EMK May 2023

ZEM Ports North Sea WP 3 Case Study for port infrastructure to new E-ferries and analysis of generic barriers

Photo: Ellen at berth in Søby, EU Horizon 2020 reporting

Prepared by Ærø Energi- og Miljøkontor (EMK) for the Municipality of Ærø, May 2023

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Abstract

The report is a case study analysing port infrastructure strategies for the charging of battery electric ferries on the Island of Ærø participating in the ZEM Ports North Sea project. Barriers are identified from the EU Horizon 2020 E-Ferry project and its charging station in the port of Søby. These findings are used to define three alternative strategies for design and operational setup of shore infrastructure in a case study for two new E-ferry Twins planned to operate from the Island of Ærø in 2026.

In order to lower barriers from port infrastructure and grid when providing high peak power for ferries calling the port, shore-based energy storage at the port is evaluated in two of the three alternative strategies for design and operational setup. For each alternative a number of scenarios are modelled and evaluated on parameters like energy cost and energy loss, investment cost and savings compared to fossil fuel operation including CO2 emission penalties.

The markets for both renewable electric energy and fossil fuel energy are characterised by periods with high volatility. In the case study, scenarios are divided into two market regimes. One based on the period 2011-2020 reflecting an energy market of relatively low prices and some stability. The second, based on the period 2021-2023 (until end of May), reflecting extreme energy prices both on electricity and fossil fuels and high volatility. For the latter period also time dependent distribution tariffs for electricity were introduced in Denmark.

Evaluating the results of scenario models show that battery electric operation under both price regimes will have lower operating costs than conventional fossil fuel operation. For all but two scenarios, added investment costs for battery electric operation and charging infrastructure will be repaid within a reasonable time interval before end of life of batteries in the setup. If penalties, being fees or purchase of quotas, for emission of CO2e from operation is included, then all scenarios are in favour of battery electric operation. Historical cost of electricity and alternative fuel types from 2011-2023 are analysed in a comparative study, taking into consideration inherent efficiencies and energy densities of the alternatives. The comparison emphasises the operational cost saving of battery electric solution over its alternatives.

Scenarios involving shore-based energy storage are divided into two different operational strategies. The first is focussed on peak shifting to lower average electricity price. The second is focussed on added revenues from ancillary service to balance grid frequency when shore battery is not in use for charging.

Peak shifting strategies and smaller grid connection fee with shore-based batteries in the setup will not fully repay the added batteries according to model calculations. However, the difference to calculated scenarios without shore batteries is marginal. Other benefits like higher redundancy or local grid constraints then adds in favour of paying the marginal cost difference.

Strategies using the shore-based batteries for ancillary services when not charging the ferries show best results of all scenarios, especially during times with high and volatile electricity prices. An assumed 50% of available redundant capacity has been used for Frequency Containment Reserves (FCR) in modelled calculations. Profits from FCR services vary from 3,5 to 9,0 million DKK annually depending on analysed period of time for the case study. Multi-market bidding strategies could mitigate risk but are not included in this study. This could be relevant for future analysis.

The introduction of shore-based energy storage to port infrastructure and charging stations is found to have the potential to significantly lower barriers to battery electric ferry operation if ancillary services are performed as described in the case study. This way battery electric ferries could create value for grid responsible operators as well as ferry operators.

1 Content

List of abbreviations:

aFRR	Automatic Frequency Restoration Reserve
BRP	Balance Responsible Party
CFD	Computational Fluid Dynamics, Simulation software
CO2	Carbon Dioxide climate gas
C-rate	Rate of battery discharge relative to nominal capacity
DK1	Transmission area of Western Denmark
DoD	Depth of Discharge is the relative share of used battery capacity
DSO	Distribution System Operator
E-ferry	Electric battery ferry developed in EU Horizon 2020 program
EoL	End of Life describing expected battery life until SoH of 80%
ESS	Energy Storage System
ETS	Emission Trading System
FAME	Fatty Acid Methyl Ester, biofuel
FCR	Frequency Containment Reserve
Hz	Hertz, frequency measurment unit
ICE	Internal Combustion Engine
kWh	Kilo Watt hours, unit for measurement of energy
LCOE	Levelized Cost Of Electricity
LER	Limited Energy Reservoir, exemption from requirements in FCR
LFC Block	Load-Frequency Control Block
LHV	Lower Heating Value, energy density of a fuel
mFRR	Manual Frequency Restoration Reserve
MGO	Marine Gas Oil, bunkerfuel
MJ	Mega Joule, unit for measurement of energy
MVA	Mega Volt x Ampere, note that power factor must be known to convert to Mega Watt
MW/h	Mega Watt per hour is a power capacity measurement unit applied for Frequency Reserves.
MWh	Mega Watt hours, unit for measurement of energy
Pb	Brake Power, power at engine flywheel or crankshaft
PCU	Passenger Car Units
Pe	Power Effective, power needed to overcome towing resistance
PEM	Polymer Electrolyte Membrane cell for electrolysis of hydrogen
PSO	Public Service Obligation, phased out tariff for subsidies to renewable energy production
PtX	Power-to-X describing fuel derivates of hydrogen from electrolysis and synthesisis with carbon or nitrogen
PV	PhotoVoltaic Solar Panels
Rt	Towing Resistance, total resistance excercised to ship at given speed
SFOC	Specific Fuel Oil Consumption
SME	Sunflower Methyl Ester, biofuel
SoC	State of Charge typically for a lithium-ion battery
SoH	State of Health defined as remaining capacity of battery when fully charged relative to nominal capacity when battery was new
STCW	Standards of Training, Certification and Watchkeeping for Seafares
TSO	Transmission System Operator, Energinet in Denmark
V2G	Vessel-to-Grid or Vehicle-to-Grid bidirectional use of battery pack in mobile unit
VAT	Value Added Tax for the purchase of goods and services

2 Introduction

2.1 Purpose and motivation

In 2019 a novelty in ferry design was revealed when the fully battery electric ferry, Ellen, commenced operation between the port of Søby on the island of Ærø and the port of Fynshav on the island of Als. The Horizon 2020 E-ferry project involved an unprecedented 4,3 MW DC peak power charging facility in Søby. Combined with an onboard battery pack of 4,4 MWh in nominal capacity, this allows for a travelled roundtrip distance between charges of 22 nautical miles or more than 40 kilometres in the scheduled service of the ferry. According to other studies this design allows for battery operation of around 80% of all Danish national routes when looking at the route lengths (Siemens, 2017), hence making it possible to significantly cut emissions in the ferry transport sector (T. Heinemann, 2019).

As described by Buster Bukart Hansen in his master thesis “Flexibility Analysis and Demand Response Optimization of Energy System” (Hansen, 2021), the battery electric ferry Ellen in Søby, has the potential to put some stress on the electrical grid infrastructure of the port facility and the hinterland supply grid. His study was supported by the ZEM Ports North Sea project, and it also showed that smart grid solutions and the application of flexibility into the ferry charging schedule would provide benefits to the grid and savings in the average cost of electricity, even when it comes to Levelized Cost of Electricity (LCOE).

This case study will elaborate on the findings in Buster B. Hansen’s thesis by also applying revenues from grid balance and frequency reserve services conducted by the ferry operator from batteries onboard and buffer batteries ashore. For the case study the planned successors of the E-ferry in Søby will be used. They will replace existing conventional fossil fuelled ferries sailing on routes both from Søby and Ærøskøbing on the island of Ærø to ports on mainland according to Municipality’s Climate Goals. For the first successors to the E-ferry, a pair of E-ferry Twins are projected to start their operation in 2026 (Municipality of Ærø, 2022).

Generic barriers for battery operation and charging infrastructure experienced during the Horizon 2020 E-ferry project in Søby will be discussed and possible solutions to lower these barriers will be applied in the case study for the new E-ferry Twins.

2.2 Scope

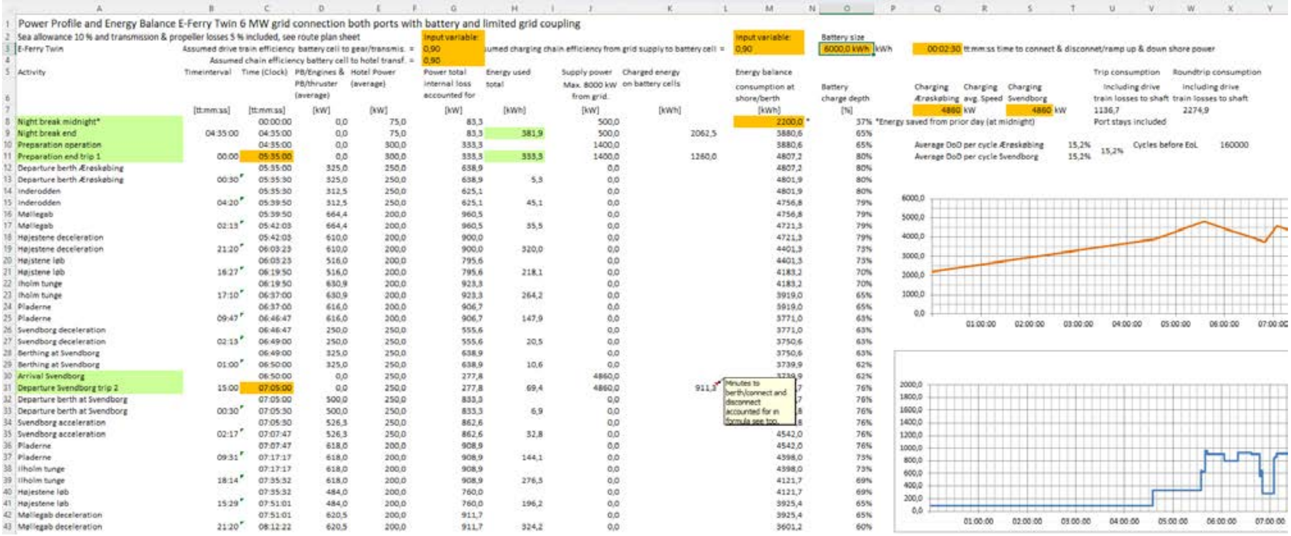
The case study will involve the following main tasks needed for scoping and sizing relevant port infrastructure and find optimisations for operation:

- Comparative study of energy price of electricity based on renewable energy certificates, conventional fossil fuel, fossil fuel including CO2 EU ETS quota prices and/or future Danish emission fee, other relevant green fuel products, here marine biofuel SME and FAME.
- Estimations of the value of energy flexibility, peak shaving and peak shifting, and description of ancillary services and market for grid frequency balancing, in particular Frequency Containment Reserve (FCR) including price study for application to the E-ferry Twin case scenarios.
- Implications to strategical choices for operation and setup in order to capitalise on system flexibility and lower barriers to battery ferry implementation and emission cuts.
- Six scenarios for estimation and sizing of shore connections and shore-based booster battery packs, hence also indirectly the battery size of the E-ferry Twins.
- Conclusions and recommendations for port electrical and charging infrastructure based on the analysed scenarios.

The case study will not look into all alternative fuel types. E.g., hydrogen or derivates thereof, often called Power-to-X products (PtX), are only described briefly. For now, the PtX industry has not been fully matured, thus product price is still very high and in too low quantities to compete with biofuels in this ferry segment.

3 Methodology and modelling

Modelling and estimations involve required charging time, battery State of Charge (SoC) during operation, C-rates (battery load), energy consumption and energy efficiency losses. From these parameters, the battery State of Health (SoH) evolution and battery lifetime can be assessed. However, still with some uncertainties. Performance of both onboard batteries and onshore batteries must be taken into consideration.



Power Profile and Energy Balance E-Ferry Twin 6 MW grid connection both ports with battery and limited grid coupling
Sea allowance 10 % and transmission & propeller losses 5 % included, see route plan sheet
E-Ferry Twin
Assumed drive train efficiency battery cell to gear/transmis. = Input variable: 0,90
Assumed chain efficiency battery cell to hotel transf. = 0,90
umed charging chain efficiency from grid supply to battery cell = Input variable: 0,90
Battery size 6000,0 kWh kWh
00:02:30 tt:mm:ss time to connect & disconnet/ramp up & down shore power

	Activity	Timeinterval	Time (Clock)	PB/Engines & PB/thruster (average)	Hotel Power (average)	Power total internal loss accounted for	Energy used total	Supply power Max. 8000 kW from grid	Charged energy on battery cells	Energy balance consumption at shore/berth	Battery charge depth
7		[tt:mm:ss]	[tt:mm:ss]	[kW]	[kW]	[kW]	[kWh]	[kW]	[kWh]	[kWh]	[%]
8	Night break midnight*		00:00:00	0,0	75,0	83,3		500,0		2200,0 *	37%
9	Night break end	04:35:00	04:35:00	0,0	75,0	83,3	381,9	500,0	2062,5	3880,6	65%
10	Preparation operation		04:35:00	0,0	300,0	333,3		1400,0		3880,6	65%
11	Preparation end trip 1	00:00	05:35:00	0,0	300,0	333,3	333,3	1400,0	1260,0	4807,2	80%
12	Departure berth Ærøskøbing		05:35:00	325,0	250,0	638,9		0,0		4807,2	80%
13	Departure berth Ærøskøbing	00:30	05:35:30	325,0	250,0	638,9	5,3	0,0		4801,9	80%
14	Inderodden		05:35:30	312,5	250,0	625,1		0,0		4801,9	80%
15	Inderodden	04:20	05:39:50	312,5	250,0	625,1	45,1	0,0		4756,8	79%
16	Møllegab		05:39:50	664,4	200,0	960,5		0,0		4756,8	79%
17	Møllegab	02:13	05:42:03	664,4	200,0	960,5	35,5	0,0		4721,3	79%
18	Højestene deceleration		05:42:03	610,0	200,0	900,0		0,0		4721,3	79%
19	Højestene deceleration	21:20	06:03:23	610,0	200,0	900,0	320,0	0,0		4401,3	73%
20	Højstene løb		06:03:23	516,0	200,0	795,6		0,0		4401,3	73%
21	Højstene løb	16:27	06:19:50	516,0	200,0	795,6	218,1	0,0		4183,2	70%
22	Iholm tunge		06:19:50	630,9	200,0	923,3		0,0		4183,2	70%
23	Iholm tunge	17:10	06:37:00	630,9	200,0	923,3	264,2	0,0		3919,0	65%
24	Pladerne		06:37:00	616,0	200,0	906,7		0,0		3919,0	65%
25	Pladerne	09:47	06:46:47	616,0	200,0	906,7	147,9	0,0		3771,0	63%
26	Svendborg deceleration		06:46:47	250,0	250,0	555,6		0,0		3771,0	63%
27	Svendborg deceleration	02:13	06:49:00	250,0	250,0	555,6	20,5	0,0		3750,6	63%
28	Berthing at Svendborg		06:49:00	325,0	250,0	638,9		0,0		3750,6	63%
29	Berthing at Svendborg	01:00	06:50:00	325,0	250,0	638,9	10,6	0,0		3739,9	62%
30	Arrival Svendborg		06:50:00	0,0	250,0	277,8		4860,0		3739,9	62%
31	Departure Svendborg trip 2	15:00	07:05:00	0,0	250,0	277,8	69,4	4860,0	911,3	[illegible]	76%
32	Departure berth at Svendborg		07:05:00	500,0	250,0	833,3		0,0		[illegible]	76%
33	Departure berth at Svendborg	00:30	07:05:30	500,0	250,0	833,3	6,9	0,0		[illegible]	76%
34	Svendborg acceleration		07:05:30	526,3	250,0	862,6		0,0		[illegible]	76%
35	Svendborg acceleration	02:17	07:07:47	526,3	250,0	862,6	32,8	0,0		4542,0	76%
36	Pladerne		07:07:47	618,0	200,0	908,9		0,0		4542,0	76%
37	Pladerne	09:31	07:17:17	618,0	200,0	908,9	144,1	0,0		4398,0	73%
38	Ilholm tunge		07:17:17	618,0	200,0	908,9		0,0		4398,0	73%
39	Ilholm tunge	18:14	07:35:32	618,0	200,0	908,9	276,5	0,0		4121,7	69%
40	Højestene løb		07:35:32	484,0	200,0	760,0		0,0		4121,7	69%
41	Højestene løb	15:29	07:51:01	484,0	200,0	760,0	196,2	0,0		3925,4	65%
42	Møllegab deceleration		07:51:01	620,5	200,0	911,7		0,0		3925,4	65%
43	Møllegab deceleration	21:20	08:12:22	620,5	200,0	911,7	324,2	0,0		3601,2	60%

Minutes to berth/connect and disconnect accounted for in formula see too.

*Energy saved from prior day (at midnight)

Charging Ærøskøbing	Charging avg. Speed	Charging Svendborg		Trip consumption Including drive train losses to shaft	Roundtrip consumption Including drive train losses to shaft
4860	kW	4860	kW	1136,7	2274,9
				Port stays included	

Average DoD per cycle Ærøskøbing 15,2%
Average DoD per cycle Svendborg 15,2%
15,2%
Cycles before EoL 160000

Figure 2.2.1 Part of spreadsheet modelling of daily energy balance and sailing schedule.

In the spreadsheet model main variables such as battery size, charging power and time for connecting and disconnecting charger are set in the top. Sailing schedule is entered in column C by altering departure times. Transit times and energy consumption for propulsion is derived from a separate spreadsheet with the power profile of the route.

For the future design phases, it is vital to further investigate the validity of this power profile. Small changes in consumption can lead to high deviation in final figures on the daily energy and battery balance.

Hotel power (e.g., power for accommodation lights and heating) can be adjusted throughout the day in the energy balance spreadsheet Figure 2.2.1 column E. Hotel power for heating is significant on a battery ferry compared to conventional diesel operation where heat losses from combustion engines can be reused for heating (T. Heinemann, 2019).

In this spreadsheet also energy efficiencies can be adjusted based on learnings from the E-ferry, Ellen, and other public projects. In this feasibility study these energy losses are based on a conservative estimate. Losses are much dependent on the design layout, sizing and choice of individual component but also on the load factor that components are utilised at.

Peak charging power cannot be obtained during the full charging period at high States of Charge (SoC). Therefore, lower average numbers are entered into the model. In scenarios, time for connection and disconnection has been set to 2,5 minutes total. This is somewhat high but allows for some throttling of charging connection during ramp up and ramp down or wasted time during less successful dockings.

Scenarios for each of the planned E-ferry Twins in the case study are based on similar number of departures as for present operation (Ærøfærgerne, 2023):

												Total charging time in operation
Departure Ærøskøbing	**05:35**		**08:35**		**11:35**		**14:35**		**17:35**		**20:35**	
Arrival Svendborg	**06:50**		**09:50**		**12:50**		**15:50**		**18:50**		**21:50**	
Port time		*00:14*	*00:14*	*00:14*	*00:14*	*00:14*	*00:14*	*00:14*	*00:14*	*00:14*	*00:14*	02:29
Departure Svendborg	**07:05**		**10:05**		**13:05**		**16:05**		**19:05**		**22:05**	
Arrival Ærøskøbing	**08:20**		**11:20**		**14:20**		**17:20**		**20:20**		**23:20**	

Figure 2.2.2 Sailing schedule on weekdays for Twin Ferry A (Source Ærøfærgerne).

The present schedule is based on a transit time of 75 minutes port to port. There will be a small deviation in transit times between legs if final E-ferry Twin design becomes a Single-Ender. Swaying the ferry on one leg of the trip adds a few minutes extra for manoeuvring depending on weather, current and sea state. For the case study a Double-Ender design of the ferry hulls is assumed, making manoeuvring time almost equal on both legs of the roundtrip.

Scenarios are based on the project description forwarded to the Danish Civil Aviation and Railway Authority (Trafikstyrelsen) by the municipality of Ærø (Municipality of Ærø, 2022). In the project description several different transit times are mentioned. However, to delimit the scope and variables, and to focus on the shore infrastructure, an average transit time, berth to berth, of 75 minutes and port time of 15 minutes respectively have been used.

Grid charging connection in the project description was 7,9 MVA for both ports and ship battery pack estimated to 6 MWh. However, this is varied in the scenarios according to the case study findings and the implementation of shore-based batteries.

Using the spreadsheet model, a number of scenarios have been prepared changing central variables to conclude on sensitivities to energy costs. Energy costs are based on two different year intervals and price regimes, and then compared to fossil fuel costs with and without CO2 quotas or CO2 emission fees. Fuel cost risks are discussed further in chapter 7.1.

The cost of energy for battery operation is somewhat more complicated to determine than for conventional fossil fuel operation. Electricity price will change during the day by the hour. Both spot price and transport tariffs are time dependent making it important to know when the charging takes place.

Average electricity spot price and tariffs from day and night charging are found and entered into the spread sheet model. Here, these prices are combined with the relevant share of charging at day and night respectively for each scenario analysed in the case study.

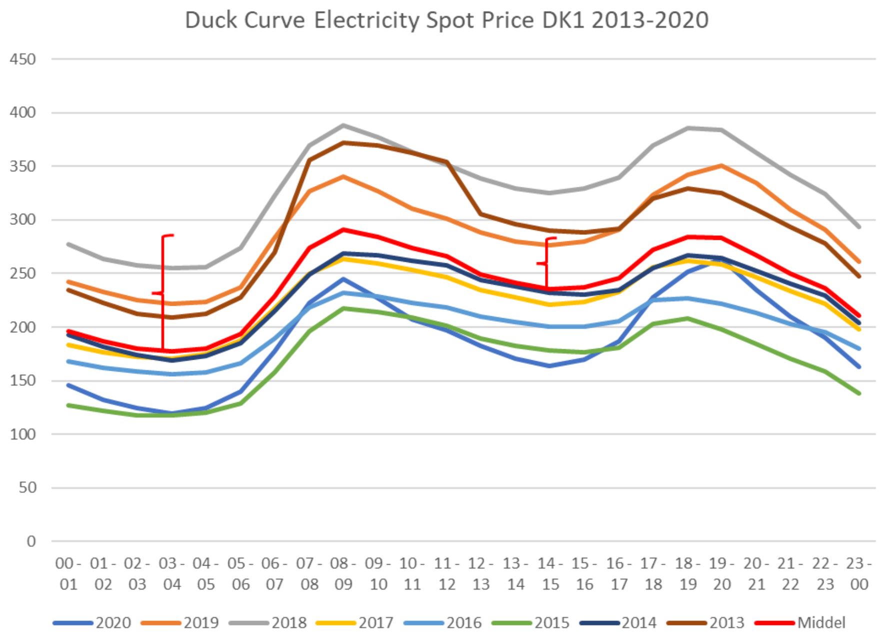


Figure 2.2.3 Hourly spot prices average DKK/MWh for electricity in DK1 (Compiled from Nord Pool data by EMK).

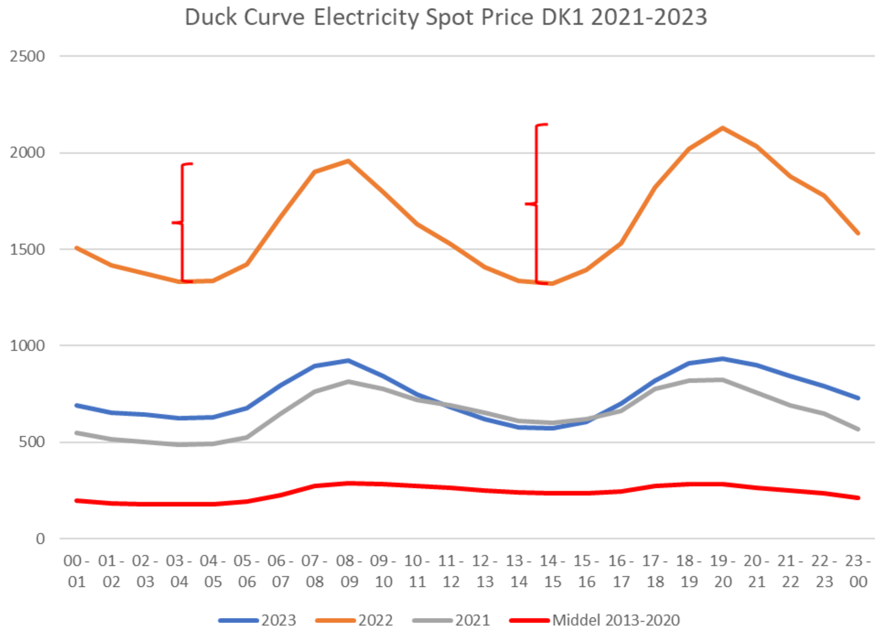


Figure 2.2.4 Hourly spot prices DKK/MWh for electricity in DK1 (Compiled from Nord Pool data by EMK)

As seen from Figure 2.2.3 and Figure 2.2.4 daily variations in hourly electricity prices have increased significantly within the latest years as prices also became more volatile on a daily and monthly basis.

The method of peak shifting allows for shifting charged electricity from peak demand prices to low demand prices and tariffs. In scenarios with battery packs ashore, flexibility for peak shifting is even more dominant. The effect has been assessed by lowering the average price during day charging in the calculations.

Being a large consumer and having battery reserves online for a part of day or night, allows for income or lower electricity rate, using demand response systems. Changing grid demand by throttling the charger, or increasing charging, can sell as a regulating or balancing service for grid Transmission System Operator (TSO) Energinet in Denmark. However, for some services demand response needs to be symmetric, meaning that one needs to be able to offer both upward and downward regulation within the same hour interval (Energinet, 2023).

With the right tools installed, Vessel-To-Grid (V2G) discharging can generate extra income for the ferry operator enhancing ancillary balancing services and demand response considerably. Keeping the grid frequency at 50 Hz is an important task for the Balance Responsible Parties (BRP). A battery ferry situated on an island like Ærø, with a well-known sailing schedule and predictable consumption, has a significant potential for FCR or mFRR service which will be discussed further in chapter 7. This way port infrastructure for ferry charging becomes a so-called *prosumer* with a charging station able of both consuming and producing energy to and from the distribution grid system.

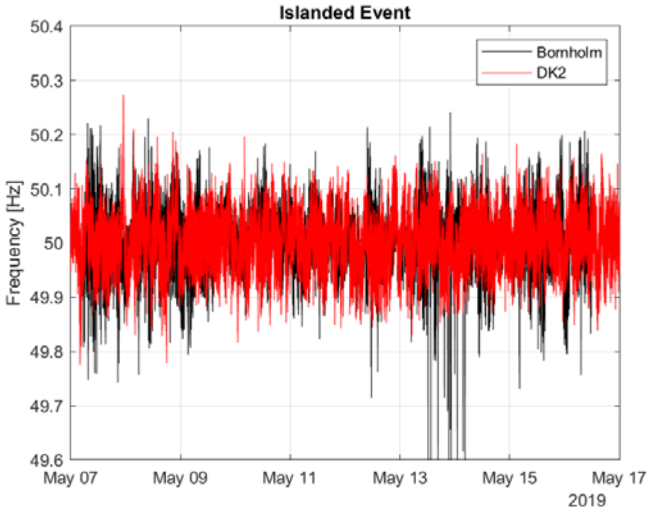


Figure 2.2.5 Data set of frequency variations in DK2 (Denmark East and Bornholm) during May in 2019. Source Andreas Thingvad, Ph.D. thesis, DTU, June 2021.

Vessel's battery pack of up to 6.000 kWh with 6 to 9 MVA of peak power connected to the grid, when vessel is at berth at night, readily available in seconds or microseconds, could be very beneficial to correct frequency imbalances in the grid. For the scenarios, further involving 2.232 kWh battery packs ashore, availability will be even better. The potential for use of batteries and Vessel-to-Grid (V2G) for grid balance, in an island perspective, has been analysed in several recent master theses e.g. by Samuel Jansson, University of Upsala (Jansson, 2019), Andreas Thingvad, DTU (Thingvad, 2021), and Buster B. Hansen, SDU (Hansen, 2021). Findings from these three theses is used for calculation of scenario 4.3 and 5.3.

For scenarios with battery packs ashore, arbitrage trading of redundant electricity reserves, when the ferry is enroute, could also gain revenues to the ferry operator. An energy company willing to offer the charging infrastructure, with shore batteries on a service contract, to the ferry operator could also perform this. Such contract could lower the investment costs for ferry operator and would most likely result in a fixed added cost to electricity price for the ferries. This will be discussed further in chapter 7.

Investment costs are ballpark figures only. More accurate figures for each choice of design, e.g. charging stations at both ports or battery packs ashore, would require extensive and costly design studies, and price quotes from suppliers. Investment costs used, are based on investment budgets from the application to the Danish Civil Aviation and Railway Authority (Municipality of Ærø, 2022) combined with market knowledge, experience from the Horizon 2020 E-Ferry project and quotes from other projects to assess deviations from the base scenario described in the application.

The E-Ferry Twin project used for this case study was modified in December 2022 (S2022-5468 Clarification of project description, 2022). The ferry size was downscaled some from 80 meter to 69,5 meter and Passenger Car Units (PCU) downed from 80 to 67 units. It has been assumed that these modifications will not change port infrastructure requirements significantly. Although a smaller ferry obtains some weight savings the relative wave resistance typically grows with shorter overall length of hull (Nielsen, 2016).

Consumption for propulsion is based on CFD (Computer Fluid Dynamics) calculations from Naval Architects for high tension steel Double-Ender hull design. Calculations are very early estimates and adopted to the route depth and draught for a fully loaded vessel.

Comparative analysis to conventional fossil fuel drivetrain is included in the case study. Also, alternative fuels are discussed in chapter 7.1 as mentioned earlier. Long term energy prices have been extremely volatile for periods and relatively stable for other periods as it can be seen from graphs below:

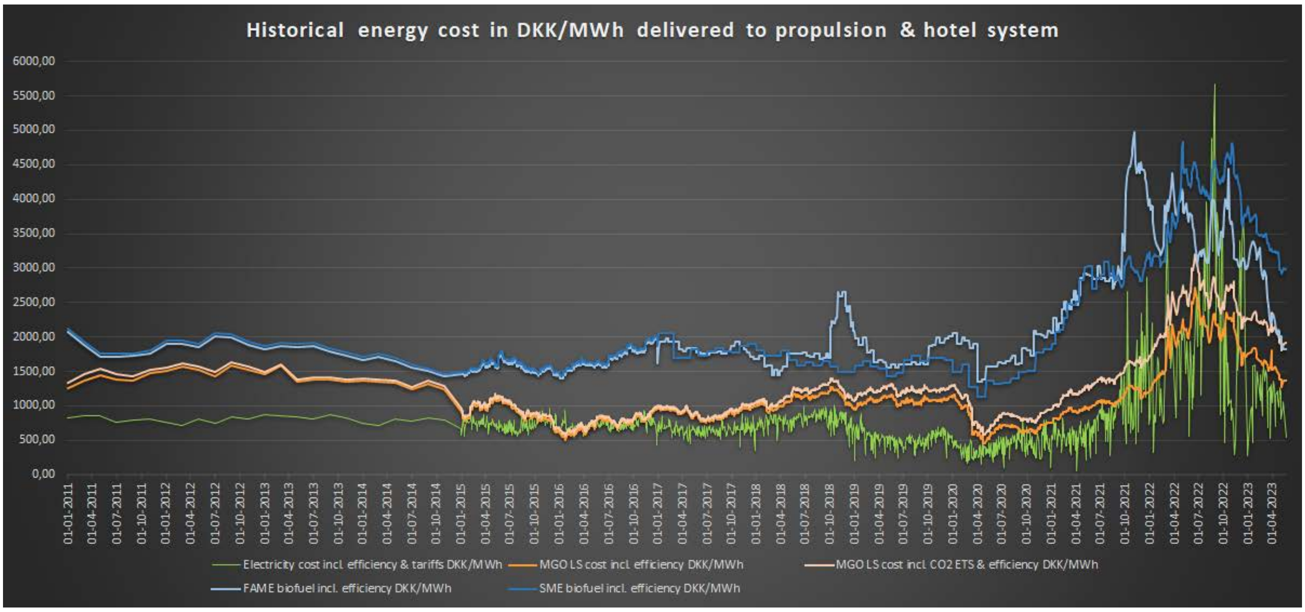


Figure 2.2.6 Long term energy cost comparison for conventional fossil fuel drive train, biofuel drive train and electric battery drivetrain charged with renewable energy. Measured per MWh input to propulsion propeller or hotel power in the ferry. Time resolution of data is monthly until end of 2014. Then almost daily from beginning of 2015 and beyond. Compiled by EMK from multiple sources, Nord Pool, N1, Evonet, Ærø Elforsyning, Energinet, Energi Danmark, Energistyrelsen, Forsyningstilsynet, Platt, Neste, Ærøfærgerne, ÆrøXpressen, European Environment Agency ETS dashboard.

To reflect both a time interval with energy price stability and a time interval with volatile energy prices, the calculated scenarios are divided into two chapters. In chapter 4, the ten-year average from 2011-2021 have been used, reflecting a time period with relatively low energy prices and high stability. In chapter 5, average energy prices are based on the period from 1st of January 2021 until 31st of May 2023, reflecting a period, during geopolitical and pandemic crisis, with high and volatile energy prices, especially for electricity spot prices but also for ancillary service for grid balancing. The latter period also corresponds with introduction of time dependent distribution tariffs for electricity in Denmark, on top of the high volatility. Time dependent tariffs will further enhance price fluctuations on daily basis.

Dividing these two periods is relevant to assess the impact of peak shifting during different economical environments and different tariff regimes. In theory peak shifting will help to keep energy cost down during high volatility periods. It is also likely that demand response and balancing service will generate a higher revenue during volatile periods. This will be tested by comparing scenarios in chapter 4 to similar scenarios in chapter 5.

4 Scenarios and operational setup during energy price stability

In this chapter calculated scenarios are described based on design choices and operational setup and energy prices from the ten-year period 2011-2021 characterised by relatively low and stable energy prices. Sailing schedules and battery or energy balance for each operational day is shown from model calculations and trade-offs are discussed. In the first scenario 4.1, calculation methods are elaborated on in more detail than for the following scenarios.

4.1 Scenario, Double-Ender E-ferry Twins 8,9 MVA grid connections both ports

The first scenario examined is very close to the description forwarded to the Danish Civil Aviation and Railway Authority (Municipality of Ærø, 2022). The peak power of both charging stations is raised from 7,9 to 8,9 MVA to cope with demand for the steel hull weight. Ship battery pack is kept at 6 MWh for each E-Ferry Twin. For this base scenario, there is no shore-based battery pack.

Battery capacity used for scenario 3.1 is calculated for a full day of operation including nighttime charging and losses in the charging chain found from the E-ferry Ellen in Søby (T. Heinemann, 2019). Results can be found in graphic below:

Figure 4.1.1 Energy balance or battery capacity used during a full day and night of operation with 12 single trips or 6 roundtrips for one E-Ferry Twin. Compiled by EMK.

Battery State of Charge (SoC) at a given time can be found by dividing y-axis kWh battery capacity used by nominal battery capacity of 6.000 kWh converted to a percentage. E.g., highest SoC at 05:35 will be 4.800 kWh / 6.000 kWh x 100 = 80 % and lowest SoC at 20:53 will be 1200 kWh / 6.000 kWh x 100 = 20 %. The top buffer will ensure sufficient capacity at battery End of Life (EoL) defined as 80% remaining of nominal capacity. The bottom buffer will ensure reserve capacity during the voyage for emergencies and contingency procedures (T. Heinemann, 2019).

The energy consumption from batteries between charges is calculated to be 1.686,7 kWh. This includes drivetrain losses from battery to propeller resulting in a Depth of Discharge (DoD) of 25 % per single trip. The energy delivered to the battery pack during the 15 – 2,5 = 12,5 minutes charging session in each port is 1510 kWh. In real life charging curves are not linear, hence a 90% of the charger's peak power rating of 8,9 MVA has been used for the calculation.

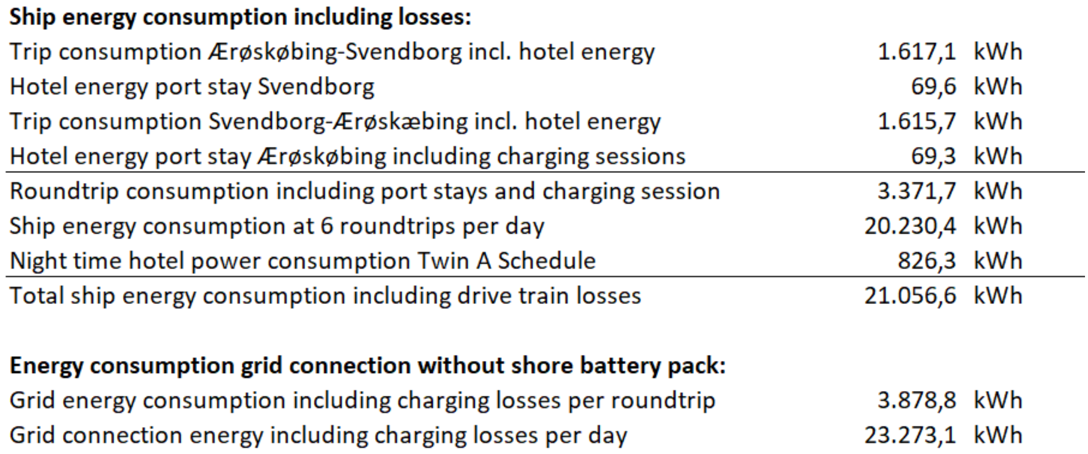
This means that 361 kWh of trip consumption in scenario 3.1, at battery EoL, are reserves from nighttime charging that can be distributed over the day of operation due to needed battery size for sufficient battery life. Earlier in the battery life, the share of nighttime charging could be higher if batteries are charged to e.g., 90% SoC each morning. The first trip of the day will of course be covered fully by nighttime charging always.

However, the large battery size (nominal capacity) is not only required to bring charging time down during the day. It is mostly required to ensure that DoD per roundtrip and charging C-rate do not become too high. High DoD per cycle will degrade battery life faster. Increase in DoD per cycle degrade battery State of Health (SoH) in a logarithmic relationship. Number of cycles before battery SoH reaches 80 % should be around 60.000 to ensure a lifetime of 15 years with 3.850 trips (battery cycles) of 25 % DoD per cycle.

For scenario 3.1 this charging speed rate (C-rate) is found to peak at 1,5 C during charging. This is a relatively high C-rate for classic lithium-ion NMC batteries, hence liquid cooling is needed or the choice of a newer lithium-ion battery type/chemistry. An alternative is a bigger battery pack which would result in a lower C-rate. Discharge rates are found to be much lower, around 0,25 C, and do not constitute for any barrier.

The combination of DoD, C-rate and lithium-ion chemistries (in the E-ferry Graphite/NMC) will decide the possible number of battery cycles when temperature is not a variable. In the ferry battery rooms, at reasonable C-rates, battery temperature can be kept almost constant within a few degrees at room temperature. This is perfect for battery cycle lifetime and also good for battery calendar lifetime. For this scenario a battery lifetime of more than 15 year can be expected based on the key parameters found above.

Energy used per trip and per day in scenario 3.1 can be found in detail in table below:



Ship energy consumption including losses:		
Trip consumption Ærøskøbing-Svendborg incl. hotel energy	1.617,1	kWh
Hotel energy port stay Svendborg	69,6	kWh
Trip consumption Svendborg-Ærøskæbing incl. hotel energy	1.615,7	kWh
Hotel energy port stay Ærøskøbing including charging sessions	69,3	kWh
Roundtrip consumption including port stays and charging session	3.371,7	kWh
Ship energy consumption at 6 roundtrips per day	20.230,4	kWh
Night time hotel power consumption Twin A Schedule	826,3	kWh
Total ship energy consumption including drive train losses	21.056,6	kWh
Energy consumption grid connection without shore battery pack:		
Grid energy consumption including charging losses per roundtrip	3.878,8	kWh
Grid connection energy including charging losses per day	23.273,1	kWh

Table 4.1.1 Energy consumption from batteries and from grid in scenario 4.1 for case study E-ferry Twin A vessel. Source EMK.

The deviation between total ship energy consumption and grid energy consumption could be explained by charging losses from high voltage grid transformer to batteries onboard and roundtrip efficiency of battery system and inverters. In total loss is estimated to be around 10% but will depend on load factor on transformers, charging line, breakers and inverters and C-rates of the battery charging sessions and finally battery temperature and internal resistance in battery cells.

Cost of energy for scenario 4.1 is calculated below based on time of use from grid connection and the 10-year average day and night electricity prices including distribution, transmission, system and balancing tariffs, the EU minimum fee and cost of green certificates for the renewable energy consumed:

Electricity consumption from grid	Per day		Per trip	
Low demand hours	4.857	kWh	405	kWh
High demand hours	18.416	kWh	1.535	kWh
	23.273	kWh	1.939	kWh
Electricity spot prices incl. green certificates				
Spot price night 10-year average	0,186	DKK/kWh		
Spot price day 10-year average	0,257	DKK/kWh		
Transport tariffs				
Low demand constant tariff until 2021	0,1053	DKK/kWh	B-high consumer	
High demand constant tariff until 2021	0,1053	DKK/kWh	B-high consumer	
Transmission & System tariff	0,0853	DKK/kWh	All consumers	
EU minimum fee and green certificates	0,0223	DKK/kWh	All consumers	
Electricity cost	Annual		Annual	
Night charging	3.116.600	kWh	906.840	DKK
Day charging	11.816.949	kWh	4.283.099	DKK
Trans., Sys., min. fee, green cert.	14.933.549	kWh	1.607.447	DKK
Total excl. VAT			**6.797.386**	**DKK**
Average price electricity excl. VAT			0,4552	DKK/kWh
Average price electricity incl. VAT (16% avg. due to tax exemption)			0,5280	DKK/kWh

Table 4.1.2 Electricity cost for scenario 4.1 with E-ferry Twins A & B both operating according to case study schedule on the route from Ærøskøbing to Svendborg based on energy price ten-year average 2011-2021. Source EMK.

When energy costs from scenario 4.1 are compared to energy costs from fossil fuel operation based on same ten-year average time span savings are evident. Fossil fuel consumption is explained in chapter 7.1.

Marine Gas Oil Low Sulfur cost					
Trip consumption	461	kg			
Annual trips	7.700	single trip			
Annual consumption	3.547.033	kg			
Fuel price MGO 10-year avg. 2011-2021*	3,655	DKK/kg	CO2/kg MGO	3,188	kg
Annual fuel costs	12.963.341	DKK			
			*delivered onboard		
Electricity night					
Daily charged	700	kWh			
Spot price night	0,1857	DKK/kWh			
Transport tariff low	0,1316	DKK/kWh	B-low customer		
Trans., Sys., min. fee, green cert.	0,1076				
Annual cost	108.568	DKK			
	Annual			Annual	
Ferry energy cost diesel excl. VAT	**13.071.909**	**DKK**		**14.243.179**	**DKK incl. ETS CO2 quotas**
Energy cost savings from battery operation	Annual				
Savings 10-year avg. 2011-2021	7.278.446	DKK incl. VAT			
Savings if CO2 ETS quotas included	8.637.120	DKK incl. VAT. ETS quotas on avg. 103,58 kr/ton CO2			
Savings if CO2 DK future fee included	22.035.309	DKK incl. VAT. Future minimum fee 1.125 kr/ton CO2			

Table 4.1.3 Calculation of fossil fuel costs with and without CO2 ETS quotas from same time period 2011-2021 for E-ferry Twins A & B hulls fitted with fossil fuel drive train for comparison. Source EMK.

Price savings for battery electric operation are calculated incl. VAT[1] and can be found at the bottom of the table above. Also, cost savings if new Danish minimum fee for CO2 is implemented, is shown for reference.

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[1] Deductible VAT is on average only 16% for ferry operator due to tax exemption for passengers and goods transport.

Comparison of energy costs will not give the full picture of savings in the base scenario of the case study.

Savings on maintenance costs and, to some extent, also crew salaries can be expected as some job positions may require lower competences according to STCW regulations. For this study only maintenance cost savings of the fossil fuel drive train has been assessed at annually 750.000 DKK per 1.500 kW power (P_b) of machinery installed. This is based on other resent EMK assessments (Hagbarth Mikkelsen, 2022).

With an estimated installed machinery capacity of 3000 kW for each new E-ferry Twin, including hotel power/thruster power, this amounts to savings of 3.000.000 DKK per year in maintenance total. However, extra maintenance cost of shore charging stations must be deducted from this. Service costs or contracts and spare parts for both stations are estimated at 1.000.000 DKK per year total in the base scenario 4.1.

All savings though, must be deducted the added investment cost of batteries and shore charging infrastructure compared to a conventional fossil fuelled ferry. For the E-ferry Twin project description, budget estimates of vessels and shore infrastructure costs have been prepared and forwarded to Trafikstyrelsen by the municipality of Ærø (Municipality of Ærø, 2022). However, budgeted costs from here seem not to cover the added requirement for peak charging capacity found when putting CFD based consumption calculations into the spreadsheet model of this case study.

The full cost of shore infrastructure for charging has not been budgeted in the municipality project description, as third-party service provider is expected to cover some investment costs. To be able to assess different scenarios and impact to investment costs if charging infrastructure is changed in various scenarios, an estimation for a revised budget for scenario 4.1 has been prepared by EMK for this study.

Note that one-time connection fee for 8,9 MVA is necessary in order to keep the sailing schedule when also covering charging losses and all drive train losses according to found energy consumption in CFD calculations from Naval Architects. Also costs of inverters, breakers, cooling systems, installation and commissioning etc. have been roughly estimated by EMK, in order for the case study scenarios to be comparative.

Investment costs per charging station			***Notes:***
Grid connection fee 8900 kVA	16.687.500	DKK	*1.875 DKK/kW peak*
AC-DC inverters 1000 kW/unit	9	units	*8,9 MW peak power*
Inverter price per unit	30.000	€	*Estimated*
Inverter price total	2.011.500	DKK	
Onshore breakers	1.000.000	DKK	*Estimated*
Shore charging transformer house	620.125	DKK	*From municipality budget*
Shore battery container	-	DKK	
Cables, boards and controlsystem	3.000.000	DKK	*Estimated*
Charging plug system	3.946.250	DKK	*From municipality budget*
Ventilation and cooling systems	890.000	DKK	*Estimated 100.000 DKK/MW*
Installation and commisioning	1.057.788	DKK	*10% of material costs*
Estimated costs per charging station	29.213.163	DKK	
Estimated costs per charging station	33.887.269	DKK	*VAT included 16%*

Table 4.1.4 Revised budget by EMK per charging station. Two stations of 8,9 MVA peak power are needed to cover base scenario 4.1. Hence investment cost for shore charging stations will be double the estimated total in table above. Source EMK + Municipality budget for project description of E-Ferry Twins (Municipality of Ærø, 2022).

Investments in vessels are not subjected to VAT but shore infrastructure is according to Danish tax regulation. Still ferry operator is only partly subjected to VAT, as explained in foot note earlier.

Other changes to port infrastructure are not included as added investment costs, e.g. new berths, or auto mooring systems, as these changes are also required for all scenarios, even if one chose to implement new conventional fossil fuelled ferries. The purpose of this case study is to perform a comparative analysis. This means, that it is not necessary to find total operating and investment cost of all scenarios, only the differences.

Compared to conventional diesel ferry operation, all investment costs for each shore charging stations in Table 4.1.4 will be added investment costs and they need to be deducted from savings on energy costs to estimate total savings from the scenario analysed.

It is difficult to assess price difference of a newbuilt battery electric ferry versus a newbuilt conventional diesel (or diesel-electric) ferry. However, in order to assess the added investment costs of introducing a battery electric drivetrain for the case study base scenario 4.1, the following comparison of drive train investment costs have been made:

Investment battery system per vessel			***Notes:***
Ship battery pack	6.000	kWh	*Nominel capacity*
Estimated cost per kWh	347	€	*Recent price quote*
Battery price total	15.520.833	DKK	
DC-DC inverters 250 kW/unit	36	units	*8,9 MW peak power*
Inverter price per unit	10.000	€	*Estimated*
Inverter price total	2.682.000	DKK	
Onboard breakers	1.000.000	DKK	*Estimated*
Boards, cables, FS, controlsystem IAS/PMS	6.000.000	DKK	*Estimated*
Ventilation and cooling systems	1.800.000	DKK	*Estimated 300.000 DKK/MWh*
Installation and commissioning	2.520.283	DKK	*10% of material costs*
Estimated cost per battery system/vessel	29.523.117	DKK	*Not subjected to VAT*
Conventional diesel electric power system			
Cost of 3000 kW diesel gensets	7.200.000	DKK	*4 gensets*
AC-DC or DC-DC inverters 750 kW/unit	4	units	*3 MW peak power*
Inverter price per unit	25.000	€	*Estimated*
Inverter price total	745.000	DKK	
Fuel system incl. pumps, tanks and piping	6.000.000	DKK	*Estimated*
Onboard breakers	360.000	DKK	*Estimated*
Boards, cables, fire system, control system	4.000.000	DKK	*Estimated*
Ventilation and cooling systems	2.800.000	DKK	*Estimated 700.000 DKK/genset*
Installation and comissioning	1.830.500	DKK	*10% of material costs*
Estimated cost per vessel	22.935.500	DKK	*Not subjected to VAT*
Added investment cost per E-ferry Twin	**6.587.617**	**DKK**	*Estimated newbuilding diff.*

Table 4.1.5 Estimated investment costs of power systems for E-ferry Twin and similar sized conventional diesel electric ferry with an installed machinery capacity of 3.000 kW. Source EMK and green upgrade report Hagbarth Mikkelsen 2022.

Added cost per battery vessel is expected to decline in future more mature markets when economies of scale bring battery drivetrain components down.

As for electric cars, buses and trains cross over point for new battery vehicles to be cheaper than new conventional Internal Combustion Engine (ICE) vehicles could be in only a few years (Fortuna, 2022).

Investment calculation, assessing alternative setups, can be a complex matter. The simple static payback method uses added investment divided by annual savings to compare different scenarios, see table on next page:

Savings on maintenance	Annual	
Maintenance savings engine system	3.000.000	DKK
Maintenance cost charging stations	- 1.000.000	DKK incl. VAT
Maintenance savings	2.000.000	DKK incl. VAT

Profit from balancing services	Annual	
Shore battery and 8,9 MVA grid conn.	-	DKK incl. VAT

Energy cost savings	Annual	
Savings 10-year avg. 2011-2021	7.278.446	DKK incl. VAT
Savings if CO2 ETS quotas included	8.637.120	DKK incl. VAT
Savings if CO2 DK future fee included	22.035.309	DKK incl. VAT

Total savings	Annual	
Savings 10-year avg. 2011-2021	9.278.446	DKK incl. VAT
Savings if CO2 ETS quotas included	10.637.120	DKK incl. VAT
Savings if CO2 DK future fee included	24.035.309	DKK incl. VAT

Added investment costs		
Shore charging stations both ports	67.774.537	DKK incl. VAT
E-ferry Twins A & B compared to diesel	13.175.233	DKK
Total added cost base scenario	80.949.770	DKK incl. VAT

Simple liniar pay back calculation	
Based on savings 10-year avg. 2011-2021	8,7 years
Based on savings if CO2 ETS quotas included	7,6 years
Based on savings if CO2 DK future fee incl.	3,4 years

Note: Present value method can be found in next figure/graph

Table 4.1.6 Simple linear pay back calculations for added investment for scenario 4.1 based on assumptions stated above and three different electricity cost scenarios, without CO2 costs and with respectively ETS quotas trading price 2011-2021 and with future agreed Danish minimum CO2 fee on fossil fuel. Source EMK.

The simple static payback method will not show if the investment is profitable if the discount rate for the investment is to be considered. An internal discount rate of 4%, typically recommended by the Danish Ministry of Transport (FIU Alm.del Bilag 21, 2018) for transport modelling and socio-economic effects, has been used below to include the alternative cost of capital for the ferry operator's investment:

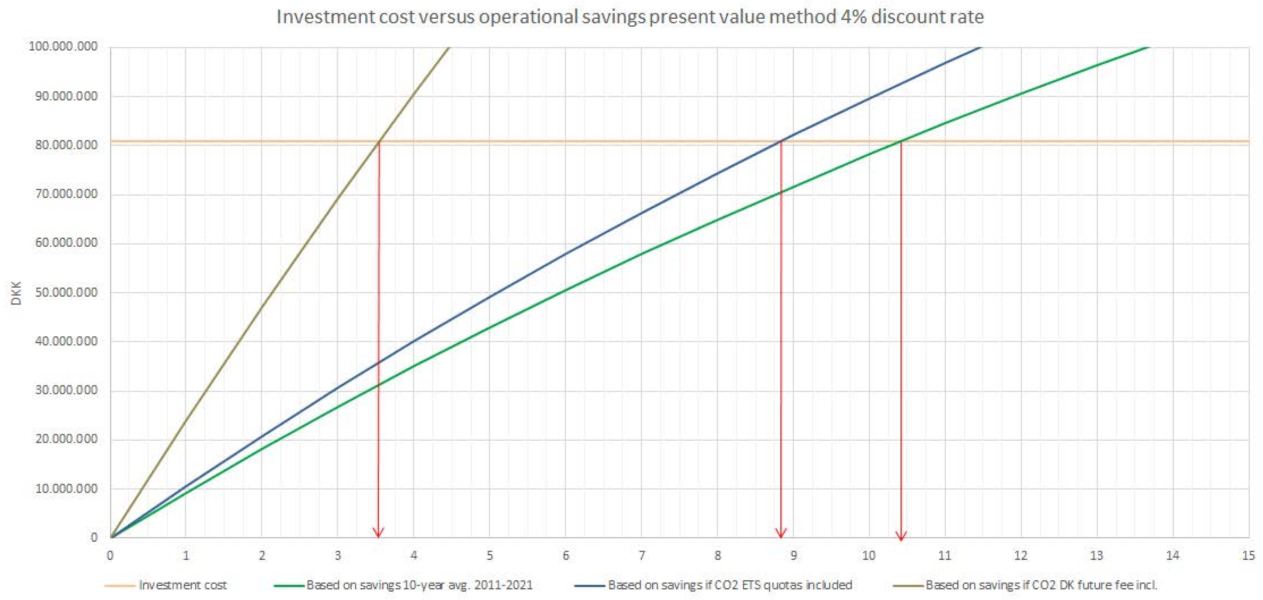


Figure 4.1.2 Accumulated savings discounted to present value with discount rate of 4% versus present investment costs incl. VAT of 16% for shore-based charging stations. Source EMK.

In the present value method, future costs are discounted back to present value here with an annual discount rate of 4% by dividing calculated added annual savings with $(1+0,04)^{y}$ where y is the year after construction. All savings are then accumulated, as above, to find saving parity with investment cost today.

In the present value method, future savings or future costs are weighted lower than present or short-term savings or costs. This will impact the time of parity making parity arriving later, or with no break-even at all in some cases if savings are marginal. The method can also be used to assess if the economic lifetime of the investment is sufficient to create profitability, e.g. before battery packs have to be replaced.

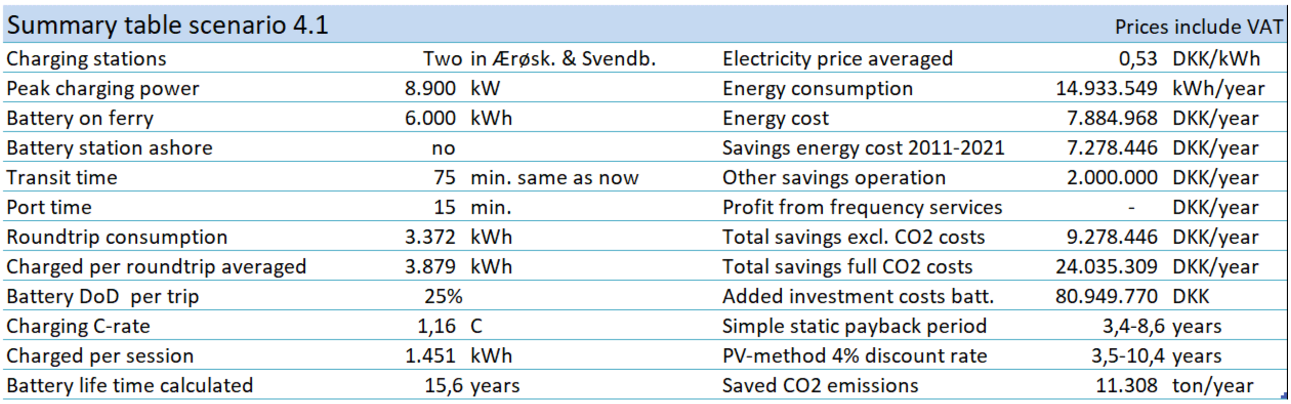
The exchange of battery modules after battery End of Life (EoL) is not included in the spreadsheet model but could be added the present value method. At estimated EoL, for this operational setup after 60.000 cycles, or +15 years, cost of battery exchange per annum at forecasted future battery price could be entered into the present value calculation.

This would result in a dip in the curves of Figure 4.1.2 after battery EoL. However battery EoL is, for most scenarios tested, years after break-even and therefore not considered relevant to apply for now. Looking for a break-even shorter than battery life is a less complex method. This way, sensitivity to long battery price forecasting and high uncertainties is also avoided.

For scenario 4.1 the present value method, with 4 % discount rate and based on input from the spreadsheet model and historical spread in energy price 2011-2021, shows break-even after 10,4 years. Break-even is before calculated EoL of ships battery pack. The sensitivity to discount rate shows that altering discount rate +/-2 % will only move time of parity +/- 1,5 years which is still a rather solid result.

However, annual savings will increase significantly already in this decade when Danish climate legislation is implemented, and national ferries need to comply with coming emission fees on CO2 equivalents and pay fully or partly for the socioeconomic costs of CO2 from fossil fuel operation (Political Agreement on Green Tax, 2022). At a combination of an emission fee and EU ETS quotas of 1.125 DKK per ton CO2, payback time of added investment for chargers and batteries will be only 3,5 years.

This is based on average energy costs from the ten-year period 2011-2021 which reflects a relatively stable energy market. The implication of a more volatile energy market with high energy costs and geopolitical crises can be found in a similar base scenario 5.1 in chapter 5 covering the time period from 1st of January 2021 to 31st of May 2023. In this period also time dependent distribution tariffs were introduced.



Summary table scenario 4.1					Prices include VAT
Charging stations	Two	in Ærøsk. & Svendb.	Electricity price averaged	0,53	DKK/kWh
Peak charging power	8.900	kW	Energy consumption	14.933.549	kWh/year
Battery on ferry	6.000	kWh	Energy cost	7.884.968	DKK/year
Battery station ashore	no		Savings energy cost 2011-2021	7.278.446	DKK/year
Transit time	75	min. same as now	Other savings operation	2.000.000	DKK/year
Port time	15	min.	Profit from frequency services	-	DKK/year
Roundtrip consumption	3.372	kWh	Total savings excl. CO2 costs	9.278.446	DKK/year
Charged per roundtrip averaged	3.879	kWh	Total savings full CO2 costs	24.035.309	DKK/year
Battery DoD per trip	25%		Added investment costs batt.	80.949.770	DKK
Charging C-rate	1,16	C	Simple static payback period	3,4-8,6	years
Charged per session	1.451	kWh	PV-method 4% discount rate	3,5-10,4	years
Battery life time calculated	15,6	years	Saved CO2 emissions	11.308	ton/year

Table 4.1.7 E-ferry Twin case study summary of inputs and findings for base scenario 4.1 with two double-ender steel hull battery electric ferries with transit time of 75 minutes and sailing schedule as of today based on 2011-2021 average energy prices.

4.2 Scenario, Double-Ender E-ferry Twins 6 MVA grid connections and 2,2 MWh shore battery for peak shaving both ports

The second scenario examined is similar to the setup described in scenario 4.1 when it comes to the E-ferry Twin design and sailing schedule. However, in scenario 4.2 shore infrastructure is changed somewhat. Grid connections are reduced from 8,9 MVA to 6 MVA to save investment costs for grid connection fees.

Instead an Energy Storage System (ESS) as a shore-based battery pack of 2,2 MWh is added to charging stations in each port. The ESS will act as buffers and be used for peak shaving during fast-charging sessions. It should be able of adding at least 2 MW of power on a continuous basis. For the rest of the time ESS can be used for peak shifting, grid balancing services or redundance if grid connection gets restricted or fails.

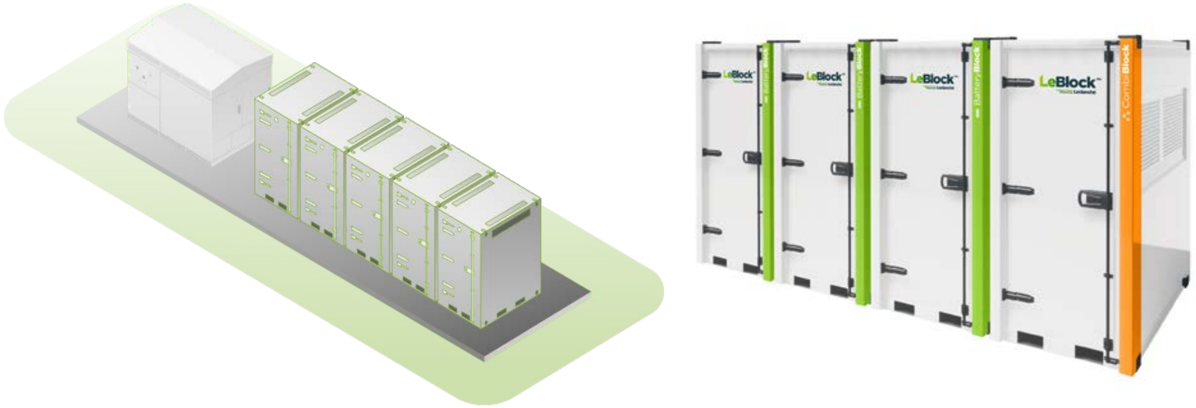


Figure 4.2.1 Leblock^{TM} ESS from battery producer Leclanché with Lithium Iron Phosphate cells. Three battery blocks and one combi block for interconnection and battery management has the size of a twenty-foot shipping container. Footprint of a 3 MWh system will be around 110 m2 including power conversion components and Energy Management System (EMS). Source Leclanché.

Onboard batteries and charging connections to the E-ferry Twins are not changed in this scenario. In table below estimated investment costs for one charging station can be found:

Investment costs per charging station with shore-based ESS			***Notes:***
Grid connection fee 6000 kVA	11.250.000	DKK	*1.875 DKK/kVA peak*
AC-DC inverters 1000 kW/unit	6	units	*6 MW peak power from grid*
Inverter price per unit	30.000	€	*Estimated*
DC-DC inverters 250 kW/unit	12	units	
Inverter price per unit	10.000	€	*Estimated*
Inverter price total	2.235.000	DKK	
Onshore breakers	1.000.000	DKK	*Estimated*
Shore charging transformer house	620.125	DKK	*From municipality budget*
Shore battery container 2232 kWh	7.812.000	DKK	*Estimated*
Cables, boards and controlsystem	3.000.000	DKK	*Estimated*
Charging plug system	3.946.250	DKK	*From municipality budget*
Ventilation and cooling systems	600.000	DKK	*Estimated 100.000 DKK/MW*
Installation and commisioning	1.861.338	DKK	*10% of material costs*
Estimated costs per charging station	32.324.713	DKK	
Estimated costs per charging station	37.496.667	DKK	*VAT included 16%*

Table 4.2.1 Investment costs per charging stations including ESS of 3 MWh storage capacity and 3 MW peak power from batteries.

Roundtrip efficiency for the shore-based ESS is expected to be 0,92 according to product specification from Tesla Megapack systems (Tesla, 2023), Leclanché (Leclanché, 2023) or SHGroup (SHGroup, 2023). This means that extra energy costs are added to cover losses for the share of energy charged to the E-ferry Twins from the shore-based ESS. Lithium iron phosphate cells are assumed and will be discharging at C-rate of around 0,9C with DoD below 25% to ensure sufficient battery life in the ESS, see Table 4.2.3.

Energy consumption grid connection with shore battery system:			
Charged from shore battery per charging sesssion	422	kWh	*Energy delivered from shore battery pack to charging system*
Sessions per day where shore battery is used	11	Sessions	*First trip consumption is provided directly by grid from night charging*
Saved grid energy during 11 charging sessions	4.647	kWh	*Daily energy deliverd from shore battery system to charging system*
Grid energy to recharge shore battery pack per session including losses	459	kWh	*Energy consumption from grid to refill shore battery system*
Grid energy to recharge shore battery pack per day including losses	5.051	kWh	*Daily consumption from grid to refill shore battery charging system*
Added energy consumption from grid per day with shore battery pack	404	kWh	*To be repaid by savings from peak shifting and lower connection fee*

Table 4.2.2 Total energy consumption from grid connection is increased due to roundtrip efficiency of shore battery system of 0,92. Source EMK.

These losses have been incorporated into the spreadsheet model for scenario 4.2 and extra 404 kWh need to be repaid by savings form peak shaving, peak shifting, lower connection fee and grid balancing services.

Each charging station with shore-based battery system will be utilized as described in Table 4.2.3 below:

Charging station with shore battery pack:			***Notes:***
Grid connection maximum continuous power	6.000	kVA	*Grid connection including power factor*
Needed continous power from shore battery pack	2.033	kW	*Shore battery pack power including losses in DC-DC inverters*
Shore battery pack nominal capacity	2.232	kWh	*Nominal storage capacity of shore battery pack*
Shore battery pack discharge continuous rate	0,91	C-rate	*Discharge C-rates can be much higher than charge C-rates*
Shore battery pack discharge duration (longest)	00:12:28	tt:mm:ss	*Short high peak disharging periods will leave sufficient time for cooling*
Battery energy per discharge cycle	422	kWh	*Energy delivered from shore battery pack to charging system*
Depth of Discharge per discharge cycle	19%	DoD	*Higher DoD reduces number of cycles before End of Life (EoL)*
Grid energy directly to ferry during port stay	1.247	kWh	*Grid connection will deliver max continuous power during port stay*
Time to recharge shore battery pack	01:23:46	tt:mm:ss	*Shore battery pack will recharge while ships are enroute*
Efficiency loss recharging shore battery pack	0,92	Efficiency	*Assumed charging roundtrip efficiency grid to shore battery to charging line*
Energy to recharge shore battery pack including losses	459	kWh	*Required energy from grid to recharge shore battery pack when ship is enroute*
Added consumption per battery roundtrip/session	37	kWh	*Losses due to shore battery system roundtrip efficiency*
Required recharging power for shore battery pack	329	kVA	*Grid connection power required including power factor*
Share battery pack charge continuous rate	0,15	C-rate	*Low C-rate important to obtain high charging efficiencies and preserve battery*
Life time cycles at DoD before SOH<70% LiFePo4 cells	90.000	cycles	*With LFP chemistries 3.850 cycles per year expected battery life time +25 years*

Table 4.2.3 Showing how shore battery system is utilized during port stay and between port stays in daily operation with the case study E-ferry Twins. Night charging not included nor peak shifting or balancing services. Source EMK.

Cost of energy for scenario 4.2 is reduced by introducing peak shaving. As seen from Table 4.2.3 delivered energy to charging station is 422 kWh per session. Utilising 80% of nominal battery capacity of 2.232 kWh, this is sufficient to peak shave four charging sessions and can be performed two times per day.

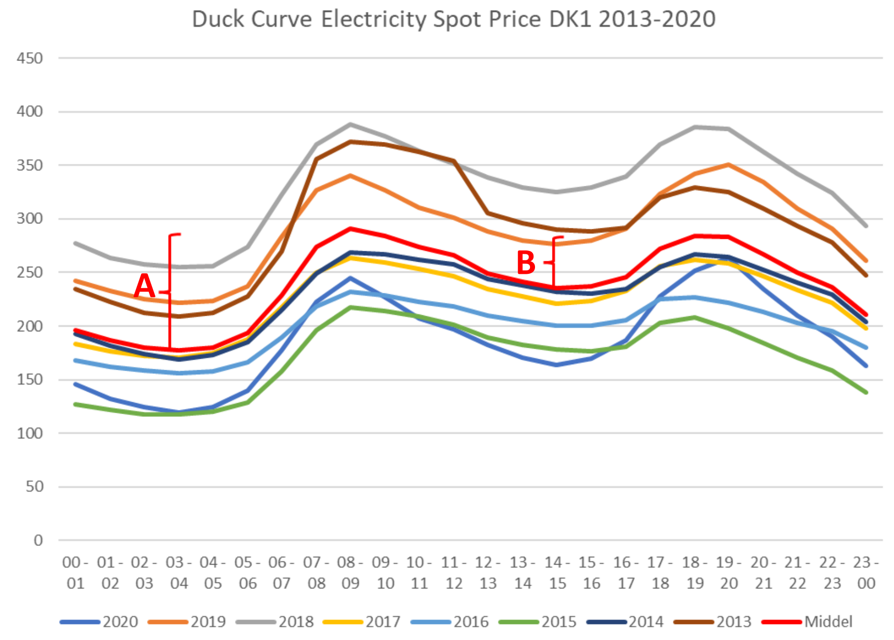


Figure 4.2.2 Hourly spot prices average DKK/MWh for electricity in DK1. Interval A is the night to morning price difference and B the afternoon to evening price difference on average for the data series 2013-2020. Compiled from Nord Pool data by EMK.

Based on the duck curve from chapter 3, average electricity spot price can be reduced by storing extra 1.785 kWh of electricity from the lowest night rates on each shore charging station. When this stored energy is used during the morning, then shore batteries can again be fully charged during the lowest rates of the afternoon on average between 14:00 to 15:00 hours. At a charge rate of 1C, equalling around 2 MW from the grid connection, refilling will only take around one hour.

This way lowest night rates are achieved for an extra 1.786 kWh per day of operation during the morning peak with a price reduction, according toFigure 4.2.2, at up to the height (A) of 0,12 DKK/kWh. In the second wave of the day another 1.786 kWh can be shaved off height (B) up to 0,05 DKK/kWh for each port or vessel.

An autonomous charging planning systems with input of daily and hourly electricity spot price and time dependent distribution tariffs will ensure alterations to charging strategies of the shore battery. This is needed in order to optimise for lowest cost when prices fluctuate due to weather conditions or changes in demand and production.

For this scenario 4.2, there are no time dependent tariffs. But in chapter 5 time dependent tariffs fluctuate quite a bit as they were introduced from beginning of 2021. Especially in years of high electricity prices the difference between low demand, high demand and peak demand distribution tariffs will increase, often with some delay. Source N1 price lists 2021-2023 (N1, 2023).

Electricity consumption from grid	Per day	Twin A		Per trip	
Low demand hours average	4.857	kWh		405	kWh
Lowest hour duck curve night	1.941	kWh		162	kWh
Lowest hour duck curve afternoon	1.941	kWh		162	kWh
High demand hours average	14.938	kWh		1.245	kWh
Daily consumption with shore battery	23.677	kWh		1.973	kWh
Daily consumption without shore battery	*23.273*	*kWh, see scenario 4.1*			
Added consumption from shore battery	*404*	*kWh*			
Electricity spot prices incl. green certificates					
Spot price night 10-year average	0,186	DKK/kWh			
Spot price lowest hour duck curve	0,177	DKK/kWh			
Spot price lowest hour duck curve afternoon	0,236	DKK/kWh			
Spot price day 10-year average	0,257	DKK/kWh			
Transport tariffs					
Low demand constant tariff until 2021	0,1053	DKK/kWh	B-high consumer		
High demand constant tariff until 2021	0,1053	DKK/kWh	B-high consumer		
Transmission & System tariff	0,0853	DKK/kWh	All consumers		
EU minimum fee and green certificates	0,0223	DKK/kWh	All consumers		
Electricity cost E-ferry Twins A & B	Annual			Annual	
Night charging	3.116.600	kWh		906.840	DKK
Charging lowest hour duck curve night	1.245.391	kWh		351.867	DKK
Charging lowest hour duck curve afternoon	1.245.391	kWh		424.758	DKK
Day charging	9.585.445	kWh		3.474.282	DKK
Trans., Sys., min. fee, green cert.	15.192.828	kWh		1.635.356	DKK
Total cost with shore battery excl. VAT				**6.793.102**	**DKK**
Total cost without shore battery excl. VAT, see scenrio 4.1				*6.797.386*	*DKK*
Average price electricity excl. VAT				0,4471	DKK/kWh
Average price electricity incl. VAT (16% avg. due to tax exemption)				0,5187	DKK/kWh

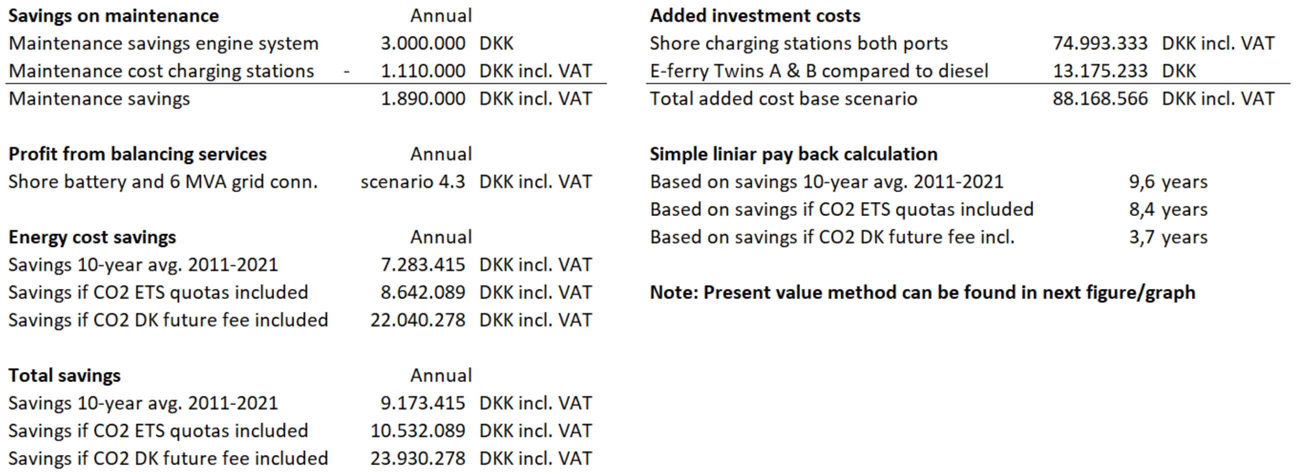
Table 4.2.4 Electricity cost for scenario 4.2 with E-ferry Twins A & B and both charging stations equipped with shore-based batteries of 2,2 MWh each. Same sailing schedule as for scenario 4.1 and calculations based on energy price ten-year average 2011-2021. Source EMK,

When electricity costs are compared to scenario 4.1, peak shifting to hours with low demand, using shore-based batteries, saves almost nothing, 4.284 DKK excl. VAT annually. Although shifted energy is quite significant, the difference between high and low demand prices, for the time period used in chapter 4, is too low to really gain from peak shifting and pay for the added 404 kWh per day per vessel which is lost due to roundtrip efficiency of the ESS shore-based system. Average price of electricity is only lowered from 0,5280 DKK/kWh to 0,5187 DKK/kWh or 1,8%. But extra 259.279 kWh annually total will be needed, although at a lower average price, compared to scenario 4.1.

In chapter 5 scenarios are subjected to much more volatile prices and higher fluctuations, resulting in a duck curve with higher amplitude. At the same time distribution tariffs are made time dependent creating further differences between low and high demand electricity costs. Comparing with scenario 5.2, will show the impact of volatile prices to peak shaving or peak shifting method.

For scenario 4.2 energy costs from fossil fuelled operation would be exactly the same as for scenario 4.1. Other savings, e.g. from maintenance, are almost the same. However added costs for maintenance of both shore-based ESS are estimated to be around 80.000 DKK annually. Source Tesla Megapack (Tesla, 2023).

Hence savings are close to similar and can found from table below:



Savings on maintenance	Annual	
Maintenance savings engine system	3.000.000	DKK
Maintenance cost charging stations	- 1.110.000	DKK incl. VAT
Maintenance savings	1.890.000	DKK incl. VAT
Profit from balancing services	Annual	
Shore battery and 6 MVA grid conn.	scenario 4.3	DKK incl. VAT
Energy cost savings	Annual	
Savings 10-year avg. 2011-2021	7.283.415	DKK incl. VAT
Savings if CO2 ETS quotas included	8.642.089	DKK incl. VAT
Savings if CO2 DK future fee included	22.040.278	DKK incl. VAT
Total savings	Annual	
Savings 10-year avg. 2011-2021	9.173.415	DKK incl. VAT
Savings if CO2 ETS quotas included	10.532.089	DKK incl. VAT
Savings if CO2 DK future fee included	23.930.278	DKK incl. VAT

Added investment costs		
Shore charging stations both ports	74.993.333	DKK incl. VAT
E-ferry Twins A & B compared to diesel	13.175.233	DKK
Total added cost base scenario	88.168.566	DKK incl. VAT
Simple liniar pay back calculation		
Based on savings 10-year avg. 2011-2021	9,6	years
Based on savings if CO2 ETS quotas included	8,4	years
Based on savings if CO2 DK future fee incl.	3,7	years
Note: Present value method can be found in next figure/graph		

Table 4.2.5 Simple linear pay back calculations for added investment for scenario 4.2 added shore batteries and based on assumptions stated above and three different electricity cost scenarios, without CO2 costs and with respectively ETS quotas trading price 2011-2021 and with future agreed Danish minimum CO2 fee on fossil fuel. Source EMK.

Comparing added investment cost and savings from lower operating cost, the simple static payback method shows one year extra to break-even compared to scenario 4.1. Although operational savings are almost the same, added investment costs are 7.218.796 DKK higher in scenario 4.2 due to the two ESS facilities in ports. These investments are not outweighed by the reduced grid connection fees or savings from peak shifting.

For the present value method with a discount rate of 4%, see results in Figure 4.2.3 on next page:

Figure 4.2.3 Accumulated savings discounted to present value with discount rate of 4% versus present investment cost incl. deductible VAT of 16% for shore-based charging stations. Source EMK.

For scenario 4.2 the present value method, with 4 % discount rate and based on input from the spread sheet model and historical average in energy price 2011-2021, it shows profitability after 11,8 years. A year later as for the base scenario 4.1. Break-even is still before calculated EoL for ships battery pack and the shore-based batteries are not cycled as deep and therefore will last even longer.

However, also in this scenario, annual savings will increase significantly already in this decade when Danish climate legislation is implemented. With the planned emission fee of 1.125 DKK per ton CO2, payback time of added investment for chargers and batteries will be only 3,9 years.

Again, this is based on average energy costs from the ten-year period 2011-2021 that reflects a relatively stable energy market. The implication of a more volatile energy market can be found in chapter 5. Here also time dependent distribution tariffs are introduced. Time dependent tariffs will have a positive impact on savings from peak shaving.

The shore-based ESS could also be used for grid balancing services and generate revenues and profits. This is evaluated in scenario 4.3 and 5.3.

Summary table scenario 4.2					Prices include VAT
Charging stations	Two	in Ærøsk. & Svendb.	Electricity price averaged	0,52	DKK/kWh
Grid connection	6.000	kVA	Energy consumption	15.192.828	kWh/year
Battery on ferry	6.000	kWh	Energy cost	7.879.999	DKK/year
Battery station ashore	2.232	kWh 2 MW contin.	Savings energy cost 2011-2021	7.283.415	DKK/year
Transit time	75	min. same as now	Other savings operation	1.890.000	DKK/year
Port time	15	min.	Profit from frequency services	scenario 4.3	DKK/year
Roundtrip consumption	3.372	kWh	Total savings excl. CO2 costs	9.173.415	DKK/year
Charged per roundtrip averaged	3.879	kWh	Total savings full CO2 costs	23.930.278	DKK/year
Battery DoD per trip	25%		Added investment costs batt.	88.168.566	DKK
Charging C-rate	1,16	C	Simple static payback period	3,7-9,6	years
Charged per session	1.451	kWh	PV-method 4% discount rate	3,9-11,8	years
Battery life time calculated	15,6	years	Saved CO2 emissions	11.308	ton/year

Table 4.2.6 E-ferry Twin case study summary of inputs and findings for base scenario 4.2 with two double-ender steel hull battery electric ferries, transit time of 75 minutes and shore batteries at charging stations. Based on 2011-2020 average energy prices.

4.3 Scenario, Double-Ender E-ferry Twins 6 MVA grid connections and 2,2 MWh shore battery + ancillary services both ports

The third scenario examined is similar to the setup described in scenario 4.2 when it comes to the E-ferry Twin design, the shore charging station with shore-based ESS and the sailing schedule with transit times of 75 min. However, in scenario 4.3 revenues from potential ancillary services, balancing the grid frequency, are evaluated using the shore infrastructure of the charging station and vessels when connected:

- 6 MVA grid connection in each port.
- 2 x Shore-based ESS each with up to 2 MW continuous, or 3 MW peak, discharge power and 2,2 MWh battery capacity.
- Vessel to Grid (V2G) discharging from E-ferry Twins to grid during night stay from onboard 6 MWh battery packs.

Ancillary service (or balancing service) in the E-Ferry Twin case study can be divided into:

- Demand response services.
- “Peaker plant” services using shore-based ESS batteries.
- V2G services using onboard batteries.

As explained in chapter 3, some of the balancing services are based on bids that needs to be symmetrical offering both up and down regulation of power to and from the grid according to strict hour intervals. Here port grid connection, charging infrastructure or excess capacity from these must be standby during the time interval in question.

The party delivering balancing services, e.g. being the ferry, port operator or a third party controlling the system, will be paid by capacity (MW/h) of the bids won to have same capacity standby in a given hour. The frequency balancing and regulating power market in region DK1 is complex and divided into several different types of services as elaborated on in chapter 7.2. The market is undergoing significant changes these years between service product types. But in total, volume of market is expected to increase in coming years due to more intermittent electricity production from wind turbines and PV solar (Energinet, 2023).

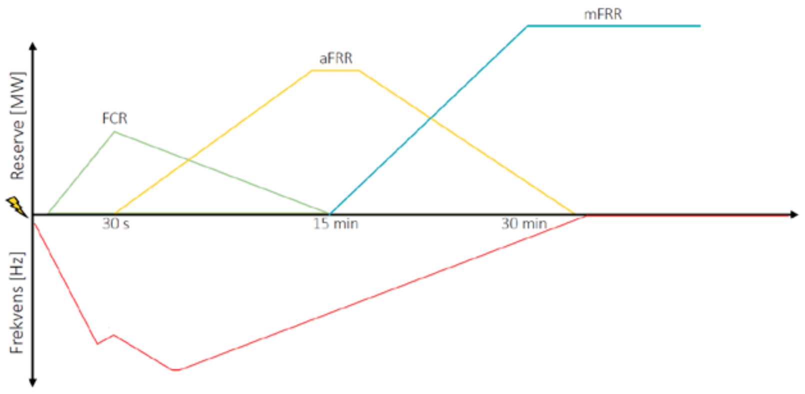


Figure 4.3.1 The three different services for stabilizing frequency through power balancing in DK1 region. Source Energinet

For this case study the service of Frequency Containment Reserves (FCR) in DK1 region has been chosen. This service is also often characterised as the Primary Reserve market for grid frequency balancing. For the time period 2011-2020, used for scenario 4.3, FCR in DK1 was a market only procured in Western Denmark. Since January 2021 the market auctions have been coupled to the German/Continental market for FCR services using the cross-border connection, first partly and since September 2022 fully. The common auctions have resulted in stronger competition leading to much lower prices for FCR services in DK1 after September 2022. But at the same time Danish providers can sell to a bigger market via cross border connection to Germany (Energinet, 5th of January 2023).

For the case study of the E-ferry Twins, operating between islands in region DK1, revenue from providing FCR service for Transmission System Operator (TSO) and Balance Responsible Party (BRP) is considered relevant. Compared to the two alternative balancing capacity services, aFRR and mFRR, the FCR service is characterised by fast response time but also relatively short activation duration of the standby capacity. Hence only a load factor off less than 1% (in 2021 only 0,05%, source Energinet) of the capacity in question will run through the physical system (grid connection and batteries) at the shore charging stations.

This is important as only the redundant capacity of the charging stations and battery systems can be used for grid balancing services. The primary focus of the setup is still to allow for full battery operation of the E-ferry Twins in this case study and not restrict sailing schedule in any way.

Grid balancing services may however affect peak shaving strategies found in scenario 4.2. Therefore savings from peak shaving is reduced 70% accordingly in scenario 4.3. In Table 4.3.1 below estimated profits from 1 kW capacity, traded in the DK1 FCR market for a full year, have been calculated. Profits are not the same for all hours of the day. For this case study two intervals were relevant to calculate. A full 24-hour day and a block of 4 hours per day, starting at midnight. The table below reflects year 2011-2020 prices. Data for load factor, throughput, efficiency, energy loss, tariffs and battery degradation are explained in chapter 7.2.

Profit on average from 1 kW of FCR capacity services in DK1 in one year											
24 hours/day	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**Average**
FCR capacity payment up, MW/h	262,78 DKK	226,33 DKK	236,87 DKK	152,90 DKK	102,56 DKK	119,28 DKK	179,59 DKK	209,86 DKK	275,69 DKK	306,59 DKK	207,25 DKK
FCR capacity payment down, MW/h	79,44 DKK	22,18 DKK	11,28 DKK	11,37 DKK	11,11 DKK	11,11 DKK	10,54 DKK	15,28 DKK	26,22 DKK	82,45 DKK	28,10 DKK
FCR capacity payment 1 kW annually	2.997,82 DKK	2.176,96 DKK	2.173,81 DKK	1.439,05 DKK	995,76 DKK	1.142,20 DKK	1.665,51 DKK	1.972,26 DKK	2.644,75 DKK	3.408,02 DKK	2.061,61 DKK
Up and down capacity during 1 year	17,520 MW/h	17,520 MW/h	17,520 MW/h	17,520 MW/h	17,520 MW/h	17,520 MW/h	17,520 MW/h	17,520 MW/h	17,520 MW/h	17,520 MW/h	17,520 MW/h
Activated reserve load factor 0,84% (2019-20)	0,147 MW/h	0,147 MW/h	0,147 MW/h	0,147 MW/h	0,147 MW/h	0,147 MW/h	0,147 MW/h	0,147 MW/h	0,147 MW/h	0,147 MW/h	0,147 MW/h
Troughput charg./disch. load factor 3,5% (2016)	0,630 MWh	0,630 MWh	0,630 MWh	0,630 MWh	0,630 MWh	0,630 MWh	0,630 MWh	0,630 MWh	0,630 MWh	0,630 MWh	0,630 MWh
Imbalance volume (2016) from 1 kW annually	0,071 MWh	0,071 MWh	0,071 MWh	0,071 MWh	0,071 MWh	0,071 MWh	0,071 MWh	0,071 MWh	0,071 MWh	0,071 MWh	0,071 MWh
Avg. Imbalance price (regulating power), MWh	355,89 DKK	278,03 DKK	283,61 DKK	234,87 DKK	172,70 DKK	194,63 DKK	223,64 DKK	327,22 DKK	289,25 DKK	192,54 DKK	255,24 DKK
Balancing settlements activated energy	25,43 DKK	19,87 DKK	20,27 DKK	16,78 DKK	12,34 DKK	13,91 DKK	15,98 DKK	23,38 DKK	20,67 DKK	13,76 DKK	18,24 DKK
Energy losses and energy management	0,079 MWh	0,079 MWh	0,079 MWh	0,079 MWh	0,079 MWh	0,079 MWh	0,079 MWh	0,079 MWh	0,079 MWh	0,079 MWh	0,079 MWh
Electricity spot price DK1, MWh	369,89 DKK	251,11 DKK	290,11 DKK	233,62 DKK	170,56 DKK	198,52 DKK	223,93 DKK	328,69 DKK	288,07 DKK	187,12 DKK	254,16 DKK
Cost of energy management and losses	29,37 DKK	19,94 DKK	23,03 DKK	18,55 DKK	13,54 DKK	15,76 DKK	17,78 DKK	26,10 DKK	22,87 DKK	14,86 DKK	20,18 DKK
Troughput incl. losses and imbalances, MWh	0,772 MWh	0,772 MWh	0,772 MWh	0,772 MWh	0,772 MWh	0,772 MWh	0,772 MWh	0,772 MWh	0,772 MWh	0,772 MWh	0,772 MWh
Transport tariffs, fees and certificates, MWh	368,14 DKK	451,67 DKK	473,28 DKK	467,64 DKK	489,28 DKK	454,29 DKK	369,06 DKK	389,42 DKK	191,88 DKK	190,09 DKK	384,47 DKK
Cost of tariffs, etc. at energy troughput, MWh	284,08 DKK	348,53 DKK	365,21 DKK	360,86 DKK	377,56 DKK	350,55 DKK	284,79 DKK	300,50 DKK	148,07 DKK	146,69 DKK	296,68 DKK
Battery degradation 1 kW annually (2%)	0,020 kWh	0,020 kWh	0,020 kWh	0,020 kWh	0,020 kWh	0,020 kWh	0,020 kWh	0,020 kWh	0,020 kWh	0,020 kWh	0,020 kWh
Battery module cost per kWh (2023)	2.587 DKK	2.587 DKK	2.587 DKK	2.587 DKK	2.587 DKK	2.587 DKK	2.587 DKK	2.587 DKK	2.587 DKK	2.587 DKK	2.586,81 DKK
Cost of battery degradation 1 kW annually	51,74 DKK	51,74 DKK	51,74 DKK	51,74 DKK	51,74 DKK	51,74 DKK	51,74 DKK	51,74 DKK	51,74 DKK	51,74 DKK	51,74 DKK
Profit from 1 kW of FCR service annually	**2.574,01 DKK**	**1.673,49 DKK**	**1.646,03 DKK**	**917,90 DKK**	**453,55 DKK**	**634,32 DKK**	**1.242,92 DKK**	**1.528,40 DKK**	**2.398,92 DKK**	**3.165,09 DKK**	**1.623,46 DKK**
4 hours/day (00:00-04:00) 1 block	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**Average**
FCR capacity payment up, MW/h	255,13 DKK	185,42 DKK	162,89 DKK	119,18 DKK	66,88 DKK	109,94 DKK	148,22 DKK	190,75 DKK	247,52 DKK	258,69 DKK	174,46 DKK
FCR capacity payment down, MW/h	85,17 DKK	20,44 DKK	10,82 DKK	13,29 DKK	17,22 DKK	11,93 DKK	12,21 DKK	14,52 DKK	23,57 DKK	91,99 DKK	30,12 DKK
FCR capacity payment 1 kW annually	496,85 DKK	301,38 DKK	253,61 DKK	193,41 DKK	122,79 DKK	178,42 DKK	234,23 DKK	299,69 DKK	395,79 DKK	513,39 DKK	298,96 DKK
Up and down capacity during 1 year	2,920 MW/h	2,920 MW/h	2,920 MW/h	2,920 MW/h	2,920 MW/h	2,920 MW/h	2,920 MW/h	2,920 MW/h	2,920 MW/h	2,920 MW/h	2,920 MW/h
Activated reserve load factor 0,84% (2019-20)	0,025 MW/h	0,025 MW/h	0,025 MW/h	0,025 MW/h	0,025 MW/h	0,025 MW/h	0,025 MW/h	0,025 MW/h	0,025 MW/h	0,025 MW/h	0,025 MW/h
Troughput charg./disch. load factor 3,5% (2016)	0,105 MWh	0,105 MWh	0,105 MWh	0,105 MWh	0,105 MWh	0,105 MWh	0,105 MWh	0,105 MWh	0,105 MWh	0,105 MWh	0,105 MWh
Imbalance volume (2016) from 1 kW annually	0,012 MWh	0,012 MWh	0,012 MWh	0,012 MWh	0,012 MWh	0,012 MWh	0,012 MWh	0,012 MWh	0,012 MWh	0,012 MWh	0,012 MWh
Avg. Imbalance price 00-04 (reg. power), MWh	267,95 DKK	196,60 DKK	221,28 DKK	185,64 DKK	125,79 DKK	164,14 DKK	184,96 DKK	265,81 DKK	232,99 DKK	192,54 DKK	130,60 DKK
Balancing settlements activated energy	3,19 DKK	2,34 DKK	2,64 DKK	2,21 DKK	1,50 DKK	1,95 DKK	2,20 DKK	3,17 DKK	2,77 DKK	2,29 DKK	2,43 DKK
Energy losses and energy management	0,013 MWh	0,013 MWh	0,013 MWh	0,013 MWh	0,013 MWh	0,013 MWh	0,013 MWh	0,013 MWh	0,013 MWh	0,013 MWh	0,013 MWh
Electricity spot price (00-04) DK1, MWh	269,48 DKK	182,94 DKK	219,83 DKK	179,29 DKK	120,94 DKK	161,22 DKK	175,92 DKK	263,30 DKK	230,47 DKK	130,35 DKK	193,37 DKK
Cost of energy management and losses	3,57 DKK	2,42 DKK	2,91 DKK	2,37 DKK	1,60 DKK	2,13 DKK	2,33 DKK	3,48 DKK	3,05 DKK	1,72 DKK	2,56 DKK
Troughput incl. losses and imbalances, MWh	0,129 MWh	0,129 MWh	0,129 MWh	0,129 MWh	0,129 MWh	0,129 MWh	0,129 MWh	0,129 MWh	0,129 MWh	0,129 MWh	0,129 MWh
Transport tariffs, fees and certificates, MWh	368,14 DKK	451,67 DKK	473,28 DKK	467,64 DKK	489,28 DKK	454,29 DKK	369,06 DKK	389,42 DKK	191,88 DKK	190,09 DKK	384,47 DKK
Cost of tariffs, etc. at energy troughput, MWh	47,35 DKK	58,09 DKK	60,87 DKK	60,14 DKK	62,93 DKK	58,43 DKK	47,46 DKK	50,08 DKK	24,68 DKK	24,45 DKK	49,45 DKK
Battery degradation 1 kW annually (0,33%)	0,003 kWh	0,003 kWh	0,003 kWh	0,003 kWh	0,003 kWh	0,003 kWh	0,003 kWh	0,003 kWh	0,003 kWh	0,003 kWh	0,003 DKK
Battery module cost per kWh (2023)	2.587 DKK	2.587 DKK	2.587 DKK	2.587 DKK	2.587 DKK	2.587 DKK	2.587 DKK	2.587 DKK	2.587 DKK	2.587 DKK	2.587 DKK
Cost of battery degradation 1 kW annually	8,62 DKK	8,62 DKK	8,62 DKK	8,62 DKK	8,62 DKK	8,62 DKK	8,62 DKK	8,62 DKK	8,62 DKK	8,62 DKK	8,62 DKK
Profit from 1 kW of FCR service annually	**440,50 DKK**	**234,59 DKK**	**183,85 DKK**	**124,48 DKK**	**51,14 DKK**	**111,20 DKK**	**178,01 DKK**	**240,67 DKK**	**362,21 DKK**	**480,89 DKK**	**240,75 DKK**

Table 4.3.1 Calculated revenues and estimated profits from 1 kW of FCR capacity service offered for 24 hours a day and 4 hours a day respectively in DK1 region from 2011-2020. Source compiled by EMK from multiple sources Energidataservice, Nordpool,

Energinet, Forsyningstilsynet (Danish Utility Regulator), Master Thesis of S. Jansson (Evaluation of KPIs and Battery Usage of Li-ion BESS for FCR Application) September 2019, Value paper of A. Thingvad et al (Economic Value of Multi-Market Bidding) June 2021.

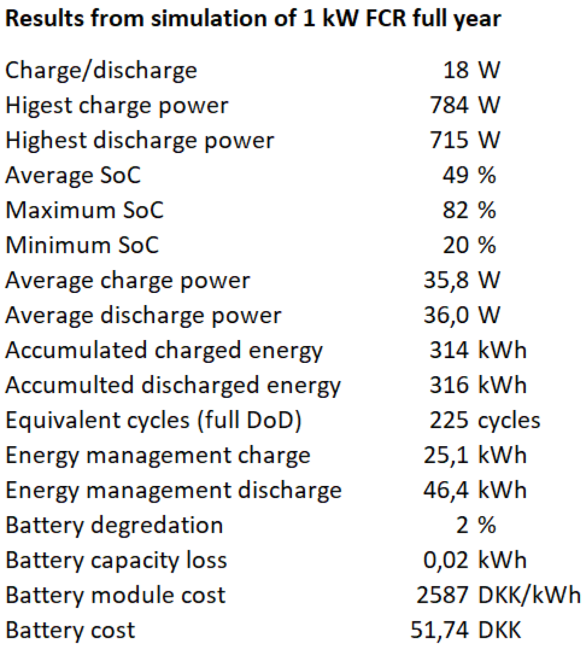
Profits from FCR services in scenario 4.3 outweighs the lower savings from peak shaving according to calculations. In addition there is still room for some peak shaving in combination with FCR services. In the spreadsheet model of scenario 4.3, shore-based batteries of two times 2.232 kWh, at the charging stations, are traded 24 hours per day in the DK1 FCR market with a capacity of two times 1,6 MW/h.

In addition, battery storage capacity of 6.000 kWh of one E-ferry Twin, or a combination of both at berth in the nighttime on the island of Ærø, will be used for V2G services and traded at the first block, 00-04 o'clock, in the DK1 FCR market with a planned capacity of 3,8 MW/h for the four hours per day.

If E-ferry Twins were divided between Ærø and Fyn during nighttime port stays the latter 4 hour per day capacity could double to 7,6 MW/h. But this setup has not been analysed in the model calculation. Thus both E-Ferry Twins are planned to be located in the port on Ærø at night according to normal practice.

Cooperation and coordination with the planned battery electric ferry from Svendborg to Skarø/Drejø could enhance FCR service capacity to be offered from the shore charging station in Svendborg in the nighttime. This could take place at first four hours (first block) after midnight adding battery capacity of the new Skarø/Drejø ferry staying overnight in Svendborg to the FCR service. An operator is allowed to aggregate services although they are at different locations within the DK1 region. This is why it is an advantage that both E-ferry Twins do not berth at the same time of an hour during their daily schedule, see chapter 2.2.

As it can be seen from Table 4.3.1, ferry operator, or third-party provider of shore charging infrastructure, would need to pay for tariffs and energy loss from activated energy according to throughput on the charging and battery systems in use. FCR is a symmetrical service offering with same up- and downward regulation capacities. Hence, volumes of electricity bought and sold in spot market should balance to zero over time.



Results from simulation of 1 kW FCR full year

Charge/discharge	18	W
Higest charge power	784	W
Highest discharge power	715	W
Average SoC	49	%
Maximum SoC	82	%
Minimum SoC	20	%
Average charge power	35,8	W
Average discharge power	36,0	W
Accumulated charged energy	314	kWh
Accumulted discharged energy	316	kWh
Equivalent cycles (full DoD)	225	cycles
Energy management charge	25,1	kWh
Energy management discharge	46,4	kWh
Battery degredation	2	%
Battery capacity loss	0,02	kWh
Battery module cost	2587	DKK/kWh
Battery cost	51,74	DKK

Table 4.3.2 Simulation results expressed at 1 kW of FCR capacity for full year based on an internal Vattenfall computer simulator and 768 kWh ESS with 550 kW grid connection to German grid (FCR service). Compiled by EMK from Master Thesis of S. Jansson, Uppsala University, (Jansson, 2019).

However, in real life, imbalances occur every day. These will be remunerated by balance settlements based on hourly price of regulating power according to registered imbalance volume per hour.

Tariffs on transport of electricity to and from the shore charging stations constitute for the largest part of cost when offering FCR service. Due to the small load factor and short activation durations in the service, battery throughput and therefore battery degradation is marginal. In DK1 and continental Europe a dead-band of ±10 milli Hz to the FCR service ensures some time for restoration of battery SoC when activated.

In the scenario calculation a success rate of won bids in the FCR market is assumed to be 50%. Geography could affect the success rate of won bids due to restrictions in local grid lines. But this problem could interfere both positively and negatively to the probability of winning depending on the expected state of local grid system.

Multimarket bidding could mitigate lost bids if assumed success rate shows to be too high in future market.

The study of Buster B. Hansen, “Flexibility Analysis and Demand Response Optimization of Energy System”, was performed as part of the ZEM North Sea Ports project and with Ærø and Søby grid system as its primary case (Hansen, 2021). His analyses showed that aggregating several sources of flexibility, including the E-ferry in Søby, in a smart grid system could decrease constraints on local 10/60 kW grid transformer station and postpone or mitigate the requirement for upgrading grid infrastructure in an energy system with a high share of intermittent production from wind turbines and PV solar. Increasing the complexity of the energy system with flexible participants, in this case, revealed greater potential in specific components.

However, in general, the E-ferry in Søby displayed little interest in discharging, in contrast, having a noticeable charging modification throughout the entire year in the analysis performed by Buster B. Hansen. Trading in the FCR market was not investigated in mentioned study. Still its findings suggest that using demand response for up- or downward regulation of frequency during planned charging sessions for the E-ferry Twins will be the most efficient way to perform said FCR service.

During charging of vessels or shore-based ESS for the E-ferry Twin operation, tariffs and losses are covered by the ferry operation and would be used anyway. Whereas V2G and shore-based ESS to grid flow and vice versa, only to perform FCR service, will incur added tariffs and losses.

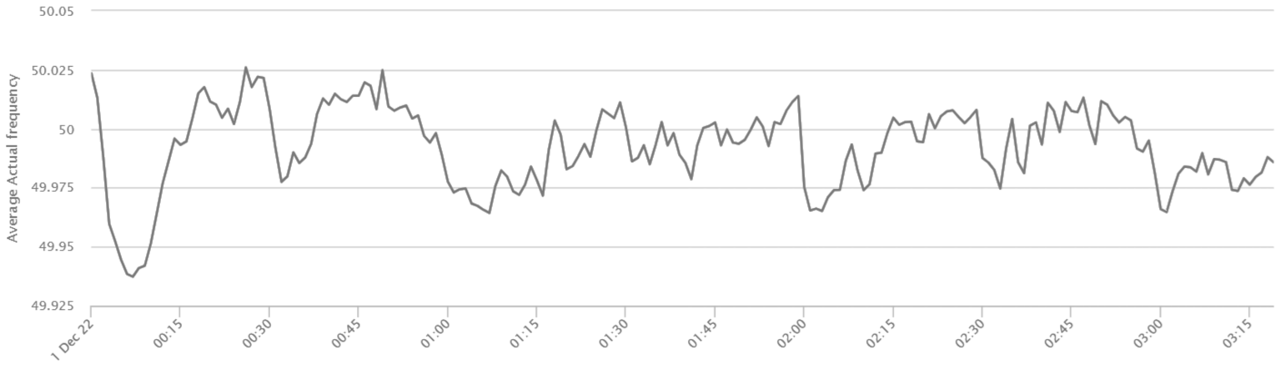


Figure 4.3.2 Grid frequency (3 hours) in the central European grid from midnight, December 1st, 2022. Source Elia Open Data portal.

Calculation of synergies between charging of E-ferries/shore batteries and periods of activated up- or downwards regulation from FCR service would be very complex as grid frequency deviates all the time. However, during long charging periods there is a high likelihood that FCR reserves will be activated during part of the period. But finding this share of time with synergies between charging and FCR services, based on historical data, is not analysed, or included in this case study. Hence full cost of tariffs and losses have been assumed in the calculation as a conservative estimate to identify profits.

FCR service strategy for scenario 4.3 summarised:				*Annually*	
FCR 24h/day service at capacity each shore battery	1.598	kW/h	±	28.005	MW/h
FCR 24h/day maximum power activated statistically	1.253	kW			
FCR 24h/day service power 30% of time below	29	kW			
FCR 4h/day service at capacity from E-ferry at berth	3.802	kW/h	±	11.101	MW/h
FCR 4h/day maximum power activated statistically	2.979	kW			
FCR 4h/day service power 30% of time below	185	kW			
In total			±	39.105	MW/h
Typical volume of DK1 tenders by Energinet before 2021			±	350.400	MW/h
Market share of DK1 if 50% bids are won				6%	

Table 4.3.3 Strategy for trading in DK1 FCR market with E-ferry Twins and shore-based ESS at charging stations. EMK.

Electricity consumption from grid	Per day	Twin A	Per trip	
Low demand hours average	4.857	kWh	405	kWh
Lowest hour duck curve night	607	kWh	51	kWh
Lowest hour duck curve afternoon	607	kWh	51	kWh
High demand hours average	17.607	kWh	1.467	kWh
Daily consumption with shore battery	23.677	kWh	1.973	kWh
Daily consumption without shore battery	*23.273*	*kWh, see scenario 4.1*		
Added consumption from shore battery	*404*	*kWh*		

Electricity spot prices incl. green certificates		
Spot price night 10-year average	0,186	DKK/kWh
Spot price lowest hour duck curve	0,177	DKK/kWh
Spot price lowest hour duck curve afternoon	0,236	DKK/kWh
Spot price day 10-year average	0,257	DKK/kWh

Transport tariffs			
Low demand constant tariff until 2021	0,1053	DKK/kWh	B-high consumer
High demand constant tariff until 2021	0,1053	DKK/kWh	B-high consumer
Transmission & System tariff	0,0853	DKK/kWh	All consumers
EU minimum fee and green certificates	0,0223	DKK/kWh	All consumers

Electricity cost E-ferry Twins A & B	Annual		Annual	
Night charging	3.116.600	kWh	906.840	DKK
Charging lowest hour duck curve night	389.185	kWh	109.958	DKK
Charging lowest hour duck curve afternoon	389.185	kWh	132.737	DKK
Day charging	11.297.858	kWh	4.094.953	DKK
Trans., Sys., min. fee, green cert.	15.192.828	kWh	1.635.356	DKK
Total cost with shore battery excl. VAT			**6.879.844**	**DKK**
Total cost without shore battery excl. VAT, see scenrio 4.1			*6.797.386*	*DKK*
Average price electricity excl. VAT			0,4528	DKK/kWh
Average price electricity incl. VAT (16% avg. due to tax exemption)			0,5253	DKK/kWh

Table 4.3.4 Electricity cost for scenario 4.3 with E-ferry Twins A & B and both charging stations equipped with shore-based batteries of 2,2 MWh each. Same sailing schedule as for scenario 4.1 and 4.2. Peak shaving reduced compared to 4.2. Calculations based on energy price ten-year average 2011-2021. Source EMK.

Peak shifting, using shore-based batteries, is reduced by 70% compared to scenario 4.2. Hence, energy costs are 86.741 DKK higher annually, not including electricity cost for FCR services. This is deducted in Table 4.3.1 and therefore already reflected in profits from FCR services in same table.

Savings on maintenance	Annual	
Maintenance savings engine system	3.000.000	DKK
Maintenance cost charging stations	- 1.110.000	DKK incl. VAT
Maintenance savings total	1.890.000	DKK incl. VAT

Profit from grid balancing services	Annual	
FCR service 24h/day	3.010.203	DKK incl. VAT
FCR service 00h-04h/day	530.839	DKK incl. VAT
Grid balancing services total	3.541.041	DKK incl. VAT

Energy cost savings	Annual	
Savings 10-year avg. 2011-2021	7.182.795	DKK incl. VAT
Savings if CO2 ETS quotas included	8.541.469	DKK incl. VAT
Savings if CO2 DK future fee included	21.939.658	DKK incl. VAT

Total savings	Annual	
Savings 10-year avg. 2011-2021	12.613.837	DKK incl. VAT
Savings if CO2 ETS quotas included	13.972.510	DKK incl. VAT
Savings if CO2 DK future fee included	27.370.699	DKK incl. VAT

Added investment costs		
Shore charging stations both ports	74.993.333	DKK incl. VAT
E-ferry Twins A & B compared to diesel	13.175.233	DKK
Total added cost base scenario	88.168.566	DKK incl. VAT

Simple liniar pay back calculation		
Based on savings 10-year avg. 2011-2021	7,0	years
Based on savings if CO2 ETS quotas included	6,3	years
Based on savings if CO2 DK future fee incl.	3,2	years

Note: Present value method can be found in next figure/graph

Table 4.3.5 Profit from FCR grid balancing service and savings from other sources plus simple linear pay back calculations for added investment for scenario 4.3 and three different electricity cost scenarios, without CO2 costs and with respectively ETS quotas trading price 2011-2021 and with future agreed Danish minimum CO2 fee on fossil fuel. Source EMK.

Comparing added investment costs and savings including estimated profits from FCR services, the simple static payback method shows significantly shorter time to break-even than for scenario 4.1 and 4.2. Added investment costs are the same as for 4.2 but the setup with FCR service generates 3.541.041 DKK annually, according to the assumptions and calculations.

According to the study of Andreas Thingvad et al, “Economic Value of Multi-Market Bidding in Nordic Frequency Markets”, DTU (A. Thingvad, 2023), profits could be further enhanced by multi-market bidding strategies. For the Nordic FCR market multi-market bidding achieved 22%-30% higher profits over five years and over the individual markets analysed. However, E-ferry Twins are operating in the DK-DE LFC block market now and not the Nordic LFC block market.

For the E-ferry Twin case study, multi-market bidding would be relevant for days where bids are not attractive or not won in the FCR auctions. Instead providing regulating power at the mFRR reserve market or entering new future aFRR market could regain some added value for time periods without won bids. Offering voluntary lower bids for some ancillary services is also a possibility. An alternative strategy could be to simply increase peak shaving back to the level described in scenario 4.2, hence saving part of the extra cost of 86.741 DKK for this FCR setup, found on the page above.

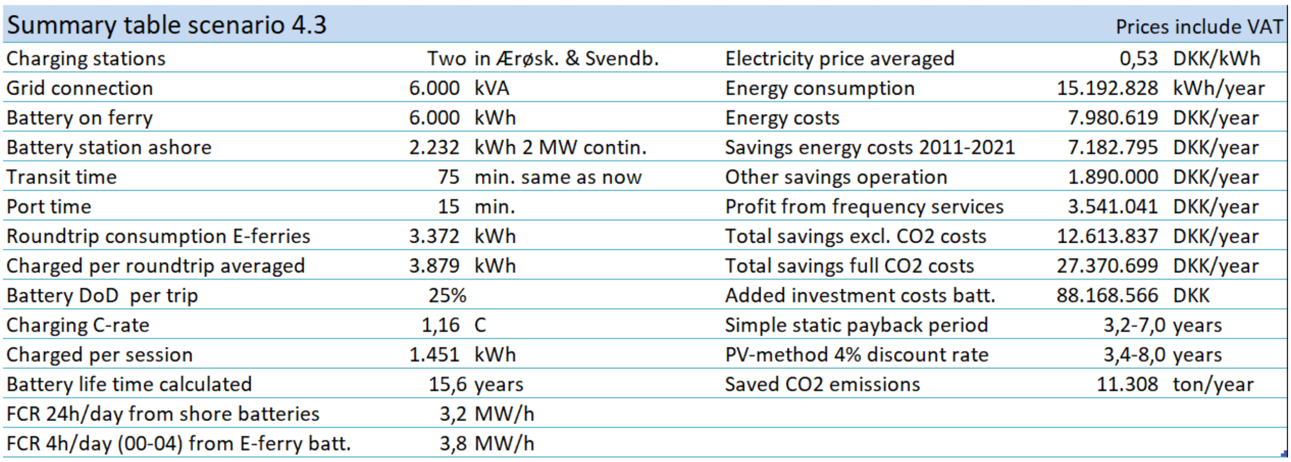
Based on electricity prices and FCR service prices from the period 2011-2020, the present value method with a discount rate of 4% shows solid results for scenario 4.3 with break-even between added investment costs and lower operational costs after 8 years, or even down to only 3,4 years, depending on the CO2 pricing regime chosen:

Figure 4.3.3 Accumulated savings discounted to present value with discount rate of 4% versus present investment cost incl. VAT of 16% for shore-based charging stations and profits from grid balancing FCR services. Source EMK.

Again, this is based on average energy costs from the ten-year period 2011-2021 that reflects a relatively stable energy market. At the same time, price for FCR service was relatively high during this period before region DK1 went into common auctions with Germany and continental Europe for this reserve market. See details in chapter 5.3

The implication of a more volatile energy market with high energy costs and higher share of intermittent production from wind turbines and PV solar can be found in a similar scenario 5.3 in chapter 5 covering the time period from start of 2021 to June 2023. In this period also time dependent distribution tariffs were introduced together with a new market regime for FCR services trading more reserve volumes across borders.

A summary of findings from this scenario 4.3 can be found in table below:



Summary table scenario 4.3					Prices include VAT
Charging stations	Two	in Ærøsk. & Svendb.	Electricity price averaged	0,53	DKK/kWh
Grid connection	6.000	kVA	Energy consumption	15.192.828	kWh/year
Battery on ferry	6.000	kWh	Energy costs	7.980.619	DKK/year
Battery station ashore	2.232	kWh 2 MW contin.	Savings energy costs 2011-2021	7.182.795	DKK/year
Transit time	75	min. same as now	Other savings operation	1.890.000	DKK/year
Port time	15	min.	Profit from frequency services	3.541.041	DKK/year
Roundtrip consumption E-ferries	3.372	kWh	Total savings excl. CO2 costs	12.613.837	DKK/year
Charged per roundtrip averaged	3.879	kWh	Total savings full CO2 costs	27.370.699	DKK/year
Battery DoD per trip	25%		Added investment costs batt.	88.168.566	DKK
Charging C-rate	1,16	C	Simple static payback period	3,2-7,0	years
Charged per session	1.451	kWh	PV-method 4% discount rate	3,4-8,0	years
Battery life time calculated	15,6	years	Saved CO2 emissions	11.308	ton/year
FCR 24h/day from shore batteries	3,2	MW/h			
FCR 4h/day (00-04) from E-ferry batt.	3,8	MW/h			

Table 4.3.6 6 E-ferry Twin case study summary of inputs and findings for base scenario 4.3 with two double-ender steel hull battery electric ferries, transit time of 75 minutes and shore batteries at charging stations. Based on 2011-2020 average energy prices and including balancing services in the FCR market.

5 Scenarios and operational setup during energy price volatility

In this chapter calculated scenarios are described based on design choices and operational setup and energy prices from the latest years from 1st of January 2021 to 1st of June 2023. This time period represents extremely high and volatile energy prices, especially for cost of electricity. Hence, it is interesting to analyse the impact to battery electric operation versus conventional fossil fuel operated ferries but also the effect of peak shifting and balancing service from changes to port infrastructure setup during such volatile periods.

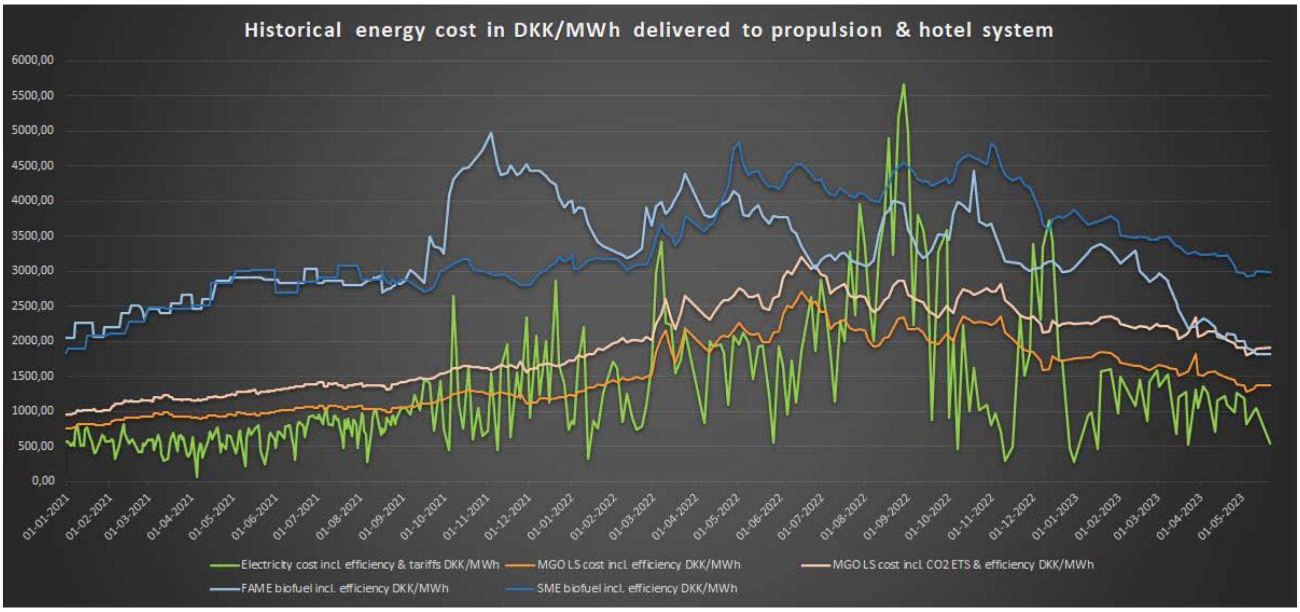


Figure 5.1 Short term energy cost comparison for conventional fossil fuel drive train, biofuel drive train and electric battery drivetrain charged with renewable energy. Measured per MWh input to propulsion propeller or hotel power in the ferry. Compiled by EMK from multiple sources, see details in Figure 2.2.6 .

Sailing schedules and battery or energy balance for each operational day are the same as for scenarios in chapter 4. However, here the impact of geopolitical crisis and high energy prices with significant fluctuations can be assessed and compared to the time period with lower energy price and higher stability from 2011-2021, analysed in chapter 4.

5.1 Scenario, Double-Ender E-ferry Twins 8,9 MVA grid connections both ports

This base scenario is similar to scenario 4.1 from chapter 4 only energy prices have been changed in the calculation to reflect the volatile and high-priced period from 1st of January 2021 to 1st of June 2023. This means that all the technical aspects of the operational setup are the same, and reference is made to these elaborated on in chapter 4.1.

Hence in chapter 5.1 the analysis will only focus on the economic impact of the changed price regime for this rather extreme time period.

Cost of energy for scenario 5.1 is calculated in Table 5.1.1 on next page based on time of use from grid connection and average day and night electricity prices including time dependent distribution, transmission, system and balancing tariffs, the EU minimum fee and cost of green certificates for the renewable energy consumed. Average price of electricity charged to the batteries has, not surprisingly, increased significantly, although distribution tariffs are reduced some, especially the time dependent night tariff:

Electricity consumption from grid	Per day		Per trip	
Low demand hours	4.857	kWh	405	kWh
High demand hours	18.416	kWh	1.535	kWh
	23.273	kWh	1.939	kWh
Electricity spot prices incl. green certificates				
Spot price night 2021-2023 average	0,904	DKK/kWh		
Spot price day 2021-2023 average	1,130	DKK/kWh		
Transport tariffs				
Low demand tariff 2021-2023	0,0282	DKK/kWh	B-high consumer	
High demand tariff 2021-2023	0,0909	DKK/kWh	B-high consumer	
Transmission & System 2023	0,1120	DKK/kWh	All consumers	
EU minimum fee and green certificates	0,0090	DKK/kWh	All consumers	
Electricity cost	Annual		Annual	
Night charging	3.116.600	kWh	2.903.819	DKK
Day charging	11.816.949	kWh	14.431.267	DKK
Trans., Sys., min. fee, green cert.	14.933.549	kWh	1.806.959	DKK
Total excl. VAT			**19.142.046**	**DKK**
Average price electricity excl. VAT			1,2818	DKK/kWh
Average price electricity incl. VAT (16% avg. due to tax exemption)			1,4869	DKK/kWh

Table 5.1.1 Electricity cost for scenario 5.1 with E-ferry Twins A & B both operating according to case study schedule on the route from Ærøskøbing to Svendborg based on energy price average 2021-2023. Source EMK.

When energy costs from battery electric operation, in scenario 5.1, are compared to energy costs from fossil fuel operation, based on same price average time span from 2021-2023, the savings are almost gone:

Marine Gas Oil Low Sulfur cost					
Trip consumption	461	kg			
Annual trips	7.700	single trip			
Annual consumption	3.547.033	kg			
Fuel price MGO avg. 2021-2023*	5,370	DKK/kg	CO2/kg MGO	3,188	kg
Annual fuel costs	19.046.041	DKK			
			*delivered onboard		
Electricity night					
Daily charged	700	kWh			
Spot price night	0,9035	DKK/kWh			
Transport tariff low	0,0352	DKK/kWh	B-low customer		
Trans., Sys., min. fee, green cert.	0,1210				
Annual cost	270.772	DKK			
	Annual		Annual		
Ferry energy cost diesel excl. VAT	**19.316.812**	**DKK**	**24.638.676**	**DKK incl. ETS CO2 quotas**	
Energy cost savings from battery operation	Annual				
Savings avg. energy costs 2021-2023	202.729	DKK incl. VAT			
Savings if CO2 ETS quotas included	6.376.092	DKK incl. VAT. ETS quotas on avg. 470,63 DKK/ton CO2			
Savings if CO2 DK future fee included	14.959.592	DKK incl. VAT. Future minimum fee 1.125 kr/ton CO2			

Table 5.1.2 Calculation of fossil fuel costs with and without CO2 ETS quotas from same time period 2021-2023 for E-ferry Twins A & B hulls fitted with fossil fuel drive train for comparison. Source EMK.

But this is only the case if fossil fuel costs are calculated without any costs of CO2 emissions. The numbers can be found at the bottom of Table 5.1.2. If CO2 ETS quotas from the relevant time period are included, then battery electric operation still shows significant savings on energy cost. Price savings if new Danish minimum fee of 1.125 DKK/ton of CO2 is implemented, is shown for reference.

MGO Low Sulphur average fuel prices excl. VAT have risen from 3.655 DKK/ton in scenario 4.1 to 5.370 DKK/ton in scenario 5.1, an increase of +47%. At the same time average electricity costs excl. VAT have gone up from 0,46 DKK/kWh in scenario 4.1 to 1,28 DKK/kWh, an increase of +178%, with record highs in third quarter of 2022. In 2023 prices dropped back some but only five months of 2023 are in weighed average for chapter 5 scenarios, see also Figure 5.1.

Again, comparison of energy cost only will not give the full picture of savings in the base scenario. Also here same savings on maintenance are to be expected as for scenario 4.1. When savings from lower maintenance costs of battery electric operation are included, then model calculation shows marginal saving compared to conventional fossil fuelled operation. Added investment costs for battery electric operations are considered the same as for scenario 4.1 and are unchanged, see Table 5.1.3 below:

Savings on maintenance	Annual	
Maintenance savings engine system	3.000.000	DKK
Maintenance cost charging stations	- 1.000.000	DKK incl. VAT
Maintenance savings	2.000.000	DKK incl. VAT
Profit from balancing services	Annual	
Shore battery and 8,9 MVA grid conn.	-	DKK incl. VAT
Energy cost savings	Annual	
Savings avg. energy costs 2021-2023	202.729	DKK incl. VAT
Savings if CO2 ETS quotas included	6.376.092	DKK incl. VAT
Savings if CO2 DK future fee included	14.959.592	DKK incl. VAT
Total savings	Annual	
Savings avg. energy costs 2021-2023	2.202.729	DKK incl. VAT
Savings if CO2 ETS quotas included	8.376.092	DKK incl. VAT
Savings if CO2 DK future fee included	16.959.592	DKK incl. VAT

Added investment costs		
Shore charging stations both ports	67.774.537	DKK incl. VAT
E-ferry Twins A & B compared to diesel	13.175.233	DKK
Total added cost base scenario	80.949.770	DKK incl. VAT
Simple liniar pay back calculation		
Based on savings avg. 2021-2023	36,7	years
Based on savings if CO2 ETS quotas included	9,7	years
Based on savings if CO2 DK future fee incl.	4,8	years
Note: Present value method can be found in next figure/graph		

Table 5.1.3 Simple linear pay back calculations for added investment for scenario 5.1 based on assumptions stated above and three different electricity cost scenarios, without CO2 costs and with respectively CO2 ETS quotas trading price 2021-2023 (to June) and also with future agreed Danish minimum CO2 fee on fossil fuel. Source EMK.

The simple static payback method shows an almost infinite time to break-even between added investment costs and savings from operation if CO2 emission costs are not considered. Same is the case for the present value method with an applied discount rate of 4%:

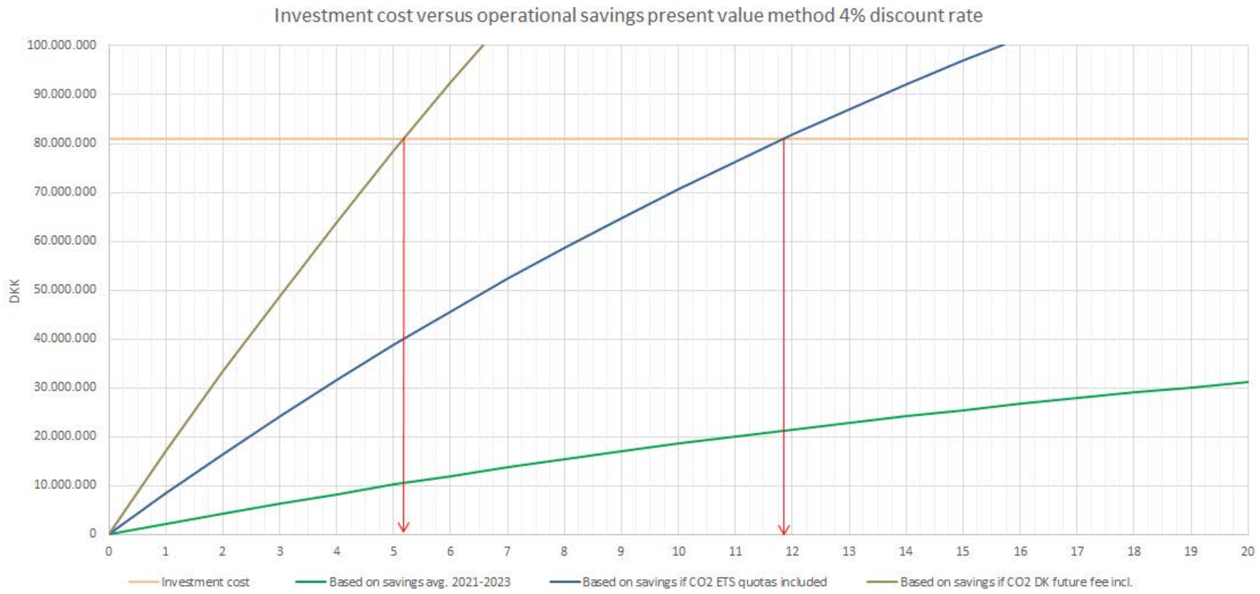


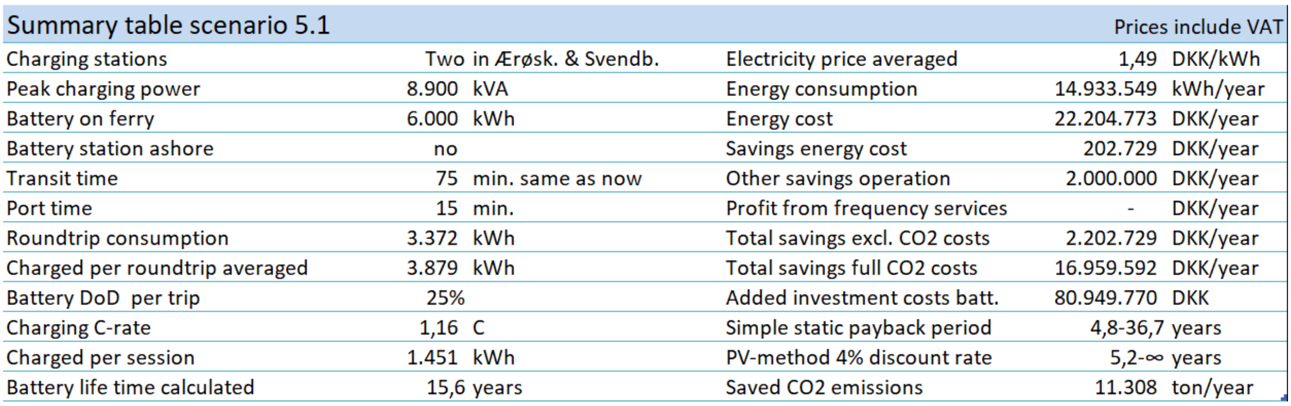
Figure 5.1.1 Accumulated savings discounted to present value with discount rate of 4% versus present investment cost incl. VAT of 16% for shore-based charging stations. Source EMK.

However if costs of CO2 emissions are considered, then base scenario 5.1 shows high profitability compared to conventional fossil fuelled operation despite the extremely high electricity price used in the model calculations for this time period.

When Danish climate legislation is implemented, and national ferries need to comply with coming emission fees on CO2 equivalents at a rate of 1.125 DKK per ton CO2, then payback time of added investment for chargers and batteries will be only 5,2 years.

This is based on average energy costs from 2021-2023, a period of crisis that reflects a high priced and volatile energy market. When looked at together with the more stable and relatively low priced energy market from 2011-2021, scenario 4.1 and 5.1 can be used to assess the outlines of the E-ferry Twin case study. Analysis in scenario 4.1 showed break-even after 3.5 years, including future Danish CO2 emission fee, and was, not surprisingly, more attractive for the battery electric setup.

Based on history it is likely that future dynamic of the energy market will be contained by these outlines. Thus realistic scenarios for the future could be made by combining results from the two.



Summary table scenario 5.1					Prices include VAT
Charging stations	Two	in Ærøsk. & Svendb.	Electricity price averaged	1,49	DKK/kWh
Peak charging power	8.900	kVA	Energy consumption	14.933.549	kWh/year
Battery on ferry	6.000	kWh	Energy cost	22.204.773	DKK/year
Battery station ashore	no		Savings energy cost	202.729	DKK/year
Transit time	75	min. same as now	Other savings operation	2.000.000	DKK/year
Port time	15	min.	Profit from frequency services	-	DKK/year
Roundtrip consumption	3.372	kWh	Total savings excl. CO2 costs	2.202.729	DKK/year
Charged per roundtrip averaged	3.879	kWh	Total savings full CO2 costs	16.959.592	DKK/year
Battery DoD per trip	25%		Added investment costs batt.	80.949.770	DKK
Charging C-rate	1,16	C	Simple static payback period	4,8-36,7	years
Charged per session	1.451	kWh	PV-method 4% discount rate	5,2-∞	years
Battery life time calculated	15,6	years	Saved CO2 emissions	11.308	ton/year

Table 5.1.4 E-ferry Twin case study summary of inputs and findings for base scenario 5.1 with two double-ender steel hull battery electric ferries with transit time of 75 minutes and sailing schedule as of today based on 2021-2023 (to June) average energy prices.

5.2 Scenario, Double-Ender E-ferry Twins 6 MVA grid connection and 2,2 MWh shore battery for peak shaving both ports

The second scenario in chapter 5 is similar to the setup described in scenario 4.2 when it comes to the E-ferry Twin design, sailing schedule and port infrastructure with shore-based battery at the charging station.

Cost of energy for scenario 5.2 is reduced by introducing peak shifting like in scenario 4.2. However price variations are much different, as spreadsheet model calculations are based on price data from 2021-2023 and time dependent distributions tariffs averaged over the same period. Hence, the duck curve for the hourly electricity spot price has a more volatile and significant expression:

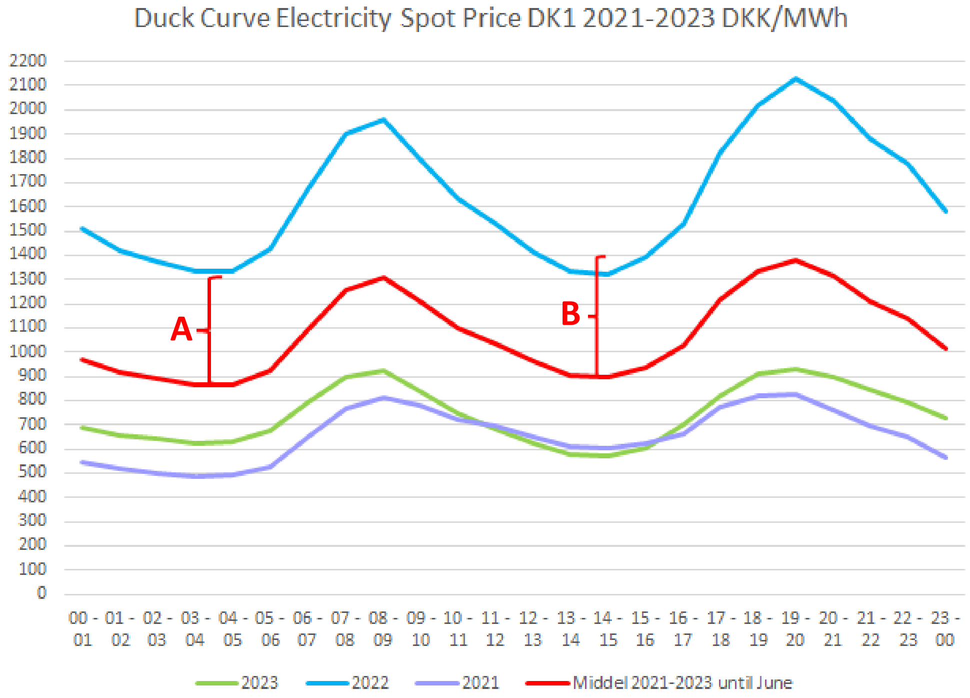


Figure 5.2.1 Hourly spot prices average DKK/MWh for electricity in DK1 (Compiled from Nord Pool data by EMK). Interval A is the night to morning price difference and B the afternoon to evening price difference on average for the data series 2021-2023.

With higher amplitudes on the duck curve, savings generated from peak shaving will increase. Again average electricity spot price can be reduced by storing extra 1.785 kWh of electricity from the lowest night rates on each shore charging station. When this stored energy is used during the morning, then shore batteries can again be fully charged during the lowest rates of the afternoon on average between 14:00 to 15:00 hours. At a charge rate of 1C (1 MW power/1 MWh capacity), equalling around 2 MW from the grid connection, refilling will only take one hour.

According to Figure 5.2.1, savings from night to morning can be up to the height (A) of 450 DKK/MWh. In the second wave of the day shaved off height (B) can be even higher up to 490 DKK/MWh for average fluctuations.

On top of this comes time dependent distribution tariffs that have varied 60 DKK/MWh between low demand charging times and high demand charging times on average in the period 2021-2023. Source N1 price lists 2021-2023 (N1, 2023).

Electricity consumption from grid	Per day	Twin A		Per trip	
Low demand hours average	4.857	kWh		405	kWh
Lowest hour duck curve night	1.941	kWh		162	kWh
Lowest hour duck curve afternoon	1.941	kWh		162	kWh
High demand hours average	14.938	kWh		1.245	kWh
Daily consumption with shore battery	23.677	kWh		1.973	kWh
Daily consumption without shore battery	*23.273*	*kWh, see scenario 4.1 or 5.1*			
Added consumption from shore battery	*404*	*kWh*			
Electricity spot prices incl. green certificates					
Spot price night 2021-2023 average	0,904	DKK/kWh			
Spot price lowest hour duck curve	0,862	DKK/kWh			
Spot price lowest hour duck curve afternoon	0,895	DKK/kWh			
Spot price day 2021-2023 average	1,130	DKK/kWh			
Transport tariffs					
Low demand avg. tarif 2021-2023	0,0282	DKK/kWh	B-high consumer		
High demand constant tarif until 2021	0,0909	DKK/kWh	B-high consumer		
Transmission & System 2023	0,1120	DKK/kWh	All consumers		
EU minimum fee and green certificates	0,0090	DKK/kWh	All consumers		
Electricity cost E-ferry Twins A & B	Annual			Annual	
Night charging	3.116.600	kWh		2.903.819	DKK
Charging lowest hour duck curve night	1.245.391	kWh		1.108.233	DKK
Charging lowest hour duck curve afternoon	1.245.391	kWh		1.227.811	DKK
Day charging	9.585.445	kWh		11.706.078	DKK
Trans., Sys., min. fee, green cert.	15.192.828	kWh		1.838.332	DKK
Total cost with shore battery excl. VAT				**18.784.273**	**DKK**
Total cost without shore battery excl. VAT, see scenrio 5.1				*19.142.046*	*DKK*
Average price electricity excl. VAT				1,2364	DKK/kWh
Average price electricity incl. VAT (16% avg. due to tax exemption)				1,4342	DKK/kWh

Table 5.2.1 Electricity cost for scenario 5.2 with E-ferry Twins A & B and both charging stations equipped with shore-based batteries of 2,2 MWh each. Same sailing schedule as for scenario 4.1 and 5.1 and calculations based on energy price average 2021-2023. Source EMK.

When electricity costs are compared to scenario 5.2 peak shifting to hours with low demand using shore-based batteries saves 357.773 DKK excl. VAT annually. The high-priced energy scenario shows higher savings from peak shifting methods than for the lower priced scenario with same peak shifting methods, see chapter 4.2, where savings were only 4.284 DKK.

This means that the added 404 kWh per day per vessel which is lost due to roundtrip efficiency of the ESS shore-based system is fully repaid, even though average price of electricity is only lowered from 1282 DKK/MWh to 1236 DKK/MWh or 3,5% compared to base scenario 5.1.

Here in chapter 5, scenarios are subjected to much more volatile prices and higher fluctuations resulting in a duck curve with higher amplitude, as seen in Figure 5.2.1. At the same time distribution tariffs are made time dependent creating further differences between low and high demand electricity costs. Comparing scenario 4.2 and 5.2 will show the impact of volatile price regimes to peak shaving or peak shifting.

For scenario 5.2 energy costs from fossil fuelled operation would be same as for scenario 5.1. Still savings of energy differs due to the peak shifting using shore-based batteries and associated savings and losses from these methods:

Marine Gas Oil Low Sulfur cost					
Trip consumption	461	kg			
Annual trips	7.700	single trip			
Annual consumption	3.547.033	kg			
Fuel price MGO avg. 2021-2023*	5,370	DKK/kg	CO2/kg MGO	3,188	kg
Annual fuel costs	19.046.041	DKK			
			*delivered onboard		
Electricity night					
Daily charged	700	kWh			
Spot price night	0,9035	DKK/kWh			
Transport tariff low	0,0352	DKK/kWh	B-low customer		
Trans., Sys., min. fee, green cert.	0,1210				
Annual cost	270.772	DKK			
	Annual		Annual		
Ferry energy cost diesel excl. VAT	**19.316.812**	**DKK**	**24.638.676**	**DKK incl. ETS CO2 quotas**	
Energy cost savings from battery operation	Annual				
Savings year avg. 2021-2023	617.746	DKK incl. VAT			
Savings if CO2 ETS quotas included	6.791.108	DKK incl. VAT. ETS quotas on avg. 470,63 kr/ton CO2			
Savings if CO2 DK future fee included	15.374.608	DKK incl. VAT. Future minimum fee 1.125 kr/ton CO2			

Table 5.2.2 Calculation of fossil fuel costs with and without CO2 ETS quotas from same time period 2021-2023 for E-ferry Twins A & B hulls fitted with fossil fuel drive train for comparison. Source EMK.

Other savings e.g. from maintenance are almost the same except for an extra cost of maintenance of shore-based ESS facilities estimated to be around 80.000 DKK annually growing 2% per year (Tesla, 2023).

Hence annual savings are a little bit higher but also have to cover higher added investment costs:

Savings on maintenance	Annual	
Maintenance savings engine system	3.000.000	DKK
Maintenance cost charging stations	- 1.110.000	DKK incl. VAT
Maintenance savings	1.890.000	DKK incl. VAT
Profit from Ancillary services	Annual	
Shore battery and 6 MVA grid conn.	-	DKK incl. VAT
Energy cost savings	Annual	
Savings year avg. 2021-2023	617.746	DKK incl. VAT
Savings if CO2 ETS quotas included	6.791.108	DKK incl. VAT
Savings if CO2 DK future fee included	15.374.608	DKK incl. VAT
Total savings	Annual	
Savings year avg. 2021-2023	2.507.746	DKK incl. VAT
Savings if CO2 ETS quotas included	8.681.108	DKK incl. VAT
Savings if CO2 DK future fee included	17.264.608	DKK incl. VAT

Added investment costs		
Shore charging stations both ports	74.993.333	DKK incl. VAT
E-ferry Twins A & B compared to diesel	13.175.233	DKK
Total added cost base scenario	88.168.566	DKK incl. VAT
Simple liniar pay back calculation		
Based on savings avg. 2021-2023 (to June)	35,2	years
Based on savings if CO2 ETS quotas included	10,2	years
Based on savings if CO2 DK future fee incl.	5,1	years

Note: Present value method can be found in next figure/graph

Table 5.2.3 Simple linear pay back calculations for added investment for scenario 5.2 added shore batteries and based on assumptions stated above and three different electricity cost scenarios, without CO2 costs and with respectively ETS quotas trading price 2021-2023 (to June) and with future agreed Danish minimum CO2 fee on fossil fuel. Source EMK.

As for chapter 4, added investments costs are 7.218.796 DKK higher in scenarios with ESS in each port. Comparing added investment costs and savings from lower operating cost, the simple static payback method still shows almost infinite time to break-even if costs of CO2 emissions are not included. If emission costs are included, scenario 5.2 indicates close to same payback time as for scenario 5.1 which had no shore-based ESS. Meaning that added cost of the ESS is approximately repaid by peak shifting or peak shaving method and lower investment for grid connection fees.

For the present value method with a discount rate of 4% see results in Figure 4.2.3 on next page:

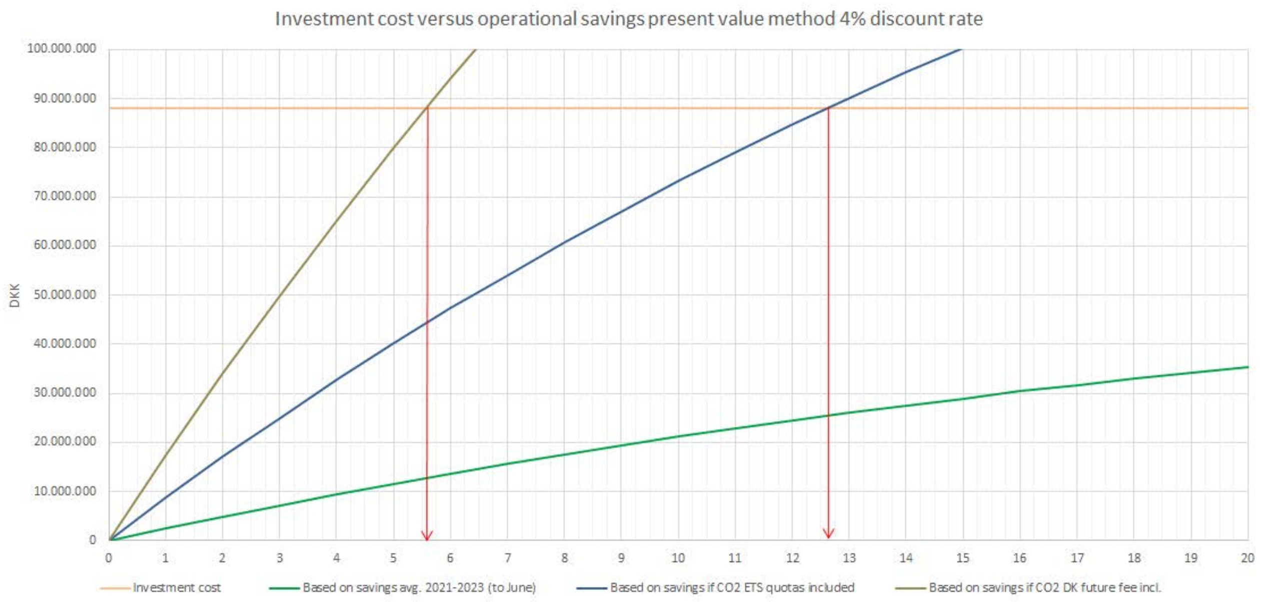


Figure 5.2.2 Accumulated savings discounted to present value with discount rate of 4% versus present investment cost incl. VAT of 16% for shore-based charging stations.

For scenario 5.2 the present value method, with 4 % discount rate, and based on input from the spread sheet model and historical spread in energy price 2021-2023 (-June), including DK future fee on CO2 emissions, shows break-even after 5,7 years. Break-even, including mentioned fee, is almost 2 years worse than similar operational setup described in scenario 4.2 that was based on year 2011-2020 price interval.

Hence, the electricity price increase (+177%) compared to the not so increased fossil fuel price (+47%) in year 2020-2023 cannot be fully repaid by peak shifting methods alone. However, the larger amplitude between daily high and low electricity price, tariffs included, will almost repay the added investment of the shore-based ESS installation when comparing to scenario 5.1. But this was also the case in 2011-2020 price regime, looking at scenario 4.1 compared to 4.2. Thus some of the extra value from peak shaving in scenario 5.2 price regime (2021-2023) helped to cover higher electricity prices as well.

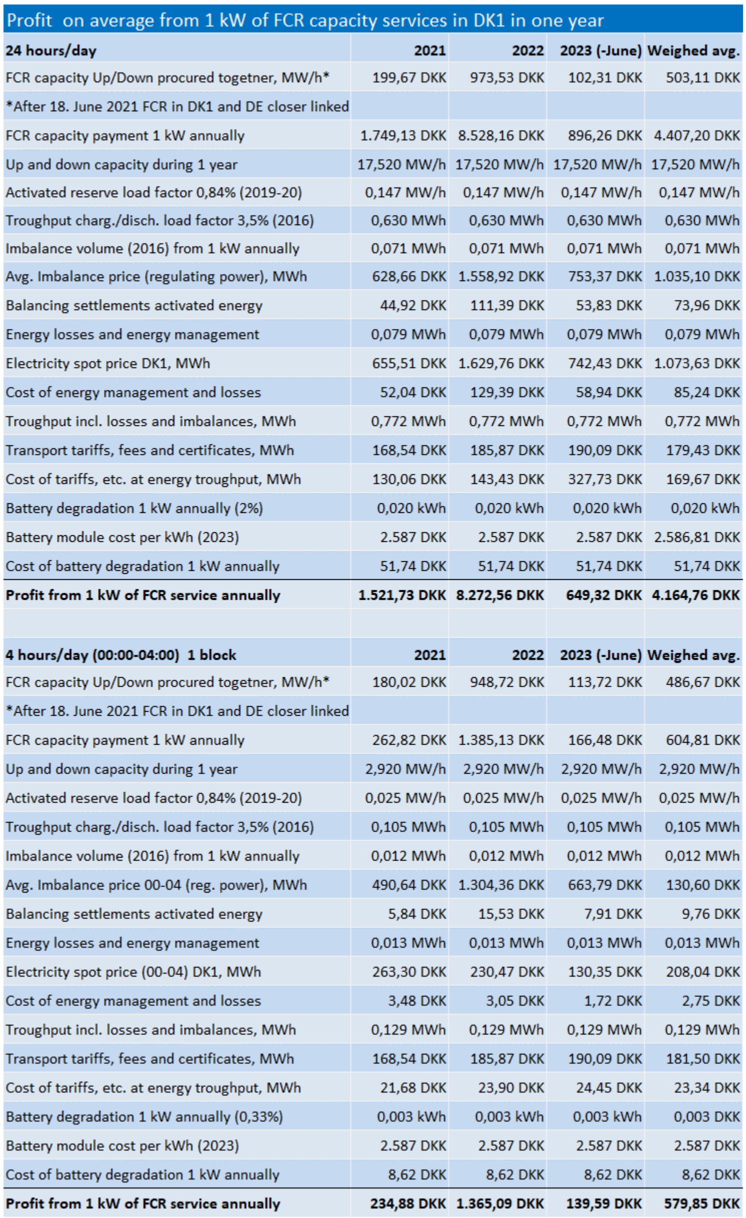
Summary table scenario 5.2					Prices include VAT
Charging stations	Two	in Ærøsk. & Svendb.	Electricity price averaged	1,43	DKK/kWh
Grid connection	6.000	kVA	Energy consumption	15.192.828	kWh/year
Battery on ferry	6.000	kWh	Energy cost	21.789.757	DKK/year
Battery station ashore	2.232	kWh 2 MW contin.	Savings energy cost 2021-2023/05	617.746	DKK/year
Transit time	75	min. same as now	Other savings operation	1.890.000	DKK/year
Port time	15	min.	Profit from frequency services	-	DKK/year
Roundtrip consumption	3.372	kWh	Total savings excl. CO2 costs	2.507.746	DKK/year
Charged per roundtrip averaged	3.879	kWh	Total savings full CO2 costs	17.264.608	DKK/year
Battery DoD per trip	25%		Added investment costs batt.	88.168.566	DKK
Charging C-rate	1,16	C	Simple static payback period	5,1-35,2	years
Charged per session	1.451	kWh	PV-method 4% discount rate	5,6-∞	years
Battery life time calculated	15,6	years	Saved CO2 emissions	11.308	ton/year

Table 5.2.4 E-ferry Twin case study summary of inputs and findings for scenario 5.2 with two double-ender steel hull battery electric ferries with transit time of 75 minutes and sailing schedule as of today, shore-based ESS and based on 2021-2023 average energy prices.

5.3 Scenario, Double-Ender E-ferry 6 MVA grid connections and 2,2 MWh shore battery + ancillary services both ports

The third scenario examined is similar to the setup described in scenario 5.2 when it comes to the E-ferry Twin design, the shore charging station with shore-based ESS and the sailing schedule. However, in scenario 5.3 revenues, costs and profits from potential ancillary services are evaluated like for scenario 4.3.

Providing ancillary services together with E-ferry Twins operation in this case study is elaborated on in chapter 3, chapter 4.3 and chapter 7.2. Hence, focus in this scenario 5.3 will be to assess how volatile spot prices, but also volatile revenues, from ancillary services will influence same operational setup compared to scenario 4.3 which had both lower and less fluctuating prices and revenues. Again, FCR service is chosen for the ancillary service to be evaluated. The table below reflects year 2021-2023 (to June) revenues, costs and profits. Data for throughput, energy loss, tariffs degradation etc. are again explained in chapter 7.2.



Profit on average from 1 kW of FCR capacity services in DK1 in one year				
24 hours/day	**2021**	**2022**	**2023 (-June)**	**Weighed avg.**
FCR capacity Up/Down procured togetner, MW/h*	199,67 DKK	973,53 DKK	102,31 DKK	503,11 DKK
*After 18. June 2021 FCR in DK1 and DE closer linked				
FCR capacity payment 1 kW annually	1.749,13 DKK	8.528,16 DKK	896,26 DKK	4.407,20 DKK
Up and down capacity during 1 year	17,520 MW/h	17,520 MW/h	17,520 MW/h	17,520 MW/h
Activated reserve load factor 0,84% (2019-20)	0,147 MW/h	0,147 MW/h	0,147 MW/h	0,147 MW/h
Troughput charg./disch. load factor 3,5% (2016)	0,630 MWh	0,630 MWh	0,630 MWh	0,630 MWh
Imbalance volume (2016) from 1 kW annually	0,071 MWh	0,071 MWh	0,071 MWh	0,071 MWh
Avg. Imbalance price (regulating power), MWh	628,66 DKK	1.558,92 DKK	753,37 DKK	1.035,10 DKK
Balancing settlements activated energy	44,92 DKK	111,39 DKK	53,83 DKK	73,96 DKK
Energy losses and energy management	0,079 MWh	0,079 MWh	0,079 MWh	0,079 MWh
Electricity spot price DK1, MWh	655,51 DKK	1.629,76 DKK	742,43 DKK	1.073,63 DKK
Cost of energy management and losses	52,04 DKK	129,39 DKK	58,94 DKK	85,24 DKK
Troughput incl. losses and imbalances, MWh	0,772 MWh	0,772 MWh	0,772 MWh	0,772 MWh
Transport tariffs, fees and certificates, MWh	168,54 DKK	185,87 DKK	190,09 DKK	179,43 DKK
Cost of tariffs, etc. at energy troughput, MWh	130,06 DKK	143,43 DKK	327,73 DKK	169,67 DKK
Battery degradation 1 kW annually (2%)	0,020 kWh	0,020 kWh	0,020 kWh	0,020 kWh
Battery module cost per kWh (2023)	2.587 DKK	2.587 DKK	2.587 DKK	2.586,81 DKK
Cost of battery degradation 1 kW annually	51,74 DKK	51,74 DKK	51,74 DKK	51,74 DKK
Profit from 1 kW of FCR service annually	**1.521,73 DKK**	**8.272,56 DKK**	**649,32 DKK**	**4.164,76 DKK**
4 hours/day (00:00-04:00) 1 block	**2021**	**2022**	**2023 (-June)**	**Weighed avg.**
FCR capacity Up/Down procured togetner, MW/h*	180,02 DKK	948,72 DKK	113,72 DKK	486,67 DKK
*After 18. June 2021 FCR in DK1 and DE closer linked				
FCR capacity payment 1 kW annually	262,82 DKK	1.385,13 DKK	166,48 DKK	604,81 DKK
Up and down capacity during 1 year	2,920 MW/h	2,920 MW/h	2,920 MW/h	2,920 MW/h
Activated reserve load factor 0,84% (2019-20)	0,025 MW/h	0,025 MW/h	0,025 MW/h	0,025 MW/h
Troughput charg./disch. load factor 3,5% (2016)	0,105 MWh	0,105 MWh	0,105 MWh	0,105 MWh
Imbalance volume (2016) from 1 kW annually	0,012 MWh	0,012 MWh	0,012 MWh	0,012 MWh
Avg. Imbalance price 00-04 (reg. power), MWh	490,64 DKK	1.304,36 DKK	663,79 DKK	130,60 DKK
Balancing settlements activated energy	5,84 DKK	15,53 DKK	7,91 DKK	9,76 DKK
Energy losses and energy management	0,013 MWh	0,013 MWh	0,013 MWh	0,013 MWh
Electricity spot price (00-04) DK1, MWh	263,30 DKK	230,47 DKK	130,35 DKK	208,04 DKK
Cost of energy management and losses	3,48 DKK	3,05 DKK	1,72 DKK	2,75 DKK
Troughput incl. losses and imbalances, MWh	0,129 MWh	0,129 MWh	0,129 MWh	0,129 MWh
Transport tariffs, fees and certificates, MWh	168,54 DKK	185,87 DKK	190,09 DKK	181,50 DKK
Cost of tariffs, etc. at energy troughput, MWh	21,68 DKK	23,90 DKK	24,45 DKK	23,34 DKK
Battery degradation 1 kW annually (0,33%)	0,003 kWh	0,003 kWh	0,003 kWh	0,003 DKK
Battery module cost per kWh (2023)	2.587 DKK	2.587 DKK	2.587 DKK	2.587 DKK
Cost of battery degradation 1 kW annually	8,62 DKK	8,62 DKK	8,62 DKK	8,62 DKK
Profit from 1 kW of FCR service annually	**234,88 DKK**	**1.365,09 DKK**	**139,59 DKK**	**579,85 DKK**

Table 5.3.1 Calculated revenues and estimated profits from 1 kW of FCR capacity service offered for 24 hours/day and 4 hours/day respectively in DK1 region from 01/01/2021 to 31/05/2023. Compiled by EMK from multiple sources Energidataservice, Regelleistung data center, Nordpool, Energinet, Forsyningstilsynet (Danish Utility Regulator), Master Thesis of S. Jansson (Evaluation of KPIs and Battery Usage of Li-ion BESS for FCR Application), September 2019, Value paper of A. Thingvad et al (Economic Value of Multi-Market Bidding), June 2021.

As for similar scenario 4.3, peak shaving methods, using shore-based ESS, have been reduced by 70% in scenario 5.3 in order to make room for as much ancillary service in the DK1 region FCR market as possible. This strategy and its operational setup for the FCR service is unchanged compared to scenario 4.3.

Revenue from FCR service became quite extreme during 2022, even more than electricity spot price. The increase in FCR revenues in 2022 alone, compared to 2011-2020 average, was close to a factor of five. 2021 FCR revenues were close to average for the prior decade and first half of 2023 showed low average revenue from FCR services.

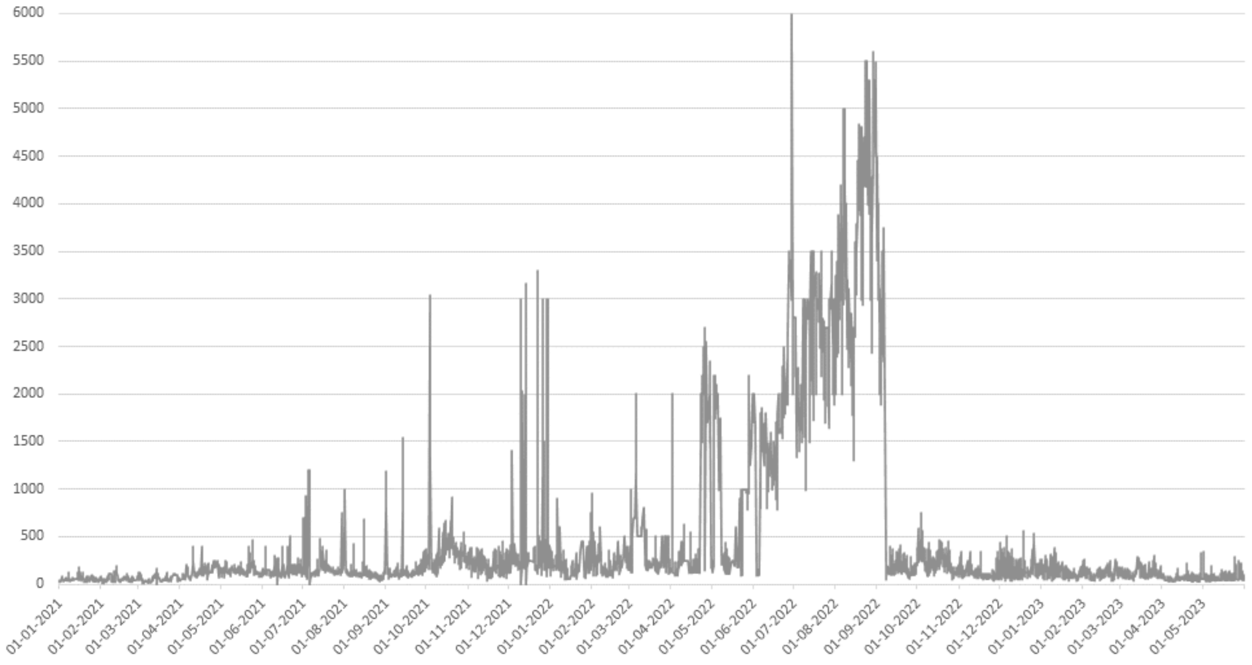


Figure 5.3.1 FCR capacity price DKK/MW/h in DK1 based on 4-hour intervals or 6 blocks per day. Source Energidataservice, Regelleistung data center and Energinet. Compiled by EMK.

FCR market for DK1-DE were closer linked up and volumes auctioned together from 7th of September 2022. This is highly visible to price in Figure 5.3.1, and the increased competition drove prices for FCR in Western Denmark down immediately (Energinet, 5th of January 2023). Still summertime is normally the high-priced period so coming summer prices of FCR should be interesting to follow.

If bids were won for all hours of FCR service in DK1 from 1st of January 2021 to 31st of May 2023 it would have averaged 4.164,76 DKK for 1 kW of FCR capacity offered symmetrically to the DK1 grid per year. From 2011-2020 the same FCR service would generate an average of only 1.623,46 DKK annually. The increase during the high price period (2020-2023) is +157%, driven almost fully by the third quarter of 2022.

For the case study calculations, success rate for won bids has been assumed to be 50% to be comparable with scenario 4.3. As explained earlier the E-ferry Twin setup will already have paid the grid connection and ship batteries, and part of the shore-based batteries as well, for operation without FCR service.

With assets already paid for, it is much easier to ensure a high ratio of won bids in the FCR market. Having almost no depreciation, the system should be very competitive compared to other assets fully designated to FCR service and with no fall-back strategy or other income to return to if bids are lost.

Days or blocks of lost bids, resulting in lost revenue, at the FCR auctions are not compensated for by alternative bidding in other markets (multi-market bidding) or higher peak shifting savings these days in the model calculations. Therefore income or value could be considered as a conservative estimate in these E-ferry Twin case study calculations.

As for scenario 4.3, profits from FCR services outweighs the lower savings from peak shaving. As mentioned earlier shore-based batteries and E-ferry batteries are traded in the same way as for scenario 4.3. Therefore same pros and cons would be relevant in this scenario 5.3. But with the difference that the increased FCR profits will also have to cover higher electricity cost than for scenario 4.3.

The fact that costs from battery throughput and derived costs of energy loss will go up, due to higher electricity spot price, is not enough to destroy profits from FCR services according to Table 5.3.1. Costs of tariffs paid for the energy throughput for the 2021-2023 time period is actually lower than for 2022-2020. Mostly due to the Public Service Obligation (PSO) which added a lot of costs to tariffs. PSO was phased out by the end of 2021 (Danish Energy Agency, 2022).

Electricity consumption from grid	Per day	Twin A	Per trip	
Low demand hours average	4.857	kWh	405	kWh
Lowest hour duck curve night	607	kWh	51	kWh
Lowest hour duck curve afternoon	607	kWh	51	kWh
High demand hours average	17.607	kWh	1.467	kWh
Daily consumption with shore battery	23.677	kWh	1.973	kWh
Daily consumption without shore battery	*23.273*	*kWh, see scenario 4.1 or 5.1*		
Added consumption from shore battery	*404*	*kWh*		
Electricity spot prices incl. green certificates				
Spot price night 2021-2023 average	0,904	DKK/kWh		
Spot price lowest hour duck curve	0,862	DKK/kWh		
Spot price lowest hour duck curve afternoon	0,895	DKK/kWh		
Spot price day 2021-2023 average	1,130	DKK/kWh		
Transport tariffs				
Low demand avg. tariff 2021-2023	0,0282	DKK/kWh	B-high consumer	
High demand constant tariff until 2021	0,0909	DKK/kWh	B-high consumer	
Transmission & System 2023	0,1112	DKK/kWh	All consumers	
EU minimum fee and green certificates	0,0090	DKK/kWh	All consumers	
Electricity cost E-ferry Twins A & B	Annual		Annual	
Night charging	3.116.600	kWh	2.903.819	DKK
Charging lowest hour duck curve night	389.185	kWh	346.323	DKK
Charging lowest hour duck curve afternoon	389.185	kWh	383.691	DKK
Day charging	11.297.858	kWh	13.797.336	DKK
Trans., Sys., min. fee, green cert.	15.192.828	kWh	1.826.178	DKK
Total cost with shore battery excl. VAT			**19.257.347**	**DKK**
Total cost without shore battery excl. VAT, see scenrio 5.1			*19.142.046*	*DKK*
Average price electricity excl. VAT			1,2675	DKK/kWh
Average price electricity incl. VAT (16% avg. due to tax exemption)			1,4703	DKK/kWh

Table 5.3.2 Electricity cost for scenario 5.3 with E-ferry Twins A & B and both charging stations equipped with shore-based batteries of 2,2 MWh each. Same sailing schedule as for scenario 4.1-3 and 5.1-2. Peak shaving reduced compared to scenario 4.2 and 5.2. Calculations based on energy price ten-year average 2021-2023 (June). Source EMK.

The reduced peak shifting, 70% compared to scenario 4.2, results in higher total electricity costs of 473.074 DKK. Actually these costs also become 115.301 DKK higher than for the base scenario 5.1 with no shore-based batteries doing peak shaving. This is because shore batteries in scenario 5.3 are still needed for charging the ferry, boosting grid power at each port stay. As for other scenarios with shore batteries, the battery throughput for the boosting strategy involves a loss of 404 kWh per day.

Savings on maintenance	Annual	
Maintenance savings engine system	3.000.000	DKK
Maintenance cost charging stations	- 1.110.000	DKK incl. VAT
Maintenance savings total	1.890.000	DKK incl. VAT

Profit from grid balancing services	Annual	
FCR service 24h/day	7.722.246	DKK incl. VAT
FCR service 00h-04h/day	1.278.522	DKK incl. VAT
Grid balancing services total	9.000.769	DKK incl. VAT

Energy cost savings	Annual	
Savings year avg. 2021-2023	68.743	DKK incl. VAT
Savings if CO2 ETS quotas included	6.242.106	DKK incl. VAT
Savings if CO2 DK future fee included	14.825.606	DKK incl. VAT

Total savings	Annual	
Savings year avg. 2021-2023	10.959.512	DKK incl. VAT
Savings if CO2 ETS quotas included	17.132.874	DKK incl. VAT
Savings if CO2 DK future fee included	25.716.374	DKK incl. VAT

Added investment costs		
Shore charging stations both ports	74.993.333	DKK incl. VAT
E-ferry Twins A & B compared to diesel	13.175.233	DKK
Total added cost base scenario	88.168.566	DKK incl. VAT

Simple liniar pay back calculation	
Based on savings avg. 2021-2023 (to June)	8,0 years
Based on savings if CO2 ETS quotas included	5,1 years
Based on savings if CO2 DK future fee incl.	3,4 years

Note: Present value method can be found in next figure/graph

Table 5.3.3 Profit from FCR grid balancing service and savings from other sources plus simple linear pay back calculations for added investment for scenario 5.3 and three different electricity cost scenarios, without CO2 costs and with respectively ETS quotas trading price 2021-2023 and with future agreed Danish minimum CO2 fee on fossil fuel. Source EMK.

Comparing added investment costs and savings, including profits from FCR services, the simple static payback method shows significantly shorter time to break-even than for scenario 5.1 and 5.2. Added investment costs are the same as for 5.2. But the setup with FCR service generates 9.000.769 DKK annually according to the assumptions and calculations for the E-ferry Twin case study found in this chapter.

Based on electricity prices and FCR service revenues from the period 2021-2023 (to June), the present value method with a discount rate of 4% shows solid results for scenario 5.3 with break-even after 9,5 years and down to only 3,6 years for added investment, depending on the CO2 pricing regime chosen:

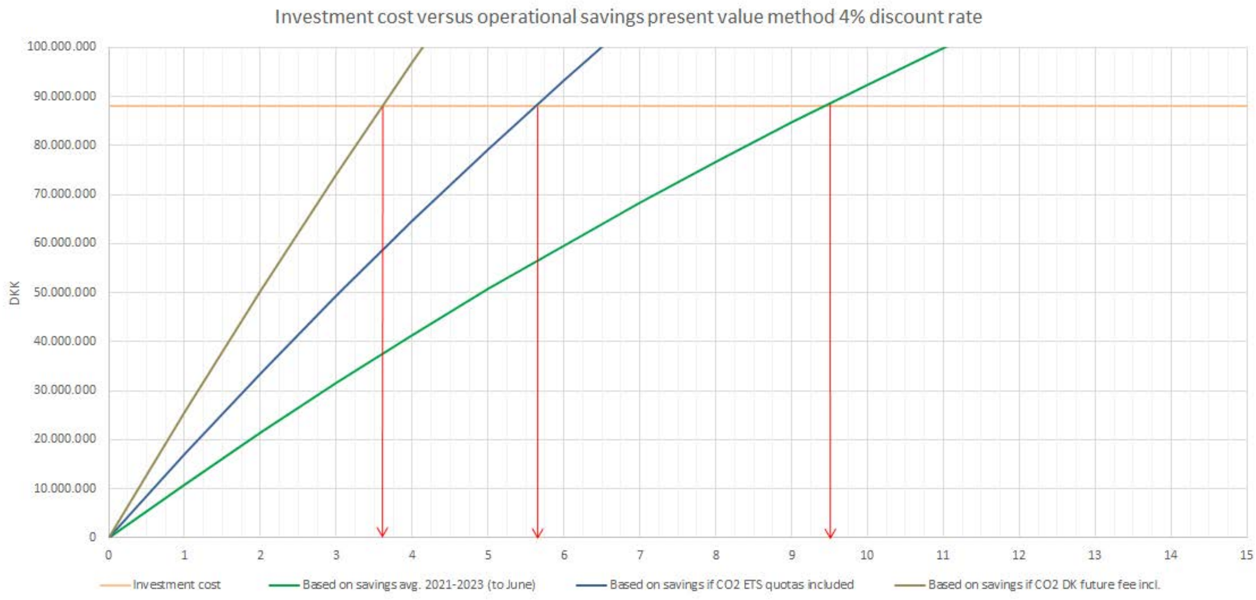


Figure 5.3.2 Accumulated savings discounted to present value with discount rate of 4% versus present investment cost incl. VAT of 16% for shore-based charging stations and profits from grid balancing FCR services. Source EMK.

Again, this is based on average energy costs from the 2021-2023 (to June). Times to break-even differs very little between scenario 4.3 and 5.3 even though they represent two very different price regimes for electricity cost. If Danish future CO2 emission fee is included difference in break-even is only a month and with no cost of CO2 difference is 1,5 years.

The interpretation could be that higher electricity cost in this scenario would almost be repaid by higher revenues from FCR service due to the volatility in a high-priced market. But this do not correspond well with the sharp drop in price of FCR capacity reserves observed from 7th of September 2022 when DE-DK LFC Block started common auctions for FCR bids. Therefore, the very similar break-even times in scenario 4.3 and 5.3 could also be coincidental created by some low probability events or extremes in the energy market for ancillary services. This should be investigated further but is not included in this case study. The future of ancillary service and in particular FCR capacity pricing is elaborated on in chapter 7.2.

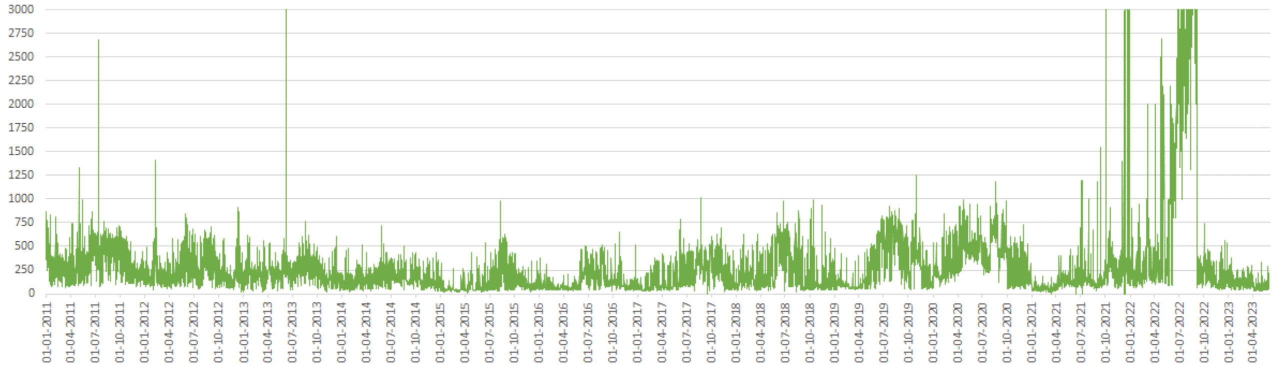


Figure 5.3.3 FCR capacity price in DKK per MW/hour for DK1 from 2011-2023 (to June). Higher price trends in late summer months are visible most years. Compiled by EMK from Energidataservice, Energinet and Regelleistung Data Center.

One thing though, supports solid future revenues from ancillary services. The share of intermittent production from wind turbines and PV solar has just started to rise and is already seen to have impacted grid frequency balancing, especially in the late summer period, see graph in Figure 5.3.3 above.

Finally, lower tariffs for electricity transport were seen in the time period 2021-2023 with the phase out of Public Service Obligations (PSO) and also lower distribution tariffs at N1 which is local Distribution Service Operator (DSO) on the islands of Ærø and used for this case study. Downward trends in tariffs in scenario 5.3 though, are insignificant compared to the rise in electricity spot prices especially for year 2022 prices.

A summary of findings from this scenario 5.3 can be found below:

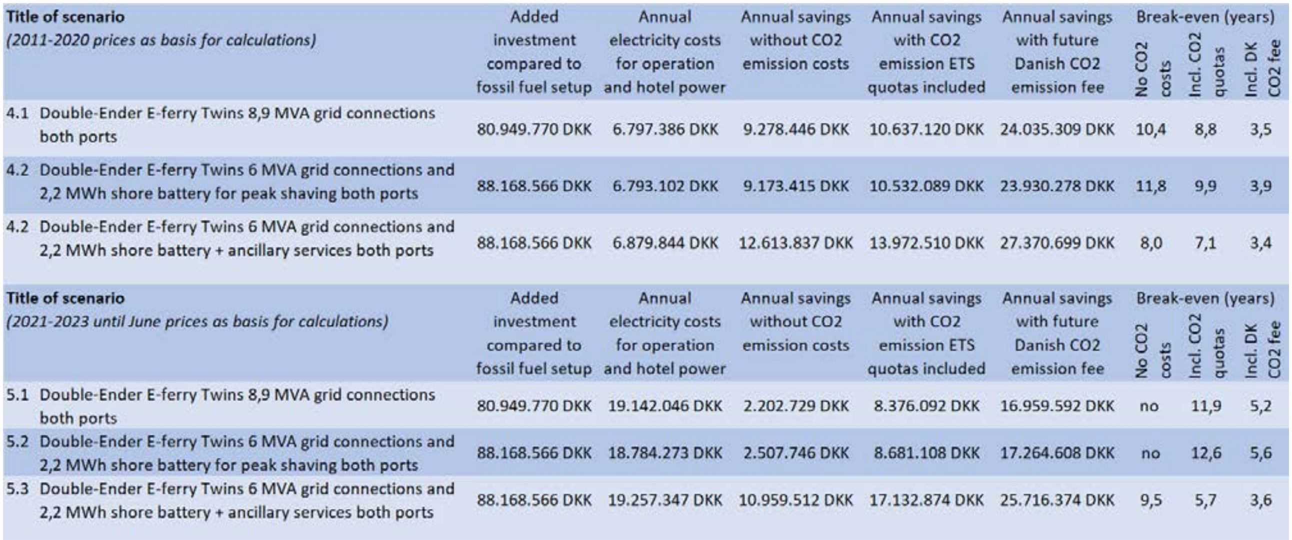
Summary table scenario 5.3					Prices include VAT
Charging stations	Two	in Ærøsk. & Svendb.	Electricity price averaged	1,47	DKK/kWh
Grid connection	6.000	kVA	Energy consumption	15.192.828	kWh/year
Battery on ferry	6.000	kWh	Energy costs	22.338.522	DKK/year
Battery station ashore	2.232	kWh 2 MW contin.	Savings energy costs 2011-2021	68.743	DKK/year
Transit time	75	min. same as now	Other savings operation	1.890.000	DKK/year
Port time	15	min.	Profit from frequency services	9.000.769	DKK/year
Roundtrip consumption E-ferries	3.372	kWh	Total savings excl. CO2 costs	10.959.512	DKK/year
Charged per roundtrip averaged	3.879	kWh	Total savings full CO2 costs	25.716.374	DKK/year
Battery DoD per trip	25%		Added investment costs batt.	88.168.566	DKK
Charging C-rate	1,16	C	Simple static payback period	3,4-8,0	years
Charged per session	1.451	kWh	PV-method 4% discount rate	3,6-9,5	years
Battery life time calculated	15,6	years	Saved CO2 emissions	11.308	ton/year
FCR 24h/day from shore batteries	3,2	MW/h			
FCR 4h/day (00-04) from E-ferry batt.	3,8	MW/h			

Table 5.3.4 6 E-ferry Twin case study summary of inputs and findings for scenario 5.3 with two double-ender steel hull battery electric ferries, transit time of 75 minutes and shore batteries at charging stations. Based on 2021-2023 (to June) average energy prices and including balancing services in the FCR market with averaged profits from same period.

6 Comparative analysis of scenarios

6.1 Comparison of added investment costs versus savings for all scenarios

In Table 6.1.1 below added investment costs for E-ferry Twins of all scenarios are summarised and compared to annual savings based on the two different time intervals and price regimes analysed. Cost of electricity is compared to cost of fossil fuelled operation of ferries with same weight and hull shape and on same route and schedule:



Title of scenario *(2011-2020 prices as basis for calculations)*	Added investment compared to fossil fuel setup	Annual electricity costs for operation and hotel power	Annual savings without CO2 emission costs	Annual savings with CO2 emission ETS quotas included	Annual savings with future Danish CO2 emission fee	Break-even (years)		
						No CO2 costs	Incl. CO2 quotas	Incl. DK CO2 fee
4.1 Double-Ender E-ferry Twins 8,9 MVA grid connections both ports	80.949.770 DKK	6.797.386 DKK	9.278.446 DKK	10.637.120 DKK	24.035.309 DKK	10,4	8,8	3,5
4.2 Double-Ender E-ferry Twins 6 MVA grid connections and 2,2 MWh shore battery for peak shaving both ports	88.168.566 DKK	6.793.102 DKK	9.173.415 DKK	10.532.089 DKK	23.930.278 DKK	11,8	9,9	3,9
4.2 Double-Ender E-ferry Twins 6 MVA grid connections and 2,2 MWh shore battery + ancillary services both ports	88.168.566 DKK	6.879.844 DKK	12.613.837 DKK	13.972.510 DKK	27.370.699 DKK	8,0	7,1	3,4
Title of scenario *(2021-2023 until June prices as basis for calculations)*	Added investment compared to fossil fuel setup	Annual electricity costs for operation and hotel power	Annual savings without CO2 emission costs	Annual savings with CO2 emission ETS quotas included	Annual savings with future Danish CO2 emission fee	Break-even (years)		
						No CO2 costs	Incl. CO2 quotas	Incl. DK CO2 fee
5.1 Double-Ender E-ferry Twins 8,9 MVA grid connections both ports	80.949.770 DKK	19.142.046 DKK	2.202.729 DKK	8.376.092 DKK	16.959.592 DKK	no	11,9	5,2
5.2 Double-Ender E-ferry Twins 6 MVA grid connections and 2,2 MWh shore battery for peak shaving both ports	88.168.566 DKK	18.784.273 DKK	2.507.746 DKK	8.681.108 DKK	17.264.608 DKK	no	12,6	5,6
5.3 Double-Ender E-ferry Twins 6 MVA grid connections and 2,2 MWh shore battery + ancillary services both ports	88.168.566 DKK	19.257.347 DKK	10.959.512 DKK	17.132.874 DKK	25.716.374 DKK	9,5	5,7	3,6

Table 6.1.1 Added investment costs due to battery electric operation including shore charging stations and batteries onboard E-ferry Twins versus savings from operation compared to fossil fuelled operation. Time to break-even analysed with present value method.

In the last three columns of the table, payback time of added investment costs, by savings from operation, can be found in years and based on present value method at a discount rate of 4 %. For each scenario three ways of determining the cost of fossil fuel have been applied.

First costs of MGO Low Sulphur delivered on board with no cost of CO2 emissions included. Second costs of fuel including procurement of ETS quotas for calculated CO2 emissions from conventional bunker. Finally cost of fuel including the planned introduction of CO2 emission fee of total 1.125 DKK/ton CO2 when fully implemented in 2030 according to agreement in the Danish Government and political opposition (Political Agreement on Green Tax, 2022). The latter is very close to suggested fee from the Danish “Wisemen” council advisory of 1.200 DKK/ton CO2 (Danish Environmental Economic Council, 2020).

Calculated emission for fossil fuel operation is the same for all scenarios, **11.308 ton of CO2 per year**. This is also the emission savings from a grid to propeller perspective. Sailing schedule is not changed between scenarios. It is assumed that all electricity will be purchased on renewable energy certificate contracts.

From comparing chapter 4 and 5 scenarios in Table 6.1.1, sensitivities to energy costs, and especially the volatility of energy costs, can be assessed. Not surprisingly do scenarios in chapter 4, based on 2011-2020 prices, perform better than chapter 5 scenarios which was based on 2021-2023. In the latter time period both energy crisis and structural changes have introduced much higher increases to electricity costs than for fossil fuel costs. Cost increase for electricity for scenarios in chapter 5 was found to be around 177% higher. This should be seen in relation to a rise of 47% “only” in cost of fossil fuel between the time periods.

Peak shifting can, to some extent, gain back some value when prices become high if they are also volatile. This seems to be the case, analysing long term daily price data from the two time periods, see Figure 2.2.6 for price development. For scenario 5.2, where peak shifting is introduced, using shore batteries, it shows saved electricity costs of 357.773 DKK compared to base scenario 5.1 with only a little peak shaving.

Hence, the saved electricity costs of scenario 4.2 compared to scenario 4.1 is only 4.284 DKK annually. Thus volatile daily prices, and the introduction of time dependent distribution tariffs, mitigates 353.489 DKK of the increase in electricity costs for chapter 5. But only if peak shifting is performed, using shore batteries as suggested in scenario 5.2.

The introduction of shore-based batteries in scenario 4.2 and 5.2 will save investment costs for grid connection fee. But still total added investment costs of port infrastructure becomes 7.218.796 DKK higher, when charging stations are added Energy Storage Systems (ESS) of 2.232 kWh in each port. This cost is not fully recuperated by the peak shifting, neither in scenario 4.2, nor in scenario 5.2 price regimes.

There could be other benefits to installing shore-based ESS capacity apart from saving grid connection fee or doing peak shifting. In some ports grid infrastructure could be limited or fragile. Thus an element of redundancy is introduced with shore batteries. From the perspective of the Balance Responsible Party (BRP) and perhaps also the Distribution System Operator (DSO) running the local distribution grid, all flexibility is highly valued.

The bigger the battery connected the less of a burden for the grid operating parties. Port infrastructure and battery ferries could become an asset for smart optimisation of the local, national and international grid connections, as elaborated on by Buster B. Hansen in his thesis (Hansen, 2021). The value of this flexibility, seen from the perspective of the ferry or port operator, is analysed in scenario 4.3 and 5.3. Results show that shore batteries, situated at each port, could lower barriers significantly to battery electric ferry operation.

Using the shore-based batteries through the day for ancillary service at Frequency Containment Reserve (FCR) auctions together with same service, also using vessels battery pack in the four hours after midnight, shows much better performance than peak shifting. Scenario analysis in both chapter 4.3 and 5.3 indicates that ancillary service is highly profitable. Peak shifting in scenario 4.2 and 5.2 cannot compete with potential profits from ancillary services according to estimated savings in analysed scenarios.

For the 50% of time periods where auctions for FCR capacity are not assumed to be won, peak shifting is still an attractive alternative to generate some extra savings instead of profits from ancillary service. But to keep this case study analysis on the conservative side such savings are not included in scenario 4.3 and 5.3 calculations. Multi-market bidding strategies have shown to gain 20-30% extra value in other studies and could be relevant in future studies for port infrastructure and battery electric ferries (A. Thingvad, 2023).

Sensitivity for scenarios, with ancillary services included, is significant, of course to price of FCR capacity but also to the success rate of won bids at auctions. Revenues from 1 kW/h FCR capacity, in period 2021-2023, is 143% higher compared to period 2011-2020. Scenario 5.3 shows extreme value creation from trading flexibility in region DK1 FCR market, especially for the third quarter of 2022, but also in the period before. In total scenario 5.3 shows a potential of 9.000.769 DKK annually in profits based on 2021-2023 prices against 3.541.041 DKK annually in profits for the period 2011-2020.

Maybe “the party is over” after the full implementation of a common FCR capacity auction for the DE-DK LFC block at the 7th of September 2022. Although market volume became much larger for Danish providers of FCR service prices will most likely trend much lower due to better competition. Still intermittent renewable energy sources like wind turbines and PV solar could accelerate FCR revenues again, especially in the summertime. Such trends are being seen already when sun is shining, and wind is blowing. Future development of the markets for ancillary service is discussed in chapter 7.2. Share of won bids at FCR auctions will affect FCR revenue proportionally. Hence, sensitivity is also high to this. However this factor could be mitigated by multi-market bidding or by fall-back strategies of peak shifting.

Potential added cost of CO2 is the final big factor affecting the scenarios in the case study. For scenarios in chapter 4. For the time period 2011-2020, cost of CO2 emissions did not apply to Danish ferries. If CO2 quotas from the EU Emission Trading System (ETS) had been applied, as can be seen from columns in Table 6.1.1, such quotas still traded at a relatively low price per ton of CO2, in 2011-2020 only adding 1.358.674 DKK to fossil fuel cost per year. For scenarios in chapter 5, EU ETS quotas had risen significantly in time interval 2021-2023, adding 6.173.363 DKK to fossil fuel cost per year.

EU ETS is not enforced to national ferry shipping yet. It is however planned that a fixed CO2 emission fee of 1.125 DKK/ton CO2 will be fully implemented in 2030 as mentioned earlier. Only a few years after the completion of the E-ferry Twin newbuildings. The planned CO2 emission fee would have constituted for a 49,3% share of total fossil fuel costs in chapter 4, following the fossil fuel price from 2011-2020. For chapter 5 this share would have been little less, but still significant 39,7% of total fossil fuel costs, in the period 2021-2023 on average.

Therefore the last column of annual savings and break-even calculations with CO2 emission fee, included in Table 6.1.1, is the most relevant in order to forecast future costs and savings of the operational E-ferry setup and related port infrastructure on the island of Ærø.

In the low-price scenarios of chapter 4, annual savings, CO2 fee included, vary between 23.930.278 DKK and 27.370.699 DKK per year with scenario 4.3 as the best case. This means that added investment of shore charging infrastructure and vessels battery electric drivetrain would be repaid in less than 4 years.

In the high-price scenario of chapter 5, annual savings, CO2 fee included, varies more, between 16.959.592 DKK and 25.716.374 DKK per year with scenario 5.3 as the best case again. For this scenario, the added investment would also be repaid after less than 4 years even though electricity prices did go up significantly. This means that higher electricity costs are almost fully mitigated or repaid from the extreme profits from ancillary in this last scenario.

With CO2 fee included all scenarios show short time to break-even. Best economic solution or setup is vitally dependent on the potential to add revenues from Frequency Containment Reserves (FCR). In scenario 4.2 and 5.2, with no FCR income, total savings are lower than for scenario 4.1 and 5.1 which have no shore-based batteries. It is only relatively small differences between 4.1 and 4.2 scenarios respectively 5.1 and 5.2, and still all scenario with CO2 fee included show an economic advantage over fossil fuel costs. Not to forget the environmental advantage of saving 11.308 ton of CO2 per year going full battery electric.

For most scenarios examined parity between added investment costs and savings will occur within 13 years and therefore no replacement costs of batteries are introduced. They will then be paid by further cost savings after time of parity (break-even). Battery End of Life (EoL) is defined at 80 % remaining of normal battery capacity in this case. Initial battery capacity in the scenarios is chosen to ensure at least 15 years of battery life when looking at DoD and C-rates.

From an operational point of view, the best generic charging strategy would be to have charging possibilities in both ports as chosen for this case study. This way port time is utilised for charging at all times and the depth of discharge (DoD) per cycle for onboard batteries is cut in half allowing for more cycles in total lifetime or alternatively a lighter and less costly onboard battery.

At the same time some resilience in case of charger problems is gained, as half the charging is still possible in one port. However, establishing two strong charging stations is typically also more costly in fixed cost than building just one station for high peak performance in one of the ports. For this case study results seem to outweigh the extra cost of two charging stations and two shore-based battery packs.

6.2 Assumptions, compatibility and choice of design and technology for case study

Investment costs are estimated figures only, as explained in chapter 2.2. More accurate figures for each design solution would require more extensive and costly design studies and more price quotes from suppliers. Therefore, found results should only be used for the preliminary screening of design ideas and setups.

Government funding is expected to be part of finance for the E-ferry Twins and port infrastructure. However, sources of finance are not discussed in the analysis. The scope is to focus on barriers to battery ferry operation and port infrastructure from a commercial point of view. Instead an internal discount rate of 4% have been applied to present value calculations. This way, case study findings will be easier to compare to other ports and ferry projects in Denmark and in the North Sea region.

National ferry operators in Denmark are not subjected to Value-Added Tax (VAT) on ticket revenues from passenger transport. Only transport of goods and cars is subjected to Danish VAT of 25 %. This means that the ferry company cannot answer deductible VAT to all investment costs. Therefore a split of the normal Danish Value-Added Tax of 25 % must be included based on the split between revenues from passenger tickets and goods and cars respectively. The fraction of non-deductible VAT has been set to 16 % in all relevant cost calculations in the spreadsheet model.

The accounting principles for partly deductible VAT for the shore-based infrastructure are complex. Ferry operators do not answer VAT to ship's investments. But VAT does apply to port infrastructure investments e.g. modification of berths and terminals or building shore charging stations. Being subjected to only partly deductible VAT could affect investment costs differently between the ferry operator and a third-party provider of charging services. This has to be investigated further and could influence optimal setup.

As it is not certain who will own the port infrastructure, partly deductible VAT has been used for port investment costs, making them more expensive than if full deductible VAT could be applied. This is done for port infrastructure in all scenarios to ensure comparability between operational setups and associated costs. With other words a worst-case approach has been applied here.

Limited grid access could be relevant to some ports to bring down barriers of B_{high} standard connection fees which are based on one-time payment of close to 2.000.000 DKK per MVA excl. VAT. If vessels have a backup generator limited grid access would indeed be interesting. However for this case study excess grid infrastructure in the ports are not expected to be sufficient for limited grid access agreements with the Distribution System Operators (DSOs) in each port. Thus the full grid connection fee is assumed to be paid. Nevertheless, in most cases limited grid access should be subject to deeper investigation and analysis.

A lot of the investment costs are associated with purchase and instalment of inverters AC/DC in charging stations and inverters DC/DC for battery packs both onboard vessels and at port for scenarios where shore-based booster batteries are chosen for a smaller grid connection. This case study is based on findings from the EU Horizon E-ferry in the port of Søby (T. Heinemann, 2019). But other solutions could also be applied perhaps bringing down investment costs or operating costs from energy losses or less electronic parts.

Example given, the Danish company Nerve Smart Systems has developed an intelligent system for energy storage and management with EU Horizon 2020 and Danish EUDP funding. The Nerve Switch Systems allows for battery modules and cells to switch between connection in series and parallel in an intelligent manor to output and adjust voltage directly to the DC bus. The added hardware switches also improve the possibility for optimised cell balancing. A vital and time-consuming part of battery management (Nerve Smart Systems, 2023).

Figure 6.2.1 Containerised battery system with Nerve Switch System hardware. Source Nerve Switch System ApS.

With the Nerve Switch System costly DC/DC inverters in connection with battery stations ashore can be avoided and higher charging chain efficiency is would theoretically be gained. However, this technology is not yet matured fully for use in port infrastructure and potential savings are therefore not included in scenarios with shore-based batteries. But it could be relevant to investigate further in future studies.

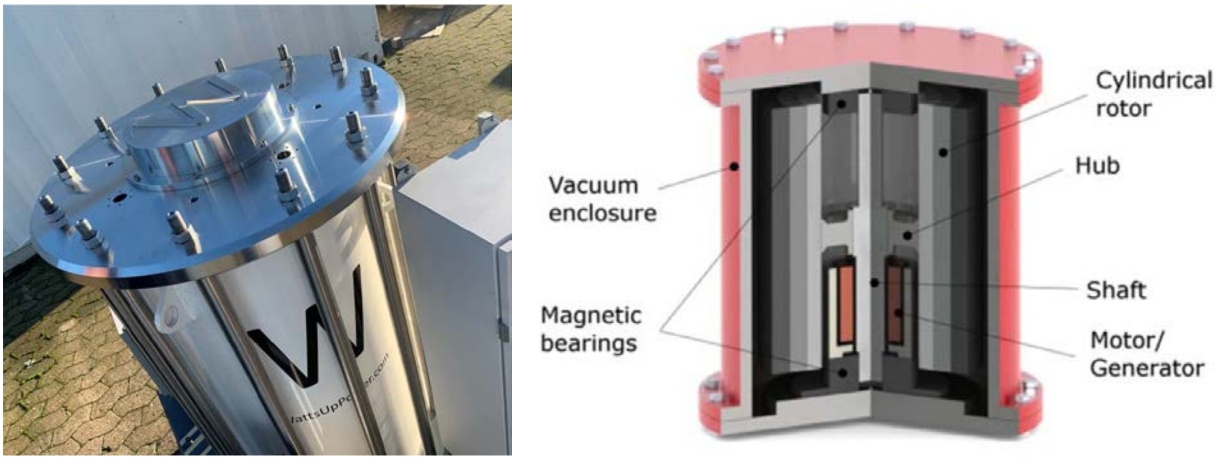


Figure 6.2.2 Flywheel kinetic energy storage device of 250 kWh and 1 MW of output. Source WattsUp Power product page 2023 and the Danish Maritime Fund project page 2016.

Other storage technologies like flow batteries or inertia gyro wheel technology (flywheel energy storage) could also be relevant to screen for the shore-based installation. Investment costs and gravimetric energy density of these have not been able to compete with lithium iron phosphate battery systems yet, but this could change over time and there could be other advantages apart from economical (Nikolaj A. Dagnæs-Hansen, 2019).

This case study is based on findings from the EU Horizon 2020 E-ferry project and therefore same battery and inverter technologies are assumed to be used for all calculations.

7 Energy cost, grid connection and sensitivities

7.1 Energy cost and efficiencies

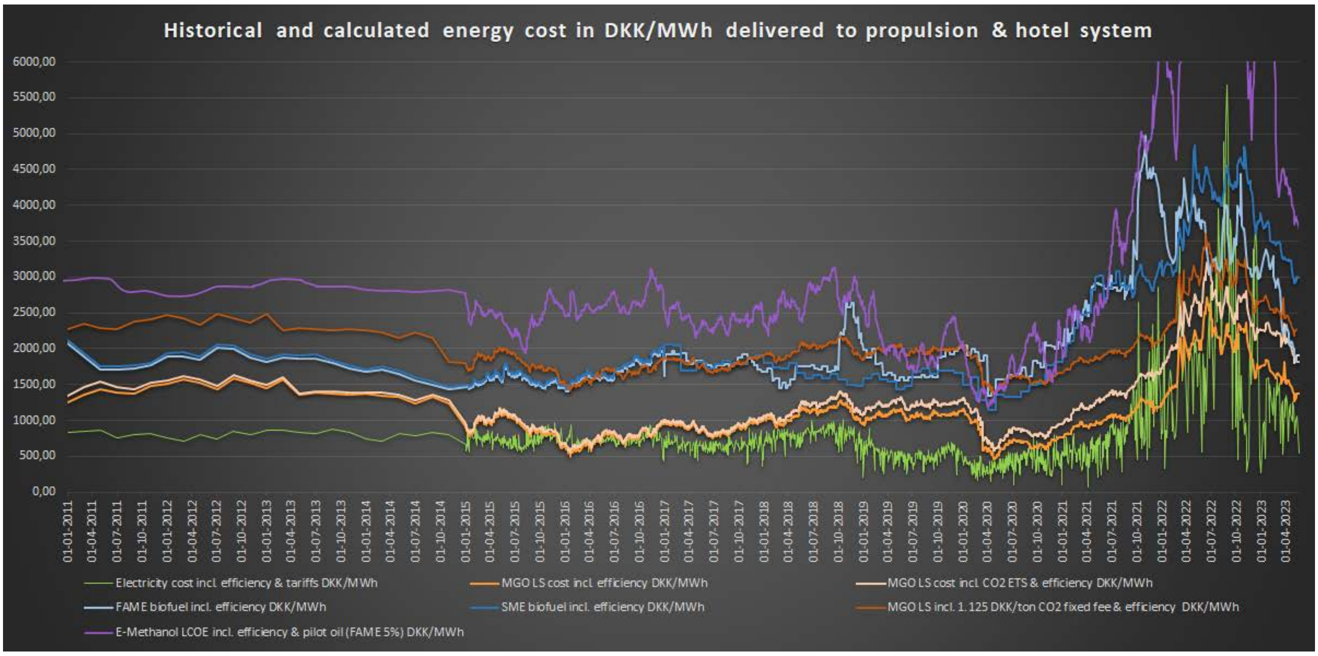


Figure 7.1.1 Long-term energy cost comparison for conventional fossil fuel drive train (Marine Gas Oil), biofuel drive train and electric battery drivetrain charged with renewable energy. Also comparison with calculated Levelized Cost of Energy (LCOE) for e-methanol based on hydrogen electrolysis from renewable electricity spot price and carbon capture is shown for reference, although product do not exist in market yet. Finally cost of MGO low sulphur with emission costs of either EU ETS quotas or alternatively planned Danish fixed fee of 1.125 DKK/ton of CO2 are shown for reference (to be fully implemented in 2030). For comparison all costs are measured in DKK/MWh input to propulsion propeller or hotel power in the ferry taking into consideration all upstream efficiencies of the drive train/engine systems for each technology. Compiled by EMK from multiple sources, Nord Pool, N1, Evonet, Ærø Elforsyning, Energinet, Energi Danmark, Energistyrelsen, Forsyningstilsynet, Platt, Neste, Ærøfærgerne, ÆrøXpressen, European Environment Agency ETS dashboard, Feasibility study of Power-to-Methanol in Denmark, Mathias Fuglsang, AAU June 2020.

The comprehensive long-term comparison of drive train alternatives for the E-Ferry Twin case study in Figure 7.1.1 shows that electricity market and fuel markets are getting more entangled within this decade. Energy crisis in 2022 indicates extreme volatility in both market sectors and the advent of electrofuels (e-fuels), e.g. e-methanol based on hydrogen electrolysis using renewable electricity, will most likely introduce an even stronger interconnection between market sectors.

Although not available in the fuel market yet, Levelized Cost of Energy (LCOE) for Danish production of e-methanol is shown in purple in Figure 7.1.1 above. E-methanol is central to strategies for green transition in shipping, at least for larger vessels and long-distance journeys (Danish Government´s strategy for PtX, 2021). The purple graph is based on DK1 electricity spot price development including green certificates, system, transmission and balance tariffs but with no distribution tariff added.

Estimated production cost (LCOE) for e-methanol at an electricity price of 398 DKK/MWh, tariffs above included, was found to be 4124 DKK/ton by Mathias Fuglsang in his “Feasibility Study of Power-to-Methanol in Denmark”, Master Thesis, Aalborg University (Fuglsang, 2021). Based on his finding cost the purple curve was compiled by EMK.

When comparing to international studies for e-methanol, estimated LCOE from the feasibility study referred to above is in the lower half, but results in international studies vary a lot from 2.500 to 8.000 DKK/ton, depending on electricity price and method or pathway to e-methanol but also assumed level of maturity of the technology (IRENA & Methanol Institute, 2020)

The Danish feasibility study considers strategies for time dependent use of electricity, revenues from excess heat to district heating, credits from Direct Air Capture (DAC) of CO2 for synthesis and uses a highly efficient Polymer Electrolyte Membrane (PEM) cell for electrolysis. Costs of water and transport of e-fuel to vessels are not accounted for and it is assumed that distribution tariff can be avoided as mentioned.

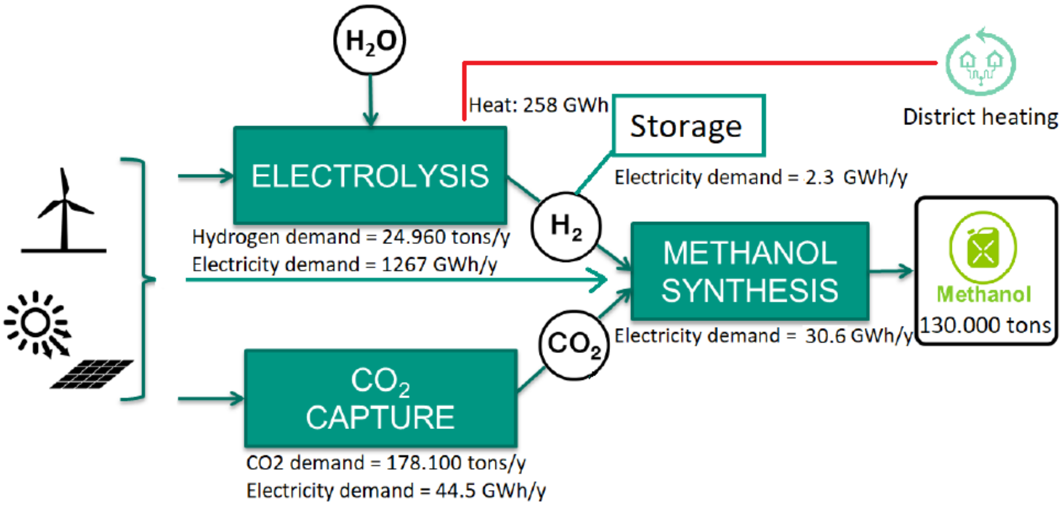


Figure 7.1.2 Estimated electricity, hydrogen and CO2 demand for production of 130.000 tons of e-methanol per year at PtX Fjord facility in Aalborg, Denmark (Source Mathias Fuglsang, Master Thesis, Feasibility study of Power-to-Methanol in Denmark, June 2020)

Same e-methanol could of course be produced off grid on one of the planned Danish Energy Islands (Danish Energy Agency, 2023) or using a direct line of electricity connection from wind or solar assets to the plant, thus saving all tariffs and detaching from the electricity spot price. LCOE was found to be 320 DKK/MWh for offshore wind and 298 DKK/MWh for onshore/land wind turbines, according to estimations from Energinet (Energinet, 2015) and Danish Energy Agency (Danish Energy Agency, 2022).

Above electricity price would result in a LCOE for e-methanol at 3204 DKK/ton or 1547 DKK/MWh of power to propulsion propeller and hotel power, pilot fuel excluded. This LCOE resembles the 2020 region DK1 prices, when corrected for tariffs. Thus off grid solutions for e-methanol, based on the given assumptions, could have been competitive to biofuel or MGO with CO2 emission fee, looking at historical prices in Figure 7.1.1. But not to battery electric operation or MGO without cost of CO2 emissions.

Two types of biofuels, Fatty Acid Methyl Ester (FAME) and Sunflower Methyl Ester (SME), are also shown in the comparison of fuel alternatives in Figure 7.1.1. Both are based on esterification of vegetable oils and daily prices are based on information from Neste without transport cost to vessels (NESTE, 2023). For e-methanol, 5% pilot biofuel of FAME is used to ensure combustion. Hence, the purple curve is weighed by 95% LCOE for e-methanol and 5% FAME according to daily spot price.

Fuel consumption of the E-ferry Twins in the case study and for the graphs is found in Table 7.1.1 and based on following Specific Fuel Oil Consumption (SFOC) of vessels main engines and auxiliary engines:

Estimated consumption per trip	SFOC	kWh	kg MGO fuel
Transit deep water 85% of MCR	220	1.058,1	232,8
Manouvering, slow steaming in channels	300	558,3	167,5
Hotel power/idle during port calls	270	138,3	37,3
Weighed avg. SFOC:	**250**	1.754,7	437,6
η efficiency generatorset:			0,95
Resulting fuel consumption per single trip:			**460,7**

Table 7.1.1 Estimated fuel consumption of E-ferry hull design, but with MGO marine engines and SFOC at different engine loads during the operation (single trip and port call). Compiled by EMK.

According to Table 7.1.1 an average SFOC of 250 g/kWh reflects the efficiency of a conventional fossil fuel ferry four stroke engine to P_b, also called Brake Power at the crankshaft or flywheel, in the operational setup of the case study. Engines thermal and mechanical losses are included in the average SFOC. For a small domestic ferry, varying engine loads and distances of slow steaming in channels creates less-than-optimal conditions for fuel efficiency.

The consumption of alternative biofuel or e-methanol is found by multiplying their ratio of fuel energy density compared to MGO fuel. Energy density or Lower Heating Value (LHV) used for ratios are 42,7 MJ/kg for MGO (low sulfur), 22 MJ/kg for e-methanol, 37,3 MJ/kg for FAME, and 36,2 MJ/kg for SME. One MJ equals 0.2778 kWh.

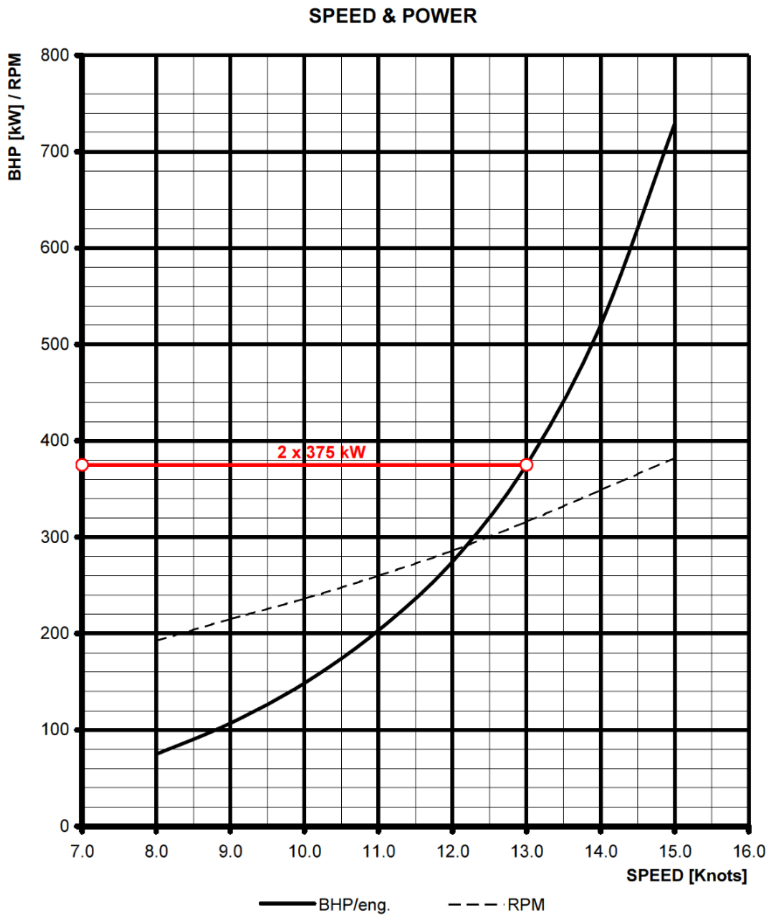
Thus MGO energy density could also be expressed as 11,86 kWh/kg fuel. However, 1000 g / 11,86 kWh = 84,3 g/kWh would only be the SFOC if there were no losses in the diesel engine. This means that thermal and mechanical efficiency losses in the combustion engine of the ferry results in an average engine efficiency of 84,3/250×100=33,7%, most of it being thermal losses. Same engine efficiency is assumed for biofuel and e-methanol for comparison in this case study. Typically small ferries will have little reuse of exhaust heat from engine. Required hotel power for lights, pumps and heating has been added to P_b.

Rest of drivetrain loss from P_b to propeller and to Effective Power (P_e) is included in the CFD calculation from Naval Architects where Towing Resistance (R_t) was found and required P_b calculated in the speed-power curve of the E-ferry hull in loaded condition. Shallow water corrections have been made for each leg of the ferry route in question to assess required propulsion power expressed at P_b.

Diesel-electric operation is assumed for all fuel-based drivetrains to better compare with battery electric operation. Therefore loss after Power from generator-set (P_{gen}) is expected to be same for battery discharge Power after $P_{bat.disharge}$.

Roundtrip efficiency of battery charge to discharge is dependent on C-rate, temperature and SoC. Based on operational experience from the EU Horizon E-ferry evaluation report a charging and battery roundtrip efficiency of 90% can be expected.

This is measured from secondary side of supply transformer at the charging station which is also the point of measurement if electricity customer is B_{low}. For B_{high} a fixed percentage is added to energy to correct for transformer loss, typically less than 2%.



Sea Allowance: 5%
Transmission: 97% for shaft and gear.
Propeller: Wageningen BB, D = 1.60m, P/D = 1 Ae/Ao = 0.55, Z = 4

Figure 7.1.3 Speed & Power curve showing required P_b for each motor of E-ferry Ellen in Søby to maintain sea speed at infinite water depth. Source EU Horizon 2020 E-ferry delivery 2.2 "Final report on hull definition and power prediction", May 2016.

7.2 Grid connection, shore-based ESS, peak shifting and ancillary services

If sufficient redundance is available in the local grid, then an agreement for limited access can substitute for the standard connection fee agreement. Peak charging power will be based on cost of installation in nearest 10 kV or 60 kV transformer and this will typically be much less than the standard connection fee.

It is likely that the required redundancy is not available without new 10 kV distribution lines to the ports in question. The electricity demand profile is to be evaluated against the grid profile at the location before such an agreement can be made with Distribution System Operator (DSO) but this needs to be investigated further.

The likelihood of limitations is fully dependent on the local grid and consumers. If evaluation shows sufficient redundancy now and things change in the future, then the full standard connection fee can be paid later on with no extra installation cost. The terms of the agreement can be found in: “Grid connection agreement for connection with limited grid access” (Dansk Energi, 2020).

For both ports, the proximity to 60kV distribution transformers could allow for ferry operator or third-party owner of port infrastructure to invest in a direct 10 kV to these themselves. This should be considered in order to obtained lower distribution tariffs and lower connections as an A_{high} or A_{low} customer.

However, combining the shore charging station with a shore Energy Storage System (ESS), as described in scenario 4.2-4.3 and 5.2-5.3, will most likely be beneficial to obtain the lowest cost of connection fee, some redundancy in case of power outage and sufficient operational safety. Limited access of grid connection could work well with batteries ashore to ensure charging of vessels batteries if grid connection to charging station is being shut off the grid in rear occasions or limited in its peak power from grid in other occasions.

In this case study a 6 MVA physical grid connection has been considered with a shore battery of 2.232 kWh and possible peak charging powers of 8,9 MW, resembling same charging peak power as for scenario 4.1 and 5.1. However, calculations have been performed using only 5,4 MVA of the grid connection capacity in daily operation and rest from the shore battery pack in each port.

Charging curve of the lithium-ion batteries onboard is not linear. Therefore an average charging power lower than the peak power has been used for spreadsheet model calculation of battery’s SoC. But on the shoreside a charging strategy needs to be chosen between optimising for low electricity cost, e.g. doing peak shifting with shore batteries, or optimising for profit from ancillary services to the Transmission System Operator (TSO) balancing frequency in the grid.

Each of the two strategies are described respectively in scenario 4.2 and 5.2 (optimisation for low electricity cost) and scenario 4.3 and 5.3 (optimisation for profits from ancillary services).

Purpose of first strategy is to save grid connection fee by using shore-based ESS for peak shaving instead. Redundant capacity on the shore-based ESS can then be used for peak shifting. This will move purchase of electricity to less costly hours of the day.

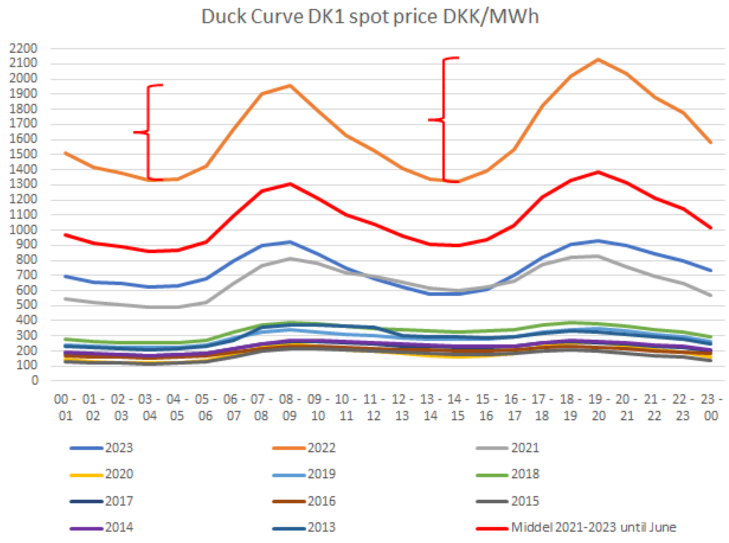
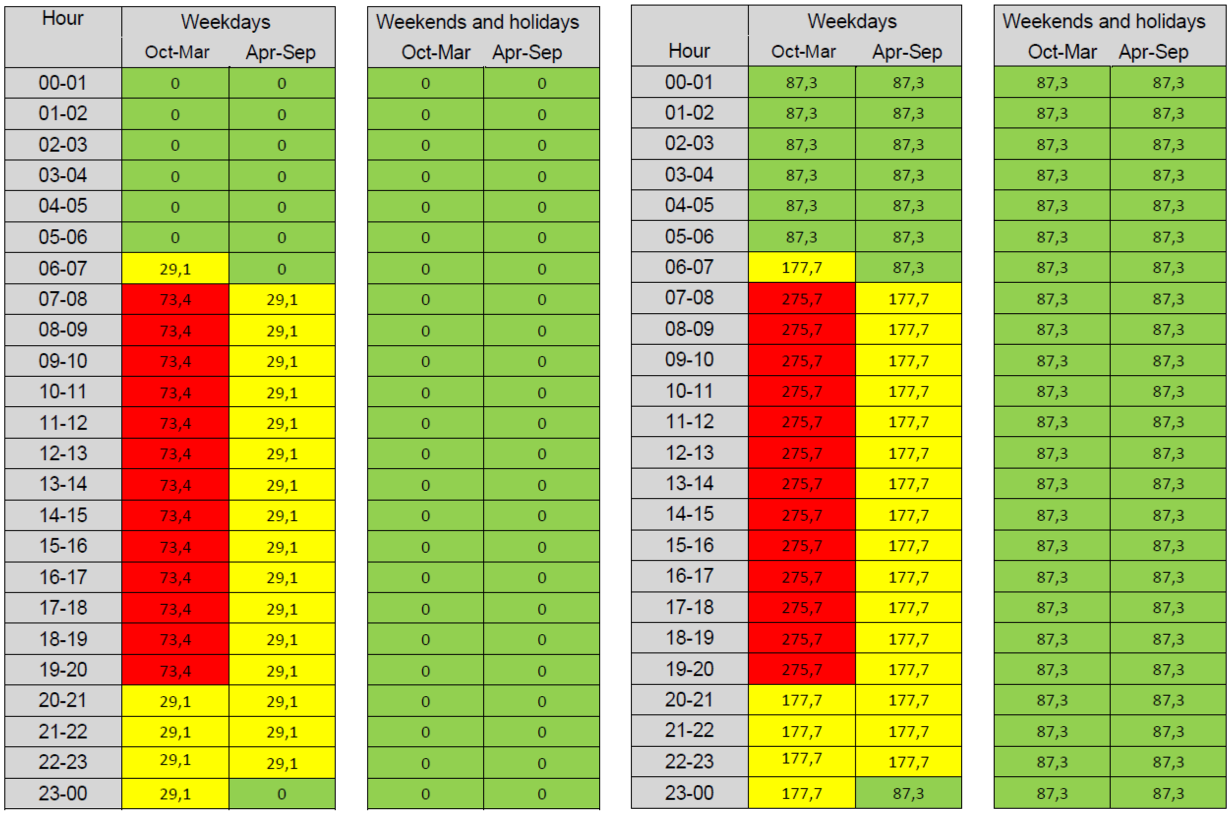


Figure 7.2.1 Variation in hourly electricity spot price year average from 2014-2023. Compiled by EMK from Nordpool DK1 data.

From 2021, time-dependent distribution tariffs were introduced to modify electricity demand. If port infrastructure is connected to 0,4/10kV transformer as B_{high}, as for the charging stations in the E-ferry Twin case study, these tariffs are quite significant, and they have been increased from 2022 to 2023:



From 1st of May 2023

Hour	Weekdays		Weekends and holidays	
	Oct-Mar	Apr-Sep	Oct-Mar	Apr-Sep
00-01	0	0	0	0
01-02	0	0	0	0
02-03	0	0	0	0
03-04	0	0	0	0
04-05	0	0	0	0
05-06	0	0	0	0
06-07	29,1	0	0	0
07-08	73,4	29,1	0	0
08-09	73,4	29,1	0	0
09-10	73,4	29,1	0	0
10-11	73,4	29,1	0	0
11-12	73,4	29,1	0	0
12-13	73,4	29,1	0	0
13-14	73,4	29,1	0	0
14-15	73,4	29,1	0	0
15-16	73,4	29,1	0	0
16-17	73,4	29,1	0	0
17-18	73,4	29,1	0	0
18-19	73,4	29,1	0	0
19-20	73,4	29,1	0	0
20-21	29,1	29,1	0	0
21-22	29,1	29,1	0	0
22-23	29,1	29,1	0	0
23-00	29,1	0	0	0

From 1st of May 2023

Hour	Weekdays		Weekends and holidays	
	Oct-Mar	Apr-Sep	Oct-Mar	Apr-Sep
00-01	87,3	87,3	87,3	87,3
01-02	87,3	87,3	87,3	87,3
02-03	87,3	87,3	87,3	87,3
03-04	87,3	87,3	87,3	87,3
04-05	87,3	87,3	87,3	87,3
05-06	87,3	87,3	87,3	87,3
06-07	177,7	87,3	87,3	87,3
07-08	275,7	177,7	87,3	87,3
08-09	275,7	177,7	87,3	87,3
09-10	275,7	177,7	87,3	87,3
10-11	275,7	177,7	87,3	87,3
11-12	275,7	177,7	87,3	87,3
12-13	275,7	177,7	87,3	87,3
13-14	275,7	177,7	87,3	87,3
14-15	275,7	177,7	87,3	87,3
15-16	275,7	177,7	87,3	87,3
16-17	275,7	177,7	87,3	87,3
17-18	275,7	177,7	87,3	87,3
18-19	275,7	177,7	87,3	87,3
19-20	275,7	177,7	87,3	87,3
20-21	177,7	177,7	87,3	87,3
21-22	177,7	177,7	87,3	87,3
22-23	177,7	177,7	87,3	87,3
23-00	177,7	87,3	87,3	87,3

Table 7.2.1 Time dependent distribution tariffs for B_{high} customers from N1 region DK1. Tariffs are in DKK/MWh. Compiled by EMK. Source of data N1 price lists 2022-2023.

For the time differentiated distribution tariffs, peak shifting is only contributing to savings on weekdays and most significant in winter months. Energy has to be shifted for some hours from night to day. Therefore, potential savings are moderate, as this requires more battery capacity. Tariffs will change slowly with some months of delay when electricity spot price goes up and down. The majority of the tariff is to cover energy losses in the distribution grid and DSO will send any changes to tariffs to the Danish Utility Regulator for approval making it a slow process.

For the other strategy of optimisation for profits from ancillary service, ferry operator could be approved as Balance Responsible Party (BRP) if power system and battery setup meet the requirement by TSO (Energinet Cases, 2023). Ferry operator will measure frequency at the site continuously and activate up or down capacity automatically if frequency deviates more than ±10 mHz from 50 Hz. Task of BRP could also be performed by a third party, e.g. port infrastructure operator.

Assets can be aggregated even though they are not located at the same facility or port. Here it is an advantage that the E-ferry Twins will call at two very different geographical locations in the region DK1. But also, that ferries are not calling in the same time interval within the hour. Ærø minute 20-35 and Svendborg minute 50-05 according to schedule in chapter 2.2.

The port infrastructure with shore-based ESS could be registered as Limited Energy Reservoir (LER). This way shore charging system is exempted from the requirement of 2 hours of full capacity activations in the

FCR service. Instead only 24 minutes is required at full capacity symmetrical up or down. Due to the symmetrical requirement, battery SOC needs to be operated relatively far from full or empty. But this is actually well in line with longevity of battery life for lithium-ion technology. They are mostly degraded at top and bottom of SoC.

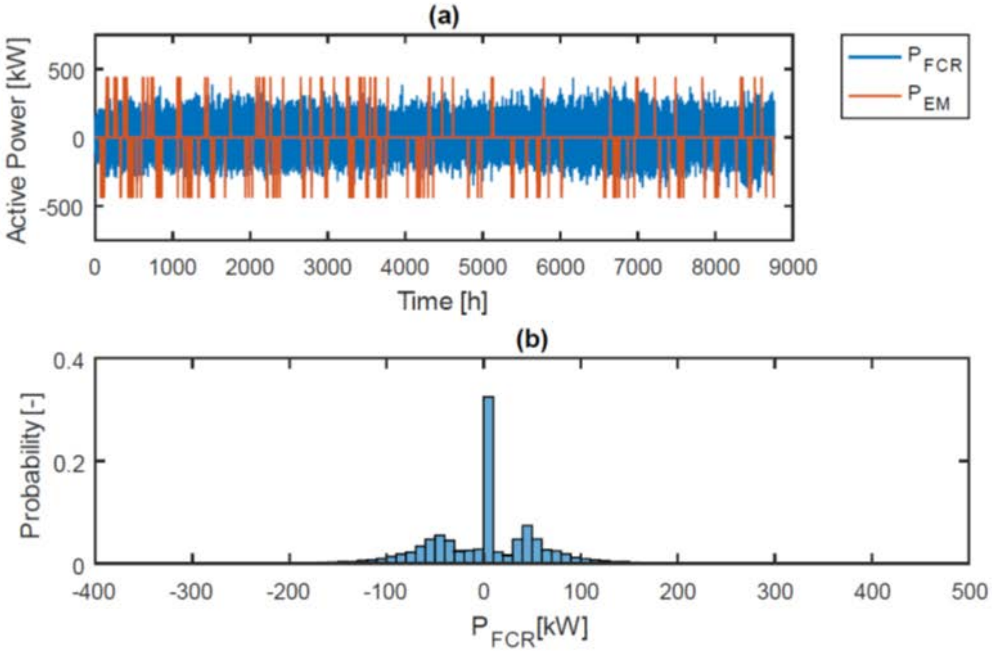


Figure 7.2.2 Simulation of activation of Frequency Containment Reserve (FCR) capacity of 550 kW system with 768 kWh of battery in the DE-DK LFC block where E-ferry Twin ports would be trading. (a) shows the FCR power activated (blue line) and the power for energy management (red line) to restore the system to around 50% SoC. (b) shows the distribution of power levels used to provide the FCR service for one year during 2016. Simulations was performed by Samuel Jansson on internal Vattenfall computer simulation model. Source Evaluation of KPIs and Battery Usage of Li-ion BESS for FCR Application, Master Thesis S. Jansson, Uppsala University, (Jansson, 2019).

The dead-band of ±10 mHz around 50 Hz in the continental FCR market is highly visible in the simulation above. The faster port charging and battery system reacts to deviation the less FCR power is needed. Still dead-band will give some short periods for restoring battery SoC. The FCR service is chosen as the preferred ancillary service in the E-ferry Twin case study because load factor, or activated energy, as a percent of capacity of won bids, is actually below 1%, and in recent years below 0,1%. Also up- and downwards regulation of FCR power will typically be less than 10% of the capacity traded in the bid.

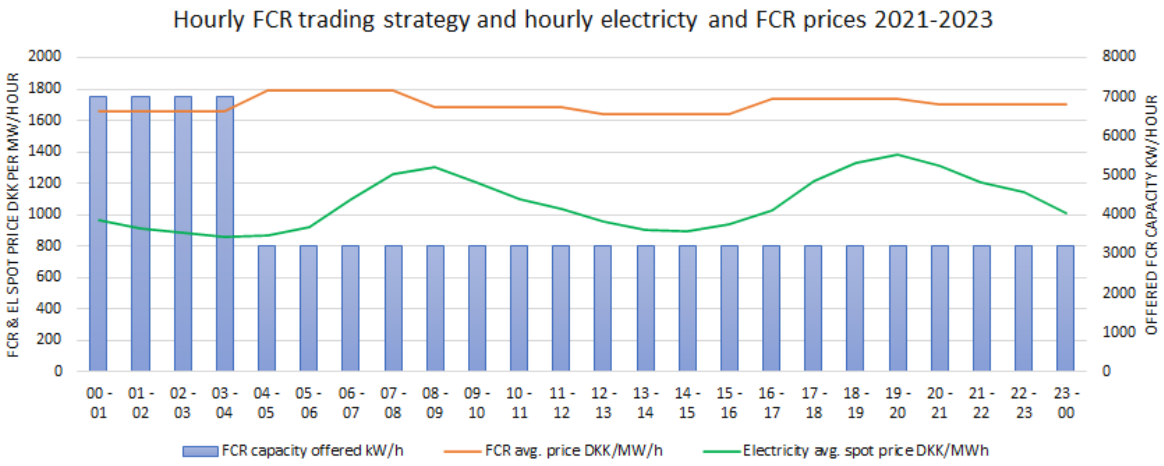


Figure 7.2.3 Strategy and E-ferry setup for trading FCR services with port ESS. From 00-04 V2G using ferry battery as well. EMK.

In the setup, illustrated in Figure 7.2.3, offered FCR capacity leaves room at the shore charging station ESS to performing the primary task of charging the E-ferries when they call port. The simulation in Figure 7.2.2 estimates a throughput of battery energy at 3,5% of the capacity traded in bids. This is higher than the ~1% or less reported by TSO (Energinet). But for a conservative estimation, throughput of 3,5% from simulation has been used to find cost of for all years in scenario 4.3 and 5.3. Higher throughput equals higher costs.

Both scenarios with ancillary service showed better performance than peak shifting or peak shaving with ESS at the port in chapter 4 and 5. But they were partly based on historical data before Danish and German markets introduced common auctions for FCR capacity. Scenarios showed high sensitivity to FCR price and therefore an extra set of data, showing historical FCR price of the German market back to 1st of July 2019, has been prepared as well. See Figure 7.2.4 below:

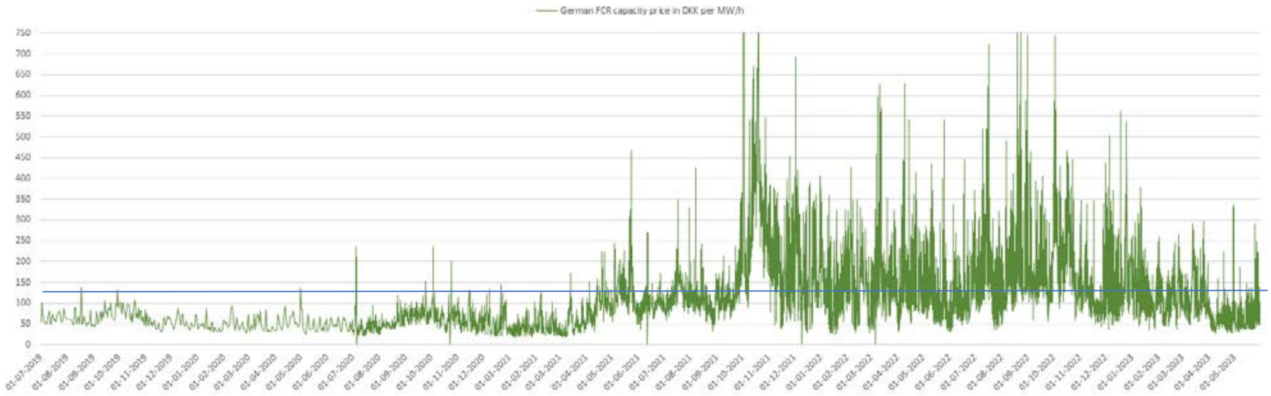


Figure 7.2.4 German FCR capacity price in DKK per MW/h. Blocks are sold at 4-hour intervals, thus block price is divided by four. Compiled by EMK. Source Regelleistung Data Center, (Regelleistung Data Center, 2023).

Average FCR price of this 5-year period is 125 DKK per MW/h. This is a lower average than both scenario 4.3 and 5.3. But still higher than 1st half of 2023. To test sensitivity of scenarios the other vital variable is electricity price. In 2023 both electricity price and tariffs were high, and at the same time FCR capacity price was low. Thus a “perfect storm” to bottom out historical scenarios with a final one for testing “worst case”.

Savings on maintenance	Annual	
Maintenance savings engine system	3.000.000	DKK
Maintenance cost charging stations	- 1.110.000	DKK incl. VAT
Maintenance savings total	1.890.000	DKK incl. VAT
Profit from grid balancing services	Annual	
FCR service 24h/day	1.203.955	DKK incl. VAT
FCR service 00h-04h/day	307.784	DKK incl. VAT
Grid balancing services total	1.511.739	DKK incl. VAT
Energy cost savings	Annual	
Savings year avg. 2023	3.479.174	DKK incl. VAT
Savings if CO2 ETS quotas included	12.591.549	DKK incl. VAT
Savings if CO2 DK future fee included	18.236.036	DKK incl. VAT
Total savings	Annual	
Savings year avg. 2023	6.880.913	DKK incl. VAT
Savings if CO2 ETS quotas included	15.993.289	DKK incl. VAT
Savings if CO2 DK future fee included	21.637.776	DKK incl. VAT

Added investment costs		
Shore charging stations both ports	74.993.333	DKK incl. VAT
E-ferry Twins A & B compared to diesel	13.175.233	DKK
Total added cost base scenario	88.168.566	DKK incl. VAT
Simple liniar pay back calculation		
Based on savings avg.2023 (to June)	12,8	years
Based on savings if CO2 ETS quotas included	5,5	years
Based on savings if CO2 DK future fee incl.	4,1	years
Note: Present value method can be found in next figure/graph		

Table 7.2.2 Profit from FCR grid balancing service and savings from other sources plus simple linear pay back calculations for added investment for close to “worst case” scenario 1st of January to 31st of May 2023. Three different electricity cost scenarios, without CO2 costs and with respectively ETS quotas trading price 1st half of 2023 and with future agreed Danish minimum CO2 fee on fossil fuel of 1.125 DKK/ton of CO2. Source EMK.

Simple linear payback times in Table 7.2.2 are still before battery EoL both with and without cost of CO2 emissions in this almost “worst case” scenario. When using present value method, still with a 4% discount rate, time to break-even will be between 4,4 and 17,3 years. The latter being very close to expected time of battery replacement. A comparison between scenario 5.3 (2021 to June 2023) and the extra scenario with 1st half of 2023 only can be found in Figure 7.2.5 below:

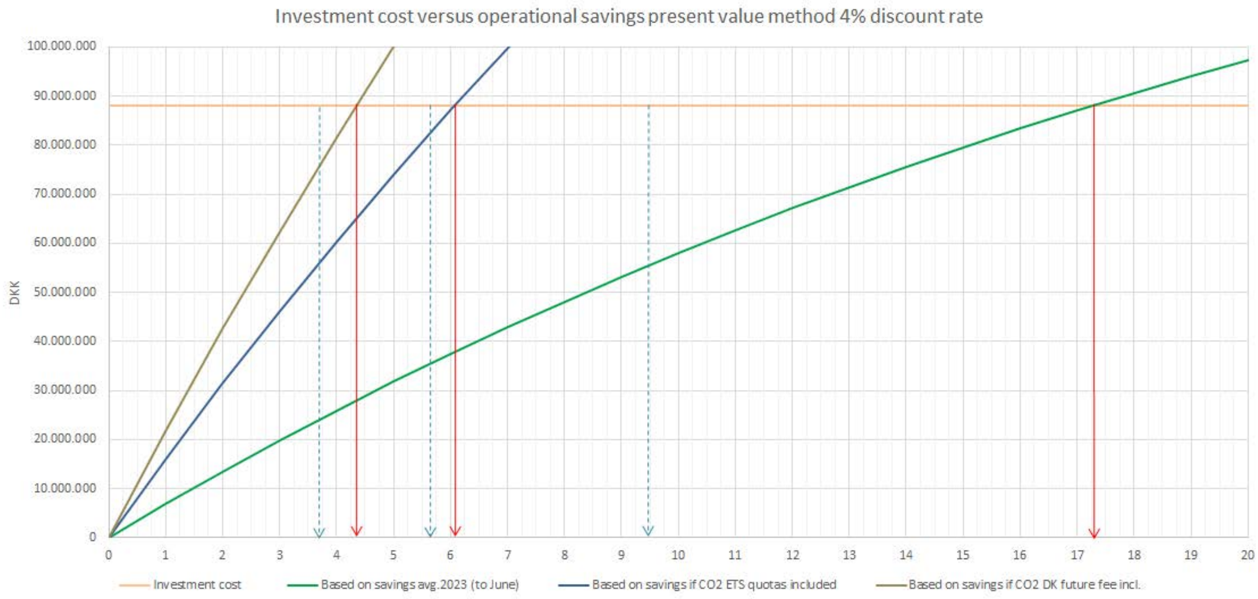


Figure 7.2.5 Accumulated savings discounted to present value with discount rate of 4% versus present investment cost incl. VAT of 16% for shore-based charging stations and profits from grid balancing FCR services for close to “worst case” time period of 1st half of 2023 (January to May). Blue dotted arrow lines are the break-even results from scenario 5.3. Source EMK.

The E-ferry Twin case study with a shore-based ESS could most likely be improved by a combination strategy with FCR ancillary service as primary source of economic optimisation and peak shifting as secondary. As mentioned also in chapter 4.3 multi-market bidding strategies could also enhance profits and optimise performance, although battery throughput and degradation would go up for some ancillary service products, especially mFRR.

With multi-market bidding chances for high success rate of won bids will increase. Theoretically ferry or port infrastructure operator can submit very low value bid for the FCR capacity, as market price, for a given hour or block, will be the price of the highest bid accepted by TSO within the hour or block. Having the capital cost paid by the ferry operation there is not much to lose except for better prices in other markets or higher savings on peak shifting.

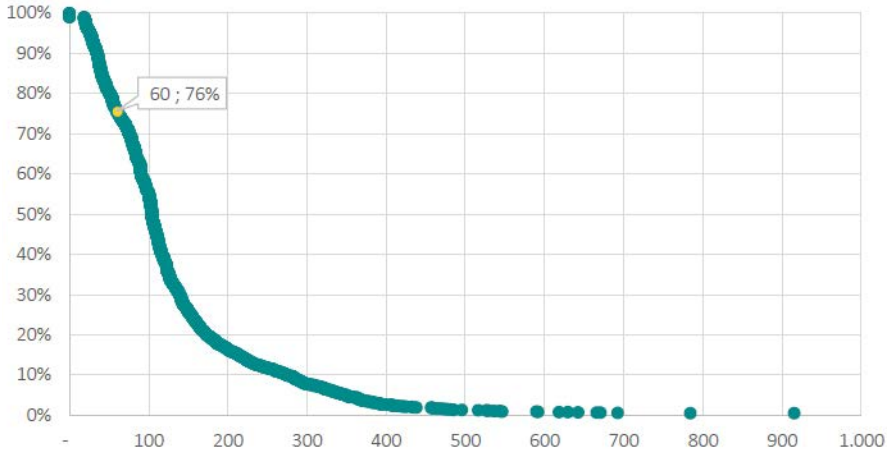


Figure 7.2.6 Accumulated market price at German FCR auction for all of 2021 converted to DKK per MW/h.

Y-axis shows accumulated occurrence of settled price and X-axis shows FCR capacity price.

E.g. if submitting a bid of 60 DKK per MW/h, probability is 76% for acceptance. Source Energinet, PtX-Case, (Energinet PtX Case, 2023).

8 Conclusion

Barriers to battery electric ferry operation are closely related to port infrastructure providing very high charging power for relatively short intervals at ferry berths. This will also challenge the surrounding grid infrastructure as described by Buster B. Hansen (Hansen, 2021). His Master Thesis, "Flexibility Analysis and Demand Response Optimization of Energy System" was prepared under the ZEM Ports North Sea project and presented an in-depth analysis of demand response solutions to mitigate the disadvantages to peak power and grid frequency stability when the E-ferry is charging in the port of Søby.

This report "Case Study for port infrastructure to new E-ferries and analysis of generic barriers" elaborates on the findings in Buster B. Hansen's thesis by also applying shore-based Energy Storage System (ESS) to the port infrastructure solution. ESS will be used for three different strategies:

- Peak shaving, reducing the required size og the grid connection by boosting charges from the ESS, hence also reducing grid connection fee for ferry or port operator.
- Peak shifting, allowing the ferry or port operator to shift charged energy with ESS from high demand hours to low demand hours, hence saving electricity costs and distribution tariff costs.
- Ancillary services, allowing the ferry or port operator to generate revenue, using the ESS for Frequency Containment Reserves (FCR) to Transmission System Operator (TSO) when ferry is not calling port or when it is idle at night in berth.

For the case study, planned successors of the E-ferry in Søby are used. They will replace existing fossil fuelled ferries sailing on routes both from Søby and Ærøskøbing on the island of Ærø to mainland. Generic barriers are identified from the EU Horizon 2020 E-Ferry project and its charging station in the port of Søby. These findings are used to define three alternative strategies for design and operational setup of shore infrastructure in a case study for two new E-ferry Twins planned to operate from the Island of Ærø.

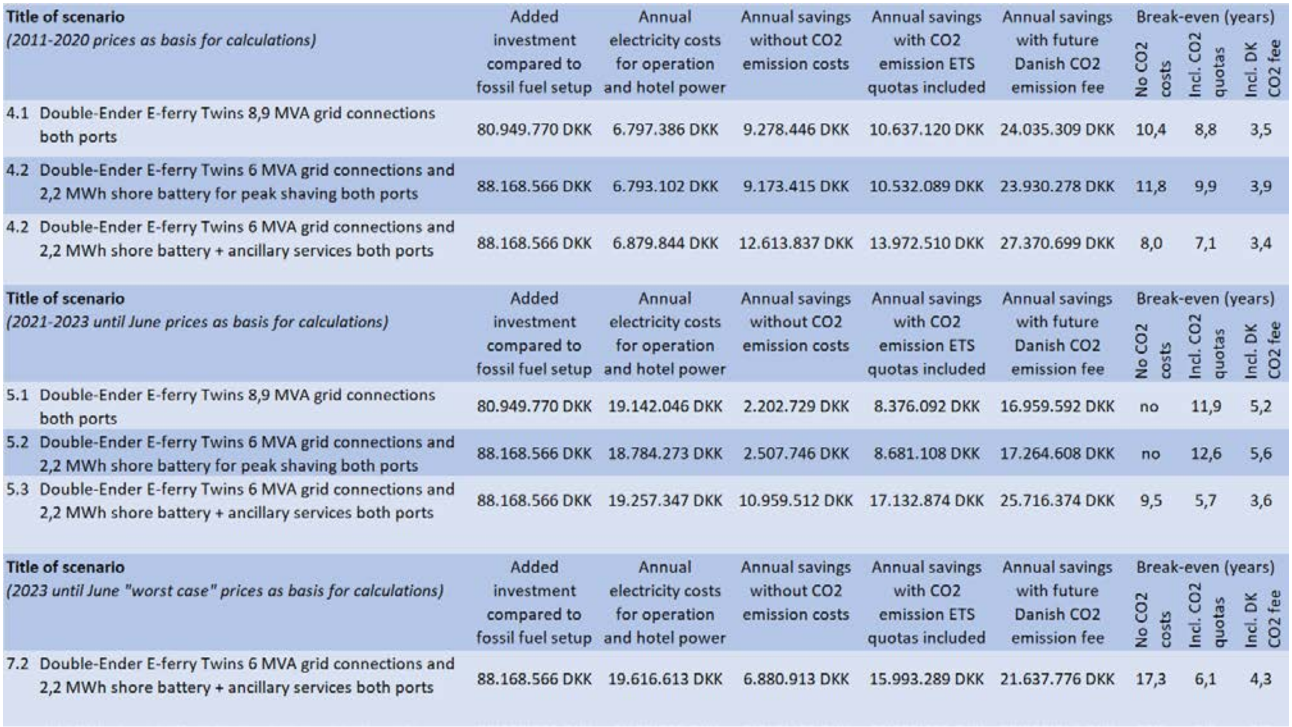
The three alternative strategies found and analysed are:

1. High peak 8,9 MVA grid connection to port charging station for direct charging of the E-ferry Twin battery packs with limited possibility for flexibility, redundancy or peak shifting (Base scenario).
2. 6 MVA grid connection to port charging station with ESS of 2,2 MWh and 2 MW of continuous power or 3 MW of peak power. Charging strategy of ESS is peak shaving and peak shifting to optimise for electricity cost savings.
3. Same infrastructure as alternative (2) with 6 MVA grid connection to port charging station with ESS of 2,2 MWh and 2 MW of continuous power or 3 MW of peak power. Charging strategy of ESS is to provide Frequency Containment Reserves (FCR) for TSO using redundant capacity in shore-based ESS when ferries are sailing. In addition E-ferry's battery pack is used for Vessel-To-Grid (V2G) enhancement of the FCR capacity when it is connected and idle at night from 00:00 to 04:00. Propulsion battery can then be recharged before daily operation.

For each alternative a number of scenarios are modelled and evaluated on parameters like energy cost, efficiency and energy loss, investment cost and savings compared to fossil fuel operation including CO2 emission penalties.

The markets for both renewable electric energy and fossil fuel energy are characterised by periods with high volatility. In the case study, scenarios are divided into two market regimes. One based on the period 2011-2020 reflecting an energy market of relatively low prices and some stability. The second based on the period 2021-2023 (until end of May) reflecting extreme energy prices both on electricity and fossil fuels and high volatility. For the latter period also time dependent distribution tariffs for electricity were introduced in Denmark.

Evaluating the results of scenario models show that battery electric operation under both price regimes will have lower operating costs than conventional fossil fuel operation. For all but two scenarios, added investment costs for battery electric operation and charging infrastructure will be repaid within a reasonable time interval before end of life of batteries in the setup. If penalties, being fees or purchase of quotas, for emission of CO2 from operation is included, then all scenarios are in favour of battery electric operation.



Title of scenario *(2011-2020 prices as basis for calculations)*	Added investment compared to fossil fuel setup	Annual electricity costs for operation and hotel power	Annual savings without CO2 emission costs	Annual savings with CO2 emission ETS quotas included	Annual savings with future Danish CO2 emission fee	Break-even (years)		
						No CO2 costs	Incl. CO2 quotas	Incl. DK CO2 fee
4.1 Double-Ender E-ferry Twins 8,9 MVA grid connections both ports	80.949.770 DKK	6.797.386 DKK	9.278.446 DKK	10.637.120 DKK	24.035.309 DKK	10,4	8,8	3,5
4.2 Double-Ender E-ferry Twins 6 MVA grid connections and 2,2 MWh shore battery for peak shaving both ports	88.168.566 DKK	6.793.102 DKK	9.173.415 DKK	10.532.089 DKK	23.930.278 DKK	11,8	9,9	3,9
4.2 Double-Ender E-ferry Twins 6 MVA grid connections and 2,2 MWh shore battery + ancillary services both ports	88.168.566 DKK	6.879.844 DKK	12.613.837 DKK	13.972.510 DKK	27.370.699 DKK	8,0	7,1	3,4

Title of scenario *(2021-2023 until June prices as basis for calculations)*	Added investment compared to fossil fuel setup	Annual electricity costs for operation and hotel power	Annual savings without CO2 emission costs	Annual savings with CO2 emission ETS quotas included	Annual savings with future Danish CO2 emission fee	Break-even (years)		
						No CO2 costs	Incl. CO2 quotas	Incl. DK CO2 fee
5.1 Double-Ender E-ferry Twins 8,9 MVA grid connections both ports	80.949.770 DKK	19.142.046 DKK	2.202.729 DKK	8.376.092 DKK	16.959.592 DKK	no	11,9	5,2
5.2 Double-Ender E-ferry Twins 6 MVA grid connections and 2,2 MWh shore battery for peak shaving both ports	88.168.566 DKK	18.784.273 DKK	2.507.746 DKK	8.681.108 DKK	17.264.608 DKK	no	12,6	5,6
5.3 Double-Ender E-ferry Twins 6 MVA grid connections and 2,2 MWh shore battery + ancillary services both ports	88.168.566 DKK	19.257.347 DKK	10.959.512 DKK	17.132.874 DKK	25.716.374 DKK	9,5	5,7	3,6

Title of scenario *(2023 until June "worst case" prices as basis for calculations)*	Added investment compared to fossil fuel setup	Annual electricity costs for operation and hotel power	Annual savings without CO2 emission costs	Annual savings with CO2 emission ETS quotas included	Annual savings with future Danish CO2 emission fee	Break-even (years)		
						No CO2 costs	Incl. CO2 quotas	Incl. DK CO2 fee
7.2 Double-Ender E-ferry Twins 6 MVA grid connections and 2,2 MWh shore battery + ancillary services both ports	88.168.566 DKK	19.616.613 DKK	6.880.913 DKK	15.993.289 DKK	21.637.776 DKK	17,3	6,1	4,3

Table 8.1 Added investment costs due to battery electric operation including shore charging stations, ESS and batteries onboard E-ferry Twins versus savings from operation compared to fossil fuelled operation. Time to break-even analysed with present value method and discount rate of 4%. Source EMK.

Peak shifting strategies and smaller grid connection fee with shore-based batteries in the setup will not fully repay the added batteries according to model calculations. However, the difference to calculated scenarios without shore batteries is marginal. Other benefits like higher redundancy or local grid constraints then adds in favour of paying the marginal cost difference for this alternative compared to base scenario with no ESS in the port infrastructure.

Strategies using the shore-based batteries for ancillary services, when not charging the E-ferries, show best result of all scenarios, especially during times with high and volatile electricity prices. An assumed 50% of available redundant capacity has been used for Frequency Containment Reserves (FCR) in modelled calculations. The probability of winning bids is illustrated in Figure 7.2.6 based on auctions in 2021. But ferry or port operator's low cost of FCR capacity could indicate that a higher success rate of won bid is achievable. However, assumptions are kept conservative for the most part in scenario modelling.

Profits from FCR services vary from 3,5 to 9,0 million DKK annually depending on analysed period of time for the case study in chapter 4.3 and 5.3. The "worst case" scenario tested in chapter 7.2 bottomed out at 1.5 million DK in profits for this setup. But is only based on 5-month interval of trading in the FCR market at the worst time of year.

Multi-market bidding strategies could mitigate risk and were shown by Andreas Thingvad (A. Thingvad, 2023) to potentially contribute with 20-30% added value in analysis from Nordic Reserve market. Multi-market bidding could be relevant for future analysis and would involve complex optimisation models or machine learning to plan optimal solution way ahead as bids, e.g. in the FCR auctions, are submitted the day before.

In chapter 7.1 barriers to battery electric ferry operation associated with risk of added investment for port infrastructure in a dynamic market of ever-changing energy costs are evaluated, comparing alternative fuel types to fully electric operation. Historical cost of electricity and fuel prices from 2011 to present time are analysed in a comparative study, taking into consideration inherent efficiencies and energy densities of the alternatives.

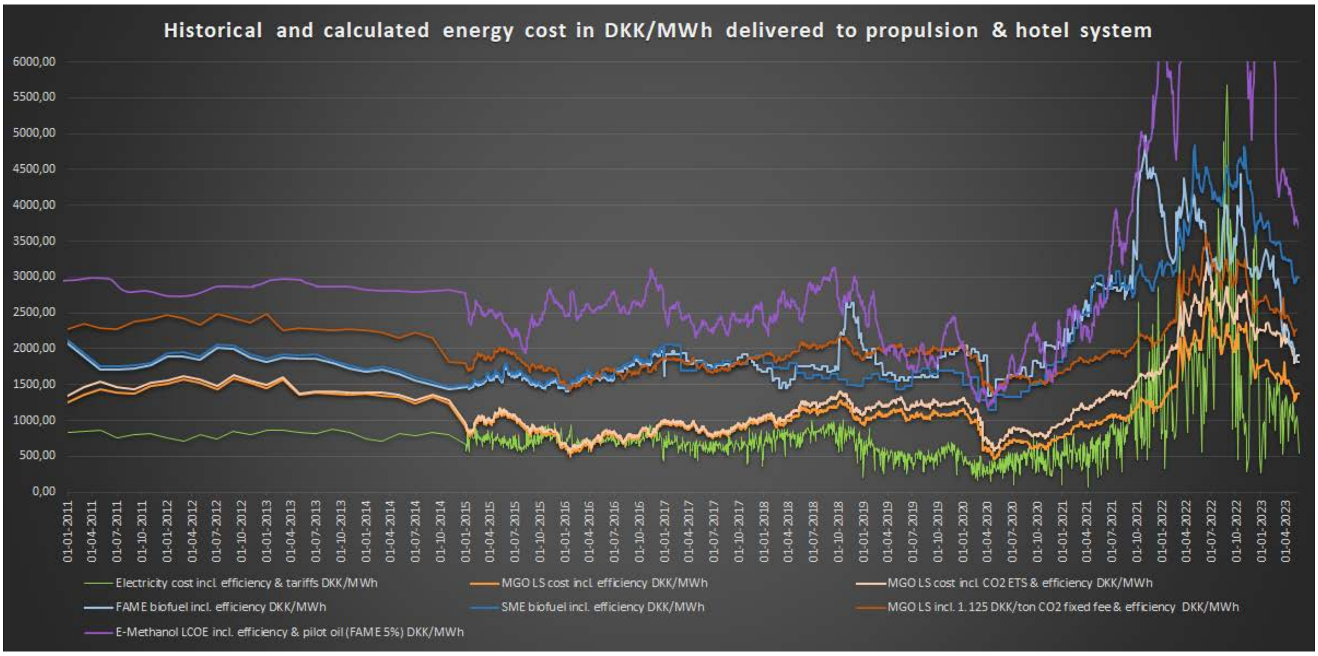


Figure 8.1 Long-term energy cost comparison for conventional fossil fuel drive train (Marine Gas Oil), biofuel drive train and electric battery drivetrain charged with renewable energy. Also comparison with calculated Levelized Cost of Energy (LCOE) for e-methanol is shown for reference, although product do not exist in market yet. Details can be found in chapter 7.1. Compiled by EMK from multiple sources (also see Figure 7.1.1 for details).

The comparison emphasises the cost saving on running or operation costs of battery electric solutions over its alternatives. Also future fuel of e-methanol produced from electrolysis and carbon capture, using renewable electricity sources, is illustrated by its calculated cost. The cost is based on historical electricity price in DK1 and forecasted production and investment costs prepared by Mathias Fuglsang in his Master Thesis, “Feasibility Study of Power-to-Methanol in Denmark” (Fuglsang, 2021).

Alternative fuels like biofuel and e-methanol are all significantly more expensive than fossil fuel when efficiencies are accounted for. Therefore it must be concluded that added investment costs of battery operation compared to alternative fuels would obtain even shorter time to break-even than for conventional bunker.

The introduction of shore-based ESS to port infrastructure and charging stations is found to have the potential to significantly lower barriers to battery electric ferry operation if ancillary services are performed as described in the case study. This way battery electric ferries could create value for grid responsible operators as well as ferry operators.

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10 List of figures

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