Jernbane-
direktoratet

NULLFIB

Final report

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Summary

Continued use of fossil diesel as an energy-carrier on the non-electrified parts of the Norwegian railway network does not comprise a forward-looking solution and is not in line with the applicable policies involving climate and the environment. The Norwegian Railway Directorate has been tasked with facilitating for the efficient use of public funds in the railway sector in order to get the most railway for the money.

Development with full electrification of the railway stretches that have remained non-electrified up to this point has been assessed to be a solution involving high development costs. The Norwegian Railway Directorate has therefore, through NULLFIB[1], evaluated alternatives in order to find a form of operation that is climate and environmentally friendly, cost-efficient and which is feasible to implement in the medium term.

The Norwegian Railway Directorate has made an assessment and evaluation of new technological solutions for operation of railways based on the following forms of operation:

- Hydrogen
- Biogas
- Biodiesel
- Full battery
- Battery operation with partial electrification.

The engineering assessment of new underlying knowledge is that battery-based technology is most relevant for being a permanent solution that can replace the use of fossil-based diesel with railway lines. In order for this technology to be able to be used in most of the operations that currently utilise fossil diesel, it is necessary that the use of batteries be combined with a charging system that can charge trains while they are running. This gives rise to a form of operation with batteries in trains combined with partial electrification being recommended as the primary solution for the non-electrified stretches of railway lines.

For a change of technology to be successful, the solution must possess technological maturity, which means that challenges associated with usage are reasonable and solvable. All the railway line's actors must also have the will to place the solution into service, as well as sufficient financing and the political will to initiate the requisite measures in order to implement the change. The recommended solution is considered to have the greatest potential for achieving this.

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[1] ZERO emission solutions for non-electrified rail lines

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1 Introduction

Norway has up to 2030 to cut 45 percent of its greenhouse gas emissions. The transportation sector is responsible for 30 percent of the total emissions, hence much must be done in this sector up to 2030. Technological developments concerning solutions with zero emissions are on the other hand occurring quite rapidly. There thus is a need to survey the relevant zero emission solutions that would be able to have a positive effect on the sector's emissions and at the same time provide financial savings. The Norwegian Railway Directorate has thus carried out the project "ZERO emission solutions for non-electrified rail lines" (NULLFIB). The intent is to investigate the available choices for zero emission solutions and make recommendations for further commitments. This is the project's final report.

1.1 Background

As of 2019 there are seven railway lines that are not electrified and where the trains use diesel, which involves greenhouse gas emissions[2]. If we replace diesel with zero emission solutions on these lines, we would in consequence achieve an emission-free railway that is better equipped for the future. A transition to such zero emission solutions would be able to provide favourable economic savings and at the same time increase the ability of the railway to compete with other forms of transportation. However, technological developments concerning solutions with zero emissions are occurring extremely rapidly. The Norwegian National Rail Administration's *"Strategy for form of operation for non-electrified railway lines"* was prepared in 2015 and is already outdated today in relation to the current status of technology. The Railway Directorate has therefore seen it to be necessary to update the underlying knowledge so that the sector is able to make correct and wise decisions in its efforts to equip the railway and the sector for the future.

ZERO emission solutions for non-electrified rail lines (NULLFIB) is an investigatory project carried out by the Norwegian Railway Directorate in partnership with Norske Tog AS, Bane NOR AS and vehicle manufacturers during the space of time from January to December 2019. The purpose of NULLFIB is to update our underlying knowledge for a possible transition to forms of operation other than fossil-based diesel for the non-electrified stretches, and the railway sector in general. The Norwegian Railway Directorate is also, through its 2019 Letter of Allocation, been tasked with preparing an evaluation of the feasibility of a pilot project with hydrogen operation. Since the content of this overlaps with NULLFIB, this work has been co-ordinated as one project and is being delivered together.

The project thus seeks to address the following questions:

- Precisely which zero emission solutions are assessed to comprise alternatives to fossil fuels?
- Precisely which zero emission solution provides the best financial savings?
- What is the best alternative for further efforts?

1.1.1 The greenhouse gas emissions from transportation must be reduced

Strict obligations exist in association with reductions of Norwegian greenhouse gas emissions in the run-up to 2030 and 2050. Norway is obligated to reduce its emissions by at least 40 percent below 1990 levels by 2030.In addition, the goal is to become a low-emission society in 2050 with emissions that are 80-95 percent less than in 1990. Furthermore, the National Transport Plan (NTP) for 2018-2029 expects the transportation sector to help reduce greenhouse gas emissions in line with Norway's

[2] Non-electrified railway stretches: Meråker Line, Nordland Line, Røros Line, Rauma Line, Solør Line, Stavne-Leangen Line and Numedal Line. Diesel is currently used in these places to drive the trains.

climate goals/targets in the Climate Policy White Paper (Report to the Storting No. 21, on Norwegian Climate Policy) and the Climate Agreement (Recommendation to the Storting 390 S 2011-2012). The sitting government has in this context tightened the emission goals for non-quota mandatory sectors where emissions from transportation are included. Stricter targets now comprise a 45 percent reduction before 2030, something that involves large reductions having to occur in transportation in the relatively near future. It thus is important that the railway be modernised and developed in a direction that is compatible with the goals of the national climate policy.

1.1.2 Railways as a part of the solution

As previously mentioned, transportation is responsible for around 30 percent of the total emissions, and thus is the largest source of greenhouse gas emissions in Norway[3]. The portion of the total emissions attributable to railways is however marginal, with about 0.05 percent relative to road traffic at 17 percent. Regardless, in 2018 the railway carried nearly 78 million passengers and over 35 million tons of goods, with total growth of 15 and 12 percent respectively since 2013[4]. The climate policy benefits will thus lie in the ability of the railways to carry passengers and goods that otherwise would be transported on roads. Transfers of transportation from the roads to the railway would thus involve crucial emission reductions from the sector as a whole. This is related to the railway being more energy-efficient and a climate-friendly form of transport. It thus is of significance that choices be made that strengthen, rather than weaken, the competitiveness of the railway against other forms of transportation in a transportation market subject to competition and price-sensitivity. This involves the railway having to be sufficiently equipped for an increase in the number of passengers and goods during a time when mobility must increasingly involve zero emissions.

1.1.3 Objective of the project

The objective of the project is to provide a professional technical recommendation for further efforts for a zero emission solution that can replace fossil-based diesel use by the railway. There is therefore a need to update the underlying knowledge of technology and modes of operation. This will create an updated basis for evaluating the available choices that could replace ordinary diesel operation. The NULLFIB project will on the basis of this recommend the most relevant zero emission solution that would be able to contribute to the overall goal of "a transportation system that is safe, promotes the creation of value and contributes to the transition to a low-emission society".

The final report builds on the attached sub-reports that have been prepared under the auspices of NULLFIB. The sub-reports go into further detail on significant factors associated with each of the zero emission solutions (technologies) evaluated. These reports form a foundation of knowledge on which to compare different alternatives in this final report. The comparison will be made based on a set of parameters prepared by the Norwegian Railway Directorate that it believes will be central to ascertaining topicality. This will form a basis for a conclusion concerning the choice of concept and recommendations for further efforts.

1.2 Delineation

The Norwegian Railway Directorate has seen a need to limit the investigation in terms of time, space and scope. A decision has thus been made to report on the topicality of the technologies based on the data that is available at the time of writing. The Nordland Line has been chosen as the railway line for a case study. The Nordland Line is the most challenging railway stretch with respect to length, profile, tunnels and weather, which comprise crucial factors for feasibility. A topicality assessment based on

[3] Norwegian Environment Agency. 2019. "Greenhouse gas emissions from transportation". Fetched from: www.miljostatus.no.

[4] Statistics Norway. 2019. "Railway transportation". Fetched from: www.ssb.no.

the Nordland Line would thus indirectly address much about the possibility space for the remaining and less challenging railway lines that are relevant in this context. The result will in other words survey the possibility space for the different zero emission solutions with the Nordland Line as a basis.

The relevant alternatives that will be evaluated through NULLFIB are: full battery, standard contact line (CL), battery operation with partial electrification., hydrogen, biogas and biodiesel. These technologies are considered to be relatively established in relation to other and more special variants that have not been considered. In addition, these technologies have been successfully tested and implemented as energy carriers for trains in other countries, which will make for a good basis for estimates and assessments connected with technological maturity, cost and feasibility.

1.3 Layout

The final report is structured in a manner that facilitates a logical and systematic review of the NULLFIB project.

- Chapter 2 describes the different forms of operation that are included in the evaluation. A description will be given here of each concept with the requisite information concerning technological functionality and availability in the form of maturity.
- Chapter 3 presents assessments that have been made based on cost-efficiency analyses of the selected technologies using the Nordland Line as a point of departure. In order to be able to make good evaluations of the finances, the Norwegian Railway Directorate has posed a need to separate economic assessments from the operating finances situation for train operators in chapter 3. This is due to the profitability for the train operators being regarded to be crucial to the feasibility and thus needing to be separated out from economic assessments.
- Chapter 4 compares the different forms of operation on based on scores assigned for the prepared parameters, which are described in *Appendix A.* The assessments in chapter 4 build on the information that has been presented in the attached sub-reports.
- Chapter 5 contains conclusions, recommendations and significant reservations.

Each of the sub-reports addresses every one of the assessed technologies and describes and evaluates them in detail in relation to suitability as an energy carrier for an alternative form of operation.

- Sub-report 1 looks at a financial analysis of the different technologies in the form of a case study of the Nordland Line.
- Sub-report 2 looks at technology associated with the use of batteries as an energy carrier for railway vehicles based upon a case study of the Nordland Line.
- Sub-report 3 looks at infrastructure associated with partial electrification and is a case study of this technology on the Nordland Line.
- Sub-report 4 looks at technology for infrastructure and vehicles associated with the use of hydrogen, biogas and biodiesel as an energy carrier for railway vehicles and infrastructure.

2 Relevant zero emission solutions

This chapter contains a brief description of the alternatives that can be utilised as energy carriers for the operation of trains in order to replace the use of ordinary diesel. A presentation follows below of each technology that the Norwegian Railway Directorate has evaluated in the NULLFIB project.

2.1 Standard contact line

What is called an electrified railway, or electric railway, is a railway line that is equipped with a contact line system (CL system). A contact line system is an electrical high voltage system where current is supplied to the train from a contact wire (copper wire) that is suspended above the rails and is returned to the transformer through rails and return lines. The trains are equipped with a pantograph on the roof that is dragged along the contact line and makes the requisite contact between the vehicle and the CL system to transfer energy in the form of current to drive the vehicle.

There is no storage of energy in the train, rather it is the fixed infrastructure (the CL system) that continuously supplies the vehicle with the needed energy.

The CL system is the most-used system for supplying energy to railway vehicles in Norway, and comprises about 66% of the national railway network.

The vehicles that are used on electrical railways have a simple, robust and well-tried design, which makes for high reliability, low maintenance costs and high energy efficiency. The fact that energy is not stored in the vehicle is favourable from a safety-related perspective, however it poses challenges if there are deviations in the CL system.

Electrified railways have many good characteristics, but they also pose significant challenges. There are high investment costs associated with construction of CL systems that are of such an order of magnitude that a certain amount of traffic is needed on the railway line in order to make it economically profitable to invest in a CL system. For those railway lines that have still not been electrified, this has been a threshold for use of this system.

2.2 Full battery

Energy to drive trains can be stored in a battery. A pure battery concept (full battery) is based on the operation being performed with energy that is stored in a battery that is large enough to carry out the planned traffic without the battery being charged underway. The vehicles that are used are in principle nearly the same as the vehicles that are used for electrified railways, but they are supplied with energy from a batter that is a part of the train. Instead of a CL system along the entire railway line, this concept must have charging stations at the end points. The charging at the end points will thus require stopping operation until the battery has been charged. To reduce the charging time, special charging stations must hence be built with the possibility for faster charging.

Operating models with full battery are known on railways but have been limited however to shorter lines with adequate stopping times for battery charging at the end stations or replacement operations. There are some challenges associated with the operation of longer lines and traffic that runs more or less continuously. For this type of operation (which is relevant in Norway) challenges arise associated with the weight and volume of the battery packs, the charging time, charging stations, access to vehicles and operative challenges associated with the logistics at the end stations.

The concept comes out well financially, but as of today is not a feasible and available solution for all parts of the traffic on the "non-electrified" railway lines. For some traffic systems this requires a battery configuration (weight) that violates the requirement for acceptable axle weight for train sets or affects the possibility of freight operators to have profitable operation. This is due to the concept with the addition of separate battery vehicles allowing a reduced amount of goods. More can be read about this technology in sub-report 2.

2.3 Battery operation with partial electrification

Battery operation with partial electrification is in principle a combination of electrified railway and full battery. The vehicles that are used are hybrids and can utilise CL systems for propulsion and charging underway (charging railway stretches), in addition to being able to use the energy stored in the battery to drive the train on non-electrified stretches (battery railway stretches).

The concept has a significantly lower impact in terms of the challenges associated with high investment and maintenance costs for CL in comparison with expansion out to full electrification. With the construction of a CL system for parts of a railway stretch (charging railway stretches), this provides significant financial savings. In addition, there are extremely large differences between the construction costs for CL systems on different parts of a stretch. By only mounting a CL on stretches without the difficult and expensive parts of the infrastructure, for example tunnels and overpass bridges, a further reduction in the investment costs is achieved.

By not making the distances too long between each charging stretch, the vehicle-related challenges can be avoided that are associated with the use of batteries on longer stretches or with traffic systems with nearly continuous operation.

While being driven, a vehicle can receive approx. 10 times as much current from the CL though the pantograph than for a vehicle that is standing still. The construction of CLs on sections of a railway line stretch will enable quick-charging of the battery of a moving vehicle. The charged battery will give the vehicle sufficient energy to drive out to the next charging stretch.

The technology for implementing this concept is relatively mature and access to the vehicles and technology is relatively good for passenger train goods/train sets and infrastructure elements, but not mature when it concerns solutions for freight train vehicles/locomotives.

Simulations carried out by the vehicle manufacturers for passenger trains with battery operation confirms that battery trains (even with current battery technology) combined with partial electrification is feasible as an operating model with most traffic systems. More can be read about this technology in sub-report 3.

2.4 Hydrogen

Energy to drive a train can be stored as hydrogen. Hydrogen is filled into the vehicle as a pressurised gas or as a cooled fluid, and is converted to electricity using fuel cells in which the hydrogen reacts with air and forms electric energy, surplus heat and water. To make this function as an operative train, it must be constructed as a standard electric train and equipped with a battery to supply the propulsion system in addition to there being a need for equipment to store and convert hydrogen to electricity. A hydrogen train is in principle a battery electrical train with a hydrogen-driven battery charger.

There primarily are three manners of producing hydrogen: (i) reforming of natural or biogas, (ii) electrolysis and (iii) production of hydrogen as a residual product from other industrial processes. Most of the hydrogen that is produced today goes to the production of ammonia that is used in the production of fertiliser. Reforming of natural gas is the dominant production method on a global basis. This production method is however associated with significant emissions of $CO2$. Electrolysis currently comprises approx. 2% of global hydrogen production, and most of this is produced by using ordinary electrical power.

At present, there is no large-scale production of hydrogen in Norway, and users of liquid hydrogen must have it delivered from other countries in Europe. There have been some ten smaller hydrogen filling stations for road traffic in Norway based on electrolysis, but these have either been shut down due to poor profitability or have been temporarily closed due to the station at Kjørbo in Sandvika having exploded after the leakage of hydrogen gas from a storage tank.

There is at present an operative trial project with hydrogen trains in Europe, and it is expected that there will be a couple of projects in the near future. There is a European manufacturer that has put so much into this technology that prototypes have been built. There are also a couple of other vehicle suppliers that have developed concepts without having built any. The technology for railway vehicles is thus at present only available in what must be defined as prototypes.

The technology is associated with challenges related to safety, which is connected to the physical properties of hydrogen. Tunnels and enclosed areas are especially challenging in terms of safety. The technology also seems to have challenges related to safety and operating finances. The regulations for the use of this technology in railways are considered to not be fully developed. On the overall, this technology is assessed to not be mature in relation to use in Norwegian railways as it stands today. More can be read about this technology in sub-report 4.

2.5 Biogas

Energy to drive trains can be stored as biogas. Biogas is filled into the vehicle as pressurised gas or as a cooled fluid, and is converted to mechanical movement with the use of a combustion engine. In order to get this to function as an operative train, it must be built as a standard diesel-driven train, where diesel engines are replaced with gas engines, and diesel tanks are replaced with gas tanks. A biogas train is in principle much like a diesel train, but with adjustments made to the engine and tank systems.

Biogas is produced by the waste gas from decomposition of biological material being collected and purified such that nearly pure methane is obtained. Biological material that can be used in biogas production includes for example food waste, slaughterhouse waste, waste water sludge and animal dung.

In 2018, there were 35 producers of biogas in Norway, with 11 installations for upgrading the biogas. In recent years, biogas has experienced strongly increasing use in land-based transportation and especially in relation to buses and lorries.

There is currently a trial project with a gas train in Europe. None of the European manufacturers of railway vehicles have stated that this is a technology that they wish to make efforts to develop.

The technology is associated with challenges related to safety, which is accentuated by the physical properties of biogas. Tunnels and enclosed areas are especially challenging in terms of safety. On the overall, the technology is assessed as not being mature in relation to its use with Norwegian railways. More can be read about this technology in sub-report 4.

2.6 Biodiesel

Energy to drive trains can be stored as biodiesel. Biodiesel is in principle the same as ordinary diesel, but the raw material for biodiesel is of an origin other than that of the ordinary diesel. A biodiesel-driven train is technically nearly equivalent to a diesel train. The similarity with ordinary diesel causes this energy carrier, in technical and practical terms, to often be considered to be the fastest and easiest way to replace the use of fossil diesel.

Biodiesel is produced by the extraction of oil from plants containing oil as well as other biological material containing fats and oils. Biodiesel is often divided into groups based upon the specific raw material that the biodiesel has been extracted from. Biodiesel produced from edible vegetable oils for example such as rape seed oil, sunflower seed oil or palm oil, is often referred to as first-generation biodiesel. Biodiesel produced from non-edible agricultural products and forestry waste, non-edible vegetable oils, recycled oils (cooking oil, frying oil, etc.), waste (from for example the slaughterhouse industry) and energy crops that are planted with the intent of being used for the energy industry) is called second-generation biodiesel. Third-generation biodiesel is produced from algae-based raw materials (microalgae and macroalgae).

There are some ethical dilemmas associated with some of the sources for the production of biodiesel, as well as the land use. It is ethically challenging that raw materials that could have been used for food are being used for fuel. It is also ethically challenging that areas that could have been used for cultivating food are used for cultivating raw materials for fuel. Production of palm oil has in addition been associated with deforestation in vulnerable areas.

During the first half-year of 2019, biofuel comprised 17% of all fuel used in road traffic, with biodiesel comprising about 90% of this. There has been a strong increase in the use of biodiesel and a trend towards the percentage share of second-generation biodiesel being strongly increasing. Most of the biodiesel is imported, but plans exist for domestic production, and it is uncertain that the portion of Norwegian-produced biodiesel can be increased in the near future.

As of today, all of the European manufacturers of railway vehicles are able to offer vehicles that can utilise biodiesel as an energy carrier.

The energy carrier that as stated is associated with some ethical dilemmas. The technology for use in railways is well-tried and commercially available in a mature market. The technology that is used to convert diesel and biodiesel in railway vehicles is however associated with high energy costs and high maintenance costs. This contributes to weakening the competitiveness of the railways against other forms of transport. Use of biofuels as a replacement for ordinary diesel is beneficial in relation to the climate, but it does not however change the local emissions connected with production. Biofuels are also a limited resource, and there is an issue on whether it is right to utilise it in a process with such low energy utilisation, especially when other and more efficient alternatives exist. More can be read about this technology in sub-report 4.

3 Evaluation of financial conditions

This chapter concerns assessments of the economics and operating finances that have been performed by the Norwegian Railway Directorate for NULLFIB. The chapter builds on a separate cost-efficiency analysis of switching from diesel operation to zero emission technologies on the Nordland Line (sub-report 1). A cost-efficiency analysis is a type of economic analysis in which different measures are evaluated against each other. Cost-efficiency analyses are relevant in those cases where the utility of the measures is the same, but the costs are different. The purpose of the analysis is to find the measure that achieves zero emissions on the Nordland Line for the lowest possible cost to society. In order to be able to compare the different technologies in a good manner, in our opinion it is best to calculate a present value over a number of years for the different technologies, called the present value method.

There is however a general uncertainty associated with economic calculations far out into the future. In contrast, we believe that the quantitative basis in this context is sufficient. This is based on evaluations of estimates from the technical environments at the Norwegian Railway Directorate, Bane NOR AS, Norske Tog AS, CargoNet and the Norwegian Environment Agency. The estimates are also based on evaluations in technical reports from Norconsult and SINTEF. The quantitative calculations will thus give a good decision-making basis based on the best available and accessible information. In the following, the results are presented of the cost-efficiency analysis for the economics considerations and the operating finances considerations, respectively.

3.1 Economics

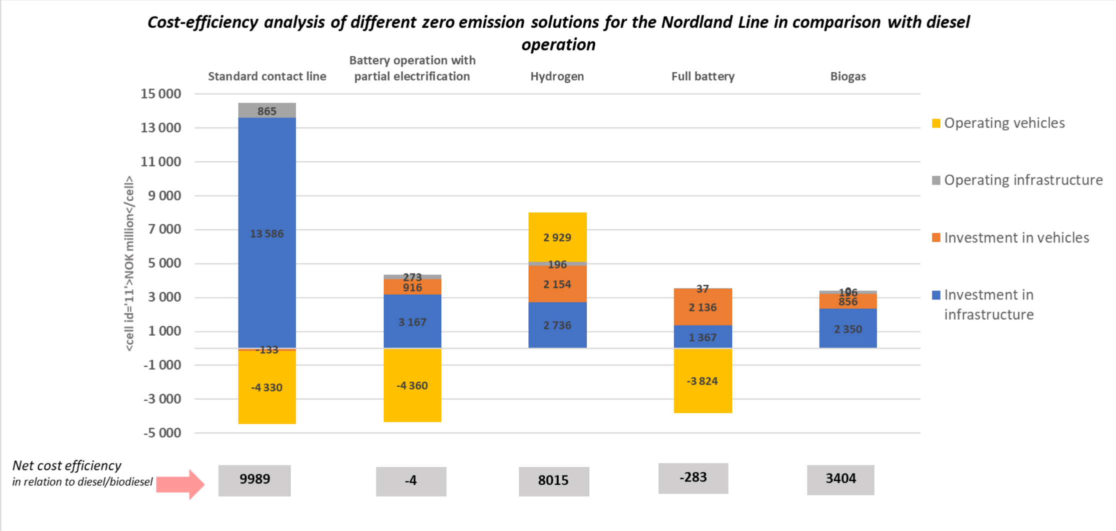
The Nordland Line is operated today using diesel trains that have large CO_2 emissions. These trains also have higher operating expenses than electrical trains, both for passenger traffic and freight traffic. A transition to use of electrical trains hence would be beneficial to both the climate as well as the operating costs of the vehicles. The problem with standard contact lines is that the investment costs for the railway infrastructure is high. The Norwegian Railway Directorate has investigated what is most cost-efficient of the following zero-emission technologies: full battery, standard contact line, battery operation with partial electrification, hydrogen, biodiesel and biogas.

An emphasis is placed on the following changes in costs by going over from diesel operation to the above-mentioned technologies:

- Investments in the railway infrastructure
- Investments in vehicles
- Operating costs of railway infrastructure
- Operating costs of vehicles

It is the total of these changes in costs that defines precisely which technology is the most cost-efficient. In order to determine the length in time for which the present value will apply, the lifespan of the technology that is assumed to be the longest will be used. This means that standard contact line will be taken as a basis for establishing the number of years the calculation will be across, and the time basis thus will be 75 years. We are adding in reinvestment in infrastructure for charging systems associated with the full battery solution that has an assumed lifespan of 40 years. Batteries will be replaced every 15 years. Infrastructure associated with tunnels for biogas and hydrogen have an assumed lifespan of 30 years. Filling stations for hydrogen and biogas have an assumed lifespan of 20 and 30 years, respectively. The vehicles will be replaced after 30 years in operation. By adding in such reinvestments, we can compare the different technologies in relation to how good they come out to be in terms of economics. The results from this investigation appear in *Figure 1* which shows the present value in millions of 2019 NOK over 75 years.

Figure 1: Cost-efficiency analysis – result basis alternative - Present value 75 years



The figures above and under the columns show the net effect in NOK millions of going over from diesel operation to other technologies. This means that the figures indicate the sum of positive and negative values (above and below 0) and consequently give the total net effect in NOK millions for each form of operation. For example, operation of vehicles for battery operation with partial electrification lies below 0 because the difference in relation to diesel is negative due to cheaper operation by the battery operation in relation to diesel. Investments lie above 0 due to there being investments in railway infrastructure with the partial electrification that do not exist with diesel operation. The sum for this cost difference in relation to diesel for all the four components shown in the figures give the figures above and below the columns. For biodiesel, the same costs are assumed as for diesel, and the numbers in the figure are this a corresponding cost difference in relation to biodiesel.

Both full battery operation and battery operation with partial electrification will be more cost-efficient than the use of diesel. Full battery gives an estimated cost savings for society of NOK 283 million and battery operation with partial electrification gives an estimated cost savings for society of NOK 4 million in comparison with the use of diesel. Whether battery operation with partial electrification would be more cost-efficient than diesel is extremely sensitive to assumptions concerning growth in train traffic, since the difference is only NOK 4 million. We have assumed that biodiesel has around the same cost as diesel and has the value 0, this means that battery operation with partial electrification comes out scarcely better than diesel in the basis alternative, in other words NOK 4 million.

In the basis alternative, it has been taken as fundamental that there will be a 5% increase in the train-kilometres driven for passenger traffic every year up to 2030 and no growth subsequently. For freight traffic, the growth follows the forecasts concerning transportation work that the preparation of NTP 2022-33 is predicated upon. An alternative has been looked at with somewhat more growth than this, where battery operation with partial electrification and full battery come out to look still better.

Full battery and battery operation with partial electrification come out the best of all technologies that require investments in railway infrastructure. This is because the technologies have much lower operating costs for the vehicles than for hydrogen, biogas and biodiesel, and that it is not necessary to make such large investments in the railway infrastructure as it is with standard contact line, where NOK 14.1 billion in investments have been estimated.

Biogas, hydrogen, battery operation with partial electrification and full battery require significant investments in the railway infrastructure, but not as high as standard contact line. Partial electrification of 217 kilometres that are necessary to be able to run battery trains on the Nordland Line with charging while running is estimated to cost NOK 3.3 billion. Charging systems associated with full battery operation have an estimated cost of NOK 1.1 billion.

Biogas and hydrogen are not advisable with respect to implementing the most cost-efficient technology possible. There are safety aspects with biogas and hydrogen that also argue that these technologies ought not to be placed into service on the Nordland Line.

The recommendation based on the cost-efficiency analysis must then be to implement full battery operation or battery operation with partial electrification in order to replace the present diesel operation on the Nordland Line. An alternative technology that appears to come out about equal to diesel is biodiesel. No possible economic gains have been quantified of reduced CO_2 emissions, but a sensitivity analysis has been done for a strong increase in diesel prices. This will not however change the ranking of the technologies, but just involve all technologies being able to come out better in relation to diesel operation.

Some sensitivity analyses have been performed of a number of train-kilometres for freight traffic and passenger traffic not growing in the future but staying at the present level, stronger growth in freight traffic than the basis alternative, no price drop in batteries and a 40% increase/reduction in the investment costs and a price increase in diesel/biodiesel. No alternative changes the primary conclusion concerning the choice of technology based on an economic perspective. Different sensitivity analyses can change the ranking of full battery, battery operation with partial electrification and biodiesel, but not the fact that the three technologies that come out best are these three. On the overall, full battery comes out the best, but in a number of sensitivity analyses battery operation with partial electrification comes out either the same or better than full battery. Strong growth in the train traffic can for example involve battery operation with partial electrification coming out best, due to lower battery costs for the vehicles. It is higher infrastructure investments in the railway that cause battery operation with partial electrification in most alternatives to come out poorer than full battery.

No benefits have been calculated for reduced climate emissions and local emissions. If the diesel tax such as it is today and in the calculations in future do not cover such socio-economic costs, then there may be a benefit of zero emission technology that comes in addition to what we have calculated. This would nevertheless not change the ranking of the technologies. In other words, the most cost-efficient for replacing the present polluting diesel technology is the full battery solution, battery operation with partial electrification or biodiesel. The sensitivity analysis that involves increased prices for diesel, would however be a corresponding effect as if the diesel tax were increased. This shows that battery operation with partial electrification and full battery would clearly be more cost-efficient than diesel. This means that the costs of investments in the railway infrastructure and in new vehicles for battery operation with partial electrification and full battery will be earned back in socio-economic terms by cheaper operation of the vehicles.

3.2 Operating finances

A transition from the use of diesel to technologies such as standard contact line, battery operation with partial electrification or full battery will result in trains improving their position as a form of transport in relation to other forms of transport. The primary reason or this is lower operating costs for the vehicles, something that can result in better earnings for train operators and/or reduced prices for both freight customers and passengers travelling by train.

In the calculations in *Table 1* below, it has been taken as fundamental that diesel locomotives have an operating cost of NOK 71.4 per train-kilometre whereas electric locomotives/battery locomotives with partial electrification or full battery has operating cost of NOK 28.4/29 per train-kilometre for freight. Corresponding figures for passenger train locomotives are NOK 39.7 for diesel and NOK 18.9/19.5 for electric/battery locomotives.

Table 1: Operating expenses vehicles for all technologies

	Diesel	Biodiesel	Hydrogen	Biogas	Partial elec. with battery operation	Full battery	Standard CL
Operating expenses vehicles goods per train-kilometre	NOK 71.4	NOK 71.4	NOK 89.3	NOK 71.4	NOK 29.0	NOK 33.4	NOK 28.4
Operating expenses vehicles passenger per train-kilometre	NOK 39.7	NOK 39.7	NOK 49.6	NOK 39.7	NOK 19.5	NOK 19.5	NOK 18.9

Full battery operation has a somewhat higher operating cost per train-kilometre than battery operation with partial electrification for freight with NOK 33.4 NOK and correspondingly NOK 29 for battery operation with partial electrification. This is due to battery vehicles being required and extra train-kilometres being driven due to this. There are also more costs with full battery operation such as more expensive vehicles, a large quantity of batteries and extra costs for battery vehicles, which make full battery operation more expensive for the operators than battery operation with partial electrification for both freight and passenger trains. The present value of investments in vehicles/battery carriages for freight and passenger trains is NOK 3.9 billion for full battery and NOK 2.7 billion for battery operation with partial electrification. Purely in terms of the operating finances, battery operation with partial electrification is better than full battery operation.

Battery trains, either with partial electrification or full battery operation, would give a drastic reduction in costs in comparison with current diesel operation, something that provides a foundation for better operating finances for both train operators and freight customers. Trains would be able to stand stronger in the competition with other means of transport and political goals concerning the transfer of freight and passenger traffic from roads to railways would potentially be easier to meet.

Freight transport is marked by competition between different forms of transport, for example railways and lorries, and it is presumed that the freight operators will reduce their prices when the operating costs go down so much as with the transition from diesel to battery trains or electric trains. It is presumed that such reductions in operating costs when subjecting the passenger traffic to competition would result in lower tenders and smaller public purchases of passenger traffic and better operating finances for the operators.

We have not taken it as fundamental that there will be an increase in the diesel prices in consequence of a stricter climate policy. Any possible strong increase in the diesel prices would make the benefits for the business community still larger for a transition to electrical trains and battery trains. There could also be marketing benefits in that goods the companies produce would be transported in an environmentally friendly manner.

3.3 Summary and uncertainty

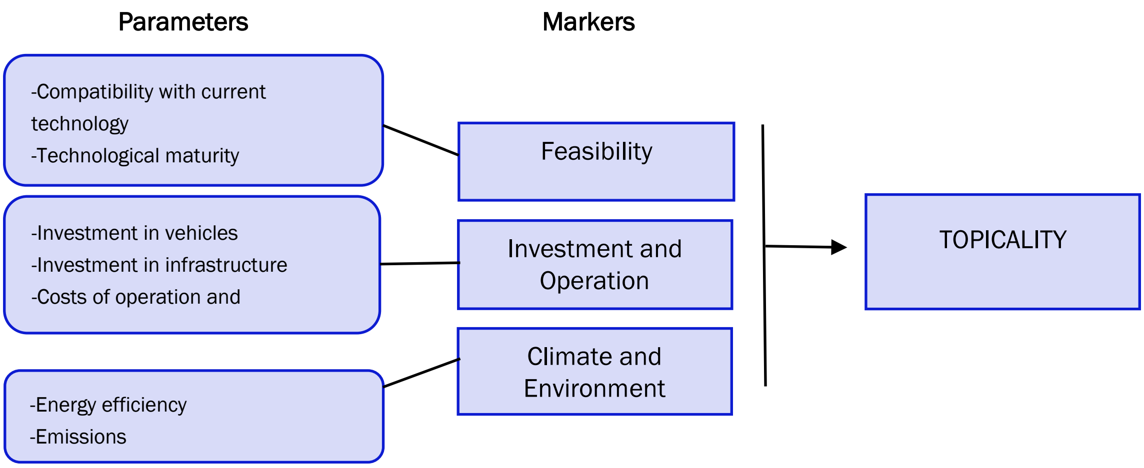
The conclusion is that full battery trains or partial electrification with battery operation seem to be the best zero emission solution in terms of the costs of those technologies that require investments in the railway infrastructure. Biodiesel is a good alternative solution with around the same total cost picture as diesel. It is presumed that a reduction in operating costs for the locomotives in a transition to battery and/or electrification would result in benefits for freight customers with reduced costs for freight transport, and lower tenders for driving trains on the Nordland Line from subjecting the passenger train traffic to competition.

Some uncertainty exists however in the calculations. In this regard, price trends in fuels, as well as uncertainty in estimates of infrastructure investments, will be of significance. On the overall, based upon the above-mentioned calculations with sensitivity analyses, it seems nevertheless robust that full battery or partial electrification with battery operation is the best solution, with biodiesel as an alternative. For investment costs, the uncertainty for electrification and partial electrification has been quantified at +/- 40%. We cannot however quantify the uncertainty at the present point in time for other technologies, in other words exactly how large the variation could be in the estimates. This must occur during a later phase of the investigatory work. Due to this uncertainty, it is somewhat uncertain whether full battery is more cost-efficient than battery operation with partial electrification, since the estimates for partial electrification are presumed to be much more certain than for full battery operation.

4 Scores on important evaluation parameters

This chapter presents the comparison of the different zero emission solutions for purposes of assessing their topicality. The Norwegian Railway Directorate is of the opinion that "feasibility", "investment and operation" and "climate and environment" are useful markers that collectively say something about the topicality of the different zero emission solutions that are being evaluated. Under each marker, different parameters have been identified that provide a basis for assigning a total score in order to express the topicality in table 5. A figure is presented below of how the different stages in the topicality assessment are shown in this final report (*figure 2).*

Figure 2: Graphical presentation of topicality assessment



The scores were assigned by the engineering/technical environment at the Norwegian Railway Directorate. A work meeting was conducted first, in order to compare the technologies and assignment of scores, followed by a revision meeting in order to revise the scores assigned. This involves the scores that are specified being characterised by engineering/technical agreement and subsequently checked. *Appendix A* contains information concerning how the assessment was performed. A scale from 1 to 10 was used, where 10 is the best score. Scores from 1-2 are deemed to be unacceptable and scores from 5 and up are deemed to be a basis for a recommendation. In order to render the gradations in the scale clearer, we have specified both scores and colours. This will potentially prevent any possible misunderstandings when the results are read. The gradations are presented in *figure 3* with four scoring categories of the scale that are being used.

Figure 3: Gradations for scaling

Low	Medium low	Medium high	High
1-2	3-4	5-7	8-10

In the following, scoring tables are presented for the different markers, each in its own sub-chapter. By way of conclusion in sub-chapter 4.4, an overall scoring table is presented that summarises and collates the scores for the three markers. The total score in table 5 depicts the average of the scoring for each marker, as well as the lowest score. We are isolating the lowest score in order to identify problem areas and are thus attributing a certain weight to the lowest score in the evaluation since it is topicality that we are addressing. Ordinary diesel has been used as a reference category for all markers.

4.1 Feasibility

The "feasibility" marker consists of three parameters: (in) compatibility with current technology, (ii) technological maturity and (iii) safety. Collectively, these express crucial assessments associated with feasibility, both technically and in terms of safety.

As shown in *table 2* each parameter for this marker is divided. This is related to a need to capture central factors in the assessment, and thus also crucial nuances associated with each parameter. For the parameter "compatibility with current technology", two questions have been posed to determine the score. These are:

- Can vehicles that utilise the new technology utilise the present infrastructure without changes?
- Can vehicles that utilise the new technology be used simultaneously as vehicles with the current technology?

For the parameter "technological maturity" the corresponding has been done and the questions that are posed for the scoring assessment are:

- How is the availability of railway vehicles with the new technology?
- How is the availability of technology for the requisite infrastructure?

For the parameter "safety" the following two questions are included in the scoring evaluation:

- Have safety challenges associated with the new technology been solved?
- Is safety involving the use of the technology adequately regulated?

Table 2: Score for the marker Feasibility

	Compatibility with current technology		Technological maturity		Safety		Result	
	Current infrastructure	Need for adaptation	Technology availability (veh.)*	Technology availability (inf.)**	Unsolved challenges	Regulation	Average	Lowest score
Full battery	7	8	3	4	6	8	6	3
Standard CL	3	8	10	10	10	10	8.5	3
Partial elec.	6	8	7	7	7	8	7.2	6
H2	1	1	5	1	1	1	1.7	1
Biogas	2	2	2	2	2	5	2.5	2
Biodiesel	9	9	8	9	8	9	8.7	8
Diesel (ref)	10	10	10	10	8	10	9.7	8

** Availability of vehicle technology*
*** Availability of infrastructure technology*

As *table 2* shows, the reference technology "Diesel" comes out the best. This is in fact also logical since this technology is in commercial use today, and consequently also has high feasibility. The same applies for "standard contact line", but this technology scores however moderately low on compatibility with the current infrastructure since major changes are required to be able to use electrical vehicles on the current non-electrified stretches. "Biodiesel" and "battery operation with partial electrification" also score extremely high in terms of feasibility, where technological maturity is the parameter that partial electrification loses most on. Hydrogen operation ("H2") scores, in contrast, the lowest on this marker. This is related with central safety challenges and large needs for extremely demanding adjustments to operations and existing infrastructure.

Full battery has a low score on "availability of vehicle technology". This is however extremely dependent upon the stretch and the operation that is being evaluated. This means that for the Nordland lkine this technology is not feasible, but for shorter railway lines it would be able to function as an alternative. In addition, developments in the technology have gone further for passenger trains than for freight locomotives. For passenger trains, the technology is relatively well-available, but for freight locomotives it is still extremely limited and not available. On the overall, this form of operation has thus been assessed a score of 3 on this parameter.

It is important to emphasise that these assessments are made on the basis of comparisons between the different zero emission solutions, based on evaluations of all operations on the non-electrified railway network. If one evaluates individual operations, the results can be different for individual technologies.

4.2 Investment and operation

The marker "investment and operation" captures conditions associated with investment needs and operating expenses in order to place the relevant technologies into service. As with the marker "feasibility", scores have been given as a point of departure for comparing the technologies. It is not the task of the Norwegian Railway Directorate to establish investment levels or operating expenses that are politically acceptable or acceptable in terms of the operating finances. Hence the scoring evaluation for each technology in this marker also adheres to comparative evaluation. This involves that in instances where large differences occur between the technologies, such will thus be pulled to the extreme points of the scale in order to clearly communicate different problem areas and the possibility space.

The marker contains three parameters: (i) vehicle investments, (ii) infrastructure investments and (iii) operating costs. The results for scores on this marker are summarised in *table 3.*

Table 3: Score for the marker Investment and Operation

	Investments vehicles	Investments infrastructure	Expenses operation and maintenance	Average	Lowest score
Full battery	3	8	8	6.3	3
Standard CL	10	1	10	7	1
Partial elec.	5	5	9	6.3	5
H2	2	6	3	3.7	3
Biogas	7	7	5	6.3	5
Biodiesel	9	10	6	8.3	6
Diesel (ref)	9	10	7	8.7	7

Biodiesel and ordinary diesel operation (reference technology) score highest on this marker. This means that these technologies, relative to the others, have low investment needs for vehicles and infrastructure. They score however medium high on expenses associated with operation and maintenance, where the electrical technologies score high. As the table shows, standard contact line and H2 have in contrast large challenges associated with investments. Chapter 3 demonstrated that there are large costs connected with vehicles for H2, and significant infrastructure costs with the expansion of the contact line network. This results in the technologies scoring in the low extreme point relative to the other technologies that require much smaller investments.

4.3 Climate and Environment

The marker "Climate and Environment" captures conditions associated with energy efficiency and different characteristics of emissions. Energy efficiency describes how well the technology utilises the added energy. This is thoroughly described in the different sub-reports and will not be further detailed here as the emphasis is on comparing the technologies. As with the other markers, the attempt has been made to rank the technologies in the scoring assessment. This means that despite all alternatives evaluated being considered to be low or zero emission, the relative performance on the marker will flash out the ones associated with even slight emissions.

The marker is divided up into the two parameters "energy efficiency" and "emissions". There has furthermore, as with the marker "feasibility", been a need to divide up each parameter with some evaluation criteria in the form of questions in order to capture crucial nuances. For the parameter "energy efficiency", there are in this context two questions that have been evaluated:

- How efficiently is the energy source utilised in the overall supply chain? [5]
- How efficiently is the energy used in the vehicle itself?

For the parameter "emissions" three questions are posed for the evaluation of scores. These are:

- Are there local emissions associated with use of the technology?
- Are there emissions of greenhouse gasses associated with use of the technology?
- Are there emissions of greenhouse gasses associated with investment in and placement into service of the technology?

Table 4: Score for the marker Climate and Environment

	Energy efficiency		Emissions			Result	
	Supply chain	Efficiency of vehicles	Local emissions	Greenhouse emission operation	Greenhouse emission investment	Average	Lowest score
Full battery	8	8	10	8	8	8.4	8
Standard CL	10	10	10	10	3	8.6	3
Partial elec.	9	9	10	9	5	8.4	5
H2	4	6	10	8	7	7	4
Biogas	2	1	2	8	8	4.2	1
Biodiesel	1	2	2	7	9	4.2	1
Diesel (ref)	3	2	1	1	10	3.4	1

All the electrical technologies (full battery, standard contact line and partial electrification with battery operation) score very high on this marker. This is related to electrical energy utilisation being extremely efficient relative to other solutions. Standard contact line scores however low with emissions associated with investment and placement into service. This is a result of large requirements for, among other things, steel and concrete for building out the necessary contact line network. The need

[5] For technologies that fetch energy from electrical power, the system boundary is placed at the power input, and for the other technologies the system boundary is placed at the energy content of the raw materials.

for additional construction and investment is also relevant for H2, which together with a relatively low energy efficiency scores medium high on this marker.

Biogas, biodiesel and ordinary diesel operation score low overall. This is given by conditions explained above, but also on the basis of there being some local emissions associated with the extraction of bio-based technologies. Together with low energy utilisation relative to electrical power-based alternatives, these solutions score consistently low on this marker.

4.4 Results of the evaluations

This sub-chapter has the purpose of collating the scores of the technologies for each marker. This will form the basis for assigning a total score based on the average of the marker scores and the lowest scores. As mentioned in the introduction, we have isolated the lowest score such that this has weight in the total assessment. Since we are attempting to evaluate topicality, and thus also point to problem areas, it would form an incorrect picture if the lowest score were eliminated with the average calculations. We have thus retained the lowest score for each technology and make this the basis for evaluating the total score in *table 5.*

Table 5: Total score for all markers

	Feasibility		Investment and operation		Climate and environment		Result
	Average	Lowest score	Average	Lowest score	Average	Lowest score	Total score
Full battery	6	3	6.3	3	8.4	8	5.8
Standard CL	8.5	3	7	1	8.6	3	5.2
Partial elec.	7.2	6	6.3	5	8.4	5	6.3
H2	1.7	1	3.7	3	7	4	3.4
Biogas	2.5	2	6.3	5	4.2	1	3.5
Biodiesel	8.7	8	8.3	6	4.2	1	6
Diesel (ref)	9.7	8	8.7	7	3.4	1	6.3

The results presented in the other sub-chapters, and in the summary table above, show that there are significant differences between the characteristics and suitability of the technologies evaluated. In the following, some key findings as shown in *table 5* will be reviewed and summarised.

The assessments associated with feasibility make it clear that three of the technologies evaluated are in practice unable to be selected at the current point in time. As *table 5* illustrates, this concerns biogas, H2 and full battery (for freight locomotives). This manifests in all the assessments for this marker, i.e. compatibility, technological maturity and safety (see *table 2)*.

The assessment associated with investment and operation indicates that investment in contact lines are challenging due to the level of investment for the infrastructure measures. This is in fact also the lowest score for this marker, something that indicates that this technology has significant financial challenges.

Assessments associated with the marker “climate and environment” show clearly that the bio-based technologies come out extremely poorly relative to the electrical solutions. At the same time, this illustrates well why continued use of diesel cannot be recommended. The electrical solutions score however consistently high on this marker, apart from CL, which involves circumstances that require emissions with its investments and placement into service.

On the overall, it is clear based upon *table 5* that partial electrification with battery operation comes out best when assessments associated with feasibility, investment and operation, as well as climate and environment, are taken as a basis. These are in fact also important evaluation points that the Norwegian Railway Directorate views as being necessary in order to establish topicality for alternative zero emission solutions for the non-electrified railway line stretches.

5 Conclusion

The purpose of the chapter is to summarise, conclude and recommend further efforts based upon the framework for NULLFIB. Sub-chapter 5.1 summarises central findings with the intent of presenting the most relevant zero emission solutions based on these assessments in chapter 3 and 4. Sub-chapter 5.2 proposes a recommendation for further efforts and central role clarifications between government agencies and the companies with the means of action. By way of conclusion in sub-chapter 5.3, important information is presented on individual reservations concerning the results.

5.1 Evaluation and elimination of available choices

A recommendation will be selected for future work on the implementation of an alternative energy carrier for diesel for the non-electrified lines. The selected alternative must be feasible for all those operations that are currently supplied with energy from ordinary diesel. In this context, challenges are associated with compatibility with current technology, technological maturity and safety for both hydrogen and biogas as shown in chapter 4. Financial conditions reviewed in chapter 3 also show that these solutions have high operating expenses, something that results in no basis for recommending these solutions. There is however extensive research taking place on hydrogen as an energy carrier for trains. The Norwegian Railway Directorate will follow this innovation and R&D activity in the immediate future, but as it appears today, hydrogen operation is assessed as not being mature enough for concrete tests/trial operations.

For the electrical solutions, for the concept with full battery there are significant challenges associated with the availability of vehicle technology for a large scope of operations that are currently being run with ordinary diesel. The concept gave, in contrast, good results for economics and operating finances, but the availability for vehicles and general technological maturity, especially for freight locomotives, involves there not being a basis for recommending further efforts with this technology.

The remaining solutions: standard contact line, partial electrification with battery operation and biodiesel, all scored extremely well in the total assessment in *table 5*. There are however some central challenges that ought to be highlighted.

5.1.1 Standard contact line

Use of contact line systems quite clearly comes out poorer in an economic comparison with the available choices. The financial calculations have however been performed based on the operation of the Nordland Line. It could thus be conceivable that other shorter railway lines with more traffic would give other results, but for the Nordland Line the standard contact line is a concept that is not further recommended. At the same time, assessments in chapter 4 show that some climate and environment-related challenges exist associated with the investments in and placement into service of this concept. On the overall, based on high infrastructure costs and environmental conditions, it has been decided to not recommend further efforts on this concept when the circumstances are weighed against other available choices.

5.1.2 Biodiesel

Biodiesel comes out well in the economic evaluation for the Nordland Line, but has challenges associated with the operating finances assessments that indicate that another alternative ought to be selected. Other railway lines may however give other results, and the results for biodiesel will be better the fewer the trains that are run. If the State has the will and the possibility to compensate operators for the additional costs in a manner that it does not weaken the competitiveness of railways against other forms of transportation, the use of biodiesel can be a quickly-acting measure to eliminate use of ordinary diesel with the railways. Challenges associated with biodiesel have however been identified in chapter 4 relating to local emissions, operating costs and energy efficiency. In addition, ethical challenges associated with this energy carrier have been identified that indicate that caution ought to be observed with utilising it as something other than a temporary measure where no good alternatives exist.

5.1.3 Partial electrification with battery operation

Battery operation with partial electrification has many good characteristics that were described in chapter 3 and 4. The concept received no red remarks in the scoring evaluation, and has extremely good conditions in terms of its economics and operating finances. In addition, it is an energy-efficient and safe propulsion solution that requires significantly less infrastructure measures than ordinary electrification. On the basis of financial conditions and assessments that have been made in order to compare the concepts, we are of the opinion that partial electrification with battery operation is the most appropriate concept for further efforts.

There exists however a need for co-ordination, testing and will on the part of the State and the railway's actors in order to place the concept into service on a large scale. The technology is dependent upon measures being undertaken both for the infrastructure and for vehicles, both of which are co-ordinated technically and in terms of time. The operating concept with partial electrification requires modifications and investments in hybrid vehicles that can be utilised both for contact line and battery operation. These vehicles provide flexibility by being able to be utilised in the entire railway network. For individual vehicle types, such as freight locomotives, suitable vehicles must be developed that at present are not commercially available. There are nevertheless significantly reduced operating expenses connected with this concept that can make it a favourable choice for the operators. This would be able to strengthen the competitiveness of the railway against other forms of transport, and thus lay the basis for the transfer of passengers from roads to rails.

5.2 Recommendations

The engineering assessment of new underlying knowledge is that battery-based technology is most relevant for being a permanent solution that can replace the use of fossil-based diesel with railway lines. In order for this technology to be able to be used in most of the operations that currently utilise fossil-based diesel, it is necessary that the use of batteries be combined with a charging system that can charge trains while they are running. This gives rise to a form of operation with batteries in trains combined with partial electrification being recommended as the primary solution for the non-electrified stretches of railway lines.

It is recommended that the Norwegian Railway Directorate shoulder the responsibility for the concept that involves battery trains combined with partial electrification being further investigated, with the goal of pilot projects for testing "battery operation with partial electrification" before 2025.

The Norwegian Railway Directorate will take the initiative in line with our role in that sector as a unifying and co-ordinating force, with all relevant actors in the sector. Rendering this tangible is done by continuing the NULLFIB project which will make proposals for mandates for further work.

5.3 Reservations

In order for recommended measures on the Nordland Line to be feasible and effective, it must a precondition that the relevant actors possess the requisite interest in carrying out the change. At the same time, it is important that the measures can be financed and that they are technically feasible. The work in NULLFIB and the recommendations that have been given have been prepared in order to render the fulfilment of these requirements probable. A pilot project will provide further knowledge and final answers to the feasibility of the concept for special Norwegian conditions. The cost-efficiency analysis has been performed for conditions that apply for the Nordland Line. In order to be able to conclude whether partial electrification is the most profitable for other railway line stretches, corresponding analyses must be performed for them.

6 Appendixes

6.1 Appendix A: Background for scoring assessments

This appendix presents how the different technologies have been assessed against each other. Each marker is presented with the different parameters that comprise the foundation for the total assessment as shown *in table 5.* These are (i) feasibility, (ii) investment and operation, and (iii) climate and environment. A presentation follows below of the evaluation criteria used as the underlying basis.

1) Feasibility

For "feasibility", three parameters are included that collectively form the total evaluation for this marker.

Compatibility with current technology

- Can vehicles that utilise the new technology utilise the present infrastructure without changes?
    - Scores of 1-2 are assigned for technologies that require adaptations of infrastructure that we at present do not know whether they can technically be carried out with the desired result.
    - Scores of 3-4 are assigned for technologies that require comprehensive measures in order to be able to be utilised in the relevant infrastructure.
    - Scores of 5-7 are assigned for technologies that require moderate measures in order to be able to be utilised in the relevant infrastructure.
    - Scores of 8-10 are assigned for technologies that require small or no measures in order to be able to be utilised in the relevant infrastructure.
- Can vehicles that utilise the new technology be used simultaneously as vehicles with the current technology?
    - Scores of 1-2 are assigned for technologies that involve conditions that cause the current vehicles to not be able to be used simultaneously with the new technology being utilised.
    - Scores of 3-4 are assigned for technologies where uncertainty associated with some parts of the infrastructure may pose challenges associated with simultaneous use.
    - Scores of 5-7 are assigned for technologies that with an overwhelming probability can be used simultaneously with the current vehicles.
    - Scores of 8-10 are assigned for technologies that with certainty can be said to be able to be used simultaneously with the current vehicles.

Technological maturity

- How is the availability of railway vehicles with the new technology?
    - Scores of 1-2 are assigned for technologies that at present are not offered by any European vehicle supplier.
    - Scores of 3-4 are assigned for technologies where railway vehicles are offered that are not standardised commercial products, but which must be regarded as prototypes.
    - Scores of 5-7 are assigned for technologies where there are a limited number of vendors of standard commercially available railway vehicles.
    - Scores of 8-10 are assigned for technologies where many suppliers exist of standardised commercially available railway vehicles in a mature market.
- How is the availability of technology for the requisite infrastructure?
    - Scores of 1-2 are assigned for technologies where solutions for the necessary associated infrastructure for the use of the technology in railways is not offered at present and is known.
    - Scores of 3-4 are assigned for technologies where solutions for necessary associated infrastructure are known but not offered as standardised products for railways, but rather must be regarded as prototypes.

- Scores of 5-7 are assigned for technologies where there are a limited number of vendors of standard commercially available solutions for the necessary associated infrastructure.
- Scores of 8-10 are assigned for technologies where many suppliers exist of standardised commercially available solutions for infrastructure in a mature market.

Safety

- Have safety challenges associated with the new technology been solved?
  - Scores of 1-2 are assigned for technologies that have safety challenges with the potential for large accidents that at present are not being handled in a satisfactory manner.
  - Scores of 3-4 are assigned for technologies that have serious safety challenges that at present are not being solved in a satisfactory manner.
  - Scores of 5-7 are assigned for technologies that have safety challenges, but where available solutions exist that with an overwhelming probability will contribute to the challenges being solved in a satisfactory manner.
  - Scores of 8-10 are assigned for technologies where no special safety challenges have been identified or which in comparison with the current technology have significantly reduced safety challenges.
- Is safety involving the use of the technology adequately regulated?
  - Scores of 1-2 are assigned for technologies that at present have important safety-related conditions that are unregulated in relation to their use in railways.
  - Scores of 3-4 are assigned for technologies where conditions of minor safety-related significance are unregulated in relation to their use in railways.
  - Scores of 5-7 are assigned for technologies for which there is little experience as to whether the safety associated with the technology is functioning as intended.
  - Scores of 8-10 are assigned for technologies where well-developed and well-tried regulation exists of the safety.

2) Investment and operation

It is not the task of the Norwegian Railway Directorate to establish acceptable levels of investments or operating costs, however we have ranked the technologies in relation to each other as an indicator based upon the available facts. Comparisons have been made for the different technologies of the levels of investment and operating expenses, where scores have been assigned relative to each other with a scale of 1-10 where 1 is the technology with the highest investment need or the highest operating expenses. Technologies with small differences have been given scores that lie close to each other, and where there are large differences the scores have been pulled towards the extreme points of the scale.

The three parameters that have been evaluated for this marker are:

- Vehicle investments
  - The costs of procuring vehicles in order to switch the form of operation in all operations on the railway from diesel to the new technology are evaluated under vehicle investments.
- Infrastructure investments
  - All requisite investments in workshops, energy supply and measures along existing railway infrastructure on the non-electrified railway stretches to place the technology into service are evaluated under infrastructure investments.
- Operating costs
  - An operator's operating expenses with operation based on the different energy carriers are evaluated under operating expenses.

3) Climate and Environment

This marker consists of the parameters (i) energy efficiency and (ii) emissions. Each parameter addresses different aspects in its segment that the Norwegian Railway Directorate deems to be important in this context.

Energy efficiency

For the different technologies, comparisons have been made of their energy efficiencies. Scores have been assigned in relation to each other on the scale of 1-10 where 1 is the technology with the lowest utilisation of the energy supplied to it. Technologies with small differences have been given scores that lie close to each other, and where there are large differences the scores have been pulled towards the extreme points of the scale.

The assessments that have been made are:

- How efficiently is the energy source utilised in the overall supply chain?
- How efficiently is the energy used in the vehicle itself?

Emissions

- Are there local emissions associated with use of the technology?
    - Scores of 1-2 are assigned for technologies that have almost equally large local emissions as the current technology.
    - Scores of 3-4 are assigned for technologies that have smaller local emissions than the current technology.
    - Scores of 5-7 are assigned for technologies that have significantly smaller local emissions than the current technology.
    - Scores of 8-10 are assigned for technologies that are not associated with local emissions with their use.
- Are there emissions of greenhouse gasses associated with use of the technology?
    - Scores of 1-2 are assigned for technologies that have almost equally large greenhouse gas emissions as the current technology.
    - Scores of 3-4 are assigned for technologies that have smaller greenhouse gas emissions than the current technology.
    - Scores of 5-7 are assigned for technologies that have significantly smaller greenhouse gas emissions than the current technology.
    - Scores of 8-10 are assigned for technologies that have marginal or no greenhouse gas emissions with their use.
- Are there emissions of greenhouse gasses associated with investment in and placement into service of the technology?
    - Comparisons of emissions have been made for the different technologies. Scores have been given in relation to each other with a scale of 1-10 where 1 is the technology with the greatest emissions. Technologies with small differences have been given scores that lie close to each other, and where there are large differences the scores have been pulled towards the extreme points of the scale.

6.2 Appendix B: Overview of associated sub-reports (in Norwegian)

All appendixes are found here.

Appendix 1 — **Sub-report 1:** Cost-efficiency analysis of introducing zero emission technology on the Nordland Line.

The report investigates what is most cost-efficient in terms of zero emission technologies (biodiesel, standard contact line, battery operation with partial electrification, full battery, hydrogen and biogas) on the Nordland Line.

Appendix 2 — **Sub-report 2:** Battery trains.

The report will provide underlying knowledge on the use of batteries as an energy carrier for railways. The report has three appendixes:

Appendix A: The Nordland Line Case Study, which is a study of the possibility for battery trains on the stretch.

Appendix B: Battery technology, which studies the current situation and future battery technology for railway vehicles.

Appendix C: Work machines, which addresses energy consumption and possible battery operation.

Appendix 3 — **Sub-report 3:** Partial electrification / Infrastructure measures.

The report contains a solution proposal for partial electrification of the Nordland Line. The proposal shows how costs are calculated for partial electrification and full electrification. The report shows energy content of the battery on the stretch, it describes grid connection and the technology for feed stations.

Appendix 4 — **Sub-report 4**: Hydrogen, biogas and biodiesel.

The report will provide underlying knowledge on the use of hydrogen, biogas and biodiesel as an energy carrier for railways.

Appendix 5 — Trial operation with hydrogen trains.

The report provides an evaluation of the feasibility, costs and utility of a trial project with hydrogen as an energy carrier.

Appendix 6 — Analysis of alternative forms of operation for non-electrified railway lines

The report is a revised version of a report that was originally written for the Norwegian National Rail Administration in 2015. (SINTEF 2019:00997)

Appendix 7 — Investigation partial electrification of the Nordland Line (Norconsult AS).

The report provides assessments involving partial electrification with battery operation vs. full electrification, as well as assessments surrounding the selection of transformer technology.