Jari Konttori

IMPACTS OF LITHIUM-ION BATTERY UTILIZATION ON THE VESSEL'S GREENHOUSE GAS EMISSIONS

Master's thesis

Master of Engineering

Master's Degree Programme in Sustainable Development Technologies

2024

South-Eastern Finland University of Applied Sciences

Degree title	Master of Engineering
Author	Jari Konttori
Thesis title	Effects of Lithium-ion Battery Utilization on the Vessel's greenhouse emissions
Commissioned by	DNV AS
Year	2024
Pages	36 pages
Supervisor	Arto Sormunen

ABSTRACT

IMO has adopted mandatory measures for international shipping to improve vessels' energy efficiency and, for example, reduce CO_2 emissions/transport work by 40% by 2030. The IMO measures focus on the vessel's operational emissions but in the fight against climate change the net GHG emissions are essential, and therefore, the emissions resulting from the vessel's building should also be considered. The measures do not define technical solutions, and with the current technologies, battery hybrid vessels are among the solutions to improve the vessels' energy efficiency.

The objective of the thesis was to study the possible reduction of GHG emissions achieved by using a battery system on the RoPax ferry Aurora Botnia and the possibility of compensating the battery production emissions by the vessel's reduced operational emissions.

The combination of onboard measurements and literature review was used for assessing the vessel's net GHG emission. The systematic literature review was used to estimate the GHG emissions for the battery production, while the onboard measurement data collected during the vessel's operation was used to determine the GWP difference between the combustion engine and the hybrid operation. The GWP difference between the operational modes was considered to represent the operational GHG reduction achieved by the battery usage. Finally, the battery production GHG emissions were compared with the reduced operational GHG emissions to estimate the battery production emissions compensation time. The GHG emissions were compared with the functional unit GWP in t CO_{2eq}.

The results suggest an average of 7% to 22% lower GWP in hybrid mode in comparison to combustion engine mode. Also, the GWP per trip is approximately 1 to 4 t CO_{2eq} lower in the battery hybrid operation. The battery production compensation time was estimated between 31 to 116 sailed trips or 11 to 42 days, depending on the monthly GWP difference. The results support the view that the use of the battery hybrid system contributes to the vessel's net GHG reduction.

Keywords: vessel, ship, GWP, battery, GHG, emissions, hybrid

CONTENTS

1 INTRODUCTION

The International Maritime Organisation (IMO) is the UN specialized agency, responsible for the safety and security of shipping and the prevention of marine and atmospheric pollution by vessels. The IMO has set targets for shipping to reduce CO_2 and greenhouse gas (GHG) emissions. The reduction target for CO_2 intensity (CO_2 emissions/transport work) is 40% by 2030 and 70% by 2050 from the 2008 level. In addition, the objective is to reduce at least 70% of the total annual GHG emissions by 2040 from the 2008 level and to reach net zero GHG emissions around 2050. (IMO 2023; IMO n.d.b.)

To reach these targets, IMO has adopted mandatory measures for international shipping. The measures to improve vessels' energy efficiency are for instance, the Energy Efficiency Design Index (EEDI), the Energy Efficiency Existing Ship Index (EEXI), the Carbon Intensity Indicator (CII) and the Ship Energy Efficiency Management Plan (SEEMP). The intention of the EEDI, EEXI, CII, and SEEMP is to improve the energy efficiency of ships and thus reduce the GHG resulting from the operation of ships. (DNV n.d.a.; DNV n.d.b.; IMO n.d.a.)

EEDI is an energy efficiency index for new vessels. The EEDI sets the maximum permissible CO_2 emission level considering vessels' capacity and sailed distance. The emission limit is defined with the functional unit, grams of CO_2 per tonne mile. The limit is set separately for different vessel types. The maximum emission value for the period starting in 2025 is set at 30% below the reference value of 2013. The reference value represents the average energy efficiency of ships built between 2000-2010. (DNV n.d.c.; IMO n.d.a.)

EEXI is an energy efficiency index for the existing vessels in which the IMO has determined the maximum index value for different vessel types. Vessels shall demonstrate compliance with the regulation by calculation. The calculation of the EEXI is based on the calculation principle of the EEDI. If the calculated energy efficiency index exceeds the value defined by the regulation, technical changes shall be made to the vessel to reach the specified value. Operating vessels shall receive a validated EEXI during 2023. (DNV n.d.b.)

Unlike the EEDI and EEXI, which affect vessels’ technical systems and solutions, the **CII** classification system is the regulatory and monitoring mechanism for CO_2 exhaust emissions during operation. CO_2 emissions limits are set considering the vessels' cargo carrying capacity and distance travelled. The functional unit is grams of CO2 emitted per cargo carrying capacity and nautical mile. Based on emissions, ships are rated from A to E, where class A is the best rating. The rating threshold for the classification will be stringent towards 2030. (DNV n.d.a.)

SEEMP is a ship’s energy efficiency management system designed to support the ship’s owners to improve the vessels’ energy efficiency cost effectively. (IMO n.d.a.)

The measures described above do not define technical solutions for the vessel’s energy efficiency improvements. Technical solutions with current technologies are, for example, different hybrid vessels, and among these are battery hybrid vessels. The battery hybrid vessels' main sources of power are typically combustion engines and additional power is fed into the vessel’s electric distribution system from the batteries. In battery hybrid vessels lithium-ion batteries are commonly used as energy storage because of their mature technology and favourable characteristics. (Inal et al. 2021, 3.) The principal difference between a conventional combustion engine and a battery hybrid vessel’s power plant is the hybrid vessel’s battery system with semiconductor converters in addition to the combustion engine (Figure 1).

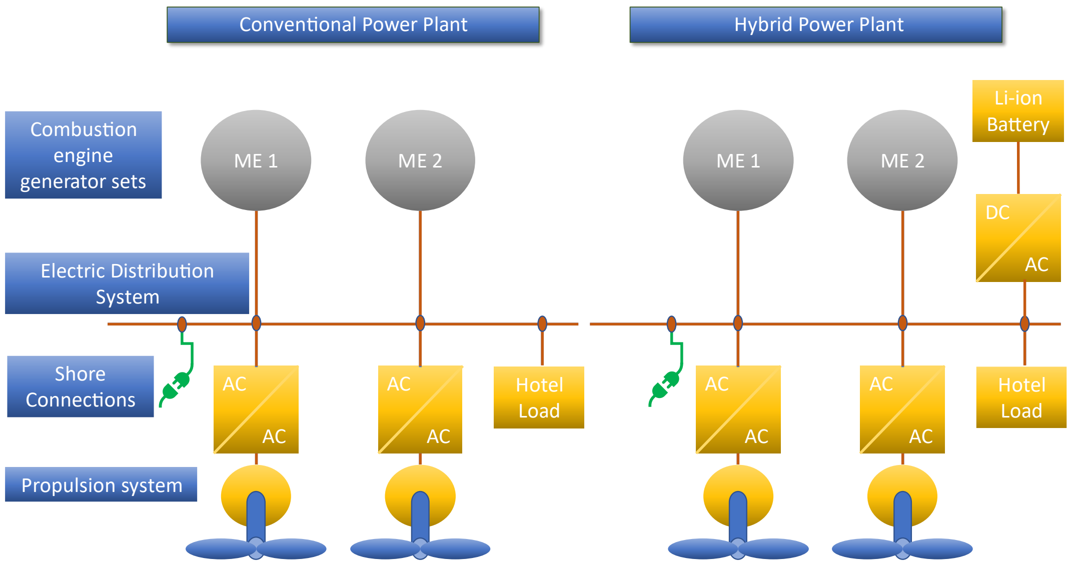

Figure 1. Principle diagram of the conventional electrical and hybrid power plant.

Battery hybrid vessels can be operated in several different modes, for instance, hybrid and combustion engine modes. In the hybrid mode, the combustion engines are operated parallel with the battery system and in combustion engine mode the battery system is disconnected and only the combustion engines are used. The correct use of a battery system can improve the vessel's energy efficiency by optimizing the combustion engine's loading conditions. The combustion engine's fuel consumption is optimised for a specific load range, which is typically between 0.7 to 1.0 of the maximum continuous rating. When operating outside of this optimised range, the engine's fuel consumption per produced energy unit increases. (Jafarzadeh & Schjølberg 2018, 501; Wärtsilä n.d.) Optimising fuel consumption close to the engine's maximum rating enables more efficient operation with fewer engines at full load and utilising the battery system for load peaks, rather than using more engines at lower load.

Engine's load demand is linked to propulsion power which is determined by the vessels' operational profile and has an impact on the benefits achieved using batteries. The operational profiles of eight vessel types operating in Norwegian waters were studied by Jafarzadeh and Schjølberg (2018). Based on operational profiles and vessels' technical data, the optimal use of propulsion engines was evaluated. In addition to the propulsion engine operation analysis, vessel types that can benefit most from the hybrid propulsion system were identified. The vessels with dynamic operating profiles and the ones operating long periods with low propulsion power benefitted most from the hybrid propulsion system (Jafarzadeh & Schjølberg 2018, 507).

In addition to improved energy efficiency, the battery hybrid vessel has further benefits. According to Damian et al. (2022), these benefits include enhanced flexibility, improved reliability, and reduced operating costs. The cost and reliability benefits of the battery system were assessed in the case study by Ritari et al. (2019). The study suggests that battery installation would be economically feasible even if the battery system was not actively used for fuel oil consumption optimisation but only as a backup power to enhance reliable operation (Ritari et al. 2019, 10).

Battery system benefits promote the use of batteries as a part of the vessel's energy production and the use of electrical- and hybrid solutions is anticipated to increase. (Inal et al. 2021, 12). The transition towards a hybrid solution is supported by figures published in DNV Maritime Forecast to 2050. According to the forecast, the total number of operating battery or hybrid vessels worldwide is 396. The number of battery or hybrid vessels currently in order is 417, which already exceeds the number of vessels in operation. (Ovrum et al. 2022, 34.)

Despite all the benefits, the battery hybrid system also has some disadvantages. The battery system is typically installed as an addition to the conventional combustion engine and therefore battery hybrid vessels' building GHG emissions are higher. IMO objectives and adopted regulations in the fight against climate change are focused on tank-to-wake (TtW) greenhouse gas emissions emitted during the operation of the vessels. However, GHGs are emitted in all stages and various functions during the vessel's life cycle such as building the vessels, charging the batteries from shore-based charging stations, and manufacturing the components installed onboard. (Ling-Chin & Roskilly 2016; Fan et al. 2021; Jeong et al. 2018.) To comply with IMO regulations, the vessel's TtW GHG emissions shall be reduced. In addition to TtW emissions, from a climate change standpoint, the reduction of net GHG emissions is essential. When estimating net GHG emissions the manufacturing emissions of the installed additional energy-saving systems, such as battery systems, shall be considered.

Battery system benefits and the vessel’s net GHG emission reduction have been estimated by life cycle analyses (LCA) and simulation methods (Fan et al. 2021; Jeong et al. 2018; Ling-Chin & Roskilly 2016). Despite several studies utilising simulations for examining batteries' effects on vessels' GHG emissions, studies based on onboard measurements using actual data from the vessel’s operation are scarce.

The present case study examined the battery system's net GHG emission reduction potential from a life-cycle perspective. Net GHG emissions were assessed by comparing the vessel’s GHG emissions difference between the combustion engine and hybrid operations to the battery system production GHG emissions. The objective of the study was to provide an answer to the question if it is possible to compensate the battery production GHG emission with the vessel’s reduced operational GHG emission achieved by the utilization lithium-ion battery system.

2 USE OF LITHIUM-ION BATTERIES ON BATTERY HYBRID VESSELS

The vessels’ net GHG emissions have been studied by LCA methods using different life cycle approaches and assessing several different vessel types, powerplant configurations, and fuel types. The examined life cycle phases included in the studies vary between building, operation, and scrapping. The assessed powerplant configuration are for example, hybrid, diesel-mechanical, diesel-electrical and fuel types included in the studies are for instance liquid natural gas (LNG), marine gas or marine diesel oil (MGO or MDO), and heavy fuel oil (HFO). The LCA results differ depending on the studied vessels’ characteristics, fuels and life cycle phases analysed in the study. (Ritari et al. 2021; Fan et al. 2021; Yu et al. 2018; Jeong et al. 2018.)

Reducing GHG emissions by using batteries on vessels with a diesel-mechanical propulsion system has been assessed with LCA methods by Ritari et al. (2019) and Yu et al. (2018). Ritari et al. (2019, 10) reported annual fuel savings of 257.5 tonnes which are achievable by retrofitting lithium-ion batteries as an auxiliary source of power on RoRo passenger vessels. Yu et al. (2018) compared emissions emitted by a diesel-electric battery hybrid vessel equipped with a solar panel with the diesel-mechanical vessel. The study discovered daily CO_2 emissions of the diesel-mechanical vessel of 165 kg and the corresponding emissions from the battery hybrid vessel of 31 kg. Both studies Ritari et al. (2021) and Yu et al. (2018) assessed the emissions or fuel savings in the operational phase of the vessel's life cycle.

Energy saving and emission limiting regulations are drivers towards alternative propulsion systems such as diesel-electric, LNG or hybrid. (Inal et al. 2021, 2). The emissions of the diesel-electric and battery hybrid vessel were compared by Ling-Chin and Roskilly (2016) using the LCA method. According to the study, the environmental impact of a battery hybrid vessel in comparison to a diesel-electric vessel is smaller in 20 out of 26 subcategories, including the global warming potential (GWP).

CO_2 emissions between LNG battery hybrid vessels and diesel-mechanical vessels during the 30-year life cycle were compared by Fan et al. (2021). The studied vessel was operating on the Yangtse River. The study demonstrated 33.44% lower CO_2 emissions in the LNG battery hybrid vessel in comparison to a similar diesel-mechanical vessel. The study considered the emissions from battery production and replacing the batteries every 10 years.

A vessel's emissions during its life cycle are affected by several variables, one of them being the electricity mix used for charging hybrid vessel batteries. To determine the whole life cycle emissions from the building, operation and eventually the scrapping of the vessel Jeong et al. (2018) carried out a life cycle impact assessment (LCIA) using modular modelling. The life cycle emissions and costs between a diesel-electric battery hybrid and a diesel-electric roll-on/roll-off passenger (RoPax) ferry operating in Scotland were compared by using the LabVIEW simulation programme. The life cycle of the ship was defined as 30 years. The LCIA reveals 3.5 x 10^6 kg CO_2-eq lower GWP on battery hybrid vessels in comparison with the diesel-electric vessel. The GWP emission reduction is achieved when batteries were charged via shore supply during the vessel's rest period and the charging energy was produced with wind power. In case batteries are charged by using the ship's power plant, the GWP is higher in battery hybrid ferry than in diesel-electric ferry. (Jeong et al. 2018, 120.)

3 LITHIUM-ION BATTERY PRODUCTION GHG EMISSIONS

To estimate net GHG emissions resulting from the vessel's battery usage the GHG emissions resulting from battery production shall be identified and considered in the net GHG assessment.

The GHG emissions and other environmental impacts of six different lithium-ion batteries using GaBi software were studied by Lai et al. (2022b). Four of the six battery types examined were NCM batteries manufactured in China. The GWP was calculated using the GWP factor for electricity production in China in 2020. The GWP from NCM-battery production was discovered to be between 114-137 kg CO_{2eq}/kWh. The main cause of variation in the reported GWP appears to be different raw materials used in battery cathode manufacturing. In addition, the report discusses higher battery production GHG emissions when cobalt and magnesium concentrations in the cathode increase. According to the study, GWP is highest in NCM111 and lowest in NCM811 batteries. The GHG emissions from battery production are suggested to fall by 90% from 2020 levels by 2060. The reduction in GHG emissions is feasible if Chinese electricity production is carbon neutral in 2060 as targeted by the government's objectives.

Winjobi et al. (2022) used GREET modelling to assess the effects of supply chains and production areas on NCM lithium-ion battery production emissions. In the modelling, different scenarios are compared with a base scenario. Baseline parameters used in the base scenario are, for example, cathode active material and battery cells manufactured in the USA, lithium acquired and processed in

Chile, and cobalt mined from the Congo and processed in China. The baseline parameters were changed according to three different scenarios in GREET modelling. The scenarios were named the best, the worst, and the dominant. In the worst scenario, the energy used in battery production was produced by coal and in the best scenario by wind power. In the best scenario, NCM111 battery production GHG emissions decreased by 48%. Emissions increased by 24% and 96% in the dominant and worst scenario, respectively, in comparison to GREET-modelling baseline values.

A literature review assessing GHG emissions from several production phases of the lithium-ion battery was conducted by Emilsson and Dahllöf (2019). The studied production phases were mining and processing of the materials, battery cell manufacturing and battery assembly. The estimated GWP of the NCM111 lithium-ion battery was between 61-106 kg CO_{2eq}/kWh. The smallest GWP, 61 kg CO_{2eq}/kWh, was revealed when renewable energy was used for the battery cell production. In contrast, when the energy was produced with fossil fuels, the projected GWP was 106 kg CO_{2eq}/kWh. The report also claims a potential 14% smaller GWP for NCM811 compared to NCM111, however, it is unclear if this can be directly applied to the estimated GWP for batteries produced using renewable energy.

The emissions from the NCM-battery production in China were studied by Sun et al. (2020). The data for the study was obtained from several leading Chinese manufacturers. The Data was collected between 2017 and 2019 from two battery manufacturers, the cathode material producer, and the battery recycling facilities. The study identified a GWP of 125 kg CO_{2eq}/kWh from NCM622-battery production. In addition, the study suggested battery recycling to reduce emissions by 31 kg CO_{2eq}/kWh. The total GWP of the battery was reported to be 94 kg CO_{2eq}/kWh when the benefits of battery recycling were considered.

4 MATERIALS AND METHODS

The vessel's GHG emissions are affected by several factors, energy efficiency being one of them. The vessel’s energy efficiency can be improved by using new technologies such as lithium-ion batteries, for example for peak shaving, reserve power and load optimisation (Ritari et al. 2021, 3). To gain further in-depth information on the impacts of lithium-ion batteries on the vessel's GHG emission a case study method was deemed suitable because it is considered an appropriate method to gain detailed insight into limited phenomena which are affected by several variables (Anttila n.d. Section 9.2.1: Tapaustutkimus).

The study was conducted on the RoPax ferry Aurora Botnia, operating between Vaasa, Finland and Umeå, Sweden. The vessel was delivered in 2021 and it has been operating on its current route since the delivery. The vessel's dimensions, power plant and propulsion information are shown in Table 1.

Table 1.The case study vessel's main dimensions and relevant power plant details

	Aurora Botnia
Length	Loa:150 m
Gross tonnage	24300 t
Main Engines	4 x 4400 kW, 31DF V8
Fuels	LNG, MGO, MDO
Propulsion	2 x 5800 kW Azipod Thruster
Battery	2 x 1100 kWh, NCM 811 Chemistry
Bow Thruster	2 x 1500 kW
Shore connection	2000 kW
Speed	20 kn

In this study, the combination of onboard measurement data and literature review was used for assessing the vessel's net GHG emission. The GHG emissions were compared with the functional unit GWP over a 100-year time horizon, in t CO_{2eq}. The systematic literature review was used to estimate the GHG emissions for the battery production, GWP_{totmfg}, while onboard measurement data collected during the vessel's operation was used to determine the GWP difference between combustion engine and hybrid operation, GWP_{totop}. (Emilsson & Dahllöf 2019, 9.) The GWP_{totop} was considered to represent the battery system's impact on the vessel's GHG emissions in operation. To further evaluate the net GWP, the GWP_{tomfg}, was compared with the GWP_{totop}. The result of this comparison was used to evaluate net GHG emissions and the possibility of compensating battery production emissions with the lower operational emissions. The result of the compensation is presented in the form of sailed trips, $N_{comptrip}$, which demonstrates the number of trips the vessel is required to sail, on its regular route, before the emissions caused by the battery production are compensated.

Figure 2 illustrates the process used for defining the vessel's GHG emissions in different parts of its life cycle and the final comparison of the GHG emissions to evaluate the battery system benefits in terms of GHG emissions.

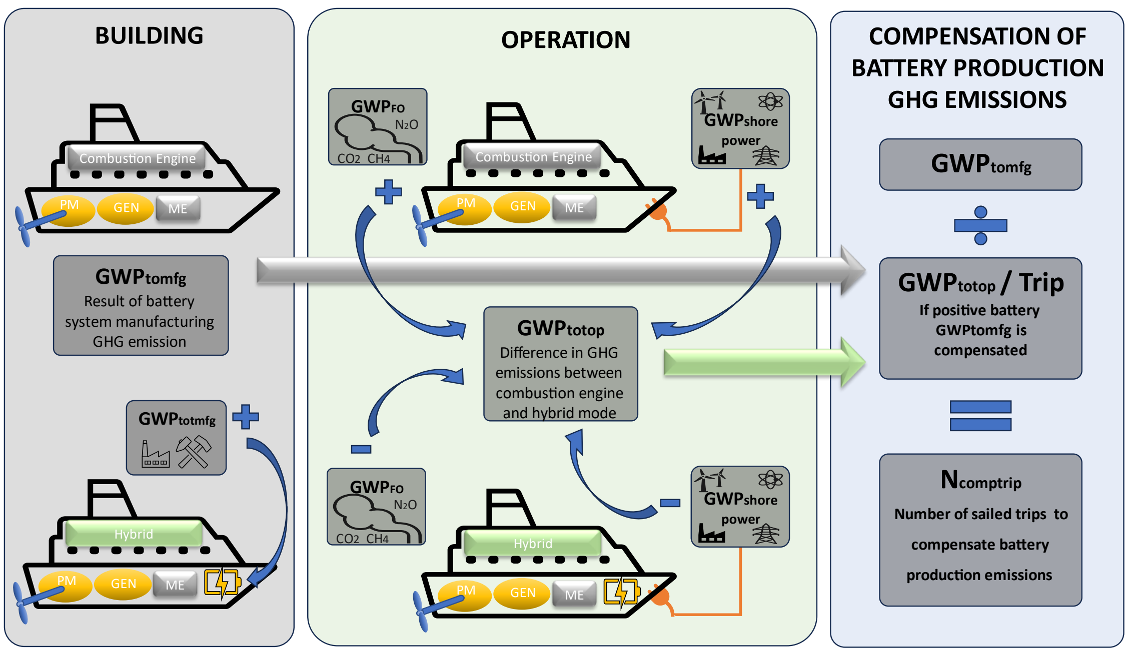

Figure 2. Process for estimating the battery system benefits in terms of the net GHG emissions. Additional emissions at the building stage, battery production emissions (GWP_{totmfg}), are compared with the GHG emissions difference between the combustion engines and hybrid operation (GWP_{totop}). If the emissions are smaller in the hybrid operations, then the operational emissions are considered to compensate for the emissions from the battery production.

4.1 Vessel's GHG emission in combustion engine and hybrid mode

The GWP_{totop} was assessed from real fuel consumption, which was defined through the combination of fuel quantity measurements in the fuel tanks and the bunkering data obtained from the bunker delivery notes. The fuel consumption data report was prepared by the vessel owner and it covered the period from September 2021 until September 2023. For the reported period, operation in combustion engine mode was between September 2021 and May 2022 and the rest of the period was operated in hybrid mode. The fuel consumption data was reported in monthly intervals separately for the used fuel type.

The fuel consumption data was analysed to select suitable data for comparison between combustion engines and hybrid operation. From the selected data, the fuel consumption difference between the operational modes, F_{saved}, was calculated.

The difference in fuel consumption between the combustion engine and hybrid mode was defined by equation 1.

$$F_{saved} = F_{batdisc} - F_{batcon} \quad (1)$$

where	F_{saved}	Difference in fuel consumption between combustion engine and hybrid mode	[t]
	$F_{batdisc}$	Fuel consumption in combustion engine mode	[t]
	F_{batcon}	Fuel consumption in hybrid mode	[t]

Based on the fuel consumption difference, F_{saved}, the GWP_{FO} was defined by equation 2.

$$GWP_{FO} = k_{fo} \cdot F_{saved} \quad (2)$$

where	GWP_{FO}	GWP resulting from fuel consumption difference between the combustion engine and hybrid mode	[t CO_2eq]
	k_{fo}	GWP factor for the fuel	[-]
	F_{saved}	Difference in fuel oil consumption between hybrid and combustion engine mode.	[t]

The GWP_{FO} is a result of the difference in GHG emissions between operational modes and it is influenced by the fuel consumption and the fuel type (Ritari et al. 2021, 9). During the reported period, the vessel was using three types of fuels, LNG, MGO and low-sulphur marine diesel oil (Marine 0.1). In the GWP_{FO} calculation, the main GHGs emitted by vessels were included for all three fuels. The assessed GHGs were carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) (Spoof-Tuomi & Niemi 2020, 41).

The GWP was calculated separately for each fuel because of the different GHG concentrations and the varied GWP of each GHG. These variables were addressed by emission factors indicating GHG content in the fuel and GWP_{100} factors addressing GHG's warming potential as shown in Table 2. These factors were used to determine fuel-specific GWP factors, k_{fo}, which were used for calculating GWP_{FO}. The GWP_{FO} represents the GHG emissions warming potential from the vessel's fuel combustion and therefore the corresponding TtW factors were used for conversions (Regulation 2023/1805, 90-91). The factors in Table 2 are extracted from EU directive 2018/2001 and EU regulation 2023/1805. The factors are in line with the IMO factors that are generally used in the shipping industry for reporting vessels' emissions, therefore, they were selected for the assessment in the present study.

Table 2 Fuels' emission and GWP factors as stated in EU legislation were used for calculating GWP.

	TtW Default emissions factors		
	Cf_{CO2} ($gCO_2/gFuel$)	Cf_{CH4} ($gCH_4/gFuel$)	Cf_{N2O} ($gN_2O/gFuel$)
MGO	3.206	0.00005	0.00018
LNG	2.75	0	0.00011
Marine 0,1	3.206	0.00005	0.00018
	GWP_{100} factors		
	CO_2	CH_4	N_2O
	1	25	298

In addition to combustion emissions, the use of LNG causes further challenges such as unburned methane slipping into the atmosphere. The phenomenon called methane slip is the result of incomplete combustion (Lehtoranta et al. 2023). When defining the GWP from LNG combustion, methane slip shall not be neglected because methane is a GHG and according to the latest assessment by the Intergovernmental Panel on Climate Change (IPCC) 29.8 times higher GWP than carbon dioxide (IPCC 2022, 1831). In the determination of GWP_{FO} for the LNG combustion, a methane slip of 3.1% of the mass of the used LNG was applied in the calculation. The used methane slip value is as stated in EU regulation for LNG Otto dual fuel medium speed engine (2023/1805, 113).

The equal methane slip of 3.1% was applied to all consumed LNG, even though parts of LNG are burned in boilers and methane slip is primarily associated with combustion engines (ABS 2022, 16). This is because LNG consumption was not measured separately for each machinery using LNG and therefore LNG consumption for boilers was not available for this study.

In the evaluation of the total GWP resulting from the vessel’s hybrid operation, the energy used to charge batteries shall be included in the assessment (Jeong et al. 2022, 20). When batteries are charged via shore supply, GHGs are emitted at the shore-based power plant and shall be added to the vessel’s combustion emission (Jeong et al. 2018, 124). When batteries are charged with the vessel’s power plant, GHG emissions are included in fuel combustion and can, therefore, be excluded from the calculation.

In this case, batteries were charged either via shore connection in Vaasa or Umeå as well as by the vessel's power plant during operation. For defining the GWP for both shore charging locations, Vaasa and Umeå, the actual (k_{elmix}) for charging electricity was used. The GWP for electricity used in Vaasa and Umeå was 0 g CO_2-eq / kWh (Vaasan Sähkö n.d.; Umeå Energi n.d.). The used electricity in Vaasa is wind power and in Umeå combination of renewable energy sources including hydro, solar and wind. For comparison, corresponding GHG intensity factors for electricity production in 2022 are for Sweden 0.007 and Finland 0.066 kg CO_{2eq}/kWh (European Environment Agency 2023).

The GWP resulting from shore power usage ($GWP_{shorepower}$) can be defined by equation 3.

$$GWP_{shorepower} = k_{elmix} \cdot E_{shorepower} \tag{3}$$

where

$GWP_{Shorepower}$	GWP of the electricity taken from shore supply	[kg CO_2eq]
k_{elmix}	GWP factor for the electricity mix used for the via shore supply.	[kg CO_2eq/kWh]
$E_{shorepower}$	Energy used via shore supply	[kWh]

The difference in the total GWP between combustion engine and hybrid mode GWP_{totop} can be defined by equation 4.

$$GWP_{totop} = GWP_{FO} - GWP_{shorepower} \tag{4}$$

where

GWP_{totop}	Difference in total GWP between combustion engine and hybrid mode	[kg CO_2eq]
GWP_{FO}	Difference in GWP resulting from different fuel consumption between combustion engine and hybrid mode.	[kg CO_2eq]
$GWP_{Shorepower}$	GWP of the energy used for batteries charging via shore supply.	[kg CO_2eq]

4.2 Lithium-ion battery production GHG emissions

GHGs are emitted at all stages in battery production, including material sourcing, manufacturing of active materials, cell production and battery assembly. In addition, the battery production supply chain is complex and often geographically widely spread. Thus, feasible methods to estimate production GHG emissions were through literature review or the use of LCA tools such as GaBi software, Ecoinvent database or GREET modelling. (Lai et al. 2022a; Winjobi et al. 2022; Kallitsis et al. 2020.) The vessel's battery chemistry NCM is a commonly used lithium-ion battery type and numerous studies examining the battery production GHG emissions are available. Therefore, a literature review was the preferred method to define battery production GHG emissions for the vessel's batteries.

In a lithium-ion battery, the battery capacity, the cathode material and the energy mix used in battery cell production have a considerable impact on the total battery production GHG emissions (Lai et al. 2022a, 1; Emilsson & Dahlöf 2019, 5; Zhao et al. 2019, 9, 17). Consequently, these factors were chosen as a basis for the inclusion criteria. More detailed selection criteria for the literature review are shown in Table 3.

Table 3. Lithium-ion battery production studies selection criteria for the literature review

	Inclusion criteria	Exclusion criteria
Publication year	2015-2023	before 2015
Research object and contents	1. GWP/GHG specified for the production of lithium-ion battery 2. Used functional unit GWP, kg CO_2 eq/kWh 3. NCM chemistry lithium-ion battery 4. Cathode material production location or GHG emissions from cathode production is defined	All four inclusion criteria are not fulfilled
Availability	Full-text access	Full-text access is not available

The latest studies were searched for using the Science Direct database and were filtered between the years 2015 and 2023. The used search term was "lithium-ion battery GWP OR lithium-ion battery GHG" entered in the database field "Title, abstract, or author-specific keywords"

Based on the battery system capacity and the GWP defined in the literature review, the total GWP_{totmfg} resulting from the battery system production can be defined by equation 5.

$$\mathrm{GWP_{totmfg}} = \mathrm{GWP_{kg\ CO2eq/kWh}} \cdot \mathrm{Bat_{cap}} \qquad (5)$$

where	GWP_{totmfg}	Total GWP emitted by battery production	[kg CO_2eq]
	$GWP_{kg\ CO2eq/kWh}$	GWP emitted by battery production per battery capacity in kWh	[kg CO_2eq/kWh]
	Bat_{cap}	Total battery system capacity	[kWh]

4.3 The net GHG emissions assessment

The vessel's battery system was installed to improve its operational efficiency and was not required for safety or operational reasons; consequently, it was considered an additional system, increasing building GHG emissions. Therefore, the battery system manufacturing GHG emissions shall be compensated by reduced GHG emissions in operation to justify the use of batteries from the global warming perspective.

If in similar conditions, the GHG emissions are lower in hybrid mode in comparison to combustion engine mode, the battery production emissions are compensated. The compensation time is affected by the fuel consumption difference between the operational modes. The compensation time for the battery production emissions shall be shorter than the battery's lifetime to be able to compensate for all battery production emissions during its lifetime. The battery's lifetime has been estimated by the manufacturer to be ten years.

Monthly sampling of fuel consumption and variations in monthly operation, between 80 to 107 sailed trips per month, restricted the compensation time estimate. Variations in operation and monthly sampling of fuel quantity prevented trip-specific or even daily fuel consumption assessment and led to trip-specific fuel consumption calculated from monthly consumption. Consequently, the GHG emissions between combustion engines and hybrid mode were compared monthly as an average per trip. The average per trip GHG emissions were determined by dividing the monthly GWP difference, GWP_{totop}, with the number of sailed trips, N_{cycle}. Equally, battery system production emissions and reduced operational emissions were compared relative to sailed trips. The result of this average comparison was an estimate of how many sailed trips in the hybrid mode are required to compensate for the battery production GHG emissions.

Estimating the number of sailed trips required in hybrid mode to compensate for battery production emissions was defined by equation 6.

$$N_{comptrip} = \mathrm{GWP_{totmfg}} / \left(\mathrm{GWP_{totop}} / \mathrm{N_{cycle}}\right) \qquad (6)$$

where	$N_{comptrip}$	Number of sailed trips to compensate battery production emissions	[-]
	GWP_{totop}	The difference in total GWP between combustion engine and hybrid mode	[kg CO_2eq]
	N_{cycle}	Number of monthly sailed trips A sailed trip is either, Vaasa – Umeå or Umeå – Vaasa	[-]
	GWP_{totmfg}	Total GWP resulting from battery production	[kg CO_2eq]

5 RESULTS

The results indicate that the battery system benefits are approximately 7% to 23% or 1.1 to 4.4 t CO_{2eq} lower operational GHG emissions in the battery hybrid mode in comparison to the combustion engine mode. Moreover, the results suggest that the battery production emissions can be compensated by the lower operational GHG emissions in 31 to 116 sailed trips, depending on the monthly GWP difference between the operational modes (Table 4).

Table 4. The difference in the emitted GHGs between the two operational modes is presented with the functional unit GWP, in addition, the battery production GHG emissions compensation time is estimated in the number of sailed trips on the vessel's regular route.

	Monthly GWP_{totop} ($t\ CO_{2eq}$) compared between the combustion engine and battery hybrid operation	
	GWP difference/trip (%)	**GWP difference/trip (t CO2eq)**
January	22.6	4.35
February	19.6	3.50
March	7.3	1.16
April	19.3	3.16
	$N_{comptrip}$	
January	31	
February	38	
March	116	
April	42	

The battery production GWP_{totmfg}, used in the $N_{comptrip}$ assessment, was estimated at 134 t CO_{2eq}. The estimate is based on the vessel's battery capacity of 2200 kWh and the GWP_{totmfg} of 61 kg CO_{2eq}/kWh for the NCM111 battery, defined by the literature review (Emilsson & Dahllöf 2019, 25). From the reviewed studies, the study conducted by Emilsson and Dahllöf (2019) was used to define the GWP_{totmfg} because the battery chemistry and the renewable energy used for the battery cell production corresponded with the vessel's batteries (Andersen 2023).

In further examination of the battery system's impact on the vessel's performance, the results propose about 4% to 23% smaller energy consumption and 27% to 31% fewer main engines' (ME) running hours per trip in hybrid mode compared to combustion engine operation. The running hours in hybrid mode are about 8.5 hours compared to 11.5 to 12 hours per trip in combustion engine mode (Figure 3).

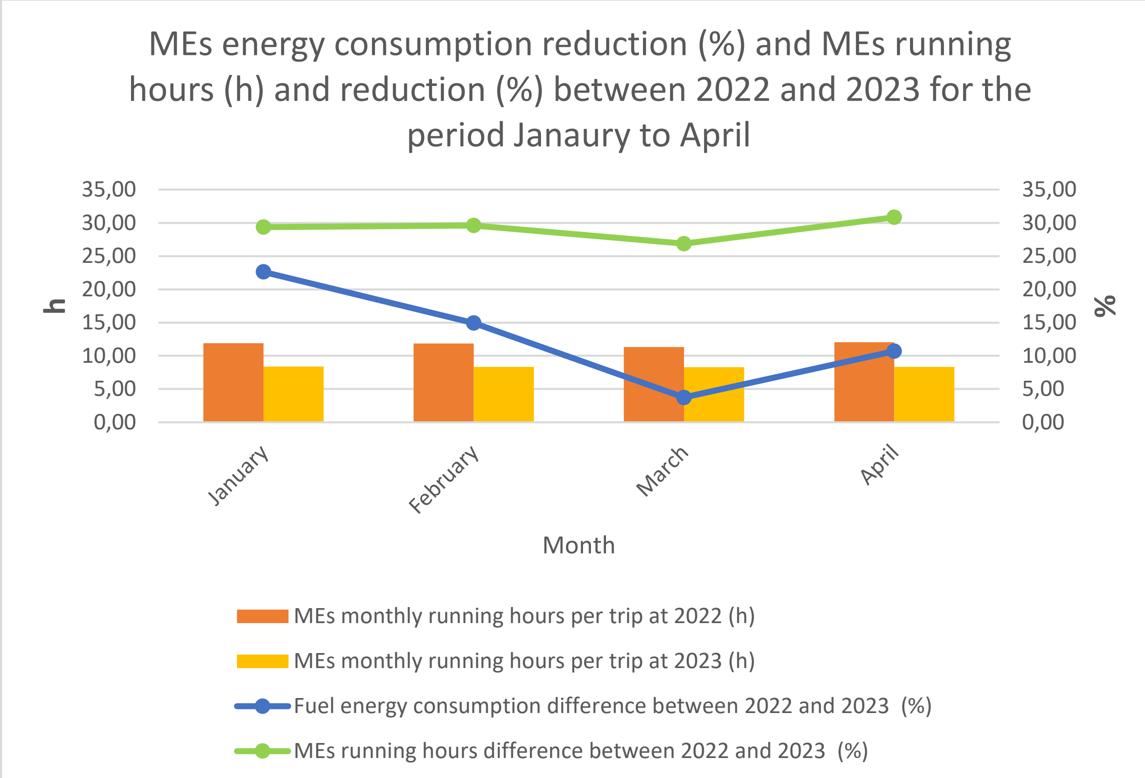

Figure 3. The MEs actual running hours as well as the energy consumption and the running hours difference between 2022 and 2023. The earlier period was operated in combustion engine and the latter in hybrid mode.

In the comparison of the corresponding months, the results suggest that the vessel's energy consumption and the MEs' running hours gradually decreased after the battery system commissioning and the start of the hybrid operation in May 2022 (Figure 4). The MEs' energy consumption was calculated from the measured fuel consumption using the energy content of 15 MWh/t for LNG and 12 MWh/t for Marine 0.1 and MGO.

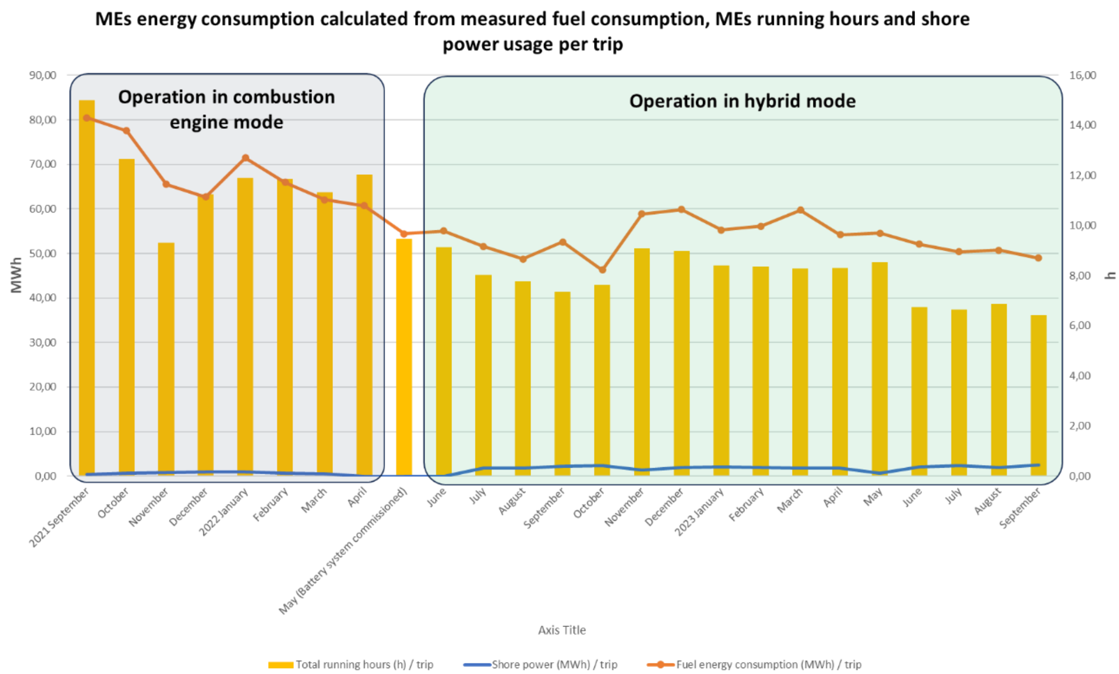

Figure 4. The vessel's energy consumption was calculated from measured fuel consumption and measured shore energy from the period September 2021 to September 2023.

In comparison with March 2022 and February 2023 with similar LNG consumption, the $N_{comptrip}$ and the GWP_{totop} were estimated at 85 trips and 1,58 t CO_{2eq}, respectively. The fuel consumption, as shown in Table 5, reveals a relatively high monthly fuel consumption difference between the fuels, however, the $N_{comptrip}$ and the GWP_{totop} are similar compared to the original assessment shown in Table 4.

Table 5. The reported fuel consumption in tons from the examined periods, January to April in 2022 and 2023. The months with similar LNG consumption are highlighted in green colour.

	The Fuel consumption (t) from combustion engine operation mode in 2022		
	LNG	Marine 0.1	MGO
January	27	220	241
February	19	231	185
March	170	157	101
April	28	330	100
	The Fuel consumption (t) from hybrid operation mode in 2023		
	LNG	Marine 0.1	MGO
January	23	403	7

February	160	177	35
March	285	136	0
April	294	76	0

The GWP_{totop} and $N_{comptrip}$ as shown in Table 6, calculated with updated information found from the latest studies, suggests shorter $N_{comptrip}$ but lower reduction GWP_{totop} compared with the results from the original analysis in Table 4. The updated data includes the GWP_{100} factors for CH_4 and N_2O, 29,8 and 273 respectively (IPCC 2022, 1831), methane slip of 2% (Spoof-Tuomi & Niemi 2020, 40) and battery production GWP of 52 kg CO_{2eq} / kWh, calculated from Emilsson and Dahllöf's report for NCM811 batteries.

Table 6. The difference in the emitted GHGs between the two operational modes is presented with the functional unit GWP, in addition, the battery production GHG emissions compensation time is estimated in the number of sailed trips on the vessel's regular route. The results are calculated with updated information found in the latest studies.

	Monthly GWP_{totop} compared between combustion engine and battery hybrid operation calculated with updated data	
	GWP difference/trip (%)	**GWP difference/trip (t CO2eq)**
January	22.6	4.28
February	21.3	3.72
March	8.6	1.29
April	22.3	3.59
	$N_{comptrip}$	
January	27	
February	31	
March	89	
April	32	

6 UNCERTAINTY ANALYSES

The error sources from both studies, the literature review and the onboard measurements, were analysed to ensure reliable outcomes from the final GWP_{totop} assessment and the $N_{comptrip}$ estimate.

The measured fuel consumption data prepared by the vessel owner included data from the operation in combustion engine and in hybrid mode. At first, the relevance and reliability of the fuel consumption data from combustion engine mode were assessed. Based on the initial assessment, the data from the first three months after delivery, September to October 2021, were rejected because of the large variation in energy consumption in comparison to the rest of the measurements (Figure 5). The variation was considered, together with the vessel owner, resulting from tuning, final commissioning and operators learning the systems of the new vessel (Teir and West 2023). In addition, data from December 2021 was excluded from further examination because of measurement errors. In December the MGO and the Marine 0.1 consumption was reported at zero tons which is not feasible. Even though the vessel was operated with the LNG, it requires 3–28% of the total fuel flow either the MGO or the Marine 0.1 as a pilot fuel (Lehtoranta et al. 2023, 3). The remaining fuel consumption data from the combustion engine operation, the period from January to April 2022, were accepted for the GWP_{totop} assessment.

Regarding the fuel consumption measurement accuracy, the fuel quantity measurement has been verified by the vessel crew by comparing the bunkering data to the onboard tank measurements. Moreover, since the final assessment is based on the comparison, the possible errors are present in both measurements and therefore the measurement error was neglected from the further analysis. The rejected and the accepted period from the reported energy consumption is shown in Figure 5.

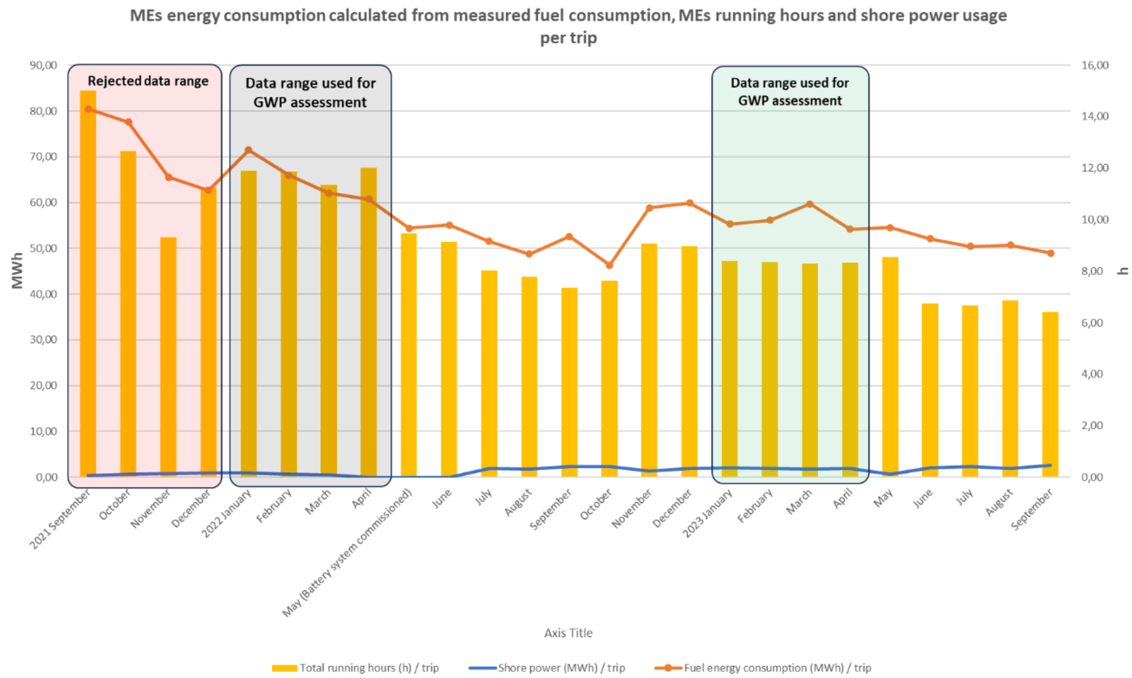

Figure 5. The vessel's energy consumption from the reported period shows high variation in the first three months after delivery. Periods rejected and accepted for the GWP assessment are highlighted.

During the ice season in the vessel's operating area, the ice conditions have an impact on the vessel's propulsion power demand, which is directly linked to the vessel's fuel consumption and GHG emissions (Majamäki et al. 2021, 2). The GHG emissions from the combustion engine operation were assessed during the ice season, therefore, the ice conditions for the same period during the following year, 2023, were compared with the ice conditions of 2022. According to the Finnish Meteorological Institute's (FMI) report, both ice seasons 2021/2022 and 2022/2023 were mild. The maximum ice extent was reported at 93000 km^2 on February 4th, 2022 and 81000 km^2 on March 12th, 2023, both indicating a mild ice season. Furthermore, the maximum fast ice thicknesses in the Bay of Bothnia during the ice season 2021/2022 varied between 30-85 cm and during 2022/2023 between 20-70 cm. However, the report from the ice season 2022/2023 stated that March 2023 was colder than average, especially in northern Finland, and the total amount of ice increased until mid-March. Different ice conditions between March 2022 and 2023 were evaluated, at least partly, to explain the lower GWP$_{totop}$ difference between March 2022 and 2023. In summary, based on the FMI reports and the analysis from the vessel owner, the ice conditions were considered comparable and the periods from January to April 2022 and 2023 were deemed suitable for the GWP assessment. (Finnish Meteorological Institute, 2023; Teir and West 2023; Finnish Meteorological Institute, 2022.)

To estimate the GHG emissions difference between the operational modes, GWP_{totop} was calculated separately for each fuel using a spread sheet. To ensure the accuracy of the calculation, the calculation results were verified by utilizing the spread sheet from the study conducted by Spoof-Tuomi and Niemi (2020). Moreover, an independent sample t-test was performed to compare the calculated GWP between the combustion engine and the hybrid operation. The t-test result revealed a significant difference in the GWP between the tested operational modes ($p = 0.006$), in other words, the use of batteries has an impact on the vessel’s GHG emissions.

The significant error sources were also assessed for the literature review of the battery production GWP. The error sources were associated with the studied battery chemistries and the GHG content of the energy used for the cell production (Lai et al. 2022, 2; Winjobi et al. 2022, 2; Emilsson & Dahllöf 2019; 27, 32). The NCM battery chemistry and the renewable energy in the cell production were used in Emilsson and Dahllöf's (2019, 25) battery production GWP assessment which corresponds with the vessel’s batteries. However, the concentration of the cathode active materials was different between the vessel’s NCM811 batteries and the assessed NCM111 batteries. The impact of different concentrations of the cathode active materials was considered in the GWP assessment with the updated information and the results of this assessment are shown in Table 6. Because of the corresponding battery chemistry and the GHG content of energy used for the battery cell production the results from the literature review were considered appropriate for estimating the GWP_{totmfg} for the vessel’s batteries.

7 DISCUSSION

The results from the case study indicated that the use of the lithium-ion battery hybrid system can reduce the vessel’s operational GHG emissions and that the battery production GHG emissions can be compensated by the reduced operational emissions. The estimated compensation time, presented in the number of sailed trips, was between 27 and 116, which corresponds to about 11 to 42 days based on the monthly average of sailed trips. The GHG compensation time compared to the estimated battery lifetime of 10 years is considered short, suggesting a significant reduction in net GHG emissions.

Furthermore, the results propose benefits including lower energy consumption and fewer ME running hours in hybrid mode operation. The benefits in hybrid mode are projected resulting from the battery system utilisation in hybrid mode. The functions that are proposed to explain the benefits are, for example, using the batteries for the reserve power, peak shaving, ME load optimisation, and charging the batteries with GHG emission-free electricity via shore connection. (Ritari et al. 2020, 10; Damian et al. 2022, 4-5)

The battery system’s functions and benefits can be explained by comparing the vessel’s operation in combustion engine and hybrid mode. When operating in combustion engine mode, regardless of the vessel’s power demand, a minimum of two MEs were running for safety reasons (Ritari et al. 2020, 10). To ensure safe operation in case of an ME shutdown, the second engine was running as a spinning reserve, even though the vessel’s power demand would not require it. In contrast, when operating in hybrid mode, the vessel was operated with one ME simultaneously with the battery system. In case of a ME shutdown, the battery system would provide power to maintain the vessel’s essential functions, while the standby engine would start and the vessel could return to normal operation.

In combustion engine mode when the ME’s load increased over the preset limit, 80 to 90% from the maximum continuous rating, the standby engine was started automatically regardless of duration or amount of additional required power. On the other hand, in hybrid mode, the power peaks were shaved with the batteries by supplying additional power instead of starting the standby engine.

In hybrid operation, when energy was available from the batteries, the ME load was optimised typically at 90% of the rated load and excess power was supplied from the batteries. On the contrary, in the combustion engine mode, two MEs were running and the MEs were operating in the less efficient load point, about 60% of the ME's maximum continuous rating. (Ritari et al. 2020, 7; Jafarzadeh & Schjølberg 2018, 501; Wärtsilä n.d.)

When the batteries were used for all three functions simultaneously with one ME, the battery capacity was not sufficient to cover the whole trip without recharging the batteries. The vessel's batteries were discharged from about 90 to 30% state of charge (SOC) while the battery capacity was 2.2 MWh, therefore, the energy used from the batteries was estimated at about 1.3 MWh per charge. Consequently, a typical trip in hybrid mode was divided into three phases operated with two different power plant configurations. Firstly, operating with the battery system and one ME, the power was supplied to the vessel's electrical distribution network simultaneously from both the ME and batteries. Secondly, the vessel was operated with two MEs, supplying power to the vessel's electrical distribution network including to the batteries. Thirdly, the final part of the trip was operated the same way as the first part, with one ME and the battery system in use. The different parts of the trip, with the energy flows from the shore connection, the batteries and the MEs, are illustrated in Figure 6.

Regarding GHG emissions, the biggest benefits gained from the battery system were evaluated during the first part of the trip when the GHG emission-free electrical energy, charged via the shore connection, is available from the batteries (Jeong et al. 2020, 20). In contrast, in the final part of the trip, the GHG emission reduction diminished because the batteries were charged in the middle part of the trip with the electricity produced by the vessel's MEs using fossil fuels. The projected advantage of charging the batteries with the vessel MEs is primarily linked to operating the MEs at a more efficient load range (Jeong et al. 2020, 20; Jafarzadeh & Schjølberg 2018, 501; Jeong et al. 2018, 124).

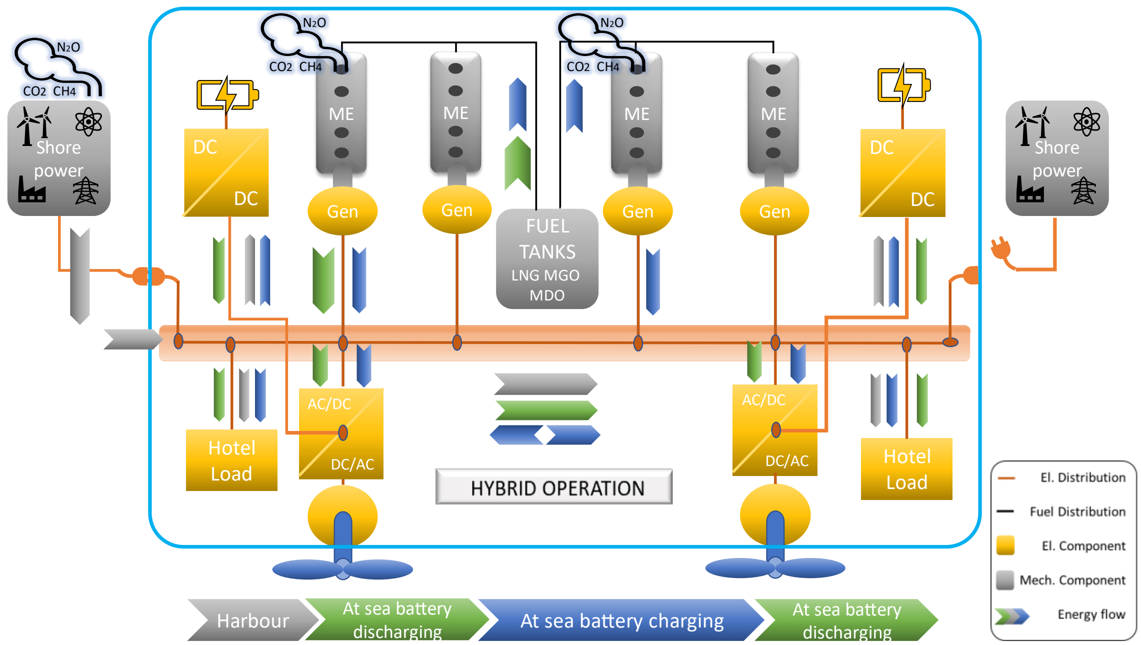

Figure 6. Port to port energy flows and the assessed GHG emission sources from the hybrid operation in different parts of the trip.

Concerning the GHG emissions assessment of the used fuels, LNG is often associated with environmentally friendly or clean fuels. LNG has benefits in terms of CO_2 and particle emissions, however, in the GWP_{totop} assessment benefits are reduced due to the methane slip (Lehtoranta et al. 2023, 2; Spoof-Tuomi & Niemi 2020, 2). Moreover, as described in Section 4.1, the LNG's benefits in the present study are further decreased since the methane slip of 3.1% was applied to all consumed LNG, regardless of the type of machinery where LNG was consumed. The LNG's impacts on the anticipated GWP reduction, between combustion engine and hybrid mode, was evaluated by comparing the periods with similar LNG consumption. The result suggested comparable battery production GHG emissions compensation time and the reduction in the GWP_{totop} as discovered in the first assessment. Therefore, LNG is estimated to have no significant impact on the calculated GWP_{totop} or $N_{comtrip}$, in comparison to other fuels.

To extend the fuel consumption data assessment outside of the already analysed period, January to April, the results show the importance of the optimal use of the battery hybrid system (Jafarzadeh & Schjølberg 2018). From June to September 2023 there has been a focus on the use of the vessel's battery system, which has further reduced the vessel's energy consumption and the ME's running hours (Teir & West 2023).

The GHG's impacts on climate change as well as the amount of emitted GHG from battery production and LNG combustion is continuously updated.
The results calculated with the updated information, $N_{comptrip}$ are not significantly different from the original analysis. The original estimate indicated 11 to 42 days of the battery production emissions compensation time compared to 10 to 32 days calculated with the updated information, which is considered insignificant in the battery's lifetime of 10 years. However, the differences discovered between the estimates are explained by the smaller GWP_{totmfg} and the methane's higher GWP_{100} factor used in the calculations with the updated information.

The present study supports evidence from the previous study by Ritari et al. (2019) who assessed the battery system's benefits through simulations and compared the estimated battery production emissions with the vessel's reduced operational CO_2 emissions. The battery production CO_2 emissions were reported to be 2.7% of the vessel's annual CO_2 emissions reduction potential achieved by hybrid system utilization. The calculated compensation time based on Ritari et al. (2019, 10) results is about 104 days, in comparison with the 11 to 42 days suggested in the present study. The difference in the compensation time is explained by the different battery production GWP. The battery production emissions used by Ritari et al. (2019, 10) were 200 kg CO_2/kWh compared with 61 kg CO_2/kWh used in the present study. Suppose the battery production GWP in the present study is applied to the calculation with the CO2 emission reduction estimated by Ritari et al. (2019, 10). In that case, the compensation time is about 32 days, which reflects with results in the present study.

The CO_2 emissions were compared between an LNG battery hybrid vessel and a similar diesel-mechanical vessel by Fan et al. (2021). The study suggested about 33% smaller CO_2 emissions for the battery hybrid compared with the diesel-mechanical vessel. The difference in the reported emissions between Fan et al. (2021) and the present study, is at least partly explained by the different GHG assessments. In the present study, the examined GHG gasses were CO_2, N_2O, and CH_4, compared with the only CO_2 assessment conducted by Fan et al. (2021). Considering only the CO_2 gives an advantage to LNG in comparison with diesel fuels, because methane slip resulting from the LNG combustion is excluded.

The GWP from the battery production discovered in the literature review was 61 kg CO_{2eq}/kWh for the NCM111 battery and 52 kg CO_{2eq}/kWh calculated for the NCM811 battery. The GWP resulting from battery production is affected by the production region because the GHG emissions from electricity production vary between the regions (Lai et al. 2022b, 12). The vessel's batteries were manufactured in Europe and Lai et al. (2022a, 12) reported the NCM811 battery production GWP in Europe at 53 kg CO_{2eq}/kWh, which is in reasonable agreement with the results in the present study.

8 CONCLUSION

The present study aimed to examine the battery hybrid system's impacts on the vessel's GHG emissions. Overall, this study strengthens the idea that the use of the battery hybrid system contributes to the vessel's net GHG reduction and supports reaching IMO's targets to reduce CO2 emissions/transport work by 40% by 2030 and 70% by 2050 from the 2008 level (IMO n.d.b.). The CO_2 emissions/transport work or economic implications were not addressed in the present study, and these could be assessed in future studies in connection with examining the benefits of increasing the battery capacity to cover the energy demand for the whole trip.

When assessing the lithium-ion battery system impacts, the result from the present study can be applied to similar vessels as a general guiding principle with consideration of at least, the vessel's operating profile, used fuels, battery capacity and GHG content of available shore energy.

REFERENCES

ABS. 2022. LNG as a marine fuel. Sustainability white paper. Available at: https://ww2.eagle.org/content/dam/eagle/advisories-and-debriefs/sustainability-whitepaper-lng-as-marine-fuel.pdf [Accessed 8 January 2024].

Andersen, R. 2023. Leclanché Corporate Presentation. Seminar presentation. 30 November 2023.

Anttila, P. n.d. Tutkimisen taito ja tiedon hankinta. Web page. Available at: https://metodix.fi/2014/05/17/anttila-pirkko-tutkimisen-taito-ja-tiedon-hankinta/#9.2%20Ilmi%C3%B6n%20kuvaus [Accessed 7 January 2024].

Damian, S.E., Wong, L.A., Shareef, H., Ramachandaramurthy, V.K., Chan, C.K., Moh, T.S.Y. & Tiong, M.C. 2022. Review on the challenges of hybrid propulsion system in marine transport system. Journal of Energy Storage, 56. Scientific journal. Available at: https://doi.org/10.1016/j.est.2022.105983 [Accessed 30 December 2023].

Directive (EU) 2018/2001.

DNV. n.d.a. CII – carbon intensity indicator. Web page. Available at: https://www.dnv.com/maritime/insights/topics/CII-carbon-intensity-indicator/index.html [Accessed 30 December 2023].

DNV. n.d.b, EEXI – energy efficiency existing ship index. Web page. Available at: https://www.dnv.com/maritime/insights/topics/eexi/index.html [Accessed 30 December 2023].

DNV. n.d.c. Energy efficient design index regulations. Web page. Available at: https://www.dnv.com/maritime/hub/decarbonize-shipping/key-drivers/regulations/imo-regulations/eexi.html [Accessed 30 December 2023].

Emilsson, E. & Dahllöf, L. 2019. Lithium-ion vehicle battery production, status 2019 on energy use, CO2 emissions, use of metals, products environmental footprint, and recycling. Technical Report. Available at: https://doi.org/10.13140/RG.2.2.29735.70562 [Accessed 30 December 2023].

European Environment Agency (EEA). 2023. Greenhouse gas emission intensity of electricity generation in Europe. Web page. Available at: https://www.eea.europa.eu/en/analysis/indicators/greenhouse-gas-emission-intensity-of-1?activeAccordion=ecdb3bcf-bbe9-4978-b5cf-0b136399d9f8 [Accessed 11 January 2024].

Fan, A., Wang, J., He, Y., Percic, M., Vladimir, N. & Yang, L. 2021. Decarbonising inland ship power system: Alternative solution and assessment method. *Energy,* 226. Scientific journal. Available at: https://doi.org/10.1016/j.energy.2021.120266 [Accessed 29 December 2023].

Finnish Meteorological Institute. 2022. The 2021/2022 ice season was mild, but long. Description. Available at: https://en.ilmatieteenlaitos.fi/ice-winter-2021-2022 [Accessed 29 January 2024].

Finnish Meteorological Institute. 2023. The ice season of 2022/2023 was mild. Description. Available at: https://en.ilmatieteenlaitos.fi/ice-winter-2022-2023 [Accessed 29 January 2024].

Inal, O. B., Charpentier, J-F. & Deniz, C. 2021. Hybrid power and propulsion systems for ships: Current status and future challenges. *Renewable and Sustainable Energy Reviews*, 156. Scientific journal. Available at: https://doi.org/10.1016/j.rser.2021.111965 [Accessed 29 December 2023].

IMO. 2023. Revised GHG reduction strategy for global shipping adopted. Web page. Available at: https://www.imo.org/en/MediaCentre/PressBriefings/pages/Revised-GHG-reduction-strategy-for-global-shipping-adopted-.aspx [Accessed 15 March 2024].

IMO. n.d.a. Improving the energy efficiency of ships. Web page. Available at: https://www.imo.org/en/OurWork/Environment/Pages/Improving%20the%20energy%20efficiency%20of%20ships.aspx. [Accessed 31 December 2023].

IMO. n.d.b. Initial IMO GHG strategy. Web page. Available at: https://www.imo.org/en/MediaCentre/HotTopics/Pages/Reducing-greenhouse-gas-emissions-from-ships.aspx [Accessed 31 December 2023].

IPCC, 2022. Al Khourdajie, A., R. van Diemen, W.F. Lamb, M. Pathak, A. Reisinger, S. de la Rue du Can, J. Skea, R. Slade, S. Some, L. Steg (eds). Annex II: Definitions, Units and Conventions. P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.) In IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Assessment report. Available at: https://doi.org/10.1017/9781009157926.021 [Accessed 9 January 2024].

Jafarzadeh, S. & Schjølberg, I. 2018. Operational profiles of ships in Norwegian waters: An activity based approach to assess the benefits of hybrid and electric propulsion. *Transportation Research Part D65*, 500 – 523. Scientific journal. Available at: https://doi.org/10.1016/j.trd.2018.09.021 [Accessed 28 December 2023].

Jeong, B., Wang, H., Oguz, E. & Zhou, P. 2018. An effective framework for life cycle and cost assessment for marine vessels aiming to select optimal propulsion systems. *Journal of Cleaner Production*, 187, 111–130. Scientific journal. Available at: https://doi.org/10.1016/j.jclepro.2018.03.184 [Accessed 27 December 2023].

Jeong, B., Jang H., Lee, W., Park C., Ha S., Kim, D. K. & Cho N-K. 2022. Is electric battery propulsion for ships truly the lifecycle energy solution for marine environmental protection as a whole? *Journal of Cleaner Production*, 355. Scientific journal. Available at: https://doi.org/10.1016/j.jclepro.2022.131756 [Accessed 8 January 2024].

Kallitsis, E., Korre, A., Kelsall G., Kupfersberger M. & Nie, Z. 2020. Environmental life cycle assessment of the production in China of lithium-ion batteries with nickel-cobalt-manganese cathodes utilising novel electrode chemistries. *Journal of Cleaner Production*, 254. Scientific journal. Available at: https://doi.org/10.1016/j.jclepro.2020.120067 [Accessed 8 January 2024].

Lai, X., Chen, Q., Tang, X., Zhou, Y., Gao, F., Guo, Y., Bhagat, R. & Zheng, Y. 2022a. Critical review of life cycle assessment of lithium-ion batteries for electric vehicles: A lifespan perspective. *eTransportation,* 12. Scientific journal. Available at: https://doi.org/10.1016/j.etran.2022.100169 [Accessed 6 February 2024].

Lai, X., Gu, H., Chen, Q., Tang, X., Zhou, Y., Gao, F., Han, X., Guo, Y., Bhagat, R. & Zheng, Y. 2022b. Investigating greenhouse gas emissions and environmental impacts from the production of lithium-ion batteries in China. *Journal of Cleaner Production*, 372. Scientific journal. Available at: https://doi.org/10.1016/j.jclepro.2022.133756 [Accessed 24 December 2023].

Lehtoranta, K., Kuittinen, N., Vesala, H. & Koponen, P. 2023. Methane Emissions from a State-of-the-Art LNG-Powered Vessel. *Atmosphere*, 14, 825. Available at: https://doi.org/10.3390/atmos14050825 [Accessed 28 January 2024].

Ling-Chin, J. & Roskilly, A.P. 2016. Investigating the implications of a new-build hybrid power system for Roll-on/Roll-off cargo ships from a sustainability perspective – A life cycle assessment case study. *Applied Energy*, 181, 416–434. Scientific journal. Available at: http://dx.doi.org/10.1016/j.apenergy.2016.08.065 [Accessed 24 December 2023].

Majamäki, E., Jalkanen, J-P. & Johansson, L. 2021. Effect of sea ice on fuel consumption and carbon intensity of shipping in the Baltic Sea area in 2009 – 2019. Traficom Publications 32/2021. Helsinki: Finnish Transport and Communications Agency Traficom.

Ovrum, E., Longva, T., Hammer, L. S., Rivedal, N. H., Endresen, Ø., Helgesen, H., Sekkesæter, Ø., Leisner, M., Hammer, K., Drösemeyer, H., Aalbu, K., Walenkiewicz, J., Schäfer, J. & Eide, M. S. 2022. MARITIME FORECAST TO 2050. Report. Available at: https://www.dnv.com/maritime/publications/maritime-forecast-2022/download-the-report.html [Accessed 24 December 2023].

Regulation (EU) 2023/1805.

Ritari, A., Huotari, J., Halme, J. & Tammi, K. 2019. Hybrid electric topology for short sea ships with high auxiliary power availability requirement. *Energy,* 190. Scientific journal. Available at: https://doi.org/10.1016/j.energy.2019.116359 [Accessed 24 December 2023].

Ritari, A., Spoof-Tuomi, K., Huotari, J., Niemi, S. & Tammi, K. 2021. Emission Abatement Technology Selection, Routing and Speed Optimization of Hybrid Ships. *Journal of Marine Science and Engineering*, 9, 944. Scientific journal. Available at: https://doi.org/10.3390/jmse9090944 [Accessed 9 January 2024].

Spoof-Tuomi, K. & Niemi, S. 2020. Environmental and Economic Evaluation of Fuel Choices for Short Sea Shipping. *Clean Technologies, 2*, 34-52. Scientific journal. Available at: https://doi.org/10.3390/cleantechnol2010004 [Accessed 10 January 2024].

Sun, X., Luo, X., Zhang, Z., Meng, F. & Yang, J. 2020. Life cycle assessment of lithium nickel cobalt manganese oxide (NCM) batteries for electric passenger vehicles. *Journal of Cleaner Production*, 273. Scientific journal. Available at: https://doi.org/10.1016/j.jclepro.2020.123006 [Accessed 25 December 2023].

Teir, J. & West, R. 2023. Technical Director & Technical Manager. Meeting. 9 November 2023. NLC Ferry Ab Oy.

Vaasan Sähkö. n.d. Wind power is good for the environment. Web page. Available at: https://www.vaasansahko.fi/en/electricity-contract-for-homes/wind-power-is-good-for-the-environment/ [Accessed 11 January 2024].

Winjobi, O., Jarod, C., Kelly, J.C. & Dai, Q. 2022. Life-cycle analysis, by global region, of automotive lithium-ion nickel manganese cobalt batteries of varying nickel content. *Sustainable Materials and Technologies,* 32. Scientific journal. Available at: https://doi.org/10.1016/j.susmat.2022.e00415 [Accessed 25 December 2023].

Yu, W., Zhoub & P. Wangb, H. 2018. Evaluation of the energy efficiency and emissions reduction of a short-route hybrid sightseeing ship. *Ocean Engineering,* 162, 34–42. Scientific journal. Available at: https://doi.org/10.1016/j.oceaneng.2018.05.016 [Accessed 25 December 2023].

Zhao, E., Walker, P. D., Surawski, N. C. & Bennett, N. S. 2021. Assessing the life cycle cumulative energy demand and greenhouse gas emissions of lithium-ion batteries. *Journal of Energy Storage*, 43. Scientific journal. Available at: https://doi.org/10.1016/j.est.2021.103193 [Accessed 18 December 2023].

Umeå Energi. n.d. Miljöpåverkan i våra produkter. Web page. Available at: https://www.umeaenergi.se/om-oss/hallbarhet/ursprungsmarkning-och-utslapp#energik%C3%A4llor_f%C3%B6r_el [Accessed 11 January 2024].

Wärtsilä. n.d. Online engine configurator. Web page. Available at: https://www.wartsila.com/marine/engine-configurator [Accessed 31 January 2024].