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Simulation-based evaluation of concepts for short sea shipping of green hydrogen

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ABSTRACT

In this study, a simulation-based approach is applied to develop concepts for short sea shipping of green hydrogen and to assess their overall energy efficiency. The study is conducted as a case study involving production of green hydrogen at an offshore site in the North Sea. Hydrogen produced at the site is first transported by pipeline to a port-based intermediate storage facility, from where it is transported onwards by ship. For the onward transport, four different hydrogen carriers are considered, namely compressed hydrogen, liquid hydrogen, ammonia, and a liquid organic hydrogen carrier.

KEY WORDS

Maritime transport; Short-sea shipping; Green hydrogen; North Sea; Discrete-event simulation

INTRODUCTION

In Europe, green hydrogen is expected to play an important role in the energy transition, in particular as a tool to decarbonize energy-intensive industries, such as heavy industry, shipping and aviation. To ensure a sufficient supply, the European Union (EU), as part of its plan REPowerEU, has set a target of reaching 10 million tons of domestic production of green hydrogen by 2030 (Notteboom & Haralambides, 2023). As many parts of the EU are densely populated, and thus have limited opportunities for increased local onshore production of green hydrogen, new offshore production facilities will be needed to reach the production target. Consequently, new transport infrastructure is also needed, and due to the general lack of hydrogen pipelines as well as challenges related to building new ones, especially through densely populated areas, we expect a growing demand for non-pipeline-based transport options. In this context, the aim of this study is to define and evaluate concepts for short sea shipping of green hydrogen.

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The study is conducted as a case study involving the production of green hydrogen at an offshore site in the North Sea. Hydrogen produced at the site is first transported by pipeline to an intermediate port-based terminal, from where it is further transported by ship. For the onward transport, four different hydrogen carriers are considered, namely, compressed hydrogen (CH_2), liquid hydrogen (LH_2), ammonia (NH_3), and a liquid organic hydrogen carrier (LOHC) (Notteboom & Haralambides, 2023). Each considered concept is defined in terms of fleet characteristics (e.g. number of ships, ship type, ship size, and ship design speed), as well as the required intermediate port-based storage capacity. The study is limited to defining requirements for the fleet and port-based infrastructure considering energy efficiency and technical feasibility. Issues concerning safety, cost-efficiency, and regulations are not considered.

Related studies

Johnston et al. (2022) present a model developed to assist stakeholders in assessing the costs of maritime transport of hydrogen in various forms over different distances. In total five different options are considered, namely, transport of hydrogen in the form of LH_2, NH_3, liquified natural gas (LNG), methanol (CH_3OH), and LOHCs. Both fixed and variable costs, including port fees, canal usage charges, fuel costs, capital and operating costs, boil-off losses and expected future environmental taxes, are considered. For distances between 4 500 NM and 10 900 NM the study found that it is most cost-efficient to transport hydrogen in the form of NH_3 or CH_3OH. The study also analyzed the impact of using hydrogen, or the hydrogen carrier, as a low or zero carbon emission fuel for ships involved. However, it found that this would result in lower costs only in case hydrogen is transported in the form of LNG.

d'Amore-Domenech et al. (2023) compares the cost-efficiency of six different options for transport of hydrogen over sea including transport of LH_2 by ship with or without port-based storage facilities, transport of CH_2 by ship with or without port-based storage facilities, and transport of gaseous hydrogen by pipeline with or without intermediate compression stations. Each alternative was assessed for different transport distances and transport volumes. They found that for a transport distance of 100 km the most cost-efficient alternative is pipeline regardless of transport volume. For a distance of 2 500 km and an annual production volume of 1.0×10^5 ton, the most cost-efficient alternative was found to be shipping of CH_2 without port-based storage facilities. For a distance of 2 500 and an annual production volume of 1.0×10^6 ton, as well as for a distance of 5 000 km and an annual production volume of 1.0×10^5 ton, the most cost-efficient alternative was found to be shipping of either CH_2 or LH_2. For all other cases they found that the most cost-efficient alternative is shipping of LH_2.

EU Science Hub (2022) assessed the costs of different hydrogen transport options including CH_2, LH_2, NH_3, and LOHC. In brief, they found that for distances up to 3,000 km, the most cost-efficient option is the transport of compressed hydrogen by pipeline. For distances between 3,000-16,000 km, transport of LH_2 by ship was found to be the most cost-efficient options. For very long distances above 16,000 km, the most cost-efficient option was found to be transport of hydrogen in the form of LOHC or NH_3.

Based on the above studies it is evident that for distances up to 1,000 km, pipeline is generally the most cost-efficient option. However, none of the above-mentioned studies account for the fact that building a pipeline between two specific locations may not always be feasible for political, geographical, or other reasons. This study aims to assess what sea transport option is best for such cases.

CASE STUDY

Overview and design approach

In the case study, hydrogen is produced at an assumed offshore wind farm located in the North Sea within the exclusive economic zone of Germany at N54°26, E6°06. The location is indicated by a triangle in Figure 1. Hydrogen produced at the site is first transported along a 190 km long pipeline, whose approximate route is marked by a dotted line in Figure 1, to an intermediate port-based terminal storage located in Bremerhaven. From there all hydrogen is transported forward by ship to Kiel along an approximately 130 NM sea route marked by a dashed line in Figure 1. As per the figure, the sea route goes through Kiel Canal. If the intermediate port-based hydrogen storage in Bremerhaven becomes full, the H_2 production has to be limited or stopped. To avoid this, the capacity of the transport system must be sufficient. Moreover, the transport system must be energy- and resource-efficient.

The case study design process is carried out as follows. First, we define the hydrogen production rate based on a previous study. Second, we analyze the sea route, e.g., in terms of operational constraints, and make a preliminary assessment of the voyage time. Third, considering the hydrogen production rate and assessed voyage time, we define a preliminary conservative solution for each considered hydrogen carrier. Fourth, using the technique of discrete event simulation together with engineering judgement, we derive a refined conceptual solution for each considered hydrogen carrier. Fifth, we assess the overall energy efficiency of each solution.

Hydrogen production

Following Eden et al. (2024), our considered assumed offshore wind farm consists of 42 Vestas V164 turbines with a total installed power capacity of 399 MW, which is reduced by 15 % due to wake effects. All electricity produced at the wind farm is used for producing hydrogen by electrolyzers requiring 3 kWh per produced kg of hydrogen. Following Eden et al. (2024), we simulate future hourly hydrogen production rates and volumes based on historical hourly wind speed data from the Copernicus ERA5 dataset specified for an altitude of 100 m covering the 11-year period 01.01.2012 – 31.12.2022 (Hersbach, et al., 2023). Accordingly, we assume that the wind conditions in the area will be similar as during the period represented by the data.

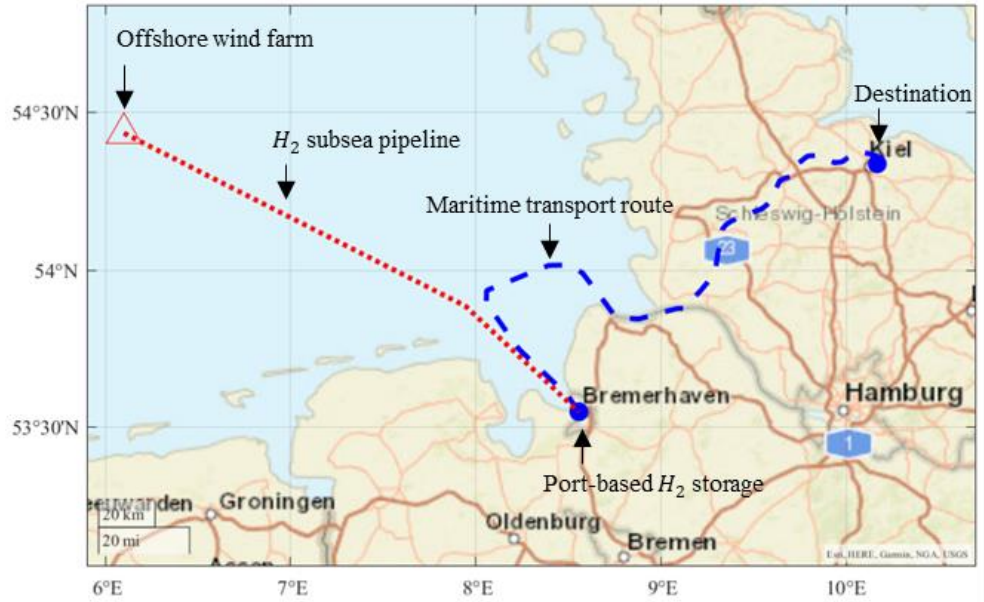

Figure 1: Production site and transport routes.

Over the considered 11-year period we simulated a total hydrogen production of around 244 000 ton. The corresponding annual, monthly, and daily averages are 22 182, 1 848, and 62 ton, respectively. However, due to variations in the prevailing wind conditions at the offshore site there are significant annual and interannual variations in the production rate. Specifically, as per Figure 2, the monthly production volume is estimated to vary between 780 and 3 050 ton.

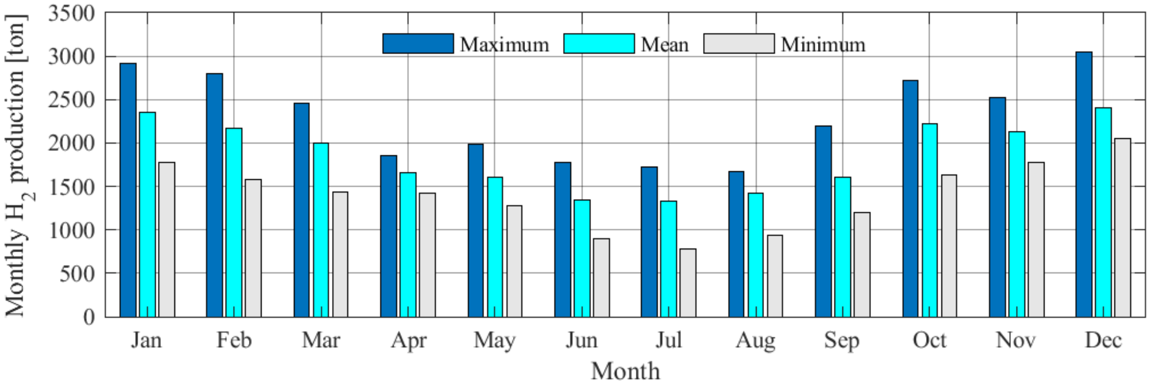

Figure 2: Annual and interannual variations in the production rate.

Sea route and operational constraints

The total distance of the sea route is 128.8 NM. Ship size and operational constraints are set primarily by the Kiel Canal as per Table 1. Following these constraints, ships are permitted to operate independently in all wind conditions without tug assistance

(UCA, 2023)**.** The maximum allowed speed in and near Port of Bremerhaven and Port of Kiel is assumed to be 5 knots. In Elbe the maximum allowed speed is assumed to be 12 knots.

Table 1: Ship size and operational constraints set by the route (UCA, 2023).

Parameter	Maximum allowed value
Ship length	200 m
Ship beam	27 m
Ship draft	8 m
Ship speed, Kiel Canal	6.5 knots
Ship speed, port areas	5 knots
Ship speed, Elbe	12 knots

Considering the ship size and operational constraints determined as per Table 1, we choose to divide the route into 5 legs as per Table 2. Accordingly, some 40 % of the route is along Kiel Canal. As per the table, Kiel Canal has a lock at each end, i.e., in Brunsbüttel and Kiel-Holtenau, where the average locking times are assumed 45 and 25 minutes, respectively (WSV, 2022). As per WSV (2022), there are typically no additional waiting or queuing times. Assuming an open water speed of 14 knots, the total voyage time is estimated at 15.74 hour.

Table 2: Preliminary voyage time estimation.

Leg nr	Description	Distance [NM]	Speed [knots]	Time [hours]
1	Bremerhaven port area	3.8	5	0.77
2	Open sea (Bremerhaven - Elbe Estuary)	52.8	14	3.77
3	Elbe	16.5	12	1.37
	Lock 1 - Brunsbüttel	n/a	n/a	0.75
4	Kiel canal	53.4	6.5	8.22
	Lock 2 - Kiel-Holtenau	n/a	n/a	0.42
5	Kiel port area	2.2	5	0.43
	SUM	128.8		15.74

Elaboration of transport solutions

Assuming that the voyage time does not depend on the type of energy carrier, the voyage time for each option is preliminary estimated as per Table 2 to 15.74 hours. Assuming that the port-turn-around time in both Bremerhaven and Kiel is around 12 hours and independent of the type of energy carrier, the total duration of a round trip is estimated at 2 x 15.7 hours + 2 x 12 hours = 55.4 hours. Thus, assuming zero down time, the maximum number of round trips per month is 13. In order to meet the transport demand during a month of peak production (3 050 ton) using a single ship, the ship's required net transport capacity is estimated at $\frac{3\,050\,ton}{13} \approx 235$ ton of hydrogen.

To meet this transport demand, we derive a preliminary solution for each considered energy carrier (CH2, LH2, NH3, and LOHC) considering the operational constraints as follows:

1. Gas carrier ship carrying CH_2 at 350 bar. Assuming as per Table 3 a density of 23.2 kg/m^3, the required volumetric cargo capacity of the ship is estimate at $\frac{235}{0.0232}\frac{ton\,m^3}{ton} \approx 10\,129\,m^3$. Because we are not aware of any reference CH_2 carriers, we use an LNG tanker as reference instead. Based on Clarksons Research (2024), a typical LNG tanker with a capacity of around 10 000 m^3 do not exceed any of the route constraints defined as per Table 1.
2. Container feeder ship carrying LH_2 in 40 feet cryogenic tank containers, each with a LH_2 capacity of 3 ton (Decker, 2019). If a single ship is used, the required FEU capacity of the ship is estimated at $\frac{235}{3}\frac{ton*FEU}{ton} = 79\,FEU$ (158 TEU). Based on Clarksons Research (2024), a typical 160 TEU container ship do not exceed any of the route constraints defined as per Table 1.
3. Ammonia tanker ship. As per Table 3, a tone of NH_3 carries around 0.178 ton of hydrogen. Hence, in order to carry 235 ton of hydrogen, the ammonia tanker needs to carry 235 ton * (1/0.178) ≈ 1320 ton of NH_3. Based on Clarksons

Research (2024), a typical 1300 DWT LPG/Ammonia tanker does not exceed any of the route constraints defined as per Table 1.

4. Chemical tanker ship carrying LOHC. As per Table 3, one tone of a typical LOHC (benzyltoluene) is assumed to carry 0.063 ton of hydrogen. Hence, in order to carry 235 ton of hydrogen the tanker needs to carry 235 ton * (1/0.063) ≈ 3 730 ton of LOHC. Based on Clarksons Research (2024), a typical 3 730 DWT chemical tanker does not exceed any of the route constraints defined as per Table 1.

Table 3 Storage densities by volume and weight (Weichenhain, 2021).

Energy carrier	Storage volume density [kg H_2/m^3 of carrier]	Storage weight density [kg H_2/ ton of carrier]	Storage weight density [ton of carrier/ ton H_2]
CH_2	23	1 000	1 000
LH_2	71	1 000	1 000
NH_3	121	178	5.62
LOHC	55	63	15.87

The above defined preliminary solutions were derived without considering stochastic factors (e.g. variations in port-turnaround times), or more importantly, the role of the intermediate port-based storage in Bremerhaven acting as a buffer against short term variations in the production rate. Based on engineering judgement, we assume that it is preferable to store hydrogen in the intermediate storage in the same format in which it is to be transported forward. Hence, the type of storage tanks to be installed in Bremerhaven depends on the choice of hydrogen carrier for the maritime transport. Among the considered hydrogen carriers, we assume that the storage of LH_2 is the most challenging. The capacity of the largest commercial LH_2 storage tank that we are aware of is 2 500 m^3 (Kawasaki, 2021). As a preliminary solution we consider a hydrogen storage with a net capacity corresponding to four such tanks, providing a total capacity of 10 000 m^3, which assuming a LH_2 density of 70.9 kg/m^3, corresponds to around 709 ton.

In order to be able to consider both stochastic factors, and the role of the intermediate port-based storage, we simulate the operations of the system using the technique of Discrete Event Simulation (DES) using an approach originally presented by Bergström et al. (2016). An overview of the applied DES model is presented in Figure 3. As per the figure the model consists of five main blocks representing different components of the system. A more detailed presentation of the blocks representing the Port of Bremerhaven, the sea voyages, and the port of Kiel is provided in Figure 4. The time step of the simulation is one hour.

In the 'hydrogen production' - block, entities that each represent one ton of hydrogen, are produced at a rate corresponding to that simulated by Eden et al. (2024). All produced hydrogen entities proceed to the 'Port of Bremerhaven' block in which they are merged into a batch corresponding to that of the cargo capacity of the approaching or waiting ship. Once a cargo batch is completed, incoming cargo entities wait in a server with a capacity corresponding to the capacity of the port-based storage minus the capacity of the waiting cargo batch (ship load). If the port-based storage becomes full, entities are directed to a storage overflow block where they are terminated.

Figure 3: Overview of the applied DES model.

In the 'ship loading' block (in Port of Bremerhaven, see Figure 4), the completed cargo batch entity is merged with a waiting/incoming ship entity, resulting in a composite entity representing a fully loaded ship. Once a composite entity has been created, it will be held up for a time corresponding to the port-turnaround time, which is modelled as a normal distribution with a mean value of 12 hours and a standard deviation of 1 hour. Subsequently, the composite entity will proceed to the 'Voyage: Bremerhaven-Kiel' block, in which it will complete one leg at a time as shown in Figure 4. Once the composite entity has reached the 'Port of Kiel' block it will be split into its original components, i.e., an entity representing an empty ship plus a number of entities each of which represent one ton of hydrogen. Following a waiting time corresponding to the port turnaround time, which is modelled in the same way as the port-turnaround time in Kiel, the entity representing the empty ship will embark on its return voyage towards Port of Bremerhaven and the entities representing hydrogen will enter the 'hydrogen market' block in which they are terminated.

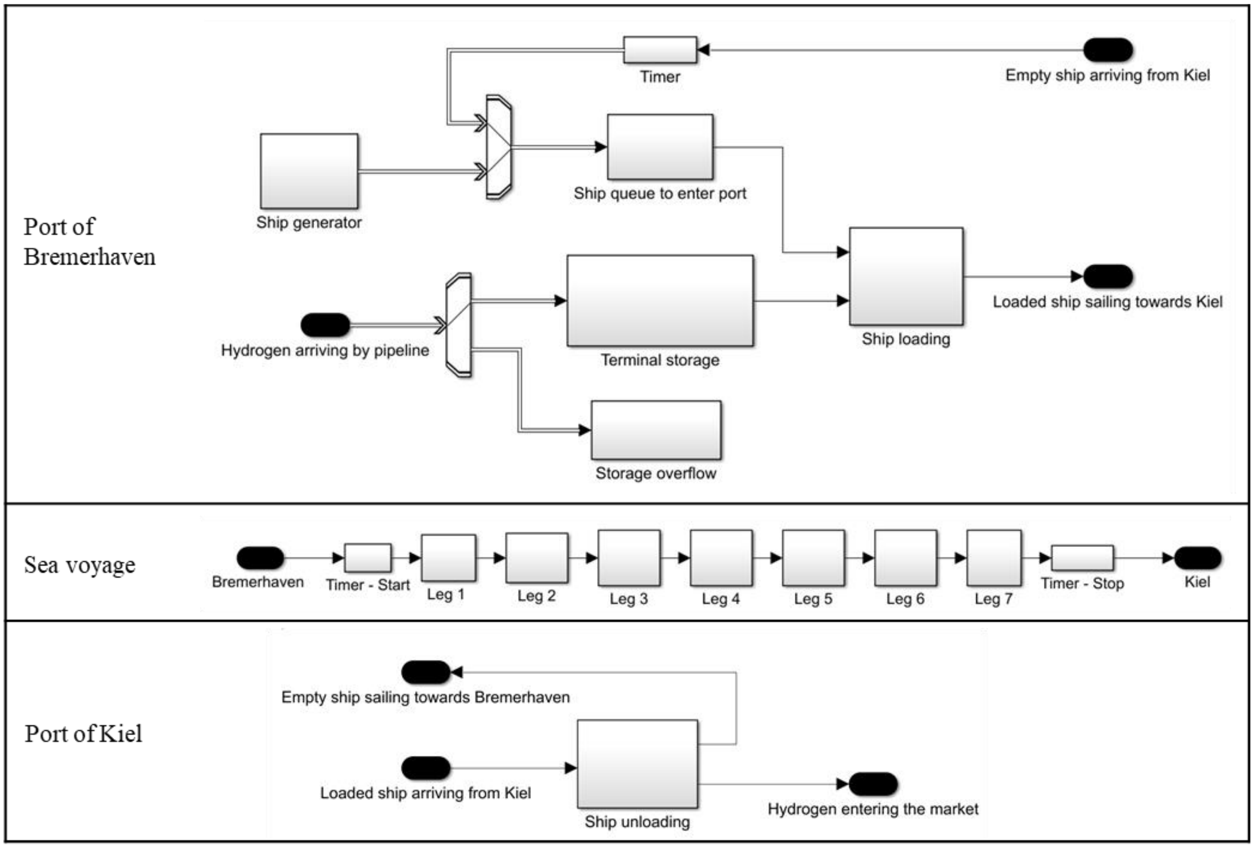

Figure 4: DES modelling of the Port of Bremerhaven, sea voyages, and Port of Kiel. The sea voyage Kiel-Bremerhaven is modelled in the same fashion as the distance Bremerhaven-Kiel.

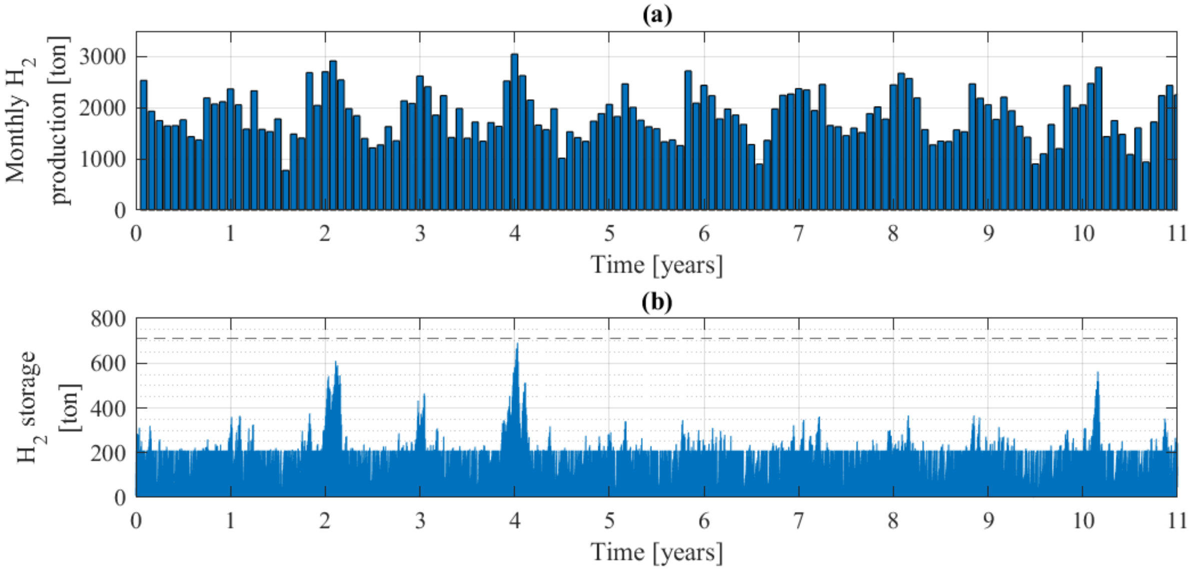

Figure 5: (a) Monthly hydrogen production and (b) the corresponding amount of hydrogen waiting for onward transport in Bremerhaven using a ship with net cargo carrying capacity of 209 ton operating as per Table 2. A storage capacity of 709 ton is sufficient to ensure that no production is lost.

With the help of the DES model, we iteratively find that a terminal storage capacity of 709 ton makes it possible to reduce the required net hydrogen cargo carrying capacity of the ship from the preliminary estimated 235 ton to 209 ton, assuming that the ship's speed is as per Table 2. For this solution, Figure 5 presents the amount of hydrogen waiting in the intermediate storage in Bremerhaven as a function of time together with the corresponding monthly production rates. As per the figure, the peak storage value appears at the start of year 4 as a result of a slightly higher than normal hydrogen production, indicating that that the required storage capacity is sensitive to variations in the production rate. As shown in Figure 6, which shows in higher detail the development of the production rate together with corresponding development of the storage volume during the considered period, the increase in storage volume is a result of an increase in the frequency of days with high production.

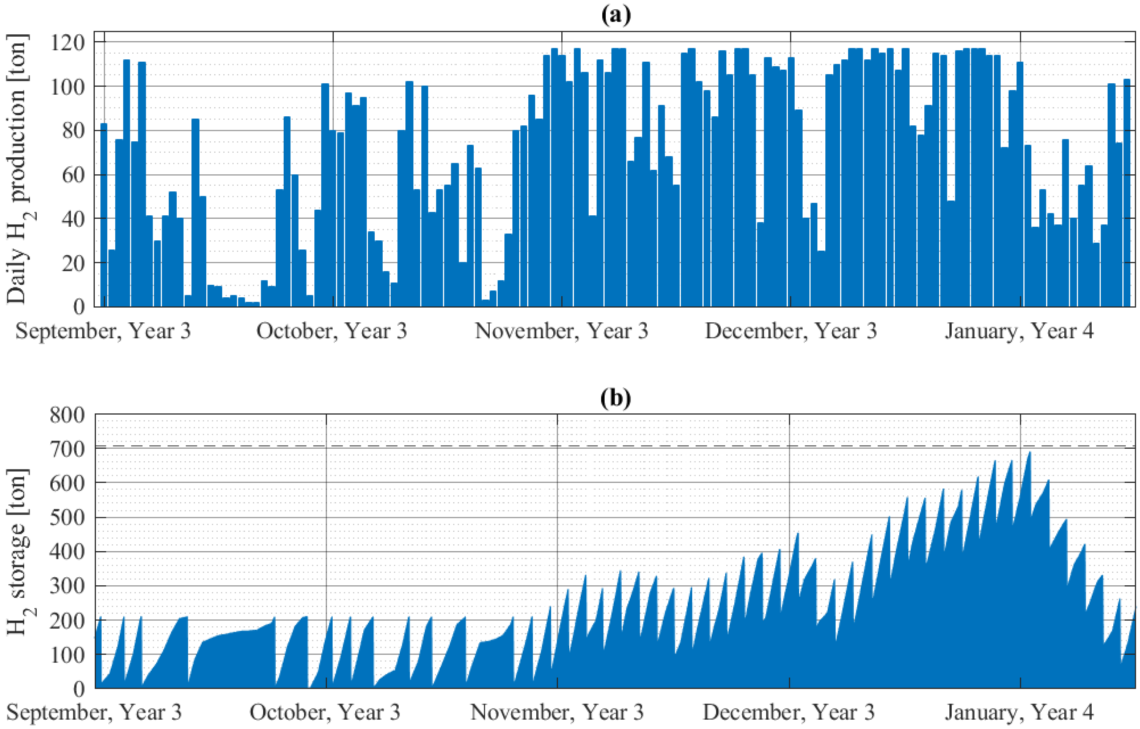

Figure 6: Detailed illustration of (a) the development of the daily production rate and (b) the resulting storage volume during the end of year 3 and start of year 4.

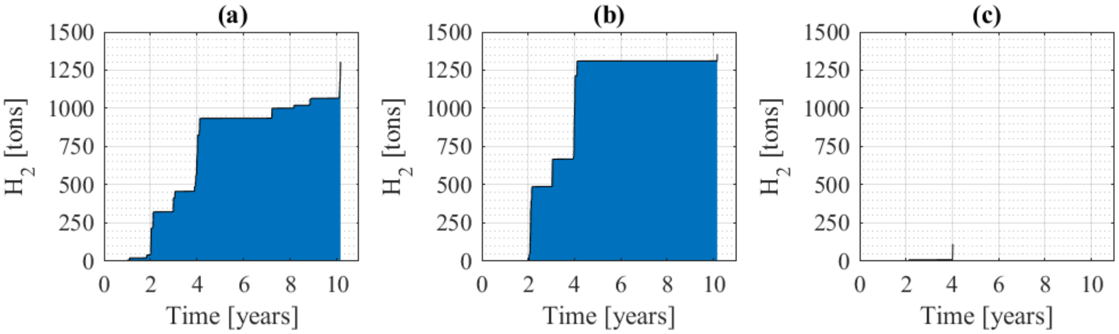

Figure 7: Amount of lost production for (a) 50 % reduced intermediate cargo storage (709 → 355 ton), (b) 10 % reduced ship cargo capacity (209 → 188 ton), and (c) reduced ship design speed (14 → 12 knots).

As also shown in Figure 5, except for a few short periods of high production, during most of the simulated operating years only a fraction of the storage capacity is utilized. This indicates that the solution is not particularly resource efficient. Measures that could be taken to reduce such waste during an average year include a reduction of the capacity of the intermediate storage and or of the transport system. To assess the cost of such measures in terms of the resulting production loss, we simulated the production losses resulting from the following system modifications: (a) reduction of the capacity of the intermediate storage by 50 % from 709 to 355 ton, (b) reduction of the ship's cargo carrying capacity by 10 % from 209 ton to 188 ton, and (c) reduction of the ship's design speed by 2 knots from 14 to 12 knots. Figure 7 presents the resulting production losses separately for each modification. As per the figure, both modification A and modification B results in a cumulated production loss of around 1 250 ton, corresponding to an annual average of 114 ton, which represents 0.5 % of the average annual production. Modification C results in an insignificant cumulated production loss of around 100 ton, corresponding to an annual average of around 10 ton. Based on engineering judgement we assess that both modification A and C would result in significant savings that would exceed the costs associated with the resulting production loss. Hence, we decide to adopt both modifications.

For the selected system design modifications, involving an intermediate storage capacity of 355 ton and a ship with a net hydrogen carrying capacity of 209 ton and a design speed of 12 knots,
Figure **8** shows the simulated development of the storage volume, the cumulated production loss, and estimated monthly production losses.

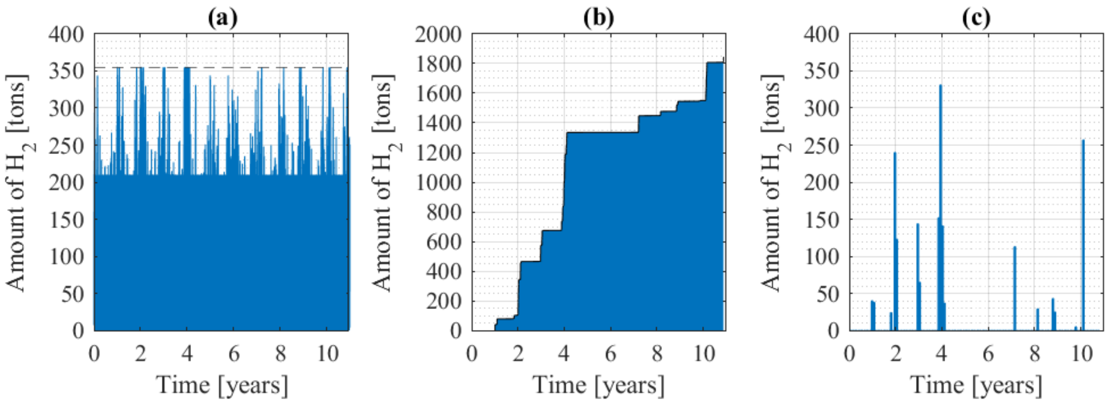

Figure 8: Development of the (a) storage volume, (b) cumulated production loss, and (c) monthly production losses for the selected system design involving an intermediate storage capacity of 355 ton and a ship with a net hydrogen carrying capacity of 209 ton and a design speed of 12 knots.

As per Table 4, for each considered hydrogen carrier we specify a simplified parametric ship design meeting the above defined requirements in terms of net hydrogen cargo carrying capacity and design speed. The dimensions and deadweight (DWT) of the ships are specified based on reference ships provided by Clarksons Research (2024), whereas the power demand at different speed are estimated as per Eq. 1.

$$V_{estimated} = \left(V_{ref\_avg} - m_v\right) \cdot \left(\frac{\sum P_{me}}{0.75 \cdot MCR_{avg}}\right)^{\frac{1}{3}} \qquad (1)$$

, where V_{ref_avg} is a ship type- and size-specific statistical mean of distribution of ship speed defined as $V_{ref\_avg} = A \; x \; B^c$, where A, B, and C are given by IMO (2021). Parameter m_v is the considered ship's performance margin, defined as 5 % of V_{ref_avg}, or one knot, whichever is lower. MCR_{avg} is a ship type- and size-specific statistical mean of distribution of MCRs for main engines and is calculated as $MCR_{avg} = D \; x \; E^F$, where D, E, and F are given by (IMO, 2021). Because diesel engines should not be operated below around 30 % of their MCR, the ships' power demand at low speed is calculated per Eq. 2.

$$P_{min} = 0.3 * \frac{P_{me(14\ knots)}}{0.85} \qquad (2)$$

Table 4: Specification of transport ships based on reference ships (Clarksons Research, 2024).

Hydrogen carrier	CH2	LH2	Ammonia	LOHC
Net H2 carrying capacity	209 ton	209 ton	209 ton	188 ton
Type of ship	Gas tanker	Container ship	LPG/Ammonia carrier	Chemical tanker
Required ship capacity (m^3, TEU, or DWT)	9010 m^3, 6800 DWT	140 TEU (70 FEU), 2010 DWT	209 ton x 5.62 ≈ 1175 ton	209 ton x 15.87 ≈ 3317 ton
Length	120 m	80 m	72 m	86 m
Beam	21 m	14 m	12 m	14 m
Draft	7 m	4 m	4 m	6 m
P_{me} (12 knots)	1660 kW	880 kW	1060 kW	1600 kW
P_{me} (6.5 knots)	590 kW	310 kW	375 kW	565 kW
P_{me} (5 knots)	590 kW	310 kW	375 kW	565 kW
Average specific fuel consumption	190 g / kWh	190 g / kWh	190 g / kWh	190 g / kWh

Each of the considered hydrogen carriers is associated with energy penalties related to the what is often referred to as ‘packing’ and ‘unpacking, i.e., the processes of converting hydrogen to the desired transportation form, and subsequently to convert it back to hydrogen at the transport destination. For some of the energy carriers there is an additional loss in terms of boil-off. In the present study, such losses are assumed to be as per Table 5. As per the table, because many of the processes have not yet been applied on a large scale, there is a significant degree of uncertainty regarding their energy consumptions (IRENA, 2022). This appears to be especially true for LOHCs. There are many different types of LOHCs and there is a large variation between the energy consumption values reported in the literature for their "packing" and "unpacking". In part, this may be due to differences between theoretical values and the actual consumption of existing equipment. The values used in this study are intended to be indicative of ‘typical’ LOHCs.

Table 5: Energy penalties and boil-off estimates for the considered energy carriers (IRENA, 2022) (Parks, Boyd, Cornish, & Remick, 2014) (Melcher, George, & Paetz, 2021).

Energy carrier	Energy consumption, packing	Energy consumption, unpacking	Boil-off
CH_2	2 – 4 kWh/kg-H2	negligible	negligible
LH_2	10 – 12 kWh/kg-H_2	negligible	Boil-off 0.05-0.25 % / day
Ammonia	0.5 – 0.8 kWh/kg-NH_3	4 – 11 kWh/kg-H_2	Boil-off 0.004 % / day
LOHC	9 - 10 kWh/kg-H_2	6-12 kWh/kg-H_2	negligible

Based on the above defined data and assumptions we calculate the energy consumption for an average round trip as per Figure 9. As per the figure, for each energy carrier we calculate both an optimistic value, based on the lower values defined in Table 5, and a pessimistic value, based on the higher values of the same table. As can be seen from the figure, we find that for both the pessimistic and optimistic assumptions, CH_2 appears to be the overall most energy-efficient option. Whether LH_2 or NH_2 is the second most cost-effective solution depends on assumptions concerning energy penalties related to hydrogen packing and unpacking.

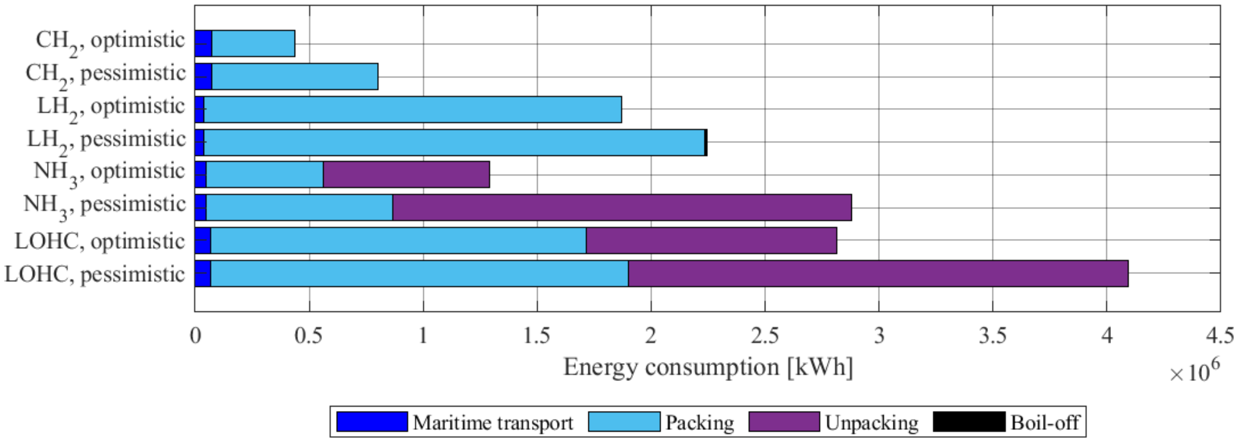

Figure 9: Comparison of the energy consumption of the different solutions for an average round trip.

CONCLUSIONS

In this study, a discrete-event simulation-based approach is applied to a case study to derive concepts for short sea shipping of green hydrogen produced at an offshore wind farm over a sea distance of around 130 NM. To meet the transport demand during a typical year, our simulation results indicate that a ship with a net hydrogen transport capacity of 209 ton and a design speed of 12 knots is needed. Among four considered hydrogen carriers, CH_2, LH_2, NH_3, and a LOHC, we find that CH_2 provides the overall best energy-efficiency. The simulation results further reveal that it does not appear resource-efficient to invest in the transport and storage capacities needed to be able to handle the expected 11-year maximum production peak without production limitations, as this would result in significant overcapacity most of the time. Future research is recommended to address safety, regulatory, and cost-efficiency aspects, as well as to investigate the required port infrastructure in detail, and to investigate potential hydrogen carrier specific differences in terms of loading/unloading times. Future research is also recommended to address uncertainties regarding how much energy is lost in the packing/unpacking of different hydrogen carriers, or through boil-off.

CONTRIBUTION STATEMENT

Author 1: Conceptualization; data curation, methodology; writing – original draft. **Author 2:** data curation, writing –review and editing. **Author 3:** data curation, writing –review and editing. **Author 4:** data curation. **Author 5:** data curation. **Author 6:** writing – review and editing. **Author 7:** conceptualization; supervision. **Author 8:** writing – review and editing. **Author 9:** conceptualization; supervision.

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