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Battery-operated ferries in Norway

A study of the possibility for electrification of ferry routes in Norway

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MASTER THESIS

May 2016

Abstract

The world's first all-electric car ferry "Ampere" has been operating the ferry route Lavik – Oppedal as one of three ferries in over a year. The ferry was introduced as a start of a revolution of green shipping in Norway. The Norwegian Government's goal for climate changes is to have proximate zero emission from the transport sector within 2050. This goal must be halfway reached by 2030. Ferry routes, which are an important part of the Norwegian transport, are the largest contributors for the emission from ships in Norway.

This thesis consists mostly of an analysis of a selection of ferry routes that are adequate for electrification based on 4 criteria's; length of the route, complexity, weather-exposure and traffic basis. The power requirement for an all-electrical ferry is estimated for ferries with a service speed of 12 knots and a capacity of 120 cars. For ferry routes that have a passage time of more than 30 minutes hybrid solutions must be considered. The power grid on each quay needs to be upgraded to be able to supply sufficient power. 12% of the ferry routes already have the necessary available effect, but the majority of the routes that are adequate for electrification have a need for reconstruction that will cost between 5 and 20 million NOK.

Keywords: Battery-operated ferries, all-electric ferries, zero-emission, green technology, climate changes

Acknowledgements

I would like to acknowledge the people who have supported me through the process of writing this thesis. First of all, I am grateful for the guidance and patience my supervisor Alf Harlem has shown me. Secondly I wish to acknowledge pedagogy student and teacher Anne Linstad and rhetoric guidance counsellor Marianne Hafstad for their most necessary help with the language usage and proofreading, and economist Tobias Schmidt for help with Excel. Without all your help, this would not be possible.

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Introduction

"The Norwegian Parliament asks the Government to make sure that all future ferry tenders meets a demand for zero-emission technology (and low-emission technology) when this is indicated by the technology."(DNV GL, 2015)

Description of the Research Problem

The plan for this thesis is to explore the challenges of electrification of the ferries in Norway. According to the media the advantages of battery operation are immense. The political view of the "green future" encourages the companies to build electrical vessels. This means that the trend is battery operation, which gives the companies with battery-operated ferries better publicity, and more people would choose those companies both to use and to invest in.

If we consider the use of batteries over a long period of time compared to the same amount of time for a diesel generator, there are high costs for both. A battery has an expiration day, but a diesel generator has not. Batteries need to be replaced with new expensive batteries. However, a diesel generator needs fuel and maintenance, which is also a cost. The line for when a battery-operated ferry is suitable considering emissions, costs, time and other considerations are an important topic for research.

To achieve the goal for climate obligation set by The Norwegian Government, the Norwegian transport sector must have proximate zero emission within the year 2050. This goal must be halfway reached within the year 2030. To do so, serious changes must be made on all the ferry routes. (Michelsen, 2016)

Research questions

1. Why are battery-operated ferries more energy efficient than diesel electric ferries?

2. How can battery-operated ferries replace the majority of diesel-operated ferries in Norway?

Theories

Zero-emission technology is such an important topic in these modern times as the awareness of global warming is focused upon. Diesel-electric vessels have a high emission of CO_2 and are less eco-friendly then battery-operated vessels. Here in Norway there are a large amount of ferry routes, with about 19 million passengers spread over 1,3 million trips each year (Norwegian Public Roads Administration, 2016). The majority of routes are in Hordaland, Møre og Romsdal and Nordland. If the ferries in these routes were battery-operated the emission in Norway will have a big cut down.

The ferry model "Zerocat™ 120" was my inspiration for choosing this topic. It is an all-electric car ferry built by the Norwegian shipyard Fjellstrand, named "Ampere". Fjellstrand has received two «Shippax awards» both as Builder and as Designer for the ferry, and also the Seatrade Clean Shipping award for 2015 (Fjellstrand AS, 2015). In the journal "Skipsrevyen" the vessel was awarded "Ship Of The Year 2014". On the "NOR-Shipping" exhibition and conference week in June 2015, which I attended, "Ampere" was nominated the "Energy Efficiency Award" (Nor-Shipping, 2015).

There are many challenges for battery-operated ferries, such as investment cost, battery lifetime and dimensioning, rules and regulations, battery internal failures, handling of voltage peaks, integrators knowledge of diesel engines dynamics and motivation of different equipment suppliers. (Maritime Battery Forum, 2015)

Batteries in Ships

"Det Norske Veritas" (DNV GL) states that the use of batteries in ships saves us for ten times more emission of CO_2 than we get from cars (Dalløkken, 2013). This is based on the emission of e.g. a Nissan Leaf compared to a conventional gasoline-operated car.

Two scientists from DNV GL have made two conclusions about production emission:

"1. In account of the environment there is much more reasonable to install advanced batteries such as lithium-ion batteries in ships than in cars.

2. The emissions saved through the use of these batteries on ships is so great that we can disregard the production emissions." (Dalløkken, 2013)

The data is based on hybrid drive of crane operation on ships, supply vessels and tugboats. In the production of a 300 kWh battery for crane operations the equivalent emissions of CO_2 are 51.6 tonnes, based on the NTNU report that specify the emission to be 172 kg CO_2/kWh (Ellingsen et al., 2014). Each battery saves 9 tonnes CO_2 that saves us 280 tonnes CO_2 per year. When we compare the use of batteries in ships and in cars, the ships are in use the whole time, but the cars are parked most of the time. A battery is worn out by time, in opposition to a combustion engine, which is worn out by use. (Dalløkken, 2013)

Expensive investment

Production of batteries and construction of all-electrical ferries are very expensive, but the investments will be earned back. Edvard Sandvik from the Public Roads Administration predicts two disadvantages. Electrical ferries are not so flexible and therefore not so easy to move from route to route, which is needed in case of landslides or other causes when ferries must replace the road for a limited time. The other reason is power failure. The power grid has an uptime of 99.6%. It is unlikely that there is a power failure on both ends of the route, but the ferries need to charge on both ends to make the trip. (Høyberg, 2015)

Technical/chemical description of a lithium-ion battery

The lithium-ion battery consists of several smaller battery cells and the electricity

Figure 1: Lithium-ion battery cell

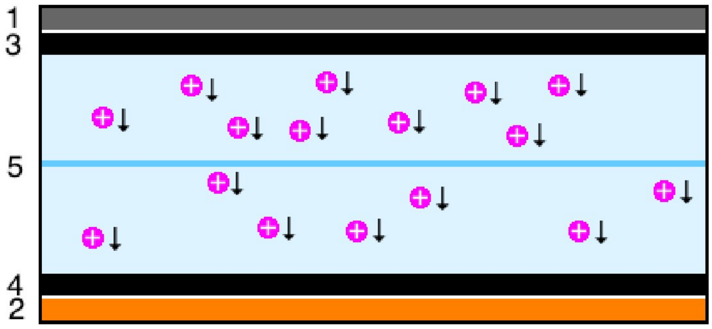

Figure 1: A cell with 5 layers in a lithium-ion battery in charging mode (BASF, 2011)

reaches the cells through conductive surfaces. The cell (Figure 1) consists of five layers; the two outer surface layers, which could be aluminium (1) and copper (2), the cathode (3) and anode (4), and in the middle a permeable separator (5). The positive electrode, the cathode, is made of a very pure lithium metal oxide. With a uniform chemical composition the performance will be better and the battery life will be longer. The anode is made of carbon graphite with a layered structure. The battery is filled with very pure liquid electrolyte so the lithium-ions can flow freely. The purer the electrolyte is, and as free of water as possible, the more efficient the charging and discharging will be. The separator between the two electrodes prevents a short circuit, but is also permeable to the tiny lithium-ions. This is called microporosity.

Charging the battery

The positively charged lithium-ions travel from the cathode, through the separator in the electrolyte, into the layered graphite structure of the anode and then stored there.

Discharging the battery

When energy is removed from the cell, the lithium-ions travel back from the anode, through the electrolyte and the separator and back to the cathode.

(BASF, 2011)

Temperature and charging

When the battery is charging, its temperature is an important factor. The ideal temperature for the cells is 20 - 30°C and the ideal charged percentage is 50 - 60%. This includes all lithium-ion batteries, in mobile phones as well as in ferries. (Stensvold, 2015a)

All-Electrical Versus Hybrid

When choosing between all-electric propulsion and a hybrid solution to operate a ferry, an important factor is the length of the route and the amount of time used on loading and discharging. Hybrid solutions are suitable for ferries that need high effect, but not the whole time (Myklebust, 2014). Hybrid solutions are most suitable for routes with a passage time of 35 minutes or more. The ferries on these routes need to charge the batteries with diesel generators during the passage to withhold the necessary power needed to make the trip.

All-electric ferries on the other hand is most suitable on shorter routes, where the land-based charging installation charges the batteries enough to make the trip without additional power. The loading/discharging time should not be below ten minutes, and there should be at least 20 arrivals each day. There are still many factors to consider for all-electric operated routes. For the battery pack to be charged enough to make the trip, a powerful land grid must be installed. A normal land grid that is built for diesel operated ferries is not powerful enough for all-electric ferry, so to replace diesel operated ferry a new and expensive land grid needs to be installed. The weather situation or the weather that specific route could be exposed to is important when choosing all-electric propulsion. The level of battery capacity is based on situations when the ferry is fully loaded and exposed to bad weather. (Stensvold, 2015a)

"Ampere", the Worlds First All-Electric Car Ferry

ZeroCat™ 120

Figure 2: "Ampere"

Figure 2: The all-electrical car ferry "Ampere" (Fjellstrand AS, 2014)

The model called ZeroCat was built by the shipbuilding company Fjellstrand AS in Omastrand in the Hardangerfjord, at the west coast of Norway in 2014 on behalf of the ferry company Norled AS. The vessel is 80.8 meters long and has a capacity of 120 car units, eight truck units and 350 passengers. There are 2 x 450 kW main electrical motors, Siemens electrical propulsion and 2 x 450 kW Rolls Royce azimuthing thrusters. The batteries are charged by land grid with a quick connection charging facilities integrated with the quay during the loading and dis-loading of cars and passengers. The trip is only 20 minutes so the batteries are frequently charged. The batteries have a lifetime calculated to be ten years. (Fjellstrand AS, 2014)

There are two different connections, "Ampere" uses the a pantograph charger that consists of four copper poles that touches four copper rails on the vessel, which is based on the same system as trains. The rails allow the vessel to move up and down with the waves. Another available connection is a more regular plug connection, but this is not used on "Ampere". Before both these connections can be made the vessel needs to lie still (Stensvold, 2015b).

Figure 3: Pantograph charger

Figure 3: The pantograph charger on "Ampere" (Stensvold, 2015c)

The mooring on "Ampere" is also a new innovation. There is a vacuum based mooring system called Cavotec Vacuum Mooring (Figure 4) that draws the vessel against the quay with a suction force of 20 tonnes. The system on the quay receives a notice via a GPS signal when the vessel approaches the quay to make ready for the mooring. Normally the mooring situation takes up too much power for an all-electric vessel to manage, but with the vacuum mooring system moor and release the vessel without the vessel using its propellers. (Stensvold, 2015b)

Figure 4: Cavotec Vacuum Mooring

Figure 4: The vacuum based mooring system on "Ampere" (Stensvold, 2015c)

Not the world's first battery-operated ferry

When "Ampere" had it's first trip, NRK posted the statement saying the vessel was "the world's first battery-operated ferry" (Storvik & Skovro, 2015). This was later corrected to "the world's first all electrical car ferry" which is more correct.

When the project "Ampere" was first introduced it was presented as some kind of revolution and an innovation of the future, even though battery-operated ships/vessels have been in operation for over 120 years. The first all-electrical ferry was first introduced as a test project on the river Spree in Germany in 1886, but because of the underdeveloped battery technology at that time the project was not a success (Sinusmagasinet, 2014). The first battery-operated submarine The "Peral" was built in Spain in 1887 (Field, 1908). Most submarines have since then always had electrical motors with batteries. The conventional submarine has an electrical engine powered by a large battery pack. When the vessel is in underwater transit it needs to be as quiet as possible which is the whole point of the electrical propulsion. The submarine also has a diesel generator that is only used when the vessel is in surface transit to charge the battery pack. (Lødøen & MacDonald, 2003)

The Bergen Electric Ferry Company Limited (BEF)

BEF was founded in Bergen, Norway, in 1894 as the first electrical ferry company. By August 1st they had two electrical ferries in operation that each carried 16 passengers across Vågen in Bergen. By the end of 1894 they had eight ferries called "BEF 1", "BEF 2", "BEF 3" etc. in routes across the harbour. Recharging stations were built so the ferries could recharge after 10 hours operation. These electrical ferries were in operation until 1926 when they started to rebuild the ferries installing gasoline motors. By 1930 all the ferries were gasoline powered (A/S Bergens Elektriske Færgeselskab, n.d.).

Later only one ferry was in operation and was named “Beffen”. In 2015 the new “Beffen” was introduced to the people of Bergen with a new battery pack, which replaced the old two-cylinder Saab gasoline engine. So, now the ferry across Vågen is finally yet again battery-operated. (Hjertholm, 2015)

Figure 5: “BEF 1” and “BEF 2”

Figure 5: The first two ferries, “BEF 1” and “BEF 2” (A/S Bergens Elektriske Færgeselskab, n.d.)

Methods

Research Design

Research methods can be divided in three ways; qualitative, quantitative and a mixed methods approach. Some times the study is more qualitative than quantitative or vice versa. It does not have to be entirely qualitative or quantitative. Mixed methods are just in the middle; as much a qualitative as a quantitative study.

In qualitative research there are more use of words, e.g. an interview with open-ended questions. A qualitative approach describes a research problem by exploring a concept or phenomenon. Qualitative method is used to explore a topic with unknown variables and theory base. (Creswell, 2009)

Characteristics of a qualitative research problem are:

"- The concept is "immature" due to a conspicuous lack of theory and previous research.

- A notion that the available theory may be inaccurate, inappropriate, incorrect or biased.

- A need exists to explore and describe the phenomena and to develop theory.

- The nature of the phenomenon may not be suited to quantitative measures."

(Creswell, 2009)

In quantitative research there are more use of numbers and interviews with closed-ended questions, such as questionnaires with multiple-choice answers. In a quantitative introduction the researcher can incorporate substantial reviews of the literature to identify research questions that need to be answered. (Creswell, 2009)

This thesis is based on hard, reliable data from already existing research. That makes me a distant researcher, and the research questions are contrived from my initial point of view. The research questions are also based on hypotheses on theory to be tested through searching existing reports and publications. Through viewing Table 1 we see that the research in this thesis is approached by a quantitative method.

Table 1: Some common contrasts between quantitative and qualitative research (Bryman, 2012)

Quantitative research	Qualitative research
Numbers	Words
Point of view of the researcher	Points of view of participants
Researcher distant	Researcher close
Theory testing	Theory emergent
Static	Process
Structured	Unstructured
Generalization	Contextual understanding
Hard, reliable data	Rich, deep data
Macro	Micro
Behaviour	Meaning
Artificial	Natural setting

Mixed Methods

The “Results”-chapter is based on a report done by researchers from DNV GL, which is only quantitative research that resulted in tables explaining the costs, the power requirements and the required measures that needs to be implemented. The “Discussion”-chapter is based on a mixed method approach with research for facts, but also for opinions, which is both quantitative and qualitative. (Creswell, 2009)

Case Study

The data collected for the “Results”-chapter is based on the DNV GL report with analysis of possible routes that are adequate for electrification. This part of the thesis is a case study, which is a qualitative method.

Data Collection

The first collected data was from the seminar “Innovation Day” which was hosted by Maritime Battery Forum on the business school BI in Oslo. Maritime Battery Forum is a world based Norwegian maritime cluster within battery based value creation, which focuses on electric ships. The seminar valuated the future environmental potential for the maritime sector. A topic on the seminar was the all-electrical ferry “Ampere”.

The next plan was to visit Norled, the company that owns “Ampere” to write a report to use as a part of this thesis. Instead of this I found that the online magazine “Teknisk Ukeblad” wrote several articles about the ferry, including an article where a journalist visited the ferry and covered most of the data needed for the initial part of the research. All the data on the technical topics regarding an all-electrical ferry is collected from “Teknisk Ukeblad” and the web page for the yard “Fjellstrand”, which built “Ampere”.

Results

Analysis of Possible Routes that are Adequate for All-Electrical Operation

Det Norske Veritas (DNV GL) has prepared an analysis of a selection of routes that are adequate for all-electrical operation. The main purpose is to analyse the need for electric power on the ferry quays and also how the grid network can be financed, and deliver the necessary effect on each quay. To find saving in fuel costs it is assumed that there are decreased costs for not using diesel. However, there are increased costs when buying electric power and also increased costs for reinforcing the power network. They have selected 52 routes, and the following criteria are the basis for these routes:

Length of the route

The energy demands of the longest routes result in low sufficiency in batteries because of the lower energy density and increased costs in larger battery packs. With todays technology batteries can not compete economically with combustion motors on the longest routes. The selected routes are shorter than 30 minutes. (DNV GL, 2015)

Complexity

The operation structure of the routes varies between the connections. Some routes can be compared with bus-routes, where each ferry stops on e.g. 10 different quays. The combination of the stops also varies throughout the days. With routes like this the cost for developing the necessary charging installations on all the quays will be very high. (DNV GL, 2015)

Weather exposure

Some of the routes in Norway are exposed to open ocean and strong wind. Places like these are not adequate for all-electric operation because of the need for high redundancy. None of the selected routes are exposed to such conditions. (DNV GL, 2015)

Traffic basis

Many of the connections have too few departures to be adequate for the analysis. Since different ferries operate these routes some simplifications are made to achieve manageable basis for calculations. It is anticipated that standard ferries with capacity of 120 cars, service speed of 12 knots and the opportunity for quick charging will be selected to operate the routes. (DNV GL, 2015)

Estimating the power requirement for an all-electric ferry

The energy demand for an all-electric ferry is based on a series of variables. The correlations between speed through water and energy demand is shown as a curve that increases exponentially. The energy that are demanded to keep the speed depends on a wet surface and the shape of the hull. The curve is shown in Figure 6. Due to the simplified assumptions that all ferries have a service speed of 12 knots and are capable of carrying 120 cars we still get a durable estimation for the use of energy and the cost for electrification of the ferry routes. It is not adequate to assume a constant speed for the passage, but we also need to estimate the effect of manoeuvring, acceleration, deceleration and lay time to get a correct impression of the use of energy. Figure 7 shows the operation profile of a passage, based on the ferry “Ampere”. The operation profile shown in Table 2 and the distance of each route gives the basis for the estimated energy demands shown in Table 3. (DNV GL, 2015)

Figure 6: Effect/speed curve

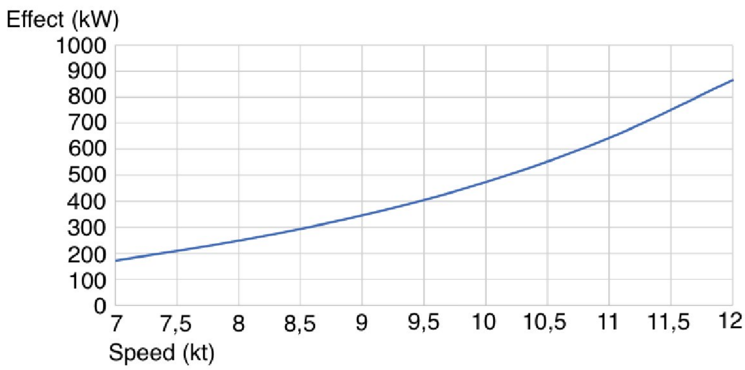

Figure 6: Effect/speed curve for a typical car ferry with the capacity of 120 cars (DNV GL, 2015)

Estimation of necessary available power on the quay

The power requirement for the ferries gives a basis for estimating the necessary power requirement on the quay for the installation to be able to charge the batteries the short time the ferries are alongside the quay. As shown in Table 3, the calculations are based on a lay-time of five minutes, which is the worst-case scenario, and it is assumed that the batteries on the ferries are capable of quick charging. It takes a considerable more amount of power for the quay installations to be capable of quick charging than is available on most quay installations on the ferry routes. The grids to the quay installations on most of the routes are just as limited as the installations so there will be battery banks available on the quays to give sufficient capacity for transferring power to the ferry while alongside the quay. The estimated power requirement is shown in table 4. (DNV GL, 2015)

Figure 7: Generic operation profile

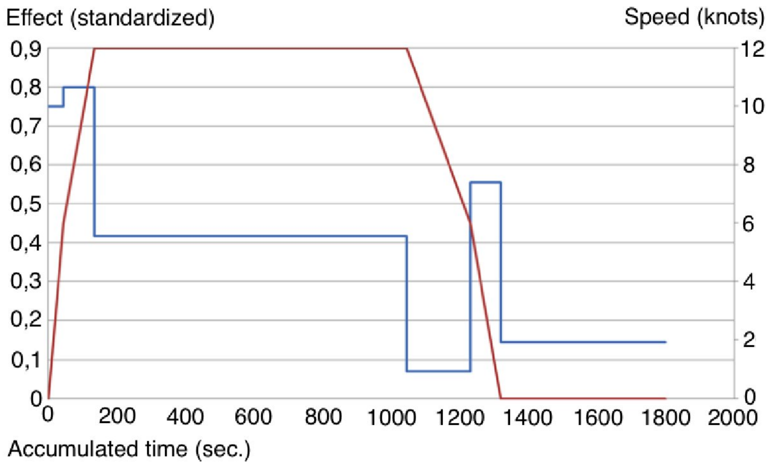

Figure 7: Generic operation profile for a standard ferry with capacity of 120 cars (DNV GL, 2015)

Table 2: Time in different operation modes, including specific fuel consumption for a conventional diesel operated ferry of the same dimensions (DNV GL, 2015).

	Departure manoeuv.	Acceleration	Passage	Retardation	Arrival manoeuv.	Alongside the quay
Time in operation mode	45 sec.	90 sec.	N/A	185 sec.	90 sec.	300 sec.
Average speed in operation mode	2 kt.	6 kt.	12 kt.	6 kt.	2,5 kt.	0 kt.
Associated engine load	75%	80%	42%	7%	56%	14%
Specific fuel consump.	210 g/kWh	217 g/kWh	204 g/kWh	209 g/kWh	N/A	250 g/kWh

Estimating the necessary fuel requirement for a conventional ferry

To estimate the fuel consumption for a conventional diesel-operated ferry we assume that both diesel- and electric operated ferries have the same energy demands per passage. With these assumptions we can use the same generic operation profile as shown in Figure 7. Specific fuel consumption in each mode (Table 2) is used to calculate the annual fuel consumption for each ferry route (Table 3). (DNV GL, 2015)

Table 3: Key parameters describing the current situation of the selected ferry routes. (DNV GL, 2015)

Ferry route	No. of ferries	Daily crossings	Dist. (km)	Energy demand pr. Trip (kWh)	Charg. effect (kW in 5 min.)	Annual electricity consump. (GWh/ year)	Annual diesel consump. (tonnes/ year)	Annual emission of CO2 (tonnes/ year)	Additional ferry costs (MNOK)
Svelvik - Verket	1	84	0.2	90	1,085	2.8	626	1,934	7.2
Launes - Kvellandstrand	1	70	1.3	134	1,606	3.4	748	2,312	10.7
Andabeløy - Abelsnes	1	43	1.3	132	1,583	2.1	453	1,401	10.6
Tau - Stavanger	3	64	14.5	646	7,755	15.1	3126	9,659	155.1
Lauvvik - Oanes	1	72	2.1	165	1,976	4.3	935	2,888	13.2
Hjelmeland - Nesvik	1	38	3	199	2,383	2.8	589	1,821	15.9*
Skipavik (R) - Nesvik	1	20	3.9	235	0	1.7	364	1,125	18.8*
Skipavik (R) - Hjelmeland	1	20	4.5	257	0	1.9	397	1,225	20.5
Kinsarvik - Utne	2	20	8.1	397	4,767	2.9	606	1,873	63.6
Utne - Kvanndal	2	42	5.6	301	3,617	4.6	973	3,006	48.2*
Løfallstrand - Gjermundshamn	2	45	7.1	358	4,300	5.9	1233	3,810	57.3*
Varaldsøy - Gjermundshamn	2	18	4	239	2,869	1.6	333	1,030	38.3*
Varaldsøy - Løfallstrand	2	17	8.2	401	4,809	2.5	520	1,606	64.1
Skånevik - Utåker	1	20	5.9	314	3,771	2.3	482	1,491	25.1*
Sunde i Matre - Skånevik	1	10	7.6	379	4,548	1.4	289	894	30.3
Sunde i Matre - Utåker	1	10	3.4	217	2,602	0.8	169	521	17.3*
Jektevik - Nordhuglo	1	7	3.9	235	2,822	0.6	128	394	18.8
Jektevik - Hodnanes	1	41	2.4	177	2,121	2.6	569	1,758	14.1*
Nordhuglo - Hodnanes	1	12	2.6	185	2,214	0.8	174	536	14.8*

Hatvik - Venjaneset	1	58	3.3	210	2,523	4.5	950	2,935	16.8
Jondal - Tørvikbygd	1	38	5.2	284	3,407	3.9	831	2,567	22.7
Leirvåg - Sløvåg	1	36	5.7	307	3,683	4	849	2,622	24.6
Breistein - Valestrandfossen	1	66	2.5	181	2,167	4.4	935	2,890	14.4
Hella - Dragsvik	3	48	1.8	153	1,840	2.7	583	1,801	36.8*
Vangsnes - Hella	3	46	4.3	251	3,009	4.2	892	2,757	60.2*
Vangsnes - Dragsvik	3	46	4.9	272	3,266	4.6	965	2,983	65.3
Lote - Anda	1	74	2.1	165	1,980	4.5	963	2,975	13.2
Fodnes - Mannheller	2	108	3.3	211	2,532	8.3	1,775	5,484	33.8
Isane - Stårheim	1	40	4.4	255	3,056	3.7	787	2,433	20.4
Årvik - Koparneset	2	68	2.5	181	2,167	4.5	964	2,977	28.9
Hareid - Sulesund	2	72	7.7	385	4,618	10.1	2,115	6,535	61.6
Volda - Folkestad	1	64	3.3	212	2,546	5	1,057	3,267	17
Volda - Lauvstad	2	32	7.5	376	4,510	4.4	919	2,839	60.1
Festøya - Hundeidvika	1	30	4.8	269	3,234	3	624	1,927	21.6
Festøya - Solavågen	2	84	4.4	256	3,075	7.9	1,663	5,139	41
Sykkylven - Magerholm	2	112	3.7	228	2,733	9.3	1,980	6,119	36.4
Stranda - Liabygda	3	60	2.8	192	2,308	4.2	902	2,789	46.2
Eidsdal - Linge	3	58	2.7	188	2,261	4	856	2,644	45.2
Geiranger - Hellesylt	2	16	19.9	860	10,322	5	1,036	3,202	137.6
Molde - Vestnes	3	74	11.5	532	6,385	14.4	2,985	9,225	127.7
Molde - Sekken	1	18	11.5	531	6,376	3.5	725	2,241	42.5
Sølsnes - Åfarnes	1	73	3.4	216	2,588	5.7	1,225	3,785	17.3
Kvanne - Rykkjem	1	68	2.5	179	2,144	4.4	954	2,947	14.3
Halsa - Kanestraum	2	78	5.4	295	3,538	8.4	1,768	5,464	47.2
Flakk - Rørvik	3	30	7.4	372	4,468	4.1	853	2,637	89.4
Levang - Nesna	1	32	8.5	414	4,973	4.8	1,011	3,123	33.2
Bognes - Skarberget	2	48	8	393	4,721	6.9	1,441	4,451	62.9
Kjøpsvik - Drag	1	22	13.6	613	7,358	4.9	1,020	3,153	49.1
Forøy - Ågskardet	2	48	2.6	184	2,210	3.2	693	2,140	29.5
Refsnes - Flesnes	1	36	5.5	298	3,570	3.9	823	2,545	23.8

Svensby - Breivikeidet	1	38	6.2	325	3,898	4.5	946	2,924	26
Lyngseidet - Olderdalen	1	32	12.6	574	6,890	6.7	1,391	4,299	45.9
TOTAL (-duplicates)	52	2,406				237.7	50,195	155,103	1,709.7

Note: * Some ferries can operate several routes; these, including the costs, are left out of the sum total.

Power supply on the ferry quays

The different ferry quays are built for existing ferries so necessary rebuilding must be completed for the new ferries to be introduced. The power grid needs upgrading to be able to supply sufficient power. Some of the quays already have an adequately functional grid for all-electric ferries, but most of them need to be reconstructed so that the grid can supply sufficient power. Table 4 shows the estimated costs for reconstructing the grid on each ferry quay, which is given by the grid company. The quays that have the value zero in the costs-column already have a sufficient power grid for electric operation.

Table 4: Reconstruction costs for the electric grid on the different ferry quays (DNV GL, 2015)

Quay	Avail. Effect on quay (kW)	Effect by re-constr. (kW)	Grid re-constr. Costs (MNOK)	Quay	Avail. Effect on quay (kW)	Effect by re-constr. (kW)	Grid re-constr. Costs (MNOK)	Total re-constr. Costs (MNOK)
Svelvik	0	1,085	0.3	Verket	100	1,250	0.5	0.8
Launes	1,606	0	0	Kvellandstrand	1,606	0	0	0
Andabeløy	1,583	0	0	Abelsnes	1,583	0	0	0
Tau	0	8,000	6.8	Stavanger	0	7,755	12	18.8
Lauvvik	0	2,000	2.2	Oanes	0	2,000	3	5.2
Hjelmeland	0	11,000	1.3	Nesvik	0	6,000	33.5	34.9
Skipavik (R)	0	0	0	Nesvik	0	6,000		0
Skipavik (R)	0	0	0	Hjelmeland		6,000		0
Kinsarvik	20	4,767	7.5	Utne	40	4,767		7.5
Utne	40	3,617	15	Kvanndal	80	3,617	8	23
Løfallstrand	4,800	0	0	Gjermundshamn	1,100	4,300	14.7	14.7
Varaldsøy	500	4,800	17	Gjermundshamn	1,100	4,300		17
Varaldsøy	500	4,800		Løfallstrand	4,800	0	0	0
Skånevik	0	4,500	5	Utåker	500	3,800	2.1	7.1
Sunde i Matre	500	4,600	5.9	Skånevik	0	4,550	5	10.9
Sunde i Matre	500	4,600		Utåker	500	3,800	2.1	2.1
Jektevik	1,000	3,000	13	Nordhuglo	0	2,823	1	14

Jektevik	1,000	3,000		Hodnanes	100	2,200	2	2
Nordhuglo	0	2,823	1	Hodnanes	100	2,215		1
Hatvik	3,000	0	0	Venjaneset	0	2,523	0.8	0.8
Jondal	0	3,407	2	Tørvikbygd	100	3,407	2	4
Leirvåg	3,800	0	0	Sløvåg	3,800	0	0	0
Breistein	200	2,167	1	Valestrandfossen	2,200	0	0	1
Hella	100	1,840	44	Dragsvik	100	1,840	12	56
Vangsnes	315	3,009	36	Hella	100	3,009	44	80
Vangsnes	315	3,266		Dragsvik	100	3,266	12	12
Lote	50	1,980	8	Anda	50	1,980	5	13
Fodnes	40	2,532	36	Mannheller	315	2,532	28	64
Isane	30	3,056	12	Stårheim	30	3,056	6	18
Årvik	100	2,167	1.4	Koparneset	100	2,167	1.4	2.8
Hareid	200	4,618	5.1	Sulesund	100	4,618	5.9	11
Volda	100	4,510	3.7	Folkestad	150	2,546	1.5	5.2
Volda	100	4,510		Lauvstad	50	4,510	11.9	11.9
Festøya	100	3,234	1.5	Hundeidvika	0	3,500	4.7	6.2
Festøya	100	3,075		Solavågen	200	3,075	1.5	1.5
Sykkylven	0	2,734	3.5	Magerholm	50	2,733	1.5	5
Stranda	100	2,308	0.5	Liabygda	50	2,308	6.6	7.1
Eidsdal	200	2,261	21.4	Linge	50	2,261	21.4	42.8
Geiranger	100	10,322	3.8	Hellesylt	50	10,322	13	16.8
Molde	0	6,385	1.8	Vestnes	2,000	6,385	10.6	12.4
Molde	0	6,376		Sekken	0	6,376	40	40
Sølsnes	0	2,588	17.8	Åfarnes	100	2,588	0.8	18.6
Kvanne	110	2,200	0.8	Rykkjem	100	2,200	7	7.8
Halsa	120	3,540	0.9	Kanestraum	100	3,600	12.1	13
Flakk	1,000	5,000	22	Rørvik	315	4,500	11	33
Levang	0	4,980	10	Nesna	0	5,500	0.8	10.8
Bognes	1,000	5,000	31	Skarberget	500	4,721	50	81
Kjøpsvik	0	7,500	12	Drag	1,000	7,500	13	25
Forøy	0	2,500	2.5	Ågskardet	200	2,500	4	6.5
Refsnes	300	3,570	35	Flesnes	70	3,570	24.5	59.5
Svensby	3,000	15,000	20	Breivikeidet	2,000	15,000	37	57
Lyngseidet	5,000	15,000	6	Olderdalen	500	10,000	45	51
Total			414.7				518.9	933.7

For an easier overview of the need for construction Figure 8 is included with the percentage of the different levels of costs on the routes. Twelve percent of the ferry routes already have the necessary available effect, but almost half of the chosen routes have a need for reconstruction that will cost between five and 20 million NOK (green and purple).

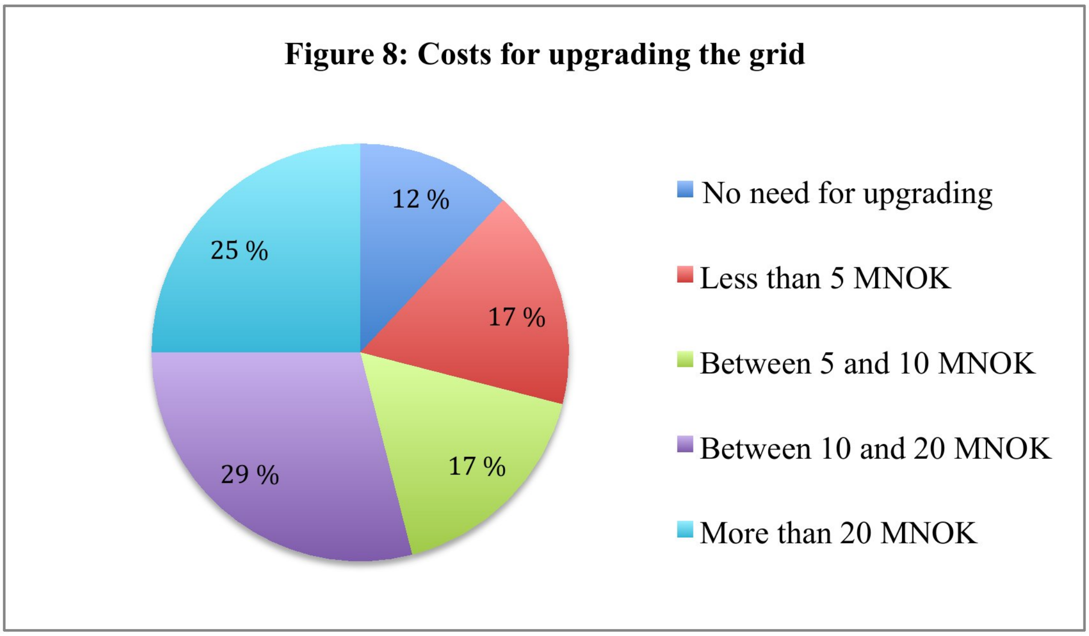

Figure 8: Summery of the need and the costs for upgrading the power grid on the ferry quays (DNV GL, 2015)

Figure 9: Effect on each quay

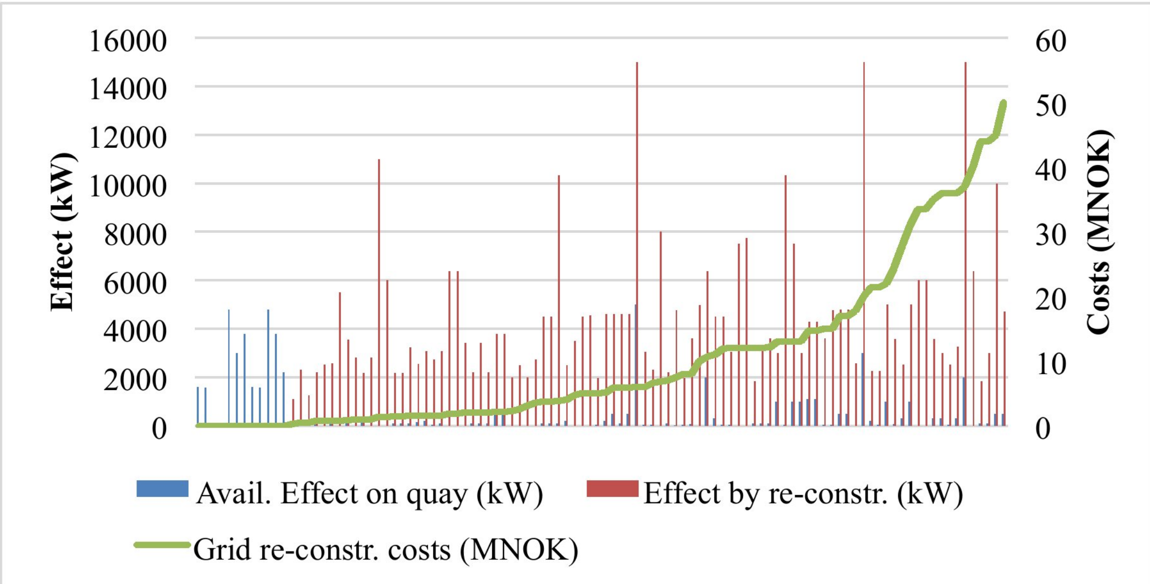

Figure 9: Available effect on each quay and the costs for upgrading the grid to the necessary effect. (DNV GL, 2015)

Figure 9 shows the available effect on the different quays where the blue lines indicates the amount of available effect before reconstruction, the red lines indicates the effect after reconstruction and the green line indicates the costs for reconstructing the grid. The green line is not proportional with need for effect. The quays on the right side of the diagram

(Figure 9) are the ones with the highest reconstruction costs, but these quays are not necessarily the ones with the need for highest available effect. This varies with the different locations. (DNV GL, 2015)

For the grid companies to be able to supply the demanded effect to the ferry quays an initial investment of 900 million NOK is stated to be necessary. In addition to this the grid companies have stated a necessary investment grant for grid connection of new users or new producers of electrical energy, or for extension and reinforcement of existing grid. This cost is estimated to be 800 million NOK. These amounts are too high for many of the grid companies and ferry companies to manage without subsidy, which could be a national plan for building the infrastructure to electrify the transport sector. (DNV GL, 2015)

Cost-effectiveness of electrification of the ferry routes

$$\text{Benefit-costs} = \frac{\text{Estimated annual costs}}{\text{Estimated average annual reduced emission of } CO_2}$$

Benefit-costs are estimated as costs per annual reduced emission of CO_2. By using the same method as used by The Norwegian Environment Agency, to estimate the costs for CO_2 reduction measures, we get an overview of the cost-effectiveness of electrification of the ferry routes. First we estimate the benefit-costs for the ferry, then the benefit-costs for the network grid upgrading. We sum up these costs to get the total benefit-costs, which is all the additional costs the measure causes. The estimations are based on the lifetime of the battery packs, which is ten years. (DNV GL, 2015)

The costs of battery solutions on vessels

The size of the battery installation is estimated by using the same dimensions of the ferry “Ampere”, which has the capacity of five times the energy the vessel demands for best redundancy. The costs are based on the size of the installation and the unit cost. The lifetime of the battery is ten years, but it is cut short when the battery is totally discharged before it is recharged. The estimation of the costs is based on number of charging cycles, investment costs and expected lifetime of the battery pack. This is evaluated on the basis of operation profile. The unit costs, which include the battery, the power maintenance system and the cable system for charging, are estimated to be 16,000 NOK/kWh. This is based on the current price of batteries, which is expected to decrease in the years to come. (DNV GL, 2015)

Diesel and electricity costs

When estimating the differences between the cost of diesel and the cost of electricity, the prices from April 2015 are used to find the cost savings. The price was 5,800 NOK/tonnes diesel and 0.3 NOK/kWh for the electricity. (DNV GL, 2015)

CO_2 reduction

The difference in reduction of emission of CO_2 from a diesel-operated ferry versus an all-electrical ferry equals all the emission of CO_2 from a diesel-operated ferry. Emission of NO_X and SO_X is not included in this analysis.

The emission factor is fixed at 3.09 tonnes CO_2 per tonnes diesel. The results are shown in Table 3. (DNV GL, 2015)

Estimated benefit-costs

The benefit-costs, costs per reduced tonnes CO_2, are based on the data from the previous chapters. The costs are estimated for each ferry route and are shown in three different figures; the ferry costs (Figure 10), the network grid costs (Figure 11) and the joint total costs for electrification of the routes (Figure 12). The values in the following figures are calculated from pre-estimated individual values in the basis of the report by DNV GL. Routes marked * are operated by more than one ferry and the quays in these routes are the points of departure for more than one route. The costs for these routes must not be counted for more than one time. (DNV GL, 2015)

Figure 10: Benefit-costs for the ferries (NOK/tonnes CO_2)

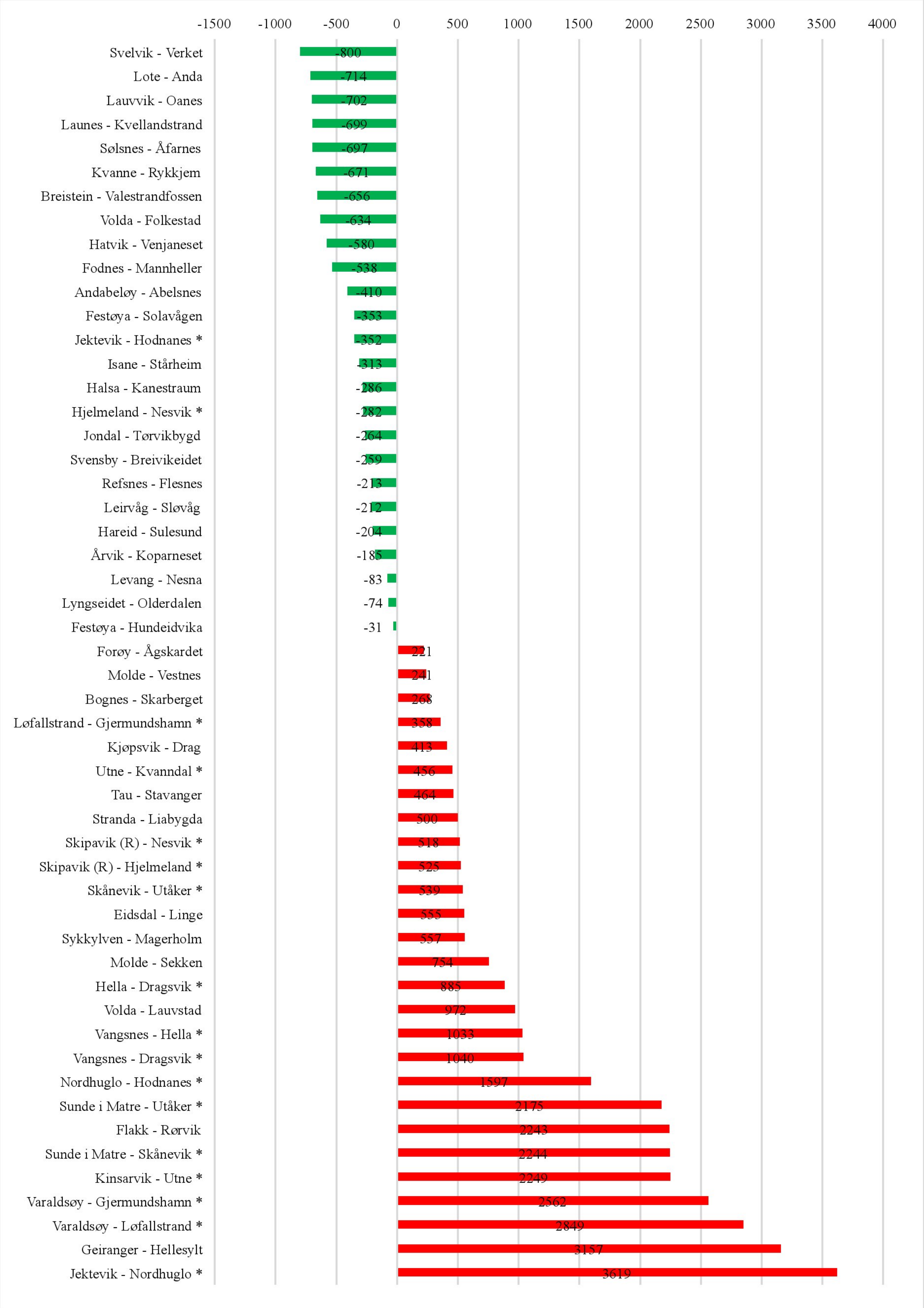

Figure 10: Benefit-costs (NOK/tonnes CO_2) for the CO_2 reduction by electrification of the ferries (DNV GL, 2015)

Figure 11: Benefit-costs for the ferry quays (NOK/tonnes CO_2)

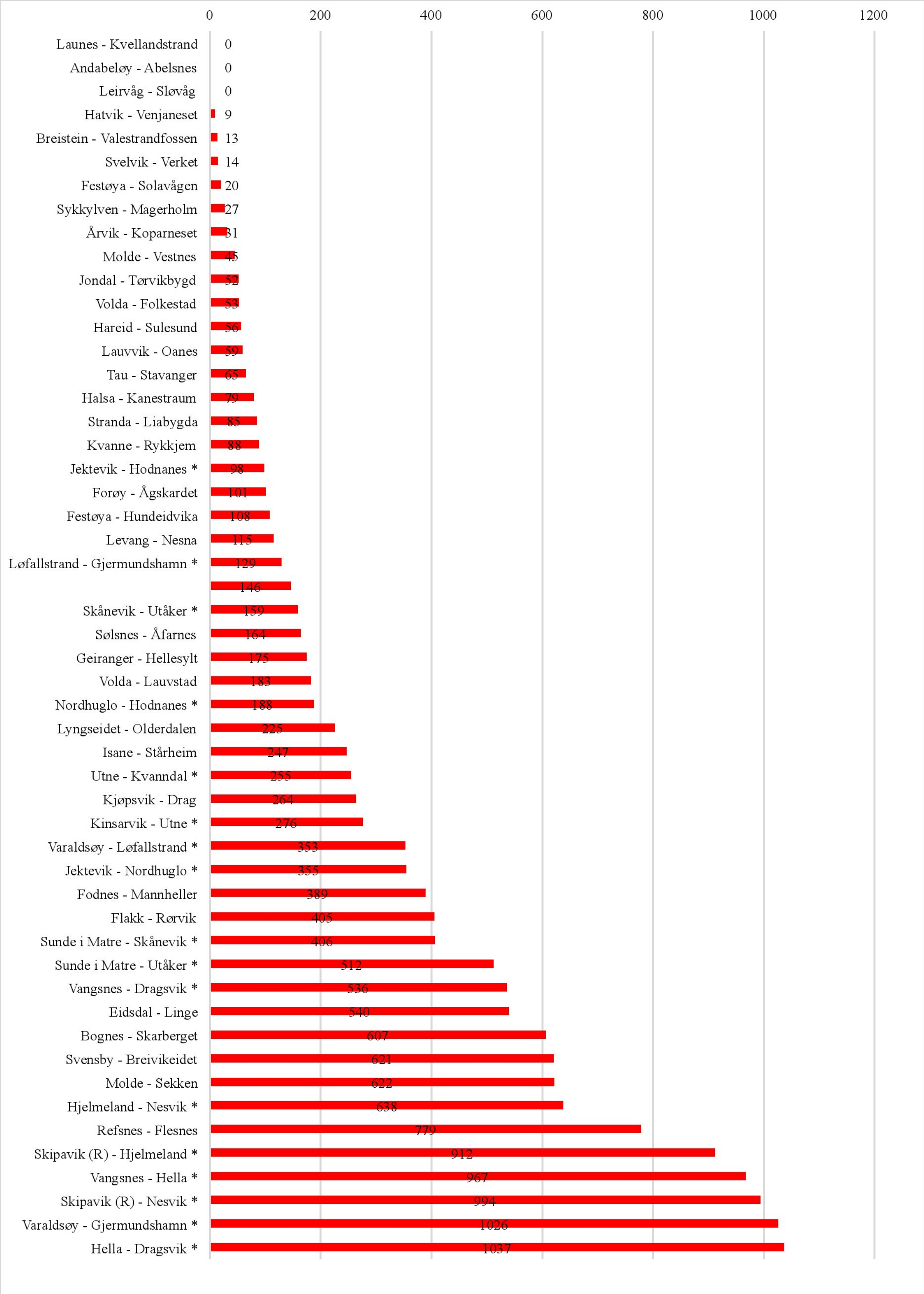

Figure 11: Benefit-costs (NOK/tonnes CO_2) for CO_2 reduction by electrification of the ferry quays (DNV GL, 2015)

Figure 12: Joint benefit-costs for the ferries and the ferry quays

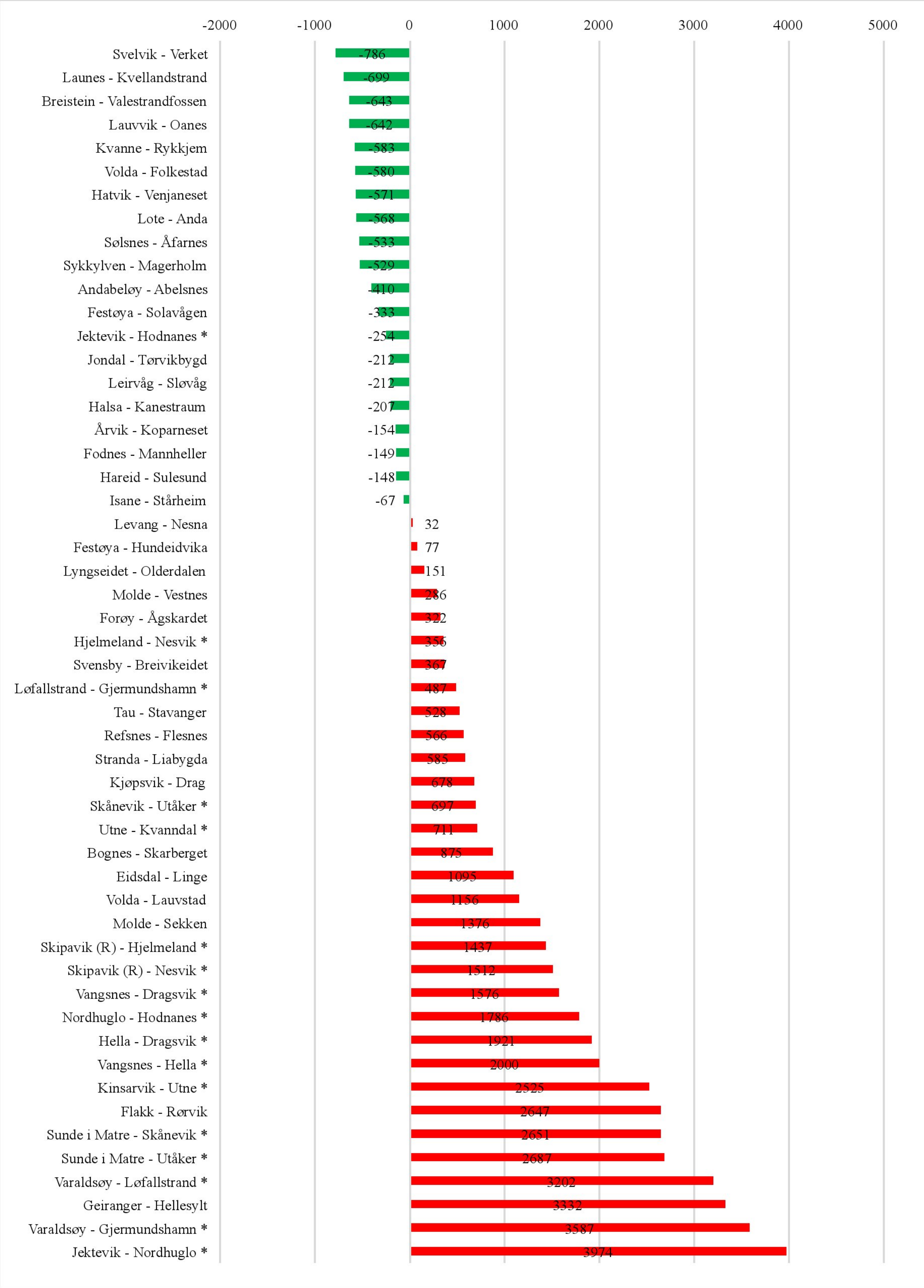

Figure 12: Joint benefit-costs (NOK/tonnes CO_2) for CO_2 reduction by electrification of both the ferries and the ferry quays (DNV GL, 2015)

Investment needs in the power grid

On March 25th 2015 the Government agreed upon a commitment to reduce emissions by 40% in Norway for the year 2030 compared to the year 1990. The biggest issues are the emission of greenhouse gases from the transport sector. Ferry routes, which are an important part of the Norwegian transport, are the largest contributors for the emissions from ships in Norway. There are 270 ferries on about 440 ferry routes in over 160 individual connections that belong to the county and national road networks. Many of the ferries in routes are old (Figure 13) and fit to be replaced by new vessels. This is a good opportunity to phase in more all-electrical ferries. These routes vary from place to place; some are simple trips from one port to another, but others are by many different ports, with different plans. All the ferry routes in Norway could be adequate for electric operation, either as all-electric operation or as hybrid solutions. (DNV GL, 2015)

Figure 13: Age distribution for ferries

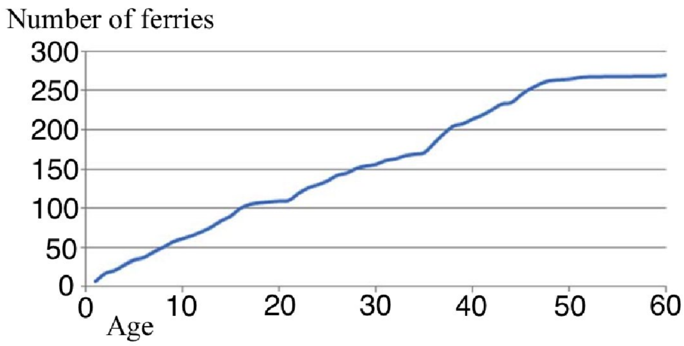

Figure 13: Accumulated age distribution for Norwegian car ferries (DNV GL, 2015)

Discussion

Wärtsilä's New Ferry Concept

Figure 14: Induction unit

Figure 14: Wärtsilä's new induction unit (Stensvold, 2016)

Induction charging

Wärtsilä Ship Design has developed a new ferry concept that is ideal for the Norwegian fjords. The innovation of this project is inductive charging, which is also known as wireless charging. This is already a known technology used on buses, trams and even mobile phones. It will be made as a joint system with vacuum based mooring that is used on "Ampere". The charger (Figure 14), which will be the size of a door, starts when the vessel is 0.5 meters from the mooring unit. It charges with a force of 1 MW and connects using four suction cups with a retaining power of 20 tonnes. This technology assures more efficient charging during the short time the vessel lies alongside the quay, which preferably is no longer than ten minutes, and less wear an tear than mechanical connections. This also assures higher safety, as there are no ropes or cables. This technology will be suitable for routes of about 5 km with a loading/discharging time of ten minutes, which includes all the routes which has been considered, by the environmental foundation Bellona, for all-electric operation. (Stensvold, 2016)

The electric effect is transferred through a fluctuating magnetic field made by current in a coil. A recipient coil uses the effect so it can be transferred to the batteries.

Wärtsilä designs the hull and other structural design in addition to the electric operated propulsion system, azimuth propellers and also automation and control system (Stensvold, 2016). In the designing process it is focused on high energy-efficiency and low resistance all over the hull. The company's rotary propeller installation and bridge system are also integrated (Wärtsilä, 2016).

According to Wärtsilä the first ferry of this new concept are supposed to be in operation on the route Anda-Lote in January 2019, which requires a ferry capacity of 100 cars and 349 passengers and crewmembers.

The project has been presented for the four largest ferry companies, and three companies have shown interest in the project and made tenders. Fjord1 made the lowest tender of 826 million NOK for ten years operation (Stensvold, 2016). In evaluating the tenders, the price counts 80% and the ferries energy and environmental efficiency counts 20% (Haakonsen, 2016).

Battery-Hybrid

Low-emission ferries have been a future priority for the companies. There are plans for both zero-emission ferries and ferries with hybrid solutions, which causes minimum emission compared to diesel-electric operation. This is not just the conventional hybrid solution, but motors fuelled by biofuel or LNG will replace the diesel motors in combination with batteries. The conventional hybrid solution usually has batteries and diesel motors, but this new concept will use the motors fuelled by biofuel or LNG as a second choice. The battery pack will be the main power source and the combustion engine will be a small backup generator.

The second ferry planned to operate the Anda-Lote route must follow the requirement made by the Norwegian Public Road Administration that the second ferry must be able to go continuous for 12 hours with as low emission as possible. To meet these requirements the ferry will use a generator engine fuelled by biofuel to charge the batteries in transit.

With this technology low- and zero-emission ferries can operate more routes than anticipated, and the segment between 60 and 120 cars are the first prioritized routes. (Stensvold, 2016)

The following ferry routes have a passage time of more than 35 minutes and are considered by Siemens as adequate for hybrid solutions:

Askvoll – Gjervik

Belvik – Vengsøy

Bodø – Moskenes

Bodø – Værøy

Bognes – Lødingen

Dagsvik – Mosjøen

Drag – Kjøpsvik

Finnøya – Sandøya

Frøyasambandet

Geiranger – Hellesylt

Halhjem – Sandvikvåg

Hansnes – Skåningsbukt

Horn – Igerøy

Horsdal – Sund

Igerøy – Tjøtta

Kaljord – Hanøy

Kilboghamn – Jektvik

Kinsarvik – Kvanndal

Krakhella – Rysjedalsvika

Lyngseidet – Olderdalen

Molde – Sekken

Nesna – Nesnaøyene

Nordnesøy – Kilboghamn

Onøyan – Stokkvågen

Ranavik – Skjersholmane

Skjeltene – Haramsøya

Stangnes – Sørrolnes

Søvik – Herøy

Tjøtta – Forvik

Øksfjord – Bergsfjord

Øksfjord – Hasvik

Ørnes – Meløysund

(Stensvold, 2015c)

Ambitions for Emission Savings

Enova, an enterprise owned by the Norwegian Oil and Energy Department, has decided to invest 133.6 million NOK in Hordaland County's new technology project for zero-emission ferries. The money will be used to develop and build land based power grids for the charging of battery-powered ferries (Sado & Moe, 2016). "Ampere" is now the only battery-powered car ferry, but the ambition is to replace all of the combustion motors in ferries in Norway with either all-electrical systems or hybrid solutions. Replacing all the ferries to electrical or hybrid solutions will cost about 3.5 billion NOK, but since electricity is more efficient than diesel, we will save about 700 million NOK per year in operation costs, according to Siemens and Bellona. The investment will be paid down within five years. Siemens and Bellona also report that 70% of the Norwegian ferry routes are suitable for electrical operation. The longest routes should have hybrid solutions, but most of the routes that have a passage time of less than 40 minutes are suitable for all-electrical operation. Sigurd Enge from the environment foundation Bellona says that 84 ferries in Norway are suitable for all-electrical operation, and 43 are suitable for hybrid solutions. This will reduce

CO_2 emissions by 300,000 tonnes per year, which is about the same as 150,000 cars (Høyberg, 2015). According to recent studies from Siemens and Bellona the electrical consumption of these 84 ferries can be delivered from the annual production from 24 wind turbines. The annual savings of diesel consumption from 84 ferries are equal to an interconnecting tanker truck convoy from The Norwegian Parliament to Gardermoen Airport. Electrification of ferries may also be the county administration's most economical measures for the upcoming years.

To reduce emissions by 30 % within the year 2030, which is promised by the Norwegian Government, there are three obtainable solutions:

1. "*A national ferry settlement that specifies the path to a ferry fleet only powered by wind and hydropower from shore*." (Moen & Hauge, 2015) There must be built more than one all-electrical ferry every three years to keep up the interest, and for the market participants to be sure of the safety of investing time and resources in contending for new contracts. If the Government set their minds to it, Norway can easily increase the number of electrical ferries from 1 to 100 in a matter of a few years. The ferry companies must be given framework conditions for long-term thinking.

2. "*Requirements for configuration and environment must be standardized.*" (Moen & Hauge, 2015) There should be standard requirements for the charging systems and quay installations. This makes it easier to impliment the new installations all over the country. The counties and the Directorate of Public Roads must follow consistent requirements, agendas and objectives.

3. "*The Government must help county administrations with the first additional investment.*" (Moen & Hauge, 2015) If the Government does not subsidise to the investments that the county administrations have to make, they might not make it past the first additional

costs of the investments. They need initial support from the Government built adequate public infrastructure to make it in the long run.

(Moen & Hauge, 2015)

Ferry-less highway

For some time now, the counties in West Norway have been planning a four-lane highway from Kristiansand to Trondheim that does not include ferries. This could, over a period of 40 years, increase emission by 10 percent. It would cost about 340 billion NOK and the number is still increasing. To finance this the road tolls from Kristiansand to Trondheim will be about 3,700 NOK. The ferry tolls for the same distance is now 840 NOK. If we are to meet the Governments plans for zero-emission within 2050 the plans for a ferry-less highway on the entire southwest and west coast needs to be stopped. If the Government has reserved a budget for this plan it needs to be changed to benefit the project for zero-emission ferries. (Michelsen, 2016)

The NOx-fund

The NOx-fund's primary objective is to reduce emissions of nitrogen oxides. The environmental agreement of NOx 2011 - 2017 that was signed by the 15 founding business organizations and the Ministry of Environment constitute the scope for the work in the NOx-fund. The fund gives economic support to companies that take measures in reducing emissions of NOx, and they have an annual availability of 600 million NOK for these purposes. The organizations agree on charge exemption as long as the agreed upon reductions of NOx is obtained. Instead of paying a Government charge, the operators pay a lower rate to the NOx-fund, which then supports emission reduction measures. (Hirth, 2016)

The NOx-fund supports battery operation

The NOx-fund adapts for more investments in battery technology, either for hybrid solutions or for all-electric operation. When the companies use battery technology the support increase from 300 NOK to 500 NOK per reduced kg NOx, but not more than 80% of the additional expenses. This is one of many factors that prove both the economic and the environmental advantage of battery technology.

A battery pack for the installations cost from $1,000 to $1,500 per kWh, but Tesla has recently produced a battery pack called Powerpack that cost only $250 per kWh (Haram, 2016). In the near future batteries will be so cheap that support from the NOx-fund will cover about 80% of the total cost of a battery pack. This will be a reality within three years. In addition to this, the Government has removed most of the treatment fee for the land grid. (Haram, 2016)

Example of a small diesel-operated cargo vessel:

Engine:	Diesel consumption:	NOx-emission:	7,000 h/year:
1,000kW	172kg/h	8.3kg/h	58,000kg NOx

(Haram, 2016)

If the oil price is $500 per tonnes, the diesel consumption is 172kg per hour. The oil price has been very low the last year, and was $270/tonnes in January, but we must assume that it will increase, and then electric operated vessels can compete economically with diesel-operated vessels. (Haram, 2016)

If the same vessel is re-built as an all-electric operated vessel and we assume that the support has increased to 500 NOK per reduced kg NOx the support will be 29 million NOK per year. When we then assume that the travel time is ten hours the vessel needs a battery pack of 10,000 kWh. Then, if the vessel also is installed with the Tesla PowerPack with a price of $250/kWh for the installed battery, it is equivalent to an investment of 22 million NOK, which is a lot lower than the possible support from the NOx-fund for reduced emission of NOx. In this case the amount of support will be set at 80%, this lowers the price of the battery pack to four-five million NOK. Further on, if we assume that the battery is charged 10,000 times during its lifetime the cost is equivalent to 0.05 NOK per kWh. In addition to that there are the electricity rate, network tariff and the battery's loss in time. All this gives a cost of 0.60-0.80 NOK per kWh transferred from the battery pack to the propulsion. (Haram, 2016)

These calculations are based on a cargo ship on a route of 100 nautical miles, which is the distance between Stavanger and Bergen. (Haram, 2016)

The increasing support from the NOx-fund has increased the ferry companies' interest in battery-operated ferries. By January 2016 the NOx-fund had received 13 applications for electrification of vessels. Up until then they had given support to six-seven of these vessels during the fund's existence. Of these 13 vessels, five are for all-electric newbuilds, and the remaining eight are for the re-building of existing diesel-electric propulsion to hybrid solutions. (Hirth, 2016)

Energy efficiency improvement

The Government recently decided to implement measures for securing that all the county administrations uses low- and zero-emission technology for the new tenders on their own routes, which will increase in the near future. There are now 119 county and national ferry routes in Norway and many of these routes are being re-announced for new tenders. Without including the support from the NOx-fund, the extra cost for electrification of all the ferries that Bellona and Siemens suggested built as electrical ferries earlier this year would be estimated to about 3.5 billion NOK, compared to new diesel-operated ferries. (Hirth, 2015)

Revised Government budget

The Government has reserved 65 million NOK in the national budget for 2016 for electrical ferries and other green shipping. This was announced on May 10th 2016. The objective is to strengthen the commitment for environmental friendly technology in the Norwegian shipping, especially ferries.

Conclusion

Battery-operated ferries can replace the majority of diesel-operated ferries in Norway if the Government complete their commitment to reduce the emission from the Norwegian transport sector. The goal is proximate zero emission within the year 2050.

All the routes in Norway that have a passage time of less than 30 minutes can be operated by all-electrical ferries. The routes with a passage time of more than 30 minutes should be considered for hybrid solutions; with preferably electrical motors supported by motors fuelled by LNG or biofuel. Based on my findings battery-operated ferries is not more energy efficient than diesel electric ferries, with today’s battery technology. There is plenty of research on battery technology being done these days because of the high focus on green technology. With the development of modern battery technology, battery-operated ferries will probably be more energy efficient in the years to come.

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