Life cycle analysis of batteries in maritime sector

NÆRINGSLIVETS
NOx-fond

Maritime Battery Forum

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Report information

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Prepared for:	Næringslivets NOx-fond (The Business Sector's NOx Fund) Postboks 5250 Majorstuen 0303 Oslo
Prepared by:	Sarah Lasselle, consultant DNV GL Lars Ole Valøen, CTO Grenland Energy Børre Gundersen, Maritime R&D Manager, ABB Maritime Battery Forum c/o DNV GL, Sondre Henningsgård Veritasveien 1 1363 Høvik
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Executive summary

This report has been prepared by the Maritime Battery Forum in cooperation with Grenland Energy, ABB, and DNV GL for the Norwegian NOx-fund. The purpose is to perform a life cycle assessment of batteries used in a maritime setting. Two cases have been considered: a hybrid platform supply vessel (PSV) and a fully electric ferry.

The study is structured as a cost-benefit analysis, in which the extra costs of creating the battery system (the energy storage and power conversion) are compared to the emissions savings of using the battery, and an environmental payback time is calculated. The emissions considered in this study are greenhouse gases contributing to Global Warming Potential (GWP) and NO_x emissions.

For the hybrid PSV, the environmental payback period for GWP and NO_x is 1.5 months and 0.3 months respectively. For the fully electric ferry, the environmental payback period for GWP and NO_x are 1.4 months and 0.3 months, respectively, when the Norwegian electricity mix is used.

Table 1 Environmental payback period for PSV and fully electric ferry

	Environmental payback period [months]	
	GWP	NOx
Hybrid PSV	1.5	0.3
Electric ferry running on Norwegian electricity mix	1.4	0.3

The basic methodology for the analysis was to establish an operational profile for a PSV and a ferry. Based on the operational profiles, the fuel consumption was calculated for a diesel PSV and hybrid PSV, and a diesel ferry and fully electric ferry. The operational profiles and fuel consumptions were compiled with input from ABB and DNV GL.

Once the operational profiles were compiled, Grenland Energy dimensioned hypothetical battery packs which could satisfy the needs of the hybrid PSV and the fully electric ferry. ABB then provided input regarding the power conversion equipment necessary. Life cycle inventories of the battery systems necessary for hybrid PSVs and electric ferries were compiled with product information from Grenland Energy and ABB. This included information on the amounts of steel, copper, aluminum and other materials required for the complete battery system. Corresponding life cycle emissions were calculated using the Ecoinvent[1] inventory to estimate an environmental CAPEX.

The environmental payback periods were calculated with the environmental CAPEX consisting of the life cycle inventory for production of a complete battery system and the environmental OPEX consisting of emission reductions resulting from battery use.

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[1] Ecoinvent is an environmental database containing life cycle emissions data for various materials and processes.

Sammendrag

Denne studien har blitt utført i samarbeid med Grenland Energy, ABB og DNV GL på vegne av Næringslivets NO_x-fond. Formålet var å utføre en livssyklusanalyse for batterier brukt i maritim sammenheng. To skipstyper har blitt vurdert; et hybrid plattform supplyskip og en helelektrisk ferge.

Studien er strukturert som en kost-nytteanalyse, der miljøkostnaden av å lage batterisystemet (inklusive energilagring) og kraftkontrollsystemene er sammenlignet med utslippsreduksjonene ved batteridrift. En tilbakebetalingstid for miljøet er beregnet. Utslippstypene som er vurdert i denne studien er klimagasser, kjent som *global warming potential* (GWP) målt i CO_2-ekvilalenter, og NO_x.

Miljøtilbakebetalingstiden er 1,5 måneder og 0,3 måneder for henholdsvis GWP og NO_x for en hybrid PSV, og 1,4 måneder og 0,3 måneder for henholdsvis GWP og NO_x for en helelektrisk ferge med norsk strømforsyning.

Table 2 Miljøtilbakebetalingstid for hybrid PSV og helelektrisk ferge

	Miljøtilbakebetalingstid [måneder]	
	GWP	NOx
Hybrid PSV	1,5	0,3
Helektrisk ferge med norsk strømforsyning	1,4	0,3

Analysen ble utført ved å etablere operasjonsprofiler for typiske PSV'er og ferger. Operasjonsprofilene ble fastsatt etter innspill fra ABB og DNV GL. Med utgangspunkt i operasjonsprofilene ble energiforbruk beregnet for en diesel-PSV og en hybrid PSV, og en diesel- og en helelektrisk ferge. Basert på energiforbruket ble utslippsreduksjonene for den hybride PSV'en og den helelektriske fergen estimert.

Grenland Energy dimensjonerte hypotetiske batteripakker som vil tilfredsstille effektbehovene i operasjonsprofilene. For å beregne en miljø-CAPEX ble mengden stål, aluminium, kobber og andre nødvendige materialer vurdert ut fra produktinformasjon fra ABB og Grenland Energy om utstyr til energilagring og kraftkontroll. Livssyklusutslipp for de forskjellige komponentene ble hentet fra Ecoinvent-databasen[2].

Med miljø-CAPEX for et komplett batterisystem og miljø-OPEX beregnet ut i fra utslippsreduksjon som følge av batteribruk om bord på skipene, kunne miljøtilbakebetalingstid for begge skipstypene beregnes.

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[2] Ecoinvent er en miljødatabase som inneholder informasjon om livssyklusutslipp for diverse materialer og prosesser.

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1 Introduction

Batteries are becoming a relevant means of reducing emissions of both greenhouse gases and NO_x from the maritime industry. However, batteries have an environmental cost in that their production requires energy and materials. Members of the Maritime Battery Forum (MBF) report that they often receive questions regarding how environmentally beneficial batteries really are given the environmental cost of their production.

Life Cycle Assessment (LCA) is a common methodology for examining these types of issues. LCA is a means of quantifying the environmental impact of a process given all aspects of the value chain, from production to end-of-life processes, such as recycling or land-filling. LCA is particularly useful for comparing two systems – such as ships running on batteries compared to ships running on diesel – because including the entire value chain allows us to compare apples to apples.

Several LCA studies have been performed to investigate the environmental benefits of batteries used in cars. However, the question remains unanswered in the case of battery use on board ships. At the time of writing, the Maritime Battery Forum has not identified any published studies of LCA for maritime batteries. As such, the Maritime Battery Forum has received support from the Norwegian NOx-fund in order to perform a LCA of batteries for maritime use.

This study examines two ship types: a platform supply vessel (PSV) and a ferry, in which the environmental cost of employing a battery is weighed against the environmental gains by comparing the environmental performance of the ship type using a battery and running on diesel. In both cases, the analysis is structured as a cost-benefit analysis, but the analyses examine costs and benefits from an environmental perspective, not a financial one.

The environmental costs and benefits are calculated as global warming potential (GWP) and NO_x emissions.

2 Motivation for study: batteries in the context of domestic and global emissions reductions

The motivation for this study is the questions which MBF members often receive about the true environmental impacts of batteries. Members report skepticism on behalf of other actors in the maritime industry regarding the emissions necessary to create battery systems, and how these emissions stack up against the savings.

There is, however, a broader picture. The emissions savings should also be seen in the context of Norway's goals to reduce emissions from the domestic fleet. The Norwegian government has agreed - through participation in the EU quota scheme – to a 40 % reduction in the CO_2 emissions which are subject to the EU quotas by 2030 (1). Although emissions from the transportation sector are not subject to the quota system, emissions from domestic shipping are priority for the Norwegian government, and they are exploring strategies for bringing emission reductions from the transport sector in line with reductions from sectors which are subject to quotas. This is because emissions from domestic shipping constitute 9% of total Norwegian CO_2 emissions and 34% of total Norwegian NO_x emissions (2).

A DNV GL study which models the entire Norwegian fleet based on AIS data shows that even if all known energy efficiency techniques are employed in all ship types of the entire domestic fleet, it will not be possible to reduce emissions from domestic shipping by 40% (1). Alternative propulsion such as the use of fully electric vessels or biofuels is necessary to achieve the goals. Figure 1 illustrates the results of this study, modelling emissions from 2015 to 2040 with varying scenarios.

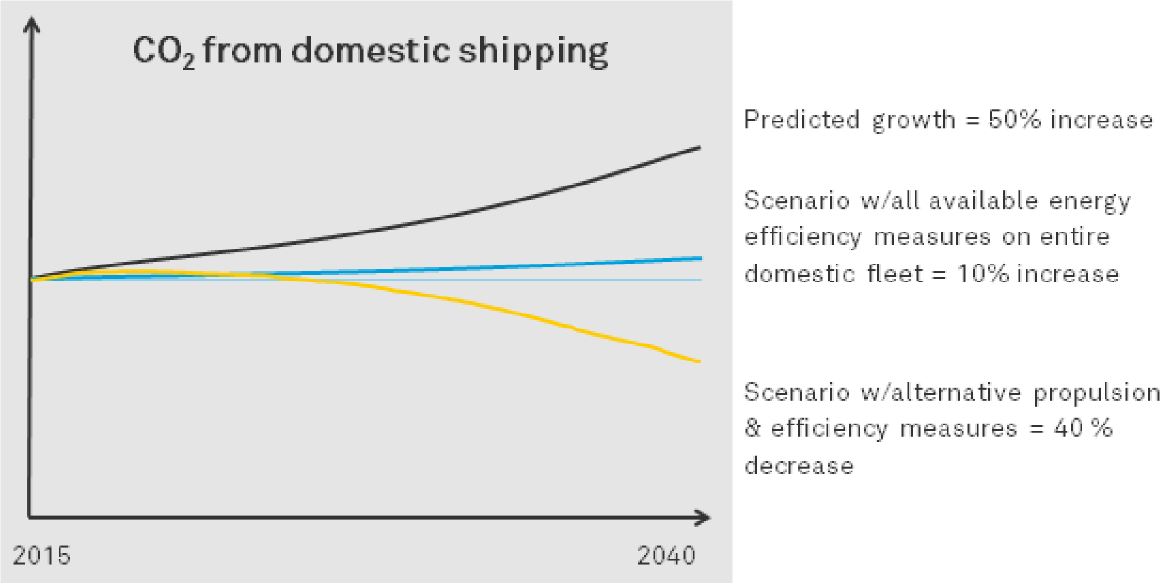

Figure 1 Predicted growth of emissions from domestic shipping in Norway

Small passenger vessels, such as ferries, and offshore supply ships account for approximately 51% of fuel consumption in domestic shipping. Along with fishing vessels, these two ship types dominate fuel consumption, and thus emissions of domestic shipping. However the study shows that all ship types, not just ferries and offshore supply ships, must employ emissions reduction techniques in order to achieve the 40% reduction target, and that electric propulsion will play an important role in the future of shipping in Norway.

On a global level, emissions from the transportation sector accounts for 14 % of global GHG emissions, and the energy sector accounts for 25 % of global GHG emissions (3). Globally, shipping accounts for 3 % of GHG emissions – approximately the same as the total GHG emissions of Germany (2). Some actors in the shipping sector may claim that the emissions from shipping are so insignificant that the shipping sector should not have to pay the economic price of sustainable technology. However, the problem of global warming is not one that can be solved by only sector or only one nation and 3 % in the context of global warming is a large percentage of emissions.

The Intergovernmental Panel on Climate Change's (IPCC) stresses that, in order to limit global warming to 2°C, all sectors will need to take action and that we must employ the known emissions reduction technologies at our disposal as soon as possible (4). This means that one sector cannot wait for another sector further up in the value chain to employ sustainable technology. All actors need to act now to reduce climate change.

While this report looks at the emissions of battery systems along the entire value chain, it is important to note that this is a snapshot of life cycle emissions for a maritime battery today. The life cycle emissions of creating a maritime battery system are subject to change, as the sectors contributing to the production process will or can employ more sustainable techniques.

3 LCA Methodology

Life cycle assessment (LCA) is a technique which evaluates the environmental performance of a process or system by compiling the material and energy inputs, evaluating the outputs and emissions, and quantifying the environmental impacts (5). LCA can be illustrated in 4 steps shown below.

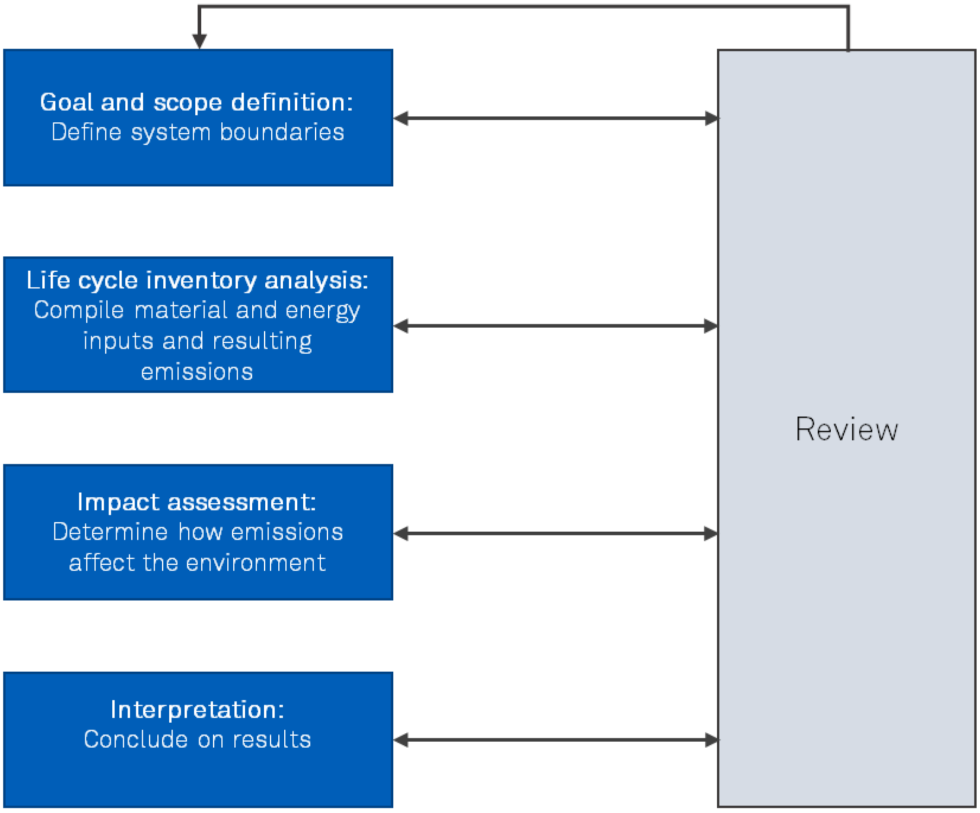

Figure 2 - Steps of LCA, as per ISO 14040

LCA is an iterative process which requires review during each step of the analysis.

Establishing the goal and scope entails establishing the functional unit of the system and the system boundaries. A functional unit in an LCA is one functional output of the system in question. In this study, the LCA is structured as a comparison between two cases or functional units.

Life cycle inventory analysis is the compilation aspect of LCA. It entails collecting information on the material and energy inputs necessary to create one functional unit, and the associated emissions to the environment. This is done in each life cycle stage and the resulting emissions are calculated based on the inputs.

Impact assessment determines how the emissions quantified in the life cycle inventory analysis will affect the environment. Emissions can be to air, water and land, and can affect the environment in terms of biodiversity, global warming, marine toxicity or human health. There are many frameworks for impact assessments.

Interpretation includes determining sources of uncertainty and discussion.

3.1 Goal, scope and functional unit

The study is structured to answer this question: Given that a battery has an environmental cost to produce (an environmental CAPEX), but operating the battery results in an environmental savings (a reduced environmental OPEX), what is the payback time of using a battery? The concept is illustrated in Figure 3 (not drawn to scale).

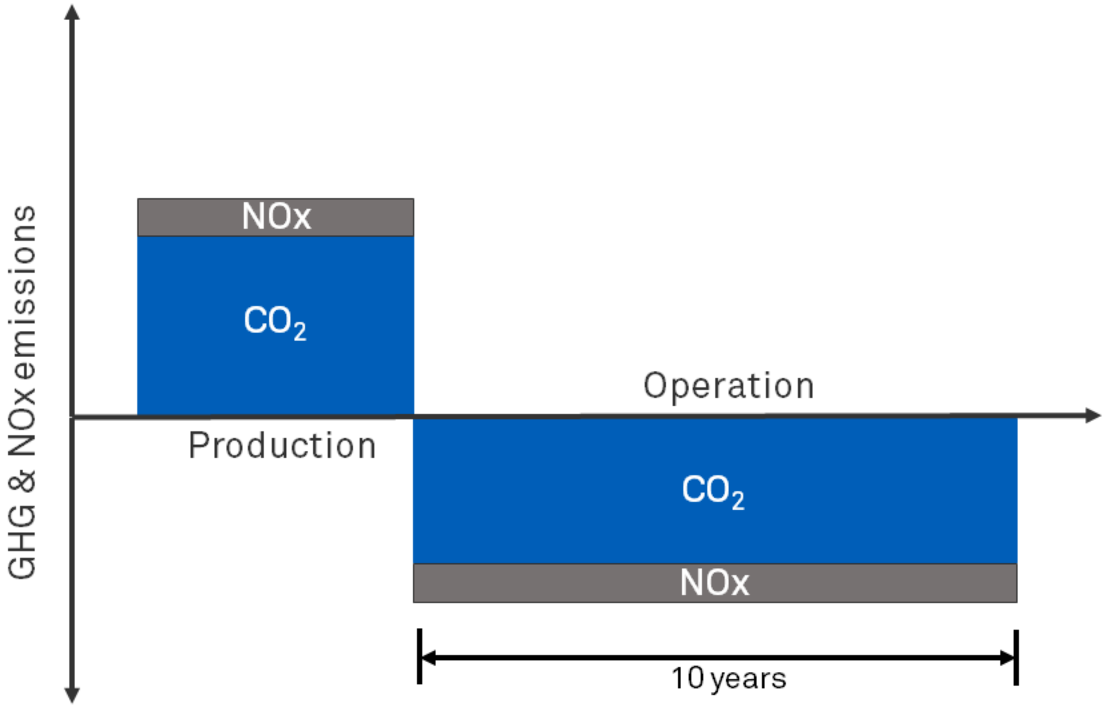

Figure 3 – Illustration of environmental cost-benefit analysis employed in this study

This study diverts from typical LCA practice in that the system output analyzed is ten years of battery use, whereas the functional unit is usually one unit of work by the system. For example, a typical functional unit for an LCA of electric car batteries is one passenger-kilometer of work performed by the car (6).

A functional unit of ten years' ship operation was chosen because the results can be presented in the structure of a typical cost-benefit analysis, and allows for the calculation of an environmental payback time.

Additionally, a functional unit of one ton-kilometer of work requires normalizing the work performed by the ship over the lifetime of the engine or battery. While this is easy to do with some certainty with respect to cars, where data about average work performed is available, this is not the case with all ship types. Ship owners do not keep information regarding how many ton-kilometers of work the ships perform. While it would be possible to calculate total passenger-kilometers for a ferry running a constant route, there is not sufficient data to perform this analysis for a typical PSV.

Because the objective of the study is to compare ships using batteries to ships without batteries, only the additional environmental costs and savings associated with battery are quantified (see Figure 4).

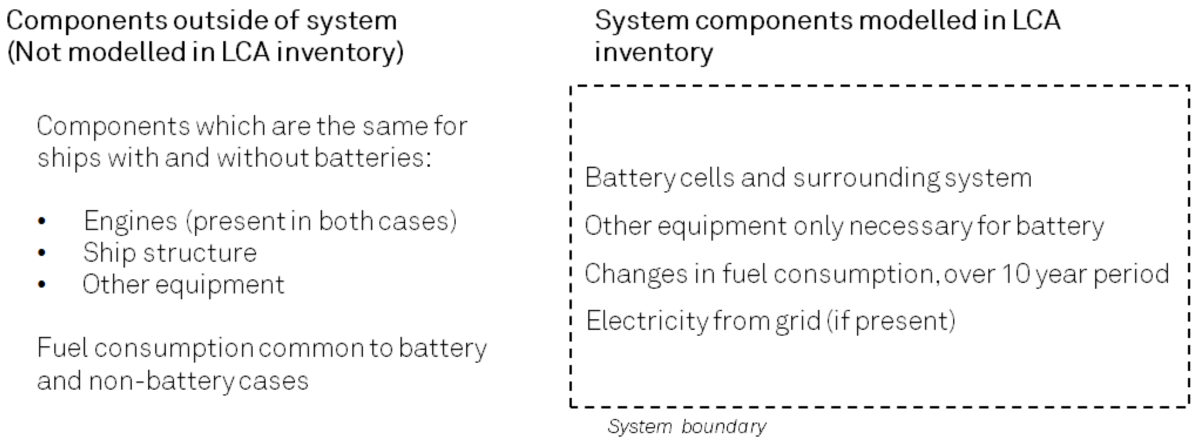

Figure 4 - Description of system boundary

3.2 Life cycle inventory analysis

In order to perform the life cycle inventory analysis and the impact assessment stages of LCA, an environmental life cycle database is employed. This study employs Ecoinvent, which is a life cycle inventory database by the Swiss Centre for Life Cycle Inventories. It contains material and process input information, and emission information (as illustrated Figure 5) for processes which are relevant for the battery systems in this study. The database provides the total greenhouse gas (GHG) and NO_x emissions for the entire life cycle of these processes. Ecoinvent database version 3.2, updated in 2015, was used.

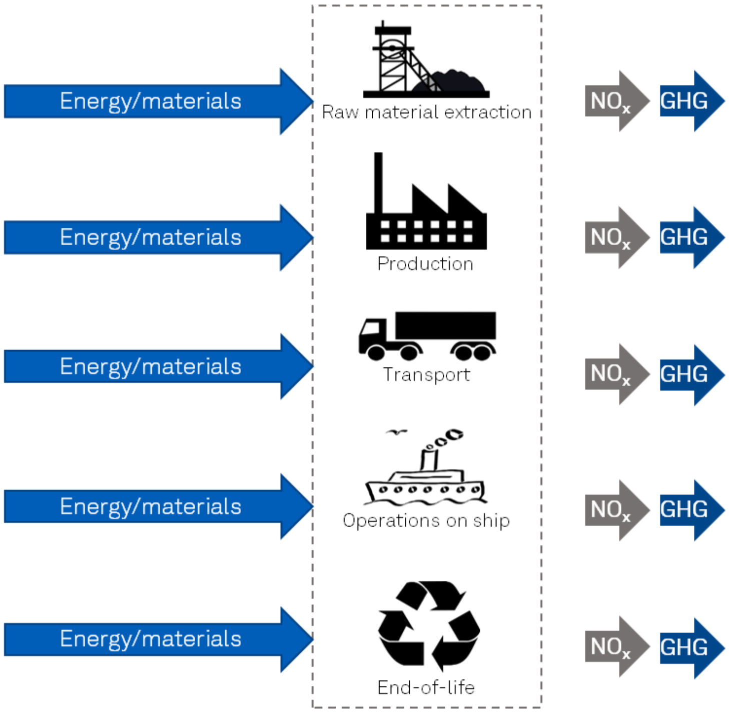

Figure 5 - Life cycle inventory analysis

An example of a process found in Ecoinvent is aluminum production in Norway. For this process, the database contains, amongst other data, cradle-to-gate information about the total GHG and

NO_x emissions for the entire life cycle of aluminum production. These life cycle emissions can be added to the overall life cycle inventory for the components of the battery system which contain aluminum.

Creating a life cycle inventory consists of choosing relevant processes (sub-inventories) from a database, as well as performing independent modelling where necessary data are not available. The relevant processes needed to produce the battery systems are determined by identifying the materials used to produce the in-scope part of the system.

The basic components of the battery cells, such as the electrolyte, separator, etc., and the other necessary materials for the battery system were already modelled in Ecoinvent. The amounts of the relevant materials were found in product information from ABB and Grenland Energy, and thus the total life cycle emissions could be calculated.

Transportation requirements and process energy for component production are estimated from product brochures, as well as ABB and Grenland Energy project experience. The life cycle emissions of the materials used to create the components in the scope of the battery system, the emissions from process energy used to create the components and emissions from transport are added together to form the environmental CAPEX.

Some of the processes in Ecoinvent correspond to specific geographic locations, and some processes correspond to global or regional averages. In this study, the global averages were chosen when the production location for the specific battery system was not known.

The energy and material inputs for the operations part of the life cycle, the environmental OPEX, are determined by calculating fuel and electricity consumption for each case. The emissions from fuel use are calculated directly, and impacts of fuel and electricity production are taken from the Ecoinvent database.

The end-of-life phase is discussed qualitatively in this report.

3.3 Impact assessment

Impact assessment is the process of determining how the various emissions of the system impact the environment. This study considers one impact category, global warming potential (GWP). This means that all GHGs which contribute to global warming – CO_2, CH_4, N_2O, etc. – are compiled for each life cycle stage. Each emission has a certain contribution to global warming, measured in CO_2 equivalents.

The contribution of the various GHGs to global warming can be calculated in different ways. This is known as characterization. The GWP impact is calculated using the ReCiPe hierarchical method (7). This means that the various GHGs are normalized to kg CO_2-equivalents based on their global warming effect in the atmosphere over a period of 100 years.

The study also considers the life cycle emissions of NO_x. Often in LCA studies, NO_x contributes to various impact categories, such human health or photochemical ozonation; the life cycle emissions of NO_x alone are not usually given. However, this study has been commissioned by the Norwegian Business Sector's NO_x -fund, whose mission is to reduce the emissions of NO_x in Norway. The emissions of NO_x are thus of particular interest.

Additionally, air pollution – particularly NOx and particulates – from international shipping accounts for several tens of thousands of premature deaths annually (8). As such, the total NOx-emissions have environmental significance beyond any impact framework employed in LCA.

4 Second life of maritime batteries

The end-of-life cycle of batteries is an important life-cycle phase. Batteries which have been used on board ships but are too used to satisfy Classification and safety requirements still have storage capacity and can be used as grid stabilizers. A pilot project to test the capability of used Li-ion batteries from electric vehicles to act as a storage buffer for the power grid is ongoing between Bosch, BMW, and Vattenfall (9).

Discussions with several battery producers in MBF indicate that while grid stabilization is promising on a technical level, there needs to be more safety procedures and infrastructure in place for batteries which have reached the end of life for the use for which they were designed. Currently, the main barrier for old batteries to be used as grid stabilization is that a battery producer will be reluctant to allow the use of their used battery for grid stabilization because any accident may be a liability for the producer. In addition a non-standardized mechanical shape and a non-standardized electronic interface makes it more technically challenging and thereby more expensive to use old batteries for grid stabilization.

MBF members also indicate that infrastructure which allows for used battery to be turned in to the producers or certified recycling facilities is not currently in place. This would be necessary to prevent individuals from obtaining old batteries, tinkering with them, and causing a potential accident.

MBF members also note that for the purposes of grid-stabilization, it is not easy to combine or mix battery systems, so finding a new home for relatively small battery systems from PSVs may be difficult. In the case of ferries, however, it would be possible to take old battery systems and employ them in shore charging systems. This option may be more feasible from a safety standpoint in that the batteries remain in the hands of the same operators, to a certain extent.

Even once the industry can come to an agreement on how to safely de-cycle used Li-ion batteries, the cells will still eventually degrade to the point of no longer being able to be used in an energy storage capacity. In that case, recycling the materials to make more batteries can be environmentally viable. One study shows that cathode production with recycled materials can decrease exergy[3] consumption by more than 50% (10). Recycling must occur more consistently in order to develop efficient processes and to perform an assessment on recycling of batteries from a life cycle perspective.

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[3] Exergy is high quality energy that can perform work, as opposed to energy which may be in the form of heat and cannot do work.

5 Case 1: Platform Supply Vessel (PSV)

The first case covered in this study is a platform supply vessel (PSV). The environmental performance of a PSV operating with a 4-generator diesel electric propulsion system (non-hybrid case) is compared with a PSV which employs a battery as spinning reserve (hybrid case). This is done by calculating the environmental costs of the extra equipment needed for the hybrid case and the environmental benefits of fuel saving. The fuel savings of the hybrid PSV compared to the non-hybrid PSV are due to the fact that a hybrid PSV can run without redundant generators.

Platform supply vessels can perform a variety of services for offshore platforms. Usually, the duties of the PSV require that the vessel employ dynamic positioning (DP). This is an operational mode in which the vessel remains completely still, so as not to collide with the platform or any other nearby structure, while servicing it. When a vessel is in DP, it is imperative that the power source to the thrusters and the propeller remain intact. For example, a sudden loss of a generator could mean that power is lost to the thruster, and that the vessel crashes against the platform. As such, there are special classification requirements for redundancy of generators (11) for vessels running in DP mode.

A PSV must have redundant generators running while in DP, so if one generator fails, there will still be enough power to maintain the ship’s position. The redundant generator must be running while the ship is in DP mode because most generators cannot start up and give power to the system quickly enough to satisfy the DP classification requirements. As a result, a PSV employing a diesel electric propulsion system will have several generators running on low load levels for which the generators are not optimized and specific fuel oil consumption (SFOC) is high.

Rather than running a redundant generator when in DP mode, the ship can install a battery. A battery acts as spinning reserve, replacing the redundant generator. In case of generator failure, the battery can provide power to the system immediately.

Although it is not always a class requirement, many PSVs also employ a redundant generator or a spinning reserve while in stand-by modes and while slow steaming. This is included in the hybrid and non-hybrid operational profiles.

The final means in which a battery can be employed to save energy on a hybrid PSV is to cover hotel loads with the battery while in port. Hotel loads are also small compared to the optimized engine loads, and it is therefore more efficient to cover hotel loads with a battery, and then re-charge the battery as needed with the generators running at optimal loads.

Table 3 summarizes the operational modes in which the hybrid PSV employs a battery to save fuel compared to the diesel PSV.

Table 3- Summary of operational differences between diesel and hybrid PSV modelled for this study

Operational mode	Diesel PSV	Hybrid PSV
Stand-by	1 redundant generator	Battery as spinning reserve
DP	1 redundant generator	Battery as spinning reserve
Slow steaming (11 kn)	1 redundant generator	Battery as spinning reserve
In-port	1 generator running at low loads	Battery covers hotel load, 1 generator recharges battery when battery state of charge reaches a minimum level

The effects of peak shaving – the use of the battery at high engine loads – are not modelled. This is because the energy savings in peak shaving are not easily quantified unless peak shaving allows for ship to run with fewer generators all together.

Figure 6 - Battery for hybrid case is used as spinning reserve and in port, not for peak shaving (Icons, ABB Ltd.)

5.1 PSV technical specifics & operational profile

The total installed power for the case vessel is 8,960 kW.

The configuration for the diesel PSV is four generators connected by a closed bus to an AC grid. The single line diagram (SLD) for the diesel PSV is shown in Figure 7.

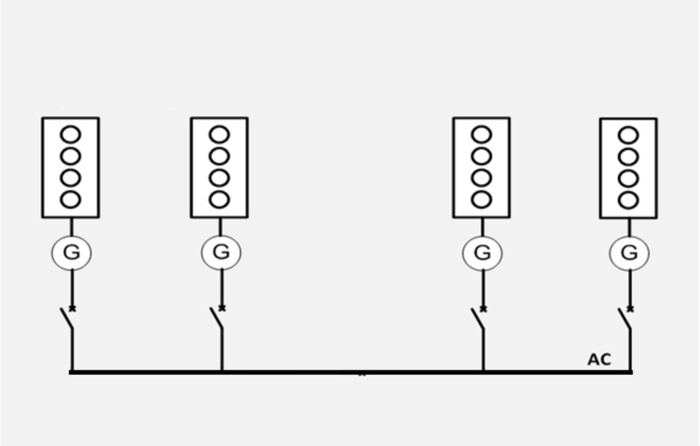

Figure 7 - Single line diagram of PSV non-hybrid case

The power conversion configuration for the PSV hybrid case includes four generator sets connected by a closed bus. An AC/DC converter switches the DC current from the battery to AC current, and a transformer controls the voltage sent to the grid. The converter and transformer are dimensioned for a maximum power output of 1 MW.

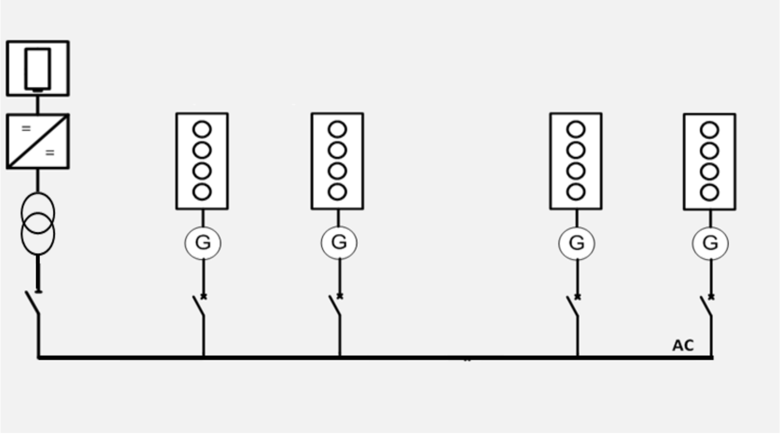

Figure 8 - Single line diagram of PSV hybrid case

In order to compare the environmental performance of a diesel and hybrid PSV, an operational mode for a typical PSV was established using project data from ABB. The operational profile is used to calculate the fuel savings from employing a hybrid system, and to dimension the battery.

A distribution of time spent in different modes for the case PSV is shown in Figure 9. The vessel spends 37% of running hours in DP mode – the mode for which there is most to gain by employing a hybrid system.

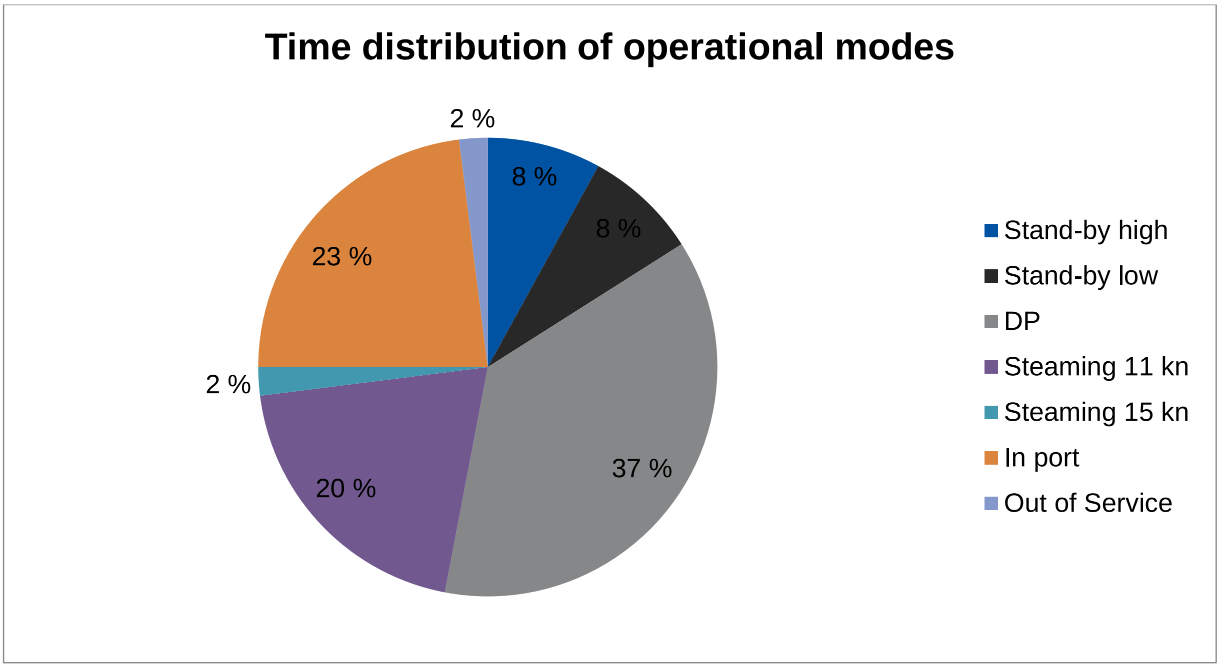

Figure 9 - Time distribution of operational modes for PSV case

The PSV modelled in this study has 4 generator sets of 2,240 kW Maximum Continuous Rating (MCR) each. The generator sets were assumed to be Wärtsilä 6R32LN, and the SFOC data was taken from EIAPP data for this make. The SFOC curve is shown in Figure 10.

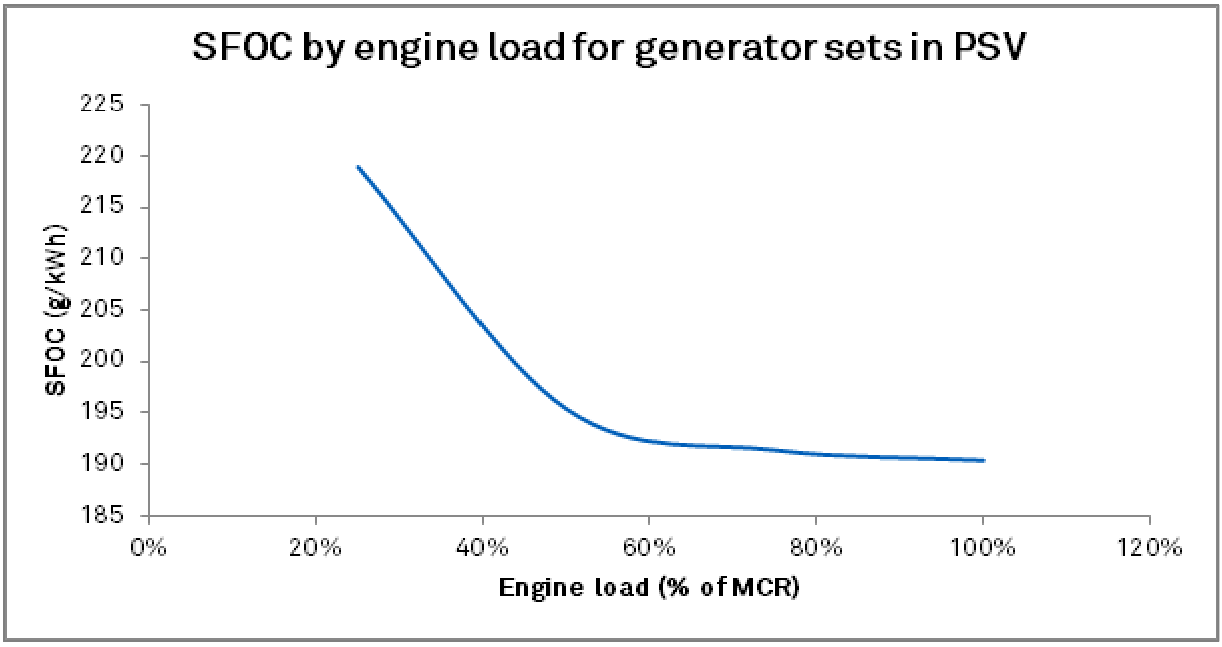

Figure 10 SFOC for Wärtsilä 6R32LN generator set

The SFOC curve shows that there is a significant increase in fuel consumption below 57% loads.

The operational profile which has been used to calculate the fuel savings has been developed with data gathered from ABB projects. The operational profiles for the non-hybrid and hybrid PSV are shown in Table 4.

Table 4 - Operational profile of non-hybrid and hybrid PSV

Non-hybrid Profile			**Generator set loads (kW)**					**Generator set loads (% MCR)**			
Mode	% time	hrs/yr	G1	G2	G3	G4	Total	G1	G2	G3	G4
Stand-by High[4]	8 %	701	450	0	450	0	900	20 %	0 %	20 %	0 %
Stand-by Low	8 %	701	755	0	0	0	755	34 %	0 %	0 %	0 %
DP	37 %	3241	710	710	710	0	2130	32 %	32 %	32 %	0 %
Steaming 11kn	20 %	1752	918	0	918	0	1836	41 %	0 %	41 %	0 %
Steaming 15kn	2 %	175	1065	1065	1065	1065	4260	48 %	48 %	48 %	48 %
In port-charging	23 %	2015	168	0	0	0	168	8 %	0 %	0 %	0 %
Out of Service	2 %	175	0	0	0	0	0	0 %	0 %	0 %	0 %
Total	100 %	8760									

Hybrid Profile			**Generator set & battery loads (kW)**						**Generator set loads (% MCR)**			
Mode	% time	hrs/yr	Battery	G1	G2	G3	G4	Total	G1	G2	G3	G4
Stand-by High	8 %	701	0	900	0	0	0	900	40 %	0 %	0 %	0 %
Stand-by Low	8 %	701	0	755	0	0	0	755	34 %	0 %	0 %	0 %
DP-2	37 %	3241	0	1065	1065	0	0	2130	48 %	48 %	0 %	0 %
Steaming 11kn	20 %	1752	0	1836	0	0	0	1836	82 %	0 %	0 %	0 %
Steaming 15kn	2 %	175	0	1065	1065	1065	1065	4260	48 %	48 %	48 %	48 %
In port-charging	6 %	504	0	504	0	0	0	168	23 %	0 %	0 %	0 %
In port-batteries	17 %	1511	56	0	0	0	0	0	0 %	0 %	0 %	0 %
Out of Service	2 %	175	0	0	0	0	0	0	0 %	0 %	0 %	0 %
Total	100 %	8760										

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[4] Stand-by high is an operational modus in which redundancy is not required by Class, but where most ship owners prefer to have a redundant generator.

Table 4 shows that the ship spends 37% of its time in DP mode. For the non-hybrid case, this means three generators running at 32% load, while the hybrid case employs two generators running at 48%. These engine loads correspond to a SFOC of 212 g/kWh and 169 g/kWh respectively.

For the hybrid case, there will be losses when the battery is discharging and charging in-port. These are estimated to be 12%, round-trip.

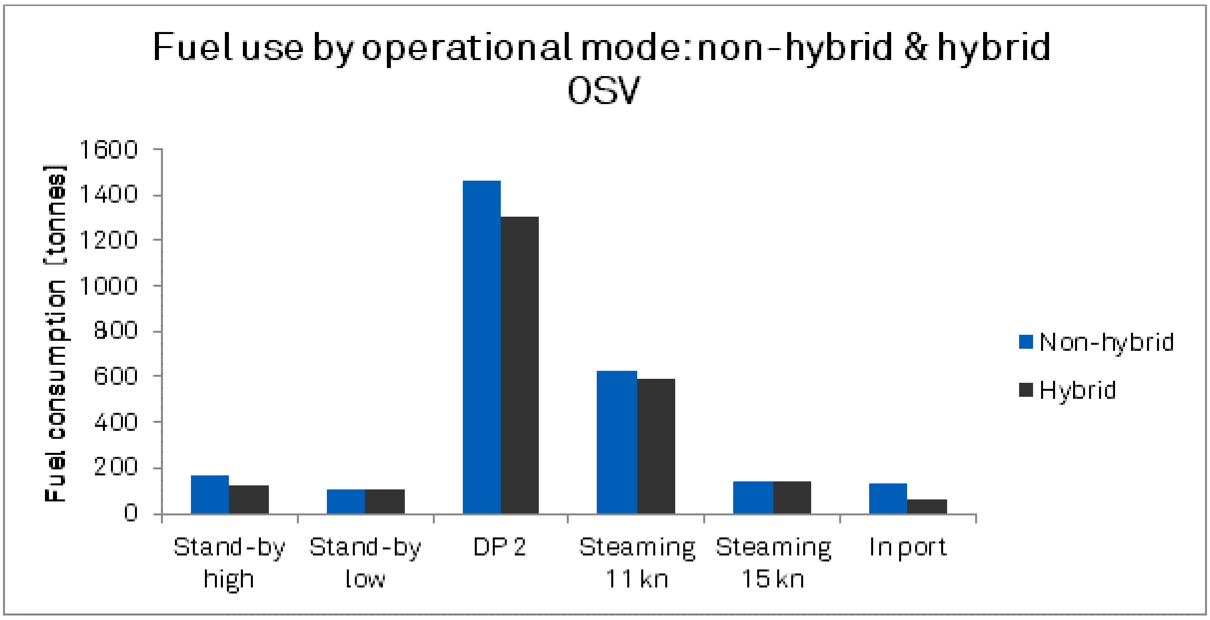

Figure 11 - Fuel consumption by operational mode, non-hybrid and hybrid case

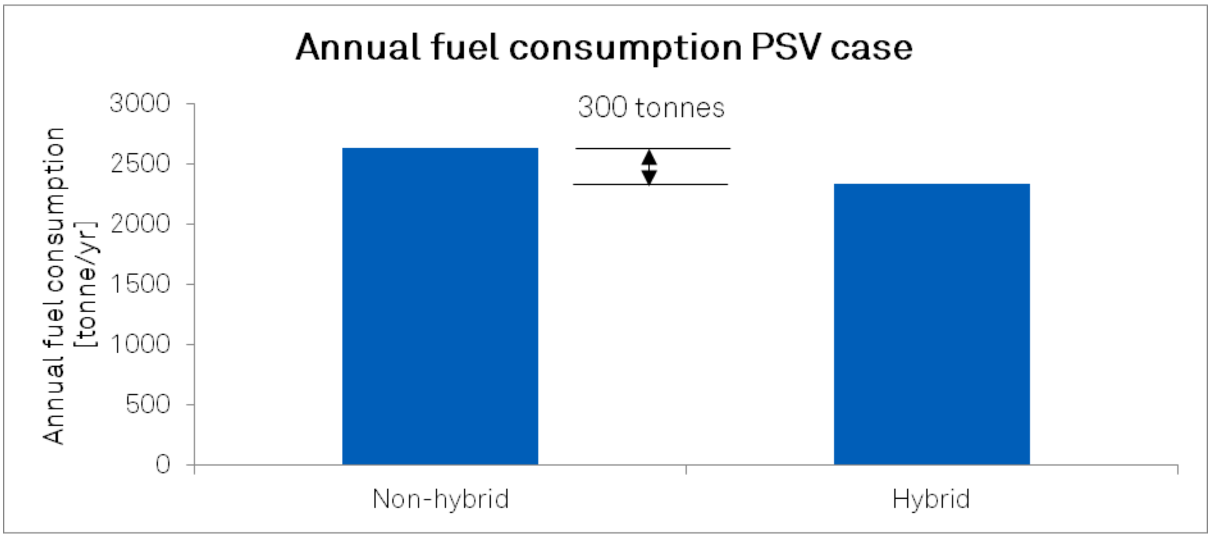

Figure 12 - Annual fuel consumption for hybrid and non-hybrid case

The total fuel savings from using a hybrid propulsion system instead of a diesel electric propulsion system is 300 tonnes. This corresponds to a 12% reduction, which is in line with ABB's project experience as well other example cases for OSVs (12), (13).

As shown in Figure 11, 50% of fuel savings occur in DP mode and 22% of fuel savings occur in port.

5.1.1 Battery dimensioning for PSV hybrid

For the hybrid case, the battery has been dimensioned in order to satisfy the power needs as outlined in Table 4. This dimensioning is based on Grenland Energy project experience. The battery is somewhat power optimized – as opposed to energy optimized – meaning that the dimensioning factor of the battery is the power output, as opposed to maximizing the amount of energy which the battery can store.

Dimensioning a battery requires a balance between the capacity to store energy and the capability to drive electric current through the system. Power optimized systems have little active material and thin electrode coatings, and an ability to drive a lot of electricity. The capacity for energy storage in a cell is based on the amount of active material, and the ability to drive current is based on the current collector foils and the characteristics of the electrode coating. Additionally, driving electricity in the system external to the cells requires aluminum and copper bus bars, connectors and cables which cost money and weight.

In essence, the battery system needs to be able to provide the necessary power and energy for the entire design life time for the expected operational profile.

The battery for the hybrid PSV is dimensioned to give 12 minutes of spinning reserve, i.e. 12 minutes of generator redundancy which will allow the vessel to remove itself from the platform in case of failure during DP mode. 12 minutes spinning reserve was chosen based on the risk associated with the chosen operational profile. While in port, the battery is assumed to run by charging for 20 minutes and discharging for 60 minutes. The battery's characteristics are shown in Table 5.

Table 5 - Battery specifics for hybrid PSV case

Total capacity	323 kWh
Max voltage	768 V
Lifetime	10 years
Spinning reserve time	12 minutes
Lifetime no. port charging cycles	>15,000 cycles before battery operational time is decreased below the 12 minutes required for the DP operation.

The necessary spinning reserve is based on what is known as the minimum time requirement for PSV operations. When a PSV is performing operations in DP-mode, a consequence analysis must be performed in which the minimum time requirement is constantly assessed based on the type of operation, the forces acting on the vessel, and other safety conditions. The minimum time requirement is defined as the minimum time for the remaining capacity – after a worst case single failure – must be available to the vessel. It is normally determined by maximum time needed to terminate ongoing operations, given the worst case single failure, such as failure of a generator. For a given operation, this means that a battery can act as spinning reserve if it can provide the necessary capacity for as long as the minimum required time for the operation in question, as determined by the consequence analysis.

30 minutes is given in the DNV GL rules as the normal minimum time requirement because this is enough time in many cases to safely terminate operations that a vessel would be performing. The

minimum time requirement is determined by many factors for that specific operation, and the DNV GL rules require that the operator always be conservative in their assessment of the minimum time requirement. In some situations the minimum time requirement would be longer than 30 minutes, but it is possible for the minimum time requirement to be as low as 12 minutes.

Since a minimum time requirement of 12 minutes is not the norm but can be acceptable depending on vessel operations and conditions, and it was given as the typical requirement for the operational profile in question, this was accepted as the dimensioning factor for the battery system. Further discussion of increasing the battery to cover 30 minutes of spinning reserve is covered in the uncertainty discussion of this study.

The basic component of the battery on board the ship is the Lithium-ion battery cells. The cell type employed in this study is an 18650 type cell, where the internals of the cell are placed inside a thin walled steel can. The cells consist of a separator, a cathode with aluminum foil and active material, an anode with copper foil and active material (artificial graphite), an electrolyte, and a steel can and header. The cathode active material is assumed as NMC $Li(Ni0.45Mn0.45Co0.10)O_2$), although many different electro-chemistries exist.

The NMC material in general offers good cyclability and adequate power characteristics when properly designed into a battery cell. For the PSV hybrid, the battery needs to be able to discharge at high rate in case the battery needs to be used as a spinning reserve. The capacity required here would be a minimum of 185 kWh. At the same time, the battery needs to fully charge in 20 minutes and discharge in one hour while in port. Of these requirements, the 12 minutes discharge and the 20 minutes charge require a somewhat power optimized cell design whereas the discharge in port require a more energy optimized cell design. The best cells for this purpose are cells that have sufficient power to be able to sustain the fast charge and the spinning reserve while having as much energy as possible to be able to support the port energy requirements. The technical requirements need to be fulfilled at the lowest possible cost.

The battery is more than cells packed in a box. The cells are packed into modules, which are then packed into sub packs. Sub packs are placed together in series to make a string. Strings have system voltage and are connected in parallel to form the complete system. An air cooling unit sits on top of each string. The point of packing the cells into modules, sub packs, and then strings is to provide modularity to design and optimize the systems, and to provide a physical structure for bus bars, fuses, and other mechanisms to control the flow of power as well as facilitating electronic control systems and ensuring the necessary safety.

Figure 13 and Figure 14 illustrate the battery modules, sub packs, and strings as employed in the PSV hybrid case.

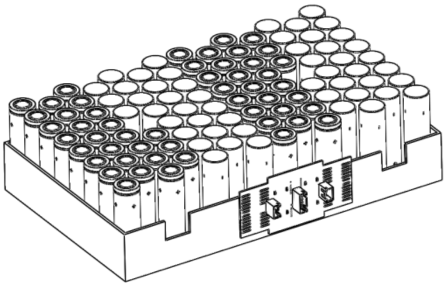

Figure 13 - Concept illustration of module with li-ion cells enclosed (14)

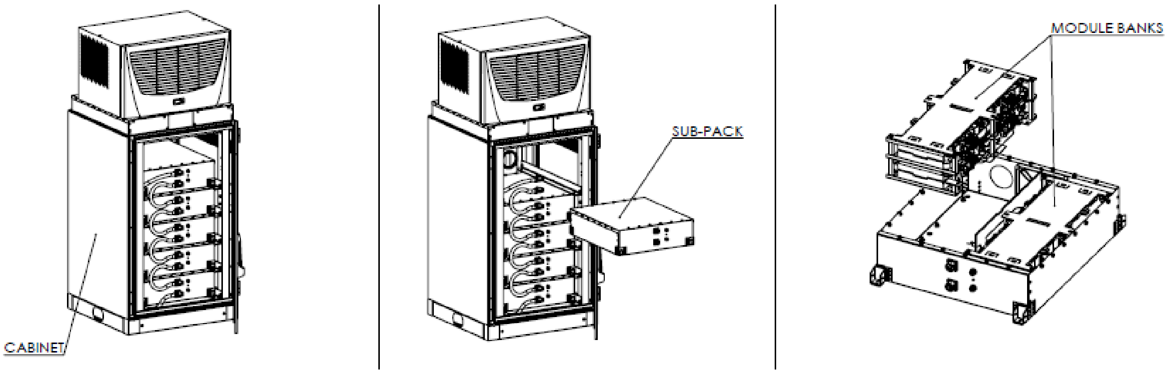

Figure 14 - Building blocks of battery system: modules, sub packs, and string (cabinet) (14)

Table 6 - Basic components of battery unit

Total cells	44,928
Cells per module	104
Modules per sub pack	8
Sub packs per string	6
Strings per battery unit	9

In total, the battery unit consists of 44,928 Li-ion cells. Besides the cells, the materials in the battery unit include steel encasing, aluminum and copper bus bars, wiring, and circuit boards and programmable logic computers for the accompanying control system.

This study employs the battery cells and surrounding system as designed by Grenland Energy. Grenland Energy battery modules are built using the 18650 size cylindrical cells with internals of the cells packaged in a steel cylinder. However, there are different means of structuring a system in order to cover the power needs as stipulated by the operational profile. Li-ion batteries come in formats other than the can cells chosen here, but the total amount of active material and ability of the system to drive current will be similar, even if different cell constructions or different types of modules are employed.

5.1.2 PSV life cycle inventory

The cycle inventory is compiled by calculating the fuel consumption of the diesel and hybrid PSV, and by estimating the material and energy inputs necessary for the battery system. In keeping with a typical cost-benefit analysis, only the parts of the system unique to either the diesel or hybrid PSV are included in the life cycle inventory.

Table 7 System components modelled in the life cycle inventory for PSV case

Environmental CAPEX	Energy storage (cells, module, sub packs, strings, cooling units) Converter Transformer Extra cabling compared to diesel PSV
Environmental OPEX	Fuel savings compared to diesel PSV

The environmental CAPEX was determined by identifying a bill of materials and process energy. Most of the information for the bill of materials – the types of materials, process energy, and amounts used in each part of the entire system – is obtained directly from discussions with ABB and Grenland Energy. While some of the information is publicly available, most of the material and weight information is proprietary information. So the exact amounts for each individual part of the system are not listed here.

The bill of materials for the PSV hybrid system, i.e. the environmental CAPEX, is given in Table 8 and Table 9.

norwe

Table 8 Bill of materials for PSV hybrid system – energy storage

Energy storage	
Battery cells	Source of material and mass information
Separator	Generic 2Ah 18650 power cell design (15)
Aluminum wrought alloy (Cathode Al foil)	Generic 2Ah 18650 power cell design (16)
Cathode active material	Estimated based on cell capacity (17)
Anode Cu foil	Generic 2Ah 18650 power cell design (16)
Anode active material	Estimated based on cell capacity (17)
Electrolyte	General Li-ion electrolyte formula
Steel	Weight of dummy cells (15)
Electrical process energy	Grenland Energy discussions with cell producer
Transport	Estimated based on weight and distance
Metal working for copper, steel, and aluminum components	Estimated based on weight of components
Modules (8 modules per sub-pack)	
Aluminum	Grenland product designs and dimensions
Copper	Grenland product designs and dimensions
Acrylonitrile butadiene styrene (ABS) plastic	Grenland product designs and dimensions
Steel (electrogalvanized steel)	Grenland product designs and dimensions
EPDM 70 shore (BMS card holder)	Grenland product designs and dimensions
PCB (BMS printed circuit board)	Grenland product designs and dimensions
Transport	Estimated based on weight and distance
Metal working for copper, steel, and aluminum components	Estimated based on weight of components
Sub-pack (6 sub-packs per string)	
Aluminum	Grenland product designs and dimensions
Copper	Grenland product designs and dimensions
Copper metal working	Grenland product designs and dimensions
Steel (electrogalvanized)	Grenland product designs and dimensions
Steel (powder coated carbon)	Grenland product designs and dimensions
ABS Plastic	Grenland product designs and dimensions
Transport	Estimated based on weight and distance
Metal working for copper, steel, and aluminum components	Estimated based on weight of components
String (9 total)	
Steel (powder coated carbon)	Grenland product designs and dimensions
Aluminum	Grenland product designs and dimensions
Steel	Grenland product designs and dimensions
Transport	Grenland product designs and dimensions
Metal working for copper, steel, and aluminum components	Estimated based on weight of components

Table 9 Bill of materials for hybrid PSV - power conversion

Power conversion	
Transformer	
Material and energy inputs	
Steel (powder coated carbon)	Discussions with ABB
Copper	Discussions with ABB
Cast iron	Discussions with ABB
Insulation (epoxy)	Discussions with ABB
Electrical process energy	Discussions with ABB
Heat process energy	Discussions with ABB
Transportation	Estimated based on weight and distance
Metal working for copper, steel, and aluminum components	Estimated based on weight of components
Converter	
Low-alloyed steel	ABB environmental product declaration (18)
Cast iron	ABB environmental product declaration
Copper	ABB environmental product declaration
Aluminum	ABB environmental product declaration
Polyethylene	ABB environmental product declaration
Electrical process energy	ABB environmental product declaration
Heat process energy	ABB environmental product declaration
Transportation	Estimated based on weight and distance
Metal working for copper, steel, and aluminum components	Estimated based on weight of components
Cables	
Aluminum	Estimated based on 300 cm2 and 75 m total cables
Transport	Estimated based on weight and distance
Metal working for copper, steel, and aluminum components	Estimated based on weight of components

All parts of the battery system are assumed to be transported over land and sea, 16,200 km and 900 km respectively. This corresponds to a trip from China to main land Europe by ocean freighter and a lorry trip from mainland Europe to Norway.

The steel used in the battery system is processed locally in Norway. The electronic components are mostly manufactured in Europe, whereas the cells are transported from Asia.

One aspect of the system for which little data was available was process energy. In the case of the converter, an environmental product declaration (18) was available. Process energy for the transformer was assumed to be the same on a per kg basis as for the converter.

For the battery cells, the reported process energy per cell is based on information from the cell producer. The producer has given the total electrical energy consumption per cell of 200 kWh per kWh of cells.

For the other system components, the process energy is assumed to be accounted for as metal working processes which are found in Ecoinvent. The assembly of the battery system is performed manually at Grenland's facilities. An electricity requirement of 0.014 kWh per kWh battery capacity for welding was assumed (19).

The life cycle inventory for the hybrid PSV case also includes the fuel savings which are calculated according to the operational profile in Table 4 and the SFOC for the generators given in Figure 10.

As shown in Figure 12 the fuel saved by employing a hybrid system is 300 tonnes per year for the given operational profile. In the life cycle inventory, this is included as a negative GWP and negative NO_x emissions corresponding to the CO_2 and NO_x emissions which are avoided due to the fuel savings and the savings in the life-cycle emissions of MGO production.

One tonne of MGO corresponds to 3.2 tonnes of CO_2 (20) from combustion and 0.5 tonnes CO_2 equivalents in its production (21). One tonne of MGO corresponds to 0.044 tonnes NO_x from combustion (20) and 0.00167 tonne NOx from production (21). The NO_x emissions from the PSV are assumed not to include use of NO_x reducing technologies.

Table 10 - Emissions from MGO

	From production	From combustion
GWP (kg CO2-eq per kg MGO)	0.5	3.2
NOx (kg per kg MGO)	0.00167	0.044

5.2 Results of PSV case

5.2.1 Environmental CAPEX of battery system

The environmental CAPEX of the hybrid system for the PSV case is shown in Figure 15 and Figure 16.

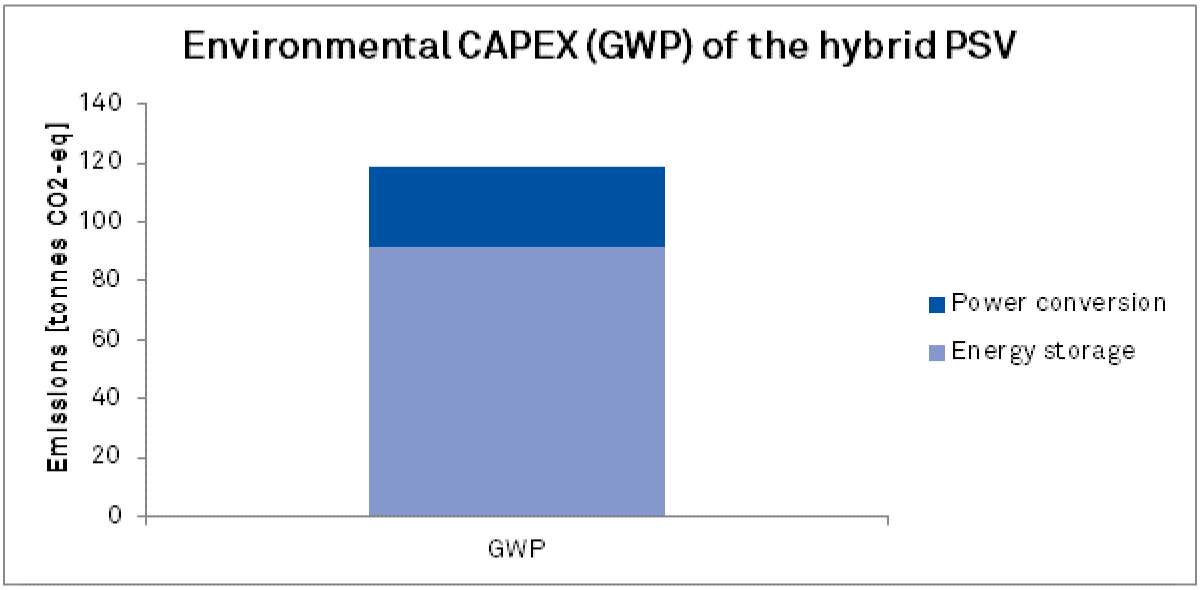

Figure 15 - GWP CAPEX of hybrid PSV

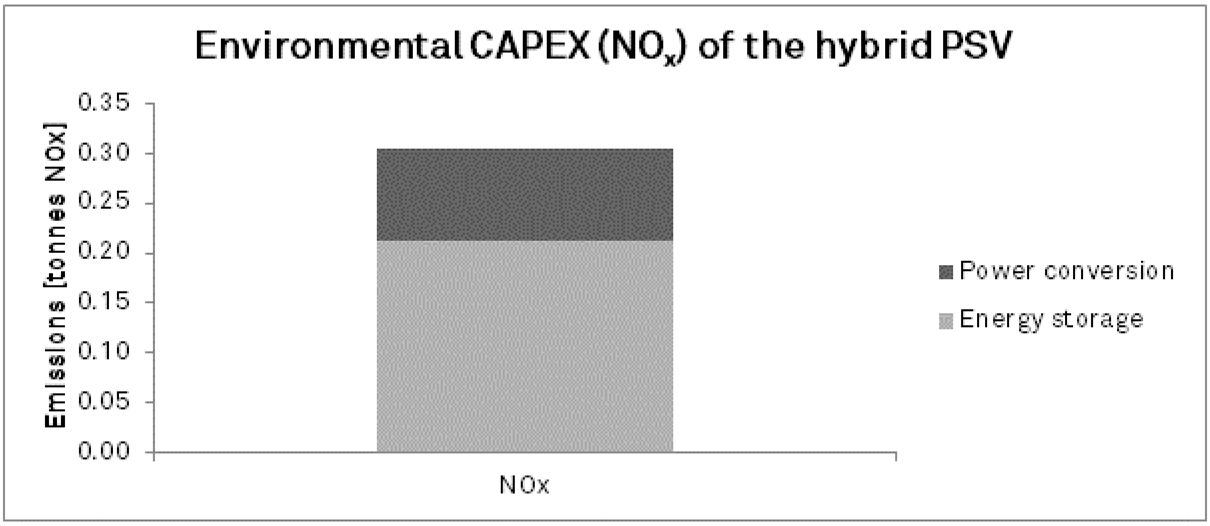

Figure 16 - NO_x CAPEX of hybrid PSV

The environmental CAPEX of the PSV is 119 tonnes CO_2-eq and 0.3 tonnes of NO_x. Most of the emissions come from producing the energy storage part of the system, i.e. the battery cells and packaging.

Figure 17 and Figure 18 show that the battery cells dominate the environmental CAPEX for the energy storage components of the hybrid PSV. This is mainly due to the process energy needed to make the cells. The process energy used to make the battery cells is assumed to originate from the global average electricity mix (GLO) (21).

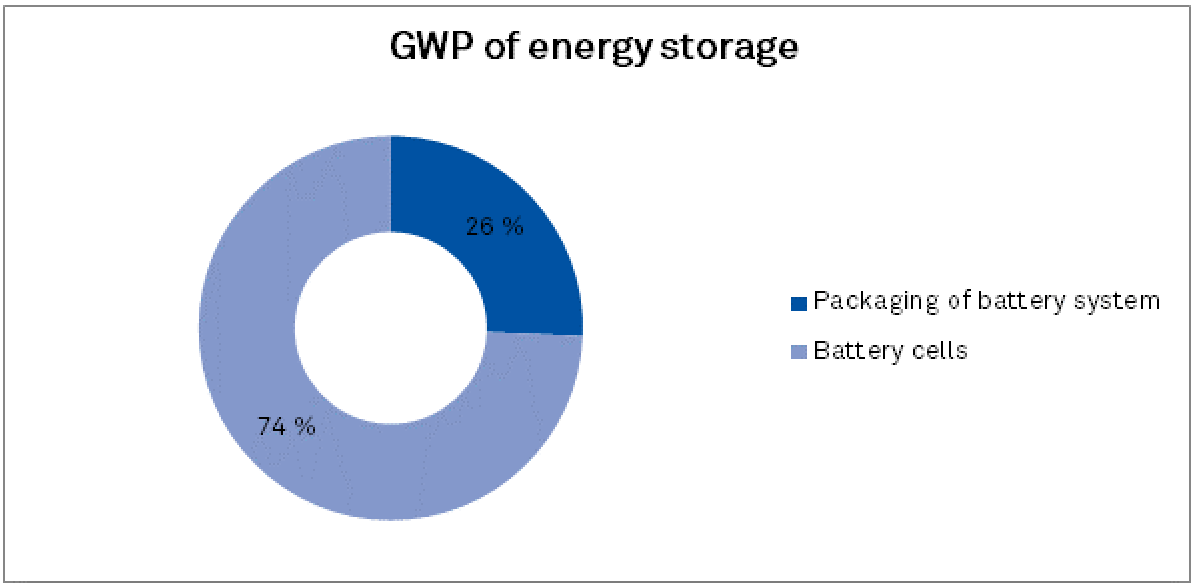

Figure 17 - Distribution of GWP from production of energy conversion for hybrid PSV

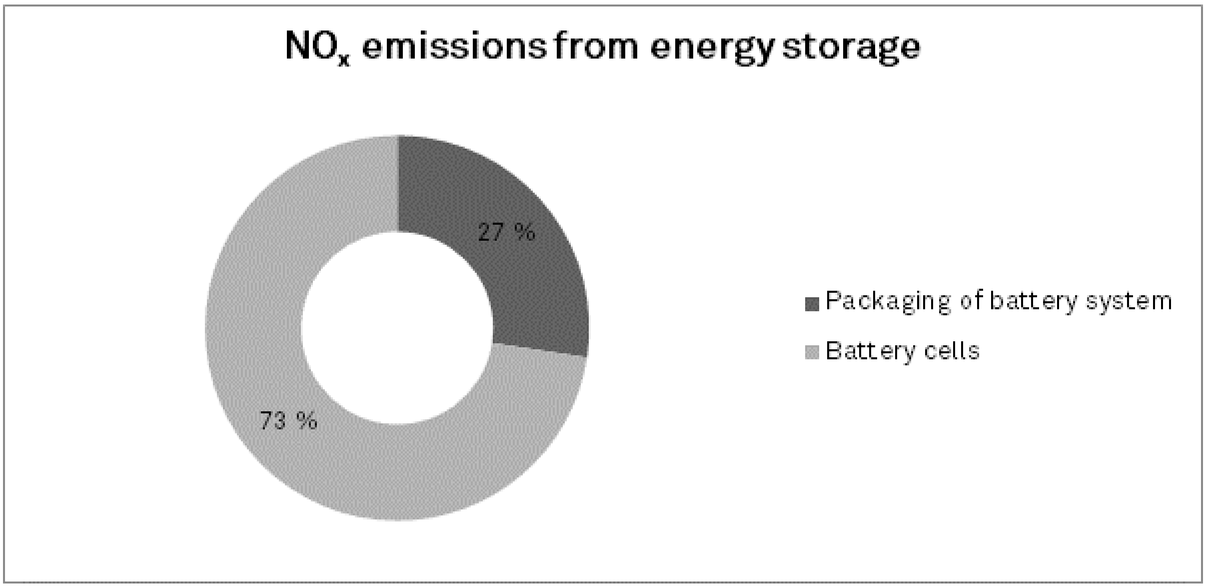

Figure 18 - NOx emissions from production of energy storage for hybrid PSV

5.2.2 Life cycle results of the PSV-hybrid

The annual fuel consumption for the hybrid PSV case is 300 tonnes less than that of the non-hybrid PSV case. This corresponds to a GWP savings of 962 tonnes CO_2-eq per year, and 13 tonnes of NO_x per year.

Given these emission savings and the environmental CAPEX shown in Figure 15, the payback period for GWP and NO_x of the hybrid PSV is 1.5 months and 0.3 months, respectively.

Figure 19 and Figure 20 show the life cycle GWP and NO_x emissions, respectively, of the hybrid PSV. The emissions in year 0 correspond to the environmental CAPEX (the extra environmental costs due to the production of the battery system). The negative emissions in years 1-10 correspond to the emissions savings compared to using a diesel PSV. The life cycle emissions are shown for 10 years because that is the assumed life-time of the battery.

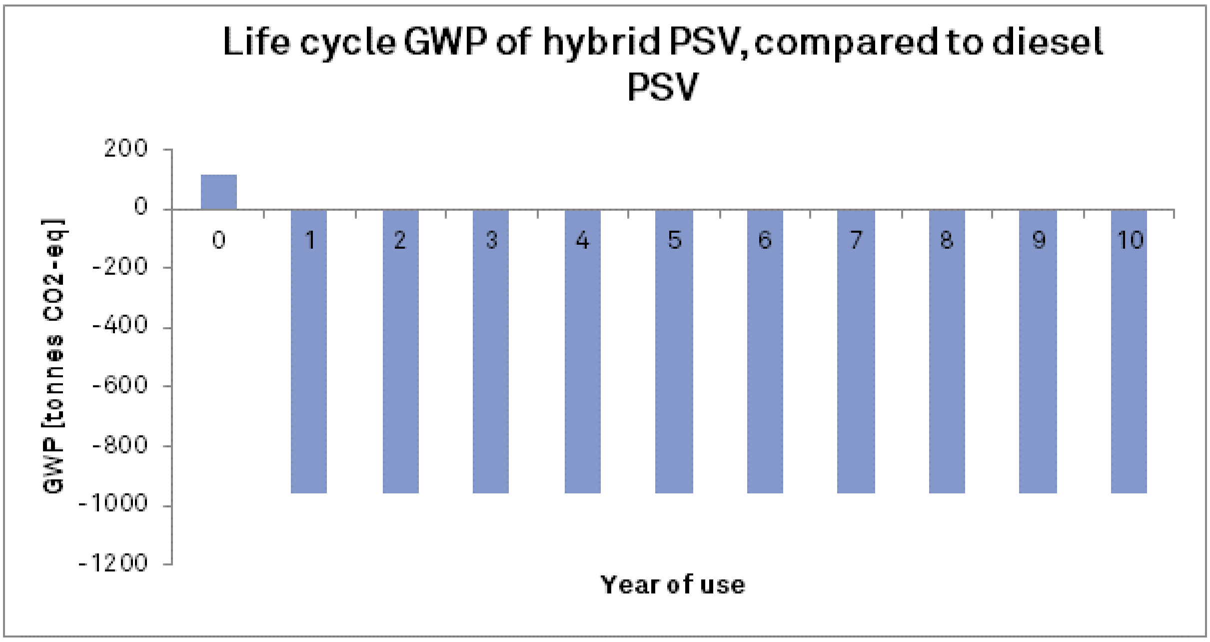

Figure 19 - Life cycle GWP of hybrid case

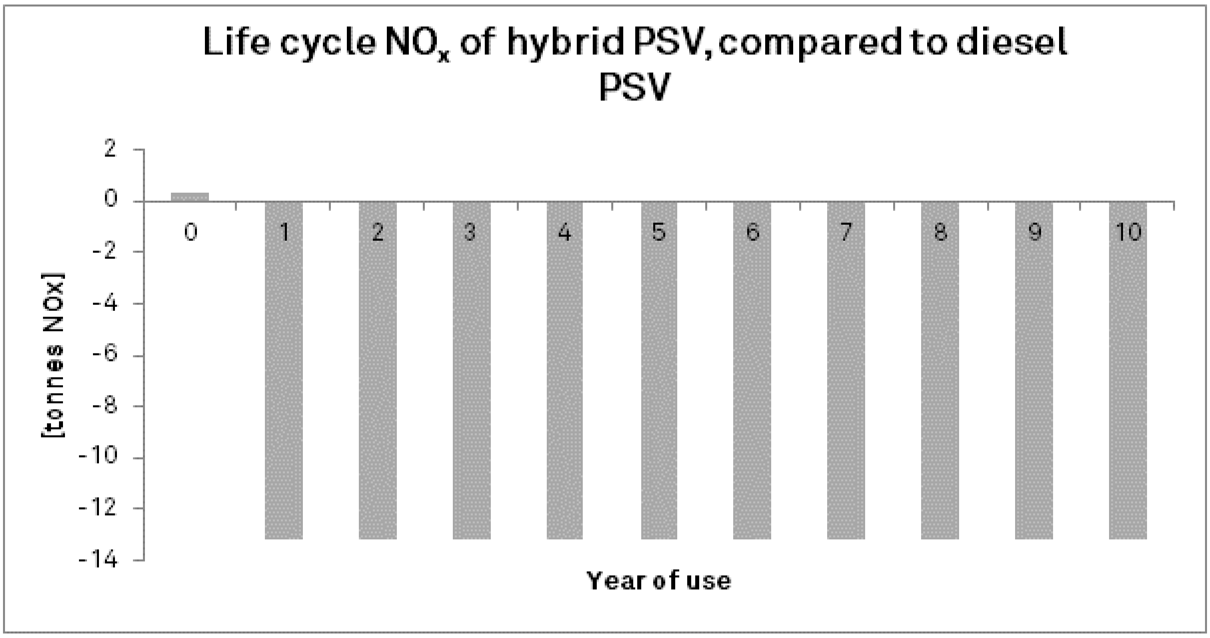

Figure 20 - Life cycle NOx emissions of hybrid case

Table 11 - GWP and NOx payback times for the hybrid PSV

GWP payback time	NOx payback time
1.5 months	0.3 months

The payback period of GWP and NO_x is dependent on the total process energy for cell production and assumed electricity mix for creating the battery cells. In this study, the global average electricity mix is assumed.

In the case of NO_x, a vessel may employ other NO_x-reduction technologies, such as a Selective Calatycal Reduction (SCR) unit, whose environmental CAPEX for NO_x would be smaller than that of a battery system because it is smaller and less complex, and can achieve NO_x-reductions of 70 %. Such a system would have a smaller NO_x-payback period but may have an adverse effect on GWP because the SCR reaction creates CO_2 emissions when urea is used as a reductant. Additionally, NO_x-reduction technologies such as SCR do not help to reduce NOx further up in the value chain because they do not reduce fuel consumption.

6 Case 2: Ferry

The second case analyzed in this report is that of a 100 PBE newbuild ferry operating in Norwegian waters, servicing a route of 5.5 km. This case compares the environmental performance of a diesel electric ferry to a fully electric ferry.

Ferries are an interesting case for electric propulsion because they operate relatively short distances on fixed routes, allowing for frequent battery charges and manageable battery sizes, and thus making the battery case easy to optimize from a financial and safety perspective.

Additionally, as part of their maritime strategy, the Norwegian government has set standards requiring zero and low emission propulsion for Norwegian ferries – when technically feasible – which are part of the federal road network (22), making electric ferries a particularly interesting case for Norway.

6.1 Ferry technical specifics & operational profile

The diesel electric ferry has two generator sets each connected to a DC grid. The total installed capacity is 2000 kW. The SLD is shown in Figure 21.

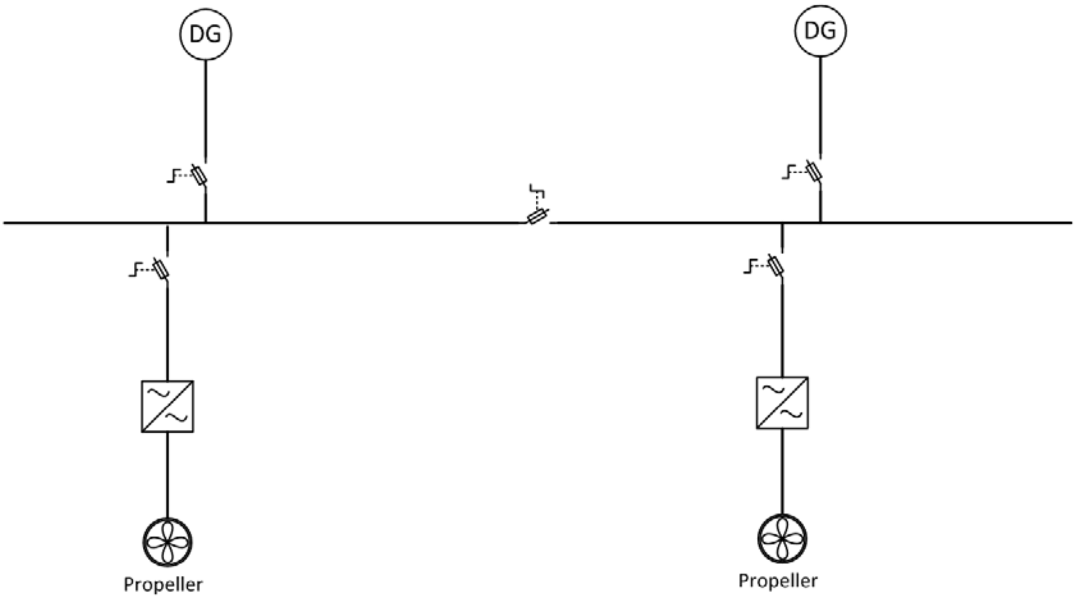

Figure 21 SLD for diesel electric ferry

For the fully electric ferry, a transformer takes down voltage from the land-based net. A converter switches from AC current from net to DC, followed by a switch panel. The battery system is connected to a DC grid with two converters and two rectifiers. The hotel loads are covered by an AC power station. The SLD for the fully electric ferry is shown in Figure 22.

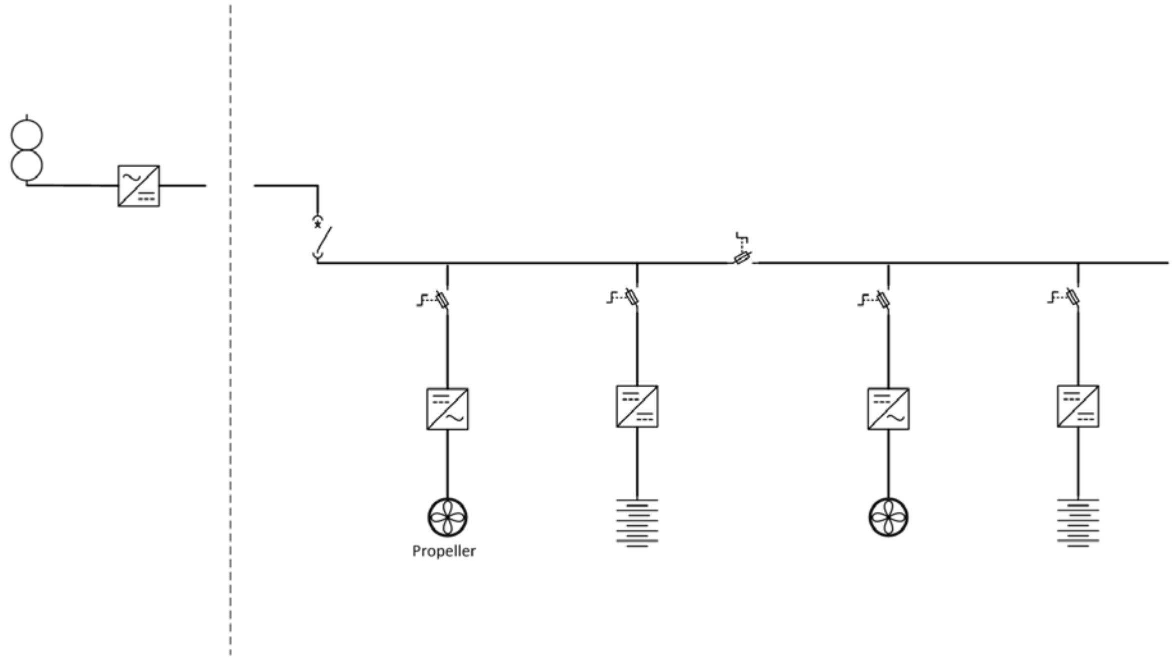

Figure 22 SLD for fully electric ferry

The ferry is assumed to employ a mooring device which will keep the ferry moored without using the propeller to push against the quay.

The operational profile for the ferry is developed by dividing up the ferry route in pieces: maneuvering from port, accelerating, cruising, decelerating, maneuvering to port, and unloading/loading. Each operational phase has an associated time, speed and power requirement.

In general, the maneuvering, accelerating, decelerating and load/unloading phases will take nearly the same amount of time and power for a given 100 PBE ferry on any ferry route, although the time will vary somewhat depending on length. The time for loading and unloading will also vary from connection to connection, depending on the timetable. The amount of time spent in cruising phase will depend on the length of the route and the speed. For this study, it is assumed that the cruising speed of the ferry is 11 knots. The operational profile, and thus energy demand for the electric ferry and the fuel consumption of the diesel electric ferry are developed by calculating the power needed from each operational phase for a 100 PBE ferry to complete one route, and then scaling up the energy consumption to match the number of routes per year.

The ferry is assumed to run 38 single trips per day, resulting in a total 13,870 trips per year. Each trip consists of 20 minutes of sailing time and 10 minutes of charging time. The rates of unloading and loading are 40 PBE per min and 20 PBE per min, respectively. This means that a 100 PBE should be able to load and unload in 7.5 min. 10 minutes was therefore deemed to be a conservative estimate with respect to loading/unloading. This is also consistent with the Lavik-Oppedal 120 PBE electric ferry (23).

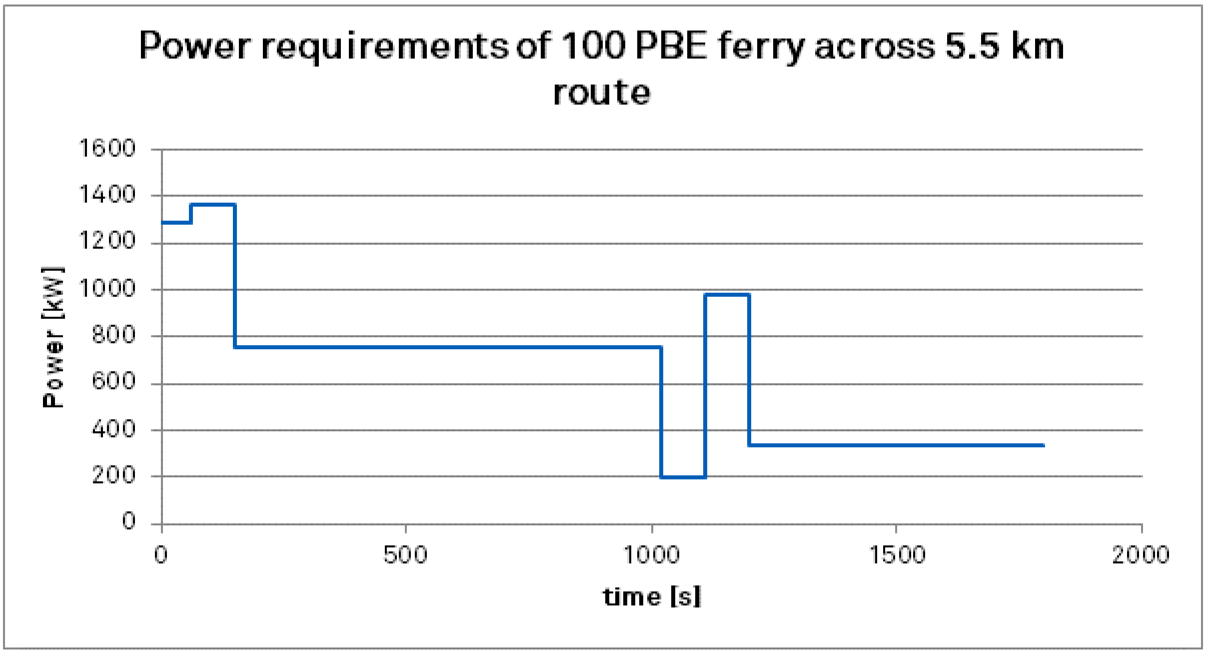

Figure 23 - Operational profile for 100 PBE case ferry

The power requirements for each phase of the route are calculated using a database of speed-power curves developed by LMG Marin. The power requirements given in Figure 23 also include constant hotel loads of 90 kW. Given these power requirements and assuming that the maximum required power should correspond to 80% MCR, the minimum installed power required to handle maximum propulsion power and hotel load is 1,700 kW for this 100 PBE case ferry. The installed power of similar-sized ferries tends to be higher (up to 2,000 kW) in order to include a safety margin for bad weather (24).

For the purposes of this study, the diesel ferry is assumed to run with two engines with MCR of 1,200 kW and 800 kW. This allows for the larger generator to cover the power needs in most operational modes at optimized load levels.

The SFOC data used to calculate MGO consumption is from the EIAPP data for Wärtsilä L20C engine, shown in Figure 24.

Figure 24 - SFOC by engine load for Wärtsilä 20Cengine (MCR 880 kW)

The operational profile used to calculate the fuel consumption of the diesel electric ferry is shown in Table 12.

Table 12 - Operational profile for diesel ferry

			Generator set load [kW]			Generator set load [%]	
	% time	Tid [hr/yr]	G1	G2	Total	G1	G2
From quay maneuvering	3 %	231	772	515	1,287	64 %	64 %
Acceleration	4 %	347	820	547	1,367	68 %	68 %
Cruise	38 %	3,352	756	0	756	63 %	0 %
Deceleration	4 %	347	202	0	202	17 %	0 %
To quay maneuvering	4 %	347	976	0	976	81 %	0 %
Loading/unloading	26 %	2,312	337	0	337	28 %	0 %
Out of service	21 %	1,825	0	0	0	0 %	0 %
Total	100 %	8,760					

Based on the SFOC in Figure 24 and engine loads and time specified in Table 12, the total annual fuel consumption for the diesel electric ferry is 1035 tonnes MGO (12,271 MWh).

The power requirements shown in Figure 23 are power requirements for the propeller. These are used to dimension the battery pack. The battery for the fully electric ferry has higher power consumption than what is shown in Figure 23 and Table 12 because of losses which occur when charging and discharging the battery. A 5% loss for charging and 5% for discharging is assumed (10% round trip). The power requirements for a fully electric ferry to cross the 5.5 km route are shown in Figure 25, including the 5% losses from discharging.

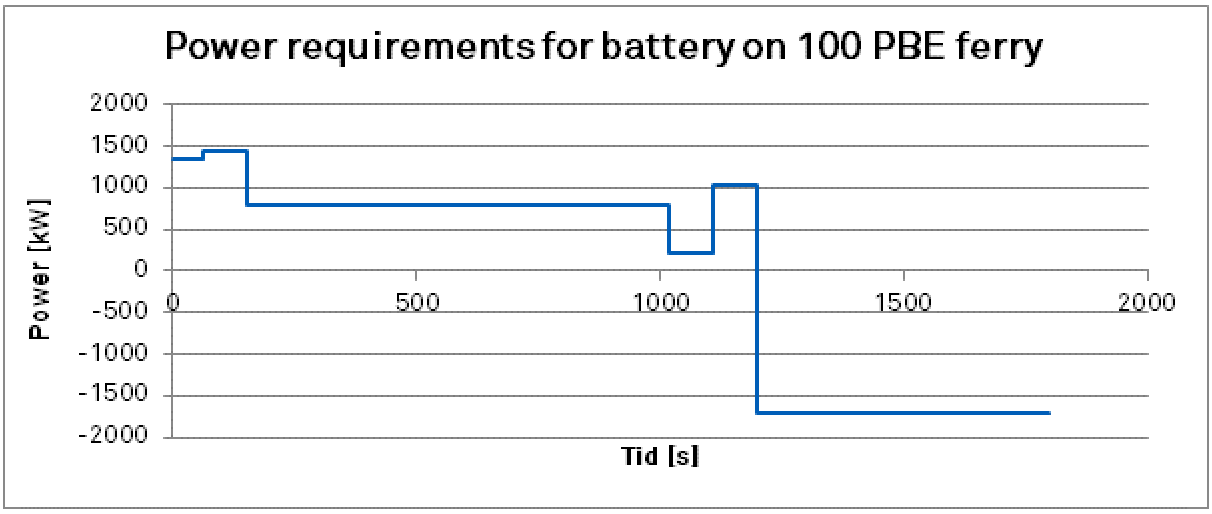

Figure 25 - Power requirements for battery on 100 PBE ferry

The power requirements while mooring are lower for the fully electric ferry because it is assumed that an automatic mooring device, such as the Cavotec Moormaster (25), is used. In contrast, a diesel ferry usually uses the propeller to push against the quay and hold the ferry in place. With an automatic mooring device, it is assumed that the power requirements during charging consist of the 90 kW hotel loads. In rough weather, there may still be some need for the propeller to stabilize the vessel, but this is considered negligible for the purposes of modelling power consumption.

Figure 25 shows the charging peak as designated by the negative power output. The maximum charger output is 1,900 kW, of which 1,810 kW goes to the battery after 90 kW hotel loads. With losses of 5% from charging, 1,710 kW goes into the battery. Thus, the battery has enough charging capacity to fulfill the power requirements.

It is assumed that the ferry charges after each journey in order to maintain a minimum of 50% state of charge (SOC) at all times during the route, as required by DNV GL Classification. In order to satisfy these requirements, it is assumed that the battery re-charges fully in ten minutes at each quay. Given the battery power requirements shown in Figure 25, the battery consumes 283 kWh during one journey. However, there is a 5% loss when re-charging the battery. On the land side, there is a transformer and converter, each of which lead to approximately 5 % losses. With all losses taken into account, the fully electric ferry consumes 330 kWh of electricity per route and 4,575 MWh per year from the grid.

Given 10 minutes of charging time, this ferry would need the land infrastructure to supply around 2 MW of power. According to a DNV GL study, 5 of the 90 ferry quays in routes which are part of the Norwegian federal road system and suitable for battery routes contain more than 2 MW (26). Many more can have more than 2 MW with affordable network expansion. Because network building is not part of the scope of this study, and because quays with enough power are available though not common, it is deemed reasonable that the electric ferry charges directly from the available grid, and not from a battery on shore.

The fully electric ferry has a yearly energy use of 4,575 MWh per year, compared to the diesel ferry with a yearly fuel use of 12,271 MWh. This large difference is explained by the fact that a diesel engine as an efficiency of approximately 40%, while electric propulsion has an efficiency of 86%, including the battery losses of charging and the losses from the converter and transformer on land.

6.1.1 Battery dimensioning for fully electric ferry

The battery system for the ferry is between power optimization and energy optimization because the battery needs to be able to charge rapidly according to operational profile, and therefore needs a good ability to drive current. As such, the cell compositions and amount of active material per cell are assumed to the same as for the PSV case.

The fully electric ferry runs on a battery with the characteristics outlined in Table 13 and battery components outlined in Table 14.

Table 13 - Battery specifics for fully electric ferry

Nominal capacity	1,078 kWh
Max voltage	768 V
Design lifetime	10 years
Power total Short duration	8,064 kW
Continuous power (50% SOC)	4,032 kW
Charge power (continuous)	3,145 kW
Peak charge power (10s)	4,193 kW

The peak charge and the life time set the requirements for the dimensions of the battery system. A relatively high charge acceptance is required in order to replenish the energy consumed while operating the ferry. The number of charge-discharge cycles exceeds 138,000 and the battery is designed to meet the energy requirements after 10 years of ferry operation. This requires a significant oversizing of the battery. The heat production during discharge of a Li-ion battery cell is lowest for intermediate SOC (27), so in order to ensure sufficient cycle life, batteries need to be cycled at intermediate SOCs.

Table 14 - Basic components of battery unit for ferry case

Total cells	149,760
Cells per module	104
Modules per subpack	8
Subpacks per string	6
String per battery unit	30

The other difference between the PSV and the ferry case is that the ferry employs a battery room, instead of each string having its own cabinet. In this case, each string has a steel rack, and the steel for the battery room is modelled based on a 60 m^2 battery room. Unlike the PSV, the battery room is cooled by three cooling units total instead of one cooling unit per string.

6.1.2 Ferry life cycle inventory

The life cycle inventory is compiled by calculating the fuel consumption and electricity consumption of the diesel and electric ferry, respectively, and by estimating the material and energy inputs necessary for the battery system. In keeping with a typical cost-benefit analysis, only the parts of the system unique to either the diesel or electric ferry are included in the life cycle inventory.

Table 15 - System components modelled in the life cycle inventory for PSV case

Environmental CAPEX	Battery system (cells, module, sub packs, strings, cooling units) Mooring device Converters/rectifiers Transformer Extra cabling compared to diesel ferry
Environmental OPEX	Fuel savings compared to diesel ferry Electricity requirements from grid to charge battery

The bill of materials for the ferry is similar to that of the PSV case. No environmental product declarations were available for the rectifiers, so the environmental product declarations for the converters were used. According to ABB, a rectifier is a less complicated machine, with less steel and copper. As such, using the environmental product information on a per kWh basis for the converters in place of a rectifier is a conservative estimate.

Table 16 - Bill of materials for electric ferry – energy storage

Energy storage	
Battery cells	Source of material and mass information
Separator	Generic 2Ah 18650 power cell design (15)
Aluminum wrought alloy (Cathode Al foil)	Generic 2Ah 18650 power cell design (16)
Cathode active material	Estimated based on cell capacity (17)
Anode Cu foil	Generic 2Ah 18650 power cell design (16)
Anode active material	Estimated based on cell capacity (17)
Electrolyte	General Li-ion electrolyte formula
Steel	Weight of dummy cells (15)
Electrical process energy (medium voltage)	Grenland Energy discussions with cell producer
Transport	Estimated based on weight and distance
Metal working for copper, steel, and aluminum components	Estimated based on weight of components
Modules (8 modules per sub-pack)	
Aluminum	Grenland product designs and dimensions
Copper	Grenland product designs and dimensions
Acrylonitrile butadiene styrene (ABS) plastic	Grenland product designs and dimensions
Steel (electrogalvanized steel)	Grenland product designs and dimensions
EPDM 70 shore (BMS card holder)	Grenland product designs and dimensions
PCB (BMS printed circuit board)	Grenland product designs and dimensions
Transport	Estimated based on weight and distance
Metal working for copper, steel, and aluminum components	Estimated based on weight of components
Sub-pack (6 sub-packs per string)	
Aluminum	Grenland product designs and dimensions
Copper	Grenland product designs and dimensions
Copper metal working	Grenland product designs and dimensions
Steel (electrogalvanized)	Grenland product designs and dimensions
Steel (powder coated carbon)	Grenland product designs and dimensions
ABS Plastic	Grenland product designs and dimensions
Transport	Estimated based on weight and distance
Metal working for copper, steel, and aluminum components	Estimated based on weight of components
String (30 total & includes battery room)	
Steel (powder coated carbon)	Grenland product designs and dimensions
Aluminum	Grenland product designs and dimensions
Steel	Grenland product designs and dimensions
Transport	Grenland product designs and dimensions
Metal working for copper, steel, and aluminum components	Estimated based on weight of components

Table 17 - Bill of materials for electric ferry - power conversion

Power conversion	
Transformer	
Material and energy inputs	
Steel (powder coated carbon)	ABB environmental product declaration
Copper	ABB product catalogue
Cast iron	ABB product catalogue
Insulation (epoxy)	ABB product catalogue
Electrical process energy (medium voltage)	ABB product catalogue
Heat process energy	ABB product catalogue
Transportation	Estimated based on weight and distance
Metal working for copper, steel, and aluminum components	Estimated based on weight of components
Converter / rectifier	
Low-alloyed steel	ABB product information (18)
Cast iron	ABB product information
Copper	ABB product information
Aluminum	ABB product information
Polyethylene	ABB product information
Electrical process energy (medium voltage)	ABB product information
Heat process energy	ABB product information
Transportation	Estimated based on weight and distance
Metal working for copper, steel, and aluminum components	Estimated based on weight of components
Cables	
Aluminum	Estimated based on 300 cm2 and 75 m total cables
Transport	Estimated based on weight and distance
Metal working for copper, steel, and aluminum components	Estimated based on weight of components
Mooring device	
Cast iron	Data sheet from Cavotec (25)
Aluminum cables	Estimated based on 300 cm2 and 30 m total cables
Transport	Estimated based on weight and distance
Metal working for cast iron	Estimated based on weight of components

6.2 Results ferry case

6.2.1 Environmental CAPEX of ferry case

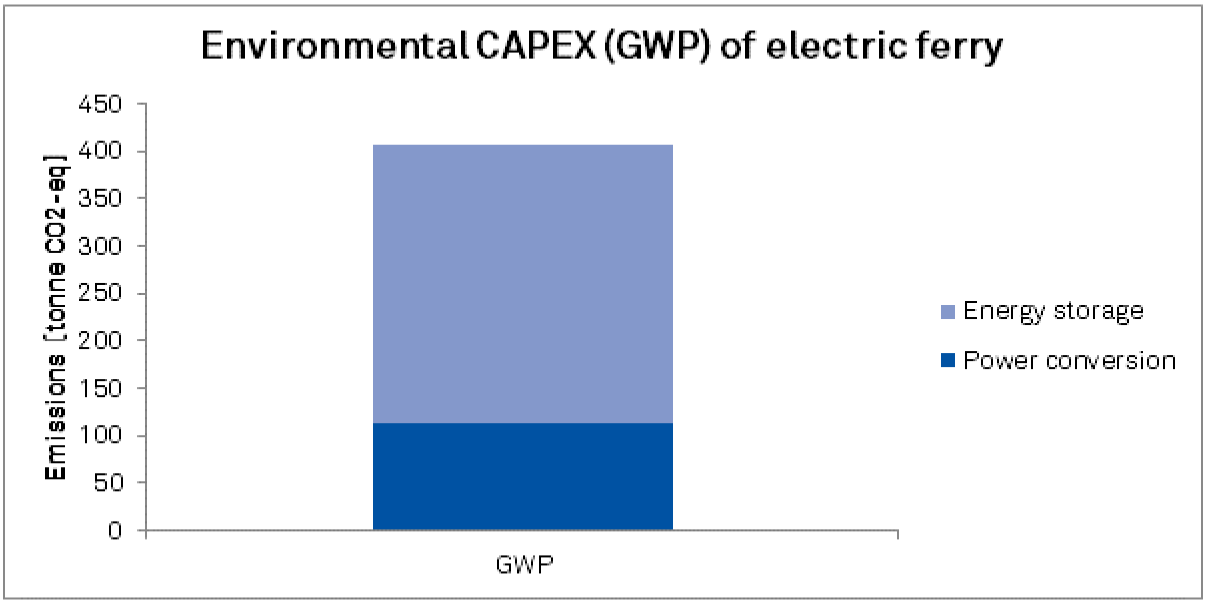

Figure 26 GWP CAPEX of fully electric ferry

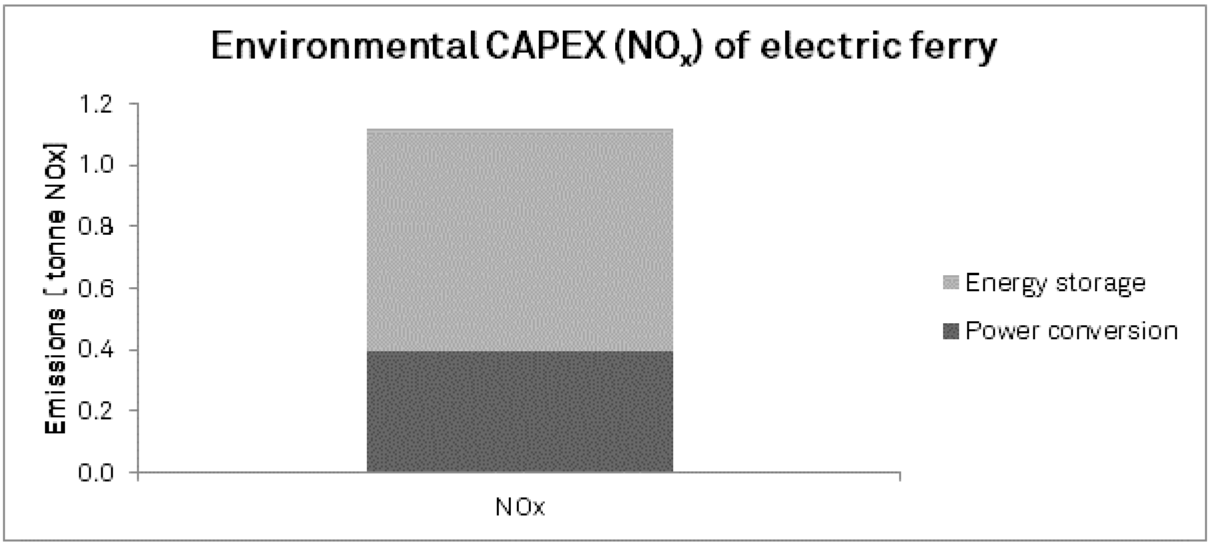

Figure 27 NO_x CAPEX of fully electric ferry

The environmental CAPEX of the fully electric is 429 tonnes CO_2-eq and 1.2 tonnes of NO_x. As was the case for the PSV, most of the emissions come from producing energy storage, i.e. the battery cells and packaging. The NO_x emissions from power conversion are low because it is assumed that process energy to make the converter and transformer come from the Finnish electricity mix, which is relatively clean regarding NO_x emissions.

The process energy used to make the battery cells is assumed to originate from what is designated as the global average electricity mix in Ecoinvent.

Figure 28 and Figure 29 show that the battery cells dominate the environmental CAPEX for the energy storage components of the electric ferry. Again, this is due to the process energy needed to make the cells. The results for the ferry are similar to those of the PSV because the same cell types are assumed, and because the same amount of process energy per kWh cell capacity is assumed.

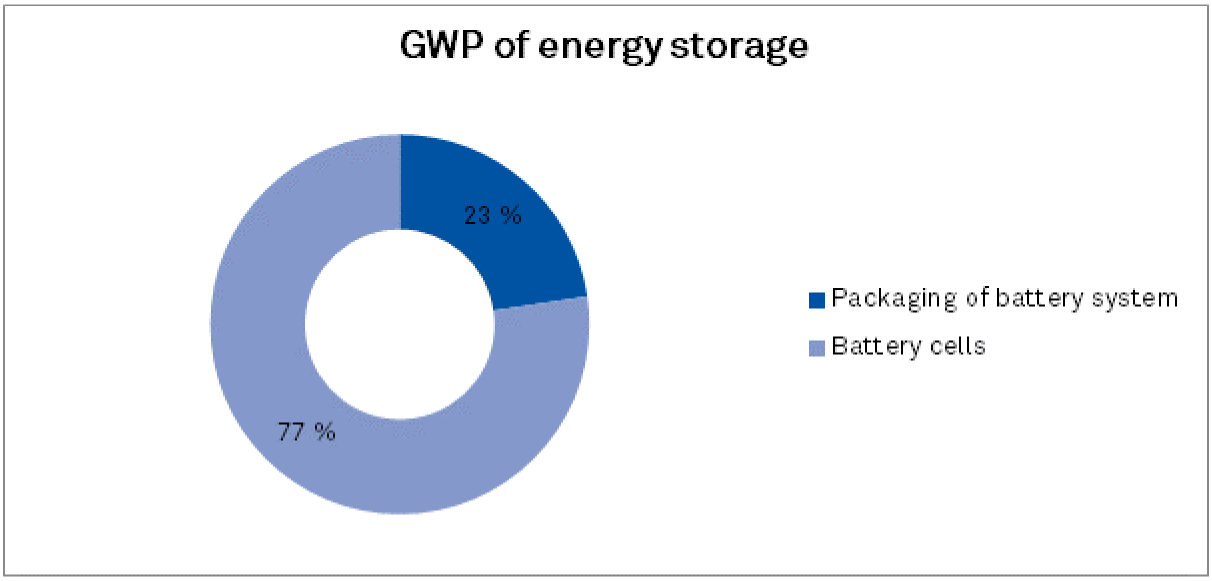

Figure 28 GWP emissions of energy storage for electric ferry

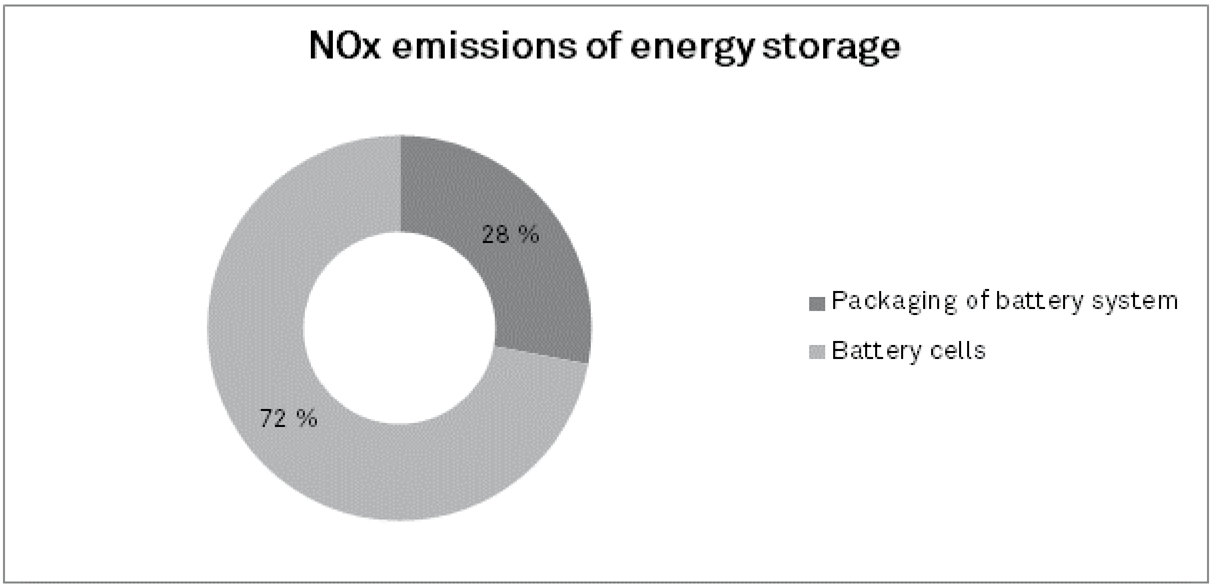

Figure 29 NOx emissions of energy storage for electric ferry

6.2.2 Life cycle results of ferry case

Figure 30 and Figure 31 show the life cycle GWP and NO_x emissions, respectively, of the fully electric ferry. The emissions in year 0 correspond to the environmental CAPEX (the extra environmental costs due to the production of the battery system) compared to the diesel ferry. The negative emissions in years 1-10 correspond to the emissions savings compared to using a diesel ferry. The emissions savings constitute the difference between emissions savings of using a battery system compared to a diesel system and the emissions of producing electricity to run the battery. The results shown in Figure 30 and Figure 31 are generated using the Norwegian electricity mix, and the life cycle emissions therein. The life cycle emissions are shown for 10 years because that is the assumed life-time of the battery.

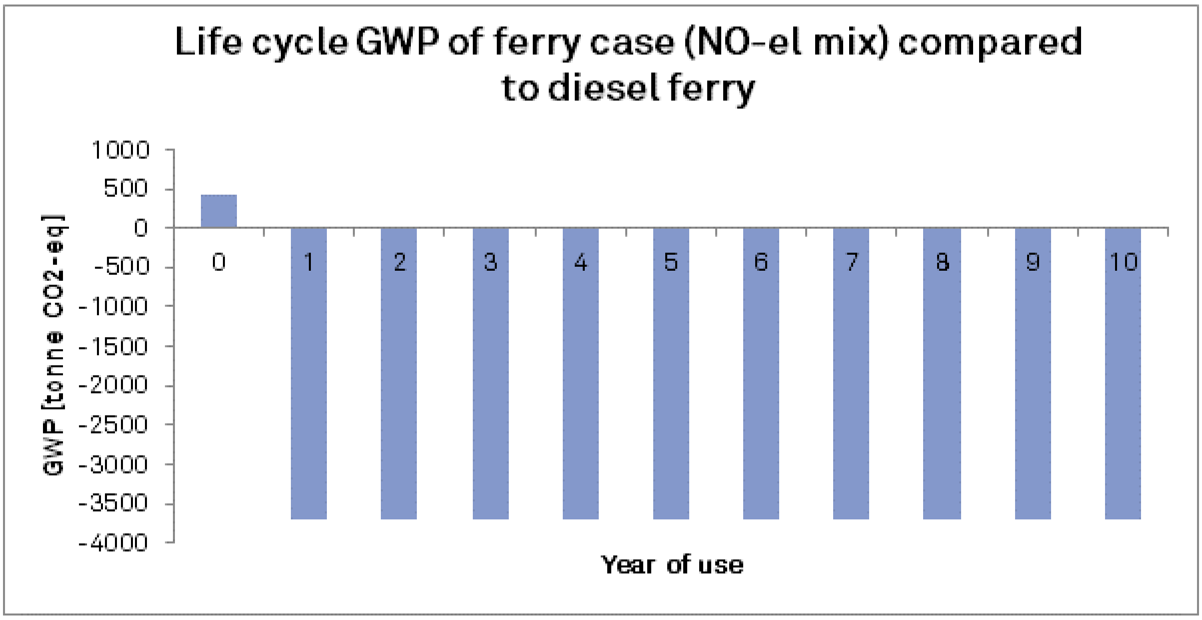

Figure 30 - Life cycle GWP emissions of electric ferry, using the Norwegian electricity mix

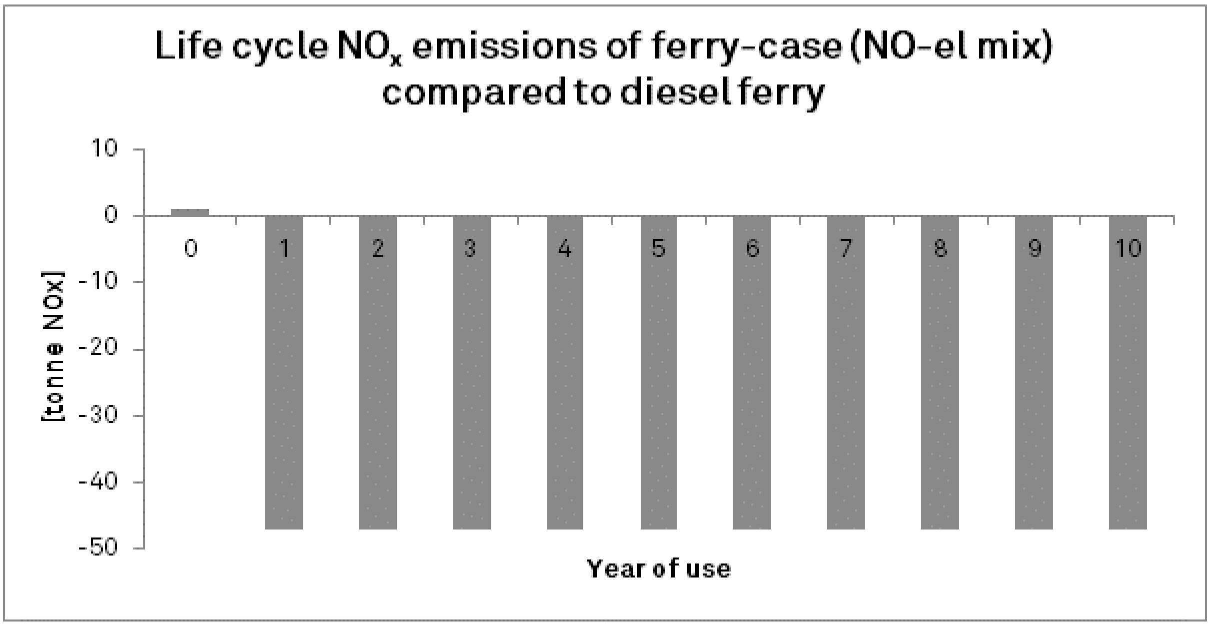

Figure 31 Life cycle NO_x emissions of electric ferry

The payback periods of the electric ferry for GWP and NO_x emissions are 1.4 months and 0.3 months, respectively.

The fully electric ferry does not need diesel generators on board because the battery is designed to fulfil all power requirements. As such, it would be possible to build the life cycle inventory of the diesels generators and count the emissions related to their production as a savings, i.e. subtract the emissions of producing the generators from the CAPEX. In the case of the electric ferry, the CAPEX is so small compared to the emissions savings that this was deemed unnecessary as it would not affect the conclusion, but it should be noted that the CAPEX over the battery system is conservative since the savings of not producing the diesel engines are not included.

The results in Figure 19 and Figure 20 are produced by assuming that the ferry consumes electricity produced with the Norwegian electricity mix (as compiled in the Ecoinvent database), which is 92 % hydropower (28). Such a mix has a GWP of 0.03 kg CO_2-eq per kWh and 5.21×10^{-5} kg NO_x per kWh. By contrast a kWh of MGO corresponds to 0.33 CO_2-eq per kWh and 0.004 kg NO_x per kWh of MGO, including emissions from combustion and production.

The electricity mix for the EU has a GWP of 0.47 kg CO_2-eq per kWh and 0.0008 kg NO_x per kWh, meaning that the MGO has lower GWP emissions on unit energy basis than the EU electricity mix (as compiled by Ecoinvent). However, the energy savings from the electric ferry are still so high due to increased efficiency of a battery compared to a diesel electric motor, that the electric ferry is still an environmentally attractive option from an environmental life-cycle perspective. This is shown in Figure 32, Figure 33, and Table 18, in which the life cycle emissions for the electric ferry are shown with Norwegian, EU, and global electricity mixes.

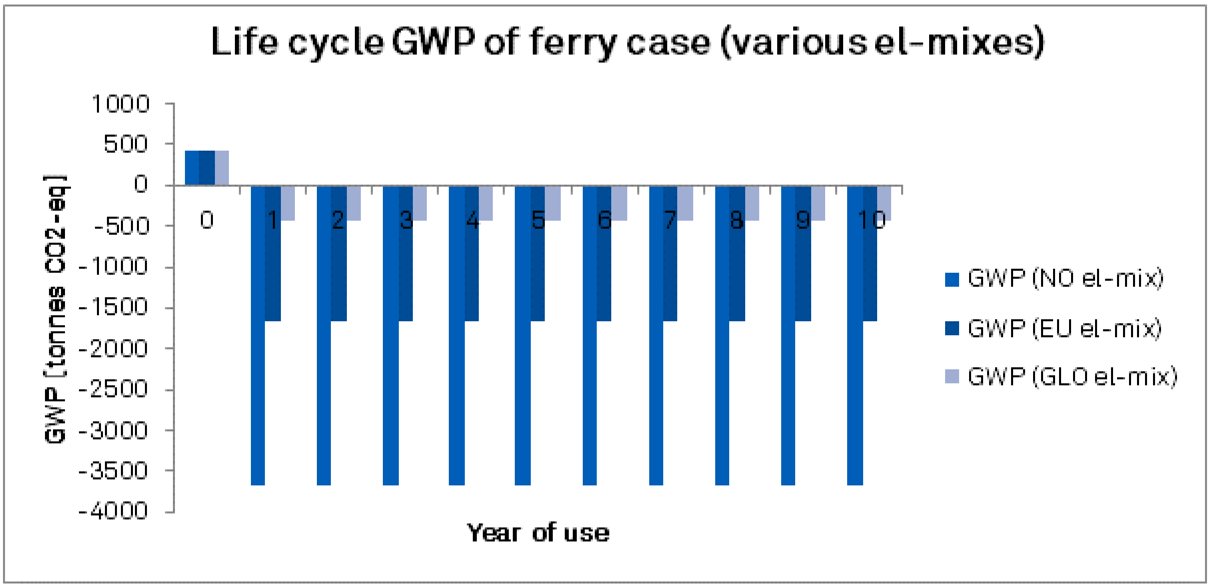

Figure 32 Life cycle emissions of electric ferry using various electicity mixes

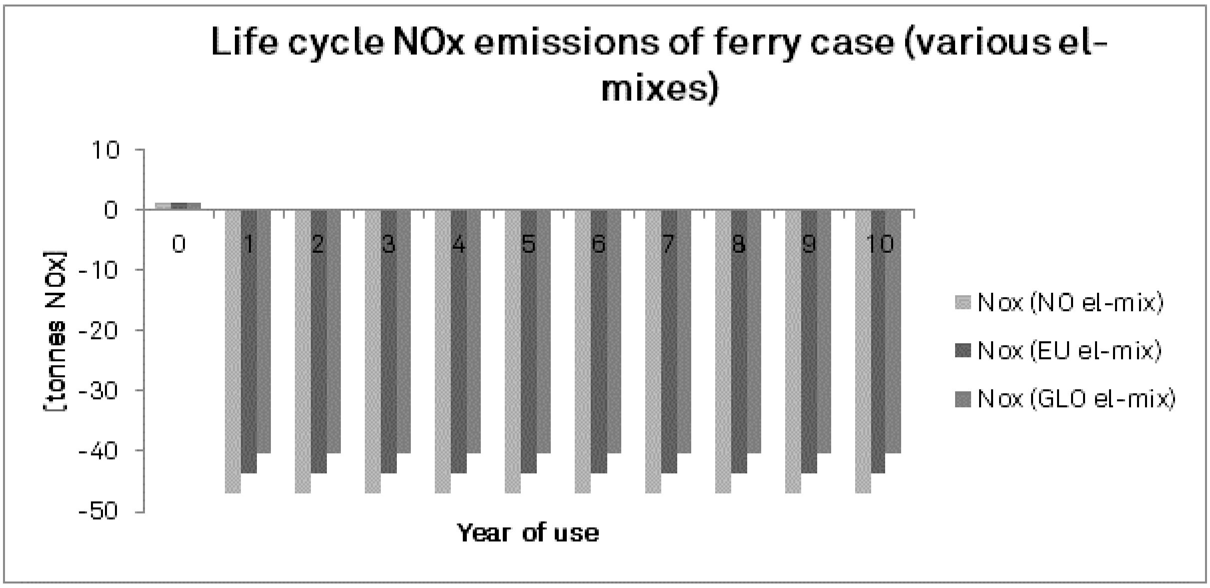

Figure 33 Life cycle emissions of electric ferry using various electicity mixes

Table 18 GWP and NO_x payback times for fully electric ferry with various electricity mixes

Electricity mix	GWP payback time (months)	NO_x payback time (months)
Norwegian	1.4	0.30
EU	2.5	0.32
GLO	11.8	0.35

There is little variation in the payback time for NO_x because the fuel savings are large and the differences in NO_x emissions per kWh compared to MGO are less variant than GWP emissions for the different electricity mixes.

Figure 32 and Table 18 show that the electricity mix has a significant effect on the GWP payback period for the electric ferry. Understanding the sensitivity of the life cycle emissions to the electricity mix is interesting because it shows the current upper bound of emissions savings when clean electricity mixes are employed. In the case of the electric ferry, the energy savings of employing the battery are so large that there are still emissions savings even when a dirtier electricity mix is used. However, even if this was not the case, the emissions from MGO do not have the potential to decrease beyond efficiency measures. Emissions from MGO result from the combustion of hydrocarbon chains. This cannot be changed or reduced, but the emissions from electricity can be reduced by using renewable energy sources. Batteries allow for the use of more renewable energy to fuel the transport sector; the continued use of MGO and simply employing energy efficiency measures do not.

6.3 PSV and Ferry Case: Uncertainty

The GWP for the energy storage portion of the battery systems of the hybrid PSV and fully electric ferry is 285 kg CO_2-eq/kWh and 273 kg CO_2-eq/kWh, respectively. Similar LCAs of Li-ion batteries for cars indicate a GWP of 60-173 kg CO_2-eq/kWh for energy storage (19), (6). The energy storage for a ship should have a higher GWP than that of a car, because the packaging and control systems are larger. However, the dominating process contributing to GWP in both studies was found to be the process energy per kWh-cell. Therefore it is reasonable to expect that the GWP per kWh capacity of a battery system for a car and a ship would be in the same order of magnitude, which the results of this study reflect.

One of the most important aspects of the environmental CAPEX is the process energy required to make the battery cells. For the purposes of this study, the cell manufacturer has given an approximate energy use of 200 kWh per kWh-cell, and this number has been used in the life cycle inventory. Several studies exist which already model the production processes of battery cells, and Ecoinvent has its own inventory for Li-ion batteries used in cars. One study performed in conjunction with Miljøbil Grenland (19) calculated the process energy requirements per kWh-cell based on total electricity use and cell production at a factory over an 18 month period. The study found that the lower bound was 163 kWh per kWh-cell, the asymptotic value (i.e. the value to which most data points converged) was 267 kWh per kWh-cell, and the average was 644 kWh per kWh-cell. It is, however, important to keep in mind that for that study, the cell manufacturing rate was not constant over the period and the cells factory also ran other equipment not pertaining to the cells production.

It is also possible to use the projected data for the Tesla Gigafactory as a means of gaging process energy per kWh cell capacity. This factory is supposed to consume around 2.32 GWh per day for a total cell output of 35 GWh annually as well as a battery pack capacity of 50 GWh annually. Assuming operation 365 days a year, the total annual electricity consumption is around 847 GWh annually, giving around 24 kWh/kWh cell (29). This number does not include the battery pack production that is also included in the electricity consumption. The electricity consumption for pack manufacturing is far lower than for cell manufacturing since there are no stringent climatic requirements for battery pack manufacturing.

For both the PSV and the ferry case, cells with thinner coating, longer current collector foils and less energy content per cell compared to the cells to be manufactured at the Tesla Gigafactory are used. The electricity consumption is higher per cell for such cells. Tesla is furthermore assuming 30% lower electricity consumption for cell manufacturing compared to other battery plants because of its size. Taking all these considerations into account, the cell electricity consumption for cells used in the ferry and PSV cases would be less than 100 kWh/kWh cell, given the parameters of the Tesla factory.

A study by the US EPA indicates 208 kWh/kWh-cell primary energy use for cell manufacture, but this also includes the energy requirements to create the components of the cell, which are already accounted for in the sub-inventories chosen from Ecoinvent in this study. The Ecoinvent database lists the process energy of 0.11 kWh per kg battery cell, compared to 1.67 kWh per kg battery cell in this study.

These different studies indicate that an estimation of 200 kWh per kWh-cell has significant uncertainty. In addition to uncertainties introduced by the varying results of other studies, there are several types of cells produced at the factory which have different energy requirements, so the average electricity per kWh is not necessarily accurate. However, the majority of process energy in cell production is used for dry rooms and heating for the coating process which are vital to cell quality (19). According to conversations with Grenland Energy, the cell producer in question has energy requirements for the dry rooms corresponding to a sub-tropical climate zone. The energy requirements will be lower for cells manufacturing in drier climates and higher for cell manufacturing in wetter climates.

Given these uncertainties, the value of 200 kWh electricity use per kWh-cell has been employed in the study, without modification. The effect of using the average electricity use as reported by the previous study (19) of 644 kWh increases the GWP payback time of a hybrid PSV from 1.5 to 2.8 months. Changing the electrical process energy to 644 kWh increases the GWP payback time of the ferry case from 1.4 to 2.5 months.

By using 50 kWh of electricity input per kWh battery cell, the GWP payback time of a hybrid PSV decreases from 1.5 to 1.0 months. Changing the electrical process energy to 50 kWh decreases the GWP payback time of the ferry case from 1.4 to 1.0 months.

As noted previously, the global electricity mix is assumed for the process energy used to produce the battery cells. This makes the result sensitive to the amount process energy because this mix is relatively dirty.

Other sources of uncertainty are related to the completeness of the life cycle inventory for environmental CAPEX. For the purposes of this study, the largest components of power conversion and energy storage were identified, especially the metals. The inventory could be made more complete to include, for example the cabinets in the control system, the fire extinguishing equipment, etc. In the case of the electric ferry, the environmental CAPEX is underestimated because savings from not making the diesel engines are not quantified.

The environmental CAPEX would have to be wrong by several orders of magnitude in order to significantly change the payback time of using batteries on board ships. Additionally, the results show that the most important aspects of the system are the fuel and electricity use of the ship and the energy requirements to make the cells.

In the hybrid PSV case, the battery is dimensioned to give 12 minutes of spinning reserve. This was based on the assumed risk of the operational profile, but according to DNV GL class rules a minimum time requirement of 30 minutes is normal for many kinds of PSV operations. As such, some operators may prefer to have a battery which dimensioned for 30 minutes of spinning reserve, rather than 12 minutes. The environmental cost is mostly related to the energy storage, so that increasing the spinning reserve to 30 minutes would approximately double the environmental CAPEX. This means that the environmental payback time would be three months for GHG and 0.6 months for NO_x, respectively if the spinning reserve is increased to 30 minutes.

7 Conclusions

The results of this study show that the environmental CAPEX of producing batteries for a PSV and ferry is negligible compared to the fuel savings from using batteries. For the PSV and ferry case, the environmental payback (GWP & NOx) is 1.5 month for GHG and 0.3 months for NOx.

Previous studies show that PSVs and ferries constitute more than half of emissions from domestic shipping, and that the Norwegian government's targets for emissions reductions will not be met with energy efficiency measures alone. This LCA shows that the use of electric propulsion to achieve emissions savings domestically will not result in emissions further up the value chain which are larger than the savings.

Although there are some aspects of uncertainty regarding the environmental CAPEX of the battery systems, these uncertainties are not large enough to change the conclusion. Even if the environmental CAPEX increases by a factor of 10, the conclusion will be not change for an OSV or for a ferry employing Norwegian electricity mix.

The most important factor for determining the environmental CAPEX of the battery systems was the process energy per kWh cell capacity. The amount of energy is uncertain, but the process energy also represents a link in the value chain which has potential for improvement, as this process energy can be produced with renewable sources. The battery systems in a maritime setting represent significant emissions savings with potential for an even shorter environmental payback time. The continued use of MGO cannot achieve such savings.

In both cases there is a discrepancy between the environmental payback and the financial payback. Although the financial payback was not in the scope of this study, other studies and ABB and Grenland Energy's own project experience indicate a financial payback period in the order of magnitude of 5 years (30). This should be noted by policy makers, who can employ incentives which can bring the financial payback time more in line with the environmental one.

The results of this study show that there the environmental impact of creating the battery system is small compared to the emissions savings. The environmental cost of creating the batteries is not a valid argument to deter policy makers and ship owners from encouraging and using batteries in a maritime setting. These potential emission reductions can play an important role in reducing emissions from domestic and international shipping.

8 Bibliography

1. **DNV GL.** *Reduksjon av klimagassutslipp fra norsk innenriks skipsfart.* s.l. : Klima- og miljødepartementet, 2016. Report No.: 2016-0150.

2. —. *Vurdering av tiltak og virkemdiler for mer miljøvennlige drivstoff i skipsfartsnæringen.* s.l. : Klima- og miljødepartmentet, 2015. Report No.Ø 2015-0086, Rev. 0.

3. **IPCC.** *Climate Change 2014 Mitigation of Climate change: Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* s.l. : Intergovernmental Panel on Climate Change, 2014.

4. **Levin, Kelly og Tompkins, C. Forbes.** Analyzing the IPCC report: 6 things you need to know about reducing emissions. *World Resources Institute.* [Internett] 13 April 2014. http://www.wri.org/blog/2014/04/analyzing-ipcc-report-6-things-you-need-know-about-reducing-emissions.

5. **ISO.** *14044: environmental management - life cycle assessment - requirements and guidelines.* s.l. : International Organization for Standardization, 2006.

6. **EPA.** *Application of Life-Cycle Assessment to Nanoscale Technology: Lithium-ion Batteries for Electric Vehicles.* available at [https://www.epa.gov/saferchoice/partnership-conduct-life-cycle-assessment-lithium-ion-batteries-and-nanotechnology] : United States Environmental Protection Agency, 2014.

7. *ReCiPe 2008: A life cycle impact assessment method which comprises harmonized category indicators at the midpoint and endpoint level.* **Goedkeep, Mark, et al.** Report I: Characterization, Amersfoort : Ruimte en Milieu, Ministerie van Volkshuisvesting, Ruimtelijke Ordening en Milieubeheer, 2013, Vol. First edition version 1.08.

8. **Air pollution from Ships. *Transport and Environment.* [Internett] 2015. https://www.transportenvironment.org/what-we-do/shipping/air-pollution-ships.**

9. Grolms, Martin. Resurrected batteries to stabilize power grid. *Materials Views.* [Internett] 26 January 2015. http://materialsviews.com/resurrected-batteries-stabilize-power-grid/.

10. *Recyling rechargeable lithium ion batteries: Critical analysis of natural resource savings.* Dewulf, Jo, et al. Ghent : Resources, Conservation and Recycling, 2009, Vol. 54(2010)229-234.

11. DNV GL. Part 6 Additional class notation, Chapter 3 Navigation, manoevring and position keeping. *DNV GL Rules for classification of ships.* 2016.

12. *Hybrid retrofit solution for an LNG offshore vessel.* Westcon Power & Automation. Amsterdam : Electric and Hybrid Marine World Congerence 2016, 2016.

13. *Hybrid propulsion system concept based on "Propulsion System Planner".* Kawasaki Heavy Industries. Amsterdam : Electric & Hybrid Marine World Expo 2016, 2016.

14. Grenland Energy. Schematic: Battery components explained. 2016. rev. 1.

15. *Transport Properties of LiPF6-Based Li-Ion Battery.* Valøen, L. O. og Reimers, J. N. 5, s.l. : Journal of The Electrochemical Society, 2005, Vol. 152, ss. A882-A891.

16. *Design and Simulation of Spirally-wound Lithium-Ion Cell.* Spotnitz, R., et al. s.l. : Battery Deisgn LLC, CD-adapco.

17. *Li-ion battery materials: present and future.* Nitta, Naoki, et al. 5, s.l. : Materialstoday, 2015, Vol. 18. 252-264.

18. ABB. Drive IT Low Voltage AC Drive, ACS800 frequency converter, 630 kW power. *Environmental Product Declaration.* s.l., Finland : ABB Oy, 2003.

19. *Life Cycle ASsessment of a Lithium-Ion Battery Vehicle Pack.* Ellingsen, Linda Ager-Wick, et al. 1, s.l. : Journal of Industrial Ecology, 2013, Vol. 18. 113-124.

20. DNV. *Environmental Accounting system for ships based on AIS ship movement tracking.* 2008. DNV report 2008-1853, rev. 1.

21. Wernet, G., et al. The ecoinvent database version 3 (part I): overview and methodology. *The International Journal of Life Cycle Assessment.* [online] 21(9), pp. 1218-1230, 2016, Vol. Available at: <http://link.springer.com/10.1007/s11367-016-1087-8>, [Accessed 30.08.2016].

22. *Inst. 78 S (2015-2015): Instilling til Stortinget fra energi- og miljøkomiteen.* Energi- og miljøkomiteen. 2016. Dokument 8: 126 S (2014-2015).

23. Norled. E39 Lavik - Oppedal fergerute. *Norled.* [Internett] 2016. https://www.norled.no/contentassets/a4aa7bd2b2304c6d8aaf5df4c97a4d94/52019_plakat_rute1046_k3.pdf.

24. IHS Fairplay. Sea-web ship search. *IHS Maritime Sea-web Insight.* [Internett] IHS Fairplay , 2016.

25. Cavotec. Cavotec data sheets - MoorMaster 400 Automatic mooring system. *Cavatoc.* [Internett]

26. DNV GL. *Elektrifisering av bilferger i Norge - kartlegging av investeringsbehov i strømnettet.* s.l. : EnergiNorge, 2015. Report No.: 2015-0500, Rev. 0.

27. *The Effect of PHEV HEV Duty Cycles on Battery and Battery Pack Performance.* Valøen, Lars Ole og Shoesmith, Mark I. s.l. : Miljø Innovasjon AS, Nystrandvegen 59, N3944 Porsgrunn, Norway; E-One Moli energy (Canada) Ltd., 20,000 Stewart Crescent, Maple Ridge, BC V2X 9E7, 2007.

28. The World Bank. 3.7 World Development Indicators: Electricity production, sources, and access. *World Development Indicators: online tables.* [Internett] 2015. http://wdi.worldbank.org/table/3.7.

29. Mearian, Lucas. News: If Tesla's Gigafactory can run on 100% renewalbe energy, why can't others? *Computerworld.* [Internett] Computerworld, 9 September 2014. http://www.computerworld.com/article/2604352/if-tesla-s-gigafactory-can-run-on-100-renewable-energy-why-can-t-others.html.

30. *The first liquified natural gas - battery hybrid installed by Fiskerstrand.* Kjerstad, Einar. Amsterdam : Fiskerstrand, 2016. Electric & Hybrid Marine World Expo 2016.

31. ecoinvent. ecoinvent in Brief. *ecoinvent Centre.* [Internett] http://www.ecoinvent.org/about/about.html.

32. *Resource demand for the production of different cathode material for lithium ion batteries.* Swart, Pilar, Dewulf, Jo og Biernaux, Alexis. 2014, Journal of Clearner Production, ss. 391-399.

33. *The ecoinvent database syste: a comprehensive web-based LCA database.* Frischkencht, R. og Rebitzer, G. 2005, Jornal f Cleaner Production, ss. (13)1337-1343.