Developing zero emission small ships

Figure 1 ESNA ZES SES CTV © ESNA AS - all rights reserved

There is a green revolution in ship technology going on these days. We are currently witnessing a wave of zero emission propulsion ideas entering the market like battery powered car ferries for short routes, power shaving batteries onboard offshore hybrid service vessels and cruise liners that can enter protected fjords purely on batteries. Such efforts are fine for the local environment, but will hardly contribute significantly to bring down the CO_2 emission of the global shipping fleet by 50% within 2050 as is the goal of the International Maritime Organisation (IMO).

There is a strong push from the public as well as governments, industries and NGOs in support of the UN's sustainable goals to counter the threats to our planet caused by the global warming.

This development is just in the beginning and is strongly supported by class societies and maritime administrations such as DNV GL, Lloyds Register, Bureau Veritas, Korean Register, Royal Society etc. Serious discussions and development work are taking place pointing to the opportunity of changing the future fuel from fossil fuels, typically characterized as hydrocarbon chemical compounds of C_yH_x, to hydrogen rich compounds without carbon.

Two viable solutions are either to replace the carbon (C), with nitrogen (N) to form NH_3, ammonia, or to get rid of the carbon, i.e. pure hydrogen (H_2). The production of both these fuels can be based on electrolysis processes powered by renewable energy. Alternative solutions based on fossil fuels in combination with carbon capture and storage (CCS) seems less promising now than a few years back.

'What we are seeing today is opening a whole new landscape of opportunities,' says Nere Skomedal, Naval Architect and co-founder of ESNA.

ESNA has worked towards lower emission technologies since the company was founded in 2015. In 2019 they were awarded funding from Regional Research Council Agder and joined forces with NORCE and Prototech to develop 'zero emission small ships' (ZES Ships).

Hydrogen is a commonly used industrial gas. Today it is mainly made from steam reforming of natural gas. But with pioneering companies like NEL Hydrogen, electrolysis production and filling stations are rapidly being made available in cities for cars, buses and trucks. Port based and even offshore filling stations, providing green hydrogen, are on the horizon.

A challenge with hydrogen is transportation. Either it must be stored and transported as a liquid at -253˚C at one bar pressure, or as compressed gas at high pressures (250 - 700 bar). The low temperature of liquid hydrogen, or high pressure of compressed hydrogen, in combination with the low density of hydrogen, means that the tanks used for storage and transport are expensive, heavy and large for long haul shipping. Such tanks reduce both the space and weight available for cargo significantly.

We therefore believe hydrogen is best utilized in a setup where the hydrogen can be produced locally. This can be an excellent setup for small ships in short haul daily traffic in and out of the same port. This solves the transportation challenges, but hydrogen is also highly explosive and requires strict adherence to safety measures during design and operations.

Since storage and transport of ammonia in large volumes is well known, ammonia seems to be the best option for large ships. Ammonia is one of the most common chemicals, almost 200 million tons are produced every year and is transported by trucks, railways, pipelines and ships all over the world. It is either shipped as liquid ammonia at -33˚C at atmospheric pressure or as compressed gas at 8.5 bar at 20˚C. It can be stored and transported with the same tanks and equipment as LPG (propane).

Ammonia is toxic and must be handled with care. It is the most important element in fertilizers and is also used in most industrial refrigeration systems, both on land and onboard ships, such as fishing vessels and carriers with refrigeration possibilities. This means that many ships today already have elements of onboard filling and storage system for a carbon free fuel, along with access to a land based fueling and distribution system, which can be scaled up relatively easily and distributed to more ports.

Ammonia burns slowly and is for internal combustion engines (ICE) therefore best suited for slow speed engines. Both MAN and Wärtsilä are modifying large two stroke diesel engine designs to be fuelled by ammonia. For smaller ships a higher efficiency is seen when ammonia or hydrogen are used in fuel cells. Fuel cells makes electrochemical use of ammonia and hydrogen rather than combustion.

Proton-exchange-membrane (PEM) fuel cells require very pure hydrogen made from electrolysis. Solid-oxide fuel cells (SOFC) are more robust and can be fuelled by many different alternative fuels, including ammonia.

If ammonia or hydrogen is chosen as fuel, the energy will be transformed into electrical energy to supply electrical drivetrains and the hotel load. 'Fuel cells onboard small ships will be installed in combination with batteries. Fuel cells are costly pr power units, but excellent for providing a steady state power demand. Batteries are costly and heavy pr energy units, but excellent at handling rapid changes in power demand,' says Sebastian Farmen, electrical engineer at ESNA AS.

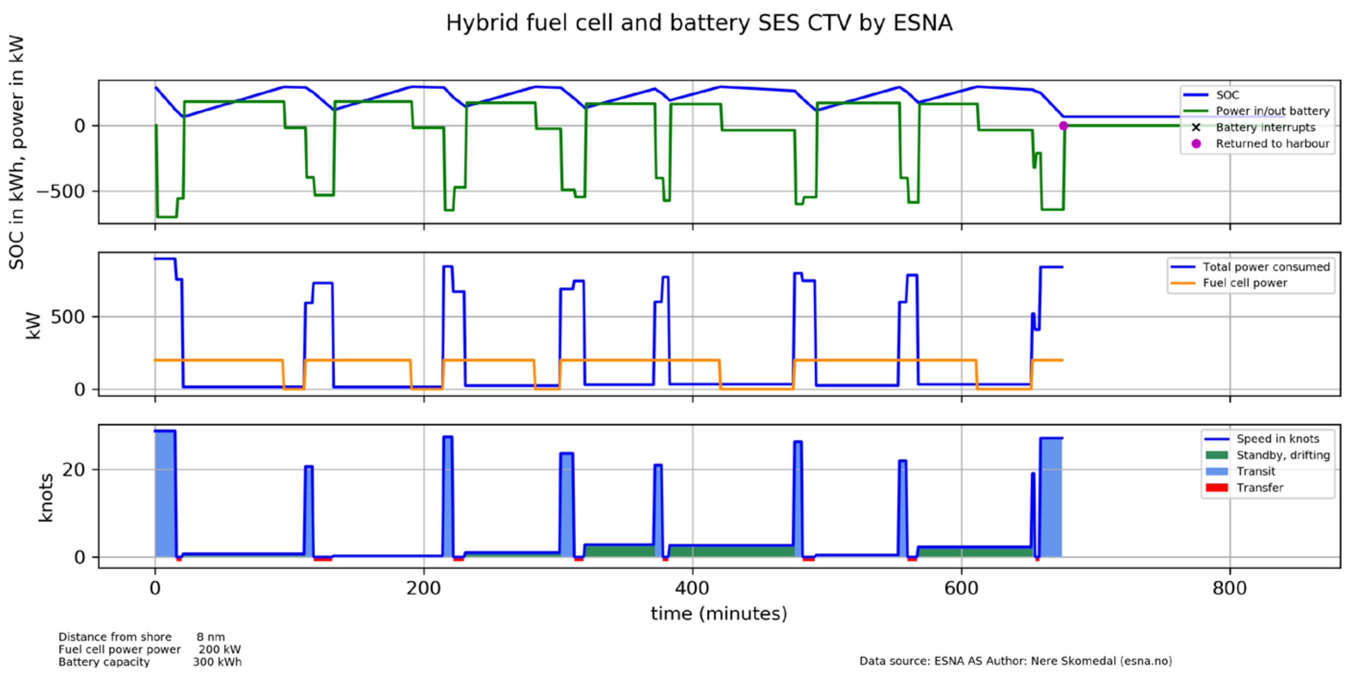
One challenge is that there are no design rules for ammonia or hydrogen fuelled ships. The IMO IGF code for alternative fuels can be used to provide an equivalent safety level, as for the use of diesel fuels. National maritime administrations and ship class societies have indicated interest in completing the development of such rules for hydrogen and ammonia. Taking the alternative fuels route through a classification society is a cumbersome, but a possible process. The faster clear rules for ammonia and hydrogen is implemented, the faster mass implementation of ammonia and hydrogen fuelled ships can take place.

Due to the increased weight of energy storage and electric machinery, when compared to diesel fuel and ICE, zero emission small ships will only be possible, if the ship is designed with extremely low propulsion resistance and uncompromised low light ship weight. Only then can a zero emission drivetrain, with sufficient energy and power to handle the tasks during vessel operations, be possible.

This is especially a challenge for high speed vessels such as passenger vessels. As these vessels need to be able to sustain a high power level for a long time, the weight and cost of zero emission solutions are very difficult to overcome. However, when considering the daily load profile and combined use of hydrogen and batteries, ESNA has found an economical and technical feasible solution for offshore wind Crew Transfer Vessels (CTV). The key is to minimize power and energy requirements.

For this ESNA has developed a simulation tool which can simulate thousands of wind farm operation day trips. This is used to optimise vessel size vs. battery, fuel storage and fuel cell capacity. Parameters like speed loss, transit speeds, transfer time, transfer push force, standby time and weather conditions are represented by statistical distributions and randomly chosen for each operation. The program is an in-house software tool utilizing Monte Carlo simulation. It can easily be adapted to various vessel sizes, types and operational profiles.

Such a tool is necessary to select optimum main dimensions, speed and resistance performance and not at least the maximum power need and total voyage energy consumption. We cannot oversize anything, since it would not only affect the price, it would also affect the light ship weight and

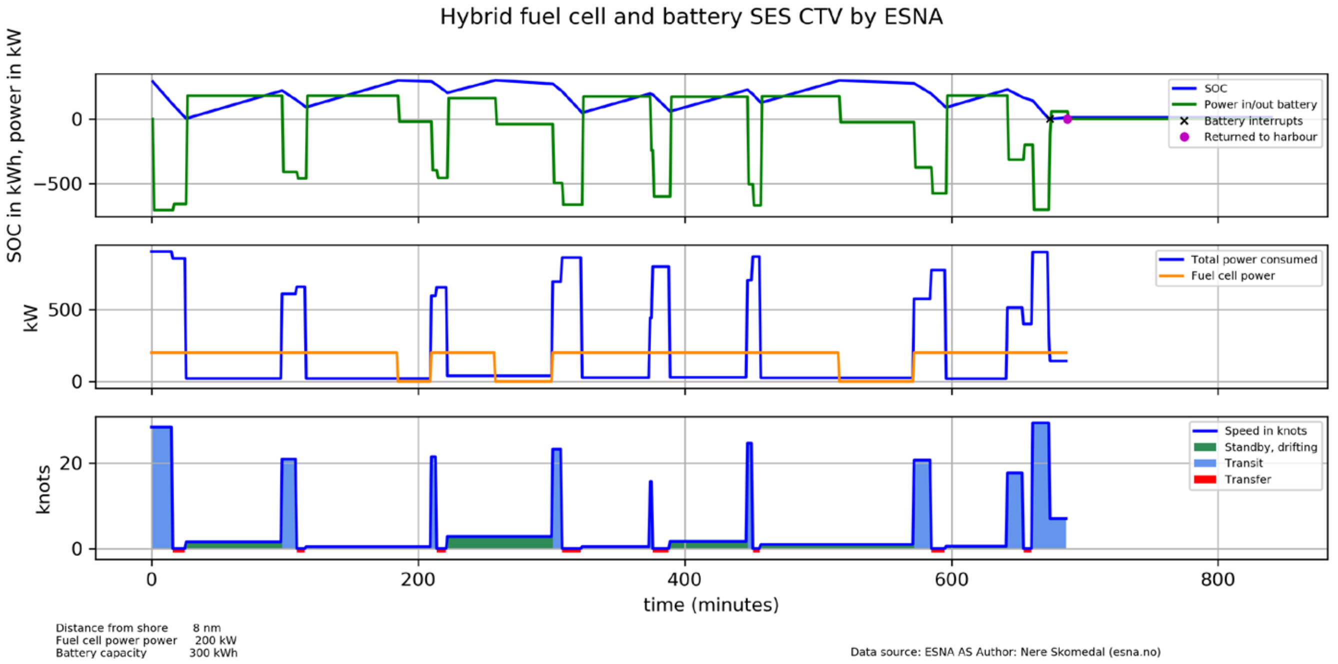


Trip duration= 676 minutes = 11:16 h
Sum energy consumed= 1968.1 kWh
Max power= 900.9 kW
Minimum power= 15.2 kW
Average power usage= 174.7 kW
Max speed= 28.7 kts
Average speed= 4.0 kts
Sailed distance = 44.76 nm with 8 transfers
Energy produced by FC= 1736.7 kWh, i.e. approx 104 kg of H2
Specific fuel cons 60.1 g/kWh
Battery SOC at start 300.0 kWh
Battery SOC at finish 68.6 kWh
Minimum battery SOC= 66.6 kWh
Number of interrupts= 0 at []

Mode distribution

TF 11.2 pct Transit, using Fuel cells and batteries
TRF 9.5 pct Transfer, using Fuel cells and batteries
STC 56.4 pct Standby, using Fuel cells and charging batteries
STB 22.9 pct Standby, powered by batteries of 676 minutes

Figure 2 One day wind farm operation simulated by ESNA



Trip duration= 687 minutes = 11:27 h
Sum energy consumed= 2164.1 kWh
Max power= 901.8 kW
Minimum power= 19.1 kW
Average power usage= 189.0 kW
Max speed= 29.4 kts
Average speed= 3.8 kts
Sailed distance 44.02 nm with 8 transfers
Energy produced by FC= 1876.7 kWh, i.e. approx 113 kg of H2
Specific fuel cons 60.1 g/kWh
Battery SOC at start 300.0 kWh
Battery SOC at finish 12.6 kWh
Minimum battery SOC= 0.0 kWh
Number of interrupts= 1 at [674]

Mode distribution

TF 11.9 pct Transit, using Fuel cells and batteries
TRF 11.2 pct Transfer, using Fuel cells and batteries
STC 56.9 pct Standby, using Fuel cells and charging batteries
STB 18.0 pct Standby, powered by batteries
TC 1.9 pct Transit, using Fuel cells and charging batteries of 687 minutes

Figure 3 One day wind farm operation simulated by ESNA

100% (10000 of 10000) |##################|
Elapsed Time: 0:04:02 Time: 0:04:02

Number of simulations 10000
Distance from shore 8 nm
Fuel cell power 200 kW
Battery capacity 300 kWh
Battery max power 900 kW

Variable	unit	mean	st.dev	min	max
Trip duration	min	726	33	663	823
Trip energy	kWh	2197	188	1573	2877
Trip fuel consump.	kg H2	116	11	79	156
Trip max power	kWh	914	28	789	965
Trip max speed	kts	28.2	0.7	24.9	29.3
Trip sailed dist	nm	47.9	4.9	30.2	66.9
Trip FC produced	kWh	1935	186	1313	2597
Trip SOC at fin.	kWh	37.8	25.2	0.0	115.8
Trip transfers		8.1	0.7	6	11
Trip interrupts		0.47	0.72	0	7
On battery standby	%	20.1	7.1	0.0	44.0

Figure 4 The result of 10000 simulations

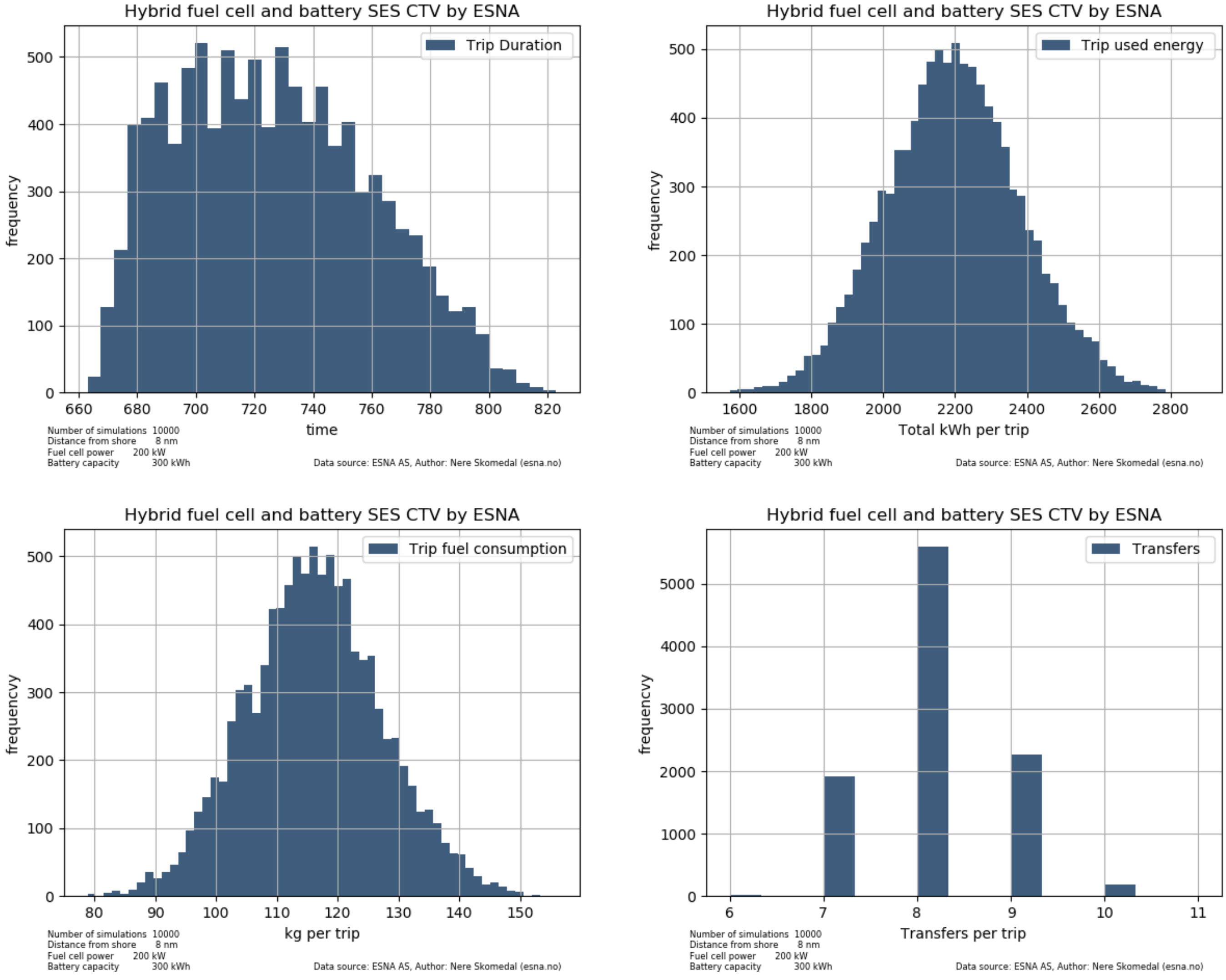


Figure 5. Frequency plot of trip duration, total energy usage, kg H2 used in the fuel cell and number of transfers completed.

performance. But we cannot undersize either. 'Our simulations tool and experience help us perfect-size,' says Nere Skomedal.

In early 2020 ESNA introduced the hydrogen ZES SES CTV (Figure 1), built entirely on available, and tested systems. With a length of 18 m, the CTV can carry 12 offshore technicians, reach top transit speed of 30 knots and access wind turbines in up to 1.8m significant wave height. She is well suited for whole day operation serving wind farms or other offshore installations situated 5-20 nautical miles offshore.

Two simulations are shown (Figures 2, 3) for the ZES SES CTV operating in a wind farm 8 nautical miles from the port. The fuel cell capacity is 200 kW and effective battery capacity is 300 kWh with a battery which can provide 3C of discharge power, i.e. 900 kW. Total energy is then 2900 kWh for a 13-hour day.

The vessel is running on fuel cells with constant load, most of the power variations are supplied by the batteries. The fuel cells are only switched off when the batteries are fully charged and thereafter remain switched off, as long as the total power needed is less than the maximum battery discharge power and there is still energy left in the batteries. If that is not the case, the fuel cells are switched on and battery charge/discharge power adjusted accordingly.

As seen, the second simulation (Figure 3) experienced a battery interrupt at 674 minutes, marked with a black cross shaped marker. It took place under the homebound transit, because the battery went to empty and the speed had to be reduced, so the fuel cell could supply sufficient energy for the last part of the journey to port. In a real case scenario, the skipper would probably had slowed down before the battery empty warning alarm was given, but the results for the total duration and energy consumption would not have been very much different from this simulation.

In Figure 4 the statistical results of 10000 simulations are shown. As seen an average of 116 kg hydrogen is consumed, the mean daily sailed distance is 47.9 nautical miles. In average 8.1 turbine transfers are carried out and only during 47% percent of the days did the captain have to adjust the operation power usage due to low battery state of charge. Frequency histogram over trip duration in hours, used energy in kWh, hydrogen consumption in kg and number of transfers performed are shown in Figure 5.

'There is no limit to how good you can get in pursuit of perfection' comments Trygve Espeland, Naval Architect and co-founder of ESNA. 'These examples show that a zero emission small ship, based on a combination of hydrogen PEM fuel cells and Li-ion batteries, is very suitable for CTV operations'.

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