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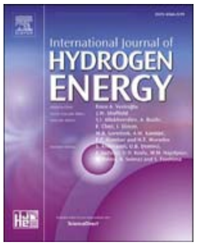

# Techno-economic modeling of zero-emission marine transport with hydrogen fuel and superconducting propulsion system: Case study of a passenger ferry

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## HIGHLIGHTS

- Superconducting ferry consumes the least amount of hydrogen.
- Hydrogen in gas form is more appropriate for short distances and lighter ferries.
- The high energy demand for compressed hydrogen gas ferries restricts their usage.

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## ABSTRACT

This paper proposes a techno-economic model for a high-speed hydrogen ferry. The model can describe the system properties i.e. energy demand, weight, and daily operating expenses of the ferry. A novel aspect is the consideration of superconductivity as a measure for cost saving in the setting where liquid hydrogen ($LH_2$) can be both coolant and fuel. We survey different scenarios for a high-speed ferry that could carry 300 passengers. The results show that, despite higher energy demand, compressed hydrogen gas is more economical compared with $LH_2$ for now; however, constructing large-scale hydrogen liquefaction plants make it competitive in the future. Moreover, compressed hydrogen gas is restricted to a shorter distance while $LH_2$ makes longer distances possible, and whenever $LH_2$ is accessible, using a superconducting propulsion system has a beneficial impact on both energy and cost savings. These effects strengthen if the operational time or the weight of the ferry increases.

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## Introduction

Greenhouse gas (GHG) emissions are an important concern for the world, and a special attention has given to the maritime industry, which is responsible for 7–8% of the GHGs [1]. The amount of carbon emission could increase 50–250% by 2050 if the trend is not changed. Nearly 40% of the population in the world resides near a coastline, and 2.1 billion passengers use maritime facilities for transportation in a year [2], while high-speed ferries have the highest carbon emission per passenger-kilometer in this sector [3]. Therefore, both carbon reduction and energy efficiency influence marine technology. Norway is a front-runner in the race to decarbonize transport. The Norwegian Government recently launched its Climate Plan 2021–2030, which aims to halve domestic maritime transport emissions by 2030, relative to the 2005 level. Among its measures are emission standards for maritime transports under the jurisdiction of the public sector. Of particular relevance to this paper, conventional and high-speed ferry services provided by regional governments will face zero emission requirements by 2023 and 2025, respectively [4]. Diesel provides 95% of marine fuels; however, batteries and green hydrogen including both compressed hydrogen ($CH_2$) and liquid hydrogen ($LH_2$) could provide zero-emission power to replace diesel [2]. Batteries seem appropriate for small ferries and short trips, while $LH_2$ is considered the best option for longer trips with larger vessels [5,6].

The safety risk of a hydrogen high-speed ferry has already been assessed: It is acceptable and similar to a conventional fossil fuel ferry [7,8]. In Ref. [9], all steps of the flow of hydrogen, from the tank on land until $LH_2$ reaches fuel cells, are reviewed for an $LH_2$ cargo vessel. Several previous works [10–12] have undertaken feasibility assessments and correctly indicated that the high cost of hydrogen is a barrier to its implementation in the maritime industry, however, this cost contributes to zero greenhouse gas emissions. The zero emission technology in marine could lead to abatement costs in the range of 3000–18000 NOK per $CO_2$ ton in Norway [13]. It is also predicted that the cost of hydrogen (especially in liquid form) will decrease in the future and make it more compatible with conventional fuels (e.g. diesel) [3] but is rarely recommended a new technology as a solution to abate costs of hydrogen ferries.

Since $LH_2$ is expensive compared with other fuels, it is not compatible with other options economically, unless new and innovative technologies are implemented to reduce the cost. The very low boiling point of $LH_2$ (20 K or −253 °C) allows one to use it as a coolant for superconductors. Superconductors, below the critical temperature, have zero resistivity and thus close to 100% efficiency. They have the potential to be used in a wide range of applications. Superconductors in motors – which could be used in the propulsion system of the ferries – could make them lighter, less noisy, more compact, and more efficient [14]. Nevertheless, the high expense of cooling has been a barrier to their usage. Implementing $LH_2$ in marine technology gives an opportunity to use superconductors since $LH_2$ could be used as both coolant and fuel.

In Norway, there are strong societal and political motivations to shift to zero-emission transport, especially in the maritime sector. Several companies in Norway investigate the potential of the use of hydrogen for ferries and ships. In this study, a techno-economic analysis methodology is proposed for hydrogen ferries, and a case study is performed. Since it is expected that $LH_2$ emerges on a large scale in the maritime industry, the potential of the use of superconductors has been also examined. The purpose of introducing superconductivity to the maritime industry is to make $LH_2$ more economic and decrease the cost gap with the other fuels in this sector. This not only helps reduce carbon emissions in the environment but also saves a noticeable cost on society.

For the case study, a high-speed ferry is chosen and investigated with hydrogen as fuel, considering hydrogen both in compressed gas form and liquid form. To address the energy transition in a more comprehensive manner, green hydrogen is considered for the case study, meaning that the hydrogen fuel is assumed to be produced by renewable energy. Then, the corresponding fuel cost is based on the green hydrogen. Moreover, the effect of a superconducting motor for the propulsion system is studied when $LH_2$ is implemented.

## Methodology of techno-economic modeling and analysis

In this chapter, first, a general overview of the methodology is given as indicated in the flowchart of Fig. 1. Then each step in the figure is explained in the sub-sections and finally, detailed flowcharts of the approach are shown at the end of this chapter.

### Hydrogen mass requirement

First, it is essential to find out how much hydrogen is required for planned ferry operations. Ref [5] characterizes the hydrogen mass requirement. We build on their contributions, but with some modifications.

To calculate the weight of hydrogen, the energy demand of the ferry is needed. The *load profile* of a ferry describes the output power of the motor of the propulsion system against time. To obtain the input power of the motor, the amount of power demanded at each point in time should be divided by its efficiency. At the same time, the hotel and heating loads should be acquired. Therefore, the energy demand of the ferry in 24 h (or during operational hours in a day) is as follows:

$$\begin{aligned} &\mathit{Energy\ demand}\ [kWh] = \\ &\sum_{i=1}^{24} \frac{\mathit{power\ load}\ [kW]}{\mathit{efficiency\ of\ motor}} \times \mathit{time}[h] \\ &+ \sum_{i=1}^{24} (\mathit{hotel\ load} + \mathit{heating})\ [kW] * \mathit{time}[h] \end{aligned} \tag{1}$$

This amount of energy should be extracted with hydrogen fuel cells. Since some amount of the energy is lost in the fuel cells, the initial energy content of hydrogen could easily be obtained by knowing the efficiency of the fuel cells (The average efficiency of fuel cells is assumed 50% in this study according to TECO 2030 [private communication]).

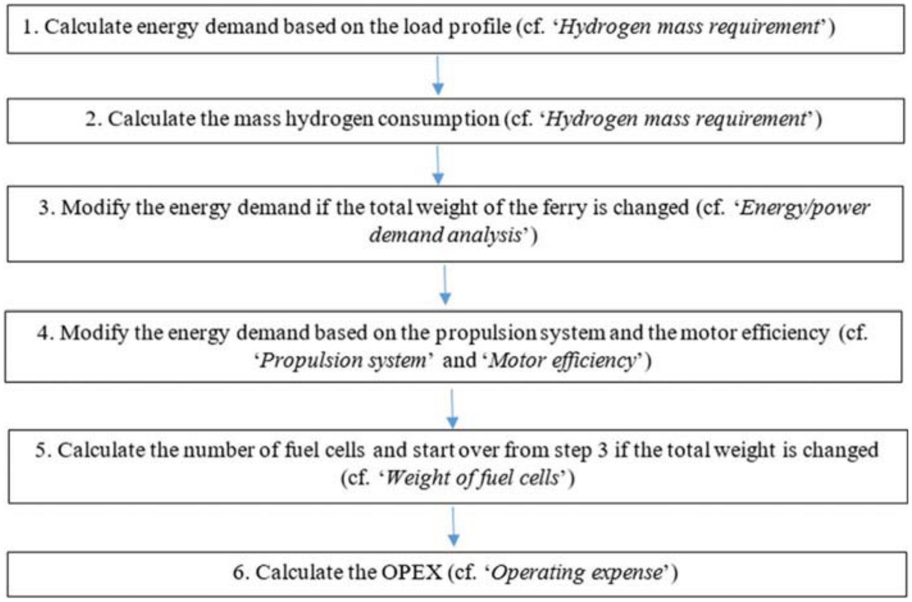

**Fig. 1 – An overview of the methodology.**

$$Energy\ content\ of\ hydrogen = \frac{Energy\ demand}{efficiency\ of\ fuel\ cells} \tag{2}$$

Finally, the mass of hydrogen is obtained in Equation (3) where 3.6 denotes the conversion rate of hydrogen from MJ to kWh, and LHV stands for the low heating value of hydrogen being 119.96 MJ/kg:

$$Mass\ of\ hydrogen\ [kg] = Energy\ content\ of\ hydrogen\ [kWh] \times \frac{3.6\ \left[\frac{MJ}{kWh}\right]}{LHV\ \left[\frac{MJ}{kg}\right]} \tag{3}$$

Equation (3) enables estimating the required amount of hydrogen to cater to the energy demand. However, for $LH_2$, about 15% of the total hydrogen has to remain in the tank to keep the tank cold [11]. For $CH_2$, a few percentages of hydrogen mass should also remain in the tank for less challenge in refueling. The higher the initial pressure of the tank, the less increase in temperature during refueling. The temperature inside the compressed hydrogen tank should not exceed 85 °C due to embrittlement in the walls of the tank. Thus, the hydrogen tank should not be evacuated completely to keep some initial pressure inside the tank [15]. Although the amount of initial pressure/mass could vary depending on the final pressure, mass flow rate, initial temperature, and ambient temperature, assuming 3% of final mass as the initial mass seems reasonable for a 700 bar hydrogen tank [16]. Moreover, an excess of 30% of hydrogen is considered for margin in unpredictable situations (such as harsh weather) for both $LH_2$ and $CH_2$. Therefore, the total mass of hydrogen inside the tank is obtained by Equation (4):

$$Mass\ of\ hydrogen\ inside\ the\ tank\ [kg] = 1.3 \times Mass\ of\ hydrogen\ [kg] \times (1 + initial\ mass\ ratio) \tag{4}$$

where initial mass ratio $= \begin{cases} 0.03 & for\ CH_2 \\ 0.15 & for\ LH_2 \end{cases}$

### *Energy/power demand analysis*

Weight is a factor that could affect the energy and/or power demand of the ferry. One percent change in the weight of the high-speed ferry leads to one percent change in the energy (power) demand [11]. In other words, this explanation could be written in the form of Equation (5).

$$Modified\ energy(power)\ demand = energy(power)\ demand \times \frac{new\ mass}{old\ mass} \tag{5}$$

Therefore, it is important to examine how the form of hydrogen influences the weight of the tanks and thus the weight of the ferry. $CH_2$ and $LH_2$ need different types of tanks, which makes their weights different. Moreover, for an $LH_2$ ferry, an evaporator is required to heat up the cryogenic hydrogen to be able to be used in the fuel cells. The reason for using an evaporator is that proton exchange fuel cells (PEM) are operated above 0 °C, while the temperature of liquid hydrogen is −253 °C. Table 1 shows how these materials could affect the final weight, where gravimetric specification indicates the ratio of the empty tank mass to the hydrogen stored mass. The weight of the $CH_2$ tank is heavier, implying a

**Table 1 – Gravimetric specification of different types of hydrogen tanks (Data from Ref. [11]).**

| Types of Tank | Gravimetric Specifications (Empty tank weight/ Hydrogen stored weight) [kg/kg] |
|---|---|
| 10000 psi (~ 700 bar), composite | 23.69 |
| $LH_2$ tank | 8.7 |
| $LH_2$ tank with considering an evaporator | 9.4 |

**Table 2 – Efficiencies of conventional and superconducting motors in different ranges of power[a].**

| | Full power | 30%–50% of power |
|---|---|---|
| Efficiency of Conventional motor | 95% | 30%–75% |
| Efficiency of Superconducting motor | 98% | 97% |

[a] The data is provided by American Superconductor.

higher energy demand for the ferry due to the weight disadvantage.

### Propulsion system

The amount of energy that is extracted from hydrogen is transferred to the propulsion systems to run the ferry. The accessibility of $LH_2$ allows one to use the superconducting motor as part of the propulsion system. While conventional propulsion systems use a gearbox for adjusting the revolutions per minute (rpm) of the motor, the superconducting motor does not require this facility. It means that the superconducting motor could operate at the desired rpm. Since the gearbox is responsible for 3% (on average) of energy losses in the system, using a superconducting motor could save a considerable amount of energy by eliminating the gearbox from the propulsion system [14].

The superconducting propulsion system is already manufactured by American Superconductor and implemented by the U.S. navy. On one hand, eliminating the gearbox reduces the weight of the propulsion system. Moreover, a superconducting motor is also lighter than a conventional one. On the other hand, the superconducting propulsion system requires a cooling system, which adds weight. For a large-size vessel, the superconducting propulsion system is lighter than the conventional one, however, for small and middle sizes (including the ferry we investigate in this article), the weight of both types of propulsion system is comparable to each other [private communication with American Superconductor[1]]. Therefore, the difference in the weight of the conventional and superconducting propulsion systems is neglected in this study.

### Motor efficiency

Since the ferry does not operate at a constant power rate, the efficiency of the motor should be known at different levels of utilization of power. This helps to evaluate how much energy is lost in motors during the journey. Table 2 shows the efficiency of both conventional motor and superconducting motor.

The number of data in Table 2 is limited, therefore a polynomial function has been used to interpolate the relationship between efficiency and power. The curve fitting of data in Table 2 is projected in Fig. 2.

### Weight of fuel cells

Since the weight of the $CH_2$ ferry is greater than $LH_2$ one (due to the heavier storage tank; cf. Table 1), the energy demand for the $CH_2$ ferry is higher than the demand for the $LH_2$ ferry. This energy demand is obtained by PEM. Each pack of PEM has a maximum output power and a certain weight. The number of packs of fuel cells could be calculated by dividing the maximum power demand of the ferry by the maximum output power of a pack of fuel cells. Adding one or more fuel cells imposes extra weight and thereby increases the energy demand of the ferry. This extra energy demand needs more fuel and therefore heavier tanks, which leads to a further increase in energy/power demand. Again, to provide the modified energy/power demand, the ferry might need extra fuel cells.

On the contrary, $LH_2$ ferry using a superconducting motor enables consuming less energy and, in consequence, less hydrogen. Therefore, the ferry might need fewer fuel cells when using superconductors. Deducting any fuel cells would reduce the total weight of the ferry, which ends up with less hydrogen consumption and energy demand. Thus, the value of the energy demand should be calculated in a loop until it is converged to a value as shown in Fig. 3. It should be mentioned that the $LH_2$ ferry operating with a conventional motor is assumed as the benchmark. Therefore, if the fuel or type of motor is changed, the modification is applied based on this case. In other words, it is assumed that the total weight and load profile, and therefore the number of fuel cells are available for the $LH_2$ ferry running with a conventional motor. Based on this initial data, the total weight and number of fuel cells could be calculated if the form of hydrogen or type of motor is changed.

### Operating expense

For the operating expense (OPEX) analysis, fuel cost plays an important role. Table 3 shows the price of green hydrogen in both gaseous and liquid forms. In near future, although the price of green hydrogen fluctuates based on the applied technology, the range of price, in total, would remain more and less the same [1,17]. However, the small size of $LH_2$ plants is the main reason for the high cost of hydrogen in liquid form. If large-scale hydrogen liquefaction (LHL) plants with a capacity of over 50 tonnes per day are constructed, a lower cost of $LH_2$ will be accessible [14]. Ref [18] envisaged that liquefaction of hydrogen would cost $ 0.63–2.615/kg for large plants. This cost should be added to the cost of hydrogen gas to predict the final cost of $LH_2$ in the future for LHL plants.

The amount of hydrogen could be obtained by Equation (3), and the price of hydrogen is given in Table 3. Thus, the operating expenditure (OPEX) of the ferry is defined by Equation (6). It should be mentioned that the amount of hydrogen consumption is less than the amount of hydrogen inside the tank. The reason is that part of hydrogen in the tank is considered as a margin – as explained in Section '*Hydrogen mass requirement*'. The OPEX of the ferry is calculated based on the amount of hydrogen consumption, not the amount of hydrogen inside the tank. Moreover, only fuel consumption is

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[1] American superconductor is an infrastructure company that works in the energy technology fields. The company also manufactures superconducting devices such as superconducting propulsion systems.

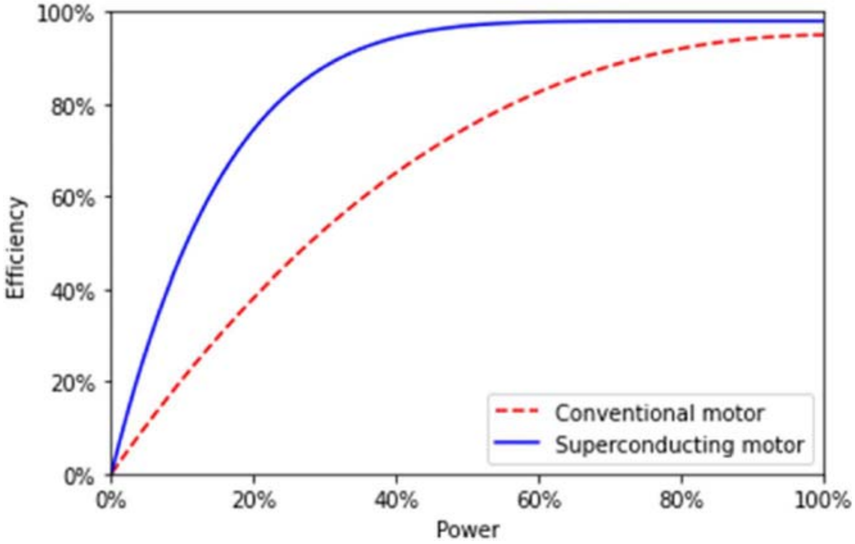

**Fig. 2 – The trend of the rise of efficiencies by increasing load of power in motors.**

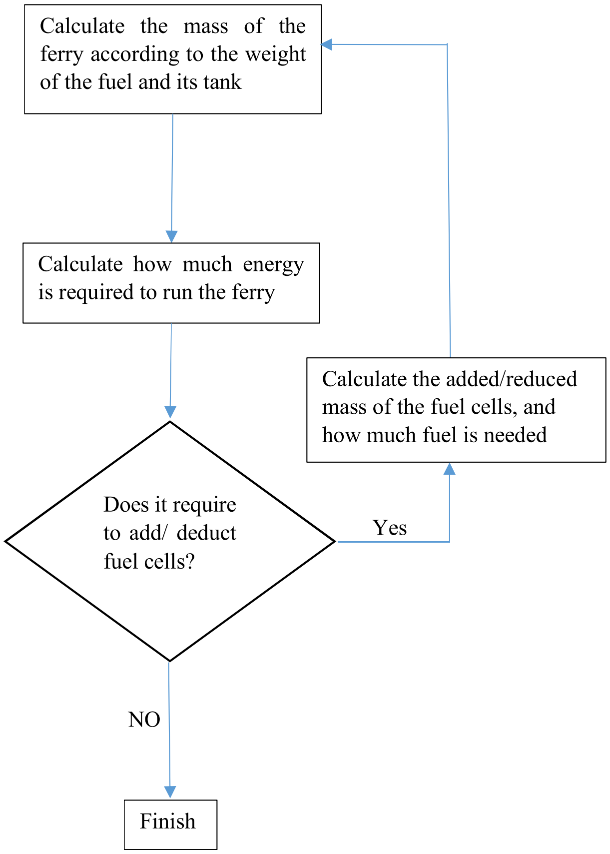

**Fig. 3 – The energy demand and the required numbers of fuel cells.**

**Table 3 – Price of renewable green hydrogen.**

| | Hydrogen gas | $LH_2$ | $LH_{2,\ LHL}$ |
|---|---|---|---|
| Price | \$ 2–5/kg [17] | \$ 9–12/kg [1] | \$ 2.63–7.615/kg |

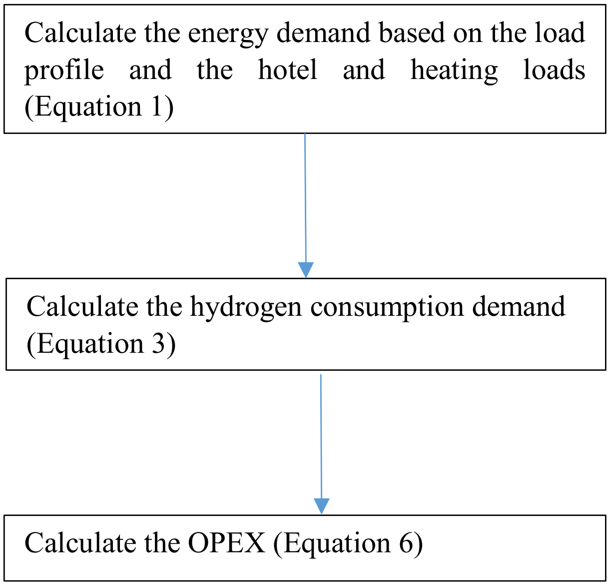

**Fig. 4 – Flowchart of a $LH_2$ ferry operating with a conventional motor.**

considered in the OPEX, and the labor and maintenance costs are not examined in this study.

$$OPEX = \text{Price of hydrogen per mass} \times \text{hydrogen consumption} \tag{6}$$

### *Flowcharts of approach*

To obtain the OPEX for the ferry, the flowcharts of the programming are presented in Figs. 4 and 5. Fig. 4 describes an $LH_2$ ferry operating with a conventional motor, while Fig. 5 illustrates a $CH_2$ ferry (left) and an $LH_2$ ferry operating with a superconducting motor (right). For obtaining equivalent energy demand for the cases in Fig. 5, the weight of the ferry is a critical parameter. It is assumed that the weight of the ferry is

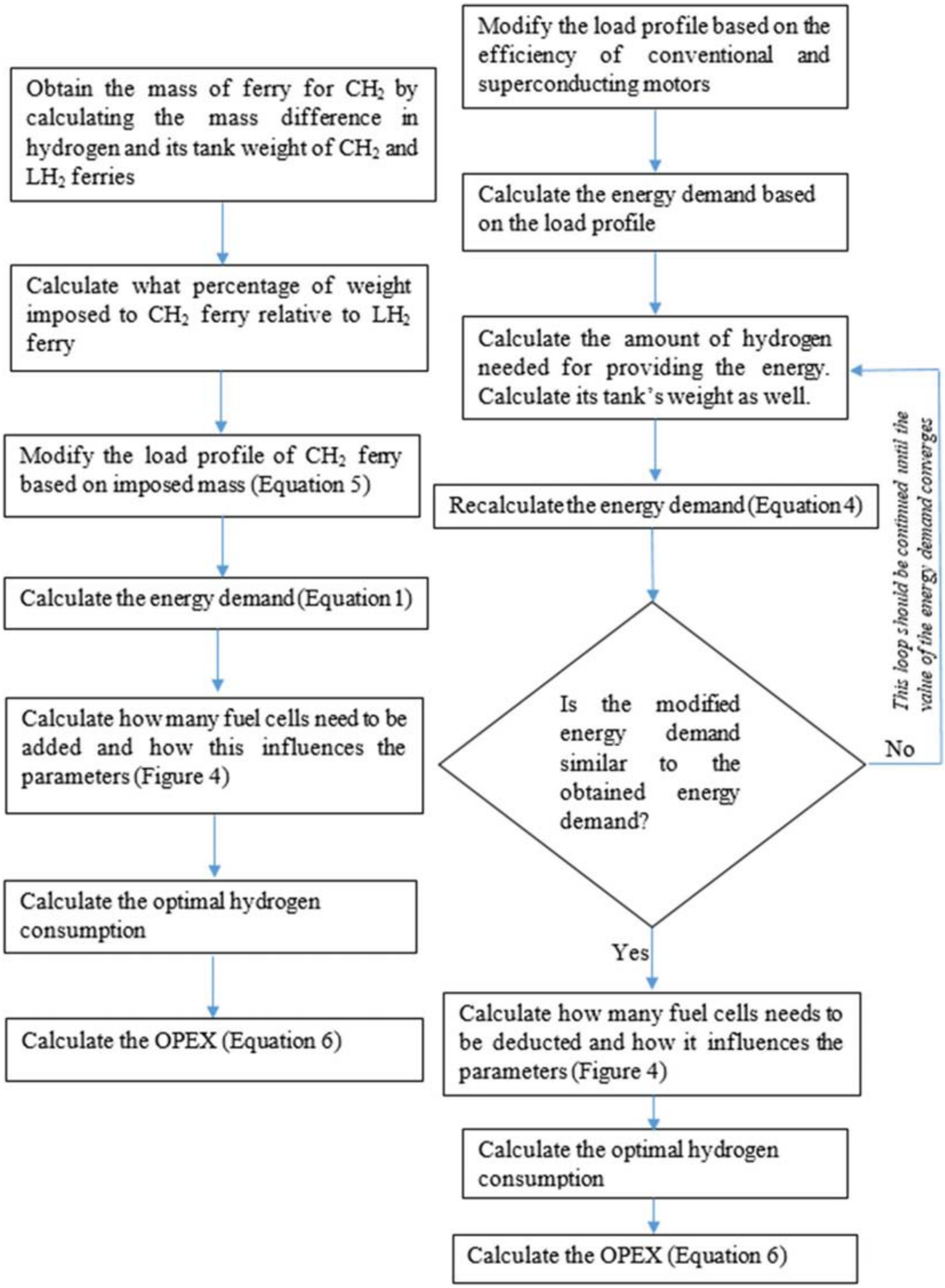

**Fig. 5** – **Flowchart of $CH_2$ ferry (left) and $LH_2$ ferry operating with superconducting motor (right).**

only affected by the amount of hydrogen, its tank, and the number of fuel cells. Moreover, it is presumed that the change in the volume of the tank and the number of fuel cells do not affect the weight of the other parts of the ferry. In other words, the total weight of the ferry changes just only with the amount of fuel, its tank, and the number of fuel cells.

In Section 'Operating expense', it is assumed that the operational time is fixed, but the ferry has the potential to be implemented in a longer operational time by some modification in the amount of hydrogen fuel, its tank size, and the number of fuel cells. The longer operational time leads to more energy demand, and in consequence, a heavier ferry. The operational time is restricted by the deadweight of the ferry. It means that the total weight of the ferry should not exceed its deadweight. More detail is explained in the flowchart shown in Fig. 6.

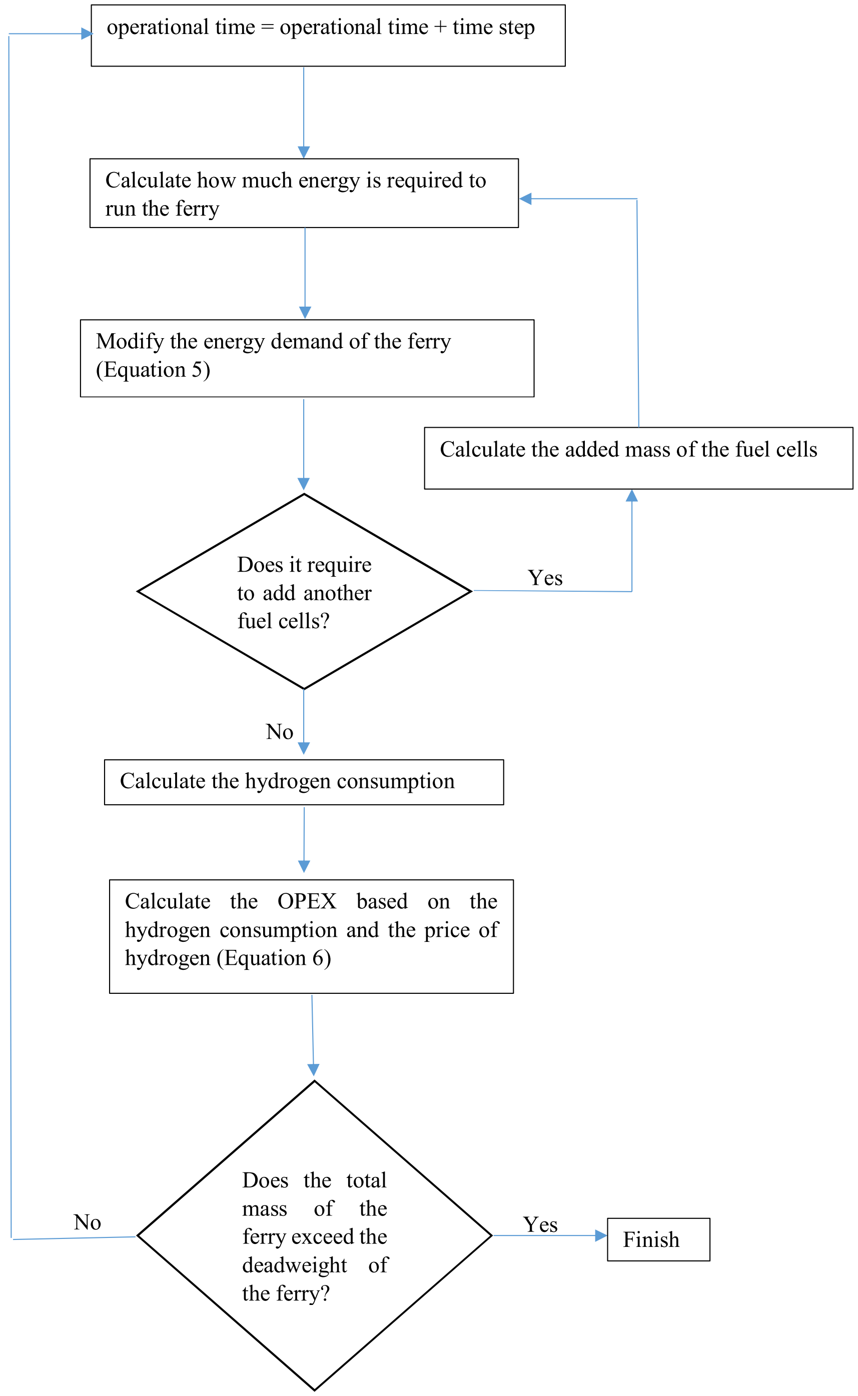

**Fig. 6 – Flowchart of the effect of the operational time on energy demand and OPEX for all cases.**

## Cases and initial data

### *Case studies*

In this paper, the high-speed ferry for investigation is given in Table 4. Operational time in this table indicates the period that the ferry starts its journey until it reaches its target.

The ferry is supposed to be operated with $LH_2$ and a conventional propulsion system; however, this study considers three different scenarios for running this ferry, which are brought in Table 5. The only difference between the first two scenarios is the type of fuel, while in the last scenario, a different motor is used compared with the others that have conventional motors as part of their propulsion system. All the raw information and assumption are considered for Case

**Table 4 – The characteristic of the ferry for the study.**

| Length | Passengers | Deadweight | Operational time | Total weight |
|---|---|---|---|---|
| 40 m | 300 | 230 tonnes | 8 h/day (3000 h/year) | 170 tonnes |

**Table 5 – Different scenarios of the high-speed ferry in this study.**

| | Type of fuel | Type of propulsion system |
|---|---|---|
| Case I | $CH_2$ (700 bar) | Conventional |
| Case II | $LH_2$ | Conventional |
| Case III | $LH_2$ | Superconducting |

II as the benchmark, and some characteristics (such as the total weight of the ferry) need to be modified and adapted for other cases.

### Power and energy demand

Before start analyzing different scenarios, having some initial information about the power/energy demand is essential. Fig. 7 shows the evaluation of the power demand of the $LH_2$ ferry operating with a conventional propulsion system in a different range of speed, which is provided by Paradis-Nautica[2] Company in Bergen, Norway. The energy demand also projects in the same figure by assuming a constant speed over the course of the 8-h operations. With this initial information, it is possible to obtain power and/or energy demand and the amount of fuel for each scenario, which will be discussed in more detail.

Besides this amount of power, the hotel load has to be considered since the energy from that part should be obtained from the hydrogen as well. The amount of power for the hotel load for this study is about 30 kW. If the hotel deck for the passenger is heated by electricity, about 60 kW of power is required for this purpose [private communication with Paradis-Nautica].

### Fuel cells

Teco2030 Company in Norway provides fuel cells with a maximum output power of 400 kW, which weighs 1300 kg. This type of fuel cell is considered the benchmark in this study to calculate the number of fuel cells that are needed to cater to the energy demand and the corresponding amount of weight that the packs of fuel cells imposed on the ferry.

### Load profile

In [16], it is represented that 75–80% of the time, a ferry operates in the highest power demand. In this study, it is assumed that the high-speed ferry operates at the highest power demand (3448 kW) in 80% of the journey time, while the other 20% is divided equally at the beginning and the finishing time of the journey. Moreover, the load profile of the high-speed ferry is assumed to rise and fall linearly, which is shown in Fig. 8.

The power demand has to be modified for Case I and Case III so that the heavier weight in Case I due to heavier tanks (explained in Section '*Energy/power demand analysis*') and more packs of fuel cells (cf. Section '*Weight of fuel cells*') lead to more power/energy demand. On the contrary, in Case III, the superconducting motor has less loss of energy. This means that less input power/energy needs to be provided to have the same output of power/energy in the motor. Therefore, less hydrogen is required in Case III compared with the benchmark, and in consequence, the total weight of the ferry would be lower. As a result, Case I has a higher peak of power while the peak is lower for Case III in the load profile. The load profile of all cases is shown in Chapter '*Results and discussion*'.

## Results and discussion

In this chapter, first, the results are shown and analysed, and then in a sub-chapter, the sensitivity analysis is implemented and described.

The load profile of the benchmark (Case II) is already shown in Fig. 8 based on the initial information, but since Case I and Case III result in different optimal weights of the corresponding ferries, they have different load profiles and, in consequence, energy demands. To obtain the equivalent load profile for other cases, the change in the weight of the ferry should be calculated. $CH_2$ requires a heavier tank thus, Case I becomes heavier. This means that Case I needs the highest power demand, and therefore highest load profile. The higher power demands need more fuel cells. Case I needs two more packs of fuel cells compared with Case II according to the highest power demand of each case and the power of each pack of fuel cells (400 kW). On the contrary, when a superconducting motor is implemented, the efficiency improves, leading to higher energy efficiency. In other words, less amount of hydrogen would be consumed; as a result, the hydrogen tank for case III would be smaller and lighter than the benchmark. That is why Case III has the lowest load profile/power demand as shown in Fig. 9. The amount of hydrogen consumption is 1970, 1667, and 1490 kg/day for Case I, Case II, and Case III, respectively.

Fig. 10-a shows the difference in the weight of the three cases, while the deadweight of the ferry is 230 tonnes. None of the cases exceeds the restriction of the deadweight, therefore they are theoretically applicable to be constructed and implemented. However, the comparison between Figs. 9 and 10-a reveals that the higher the weight of the ferry is, the more power demand it requires – as expected. To have a deeper look, Case III is slightly lighter than Case II, therefore the load profile is also a little bit lower. On the other hand, Case I is considerably heavier, due to the higher gravimetric specifications of the tank and more packs of fuel cells, hence the difference in the load profile is more noticeable.

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[2] Paradis-Nautica is a consultant company with expertise in marine technology.

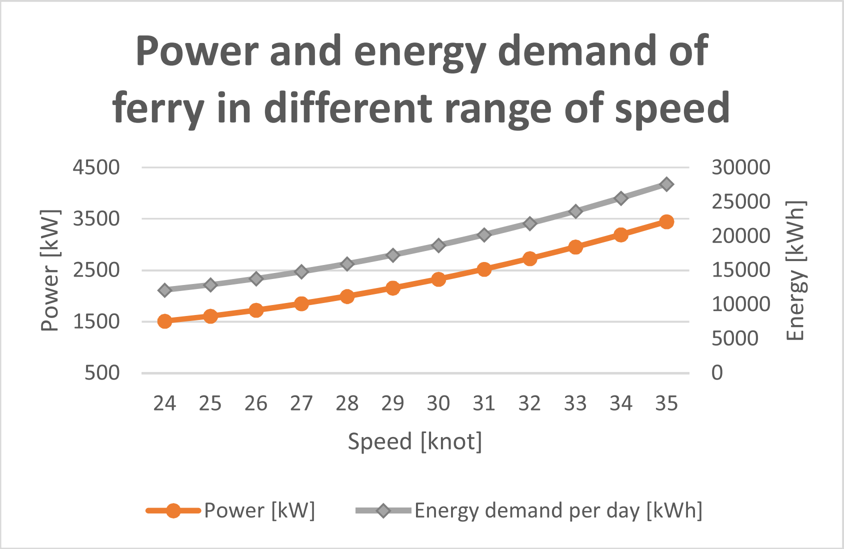

Fig. 7 – Power and energy demand of the $LH_2$ ferry in a different range of speed.

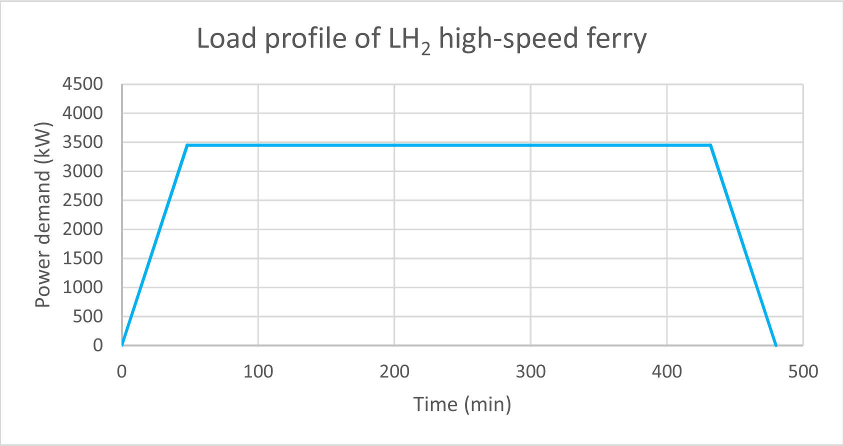

Fig. 8 – Load profile of the high-speed ferry for the benchmark (Case II in 8-h operation time).

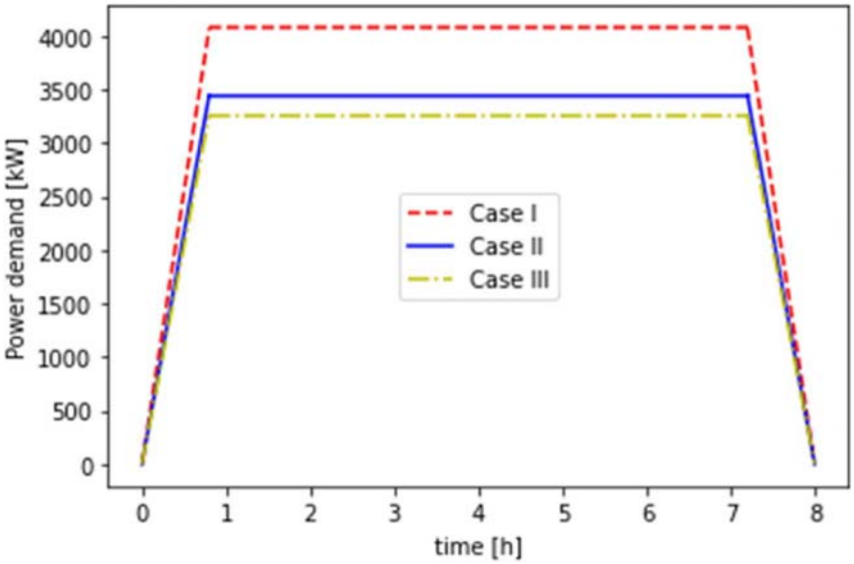

Fig. 9 – Load profiles of the ferry (Case I, Case II, and Case III) for 8-h operational time.

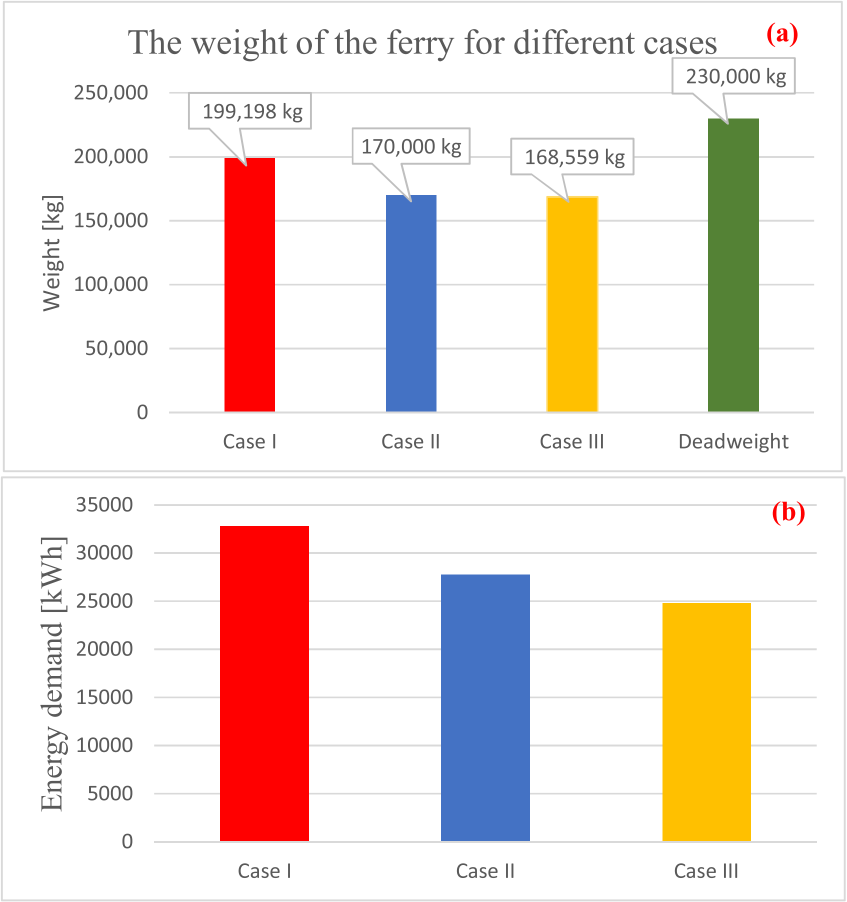

**Fig. 10 – The weight (a) and energy demand (b) of the ferry for different cases for an 8-h operation time.**

From the load profile, the energy demand can be easily calculated since the energy demand is equal to the area under the load profile. The comparison of the energy demands has brought in Fig. 10-b. Case I has the highest energy demand while Case III has the lowest. These differences in energy demands come from the variation in the weight and/or power demand of the different cases. The energy demand is a parameter that influences the daily operating cost; the other parameter is the price of hydrogen.

Based on the energy demand, the amount of hydrogen required for operations is obtained. To obtain the daily OPEX, the consumed hydrogen should be multiplied by its price (Equation (6)). Since a range of prices has been reported in Table 3, the daily OPEX is reported for the lowest, highest, and the average cost of hydrogen shown in Fig. 11 – both for the present and future when LHL plants are built.[3] For Case II and Case III, the daily OPEX is only affected by the energy demand since both cases use $LH_2$, thus the price of hydrogen is the same for both cases. Using a superconducting motor in Case III helps to reduce the energy demand and in consequence, leads to the saving cost compared with Case II. Based on the nowadays cost of hydrogen, this deduction of energy is not enough to compensate for the high price of $LH_2$ in comparison with $CH_2$. However, constructing LHL plants in the future decrease the cost of $LH_2$ considerably and could compete with $CH_2$, so that at the lowest price of hydrogen, Case III is even slightly less expensive than Case I. At the moment, the daily OPEX of Case III – despite having the lowest energy demand – is still considerably higher than Case I, which has the highest energy demand. In other words, the price of hydrogen dominates OPEX now, but the trend changes in the future so that the daily OPEX of Case III will be comparable to Case I in the future.

In the next step, the operational time has been considered a variable, and its effect on other parameters has been examined for all cases. The effects of operational time on the weight of the ferry, energy demand, and daily OPEX are shown in Fig. 12-a, Fig. 12-b, and Fig. 13, respectively. To have a better look at Fig. 13, the purple rectangle in part **(a)** is extracted and shown in part **(b)** of the figure.

With the increase in operational time, more hydrogen should be consumed to provide enough energy. Therefore, the weight of the fuel and its tanks would be heavier. Fig. 12-a demonstrates the increase in the mass of the ferry by the growth of operational time. Comparing the cases with each other demonstrates Case I has the sharpest slope, while Case III has the lowest. The restriction for all cases is the deadweight of the ferry – 230 tonnes. This means that the weight of the ferry identifies how long the ferry could operate. The longest possible operational times for Case I, Case II, and Case III are 10.7, 16.7, and 18.7 h, respectively. Moreover, a few step-

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[3] LHL is used as a subscript in Fig. 11 to show the predicted price in future.

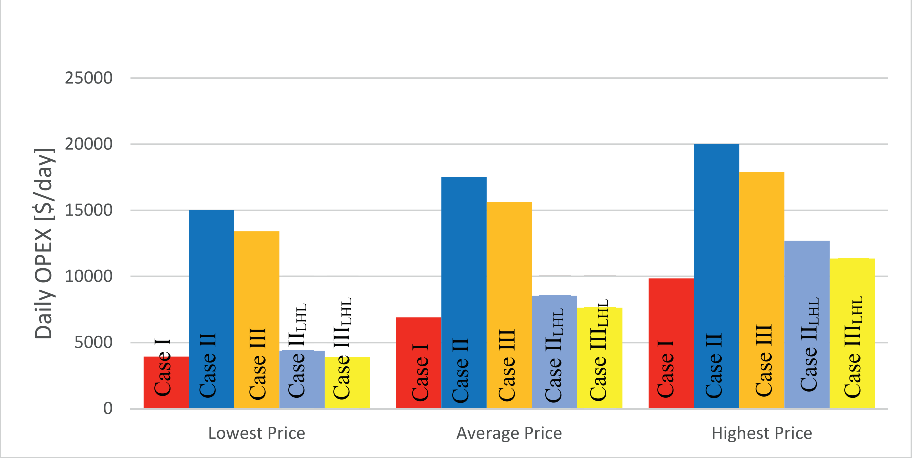

**Fig. 11** – **Daily OPEX for different cases based on the range of hydrogen price for 8-h operation time.**

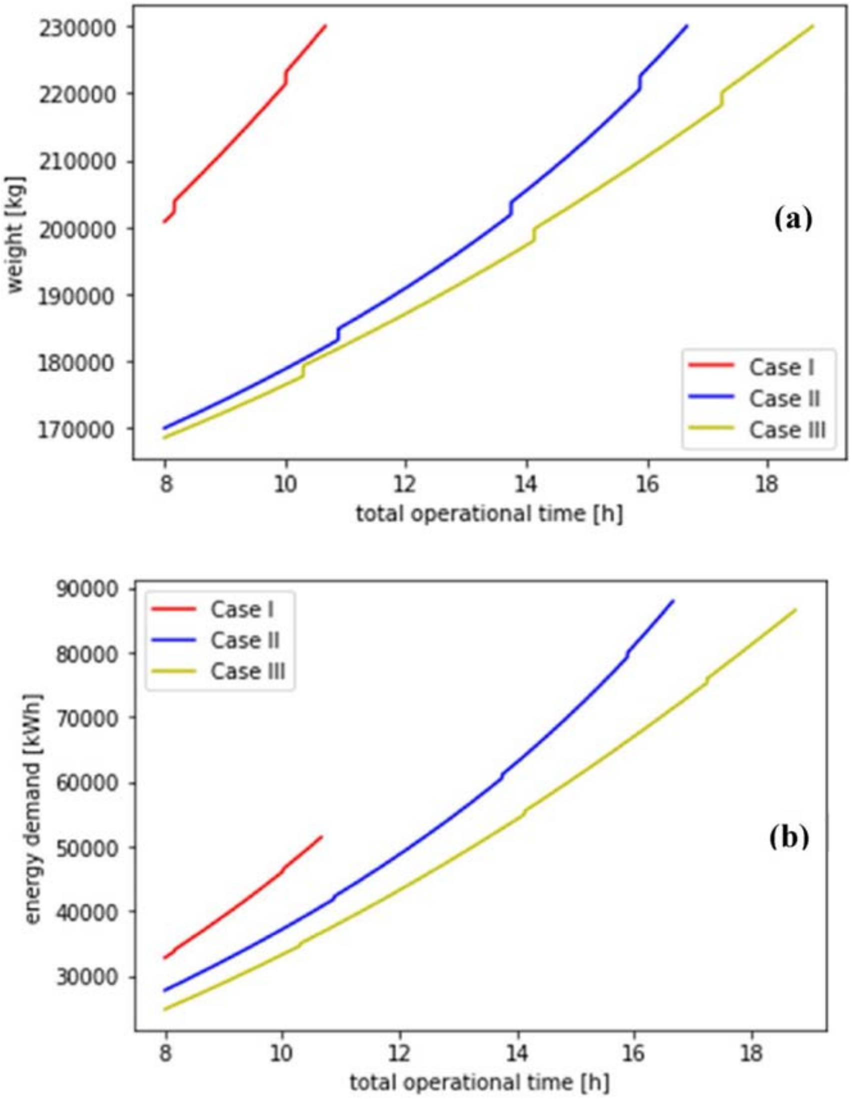

**Fig. 12** – **Effect of operational time on the mass (a) and energy demand (b) of the ferry.**

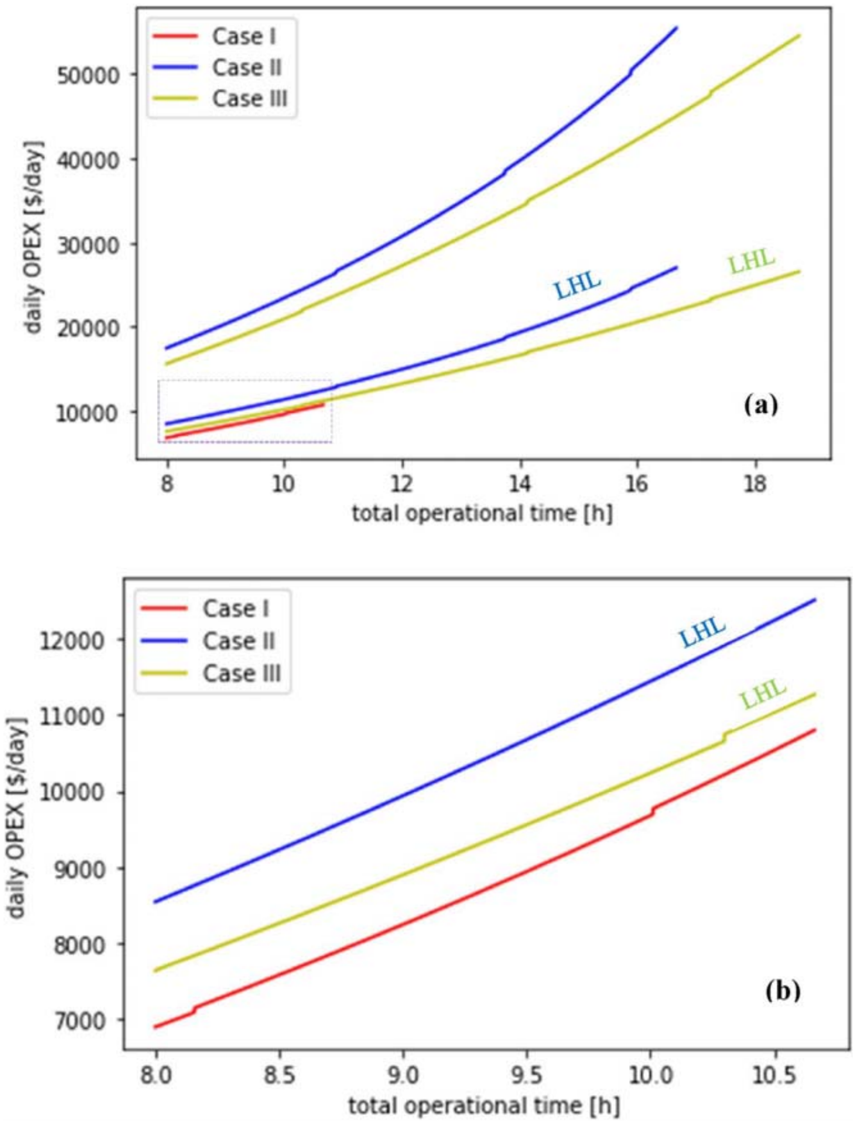

**Fig. 13 – a. Effect of operational time on the daily OPEX, b. Zoom of the purple dashed rectangle in part (a). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)**

like increases could be seen in all three cases, which are caused by adding a pack of fuel cells. In other words, each step shows one pack of fuel cells that has to be added to the system to provide power demand. Since each pack of fuel cells has considerable weight (1300 kg), the energy demand rises, thus the mass of fuel, and in consequence, the weight of the ferry grows. That is why the trend in Fig. 12-a changes when a pack of fuel cells is added. Except for those step-like rises, the rest of the profile has the same trend with linear growth.

The same trend applies to Fig. 12-b, which describes the energy demand of different cases with respect to operational time. In this figure, Case I and Case III experience the most and the least slope respectively. At the same operational time, Case I (which is fed by $CH_2$) has the highest energy demand. In the contrast, Case III operating by $LH_2$ and a superconducting motor consumes the lowest energy demand and leads to saving more hydrogen. The same step-like increase could be seen in energy demand with respect to operational time, which again stems from the added fuel cells to the system. As explained before, the increase in the weight of the ferry directly influences the energy demand.

By knowing the price of hydrogen and the energy demand in each operational time, the daily OPEX could be obtained shown in Fig. 13. It should be mentioned that only the average price of hydrogen in Table 3 is considered to obtain this figure. Based on the average price at present, despite the high energy demand of Case I, not only does this case have the lowest energy demand, but it also has the smoothest increase. The reason is the low price of hydrogen gas compared with liquid form. However, the limited operational time binds its application for a short distance. Case II is the most expensive one and has the sharpest slope: it has a higher price of hydrogen compared with Case I and requires more energy demand compared with Case III. Since LHL plants could reduce $LH_2$ prices in the future, the trend for Case II and Case III would change in the future. To be able to have a more accurate comparison, the purple dashed rectangle is extracted in Fig. 13-a and shown in Fig. 13-b. Unlike the present, the LHL plant leads to smoother growth of Case III compared with Case I by increasing the operational time, and the daily OPEX will not differ notably when Case I reaches its maximum possible operational time. Case I could not operate longer since it is already reached its deadweight but if it could, it would cross the Case III profile and become more expensive than Case III in a longer operational time. The step-like increase could be seen in the OPEX as well in Fig. 13 due to the addition of fuel cells.

### *Sensitivity analysis*

Since the accurate value of data is not always available, the sensitivity test could indicate how the variation of the input data could influence the results. It means that by setting a range of input, instead of a specific value, the percentage of the change in the output could be reported.

In this study, the average efficiency of fuel cells is used for the calculation, while in reality, the efficiency could vary based on the rate of power. Therefore, we analysed how the results vary if the average efficiency of fuel cells is changed. It is concluded that one percent change in the efficiency of the fuel cells could lead to 0.4% change in the energy demand and the weight of the ferry, while the amount of change for OPEX is about 1.8% for 8-h operational time. It also leads to two percent effect on the longest operational time. By increasing the operational time the impact of the efficiency of the fuel cells on the energy demand and OPEX rises. For example, for 10-h operational time, one percent change of the efficiency of the fuel cells affects 0.6% on the energy demand and the weight of the ferry and 2.6% on OPEX.

## Conclusion

A techno-economic model of the zero-emission high-speed ferry has been developed and a use case vessel has been studied with green hydrogen as fuel. The hydrogen fuel both in compressed gas and liquid form has been considered as the fuel of the ferry. The use of liquid hydrogen in the ferry allows implementing of a superconducting motor in the propulsion system. All different scenarios have been investigated and the benefits and downsides of each scenario have been examined in this study. The ferry fed by compressed hydrogen gas is the most economic one among all scenarios at the moment, although it has the highest energy demand (33000 kWh compared with 28000 kWh for the liquid hydrogen ferry and 25000 kWh for the superconducting ferry) and hydrogen consumption (1970 kg/day compared with 1667 kg/day for liquid hydrogen ferry and 1490 kg/day for the superconducting ferry). On the other hand, liquid hydrogen allows the ferry to be run for a longer distance and operational time, and using a superconducting propulsion system reduces the hydrogen consumption and, in consequence, the operating expense. Nevertheless, to be able to compete with compressed hydrogen gas, the cost of liquid hydrogen needs to be reduced. Therefore, as this study has shown, fabricating liquid hydrogen plants on large scale decreases the price considerably so that it could compete with compressed hydrogen gas economically in the maritime industry in the future. The heavier (or bigger size) and the longer operational time of the ferry are the other factors that could make liquid hydrogen ferries less expensive compared with hydrogen gas ones.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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