

R&D-project

Battery/fuel cell fast ferry



Trondheim/Sandtorg

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Summary

This report commissioned by the NOx Fund have estimated total diesel consumption for all scheduled fast ferries in Norway, and explored opportunities for low and zero-emission operation.

Today all fast ferries in Norway have propulsion systems based on fossil fuels. The report finds that in 2015, the fast ferry sector used 86.4 million liters of diesel, about 1% of Norway's total consumption of petroleum products.

Through a case study of two routes, Trondheim Vanvikan and Trondheim Brekstad, the research finds that a technology shift in the fast ferry sector, is possible. On shorter distances, where it is possible to charge frequently, the study shows that a battery hybrid solution is technically feasible and can provide ship owner big savings in operating costs and greenhouse gas emissions. When it is technologically possible, batteries are preferred over fuel cell / hydrogen, because it is cheaper and more cost saving. With longer distances and increased energy demand, the study shows that hydrogen and fuel cells may be technically feasible. The development of hydrogen production and fuel cell technology will play a significant role for a technology shift in the fast ferry sector. Hydrogen is as a fuel, 4 times lighter than diesel (per kW to propeller), and fuel cells are lighter, or as light as, internal combustion engine.

The report concludes that from a technological standpoint, the entire sector can become zero emission in 2022. The way forward will require close cooperation between the supplier industry and customers. The report provides further suggestions about the extent of this interaction.

We would like to thank the NOx-fund for letting us conduct this study.

We also thank all who have contributed data and ideas in the process. Special thanks to AS Øra, IFE / Bluecraft, Samferdselssjefen in Sør-Trøndelag, AtB, Ruter, Sjøfartsdirektoratet and Fosen Namsos Sjø.

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2 IMPORTANT CONCEPTS AND DENOMINATIONS

Amp	Ampere, unit of flow rate
BMS	Battery Management System – Software to monitor the condition of the batteries and controls the cooling system etc.
Fuel cell	An electrochemical cell that supplies direct current (in this context) hydrogen, by allowing it to react with oxygen. The fuel cell operates electric motor. The fuel cell is like a battery that continuously filled with chemically bound energy.
Cell	The smallest unit in the battery, where the electrochemical conversion takes place.
Cycle life	Number of charge and discharge cycles which battery can have before it can't perform as it should. Cycle life is determined by the specific charge and discharge conditions. The battery life will be influenced by the c-rate and depth of cycles as well as conditions such as temperature and humidity.
C- rate	C-ratio is a measure of how much power the battery can be charged or discharged with respect to the total battery capacity. If, for example you charge with 1C, you charge with an effect that makes the whole battery be discharged in one hour. For a battery with a capacity of 100Amp hours it will correspond to a discharge power of 100 amps. A high C-rate means in practice that one can have a higher performance and faster charging.
DC	"Direct current" Power to go in only one direction. Batteries may only be charged with DC.
DOD	"Depth of Discharge" - shows how much of the capacity of the battery used before it must be recharged. Battery Suppliers with NMC chemistry will usually never recommend more than 80% DOD, and this means that the battery should never be drained more than 80% of the total capacity. This can be very important for battery life
Diesel-electric	The diesel engine is connected to a generator that produces electricity for an electric motor.
Diesel-mechanic	Diesel engine mechanically coupled to a propeller via clutch.
EOL	End of life, Estimated maximum life span of a battery
Hydrogen (H₂)	The lightest element, which acts as an energy carrier.
IP (Intellectual Property)	Generic term for legal protection of intellectual property.
Catamaran	Boat with two relatively slim hull, and is the most common type of high-speed craft. Provides excellent stability at high speeds.
kW	Effect

kWh	A kilowatt-hour is the amount of energy which corresponds to a power consumption of one kilowatt over a one hour period.
Load/load profile	Load means how much energy is being used, and load profile shows the variation in load at different times.
Hovercraft	Use overpressure to create an air cushion under the hull. Large parts of the vessel is lifted above the water, which reduces friction with the water and minimizes energy losses
NMC	Lithium ion, nickel - manganese - cobalt chemistry used in most providers for marine applications.
Peak shaving	Cargo of a vessel is not always smooth, and sometimes will require more energy and others less. The batteries can keep the load stable on the combustion engine and provide additional capacity and smooth the spikes in load. This saves energy and causes less engine wear.
PAX	Passenger Capacity
PMS	Power Management System
Cycle	One charge and discharge of the battery.
Volt	Unit of electrical potential
Parallel hybrid	The diesel engine and batteries are interchangeable in the driveline.
Series hybrid	In a series hybrid, only the electric motor is used and the energy coming directly from the battery or from a diesel generator.

3 FAST FERRIES IN COMMERCIAL TRAFFIC

3.1 High speed Light Craft (HSLC)

Fast ferries are a category of passenger boats that are characterized by having a speed of at least 20 knots, and has a requirement for passenger capacity of more than 12.

«Hurtigbåtenes Rederiforbund» defines a speedboat as: "A vessel as defined in the 1974 SOLAS Convention Chapter X. Vessels with lower speed than 20 knots are not considered as high-speed craft. For vessels under 50 GT requires a passenger certificate.

3.2 Energy consumption for fast ferries

Generally, high speeds consume a great amount of energy, relative to slow-moving vessels. Modern fast ferries are built from lightweight materials and can go at high speeds. Materials in carbon is common to minimize the weight of the vessel. Fast ferries tend to have a hull design that allows the boat to deadrise, to minimize water resistance. This is positive for reducing energy demand at high speeds, but factors such as air and wave resistance plays a greater role in energy consumption.

Even though the fuel consumption of many fast ferries has been reduced significantly in recent years, especially when using lighter construction materials, fast ferries remains one of the most energy-intensive transportation means per passenger-km. The table below clearly shows how energy intensive passenger fast ferries are, compared to other methods of transportation.

Tabell 2.33. Energiforbruk for innenlandsk persontransport. Energiforbruk per passasjerkm, for personbiler, motorsykler og mopeder er energiforbruket per personkm. MJ/pkm. 1994 (1993 for sjøfart), 1998 (2000 for T-bane og sporvogn) og 2004 (2005 for rutebusser)

	1994	1998	2004
Personbiler - bensin	1,528	1,501	1,449
Personbiler – diesel	1,211	1,167	1,111
Drosjer	2,855	2,646	2,332
Motorsykler	1,328	1,334	1,324
Mopeder	0,827	0,827	0,827
Rutebusser	0,981	0,850	0,840
Jernbane - elektrisk		0,566	0,630
Jernbane - diesel		1,011	1,073
T-bane		0,631	0,685
Sporvogn		0,798	0,736
Rutefly	2,620	2,789	2,745
Bilferger	1,565	1,251	1,245
Hurtigbåter	5,496	6,891	13,226 ¹
Hurtigruten	1,321	1,328	1,599

¹ Det foreligger ikke tall for hurtigbåtenes godstransportarbeid for 2004 og hele energiforbruket går derfor til persontransportarbeid

3.2.1 Power requirements for fast ferries

Below is an analysis of the power requirement for different types of vessels and the power needed for each of them, to illustrate the significant difference in terms of power requirement to reach the vessel's service speed. "Big one" are typical large ferries such as the "Ladejarl" that serviced the Trondheim- Kristiansund route before Terningen took over. The power requirement for Hurtigruten is an estimate as these figures are not publicly available. It is more than twice as large power requirement for Trondheimsfjord2, and three times as large for Trondheimsfjord1 compared to Ampere. This illustrates the relatively large difference between a regular ferry and a fast ferry, and challenges related to low- and zero-emission technology on fast ferries. It also shows that if the technology challenge in the speedboat sector is solved, this can be transferred to the new maritime sectors that have so far no low emission and zero-emission solutions available. This applies especially regarding hydrogen and fuel cell technology.

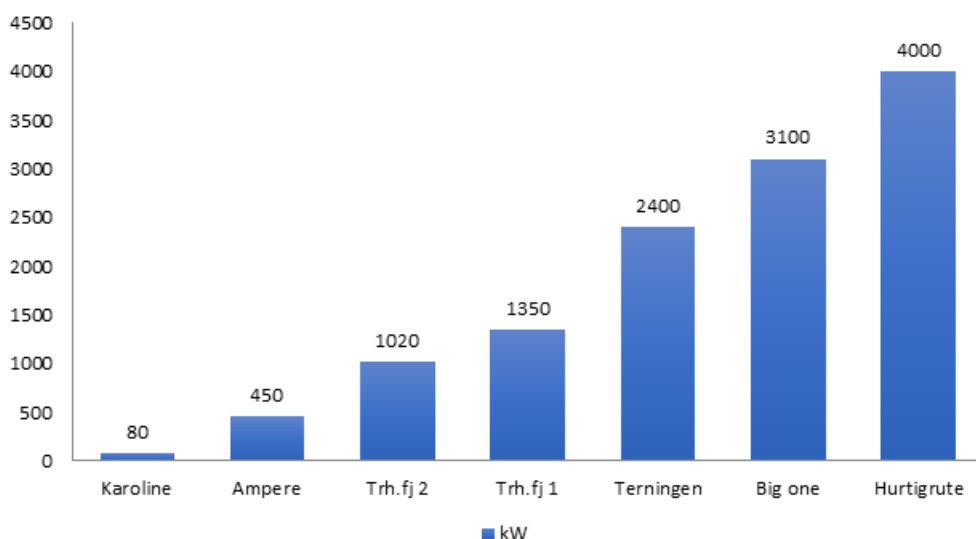


Figure 1 The power requirement for different types of vessels to reach the vessel's service speed

3.3 Licencing and political decisions

Licensing are governed by Yrkestransportlova (Occupational Transportation Act). Vegdirektoratet (Norwegian road directorate) is permit authority on highway ferries and the county is permit authority on other lines. Operators of express routes are determined by competitive bidding.

3.3.1 Political decisions

In 2013, the Norwegian parliament requested the Government that it should;

Require that all new government vehicles, and all new taxis, ferries, ferry boats and trains, use low- or zero-emission technology when it is technologically possible.

Furthermore, these decisions in the budget compromise of 01/12-2015;

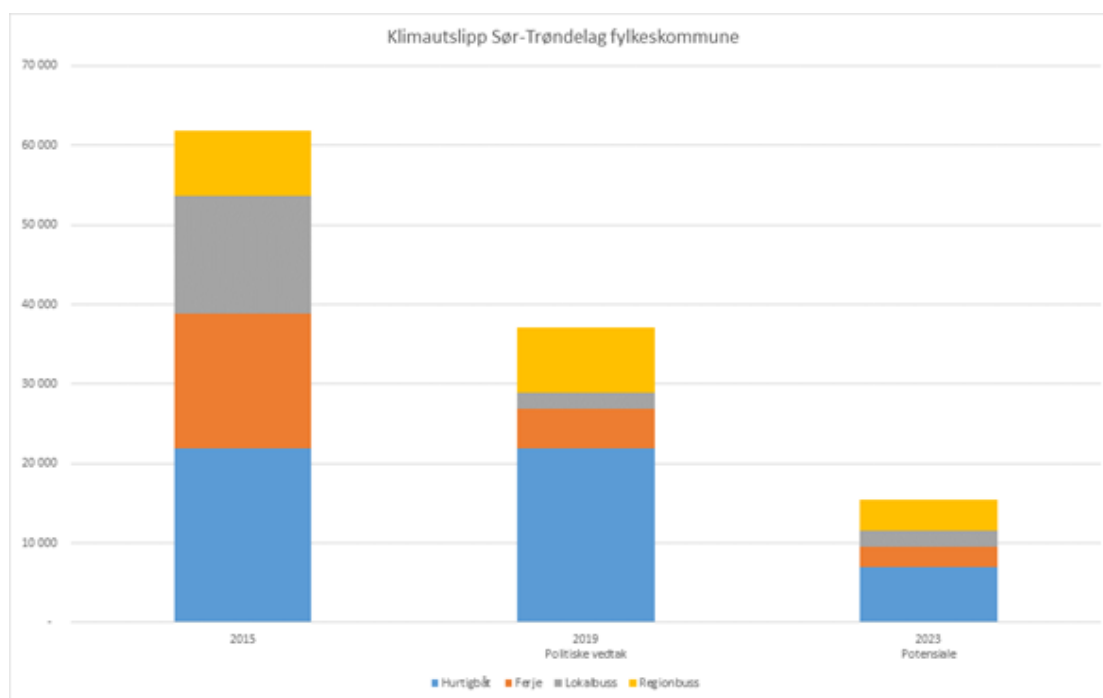
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| Resolution 54 | Parliament asks the Government to consider whether it is necessary to introduce separate schemes targeting counties or further strengthen existing arrangements for the use of new technologies in public tenders, and requests the government to return to Parliament with the assessment of the revised national budget. |
| Resolution 55 | Parliament asks the government to ensure there are strict requirements for noise and NOX and particle emissions in the tendering processes. |
| Resolution 56 | Parliament asks the government to ensure that the development of new and immature technology for emissions reductions in shipping, focus is given in the preparation of a new agreement and a mandate for Enova. |
| Resolution 59 | Parliament asks the government to act to ensure that all county and municipal ferries and speedboats using low- or zero-emission technologies by new contracts and the already existing routes. |
| Resolution 60 | Parliament asks the Government to consider whether it is appropriate to abolish the limit of 400 tons for vessels that have low electrical fee, and return it to Parliament for further consideration. |

In the state budget for 2017 they have considered that the expenditure on the purchase of highway ferry services increases, partly because of environmental requirements in tenders.

Furthermore, the Government proposes in the state budget for 2017;

... To increase the overall rate of the CO₂ tax on mineral oil and tax on greenhouse gases HFCs and PFCs. Both the rates will now, in line with the recommendation from the Green Tax Commission, reach the same level as the CO₂ tax on petrol and diesel fuel, measured in NOK per ton of CO₂ equivalent.

The figure below shows the emissions from public transport in Sør-Trøndelag in 2015, and illustrates the large proportion speedboat takes - even with only six vessels. Column No. 2 demonstrates the effect of specific tenders will have on greenhouse gas emissions, and the last column demonstrates the potential they have, based on their own estimates.



Figur Klimautslipp fra kollektivtrafikken i Sør-Trøndelag i 2015. Kilde: Sør Trøndelag Fylkeskommune

Source: Sør Trøndelag County Council

3.4 Completed projects and experiences

It has already been carried out several projects with battery operation, and there are empirical data proving that battery operation (primarily) works, is profitable for ship owners, improve the working environment and reduce greenhouse gas emissions. There currently are 17 ferries in order with low emissions and zero-emission technology, all based on use of batteries for energy storage. There are both new construction and remodeling that are included in these 17 ferries. It is also expected that it will be commissioned a substantial number of electric ferries beyond these in the years ahead. In Norway there is no vessel operated with hydrogen and fuel cell, either in the ferry sector or on other vessels.

Three examples of successful full and partial electrification of different vessels is battery ferry Ampere, fishing boat Karoline and hybrid passenger boat, Vision of the Fjords.

3.4.1 Ampere

Ampere is the world's first all-electric ferry and operate the route Lavik-Oppedal. The ferry came as a result of a development contract advertised by the Public Roads Administration in 2011, where it was set stricter standards for emissions and fuel consumption (at least 20% reduction). Norled won the tender with an electrical solution, which according to NPRA beat competitors on both economic and environmental parameters. In 2015 the ferry launched with drivetrain from Siemens and batteries from Corvus. After a year in operation, the "fuel costs" according to Norled have been reduced by 80%. Greenhouse gas emissions have been reduced by almost 100%.

Ship owner	Norled
Wharf	Fjellstrand
Length	80,8m
PAX	360
Effect	450 kW
Battery capacity	1 MWh
Speed	10-12 knots
Crossing	20 min
Energy pr crossing	150 kWh
Calls pr day	34

3.4.2 MK Karoline (Selfa El-Max 1099)

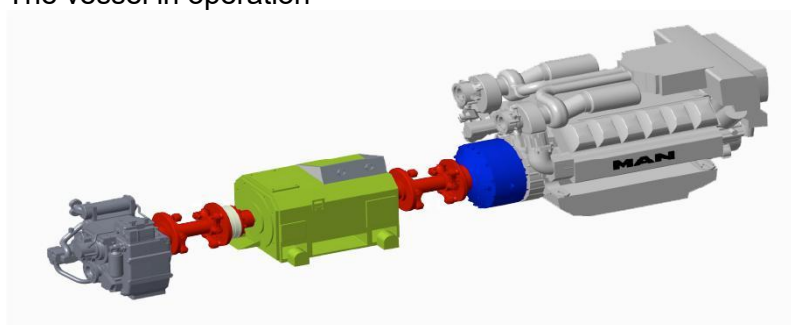
MK Karoline was in 2015, the world's first hybrid-electric coastal fishing boat. The boat came as a result of conscious investment in climate-friendly production and products by Selfa Arctic AS. The powertrain are supplied by Siemens, and the battery pack are from Corvus. The fishing boat has now sailed in one and a half years without interruptions, and feedback from the owner is that the working environment has been significantly improved as a result of electrification. Operating data is logged and reported in a research project which also MAROFF and FHF contribute to. Operating data and operational experience from Karoline has been important to see in practice how battery-electric propulsion works, and to further develop the technical aspects of the vessel. MK Karoline, will in 2017 get installed fuel cell and hydrogen tank to replace the diesel generator.

Ship owner	Øra AS (Bent Gabrielsen)
Wharf	Selfa Arctic
Length	10,99 m
Effect	80 kW
Battery capacity	195 kWh
Speed	8,3 knots

3.4.3 Vision of the Fjords



The vessel in operation



Parallel hybrid propulsion solution provided by Mancraft AS Bergen

This vessel was delivered in July 2016. The vessel goes zero emission at 8 knots in the UNESCO protected area called Nærøyfjord. The distance is 8 nm. The vessel goes on combustion engine "full discharge" in 19.9 knots the rest of the stretch-which also is 8 nm. The vessel was authorized by the Norwegian Maritime Directorate in July 2016. Operating experience so far has been very good, and the company plans to build new vessels for delivery in July, with zero-emission solution.

Ship owner	The Fjords
Wharf	Brødrene AA
Length	40m
Effect, kw on electric motor	300 kW
Battery capacity	600 kWh
Speed, full throttle	19,9 knop

3.5 Electric propulsion

3.5.1 *General*

Battery-electric vessel is particularly suitable for operation with large variations in load, since batteries are more suited to the top and bottom points in the output compared with diesel (mechanical and electrical) motors. Passenger boats like ferries and fast ferries goes into this category since they often maneuver, accelerating and stopping during operation time. In addition to a suitable load profile, are also passenger boats frequently docked and with the access to power and recharging from the land between each trip they take.

In addition to environmental and economic benefits, the battery operation is positive for passengers and operators. Battery operation leads to less noise and vibration, and improve air quality in the port area.

3.5.2 *Maintenance*

The electric motor has significantly fewer "loose" parts than a conventional diesel engine. This reduces engine wear and require less maintenance. Depending on engine type and operating profile, fast shipping companies often carry out annual maintenance / repair of diesel engines. AtB for instance state that they calculate 2.8 million a year on maintenance of Trondheimsfjord 2. Motors to Trondheimsfjord 2 must also be replaced after 6000-8000 hours of operation which represent a significant cost.

3.5.3 *Charging systems*

Charging the battery is an important part of the total battery solution and possibilities for recharging may vary from county to county and port to port. Electrical providers play an important role in the electrification of ships, and it will place greater demands on network capacity in port areas than is often available today. The passenger boats have a timetable to keep, which makes it desirable to charge as soon as possible. High voltage power grids make that enough power can be supplied to the charging system for rapid charging. Possible solutions are to expand network capacity with transformer stations that can deliver 690 volts.

Another solution to compensate for insufficient network capacity is to use battery banks on land. This means that the network can recharge at low power, which do not harm the net too much, when the boat is running. When the boat arrives at the quay, the batteries will take out enough amount of energy with higher power for shorter time than the net powers. Battery banks on land is a solution that has proven to work for ferries like Ampere.

3.5.4 *Charging onboard*

Diesel Generator can generate electricity to charge the batteries while the vessel is in operation. This can be a favorable solution for vessels and operating profiles that make batteries insufficient in supplying enough energy to needed effect. A diesel generator may also compensate for insufficient network capacity in the port area in which the vessel operates. In the future, the diesel generator is replaced by the fuel cell and hydrogen.

3.5.5 Cost of battery-electrification

The investment costs related to the electrification of the vessels are relatively high compared to traditional fossil solutions. This is associated with high battery prices. The cost figures for battery also varies, depending on the chemistry and cell supplier the battery manufacturer's use. Price per kWh for lithium-ion batteries NMC is of from 500-700 USD as of December 2016. With volume production, and increased energy density, these prices are expected to fall in coming years. Operating costs for the battery-electric operation is significantly lower, since electricity is cheaper than fossil fuels.

Energy density of different energy carriers

The figure below shows the energy density of different fuels. It gives an indication of the low amount of energy per kg batteries compared to diesel, and illustrates the challenge with battery-electric operating speed craft where weight is essential. Considering weight makes hydrogen more advantageous for speedboats than diesel and battery.

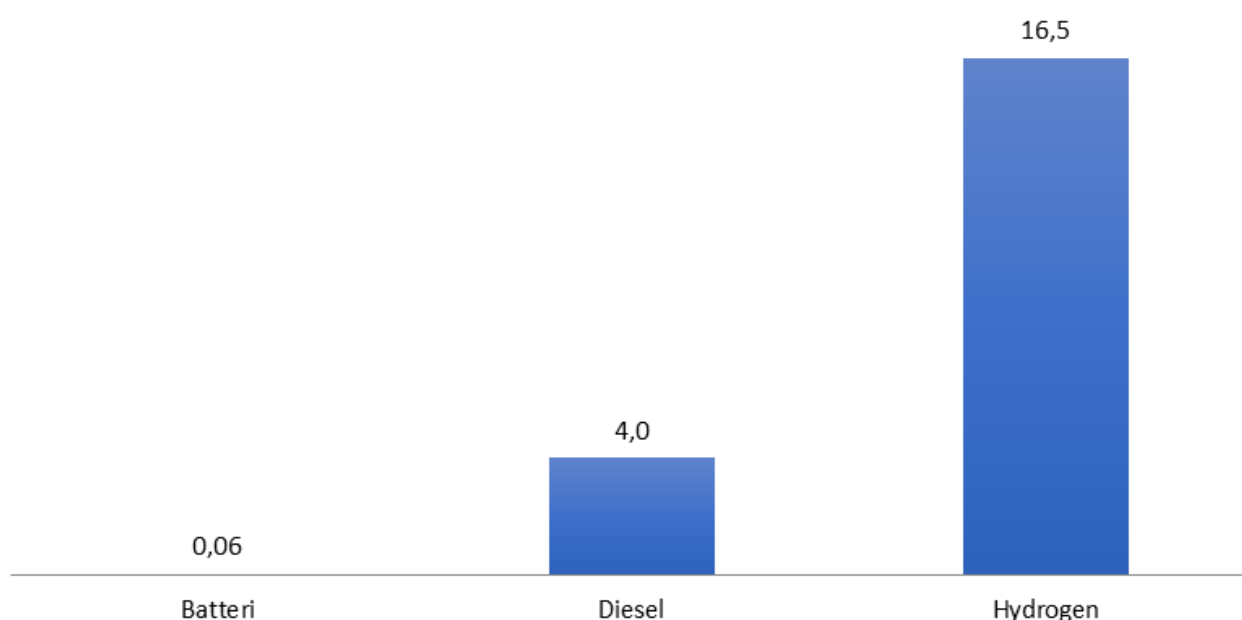


Figure: Energy flow in kWh per kg energy carrier. Note: This is the amount of energy supplied to the gear and shaft in the propulsion system.

Energy amount per ton energy carrier will then be:

Battery	60 kWh
Diesel	4 000 kWh
Hydrogen	16 500 kWh

3.6 Hydrogen and fuel cell

Hydrogen can be produced with renewable energy sources, and thus represents an energy carrier that can be completely emission free. Hydrogen appears immature compared to battery technology when used in maritime applications. Technically, there are some factors with hydrogen operation at sea, which is difficult to assess due to lack of testing. For example, uncertainty about whether various salts in the air can have an impact on the processes in the fuel cell. Filling and other factors related to the use of hydrogen also needs research and practical testing. Limited regulatory framework and class standards are factors to be taken into account in the development of hydrogen and fuel cells in boats.

The fuel cell has an efficiency of about 50%. The energy loss adds warmth, and can be partially used for heating the vessel.

The technology to produce hydrogen is known and there are currently major players such as NEL which are specialized in this. Fuel cell technology is however not mature in the maritime sector. This means that the first maritime projects will be prototypes, where the technology for the first time being tested with Norwegian suppliers. Development of prototypes and approval work, will according to suppliers incur significant costs. The price of hydrogen is also currently relatively expensive compared to electricity from the grid and conventional fuels. Pump price of hydrogen from the supplier Uno-X is NOK 90 incl. VAT per kilogram. The price of hydrogen in large quantities is expected to be significantly lower (IFE), and Reinertsen sets to produce hydrogen for 12 NOK / kg. Reinertsen will produce hydrogen from natural gas, in a process where the hydrogen is separated from carbon and carbon in the form of CO₂ is pumped back to the oil reservoir. Also, hydrogen production by electrolysis is expected to be cheaper (IFE). Considering the current development in hydrogen production, we will use 25kr/kg in this analysis.

3.6.1 *Development contract for hydrogen ferries 2017-2021*

Statens Vegvesen (NPRA) shall publish a development contract for hydrogen ferry, and it is expected that a regulatory framework to be developed in the same period as the contract. NPRA reckon that the ferry will be 100MNOK more expensive than a conventional battery Ferry. The first ferry will be in operation in summer 2021 (NPRA, 2016). NPRA has referred to earlier development projects such as LNG and electric ferries, saying that if the technology proves useful in ferry services then they will also follow this technology from the pilot through the early stages and towards commercial product. Norwegian Public Roads Administration has therefore expressed the intention that it will be built several hydrogen ferries than just this prototype. The development contract is central to the overall plan that we put forth in paragraph 7.

4 DIESEL CONSUMPTION I FAST FERRY SECTOR

4.1 Method for calculation of fuel consumption

Due to competitive reasons, most ship operators were not willing to give up diesel consumption for its vessels. Only Routes in Oslo and Sør-Trøndelag County Council gave precise consumption figures. Several counties reported instead a total distance run for their fast ferries in 2015.

Declared total diesel consumption (2015)

Oslo/Akershus

Sør-Trøndelag County Council

Declared total distance traveled (2015)

Finnmark

Nordland

Møre og Romsdal

Sogn og Fjordane

Hordaland

In cases where it was not possible to obtain the distance traveled, it was made a calculation based on charts and route departures. The calculation was done by measuring the distance of the route using nautical charts and counting of the number of route departures a week. Crossings per week, multiplied by 51, which has taken some account of holidays where the boat does not follow the normal route.

Estimated distance traveled by Selfa Arctic

Troms

Nord-Trøndelag

Rogaland

Vestfold

Calculation of fuel consumption/nm

Size of vessels, engine type and service speed was used to make an estimate of how many liters of diesel vessel uses per nautical mile. Overall sailed nautical mile per year, and gallons of diesel fuel per nautical mile, plus a premium of 10% for auxiliary engines, acceleration, handling, heating etc. is then applied to calculate the total diesel consumption. Diesel consumption per nautical mile is an estimate made by professionals on ships machinery, and is a realistic but not exact, calculations. Evaluation of some routes has shown that these estimates are conservative, but approximately correct.

In some cases, express routes operate in several counties. This is not taken into account in the calculation of fuel consumption per county. Fuel consumption will in such cases only be registered in one county.

4.1.1 Emission factor

The emission factors that are assumed are as follows

Gas	Factor	Ratio	Source
CO ₂	3,17	Tonn/tonn	SSB, 2016
SO ₂	1,054	Kg/tonn	SSB, 2016
NO _x	35	Kg/tonn	NOx-fondet, 2016

4.2 Fuel consumption and emissions from fast ferries

Total diesel consumption (liters)	86 480 000
CO₂ emission (ton)	233 000
SO₂ emission (ton)	77
NO_x emission (ton)	2 570
Total cost (MNOK)	475

Price of diesel can vary from one county to another, and from one time to another. Given a price of NOK 5.50 per liter diesel, the total diesel cost for express boats in Norway in 2015, 475 million.

With these numbers as a basis, the fast ferry sector constitutes almost 1% of the total consumption of petroleum products in Norway, which in 2015 was 8.7 billion gallons (SSB, 2016). Electrification of fast ferries in Norway can therefore make a significant contribution to reducing the environmental footprint and reduce operating costs for express industry.

4.2.1 Region distribution 2015

County	Diesel consumption per year
Finnmark	7 030 000
Troms	5 858 000
Nordland	18 315 000
Nord-Trøndelag	781 000
Sør Trøndelag	9 348 000
Møre og Romsdal	6 248 000
Sogn og Fjordane	16 883 000
Hordaland	9 668 000
Rogaland	8 849 000
Vestfold	494 000
Oslo/Akershus	3 005 000
Total consumption	86 480 000

As the report investigates possibilities for low and zero-emission speedboat operation for two different distances, the list below is ranked by distance. We separate routes that are above and below 10 nm.

4.2.2 Route with distance up to 10 nm

	PAX	Knots	distance(nm)	Consumption/ nm (+10% margin)	distance/year	Consumption/ year
Fonna-Evindvik			1,3	5,5	270	1 485
Bulandet - Sandøyna			1,6	5,5	1166	6 413
Oslofergene (Byøyene)			1,7			200 000
Langevåg-Ålesund	97	27	2	2,2	22000	484 000
Espvær-Eidesvik	63	20	2	15,4	8423	129 714
Feøy-Kveitevik	42		2	19,8	7140	141 372
Nesodden-Lysaker			2			318 787
Værlandet - Alden			2,4	5,5	972	5 346
Evenes-Kjeldebotn	31	19	3	8,8	15898	139 902
Kleppestø-Strandkaiaen	180	35	3	33	35907	1 184 931
Nesoddtangen-Aker Brygge			3			1 439 872
Sandviksberget-Sætervik	48	17	4	11	8568	94 248
Sandviksberget-Skjervøy	48	17	4	11	9792	107 712
Hersvik - Saltskår	19	24	4	14,3	14385	205 706
Hellesøy-Hernar	47	24	4	13,2	9989	131 855
Myre-Øksnes-Vestbygd			5	13,2	25470	336 204
Stavanger- Byøyene - Hommersåk	62	29	5	13,2	25500	336 600
Haugesund-Røvær	84	25	5	19,8	30600	605 880
Haugesund-Feøy	40		5	22	17850	392 700
Måløy - Silda	48		5,4	13,2	7775	102 630
Reinefjorden	64		6	13,2	11011	145 345
Nordfold	48	30	6	13,2	8203	108 280

Solfjellsjøen-Vandve	80	26	6	19,8	20126	398 495
Regionpendelen			6	16,5	44188	729 102
Havsøysund-Måsøy	70	25	7	30,8	94322	2 905 118
Beiarfjorden			8	6,6	1991	13 141
Træna lokal	48	19,9	8	16,5	12110	199 815
Trondheim-Vanvikan	130	25	8	13,2	67392	954 089
Vikane-Hisarøy-Evindvik-Dingja-Sollibotn			8,6	5,5	3283	18 057
Knarvik-Frekhaug-Bergen	180	30	9	22	26026	572 572
Flybåten Tønsberg-Husvik	76	26	9	15,4	32130	494 802
Tromsø-Lysnes-Tennskjer-Vikran	147	34	10	24,2	7140	172 788
Hareid-Valderøya-Ålesund	296	34	10	33	94000	3 102 000
Florø - Ronaldsvågen - Kinn - Skorpa (vest)	70	22	10	14,3	30207	431 960
Gåsvær - Hardbakke	28	24	10	11	10691	117 601
Nordeide - Måren - Ortnevik	96	28	10	27,5	34680	953 700
Totalt						17 682 220

4.2.3 Routes with distance over 10 nm

	PAX	Knots	distance(nm)	Consumption/nm (+10% margin)	distance/year	Consumption/ year
Bindalseidet-Harangs fjord	30		11	19,8	28961	573 428
Florø - Fanøy Barekstad (Nord)	52	25	11,3	16,5	34290	565 785
Hadsel	48	25	12	19,8	30948	612 770
Stavanger-Kvitsøy	180	30	12	22	18360	403 920
Aker Brygge-Slemmestad			12			774 354
Meløy	36	19,9	13	13,2	23937	315 968
Hardbakke - Nåra - Mjømna	48	25	13	16,5	9849	162 509
Stavanger-Fisterøyene (combination boat)	85		14	29,7	4284	127 235
Florø - Svanøy - Askrova (south)	81		15,4	19,8	46536	921 413
Eivindvik - Mastrevik	48	28	15,6	13,2	11901	157 093
Skjervøy-Kvæningen og Vorterøy	50	27	16	16,5	21216	350 064
Aker Brygge-Drøbak			16			271 643
Bodø-Væran	195	19,9	17	33	42436	1 400 388
Bodø-Ytre Gildeskål	196	28	17	33	29335	968 055
Hardbakke - Utvær	48	25	17	16,5	6803	112 250
Ortnevik - Vik	96	28	17	27,5	12138	333 795
Rødøy-Melfjordbotn	80	26	21	19,8	8189	162 142
Ålesund-Valderøya-Nordøyane	147	30	21	22	69000	1 518 000
Stavanger-Hjelmeland	180	30	21	22	122094	2 686 068
Tysfjord	48	24	22	19,8	27199	538 540
Gildeskål lokalrute	23	19,9	22	11	14280	157 080

Øksfjord-Holandshamn-Svolvær	32	19,9	24	11	6003	66 033
Sandnessjøen-Austbø-Herøysteder-Vega	146	25	24	19,8	53856	1 066 349
Lille Survik-Sennabukt			25	11	4990	54 890
Sommarøy-Tussøy-Sandnesshamn	12	36	25	11	30600	336 600
Lurøy	48	24	25	19,8	29026	574 715
Alta-Kvalfjord	70	25	27	17,6	27516	484 282
Trondheim-Brekstad	130	33	27	17,6	61965	1 110 637
Hammerfest-Revsneshavn	70	28	28	19,8	66250	1 311 750
Brønnøysund-Stortorgnes	30		28	11	3779	41 569
Dyrøy-Øyrekken	70		28	19,8	102816	2 035 757
Florø - Måløy (not fast ferry?)	70		28	19,8	17408	344 678
Austevoll ruten	47	25	28	13,2	24460	322 872
Øksfjord-Langfjordhamn	70	25	29	16,5	66107	1 090 766
Harstad-Flakstadvåg	126	28	30	22	35190	774 180
Bodø-Helnessund	92	24	30	22	9010	198 220
Stavanger-Lysebotn (combination boat)	85		33	29,7	40392	1 199 642
Flåm – Balestrand	45	24	34	16,5	17340	286 110
Herøyruta	146	25	37	16,5	46510	767 415
Tromsø-Skjervøy	147	34	37,5	16,5	22950	378 675
Brønnøysund-Sandnessjøen + Brønnøysund-Rørøy (Vega)	100	19,9	38	19,8	46335	917 433
Molde-Helland - Vikebuktsekken	147	30	43	22	52000	1 144 000
Stavanger-Ryfylke	85		44	22	134334	2 955 348
Reksteren-Våge-Os	120	27	49	13,2	17279	228 083
Rosendal-Bergen	145	33	49	14,3	79914	1 142 770
Alta-Hammerfest		28	50	17,6	50000	880 000

Norheimsund-Herand-Utne-Kinarsvik-Loftshus-Ulvik-Eidfjord	85	35	53	16,5	25432	419 628
Namsos-Leka og Rørvik	97	25	54,5	13,2	59160	780 912
Trænaruten	196	28	56	33	37744	1 245 552
Bodø-Svolvær	212	33	60	33	58686	1 936 638
Forvik-Vistensteder og Tjøtta-Husvika	48	18	61	16,5	30795	508 118
Tromsø-Harstad	250	35	82	24,2	158916	3 845 767
Bodø-Helgeland	212	33	84	33	38793	1 280 169
School route i Rognsundet Kvalfjord - Pollen	50	28	90	8,8	34403	302 746
Sandnessjøen-Bodø	212	34	92	33	88323	2 914 659
Trondheim-Kristiansund	275	33	95	19,8	174420	3 453 516
Sunnhordaland-Austevoll-Bergen	240	35	95	22	251620	5 535 640
Bergen-Nordfjord	290	35	140	27,5	171360	4 712 400
Sogn-Nordfjord	190	35	140	29,7	71400	2 120 580
Bergen-Sogn-Flåm	290	35	146	27,5	193596	5 323 890
Total	67 205 488					

5 CASE: TRONDHEIM – VANVIKAN (8 NM)

Above we have accounted for the proportion of emissions fast ferries contribute nationally, and described electric propulsion as an opportunity to reduce diesel consumption. We shall in this chapter look at one fast ferry, and the ability to utilize existing technology to reduce emissions in the sector. Moreover, we have together with suppliers looked at how the development of battery technology in the long term affect the estimates made using current technology in terms of cost and reach.

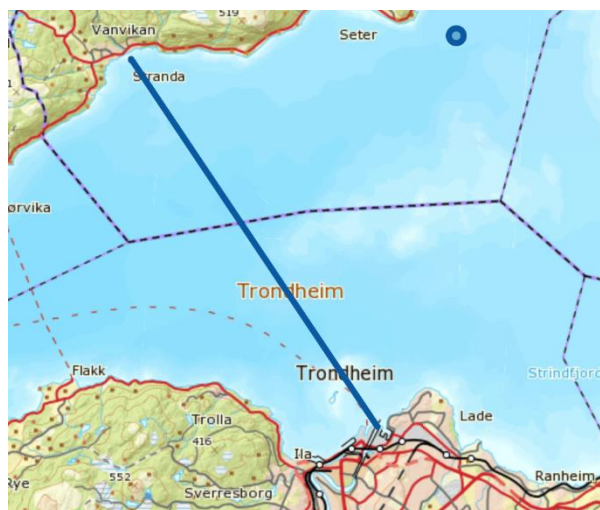
5.1 Introduction

The case study is based on an existing route where we with current technology are looking at the possibility of electrifying fast ferries either wholly or partly. Today's battery has a much lower energy density than diesel, and limitations in relation to the range becomes obvious when the weight is taken into account. We will review the technical solution and energy needs, and look at what solutions one can consider in order to achieve savings in terms of reduced use of diesel.

5.1.1 The Route

Trondheim - Vanvikan is a route in Sør-Trøndelag owned by AtB with 162 departures every week according to the current timetable. The passengers are mainly business traveler between Vanvikan west of the Trondheim Fjord and Trondheim.

Route speed is 25 knots, and the stretch of the Trondheim Fjord is about 8nm. The crossing from quay to quay takes approximately 22 minutes (including maneuvering), and lying time is approximately 8-15 minutes. Ports of call are concentrated around 0600-0900 morning / daily and 1500-1800 afternoon / day.



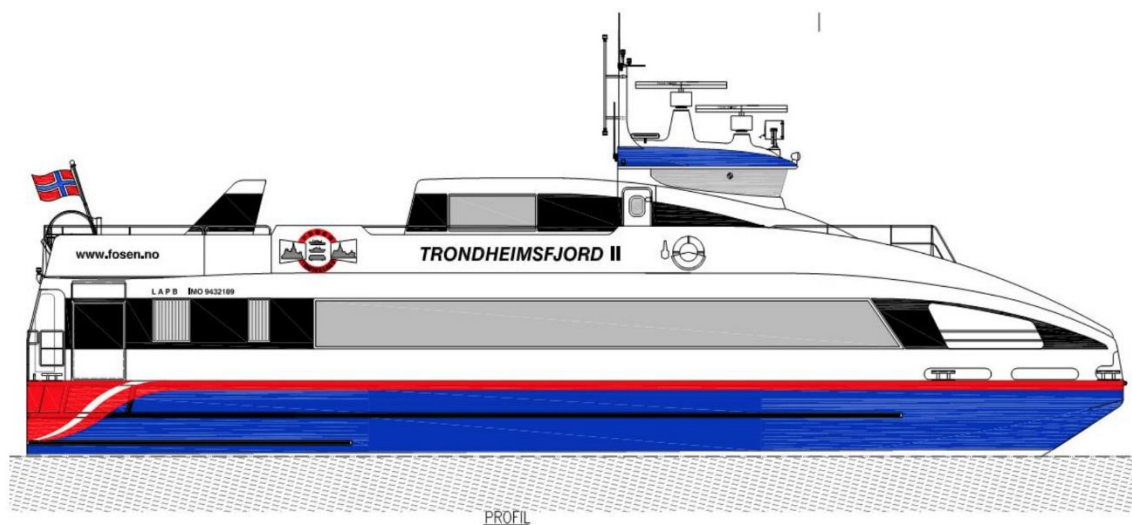
5.1.2 Timetable for 2016

810	Trondheim - Vanvikan t/r Gyldig fra: 15.08.2016
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mandag-fredag		lørdag		søndag	
Fra Trondheim	Fra Vanvikan	Fra Trondheim	Fra Vanvikan	Fra Trondheim	Fra Vanvikan
06.20	05.50	07.25	06.30	09.30	10.00
07.20	06.50	08.25	08.00	11.30	12.00
08.25	07.55	09.45	09.00	13.30	14.00
09.45	09.00	11.15	10.15	16.15	16.45
11.15	10.15	13.00	11.45	18.00	18.30
12.30	11.45	15.30	13.30	19.30	20.30
15.00	13.00	17.00	16.00	21.00	22.00
16.00	15.30	18.00	17.30	22.30	22.55
17.00	16.30				
18.00	17.30				
20.00	19.00				
21.45	21.00				
23.30	22.55				

FosenNamsosSjø operates the route with vessel Trondheimfjord 2. The vessel is a passenger catamaran built in carbon fiber by Brødrene Aa in Hyen. Passenger capacity is 130, which was part of the tender criteria from 2012. The vessel operates at a service speed of 25 knots. The time used on a voyage is spent on approximately three minutes maneuvering into / out of the harbor and about 19 minutes in service speed.

5.1.3 Technical data “Trondheimsfjord 2”



Built	2008
Passenger capacity	130
Building material	Carbon fiber sandwich
Length	24,5m
Width	8m
Top speed	32,5 knots
Motor	2 x MAN D2842 LE410 2 x 809KW @ 2160 RPM
Gear/propeller	Servo gear HD22HR-PTO/HD220 Gear ratio: 2,952:1
Auxiliary engine	Kohler 26kW
Weight	63 ton m/pax & fuels

Diesel consumption on the route is in 2015 stated to be 954 000 liters (STFK).



Fast ferry terminal in Trondheim is located at Brattørkaia.



Fast ferry terminal in Vanvikan is located inside the city center.

5.2 Electrification of fast ferry route Trondheim – Vanvikan

5.2.1 *Refit vs new build*

By building a new, you could also consider other vessel design built specifically for electric propulsion.

We still choose to only look at the possibility of reusing existing vessels so that development can take place as quickly as possible and with the use of existing and available technology.

Reuse is also positive for the total cost, with reducing time and labor spent on reconstruction. The reuse of propellers and gear with PTO, and to take consumer power from the battery and not from existing auxiliary, will make it possible to remove existing exhaust plant in its entirety.

Given that Trondheimsfjord 2 is already built to achieve high speed, and built in carbon to be easiest possible, we consider the vessel to be well suited to battery-electric drive.

5.2.2 *Assumptions*

Reconstruction (highlights)

- Main engines removed
- Existing auxiliary engines removed
- Exhaust system removed
- Gear and propeller system is retained
- Diesel tanks retained (built in)
- Electric propulsion engine installed
- Battery capacity installed
- Emergency power provided by the battery pack is divided into several strings
- The need for energy production on board will be evaluated

To be able to utilize the battery electric drive and maintain the need for regularity, there is a need for charging on both ports of call. NTE and TrønderEnergi, which are respective grid operators, have confirmed that there is excess capacity in the area near the ports of call to deliver charging current of the requested amount.

5.2.3 *Propulsion system*

It is obtained bids from two main suppliers, on chapter 5.2.6 is shown schematic diagram from Siemens over the plant. Power for the operation of the vessel obtained from land, and the battery capacity is dimensioned based on the total energy requirement for the crossing.

5.2.4 Simplified weight calculation

Below is a simplified weight calculation for refit. This shows an increase in the vessel's total weight by about 5 tons. There are, however, included some key assumptions:

- The existing transmission system and propeller systems are maintained.
- Battery weight is set at 15 kg / kWh (installed)
- It is inserted a 145kW diesel generator, weighing 600kg
- There are not compensated for increased energy consumption for the weight gain. This after conversation with the captain of the vessel who claim it is the same consumption with empty or full boat (6 ton difference). We assume that this applies to a certain point.
- One supplier of electric propulsion systems operated with a propulsion engine weight of approximately 2500 kg and of another 950 kg. We've chosen to use the latter in this calculation.
- Weight on batteries will decrease over time, and the energy density will increase as technology advance, estimating 10kg pr kWh in 2021.
- It is also taken into account that existing diesel generators for consumption power / emergency power can be removed in its entirety. These currently supplies power to ex electronics, heating and lighting board. This is provided by 2 x 26kW auxiliary engines weighing about 600 kg per item.

Component	Number	Weight (kg)	2017 (kg)	2021 (kg)
Main engine	2	-3 800		
Auxiliary engine	2	-1 266		
Diesel		-2 500		
Exhaust system		-1 000		
Sum out		-8 566		
El-main engine	2		1 900	1 900
Battery pack	572 kWh		8 600	5 720
DC-link cabinet			600	600
Transformer			800	800
Miscellaneous			1 000	1 000
Diesel			50	50
Generator	1		600	600
Sum in			13 550	10 670
Difference			4 984	2 104

Figure weight calculation Trondheimsfjord 2

5.2.5 Energy calculation and demand – current routes and current technology

Number of charge cycles is calculated by multiplying departures per week (162) with the number of working weeks (51) which provides 8476 charge cycles.

We estimate power and energy for the crossing:

Consumption per engine in service speed	140 L diesel pr motor pr hour
Estimated use of hp per hour based of fuel consumption	1400 hp
Converted to kW (hp timer x 0,73)	1022 kW
Consumption in kW per minute	17 kW
Minutes of voyage (25 knop)	19
Energy requirement pr passage	323 kWh

Energy from battery package	267 kWh
Energy from generator	54 kWh
DOD	60%
C-rate	1,5
EOL	5 years

Operating profile

Energy requirements based on Trondheimfjord 2 are logged after the monitoring of operational data during several crossings. To look at the total energy demand on the route, we create an operating profile which shows the power output per minute. In addition, calculated what the contribution of energy from onboard production via generator and charging when docked.

Alternative without generator

To operate fully electric requires a battery of about 680 kWh which will add additional 1620 kg battery. Due to the uncertainty associated with battery weight and increased consumption with added weight we choose a solution with a generator on board. A 145 kWh generator from MultsourcePower / Steyr uses about 27 L / hr and is designed to run continuously. Operating profile for this configuration is shown on the next page.

Trondheimsfjord 2									
Tidspunkt	Min	forbruk Kw	hotel	Genset Kw	Forbruk kWh/min	Forbruk kWh akk	Batteri	Batteri %	Lading
05:50	0	0,0	0	0	0,0	0,0	560,0	80 %	0
05:51	1	80,0	15	0	1,6	1,6	558,4	80 %	0
05:52	2	80,0	15	0	1,6	3,2	556,8	80 %	0
05:53	1	1022,0	15	0	17,3	20,5	539,6	77 %	0
05:54	2	1022,0	15	0	17,3	37,7	522,3	75 %	0
05:55	3	1022,0	15	0	17,3	55,0	505,0	72 %	0
05:56	4	1022,0	15	0	17,3	72,3	487,7	70 %	0
05:57	5	1022,0	15	0	17,3	89,6	470,4	67 %	0
05:58	6	1022,0	15	0	17,3	106,9	453,1	65 %	0
05:59	7	1022,0	15	0	17,3	124,2	435,9	62 %	0
06:00	8	1022,0	15	0	17,3	141,4	418,6	60 %	0
06:01	9	1022,0	15	0	17,3	158,7	401,3	57 %	0
06:02	10	1022,0	15	0	17,3	176,0	384,0	55 %	0
06:03	11	1022,0	15	0	17,3	193,3	366,7	52 %	0
06:04	12	1022,0	15	0	17,3	210,6	349,4	50 %	0
06:05	13	1022,0	15	0	17,3	227,9	332,2	47 %	0
06:06	14	1022,0	15	0	17,3	245,1	314,9	45 %	0
06:07	15	1022,0	15	0	17,3	262,4	297,6	43 %	0
06:08	16	1022,0	15	0	17,3	279,7	280,3	40 %	0
06:09	17	1022,0	15	0	17,3	297,0	263,0	38 %	0
06:10	18	1022,0	15	0	17,3	314,3	245,7	35 %	0
06:11	19	1022,0	15	0	17,3	331,6	228,5	33 %	0
06:12	1	80,0	15	0	1,6	333,1	226,9	32 %	0
06:13	2	80,0	15	0	1,6	334,7	225,3	32 %	0
06:14	1	0,0	0	0	0,0	0,0	264,1	38 %	18,4
06:15	2	0,0	0	0	0,0	0,0	282,5	40 %	18,4
06:16	3	0,0	0	0	0,0	0,0	300,9	43 %	18,4
06:17	4	0,0	0	0	0,0	0,0	319,3	46 %	18,4
06:18	5	0,0	0	0	0,0	0,0	337,7	48 %	18,4
06:19	6	0,0	0	0	0,0	0,0	356,1	51 %	18,4
06:20	7	0,0	0	0	0,0	0,0	374,5	54 %	18,4
06:21	8	0,0	0	0	0,0	0,0	392,9	56 %	18,4
06:22	9	0,0	0	0	0,0	0,0	411,3	59 %	18,4
06:23	10	0,0	0	0	0,0	0,0	429,7	61 %	18,4
06:24	11	0,0	0	0	0,0	0,0	448,1	64 %	18,4
06:25	12	0,0	0	0	0,0	0,0	466,5	67 %	18,4
06:26	13	0,0	0	0	0,0	0,0	484,9	69 %	18,4
06:27	14	1,0	1	0	0,0	1,0	503,3	72 %	18,4
06:28	15	2,0	2	0	0,0	2,0	521,7	75 %	18,4
06:29	16	3,0	3	0	0,0	3,0	540,1	77 %	18,4
06:30	17	4,0	4	0	0,0	4,0	558,5	80 %	18,4

Alternative with generator

Based on the above operating profile we will start the tour with 80% capacity on the battery pack and be down to 30% on arrival before connecting charging current. Charging time is estimated to be about 14 minutes before being able to cross again. Compared to the current system based on diesel, this will have about 7 minutes longer length with the choice of a hybrid solution.

Trondheimsfjord 2									
Tidspunkt	Min	forbruk Kw	hotel	Genset Kw	Forbruk kWh/min	Forbruk kWh akk	Batteri	Batteri %	Lading
05:50	0	0,0	0	-145	-2,4	-2,4	460,0	80 %	0
05:51	1	80,0	15	-145	-0,8	4,0	453,6	79 %	0
05:52	2	80,0	15	-145	-0,8	3,2	454,4	79 %	0
05:53	1	1022,0	15	-145	14,9	18,0	439,6	77 %	0
05:54	2	1022,0	15	-145	14,9	32,9	424,7	74 %	0
05:55	3	1022,0	15	-145	14,9	47,8	409,8	72 %	0
05:56	4	1022,0	15	-145	14,9	62,6	395,0	69 %	0
05:57	5	1022,0	15	-145	14,9	77,5	380,1	66 %	0
05:58	6	1022,0	15	-145	14,9	92,4	365,2	64 %	0
05:59	7	1022,0	15	-145	14,9	107,2	350,4	61 %	0
06:00	8	1022,0	15	-145	14,9	122,1	335,5	59 %	0
06:01	9	1022,0	15	-145	14,9	137,0	320,6	56 %	0
06:02	10	1022,0	15	-145	14,9	151,8	305,8	53 %	0
06:03	11	1022,0	15	-145	14,9	166,7	290,9	51 %	0
06:04	12	1022,0	15	-145	14,9	181,6	276,0	48 %	0
06:05	13	1022,0	15	-145	14,9	196,4	261,2	46 %	0
06:06	14	1022,0	15	-145	14,9	211,3	246,3	43 %	0
06:07	15	1022,0	15	-145	14,9	226,2	231,4	40 %	0
06:08	16	1022,0	15	-145	14,9	241,0	216,6	38 %	0
06:09	17	1022,0	15	-145	14,9	255,9	201,7	35 %	0
06:10	18	1022,0	15	-145	14,9	270,8	186,8	33 %	0
06:11	19	1022,0	15	-145	14,9	285,6	172,0	30 %	0
06:12	1	80,0	15	-145	-0,8	284,8	172,8	30 %	0
06:13	2	80,0	15	-145	-0,8	284,0	173,6	30 %	0
06:14	1	0,0	0	-145	2,4	0,0	207,7	36 %	20,8
06:15	2	0,0	0	-145	2,4	0,0	228,5	40 %	20,8
06:16	3	0,0	0	-145	2,4	0,0	249,3	44 %	20,8
06:17	4	0,0	0	-145	2,4	0,0	270,1	47 %	20,8
06:18	5	0,0	0	-145	2,4	0,0	290,9	51 %	20,8
06:19	6	0,0	0	-145	2,4	0,0	311,7	54 %	20,8
06:20	7	0,0	0	-145	2,4	0,0	332,6	58 %	20,8
06:21	8	0,0	0	-145	2,4	0,0	353,4	62 %	20,8
06:22	9	0,0	0	-145	2,4	0,0	374,2	65 %	20,8
06:23	10	0,0	0	-145	2,4	0,0	395,0	69 %	20,8
06:24	11	0,0	0	-145	2,4	0,0	415,8	73 %	20,8
06:25	12	0,0	0	-145	2,4	0,0	436,6	76 %	20,8
06:26	13	0,0	0	-145	2,4	0,0	457,5	80 %	20,8

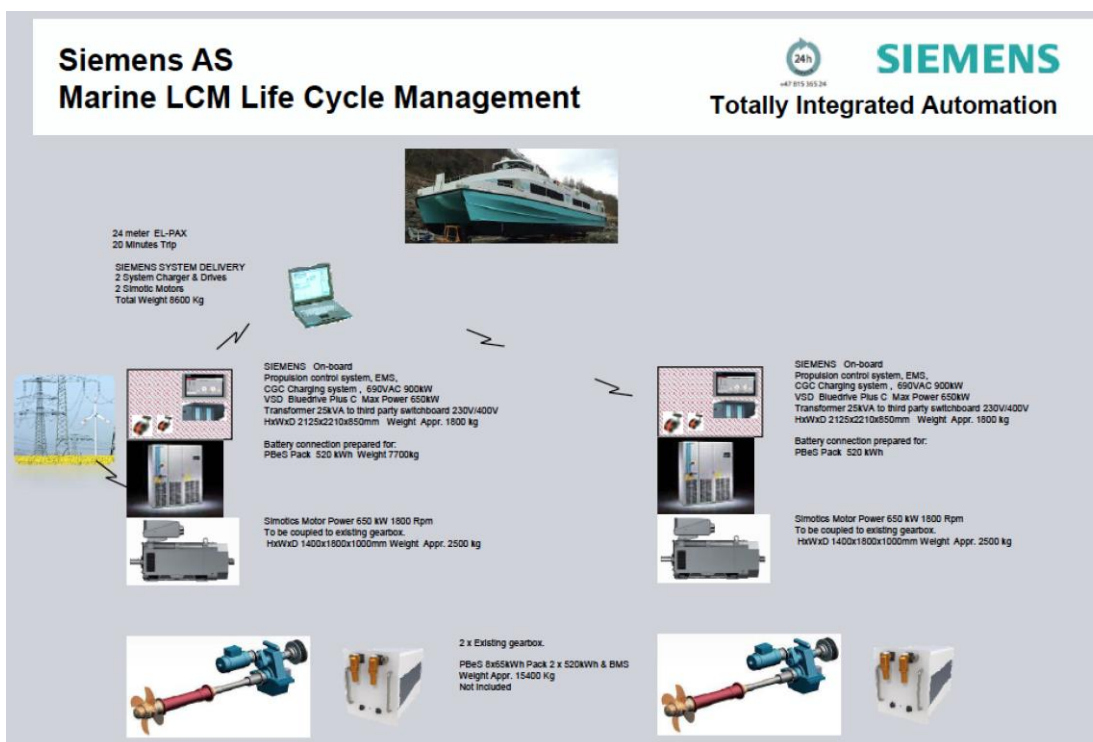


5.2.6 Main motor and propulsion

Propulsion is in our configuration provided by a permanent magnet motor which provides a good power-to-weight ratio. There exist products on the market that can be used, among others the Finnish supplier VISEDO, which is adapted to replace diesel engines for propulsion. This engine weighs 950kg and delivers 750kW at 2000 r / min with an efficiency of 96%. The alternative is a typical water-cooled induction motor is a more standardized product, but with much higher weight (about 2,500 kg) which then again must be compensated for with increased battery capacity.



Visedo Power Drum PM motor



Siemens sketch of the system

5.2.7 Existing and alternative propulsion solutions

Today's existing propulsion solution has swivel propellers from Servogear.

Alternatively, waterjets can be used. For a vessel with service speed around 25 knots will traditional propellers provide higher efficiency than jet. If the route has a speed of 25 knots, the energy consumption is about 30% higher with waterjet over conventional variable pitch propeller.

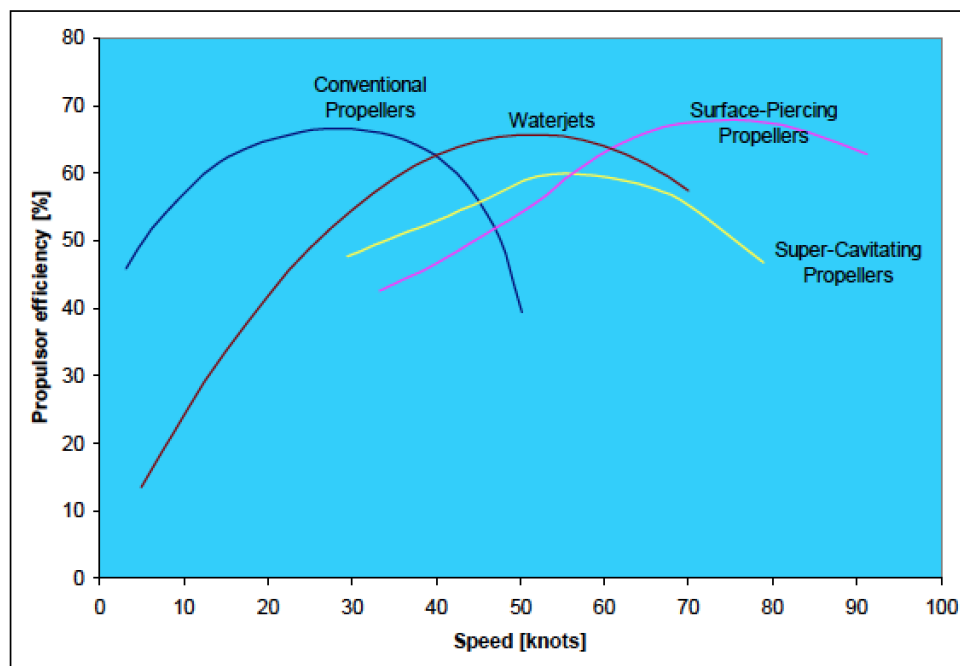


Figure: Propulsion effectivity with propeller and waterjet on different speeds

Another option is a POD solution which among others Rolls Royce and Volvo Penta has interesting solutions to. The gears and propeller are integrated in the same house that will provide a potential weight savings. A switch to POD would have led to a weight saving of 1,300 kg. Volvo Penta has stated such systems to be 10-30% higher efficiency than swivel propellers. We have been in contact with the company Rødne who owns the vessel Ryger troll, which is a 25 meter long catamaran same design as Trondheimsfjord 2 and with approximately the same weight. The difference between these two is that Ryger troll running with POD system from Volvo Penta (SE). Skipper on this vessel estimates consumption to be 150L per engine at 25 knots with a Volvo D13 at 588KW. This indicates that the consumption is not lower with a POD solution to this type of vessel.

Transition from combustion engine to electric motor will cause the gearbox to be charged with a higher torque at low revs. It is checked against the supplier of the existing gears on Trondheimsfjord 2 which can handle torque a current electric motor provides. Further alculations are therefore based on the existing gear and propeller system retained.

5.3 Battery system

In the new propulsion solution battery pack, it will be divided into four independent strings so one has several separate, discrete systems onboard. The vessel will also have two propulsion motors so that the degree of critical components is duplicated giving a high degree of security built.



Battery module: PBES

The batteries from PBES is made of 24 cells based on lithium technology composed of a module totaling 6.5 kWh. The modules are composed of one or more battery strings that together give the desired capacity. PBES batteries is stated to weigh a total of 19 kg per kWh of installed capacity. Corvus provide a weight of around 12 kg, excluding ventilation and battery. We assume a weight of 15 kg in weight calculation.

Safety requirements are extensive to such systems. Both Corvus and PBES satisfies the requirement from Sjøfartsdirektoratet and DNV GL.

Battery life is calculated from the number of charge cycles, C-rate used for charging and discharging, the average cell temperature, and how much of the capacity that is discharged each cycle (DOD). C ratio is a measure of how much power the battery can charged or discharged with respect to the total battery capacity, which in effect says something about how hard the batteries are being used.

5.4 Power supply and capacity in the harbor

The charge current on both sides of the bay are necessary so that the vessel could operate the route as intended. It is confirmed from TrønderEnergi (Trondheim) that it is available and a possible performance of 1MW capacity to the area where the boats dock. Likewise say NTE (Vanvikan) that the similar is possible on the other side of the route. Providers stipulates a construction cost of between 300 000 - 1 million US \$ per item.

At each of the ports there must be installed a charging station with an estimated capacity of about 420 Amp / 1kV. The supplier Cavotec will calculate two charging plugs on 0,5MW each and is developing a system in which the connectors are mounted on the bow so that you can drive your boat directly in plugs and avoids time-consuming handling of wiring. This will result in that the pier must be modified, but the construction cost for this is not included in this calculation. Such arrangement is already available in the Trondheim port.

5.5 Economic factors

5.5.1 Operations

For transition to electric propulsion the electricity prices will be a significant factor, including whether they are granted exemption from tariffs. Parliament has decided that it should be granted an exemption from tariffs on public transport, but this is not implemented yet. In the layout below is charge for grid therefore included.

5.5.2 Budgeted annual costs running on diesel (2015)

	Liter	Kr/L	Sum
Maintenance/year			2 800 000
Diesel	954 000	5,50	5 247 000
Totalt			8 047 000

5.5.3 Budgeted annual cost running on batteries

With 8424 departures, it gives a combined consumption of 2,527,200 kWh of electricity supplied through the main grid. Diesel consumption per trip is computed to 16.6 L, which provides an annual consumption of 140,250 L / year.

	Amount	Kr/kWh	Sum
General maintenance			1 200 000
Maintenance el-motor			150 000
Battery			1 000 000
Renting the grid 910 kW			800 000
Current (kWh)	2 527 200	0,27	683 000
Diesel (L)	140 250	5,50	771 375
Total			3 804 375

Difference in favor of electric propulsion	3 442 625 kr
--	--------------

Reduced fuel consumption with a hybrid solution	800 000 L
---	-----------

5.5.4 Simplified environmental budget

Existing drives

Ton diesel	CO₂ (ton)	NO_x (ton)
811	2 570	28

Hybrid drives

Ton diesel	CO₂	NO_x
119	380	4

5.5.5 Investment budget vessel

Generator	500 000
Propulsion system	6 000 000
Battery system	8 000 000
Modifying cost	4 500 000
Approval and documentation	600 000
Total	19 600 000

Investment budget on land/port

Trafo station x 2	2 000 000
Charging station x 2	2 800 000
Total	4 800 000

Sum investment cost	24400000
----------------------------	-----------------

5.5.6 Finance

NOx fund was established so that companies can apply for funding for mitigation. The relevant rate for reduction of NOx is NOK 500 per kg. Converted from liters to kilograms / ton the consumption for Trondheimsfjord is 811 tons when converted from liters to kilograms, corresponding to approximately 28,385 kg NOx annual emissions for commuting route of the Trondheim Fjord.

With a combination of battery and generator emissions can be reduced on the route by about 24,000 kg NOx and trigger a subsidy of 12MNOK based on current rates. The combination of the support triggering emission reduction and lower fuel costs make the payback time is relatively short (about 3-5 years).

There are also other subsidy programs regarding installations on land. Particularly through ENOVA. The county can also contribute to the cost of permanent installations on land. The adjusted cost directly linked to the vessel will then be 7.31 million kr.

Environmental accounting

	Diesel (ton)	NO _x (kg)
Diesel (Existing)	811	28 385
Hybrid	119	4 165
Savings	692	24 220

Finance with a land installation

Potential support from the NOx fund	12 110 000
Investment cost	24 400 000
Adjusted investment	12 290 000

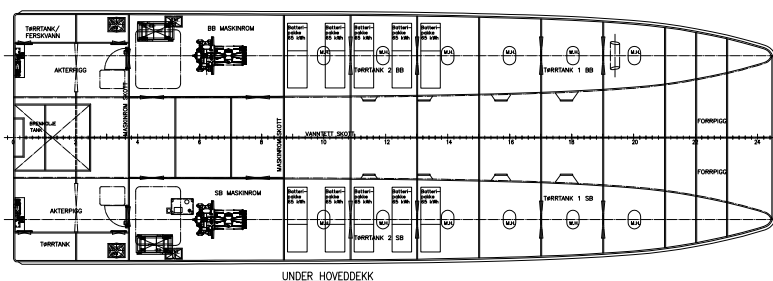
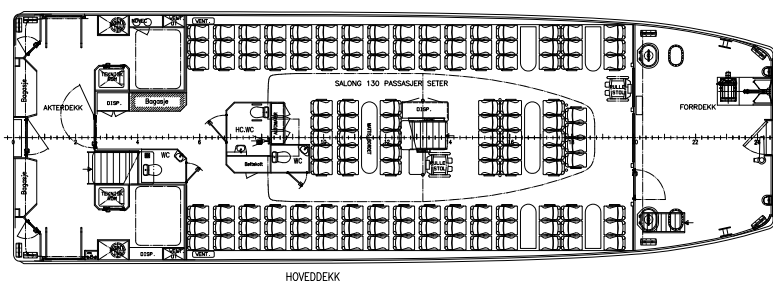
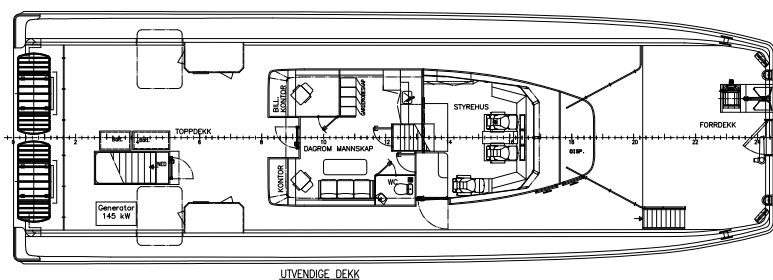
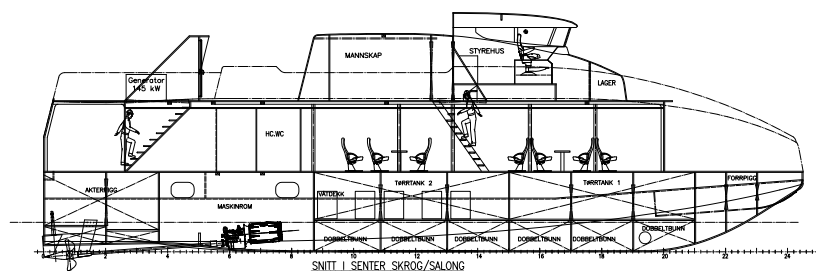
Finance without a land installation

Potential support from the NOx fond	12 110 000
Investment cost (ship)	19 600 000
Adjusted investment	7 310 000

It is possible that part of the investment can be covered by other types of state aid, an opportunity that should be explored further.

5.6 Sketch of Trondheimsfjord 2 with batteries

Below we show a cross section from the side and from the top with electric motor and battery pack plotted. The battery packs are placed in dry rooms ahead of the engine. Alternative placements based on weight distribution must be considered. The electrical cabinets and other components must also be placed here or in associated areas. Charging solution is not shown.



0	Første utkast, grunntegning fra Bika	28.11.16	U
Rev	Alterations	Date	Name
	Design	28.11.16	U
	Checked		
	Approved		
Trondheimsfjord 2 GA m/batteriel inst.			
Sheet	Drawing code	Size	Scale
1 : 1	100.1.0790	A3	1:125
			Rev
			0

5.7 Approval work

Sjøfartsdirektoratet (NMA) is the supervising authority for the shipping industry in Norway, which includes controlling that current regulations are followed. In 2015 Selfa Arctic built fishing vessel "Karoline" with a 195kWh battery pack on board. Some of the challenges was that there was no regulatory framework. NMA says;

The maritime industry in Norway is currently leading in the development and use of maritime battery systems. In collaboration with the industry NMA wants to help ensure that this advantage can be exploited and further developed in a safe manner (sdir.no, RSV nr: 12-2016)

We believe that conditions are good for the project to be completed now. This is based on the completed and ongoing projects that combine the use of diesel and battery operation. Approval of installation and components onboard will be crucial as to whether the project will be feasible, especially considering documenting fire hazard.

Although the boat will be the first of its kind, approval work is not considered a significant barrier. This is based on the regulations for battery operation is in progress, and several vessels have already been approved. The biggest challenge may be that it is desired to install as little battery power as possible, which may conflict with the approval authorities and requirements for spare capacity.

5.8 Case summary

It is realistic that the route can achieve significant reductions in costs and emissions using current battery technology.

Assuming use of current vessel, and a service speed of 25 knots, we recommend keeping the current solution with gears and propellers. The current propeller will also be a substantial advantage if the vessel is used as a prototype. The prototype will measure the correct propeller pitch and propeller diameter given that an electric motor has a different torque curve than a combustion engine.

- The infrastructure needed on land are available with enough capacity on both sides of the bay to supply the vessel with the electric energy.
- Current funding rates in the NOx Fund makes rebuilding relatively inexpensive since the consumption of diesel is so high.

The discoveries we have made in the next case Trondheim - Brekstad would suggest that one could go for fuel cell also in Trondheim - Vanvikan. We do not see this as a good alternative:

- Technology and regulations are designed for battery electric solutions
- Total consumption of energy will be lower than with fuel cell
- Power will always be a less expensive "fuel" than hydrogen, so a battery electric solution should be chosen where it is technologically possible.

5.9 Further work and future scenarios

Case studies have highlighted issues relevant for efforts to reduce emissions on the Trondheim – Vanvikan route. We see the following elements as essential to investigate to be able to realize the project.

- Stability must be recalculated again because of weight gain and changes in weight balance.
- Calculating exact effect change because of increased weight in collaboration with Boat designer

According to PBES Norway AS the amount of energy per battery will increase by 40% within five years. With that information and all else being equal, it is possible to run the route without generating electricity on board and have on board 40% more battery capacity with the same weight as today. Note that one must compensate for increased size of the battery pack with about 4 min longer charging time. With a life expectancy on batteries being 5-6 years this will coincide well with the upgrading to new cells with higher power.

The supplier industry is dynamic, and new technological solutions are being launched all the time.

MTU and Mancraft has launched solutions where electric motor and combustion engine is mounted as parallel hybrid solution. This will make installations easier and easier. Hydrogen / fuel cell can be an option as "generator"/additive effect within 4-5 years. NTNU has shown propulsion solution that can reduce energy requirements by 30-50% (see appendix).

6 CASE: TRONDHEIM – BREKSTAD (27 NM)

6.1 Introduction

Brekstad is the administrative center of Ørland municipality with about 5200 inhabitants. In 2012, Parliament decided that Norway's only fighter base will be located here. Brekstad is located at the mouth of the Trondheim Fjord. To get to Brekstad you can drive around the Trondheim Fjord, combine car and ferry via Flakk - Rørvik, car via Orkanger and then the ferry Valset – Brekstad, or take the fast ferry. The fast ferry route is important as it allows daily commuting between Trondheim and Brekstad and it is signaled an increased need to strengthen the offer related to new jobs at the fighter base. The route is already growing in number of passengers and is starting to have capacity problems on commuter departures (Hitra industry association).

6.1.1 The route

The distance Trondheim - Brekstad is 27 nm. There are two fast ferry routes on the route, where one route (800) continues to Kristiansund and is sailed with a larger vessel. Route 805 has 45 weekly departures and travel time is between 50 and 60 min (depending on if more ports of call along the way are needed). The route is operated with the vessel Trondheimsfjord 1.



6.1.2 Timetable

Operator: EosenNamsos Sig

Sist oppdatert: 09.10.2016 / v.3

800
805

Trondheim - Brekstad - Kristiansund

Gyldig fra: 15.08.2016

mandag-torsdag

fredag

lørdag

søndag

Rutenummer	805	800	800	805	800	805	800	805	800	805	800	805	800	805	800	805	800	805	800	805	800	805	800	805	800	805	800	805
Dagkoder																												
Trondheim	06.20		08.10	10.20	12.15	14.45	16.30	18.45	21.00	06.20		08.10	10.00	12.15	14.45	16.30	17.05	20.15		09.40	11.45	14.40	21.30	12.10	16.15	20.30	23.30	
Lensvik						15.20	17.05	19.20	21.35						15.20	17.05		20.50				15.15			16.50			
Hyernes	07.05		08.55							07.05		08.55						17.50		10.30	12.35	15.40	22.20	13.10	17.20	21.30	00.15	
Brekstad	D07.20		D09.10	11.10	D13.10	D15.45	D17.35	19.45	22.00	D07.20		D09.10	10.50	D13.10	D15.45	D17.35	18.05	21.15										
Sandstad			B09.50		B13.50		B18.15					B09.50		B13.50		B18.15						B16.20		B13.50	B18.05			
Kjensvikbugen			10.20		14.20		18.45					10.20		14.20		18.45						16.50		14.20	18.35			
Edøy	07.00		11.00		15.00		19.25			07.00		11.00		15.25		19.25			09.00				15.00		15.20			
Ringholmen			C11.20		C15.20		C19.45					C11.20		C15.20		C19.45						C17.55		C15.20	C19.45			
Kristiansund		07.45	11.40		15.40		20.00			07.45	11.40		15.40		20.00				09.45			18.20		15.40	20.00			

B = Korrespondanse 420

C = Signaletop til Ringholmen, Ring 911 97 009 Innen en time far avgang

D = Kgrasnorrdanse 451.

800
805

Kristiansund - Brekstad - Trondheim

Gyldig fra: 15.08.2016

mandag-torsdag

Rutenummer	800	805	800	805	800	805	800	805	800
Dekloder									
Kristiansund	08.00		12.00		16.30		20.30		
Ringholmen	C08.20		C12.20		C16.50				
Eday	08.40		12.40		17.10		21.10		
Kjersvikbugen	09.20		13.20		17.50				
Sandstad	B09.50		B13.50		B18.20				
Brekstad	06.15	07.30	D10.35	11.20	D14.30	15.55	19.00	20.00	
Agnes	07.40		14.40		16.05	19.10			
Lensvik	06.40	07.55			14.55				
Trondheim	07.15	08.35	11.25	12.10	15.35	16.55	20.00	20.50	

fredag

	800	805	800	805	800	805	800	805	800
	08.00		12.00		16.30	20.30			
	C08.20		C12.20		C16.50				
	08.40		12.40		17.10	21.10			
	09.20		13.20		17.50				
	B09.50		B13.50		B18.20				
	06.15	07.30	D10.35	13.20	D14.30	15.55	18.15	19.00	
	07.40		14.40		16.05		19.10		
	06.40	07.55			14.55				
	07.15	08.35	11.25	14.10	15.35	16.55	19.05	20.00	

lørdag

	800	805	805	805	800
	08.30	10.40	12.40	17.00	
	08.55				
	09.30	11.40	13.30	17.50	

søndag

	800	800	800	800
	10.30	14.30	18.50	
	11.30	15.30	19.50	

B = Korrespondanse 420

C = Signaletop til Ringholmen, Ring 911 97 009 innen en time fra avgang

D = Korrespondanse A51.

Ved driftsavvik - se atb.no eller fosennamsos.no
For mer informasjon - se atb.no / Ruteopplysning 177 / AtB Reise-app

The vessel is a passenger catamaran built in carbon fiber composite by Brødrene Aa in Hyen. The vessel operates at a service speed (according to tender) at 33 knots, where the time spent on the voyage is distributed on approximately two minutes maneuvering into / out of port, and about 50 minutes in service speed crossing the fjord. With more ports of call, they are distributed somewhat differently, but we spend 50 min in service speed in calculation.

6.1.3 Technical data

Trondheimsfjord 1



Built	2008 (rebuilt to waterjet in 2014)
Passenger capacity	130
Building material	Carbon fiber
Length	24,5m
Width	8m
Top speed	35 knots
Main engine	2 x MTU V12 1069kW
Propulsion	Waterjet KaMeWa
Auxiliary engine	Kohler 26kw
Weight	63t incl. pax & fuel /50t ex pax & fuel

Diesel consumption on this route was in 2015 stated to be approximately 1.11 million liters of diesel (STFK).

6.1.4 Battery propulsion

This is not possible today and in the foreseeable future because of the high weight of the battery pack.

6.1.5 Hybrid diesel/electrical propulsion

Like on Trondheimsfjord 2 we can envision a combination of installed battery capacity and power generation on board by diesel generators. After a conversation with the supplier of the diesel generator that was proposed for installation in Trondheimsfjord 2, it is possible to stretch the capacity of this into a continuous power output of 170kW. If there will be installed four diesel generators, and we use the same size battery as the Trondheimsfjord 2, there will be sufficient capacity (production + installed) for operating the vessel from the pier and about 25 min in service speed. One would then increase vessel weight compared with current propulsion solution with between 8 and 12 tons with this setup. We find it not realistic to increase the vessel weight even further with more installed capacity, or production on board. To realize this option, we must find solutions that allow for more power production on board, or wait for higher energy density batteries.

6.1.6 Fuel cell and hydrogen

Progress with hydrogen and fuel cell seems to be the most realistic solution. The system will then consist of a hydrogen tank, a fuel cell system, and a battery pack to equalize consumption since the fuel cell should go on stable load to increase longevity. The propulsion system with an electric motor and associated components will be added to this. There will probably be no need for charging infrastructure of the battery pack on land, since the battery is charged by the surplus energy from the fuel cell on board. Tank capacity is dimensioned to only fill hydrogen at one of the ports of call.

6.2 Calculating weight for chosen solution

The weight of a fuel cell system with a 1400 kW output is uncertain, so we have made some calculations from different suppliers. In addition, we must add hydrogen and a fuel tank, as well as system installation. In total the vessel will have an increased weight of at least 1300 kg with hydrogen and battery pack, if one chooses Visedo's el-engine solution. The solution from Powercell does not include all components of the system, and the system from Ballard is not yet set up for stacking several units together. See table below for complete weight calculation.

Component	Number	Weight (kg)	Hydrogenics	Ballard	Powercell
Main engine	2	-7 000			
Auxiliary engine	2	-1 200			
Diesel		-2 500			
Exhaust system		-500			
Sum out		-11 200			
kW/kg			0,150	0,352	0,6
El-main engine	2		1 900	1 900	1 900
Battery pack	200 kWh		3 000	3 000	3 000
DC-link cabinet			600	600	600
Transformer			800	800	800
Fuel cell			9 333	3 977	2 333
Hydrogen			200	200	200
Hydrogen tank	21		2 100	2 100	2 100
Sum inn			17 933	12 577	10 933
Difference			6 733	1 377	-267

Weight accounting Trondheimsfjord 1 hydrogen.

6.3 Energy calculation

The main difference from Trondheimsfjord 2 is that this boat was rebuilt with waterjet propulsion in 2014 to satisfy the tender criteria for the route with speed at 33 knots. From Section 3.2.2 we saw that the efficiency of the jet is higher at these speeds compared to propeller that boat was delivered in 2008.

Consumption per engine in service speed	185 (total 370) L/hour
Power in hk (370/0,2)	1850 hp
Power in kW (hp x 0,73)	1350 kW
Power i kW/min	22,5 kW
Crossing (33 knop)	50 min
Energy to cross in service speed	1200 kWh

The power requirement is 1350 kW for service speed 33 knots, and with 50 minutes in service speed the total energy demand for the route per departure is approximately 1200 kWh including maneuvering to / from the wharf.

6.3.1 Fuel cell – size and price estimate for Trondheimsfjord 1

	Alt A)	Alt B)	Alt C)
Installed power fuel cell system (kW)	450	900	1 400
Weight, fuel cell system (kg)	1 125	2 250	3 500
Energy production, fuel cell system on one tank (kWh)	450	2 000	3 000
Hydrogen, full tank (kWh)	900	4 000	6 000
Hydrogen, full tank (kg)	27	121	182
Hydrogen, full tank (gas at 350 bar, m ³)	1,1	4,7	7,1

Assumptions:

Energy density, fuel cell system (kW/kg)	0,4
Efficiency, fuel cell system	50%
Density, H ₂ -gas at 350 bar (kWh/L)	0,85
Energy density, hydrogen (kWh/kg)	33

In calculating the energy required per departure, we rely on a system with an output of 1400kW which should be sufficient to operate the vessel in service speed. We will then have some surplus production that can be stored in a battery pack to possibly supplement in demanding conditions, for emergency propulsion, and to shut off the fuel cell while at the docks.

Fuel cell – estimated investment	EUR/kW	1400kW (NOK)
2017	3 200	40 768 000
2018	2 200	28 028 000
2019	1 900	24 206 000
2020	600	7 644 000

Prices and sizes by Bluecraft

6.3.2 Power demand hydrogen

The energy density in hydrogen (kWh / kg) is 33 giving $6000/33 = 182$ kg hydrogen to produce 3000kWh (efficiency fuel cell = 50%). That is about 73 kg hydrogen for crossing from Trondheim to Brekstad. One tank will be enough to meet the energy requirement for a round trip, and only one charging facility are required.

This shows that it is technically possible to run routes with electric propulsion motor driven by a fuel cell of 1400 kW.

Prices of hydrogen is expected to fall, and Reinertsen (2016) claims to be able to produce hydrogen for 12 NOK / kg. Also, hydrogen production by electrolysis is expected to be cheaper (IFE). If we assume a price of 25 kr / kg within the next 5-10 years, the annual cost for Trondheimsfjord 1 will be at around 4.2 million.

	Kg hydrogen	NOK/hydrogen
One crossing	73	1825
Week	3285	167 535
Year (51 weeks)	82 125	4 188 375

We estimate the price for hydrogen to be at 25kr/kg in 2019.

6.3.3 Hydrogen tank

Hexagon Raufoss produces approved hydrogen tanks in composite material. The solution with the composite reduces weight on the tanks significant relative to steel tanks. With a hydrogen amount of 182 kg the following solution is suggested:

Dimensions, hydrogen tanks in mm	420 x 3600
Kg hydrogen per tank	8,7
Pressure	350 bar
Number of tanks	21
Price per tank	12 000 EUR
Total cost of 21 tanks	2 300 000 NOK
Safety mechanism	TPRD

6.4 Investment budget (prices for 2019)

Filling station on land, either Trondheim or Brekstad	15 000 000 (TBD)
Production facility	15 000 000
Fuel cell	24 206 000
Hydrogen tanks on board	2 300 000
Propulsion system	6 000 000
Battery pack	1 250 000
Cost to rebuild	5 000 000
Approvals	250 000
Total cost:	69 006 000

6.4.1 Budgeted annual costs with diesel (2015)

	Liters	Kr/L	Sum
Maintenance/year			2 800 000
Diesel	1 110 000	5,50	6 105 000
Total			8 905 000

6.4.2 Budgeted annual costs with hydrogen hybrid (2017)

	Amount kg	Kr/kg	Sum
General maintenance			1 200 000
Maintenance el-motor			150 000
Battery			37 500
Renting the grid 910 kW			800 000
Hydrogen	82 125	25	4 188 375
Total			6 375 875

Difference in favor of hydrogen + battery	2 529 125
Reduced liter diesel	1 110 000

6.4.3 Environmental budget Trondheimsfjord 1

	Diesel (ton)	CO ₂ (ton)	NO _x (kg)	SO _x (kg)
Existing	944	3 000	33 040	1 000
Hydrogen/battery	0	0	0	0
Potensial reduced emissions	944	3 000	33 040	1 000

6.4.4 Finance

Potential support from NOx-fund	16 520 000
Investment cost	69 006 000
Investment adjusted for support	52 486 000

The investment will be 22,486,000 NOK if the county will pay for production facilities and filling station.

Potential support from NOx-fund	16 520 000
Investment cost (vessel)	39 006 000
Investment adjusted for support without filling station	22 486 000

6.4.5 Filling station

Since our solution Trondheimsfjord 1 involves a relatively high consumption of hydrogen (4100 kg per week), calculations from IFE shows that it can be profitable to have local manufacturing facility. This is assumed in this setup.

6.4.6 Further investigation of hydrogen

Technically, there are some parameters with hydrogen operation at sea, which is difficult to assess due to lack of testing. For example, uncertainty about whether various salts in the air can have an impact on the chemical reactions in the processes in the fuel cell.

Furthermore, filling time is so complex and represent a critical point, such that it requires a separate research project. There are several factors that cost / benefit / safety assessments to be done on what is optimal fill rate.

Non-existent regulatory framework or class standards and factors that can make the development of a hydrogen-powered speedboat challenging.

Summed up our option with hydrogen propulsion in fast ferries seems to be interesting, but is something for the near future. It seems appropriate to try out the technology on a vessel not used for passenger transport as it is very strict regulations for such vessels. It is also desirable to try out the technology in a one-man boat, where the owner knows the technology, and the technology can be tested in a smaller scale before it is used in passenger transport. This forms the basis of paragraph 7 in our study.

6.4.7 Vessel design

In a meeting with FosenNamsosSjø we were advised about capacity challenges on the route and an increased need for passenger capacity. The solution may be a new vessel with capacity of 180 pax and a design with cutting hull instead of the semi-planing hull of today's vessels. The shipping company concludes that the energy demand will be equal to a new vessel compared to today's vessels, and will not change these ratios. Our point of "rebuilding" in the cost setup would then be irrelevant, and replaced with a new vessel investment.

6.4.8 Safety

The lack of a regulatory framework is as mentioned earlier in this report one of the biggest challenges to hydrogen in marine applications. After discussing with suppliers of hydrogen and fuel cell solutions, we find that the safest option is to place the tanks on the roof. This has been well received by suppliers and in informal conversations with class approval company.

Sjøfartsdirektoratet (NMA) has stated that hydrogen is challenging, but they are open to help develop rules and safety procedures while the vessels are developed (Florø, 2016). It is still expected that this work will be challenging and take time, since passenger vessels has stricter safety requirements than other vessels. Key points to clarify is the location of hydrogen tanks, transport of hydrogen to the fuel cell, and refueling of hydrogen which needs refrigeration relative to the pressure. These concepts must be designed and certified to meet NMA requirements.

We believe the implementation of safety is firmly rooted in the timeline set up in Chapter 7.

6.5 Case summary

We have looked at three alternative solutions to reduce emissions on the route Trondheim - Brekstad. When batteries are out of the question because of excessive weight, we recommend hydrogen / fuel cell option.

- Increase in weight with fuel cells and hydrogen is 900 kg
- The fuel cell is 1,400 kW
- Battery: 200 kWh
- 73 kg hydrogen / crossing
- Investment cost (2019): 69,006,000
- Operating cost: 6,375,875 / year

Prototype development of vessel with hydrogen / fuel cell, as well as legislation, is essential for the introduction of this technology in the fast ferry sector.

7 FURTHER STUDIES

The report's conclusion is that it is likely that it is technologically possible to get all fast ferries to have zero emissions in 2022.

This requires further development work in several fields:

7.1.1 *Hull design*

- The transition to electric propulsion with battery or hydrogen as an energy carrier will result in a different weight distribution and possibly total weight of the vessels. Both design and safety calculations must be reviewed in detail.
- Several new hull concepts with significantly lower power requirements, both hydrofoil from NTNU and SES from Effect Ships International, which should be developed and evaluated

7.1.2 *Batteries*

- Our report shows that there are many considerations that come in before a final calculation can be made. C-Rate, DOD, lifetime calculations and calculation of the current project to see that the heat does not go up on the current charge cycles. At the same time, there must be a more real calculation of when capacity per cell increases, and the impact this will have on battery installation.
- It will be installed batteries for several billion NOK on fast ferries coming years, and usually this will lead to a race for technologically better solutions, and as a result of that lower prices.
- At hydrogen installation, there must be calculated how large battery packs that must be installed.

7.1.3 *Propulsion system*

- Transition to the use of electric motor provides new opportunities. The motors have full torque from the first rotation, and engines can go both ways. This is different from the situation today. Likewise, the engine's structural dimensions is substantially different than an internal combustion engine, this also provides new design possibilities for the propulsion system

7.1.4 *Hydrogen/fuel cell*

- This is clearly the most immature technology. The alternative of hydrogen seems technically feasible. It must be practical experiments to test how salts in sea air and other external factors may affect the electrochemical process. We must also work with approval companies to confirm where the pipes from the hydrogen tank to the fuel cell should be placed.

We believe the scheduled timeline will provide good basis for further work to transform theory into real installations in vessels.

7.1.5 Timeline

- We suggest the development, installation and pilot testing occurs on the following schedule:



Tidslinje utviklingsprosjekter

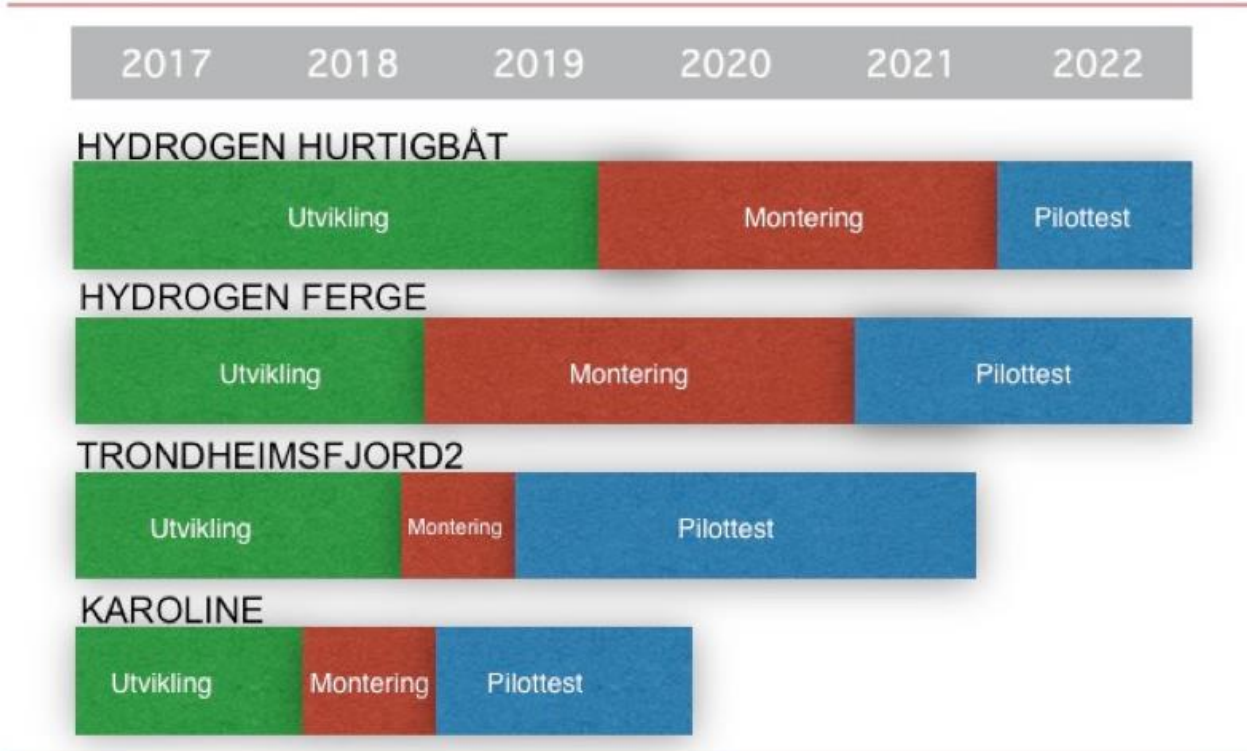


Figure: Proposed timeline for development of low or zero emission vessels

Here we will be able to get experience from the development of 4 parallel projects.

MK Karoline

- The vessel was scheduled to assemble the fuel cell in spring 2016. The project is already partially funded. Pilot testing on this vessel will have many advantages:
 - It is fairly low power, so the investment is less than the HSLC
 - There are few passengers on board during testing
 - Testing the fuel cells with sea air, rolling and bumping will be ideal for this vessel

MS Trondheimsfjord 2

- If we choose the proposed solution with the refit of existing vessels, it will be possible to get an early installation. This will provide valuable data for hydrogen fast ferry projects.

Statens Vegvesen - hydrogen ferry

- Statens vegvesen (NPRA) is now starting a development project, where they expect to buy more ferries with hydrogen operation over a few years - the first ferry will be in operation by the summer of 2021.

Development project for hydrogen fast ferry

- We believe that one or more counties should establish a parallel project phase shifted approximately 6 months after the project NPRA. NPRA has already in principle supported the idea, and that they will contribute in such a project.