MULTI-SERVICE CHARGING STATION AND/ OR ONSHORE ENERGY STORAGE AT PORT FOR ELECTRIC FERRY– A CASE STUDY FROM NORWAY

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ABSTRACT

Norway has ambitious and clear goals for transport policy. Low and zero emission technology are required also for cargo road transport and ferry services. Electric ferry propulsion and electric trucks require high charging power. Moreover, charging of ferries will demand high power for only short intervals between crossings. We investigate options to improve the net present value of the charging infrastructure investments through onshore battery energy storage and/or sale of energy for charging electric vehicles. We found that a stationary Li-ion battery at the ferry dock reduce peak power demand, but the ferry charging system has a negative net present value. The results indicate that integrated planning of several modes of transport using the same energy carrier changes the net present value from negative to positive.

INTRODUCTION

Electrification of cars and light duty vehicles are well under way in Norway. Improved availability of battery energy storage gives electric propulsion of ships and trucks renewed attention. However, ferry docks are often located in rural areas with insufficient grid power capacity. Investment in new grid capacity or onshore energy storage to reduce peak power demand is thus required. Improved grid capacity generally has high investment cost and the power capacity is only used for short time periods. Li-ion battery packs that is charged during the ferry crossing reduce grid peak power demand, but has a limited lifetime and thus increase the operating cost [1].

We propose an integrated view of electrification of the transport system as a whole. We have explored the possibility to offer charging for vehicles and trucks while waiting for the ferry. We investigate three scenarios:

(1) A base scenario with limited grid upgrade and Li-ion battery pack onshore and no sale of charging.
(2) Limited grid upgrade combined with Li-ion battery pack onshore and limited vehicle charging capacity.
(3) Full grid upgrade to provide required ferry charging power and vehicle charging equal to potential demand.

We apply these scenarios to two crossings operated by diesel-ferries today. Only the analysis of the Bognes crossing is described in detail.

Case Bognes

The case selected is among the 52 ferry crossings deemed suitable for electrification in Norway. Additional criterions are that it connects two roads with through traffic and is used by heavy-duty vehicles. It is located in northern Norway on the road E6. The crossing takes about 25 minutes. It follows a slightly irregular timetable and have 15 crossings per diurnal.

BACKGROUND

A shift in the automobile fleet in Norway to electric drivetrain is under way. Moreover, the first medium size electric trucks are tested and several transporters are waiting for large el-trucks to become available.

The estimated potential for electrification of waterborne transport in Scandinavia was 65 to 80 percent of the current ferry market [2]. Car ferries are a necessary part of the transport system. Norway has 270 ferries servicing 440 crossings. Of these, 52 use less than 30 minutes per crossing and are deemed suitable for conversion to electricity today [3].

The Norwegian electric ferry Ampere service the crossing of E39 on the Sognefjord. The capacity is 120 cars and 350 passengers. The crossing is 5.7 km long. It takes 20 minutes to cross and use 150 kWh. The ferry has 2 x 450 kW electric motors, aluminium hull and a 12 knots maximum speed. The ferry carries a one MWh Li-Ion battery pack that is charged with 0.8 – 1.2 MW for 9 minutes between each crossing. An onshore Li-ion battery at each end compensates for lack of grid power capacity.

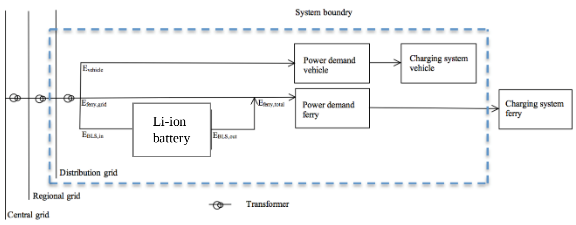
Electricity use by heavy duty trucks vary between 1.37 and 1.8 kWh/km with an average of 1.62 kWh/km [4]. An effective range of 500 km will thus require a 1 MW battery.

METHODS AND ASSUMPTIONS

We assume the ferry in these case studies will exhibit the same parameters as the electric ferry Ampere. Based on local circumstances and today’s schedule, we estimate energy demand for crossing, and energy and power demand for charging. Moreover, grid upgrade required meeting demand for peak power and related costs are estimated. The charging potential for heavy transport is calculated from analysis and processing of traffic data. Finally, we estimate lifetime and investment costs for the stationary Li-ion battery. For stationary energy storage, LiFePO4 battery is used. The net present value (NVP) of the three different scenarios are calculated.

System boundary

The system boundary for the calculations are drawn around the stationary system at the ferry dock including the local grid and transformer, see Figure 1. This includes the stationary battery and vehicle charging station as applicable in these scenarios. The ferry on-board battery is outside the system. However, the on-board battery-capacity is an important boundary condition for the onshore charging capacity. The cost of the ferry including the on-board electric propulsion system and battery is not included as we assume this is a policy decision and precondition for the study.



Figur 1 The system boundary of the analysis. The ferry charging system is outside the system analysed.

Ferry energy demand and dock charging capacity

The ferry dock charging capacity must be equal to or larger than the ferry demand for energy and power. The ferry energy and power use typically consist of five phases: acceleration away from dock, crossing at constant speed, retardation towards dock, reverse at docking and docking phase for unloading and loading, see Figure 3.

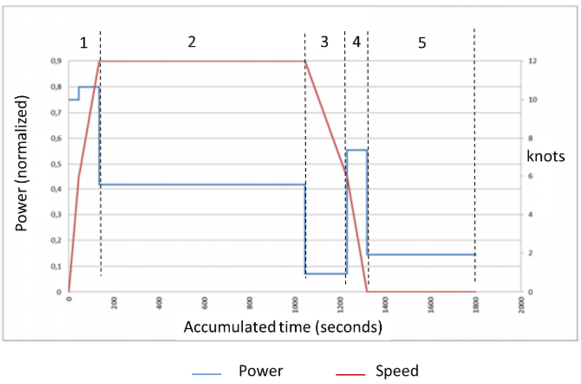


Figure 1 Typical ferry power use and speed during one crossing and docking. The five phases numbered are (1) acceleration away from dock, (2) crossing at constant speed, (3) retardation towards dock, (4) reverse at docking and (5) docking phase for unloading and loading [3].

The ferry energy use is given by the time in each phase multiplied by power, see Equation 1. T is minutes of each phase and P_f is ferry power use in kW.

Equation 1 $$Ef = \sum_{i=1}^{5} Pf \bullet Ti / 60$$

The required charging power is similarly specified by the docking time (phase 5) and energy demand, see Equation 2. Connection and disconnection of the charger use 30 seconds each, together one minute and P_c is ferry charging power.

Equation 2 $$P_c = E_f / (T_5 - 1) / 60$$

Stationary battery

Capacity

The stationary battery is sized to provide the energy required above the grid capacity at the dock. The grid power and the time available for charging limits the grid energy supply (E_g), see Equation 3. Moreover, the grid power (P_g) must be sufficient to recharge the stationary battery between each charging of the ferry. To limit degradation of the stationary battery we add 40 % capacity and initially operate the battery within 20 – 80 %, see Equation 4. The ferry timetable varies and docking time is generally longer during the night.

Equation 3 $$E_g = P_g \bullet (T_5 - 1) / 60$$

Equation 4 $$E_b = (E_f - E_g) \bullet 1.4$$

Degradation and lifetime

The degradation of the stationary battery is dependent on the state of charge (SoC). We have assumed starting at 80 % SoC and apply the same diurnal SoC-profile for all days of the year. During use, the SoC will go beyond the 20 – 80 % because of degradation. We have assumed the battery to be at the end of its lifetime when 100 % SoC is required to charge the ferry.

Degradation of the battery takes place both during cycling and when not in use. The latter is referred to as the calendar effect. We have assumed the use of a $LiFePO_4/C$ battery and calculate capacity fade is using a multi-parameter model. According to Swierczynski, Stroe [5] the capacity fade (CF) from cycle aging and calendar aging is respectively:

Equation 5 $$CF_{cycle} = 0.00024 \bullet e^{0.02717\,T} \bullet 0.02982 \bullet cd^{0.490}4 \bullet nc^{0.5}$$

Equation 6 $$CF_{calendar} =$$

$$(0.019 \bullet SOC^{0.823} + 0.5195) \bullet (3.258 \bullet 10^{-9} \bullet T^{5.087} + 0.295) \bullet t^{0.8}$$

After each month, the battery capacity fade is calculated and the corresponding new capacity is basis for the diurnal operation of the model the following month.

Vehicle charging

We estimate vehicle charging-demand from ferry transport statistics. We include electric vehicles and all vehicles more than 10 m long and calculate an hourly average of vehicles using the ferry for a typical diurnal, see Figure 2. We assume 250 kW charging power. The energy delivered to vehicles is limited by the charging time, assumed equal to the maximum waiting time for the ferry. Currently there is only one hour of the diurnal where there are three trucks on the ferry.

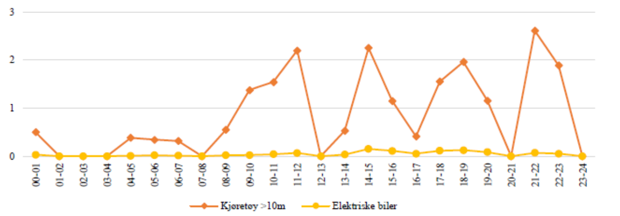


Figure 2 The average number of trucks per hour currently using the ferry during a diurnal.

Economic calculation

The cost of electricity consist of four elements, which are a peak charge based on the highest power demand during a month, a fixed energy cost, variable energy cost and an energy tax. If the grid company must invest in new lines or transformer to meet the energy demand, they forward a significant part of the investment cost is to the customer. With high peak-to-average ratio, the peak charge becomes a significant cost. Thus, we minimize peak power demand.

The stationary battery cost include in addition to the battery cells housing, battery management system and DC/DC conversion. We assume the vehicle charger cost is additional to the ferry charger. The cost items required to charge the ferry are sunk cost and not included.

We use net present value (NPV) to evaluate economic viability of the scenarios. Because the various investments have different lifetime and battery degradation is per month we use a monthly annuity for all costs, see Equation 7. Moreover, the NPV is calculated for a time-period equal to the calculated lifetime of the stationary battery.

Equation 7 $$A = NV \bullet \frac{rb(1+rb)^m}{(1+rb)^m - 1}$$

The net value (NP) is then calculated by the equation:

Equation 8 $$NV = \frac{A}{(1+rb)^m}$$

The NPV of the different scenarios is the sum of the net values of costs and income from sale of energy for charging. In addition, we calculate the minimum electricity price paid by the ferry in order to have NPV = zero.

RESULTS

In the model, the first step is to determine the energy demand. Second, we calculate demand for charging power and battery capacity if applicable. Third, we estimate stationary battery degradation and lifetime. Fourth, we calculate the net present value and sensitivity of the different scenarios.

Case 1 Bognes

Energy and power at ferry dock

The grid power currently at the Bognes ferry dock is insufficient. The grid power lines have spare capacity but the transformer must be upgraded in all three scenarios.
The grid upgrade potential consist of two alternatives. Upgrade of the transformer only to 500 kW power capacity or replacing both lines and transformer increasing power capacity to 1600 kW.

The energy use per crossing is 205 kWh. The shortest time available for charging the ferry is 9.5 minutes resulting in maximum 1295 kW power demand, see Figure 3.

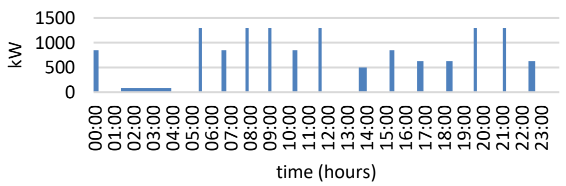


Figure 3 Bognes ferry power demand for one diurnal with today's schedule and no stationary battery. The thickness of the column represent the ferry charging time including connection and disconnection.

In scenario 1 and scenario 2, we deploy a stationary battery. The minimum time available to charge both the ferry and the stationary battery is 69.5 minutes. With the battery we may reduce peak power demand to 177 kW, see Figure 4.

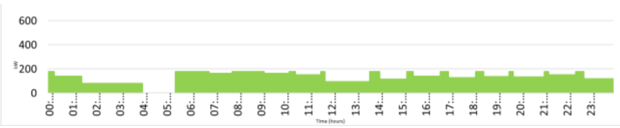


Figure 4 Bognes scenario 1 ferry power demand for one diurnal with today's schedule and a stationary battery.

In scenario 2, we deploy both a stationary battery and one 250 kW vehicle charging station. This increases the peak power load compared to scenario 1, but are still within the 500 kW upgrade option. In scenario 3 the grid lines and the transformer is upgraded to 1600 kVA and there is no battery. In scenario 3, two 250 kW vehicle charging stations are deployed.

Stationary battery degradation and lifetime

The stationary battery initial capacity is 295 kWh. With slightly more than one hour between each departure, grid peak load at 177 kW is sufficient to recharge the stationary battery between each crossing and contribute 28 kWh during ferry charging.

The stationary battery have four cycles during a diurnal. The cycles are quite similar, see Figure 5. Thus, we have used the average of the depth of discharge (DoD) in the cycle- aging calculation. The DoD is updated every month and reach 100 % after 90 months. The battery have then sustained 37 800 cycles at 25 ˚C. The inactive period in the beginning of the diurnal starting at a DoD at 76 % causing calendar degrading only contribute marginally to reduce battery lifetime.

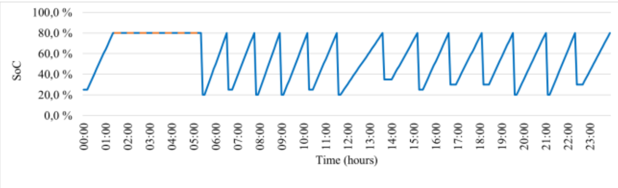


Figure 5 State of charge of the stationary battery at Bognes during on diurnal.

There is no difference in battery cycling between scenario 1 and scenario 2.

Cost and present values

The investment cost and operating cost used as basis for the annuity calculations vary between the scenarios, see Table 1. The highest cost is scenario 3, but this is also the scenario exhibiting the highest NPV, see Table 2.

Table 1 Investment and operating cost in Euro used in the analysis of Bognes.

Scenario 1	Batt invest	112 000
	Grid investment	65 100
	Power charge (177 kWp)	600/month
	Energy cost	1059/month
Scenario 2	Batt invest	112 000
	Grid investment	65 100
	Power charge (427 kWp)	1 400/month
	Energy cost	2 100/month
	Vehicle charging (250 kW)	405 000
Scenario 3	Grid investment	380 000
	Power charge (633 kWp)	2 100/month
	Energy cost	4 350/month
	Vehicle charging (500 kW)	810 000

Table 2 battery lifetime and net present value in the different scenarios.

Scenario 1	Lifetime batt (months)	90
	Net present value	-227 500
Scenario 2	Lifetime batt	90
	Net present value	1 939 500
	Minimum price of charging to ferry euro/kWh (NPV = 0)	0.084
Scenario 3	Net present value	7 031 000
	Minimum price of charging to ferry euro/kWh (NPV = 0)	0.051

Case 2 Solavågen

This case is distinctly different. There is sufficient grid power at one side of the fjord and very expensive to increase grid power on the other side. Rather, we proposed to increase on-board battery capacity and only charge on one side. The schedule and charging characteristics are similar, but require a 420 kWh stationary battery. The NPV without vehicle charging station is about the same as Bognes scenario 1. The reduced cost because of lower peak charges is thus not sufficient to balance the cost of the stationary battery. With vehicle charging the NPV with, and without stationary battery are about equal at 8 333 000 euro.

DISCUSSION

The selected cases are typical for short ferry crossing and thus relevant for other cases. There are uncertainties related to assumptions used in the calculations, technological development and income from vehicle charging.

We have assumed the ferry will have the same specifications as the first electric ferry Ampere in regular service. Ampere, however, is four years old and the next generation may have improved energy efficiency and thus reduce the need for charging. Moreover, reducing the speed from 12 to 10 knots will reduce energy use about 25 % and thus reduce the need for charging and stationary battery capacity. However, it increase the time used for the crossing 3.6 minutes, which may reduce income.

Both Li-ion batteries and electrical drivetrains are undergoing rapid development. New Li-ion battery technology may have considerable longer lifetime. This and the other assumptions discussed above may thus change NPV to positive also without vehicle charging. These improvements are, however, not likely to bring the NPV close to the values obtained with vehicle charging.

We analysed sensitivity where power charge (?), investment cost and the sale price for vehicle charging is varied between -50 % and + 50 %. The results exhibit significant sensitivity to variation in the sale price of vehicle charging, and very little sensitivity to power charge and investment cost, see Figure 6.

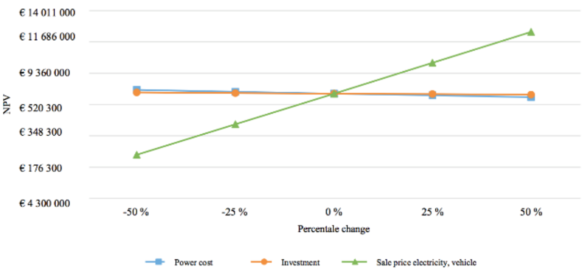


Figure 6 Sensitivity analysis of the NPV of Bognes scenario 3.

In the analysis, we have set the end of lifetime for the stationary battery when DoD reach 100 %. This is a conservative assumption. If we allow increased grid power use to compensate for insufficient battery capacity, the lifetime minimizing battery cost will be longer [1]. This will improve the net present value in both scenario one and two.

CONCLUSION

Storing energy in a Li-ion battery at the ferry dock to provide sufficient charging during the short docking time reduce peak-to-average grid load. Moreover, it will thus reduce the need for grid power upgrade. The cost of Li-ion batteries cause a negative net present value for the ferry charging energy system even when local grid power upgrade and reduced power charges are included. Providing multi-service, i.e., also sale of charging to vehicles at the ferry dock better utilise available power capacity. Moreover, the income from sale of energy to vehicles generates positive net present value for the system. The results encourage including multi-service approach into transport planning as electricity increasingly is used for all modes of transport.

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