contact wire is chosen as the electric road technology. The results show that even if you include all emissions in the entire value chain, there is a significant potential for reducing greenhouse gas emissions compared with the continued use of diesel-powered vehicles. The figure shows that after 10 years we will have a solid reduction in emissions, and we can achieve an annual reduction in greenhouse gas emissions from heavy transport of 65% by 2030 and over 75% by 2050.

In the report from work package 4.1/4.2, sensitivity analyses have been conducted with more and less traffic growth than assumed, 2.5% and 1.5% respectively, in order to see the significance. This does not change the overall picture to a significant degree.

Cost-benefit analysis

The second account is linked to socio-economic profitability of building electric roads. This is important basis information, but not essential for whether you should invest in electric roads or not. A possible challenge could be that none of the zero-emission alternatives, either those that exist today or to be expected in the future, will be economically profitable when compared to diesel.

The socio-economic cost-benefit analysis is based on the same principles and assumptions as the Norwegian Public Roads Administration and the other Norwegian transport agencies utilize in their analyses of possible future opportunities for transport development. Here, figures are given as accurately as possible for the effects of the action in NOK, and the result in terms of net benefit is presented. In other words, it is about the monetized impact of an action. Non-monetized impact is not included. The benefit of the action should reflect the consequences of the action compared with the outcome if it were not implemented. Thus, a reference option must be included in the calculation, and in this case, it is of course today's diesel-based heavy transport. The effects on public budgets of the relevant options are calculated. The economic profitability of the venture for the individual commercial players is not calculated.

Although the timing of phasing in electric goods transport by road may differ for the different technologies, it was considered best to look at the situation at a point of time when all current alternatives are expected to be operational, for example, ten years ahead in time. The comparison of the alternatives is based on average annual costs (annuities), i.e. the annual costs that correspond to the present value of the relevant cost components.

There are few good sources for costs of the infrastructure itself, while the different technologies have different degrees of technological maturity. Based on what we have found in the literature and discussions in the consortium, it was decided to make analyses based on the cost estimates shown in table 3.

Table 3. Cost estimates for the construction of electric roads.

	Low cost estimate	High cost estimate
Contact wire	13 mill[5]	18 mill[5]
Rail	18 mill[6]	26 mill[5]

The calculation example used is based on 100 vehicles travelling three times a day on the stretch Stavanger-Bergen, on each of the year's 220 working days. This equates to an average working day traffic of 300, or an annual average daily traffic (AADT) of 180. This is based on an assumption that the stretch is 200 kilometres, which is a roughly rounded figure. The result is not specifically for Bergen-Stavanger, but generally for stretches in Norway of the same length.

Table 4 below shows which categories are included in a cost–benefit analysis as well as the results of the diesel based reference option.

[5] Fraunhofer Institut für System und Innovationsvorschung (2017): Machbarkeitsstudie zur Ermittlung der Potentiale des Hybrid-Oberleitung-Lkw

[6] eRoadArlanda/Elways. 2018. See Appendix Report Work Package 4.1/4.2

Table 4. Results from the cost–benefit analysis for the current diesel transport (2016-NOK).

Parties	A0 Diesel vehicles
Transport users	357 123 280
Capital costs	61 806 405
Other costs	205 040 500
Energy costs	50 638 875
Other distance costs	39 637 500
Operating Companies	0
Energy suppliers	0
Public authorities	-24 636 375
Investments i e-roads	0
O&M for e-roads	0
Fee revenue	-24 636 375
Society at large	11 413 792
Traffic Safety	0
CO2 costs transport	16 341 067
CO2 costs infrastructure	0
Other environmental costs	0
Tax cost	-4 927 275
TOTAL costs	**343 900 697**

Positive numbers mean costs, negative numbers mean revenue or savings

Table 5 shows the socio- economic costs for an electric road compared to diesel in the calculation example in table 3.

Table 5. Cost-increase for an electric road with an AADT of 180.

	Low cost estimate	High cost estimate
Overhead line	+ Approx. 15% (390 700 084)	+ Approx. 20% (413 106 155)
Rail	+ Approx. 15% (391 275 476)	+ Approx. 30% (444 106 611)

As you can see, the various electrical road technologies are about 15-30% more costly than the diesel option, when as in the example you have an AADT on the road of 180. An overview of the factors that raise the price can be found in interim report 4.3 (in Norwegian), where the analysis used in table 4 has been performed on all four options.

As mentioned above, it is not necessarily crucial to be socio-economically profitable when the premise is that emissions need to be removed. Nevertheless, it is strongly desirable that the solutions being adopted are socio-economically profitable, not least because it makes implementation much more realistic.

How can it become socio-economically profitable to invest in an overhead line or conductor rail for 33% of a 200 kilometre stretch?

Here, a number of possible factors have been considered, such as increased traffic, longer infrastructure life, far higher CO_2 prices than the NOK 950 per ton used here, and building on new roads rather than existing roads. Among these factors it is primarily a larger traffic base that will be able to provide socio-economic profitability.

In table 6, the break-even level required in order for electric roads to be socio-economically profitable is specified.

Table 6. Break-even AADT for socio-economically profitability.

	Low cost estimate	High cost estimate
Overhead line	6–700 vehicles	8–900 vehicles
Rail	6–700 vehicles	1000–1200 vehicles

The lowest cost estimate for overhead line and rail requires an AADT of 6-700 to make the development socio-economically profitable, i.e. 4 times more than the case analysis in the cost-benefit analysis. With the highest overhead line cost estimate, 5 times as much traffic, is required, about 8-900. The highest cost estimate for rail technology requires an AADT that is 6 or 7 times larger, therefore an AADT of 1,000-1,200 vehicles in order to achieve socio-economic profitability.

A traffic count has been included in appendix III with forecasts for future developments that include the majority of arterial roads in Southern Norway. Here you can see that this is a traffic level that can already be found on some stretches in Norway and there will be more in the decades to come.

Action costs

The third audit is linked to so-called action costs, as defined by the Norwegian Environment Agency.[7]

Here the premise is that the emissions need to be removed. The calculation of action costs is done in order to compare the socio-economic costs of various alternatives to fossil fuels. In other words, action costs compare and rank the various technologies for reducing greenhouse gas emissions. The idea is to then prioritise and implement the technologies with the lowest cost first – following the principle of what gives the highest cut in emissions per Norwegian krone

The Norwegian Environment Agency sets Norway as the system boundary This means that only direct emissions in Norway will count. This means for example, that manufacturing emissions from vehicles should not be included, unless they are vehicles manufactured in Norway.

When establishing infrastructure, one can imagine that diesel emissions from construction machines should be included, but not lifetime emissions from, for example, asphalt. Also, the calculation does not include a loss of income to the State in the form of fuel fees.

The Norwegian Environment Agency has divided the action costs into three action packages:

- Action package 1 is mainly composed of measures in the cost category ”under 500 NOK/ton” and in the implementation category ”less demanding”.
- Action package 2 includes, in addition to the measures in the action package 1, mainly measures that are in the cost category ”500-1,500 NOK/ton” and in the implementation category ”medium demanding”.
- Action package 3 includes, in addition to the measures in action packages 1 and 2, measures that are in the cost category ”over 1,500 NOK/ton” and in the implementation category ”more demanding”.

In order to give an idea of the costs within the different action packages in the transport sector, an overview has been produced by the Norwegian Environment Agency (2014).[8]

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[7] Report M386. *Climate mitigation measures and emission trajectories up to 2030* The Norwegian Environment Agency 2015

[8] Report M229. *Knowledge base for low emission development.* The Norwegian Environment Agency 2014

Table 7. Action costs within the transport sector

Feasibility			
Cost:	**Relatively easy**	**Medium difficulty**	**Difficult**
Low < 500 NOK/ton	1 Electric and hydrogen cars, low level of ambition (1.5 million tons of CO_2 equivalents) 2 Electric, hydrogen operation for delivery vans, lorries and buses, low level of ambition (1.0 million tons of CO_2 equivalents) 3 Hybrid vehicles, passenger cars (280,000 tons of CO_2 equivalents) 4 Hybrid vehicle lorries (190,000 tons of CO_2 equivalents) 5 Battery ferries (40,000 tons of CO_2 equivalents) 6 Battery and hybrid operation on ships (500,000 tons of CO_2 equivalents)	7 Zero growth for passenger car mileage in the major cities compared to 2010 (500,000 tons of CO_2 equivalents) 8 Transfer of 5% goods from road to rail (170,000 tons of CO_2 equivalents) 9 Electric and hydrogen cars, passenger cars, high level of ambition (3.3 million tons of CO_2 equivalents)	
Medium 500-1500 NOK/ton	10 + 10% points biofuel for road (1.1 million tons of CO_2 equivalents.) 11 10% biofuel to ships (340,000 tons of COv equivalents)	12 Electric, hydrogen operation for delivery vans, lorries and buses, low level of ambition (2.0 million tons of CO_2 equivalents) 13 Transfer of 10% goods from road to rail (240,000 tons of CO_2 equivalents) 14 20% points biofuels for road (2.3 million tons of CO_2 equivalents.) 15 20% biofuels to ships (680,000 tons of CO_2 equivalents) 16 10% biofuels to other mobile sources (200,000 tons of CO_2 equivalents) 17 10% biofuels to aircraft (130,000 tons of CO_2 equivalents) 18 Land power to ships in port (200,000 tons of CO_2 equivalents) 19 Energy rationalization ships (150,000 tons of CO_2 equivalents)	20 Zero growth for passenger car mileage across the country compared to 2010 (1,7 million tons of CO_2 equivalents) 21 20% biofuels to aircraft (260,000 tons of CO_2 equivalents)
High > 1500 NOK/ton	22 Electrifying remaining diesel sections on rail (50,000 tonnes of CO_2 equivalents)		23 10% reduction of passenger car mileage compared to 2010 (2.1 million tons of CO_2 equivalents) 24 Transfer of 20% goods from road to rail (480,000 tons of CO_2 equivalents) 25 40% points biofuel for road (4.6 million tons of CO_2 equivalents.) 26 40% biofuel to ships (1,4 million tons of CO_2 equivalents) 27 0% biofuels to other mobile sources (400,000 tons of CO_2 equivalents)

As we will soon see an electric road asserts itself well in the "company" of the measures in the table above.

In subsequent estimates from the Norwegian Environment Agency (2017), it is operated with a cost category of between 500 and 1,500 NOK/ton relative to the target that 50% of new heavy vehicles in 2030 will be zero emission vehicles. However, the action cost is estimated to be below 500 NOK/ton based, among other things, on the following:

> *"...for heavy vehicles used for long-haul transport or with more unpredictable driving patterns, the infrastructure for charging will have to be expanded, and therefore be a barrier to the phasing-in. Several test projects have been initiated for alternative methods of charging batteries, such as along a rail in the road or with overhead lines and a pantograph. It is thought that such solutions will be introduced to the market closer to 2030".*[9]

It is estimated that the measure will contribute to reduction of 1.17 million tons of CO_2 equivalent emissions by 2030. However, with an earlier phasing-in of electric road the potential is probably higher.

In ELinGO, an analysis of action costs has been performed based on the data available. Calculations have been performed for the three different cost levels we have specified for the various technologies: NOK 13 million per kilometre of electrical infrastructure in both directions (low cost estimate for rail and overhead line), NOK 18 million (high cost estimate for overhead line) and NOK 26 million (high cost estimate for rail). In order to simplify terminology, we will hereafter refer to these as low, medium, and high cost levels respectively In interim report 4.1/4.2, all three of these options have been analysed.

As this is a summary, in the following we will only present an analysis of the medium cost estimate, i.e. NOK 18 million per kilometre to electrify the roadway in both directions. It should be noted that our anaysis of action costs is somewhat simplified compared with the analysis performed by the Norwegian Environment Agency. But we have no reason to believe that it has a significant impact on the results.

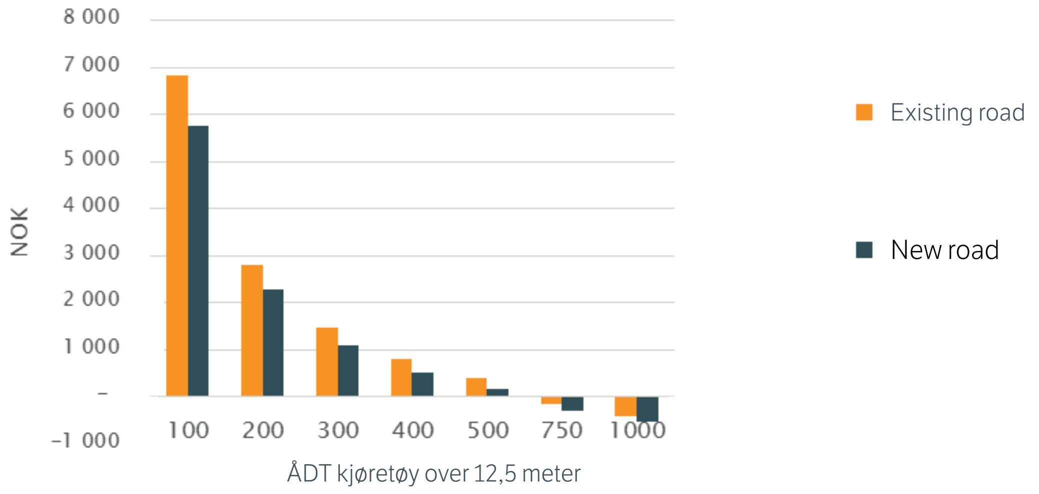

Figure 6. Action costs with the medium cost estimate for electric road – NOK 18 million.

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[9] Report M-782. *Technical calculation basis for report St. 41, Climate strategy for 2030 – Norwegian transition in cooperation with Europe.* The Norwegian Environment Agency 2017

The figure shows the following:

- The vertical y-axis has costs in NOK.
- The horisontal x-axis has the AADT for vehicles over 12.5 metres.
- The columns show the action costs for electric road per ton reduction of CO_2 at various levels of AADT for heavy vehicles. The orange columns show the cost of establishment on existing road, the black columns show the cost of establishment at the same time a new road is built.

One of the conditions here is that you only need to electrify a third of the stretch in order to have an electrified stretch of road. For an overview of other conditions, see the report from work package 4.1/4.2.

What does the figure show? The figure shows that electric road is well within action package 1 with an AADT of 500 for both new and old roads. With an AADT of 500 for new roads, the action cost is NOK 174 per ton of Co.2, for existing roads, the action cost is NOK 389 per ton of CO_2. The question one the can ask is whether an AADT of 500 for heavy vehicles is a high or low traffic figure in a Norwegian context.

Traffic figure (AADT) for heavy transport

In appendix III there is an overview of traffic figures for heavy vehicles (defined as vehicles over 12.5 metres) as well as traffic forecasts for the years 2030 and 2045. Here, a general annual growth of 2% in goods transport has been estimated, in line with the current NTP. 2030 has been chosen because it is a significant year in relation to climate obligations. 2045 has been chosen because the design of new road projects is usually based on the level of traffic in about 25 years time.

Below is a summary of the main features of the traffic counts and the assessments of which action cost classes the routes fall under. We are somewhat conservative in the conclusions, as the AADT figures also include heavy transport that is not going far. However, traffic count points within the municipal boundaries of the cities mentioned are weeded out.

- **E39 from Trondheim to Bergen:** currently (2017 figures) traffic figures are mainly under 500, and the stretch falls under action cost classes 2-3 (NOK 500-1,500 and above NOK 1,500 in action cost per ton of CO_2). However, it seems likely that the traffic base will be significantly strengthened as a result of the combination of general traffic growth and the Ferry-free E39 project, which, in addition to ferry solutions, also involves significant road improvements.

- **E 39 Bergen – Stavanger:** Here the traffic base is somewhat better than north of Bergen. From a conservative estimate, we are currently putting this in action cost class 2. Based on expected traffic growth and the opening of the Rogaland Fixed Link in 2026, there is a good basis for assuming that the stretch will be in class 1 by 2030.

- **E39 Stavanger – Kristiansand:** with an AADT of 599 at the Teistedal tunnel, which is the lowest recording, it is possible that the southernmost bit of the E39 already has a traffic base within the scope of action cost class 1.

- **E18 Kristiansand – Oslo:** with an average AADT of 1,823 at the traffic count points and 872 as the lowest recording, there is good reason to assume the stretch is already currently in action cost class 1.

- **E6 Oslo-Svinesund:** all the traffic count points here are showing an AADT of between 2,000 and 3,000. Already class 1.

- **E6/E136 Oslo (Verven) – Vestnes:** here there are AADT figures of over 500 at the count points along the E6, while the AADT figures are around 250 on the E136 northwest of Dombås. It is therefore possible that the E6 section of the stretch is already within class 1, while the E136 is probably in class 3.

- **E6/RV3 Oslo (Hvam) – Trondheim:** here the traffic base is similar to the E6 south of Dombås. As it is not expedient to build two alternative electric roads between Trondheim and Oslo, one can see the two alternatives between Oslo and Trondheim in conjunction. As a result, the Trondheim - Oslo stretch can already be counted as being with class 1.

Based on the cost of other measures and the expected growth in heavy transport over the years to come, electric road appears from moderate and optimistic cost estimates, and possibly also from conservative cost estimates, to be a relatively reasonable way of reducing greenhouse gas emissions

Technology, energy and audit conclusions

The results from ELinGO point towards the following:

- Different electrical road technologies have varying degrees of maturity. There is technology that can be used relatively quickly and provides emission reductions relatively quickly.
- The establishment of electrical infrastructure along 33% of a road stretch and 300 kWh batteries in vehicles seems to be an appropriate combination for Norwegian conditions.
- The life-cycle analysis suggests that favourable greenhouse gas accounting can be obtained by building an electric road in Norway.
- The cost-benefit analysis suggests that the socio-economic audits can go up with the traffic figures we expect in Southern Norway over the coming decades.
- The action costs suggests that the electric road can be a very favourable option compared with other alternatives for cutting greenhouse gas emissions from heavy road transport.

With promising results from the three different audits, it is natural to pose the question of what is the way forward for realising electric road in Norway.

The way forward: What do you need to do to realise the electric road?

The project looks at framework conditions in a broad sense - including political framework conditions, roles, responsibilities, legislation, barriers and opportunities both in relation to a possible demonstration project and a possible realisation of a future ELinGO scenario where goods transport along the E39 (or other stretches with sufficient base traffic) is mainly electrified.

System challenges

There are a number of system challenges to realising electric roads. The goods transport is a part of a larger system. It can be described as a (socio-technical) system consisting of a specific configuration of technology (petrol and diesel vehicles), industry (vehicle manufacturers, logistics), markets (the transport market, distribution and transportation services), policy (through legislation and regulations), infrastructure (roads, road standards, filling stations, garages), and more.

Seen as a system there are a number of conditions that complicate the realisation of electric roads. System changes require interaction between a number of factors and actors. Different actors in the system have different perceptions of technology and expected technology development, different interests and different understanding of problems, challenges and solutions. Systems are also often stable, they are primarily characterised by small incremental changes rather than radical changes. For electric roads – which can be seen as a radical systemic change of goods transport – this represents a key challenge, and is perhaps the main barrier to realising an electrified road system, since this requires a closer link between vehicle design, power transfer, road design and grid connection. In other words, electric roads represents a radical systemic change of goods transport that in itself is a complicating factor for a desired transition.

For political authorities, this poses a dilemma. Regulations, as a general rule, should be technology neutral. In the revised national budget, the principle of technology neutrality is a guiding principle for the design of the tax system:

> *An efficient and robust tax system should have the fewest number of exception, exemption, and reimbursement schemes. It is undesirable to have special rules for specific types of technology and therefore over time technology neutrality should be a goal for the design of taxation. With the taxation system putting a price on the external costs, users are given incentives to choose cars with more climate and environmentally friendly technology that produces lower emissions. Support for climate-friendly technology should be done by stimulating lower* CO_2*emissions in general, and not specific technologies. Support for technologies that over time prove to be unviable, leads to incorrect investments and socioeconomic loss.*[10]

The principle of technology neutrality can be seen as another main challenge for the realisation of electric roads. An electrification of the E39 or other stretches with a sufficient traffic base (whether conductive or inductive), means that the authorities must make a technology choice that will be problematic in relation to the principle of technology neutrality in public administration. Nevertheless, it is the state as an actor, which has largely influenced previous technology choices through regulations, business policy and state support for research and development.

It is however different for a demonstration project. A demonstration project does not have to contradict the principle of technology neutrality. On the contrary, it opens up opportunities for further technology development and can lead to a change of pace with the faster phasing in of new technology, and a technological opportunity to transform goods transport. A demonstration project will help to:

1) Clarify the maturity of the technologies (for example how they manage in colder climates, the effect of salt etc).
2) Demonstrate that the concept can solve a transport need and work for the users.
3) Show what traffic types and roads are suitable for electrification and for different technologies.
4) Clarify the costs of demonstration projects.
5) Facilitate increased acceptance.
6) Get unresolved questions on the table.[11]

Legislation – no obstacle (mind you with goodwill)

There are few barriers to creating a demonstration project in existing legislation. Firstly, the considerations for the environment (including climate) are determined to be a weighty social concern in paragraph 1A of the Public and Private Roads Act:

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[10] Notification Report to the Parliament 2 (2014–2015). *Revised national budget 2015*. Oslo: The Norwegian Ministry of Finance

[11] Hugossen, B. et al. (2013: 16). *Electrified roads for heavy goods transport. Basis for roadmap*. Report: WSP Analys & Strategi.

> *Section 1 a. The purpose of this Act is to safeguard the planning, construction, maintenance and operation of public and private roads, so that the traffic on them can move in a way that at all times ensures the provision for road users and the community. It is a general goal for the road authorities to create the best possible safety and good traffic conditions and to take into account the neighbours, a good environment and other community interests.*

In relation to the vehicle technology, any vehicles (modified vehicles with batteries, any hybrid solutions etc.) in a demonstration project could be approved separately, based on the Regulation Concerning the Approval of Vehicles and Trailers, abbreviated as the Vehicle Regulations.

The paragraphs that will be most appropriate will depend on the type and number of vehicles. Requirements for road safety, fire safety and the environment (in accordance with paragraph 1 of the Vehicle Regulations) will, of course, be documented and complied with. In view of these considerations, approval of vehicles for demonstration projects is primarily a matter of political will.

The same can be said for the infrastructure relating to the roadway and the surrounding areas that a demonstration project will interfere with. These conditions are regulated by the Public and Private Roads Act and there are a number of opportunities to approve the infrastructure needed for a demonstration project based on paragraphs 32 and 30 of the Public and Private Roads Act - so long as any requirements for planning, construction, maintenance and operation are taken care of, and that ordinary traffic can continue in line with the provision for road users and the community (under paragraph 1 of the Public and Private Roads Act). Further to the above considerations, the infrastructure associated with demonstration projects is primarily a matter of political will. At the same time, both the National Transport Plan and the recommendation from the Transport and Communications Committee are very clear on the challenges associated with legislation:

> *The committee considers that is very important to meet the new opportunities technology provides, in a proactive manner. It is important that legislation does not stand in the way of development, and that it facilitates the development and use of new technology.*[12]

Roles and responsibilities - key players

The specific technical solutions (depending on the selected electrical road technology and associated vehicles to be demonstrated) will have to comply with a number of requirements under applicable legislation in close cooperation with the road authorities. Regardless of which demonstration project is chosen, the Norwegian Public Roads Administration will be a key - if not the main actor - in one or more of the demonstration projects.

According to paragraph 9 of the Public and Private Roads Act, the role of the Norwegian Public Roads Administration is politically governed by the Ministry of Transport and Communications:

> *Section 9. The central authority for national roads is the Directorate of Public Roads led by a Director General. The King gives details on how the Directorate of Public Roads is to be organised, and what areas of control it should have and provides instructions for the Director General. The Ministry may provide guidance if an authority, such as the Directorate of Public Roads or the NPRA Regional Office, has to make a decision about if the extension, operation and maintenance of a particular national road, must be placed with a state road development company.*

To a large extent, participation in - or the handling of - any demonstration projects will therefore be subject to political guidelines. A demonstration project will (regardless of which actor) have a project manager to be involved in negotiations with the Norwegian Public Roads Administration's, Directo-

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[12] Recommendation 460 S (2016-2017). *Recommendation from the Transport and Communications Committee regarding the National Transport Plan 2018-2019.*

rate of Public Roads regarding special legislation and necessary approvals of vehicles. The project manager will also be involved in regular contract negotiations regarding construction, operation, maintenance and other deliveries. A project organisation with the Norwegian Public Roads Administration, as project manager is therefore the most natural for a demonstration project.

The funding of a demonstration project will depend on Government support. Either through direct investment and operational support by way of the state budget, through Enova support, through announcements or support via the Norwegian Research Council. Furthermore, it will be natural to have a combination of public and private funding from the various project participants. Project support from the planned CO_2 fund for goods transport is also a possibility.

Photo: Siemens

A demonstration project in the current ELinGO project is planned - but not necessarily - linked to the E39 Coastal Highway project. Specialist investigations and planning in accordance with the Planning and Building Act is already underway on several parts of the stretch. An opportunity for a demonstration project could be to integrate this as a demonstration project under the E39 umbrella. Either as a separate project or as an integral part (along a stretch of the E39).

Another possibility would be a demonstration project on a longer stretch with for example overhead line linked to ongoing and planned projects in Sweden and Germany. A demonstration project in Norway will complement these demonstration projects. While the demonstration projects in Sweden and Germany are testing different technologies inland, the demonstration projects in Norway will be able to test the corresponding or different (component) technologies linked to electrical roads in a Norwegian climate and other components necessary for realising an electric road, including organisation, public – private cooperation, and financial and business models etc.

Through such demonstration projects, Norway can contribute to a wider international effort to address the big X in the transport shift - heavy transport.

Reports from ELinGO

Technology for dynamic on-road power transfer to electric vehicles
Overview and electro-technical evaluation of the state-of-the-art for conductive and inductive power transfer technologies
Work package 2

Energy and infrastructure - demands and requirements
Work Package 3

Estimations of climate mitigation potential and costs of electric roads in Norway
Work Package 4.1/4.2

Nytte-kostnadsanalyser for alternative elforsyningsløsninger for godstransport på veg
Arbeidspakke 4.3

ELinGO – på vei mot en transformasjon av tungtransporten?
Rammebetingelser, barrierer og muligheter
Arbeidspakke 4.4

Realisation and industrialisation.
Work package 5

Evaluation of constructability of dynamic charging systems for vehicles in Norway
Appendix I

Small-scale model of Inductive charging system for long-haul trucks
Appendix II

Tungtrafikkprognoser på utvalgte veger
Appendix III

Downloadable at www.elingo.no

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