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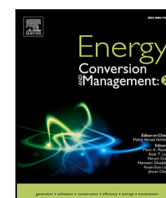
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# Energy and power density as key metrics for assessing hydrogen carriers as alternative fuels in maritime applications

E.S. van Rheenen<sup>a,\*</sup>, A.A. Kana<sup>a</sup>, K. Visser<sup>a</sup>, J.T. Padding<sup>b</sup>

<sup>a</sup> Department of Maritime and Transport Technology, Faculty of Mechanical Engineering, Delft University of Technology, Mekelweg 2, Delft, 2628CD, South-Holland, The Netherlands

<sup>b</sup> Department of Process and Energy, Faculty of Mechanical Engineering, Delft University of Technology, Leeghwaterstraat 39, Delft, 2628CD, South-Holland, The Netherlands

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## ABSTRACT

Alternative fuels are essential to decarbonising maritime transport, provided they retain high energy and power density; hydrogen carriers fulfil these criteria and represent a promising fuel option. This research quantifies the power-energy trade-offs of four hydrogen carrier fuels: namely, sodium borohydride, ammonia borane, n-ethylcarbazole, and dibenzyltoluene. Each hydrogen carrier is combined with four energy converters: proton exchange membrane fuel cell (PEMFC), internal combustion engine (ICE), solid oxide fuel cell (SOFC), and gas turbine, respectively, resulting in 16 outcomes, which were assessed using Ragone plots. For each hydrogen carrier, one energy converter is selected as a case study. Four reference cases are also examined: marine diesel oil (MDO) and methanol combined with ICE, ammonia with SOFC, and liquid hydrogen with PEMFC. These 8 case studies (carrier and converter combinations) are evaluated for performance across several shipping applications. The results indicate that ammonia borane combined with ICE and sodium borohydride combined with a PEMFC offer energy and power density profiles suitable for various vessel types, including inland ships and ocean-going vessels. These combinations also show potential for specialised vessels such as fishing boats, dredgers, tugs, and ferries, which operate under unique load profiles and duty cycles. Compared with alternative fuels, such as ammonia, methanol, and liquid hydrogen, hydrogen carriers can demonstrate higher energy and power densities. Under specific circumstances, they may achieve performance comparable to MDO, highlighting their potential for zero-emission maritime propulsion.

## 1. Introduction

The maritime industry currently generates negative impacts on the overall environment, emitting 3% of total greenhouse gas (GHG) emissions, as well as pollutants like sulfur oxides (SO<sub>x</sub>) and nitrogen oxides (NO<sub>x</sub>) [1,2]. In response, the International Maritime Organisation (IMO) has set the target of achieving net-zero GHG emissions by 2050 [3]. Beyond global regulations, many vessels operate in ecologically sensitive environments, such as inland waterways or protected nature reserves, where emission reductions are critical for conservation. Several measures exist to reduce the emissions from a ship [4–6]. The most promising way is the introduction of alternative fuels [6]. These alternative fuels range in their greenhouse gas emission reduction potential, from reducing emissions, such as LNG, to being completely carbon-free, such as ammonia or hydrogen [6]. However, these fuels often have lower gravimetric or volumetric energy density than traditional fuels.

Hydrogen carriers offer a promising solution to this challenge, as these chemicals can store and release hydrogen on demand while achieving significant energy densities. Examples of these hydrogen carriers are liquid organic hydrogen carriers (LOHCs) or sodium borohydride (SB) and potassium borohydride (KB) [7–9]. These hydrogen carriers are accompanied by technical considerations that require careful evaluation [7]. Next to alternative fuels, more options to convert chemical energy into usable energy are under investigation. Conventional energy converters, such as internal combustion engines (ICE), can be powered by hydrogen and reduce emissions to values compliant with Stage V or Euro7 standards [10]. However, as most alternative fuels have very different combustion characteristics and a lower energy density, a different, more efficient energy converter might be beneficial. Fuel cells, such as the proton exchange membrane fuel cell (PEMFC) or solid oxide fuel cell (SOFC), are generally more efficient but face

\* Corresponding author.

E-mail addresses: [EvanRheenen@proton.me](mailto:EvanRheenen@proton.me) (E.S. van Rheenen), [A.A.Kana@tudelft.nl](mailto:A.A.Kana@tudelft.nl) (A.A. Kana), [K.Visser@tudelft.nl](mailto:K.Visser@tudelft.nl) (K. Visser), [J.T.Padding@tudelft.nl](mailto:J.T.Padding@tudelft.nl) (J.T. Padding).

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technical challenges [11]. Besides these other energy converters, optimised energy management systems, batteries, and different control systems can potentially optimise the overall energy efficiency of a vessel.

Currently, many different ships, each with their own specific needs, sail around the world. Some ships are limited by available volume, others by weight. Operational demands vary as well: some vessels experience high peak power requirements, while others operate under steady loads. Historically, marine diesel oil (MDO) with ICEs satisfied most operational demands, but at a high environmental cost. As the industry transitions to alternative fuels and converters, these once-reliable performance characteristics are no longer guaranteed. Different ship types will likely require tailored combinations because alternative fuels and alternative energy converters differ significantly in power output, efficiency, and energy density. Understanding how these combinations perform in terms of power and energy density is therefore crucial to evaluating their suitability for different maritime applications.

Comparative studies that integrate system-level optimisation and evaluate both energy and power density of alternative marine fuels remain scarce. Several works have compared various more conventional alternative fuels (e.g., liquid hydrogen, methanol, ammonia) with different converters (ICE, gas turbine, PEMFC, SOFC). However, these focus mainly on fuel cells and omit hydrogen carriers (like LOHCs, SB or KB) or heat integration [11,12]. Studies that incorporate hydrogen carriers do exist. Most of these studies concentrate on a single fuel family, such as liquid organic hydrogen carriers (LOHCs) [8,13–16]. Others provide limited multi-fuel comparisons [17–19], or only broad, high-level overviews [20,21]. Finally, some single-fuel marine studies incorporate detailed integration, but without cross-fuel comparisons [9, 22]. To the authors' knowledge, no study has yet compared SB, AB, NEC and DBT on a system-level with their associated converters, including waste-heat integration and simultaneous evaluation of power and energy density.

Moreover, these other studies often neglect hydrogen carriers, only regard specific fuels, or fail to optimise for system-level integration. Additionally, they do not sufficiently account for the wide variation in energy and power demands across different ship types. This paper addresses these gaps by systematically evaluating fuel-converter combinations in terms of their energy and power density, considering diverse vessel requirements. While the underlying methods are well established, for example by [11], the integrated systems, thermochemical property data for the carriers (SB, AB, NEC and DBT), and the reactor-converter configurations are new, and the resulting performance data across multiple hydrogen carriers and energy converters, including their overall system size and weight, are reported here for the first time. Because these carriers differ strongly in their dehydrogenation behaviour and heat integration requirements, the system-level results cannot be extrapolated from existing single-fuel or carrier-family (such as LOHC) studies. The results are applied to representative ship types, explicitly linking power and energy density constraints to endurance and power requirements of different vessel types. This allows assessment of the applicability of these hydrogen carriers for different maritime applications. The key objectives of this study are to:

- Quantify the power and energy densities of selected hydrogen carriers and energy converters
- Evaluate hydrogen carrier-converter combinations for representative marine applications using Ragone plots
- Provide a comparative assessment based on size and weight of SB, AB, NEC and DBT in fuel-converter systems, including waste-heat integration

This paper, thus, evaluates alternative fuels and converters, focusing on hydrogen carriers. To cover both conventional and emerging options, this study evaluates eight fuels. Firstly, there are four hydrogen

carriers: sodium borohydride (SB), ammonia borane (AB), dibenzyltoluene (DBT) and n-ethylcarbazole (NEC). Secondly, there are four reference fuels: marine diesel oil (MDO), ammonia, methanol (MeOH), and liquid hydrogen (LH2). These fuels are analysed in combination with different energy converters, including ICEs, gas turbines (GT), PEMFCs, and SOFCs. By comparing their energy and power densities using Ragone plots, this study provides new insights into the trade-offs of alternative fuel-converter systems and their suitability for different maritime applications.

A fundamental challenge in comparing hydrogen carriers lies in their distinct system integration requirements, which result in different combinations of reactors, heat integration schemes, and converters. These differences make comparison complicated. The contribution of this work is therefore an applied one: it extends established system-level techniques to new integrated systems and to hydrogen carriers that have not been assessed in this way, comparing all fuel-converter combinations on equal terms using power and energy density as unifying performance metrics.

## 2. Method

Fig. 1 provides an overview of the entire process to deliver power to the ship's propeller, illustrating the various components that influence either energy density or power density. This section starts by outlining the relationship between power and energy density. Section 2.2 goes into detail on the energy density of these fuels, describing what is relevant. Furthermore, Section 2.3 describes the energy converters and other components relevant to calculating the overall power density. In Section 2.4, the usefulness of waste heat integration and its influence on the energy density is briefly discussed. Section 2.5 discusses assumptions and system boundaries. Finally, Section 2.6 describes how the 16 hydrogen carrier and energy converter combinations will be assessed.

### 2.1. Relation power and energy density

Some components in Fig. 1, such as the fuel and empty fuel storage, influence the energy density; other components, like the hydrogen release reactor and heat exchangers, affect the power density. The power and energy density are closely related and can be visualised in a Ragone plot [11]. The Ragone plot requires an expression for the power density and the energy density, both of which require the following definitions:

- $P$  is Power, delivered by a power converter, in [W]
- $E$  is Energy in [J]
- $\eta$  is the combined efficiency of the energy converter and reactors
- $W$  is the energy density of the fuel, in [J/kg]
- $P'$  is the power density of a single component (the power converter), in [W/kg]
- $P''$  is the power density of the whole system, in [W/kg]
- $m_w$  is the mass of the fuel, including the tank, in [kg]
- $m_p$  is the mass of the power converter, in [kg]
- $t$  is the sailing time, in [s]

The required energy,  $E$ , to sail a certain distance can be expressed as follows [11]:

$$E = \frac{Pt}{\eta} \quad (1)$$

The amount of fuel required to fulfil this demand can be expressed with  $m_w = E/W$ , so:

$$m_w = \frac{Pt}{\eta W} \quad (2)$$

To calculate the power density,  $P''$ , we define it as follows: the power of the system, divided by the total mass of the system.

$$P'' = \frac{P}{m_p + m_w} = \frac{P}{m_p + \frac{Pt}{\eta W}} \quad (3)$$

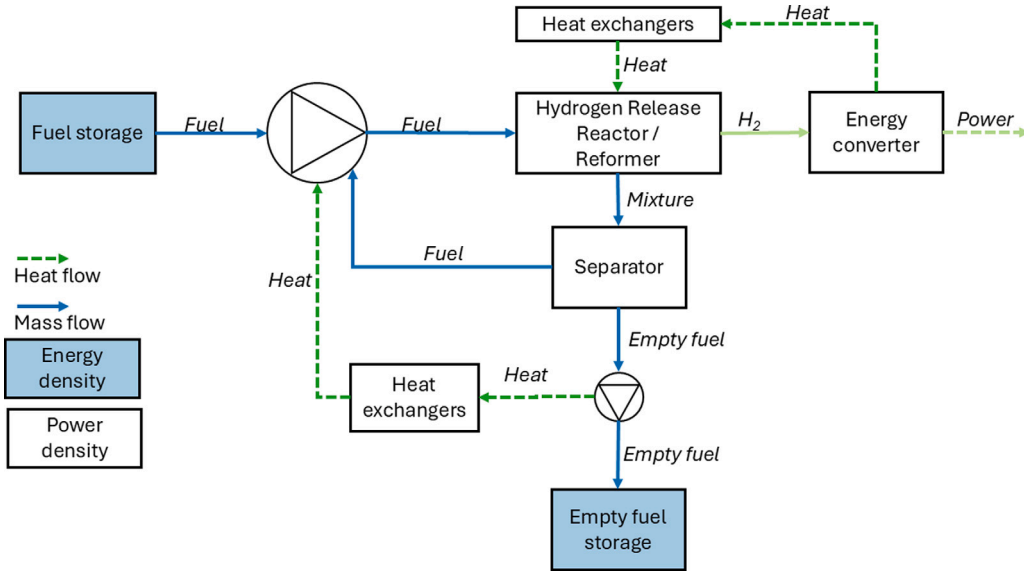


Fig. 1. Schematic of mass and heat flows from fuel storage to propulsion, including optional storage of spent fuel and integration of heat exchangers.

If we then fill in the definition of the power density of the power converter,  $P' = P/m_p$ , we get the following equation for the power density of the whole system, also used by [11]:

$$P'' = \frac{P' m_p}{m_p + \frac{P' m_p t}{\eta W}} = \frac{P'}{1 + \frac{P' t}{\eta W}} \quad (4)$$

Referring back to energy, Eq. (4) shows that, when  $t$  goes to infinity,  $P_E$  goes towards zero [11]. However, the effective energy density of the system,  $W'' = P'' t$ , does not go towards zero but tends to  $\eta W$  as  $t$  goes to infinity.

Eq. (4) shows that there is a relation between the effective power and energy density of a system. This relation can be plotted to compare different energy systems, as previously done to compare fuel cell systems for example [11]. Each of the different systems has its own efficiencies and power densities. Eq. (5) gives an example of how to combine the power densities [11].

$$P' = \left( \frac{1}{P'_{EC}} + \frac{1}{P'_{reactor}} + \frac{1}{P'_{HEX}} \right)^{-1} \quad (5)$$

## 2.2. Fuel properties and energy density

The traditional way of calculating the energy density of hydrogen carriers is to evaluate the amount of hydrogen inside the carrier, for example, by weight percentage. These energy densities can be seen in Table 1 and give a relative objective overview of the energy density of these specific hydrogen carriers. However, this method has several flaws, including the omission of key factors such as specific reaction characteristics [23], bulk fuel densities [24], and tank weight [25]. So, it does not give an accurate overview of the amount of energy available inside each of the carriers.

### 2.2.1. Hydrolysis reaction

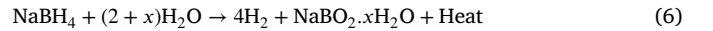
SB reacts with water to release hydrogen. This reaction with water is not useful in many settings, as the water often also needs to be brought along; however, ships have a distinct advantage here, as there is water all around. The reaction, visible in Eq. (6), shows that half of the hydrogen released stems from water. This means that the overall energy density can be doubled, especially as, theoretically, no (large) water storage is required. Hydrolysis of SB by direct use of seawater is chemically possible; however, in practice it leads to rapid fouling, chloride-induced corrosion, and contamination of the  $\text{NaBO}_2 \cdot x\text{H}_2\text{O}$  mixture, making regeneration extremely challenging. For this reason, it

Table 1

Theoretical energy densities of hydrogen carriers, calculated based on the number of hydrogen atoms, which can be extracted from the carrier. The volumetric energy density is based on the gravimetric energy density and substance density.

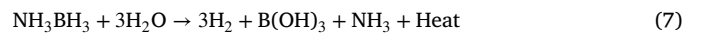
|                                                           | Gravimetric energy density [MJ/kg] | Volumetric energy density [MJ/L] |
|-----------------------------------------------------------|------------------------------------|----------------------------------|
| Sodium borohydride ( $\text{NaBH}_4$ )                    | 12.8                               | 13.7                             |
| Ammonia borane ( $\text{NH}_3\text{BH}_3$ )               | 23.5                               | 14.4                             |
| Dibenzyltoluene ( $\text{C}_{21}\text{H}_{38}$ )          | 7.4                                | 7.0                              |
| N-ethylcarbazole ( $\text{C}_{14}\text{H}_{25}\text{N}$ ) | 7.0                                | 6.6                              |

is foreseen that purified water, e.g. from a Reverse Osmosis (RO) unit, will be used on board of ships. Note that the size of this RO unit can be minimised in case water is recovered from the exit stream of the power converter (ICE, GT or fuel cell).



$x$  ranges in this equation from 0 to 4, depending on the circumstances in which the reaction occurs.

Similarly, AB also reacts with water. Unlike SB, AB releases hydrogen and ammonia. The energy density of the fuel is easy to calculate when only the hydrogen is used. Ammonia also has to be used to use more of the available energy. However, this proves to be more difficult. Firstly, ammonia dissolves excellently in water [26]. The reaction from Eq. (7) has to occur in excess water to avoid the boron oxide's crystallisation. Because of this excess, most of the ammonia will dissolve in the available water and must be extracted before it can be used. It has been mentioned that not all ammonia will dissolve in water; some of it will be released in the gas phase [23]. There are several methods to extract ammonia from pure water, but the solution also entails boron oxide and, possibly, some unreacted AB. Luckily, extracting ammonia from contaminated water is a well-researched field, due to the many other applications this extraction process has [27]. If the ammonia is successfully removed, it can either be burned directly or decomposed into hydrogen and nitrogen. To avoid complicating onboard processes, this paper does not consider the latter option.



### 2.2.2. Bulk density

Both SB and AB are powders. The particle density is often used to calculate the volumetric energy density, from the gravimetric energy

density. However, powders have two types of densities: a particle density and a bulk density. Powders or granular materials are made of individual particles, and between these particles, there are voids, which lower the overall density of the material [24]. Generally, only the particle density (e.g., the density of one single grain) is provided. However, the bulk density is much lower than the particle density, due to the voids between particles [24]. For example, the particle density of SB is  $1.07 \text{ g/cm}^3$ , whilst the bulk density is much lower. For powder, it can be  $0.550 \text{ g/cm}^3$ , whilst granules have densities in the order of  $0.510 \text{ g/cm}^3$  [24,28]. Other sources assume a 60% reduction in density [29]. This large difference negatively influences the volumetric energy density of both SB and AB. In this research, the density of both SB is assumed to be  $0.550 \text{ g/cm}^3$ . Based on preliminary, unpublished, in-house laboratory measurements and handling observations conducted by the authors, the bulk density of AB is estimated at approximately  $0.4 \text{ g/cm}^3$ . This bulk density is used to calculate the volumetric energy and power density of AB. Given the preliminary nature of the estimate, further analysis is required to assess the exact bulk density; at the moment, it is an estimate regarding the order of magnitude.

### 2.2.3. Spent fuel

Unlike traditional or conventional alternative fuels, hydrogen carriers are circular. This implies that the empty fuel, often called spent fuel and denoted by SF, must be returned to shore for regeneration. It has been hypothesised that the spent fuel can be stored in the same tanks as the fuel [20]. This requires only one empty tank to serve as a transfer buffer: you pump the spent fuel into it, and then pump new fuel into the now-empty tank, a process that avoids the need for dedicated spent fuel storage and saves weight and space. Careful tank design and mass distribution are essential to avoid potential sloshing and stability impacts [20]. However, this concept remains theoretical and has not yet been demonstrated in a maritime setting. A detailed assessment of tank stability and sloshing is beyond the scope of this study, but these concerns should be addressed in future design work.

Additionally, enhancing complexity, both SB and AB have spent fuels that are heavier than the original fuel. Eqs. (6) and (7) show the products of the hydrolysis reaction. The  $x$  in the equation for SB (Eq. (6)) depends on the temperature and other circumstances, and ranges from 0 to 4 [30]. Usually, in the circumstances after the hydrolysis reactor,  $x$  equals 2 [30]. Practically, this means an increase in weight of 2.7 times the original weight of the fuel. This means that the substance in the fuel tanks is 2.7 times heavier when re-entering the harbour as compared to leaving (if all fuel is used). For AB, this difference is only 2 times. These differences are significant and greatly reduce the energy density of the fuel, but one should note that this only occurs during the voyage. Especially if not all fuel is used, the effect is mitigated. It is thus hard to estimate the exact result of this effect. In this paper, we will assume that  $x = 2$ , as drying the fuel onboard the ship to enhance the energy density is not considered practical nor feasible.

The practical influence of the spent fuel on the overall space and weight the fuel requires is investigated in Section 4.2. To assess the effect of the spent fuel, the pure fuel and a mixture are compared in this section. The mixture consists of 1/3 fuel and 2/3 spent fuel for two reasons: first, a ship is unlikely to use all its fuel; a safety margin is always maintained. Secondly, in a container ship case study, most trips would use only 2/3 of the maximum energy [31].

### 2.2.4. Dehydrogenation energy requirements

The LOHCs have different properties than the boron-based carriers, requiring energy during the dehydrogenation process. Thorough heat integration is extremely important to avoid energy losses. These energy losses can be significant; if the hydrogen from DBT has to be used to provide heat for the dehydrogenation process, this can result in a loss of up to 35% of the total energy available [14]. NEC requires less energy

for dehydrogenation, and the dehydrogenation process occurs at lower temperatures. However, the losses can still be significant [19]. These losses can be reduced by using waste heat integration; however, this will also increase space requirements (e.g., for heat exchangers) and system complexity.

### 2.2.5. Handling considerations

Both SB and AB are stored as dry powders and must remain completely isolated from moisture during handling to prevent deliquescence and premature hydrogen release [24]. This makes onboard transport and dosing technically challenging, as these solids cannot be pumped like liquids and are sensitive to ambient humidity. Developing moisture-isolated feeding systems for these materials is a substantial engineering challenge and forms part of separate, dedicated research [24]. As this paper focuses solely on the mass, volume, and energy/power density implications of the fuels, the detailed engineering of such handling systems is not considered here.

In contrast, LOHCs are liquids under typical operating conditions and exhibit handling characteristics similar to conventional marine fuels such as MDO or HFO. Even NEC, which is solid at room temperature, becomes liquid at modest temperatures—comparable to the heating already required for HFO pumping [8]. Therefore, LOHC handling is assumed to be straightforward and falls outside the scope of this paper.

### 2.2.6. Tank weights

The tank weight is mentioned often as well when regarding the difference between the theoretical and practical energy density [11]. This is critical for liquid or pressurised hydrogen, due to the major limitations imposed on the tanks [25]. Hydrogen carriers do have some limitations on tank type, as do almost all fuels. For example, SB is either corrosive or reacts (forming hydrogen) when it comes in contact with many other metals; storage in a metal tank should thus be avoided. A plastic liner will already solve this issue [32]. AB is not well-known enough to know how to store this exactly; however, suppliers do note that it should be stored in a fridge. This is likely because of the thermolysis reaction, which can occur at relatively low temperatures and can possibly have devastating results [33]. So, a climate-controlled tank may be required, although there is no consensus on whether this is actually needed [34,35].

LOHCs do not have these issues, as they are not corrosive and do not easily react with other substances. All combined, for three of the four hydrogen carriers, the fuel tank does not appear to be a major consideration [8,36].

## 2.3. Power density

The power density consists of the power density of all relevant components to produce and use hydrogen on board the ship. The composition and quantity of components depend on the hydrogen carrier; a general overview is provided in Fig. 1. Auxiliary components such as pumps, which are required for all fuels, are not considered here. The main components are heat exchangers (if necessary), a hydrogen release reactor (which can also be a reformer or cracking system), the separator and the energy converter. This data is all combined, using Eq. (5). Different efficiencies (e.g. reactor efficiency and energy converter efficiency) are calculated by multiplication to find the overall efficiency. Finding the data to calculate the power density is done differently for each of the components.

### 2.3.1. Heat exchangers

Sizing of the heat exchangers is based on previous work [37]. First, complete heat integration is required to calculate the amount of heat each heat exchanger needs to transfer. Aspen Exchanger Design and Rating (EDR) is used to estimate the size and weight of each heat exchanger [38]. The materials from which the heat exchangers are constructed are not changed, which means that all similar-type heat exchangers are made from the same materials. It is also assumed that heat exchangers continuously scale with the power output; no discrete steps are expected.

### 2.3.2. Hydrogen release reactor and separator

Calculating the size of the release reactor can be done in several ways. One way is to use the kinetics of the governing reactions. However, the actual reactions are shaped not only by kinetics but also by factors such as reactor geometry and catalyst morphology, which substantially affect the dehydrogenation process [39,40]. Additionally, some hydrogen carriers release hydrogen in multiple steps, each with its own characteristic kinetics [39], while certain reactions cannot be encompassed by 'simple' first, second or zero-order reactions. SB, for example, likely follows the Langmuir-Hinshelwood mechanism, where the reaction order is defined by, amongst others, the temperature [41]. In short, these reactions are difficult to capture in a theoretical framework.

Another way to estimate the reactor size is to calculate the required hydrogen output flow. Combined with a catalyst to estimate effectiveness, this can be used to calculate the required hydrogen carrier flow. The throughput time (again determined by the catalyst) can be used to estimate the size of the volumetric part of the reactor. The amount of catalyst depends on the type of reactor used [42]. The combined volume and mass of the catalyst and hydrogen carrier determine the volume and mass of the overall reactor.

The required output flow is calculated in the model. The throughput time comes from experimental data from different studies. For each of the hydrogen carriers, different studies are used to find average throughput times [43–45]. These experiments are conducted in a lab setting, with relatively low catalyst amounts, and are often in batch reactors. Intrinsic catalytic reaction rates (per unit catalyst) are independent of reactor scale provided the system remains reaction-controlled and transport limitations are avoided, while the required reactor size follows from the required catalyst inventory and bed properties [46]. When scaling up, a continuous reactor is preferred over a batch reactor. Because different reactor types require different amounts of catalyst, the catalyst-to-reactor-volume ratio may change. For heterogeneous (e.g. reactions with two phases) reactors, there are two basic types of two-phase reactors: packed bed (PBR) and fluidised bed reactors [47]. In PBRs, catalyst particles occupy a defined fraction of the reactor volume, while the remaining volume consists of void space through which the reactants flow [48] (the hydrogen carrier and hydrogen in this case). As PBRs are the most widely used reactors for heterogeneous catalytic processes [47], and they have already been considered for hydrogen carriers [49], they are assumed to be used for hydrogen carriers as well.

In this setting, a PBR with a void fraction ( $\epsilon$ ) of 0.5 is estimated. This estimate represents a typical balance between sufficient reactive area in and good flow properties through fixed-bed reactors. Typical packed-bed void fractions range from approximately 0.4 to 0.6, depending on catalyst particle geometry and packing, making  $\epsilon = 0.50$  an appropriate assumption [40,48]. So, reactor volume can be estimated from the fluid volume and void fraction ( $\epsilon$ ).

$$V_{\text{reactor}} = \frac{V_{\text{fluid}}}{\epsilon} \quad (8)$$

To estimate the reactor weight, two densities must be used: one for the hydrogen carrier (mixture) and one for the catalyst.

The current data are derived from laboratory-scale systems, whereas shipboard application requires reactors at significantly larger scale [50]. Reactor scale-up is not straightforward; certain critical parameters must remain constant during scaling [51]. At the same time, mass transfer, heat transfer, impulse transfer and mixing depend strongly on reactor design and scale [51].

Packed-bed reactors can be scaled in multiple ways. Two approaches are not fundamentally constrained for the application on ships. First, numbering-up can be applied by operating multiple identical reactors in parallel. In this case, each reactor retains the same geometry and operating conditions, and therefore the local mass transfer, heat transfer and impulse transfer characteristics remain unchanged. Second,

a packed-bed reactor can be designed such that the relevant critical parameters (e.g., catalyst loading and residence time) are preserved during scale-up [51]. Since constant catalyst loading and catalyst activity per unit volume are assumed in this study, assuming the reactor performance stays similar to the one at larger scale is consistent with these established scale-up approaches.

The reactor volume scales directly with throughput times and required hydrogen throughput. For certain cases, the resulting reactor size may exceed practical shipboard spatial constraints. In such cases, the combination would be considered infeasible at system level. The present methodology therefore evaluates order-of-magnitude physical requirements rather than guaranteeing deployable configurations.

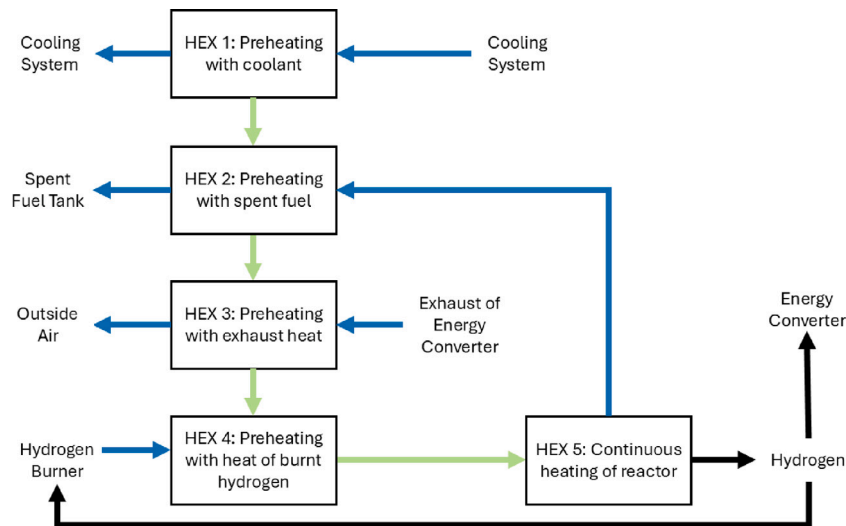
When designing the separator, two types of operation are considered in this study: normal and emergency. In normal operation, the aim of the separator is the splitting of fuel and spent fuel, or fuel, spent fuel and water. In an emergency operation, the separator is designed as an emergency dump vessel. In case of reactor malfunction (e.g., overheating), the reactor contents can be rapidly transferred to the separator to stop further hydrogen release and limit thermal decomposition of the hydrogen carrier. Because the detailed separation performance depends strongly on the specific carrier system and downstream unit operations (e.g., stripping/distillation for aqueous ammonia), separator sizing in this study is governed by the emergency dump requirement. The separator volume is therefore assumed to be 110% of the total reactor geometric volume, providing margin for level control, and minor additional hold up in piping and internals.

### 2.3.3. Energy converters

Both manufacturers (such as [52,53] for ICEs, [54,55] for GT and [56–58] for PEMFC) and literature (e.g. [59–61]) have been consulted to estimate the power density of energy converters. The differences between these can be considerable. When literature has lower estimates than industry, it may be for three reasons: (1) literature using (slightly) outdated data, (2) industry slightly overestimating their data and (3) the inclusion or exclusion of the balance of plant. Higher estimates reported in the literature often reflect projections of future performance (e.g., authors anticipating that power density will increase beyond current levels). In this study, a large dataset was compiled from both literature and established manufacturers. These differences can be addressed through Ragone plots, which employ upper and lower bounds to capture the range of valid estimates. All data is compared, and significant outliers are removed, after which the upper and lower bounds are used. One piece of literature [62] was removed as the reported power densities were an order of magnitude higher than consistent ranges found in vendor data and other reviews.

### 2.4. Waste heat integration

Extracting hydrogen from hydrogen carriers commonly occurs at elevated temperatures, ranging from 70 to over 600 °C, depending on the hydrogen carrier. This results in a heat demand. During the process of converting hydrogen to either electrical or mechanical energy, heat is produced. This heat is, again, produced at very different temperatures, depending on the energy converter. To enhance not only the overall efficiency of the system, but also the energy density (energy which can be used for propulsion) of the hydrogen carriers, a proper waste heat integration is crucial. Waste heat integration is imperative for LOHCs [14], but also important for boron-based carriers. Fig. 2 gives an overview of the various waste heat strategies that can be used to transfer heat towards the preheating and dehydrogenation processes. The approach is based on [19], where we previously calculated the effective energy density when optimal waste heat integration was used. Not all of these strategies can be applied to each hydrogen carrier or energy converter. To enhance readability and uniformity, we will always use the same numbers to indicate the heat exchangers, as mentioned in Fig. 2. This may result in combinations with, for example, only exchangers



**Fig. 2.** Waste heat strategies that can be incorporated, including numbering of heat exchangers. Heat exchangers are denoted by HEX. Not all strategies are applicable to each hydrogen carrier and energy converter. Approach based on [19].

2 and 3. Heat exchangers have a minimal temperature difference of 5 K. These heat exchangers are sized in Aspen EDR and accounted for in the power density. The upper bound of the energy density of the hydrogen carriers is assuming perfect waste heat integration, yet it still depends on the energy converter. For example, in a case where a PEMFC is used, the optimal strategy is determined with the PEMFC, not with a different energy converter. For large comparisons, such as in Section 3.1, this optimised data is used, as this section only compares different energy converters for each hydrogen carrier separately. When comparing combinations, a lower bound is used, which is achievable with very minimal heat integration (the PEMFC case), as there is usually low-temperature waste heat available.

## 2.5. Practical energy density and system boundaries

Having identified the limitations of the theoretical energy density, the following section derives a more practical formulation, along with the assumptions and system boundaries. Fig. 1 shows the system; all that falls outside this figure (such as how the power is used exactly) falls outside of the system boundaries. Inside the system boundaries fall the fuel and empty fuel storage, the heat exchangers, the hydrogen release reactors, and the separators. Even though heat exchangers are less important (as shown previously [37]) for SB and AB, they will still be considered here. Components which are comparable across fuels, such as fuel tanks and auxiliary pumps, are excluded. Similarly, water purification systems are excluded, as these are required regardless of the fuel; only a small amount of water is required for the dehydrogenation process, most can be recycled [19]. Components specific to a fuel and that significantly affect system size or mass (such as cryogenic storage for liquid hydrogen and hydrogen release reactors for hydrogen carriers) are included. In a previous paper, we integrated the available waste heat to reduce the energy penalty common with LOHCs [14,19]. A large part of the heat integration will be based on the results of that paper.

### 2.5.1. General assumptions

Tank mass is not explicitly included in the present analysis. For the considered hydrogen carriers and most reference fuels, its contribution is expected to be limited. An exception is liquid hydrogen, for which tank mass is significant due to cryogenic storage requirements and is therefore taken into account [25]. For LOHCs, storage in conventional marine fuel tanks is generally envisaged [36]. DBT requires preheating prior to hydrogen release, similar to HFO handling. NEC must remain

above a threshold temperature when entering the tank, which can be achieved by allowing it to cool down within the fuel tanks. SB and AB may require additional liners and adapted pumping systems; however, storage in conventional tanks with a thin liner is considered feasible. For both SB and AB, airtight containment is essential [24].

Although the mass of individual tanks is expected to be comparable to conventional marine fuel tanks, the lower energy density of several carriers implies larger total storage volumes and potentially additional tanks. A detailed assessment of tank sizing, arrangement, and structural implications depends on ship-specific design considerations and is therefore beyond the scope of this study, which focuses on comparative energy and power density.

Auxiliary power consumption is neglected, similar to a similar study [9].

An overall, combined efficiency of the reactor and separator is assumed to be between 95 and 99%, similar to the fuel treatment efficiencies reported by [11]. This efficiency represents the fraction of hydrogen recovered after reaction and separation. In practical applications, the separator separates unreacted fuel from spent fuel, enabling reuse within a circular fuel concept. Although the separator is explicitly modelled, it is not assumed to be perfect and minor losses may occur, which are reflected in the assumed efficiency range. For such a circular system, very high recovery is required to maintain viability; efficiencies close to 99% are therefore preferred. An efficiency of 95% is considered the practical lower limit and would only be acceptable if losses could be compensated by additional onshore separation, while lower values would compromise the feasibility of the system. Phase changes and vaporisation are not assumed to occur in the reactor, as these processes are energy-intensive and may damage the hydrogen carrier; operating temperatures are therefore assumed to remain sufficiently low to avoid vaporisation during hydrogen release [8].

Separators are included in the design and are conservatively sized at 110% of the release reactor volume, allowing full discharge of the reactor contents in the unlikely event of a runaway reaction.

### 2.5.2. Fuel specific assumptions

AB releases both ammonia and hydrogen. Hydrogen is fully present in the gas phase, together with a fraction of the ammonia [23]. The exact phase distribution remains uncertain due to the low TRL of AB, making precise system sizing difficult. Since a separator is already included in the design, no additional dedicated volume is assumed for ammonia separation. Approximately two-thirds of the usable energy originates from hydrogen and one-third from ammonia, yielding

a combined energy density of approximately 34 MJ per kg. If only hydrogen is utilised, AB delivers approximately 23 MJ per kg; this case is taken as the lower boundary. The lower bound represents scenarios in which ammonia is not utilised due to separation, emissions, or system constraints. Separation of hydrogen and ammonia is not explicitly modelled but is assumed to occur within the separator.

Water mass is excluded for SB and AB. First of all, water produced in the energy converter is assumed to be reused where possible, particularly in fuel cell systems; while theoretically possible for ICE and GT systems, practical implementation remains limited. Additional purified water can be obtained using a reverse osmosis (RO) system. The RO system is assumed to supply water of sufficient quality for use in the hydrolysis reactor without fouling. Such systems are typically already available on board. The energy usage of an RO system is very limited and considered negligible here [9].

Energy density, including the volume and mass of spent fuel, is calculated separately, and the difference between fresh and spent fuel is reflected in the reported bounds. While fuel storage mass may increase over the course of a voyage due to seawater compensation effects, this has not proven problematic in practice, as demonstrated in submarine operations [63]. The spent fuel is analysed in more detail in Sections 3.2 and 4.1, where its practical implications for ship operations are discussed.

### 2.5.3. Heat flow assumptions

LOHCs require additional heat, for preheating and releasing of hydrogen. Both of these heat requirements are included in the calculations, which may result in a lower energy density [14,19]. For the upper bound of the energy density of LOHCs, an idealised waste heat integration is assumed for LOHCs upper bound (very limited waste heat integration assumed for lower bounds). The energy density of the LOHC is thus dependent on the energy converter used, as different energy converters have different waste heat streams, resulting in more or less heat integration possible [14,19].

SB and AB release low-quality heat during the hydrogen release reaction. As this heat is at low temperatures, cooling of the reactor is not assumed. This is similar as a previous approach for a very similar process [9]. Preheating requirements are included.

### 2.5.4. Assumptions for reference fuels

The reference fuels are MDO, ammonia, methanol and liquid hydrogen. For the (more conventional) internal combustion engine, data from [11] are used. The energy density of MDO comes from [64].

Data for methanol and methanol engines are obtained from [65,66]. Due to regulatory requirements such as cofferdam spacing and filling limits [67], the effective onboard energy density may be lower than the theoretical maximum. Therefore, both the theoretical value and a conservative estimate of 90% are considered.

Data for ammonia are taken from [25]. In line with interim safety guidelines for tank arrangement, a conservative lower bound of 90% of the theoretical energy density is assumed. The SOFC efficiency is based on [68,69], and system sizing follows [11].

Data for LH2 are obtained from [25] and explicitly include tank mass and volume, as these are highly relevant for cryogenic storage. The PEMFC data are identical to those used for the other hydrogen-based cases.

## 2.6. Selection of cases

With four different hydrogen carriers and four energy converters, we end up with 16 combinations. Reference cases will be included next to these cases. These reference cases give an overview of the current situation and can be used to evaluate the carriers as compared to current technology. Comparing the full set of 20 cases (16 hydrogen carrier cases and 4 reference fuel cases) would be impractical and

difficult to present in a clear manner. Therefore, a selection of cases will be reviewed.

First, all 16 combinations will be shown. For each hydrogen carrier, its four associated energy converters will be presented together in a Ragone plot. These plots provide an initial overview of the performance range within each carrier. Based on these results, the most promising combinations will be selected for further comparison, both with one another and with the reference cases.

Reference fuels to consider are MDO, ammonia, methanol and liquid hydrogen. The first is a conventional fuel, while the other three are alternative fuels that are on the rise in the maritime sector. As not all fuels are compatible with every energy converter, they cannot all be included in every combination.

### 2.7. Data for Ragone charts

Table 2 gives an overview of all data required for the Ragone plots. For SB and AB bulk density and particle density are taken into account. The effective power density is calculated using Eq. (5) and includes the energy densities of the energy converter, reactor, separator, and heat exchangers. The latter is the least influential and is generally relatively small as compared to the reactor size [37].

## 3. Results

This section presents the Ragone plots of the 16 studies. Section 3.1 gives an overview of the average predictions for the 16 hydrogen carrier and energy converter combinations. The choice of specific case studies of hydrogen carrier and energy converter combinations is motivated in this subsection as well. The results of these case studies are shown in Section 3.2. This subsection also displays the upper and lower bounds for each combination, indicating their relative uncertainty. Section 3.3 shows the reference cases of MDO\_ICE, LH2\_PEM, NH3\_SOFC and MeOH\_ICE. Finally, Section 3.4 shows the case studies and reference cases to enable comparison.

### 3.1. Ragone plots for all fuel-converter combinations

Fig. 3 gives an overview of the different combinations for SB. SB can be integrated with an ICE, PEMFC, SOFC or GT. The figure shows that SB combined with a GT has a high power density, while combining SB with a SOFC results in a high energy density; this directly correlates with the high power density of the gas turbine and the high efficiency of the SOFC. In the gravimetric case, shown in Fig. 3(a), the PEMFC shows a high energy and power density. In the volumetric case (Fig. 3(b)), the SOFC is very similar to the PEMFC. Thus, in the next subsections, SB will be combined with a PEMFC.

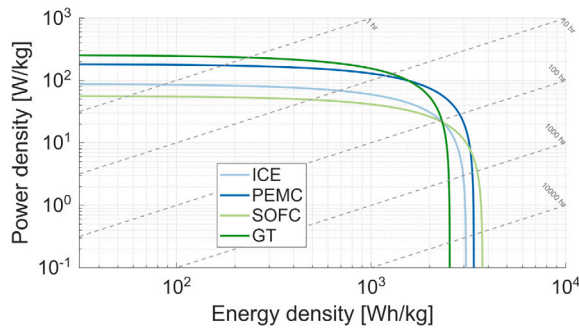
Fig. 4 shows the different energy converters possible for AB. As AB produces ammonia, the PEMFC is not incorporated. The gravimetric Ragone plot (Fig. 4(a)) shows that all three options have their own advantages; the GT has a higher power density, the SOFC will result in a higher energy density, and the ICE is always in the middle of these two. Regarding the volumetric Ragone plot, visible in Fig. 4(b), the GT and SOFC have higher power densities, while the SOFC results in a higher energy density. The ICE has a lower power density compared to both other options, but results in an energy density that lies between. The ICE does not outperform the GT or SOFC in either power density or energy density, but it occupies the middle range between the two. Because it provides a stable, balanced performance across both metrics and no single converter clearly dominates for AB, the ICE is selected as the representative case for the remainder of this study.

The Ragone plots of NEC are shown in Fig. 5. Fig. 5(a) shows the gravimetric Ragone plot, where both the PEMFC and ICE perform worse than the SOFC and GT; likely due to the amount of heat available for waste heat integration. More waste heat integration is beneficial for NEC, due to its endothermic dehydrogenation process. The SOFC

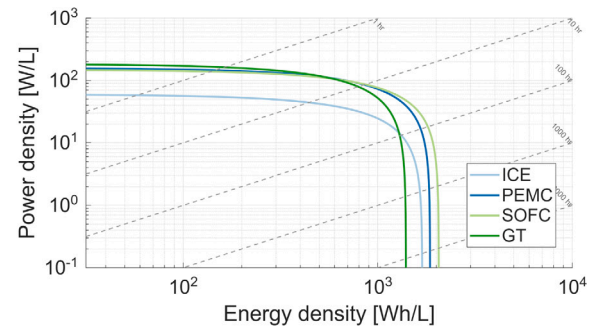
**Table 2**

Data for the Ragone charts: volumetric and gravimetric power and energy densities of different hydrogen carriers and energy converters, including reactor and heat exchanger sizes required for the case studies, which depend on the overall system power and efficiency. For hydrogen carriers where the mass of the spent fuel differs significantly from the fuel itself, an additional energy density is reported and denoted (SF).

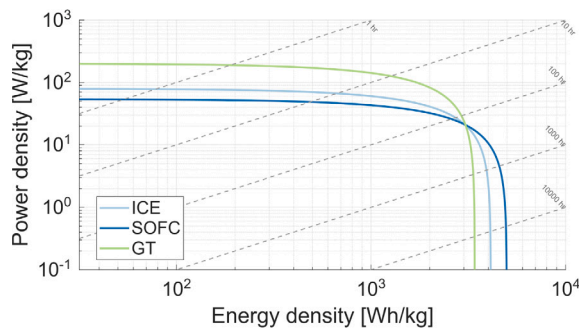
|                                                                | Gravimetric density [kW/kg] | Volumetric density [kW/L] | LHV efficiency [%]     |
|----------------------------------------------------------------|-----------------------------|---------------------------|------------------------|
| Energy converters                                              |                             |                           |                        |
| PEMFC                                                          | 0.042–0.85                  | 0.015–1.6                 | 45–55                  |
| ICE (H <sub>2</sub> )                                          | 0.10–0.21                   | 0.07–0.09                 | 35–55                  |
| SOFC (H <sub>2</sub> )                                         | 0.001–0.1                   | 0.003–0.04                | 50–60                  |
| GT (H <sub>2</sub> )                                           | 1.2–1.9                     | 0.46–0.74                 | 32–42.5                |
| ICE (MDO/MeOH)                                                 | 0.045–0.072                 | 0.033–0.055               | 35–45                  |
| SOFC (NH <sub>3</sub> )                                        | 0.025–0.035                 | 0.05–0.08                 | 45–55                  |
| Effective power density, including reactor and heat exchangers |                             |                           | Efficiency reactor [%] |
| SB (PEMFC)                                                     | 0.029–0.51                  | 0.012–0.65                | 95–99                  |
| AB (ICE)                                                       | 0.077–0.11                  | 0.048–0.064               | 95–99                  |
| NEC (SOFC)                                                     | 0.006–0.081                 | 0.003–0.19                | 95–99                  |
| DBT (SOFC)                                                     | 0.006–0.054                 | 0.003–0.081               | 95–99                  |
| DBT (GT)                                                       | 0.048–0.075                 | 0.040–0.065               | 95–99                  |
| Energy density                                                 |                             |                           |                        |
|                                                                | [kWh/kg]                    | [kWh/L]                   |                        |
| SB                                                             | 6.3–7.0                     | 3.4–3.8                   |                        |
| SB (SF)                                                        | 2.3–2.6                     | 2.7–4.9                   |                        |
| AB                                                             | 6.5–9.4                     | 2.6–3.8                   |                        |
| AB (SF)                                                        | 3.3–4.7                     | 4.7–6.8                   |                        |
| NEC                                                            | 1.3–1.9                     | 1.3–1.8                   |                        |
| DBT                                                            | 1.3–2.0                     | 1.2–1.9                   |                        |



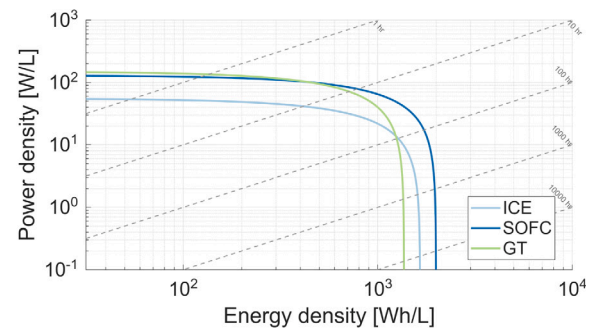
(a) Gravimetric Ragone plot



(b) Volumetric Ragone plot

**Fig. 3.** Ragone plots of sodium borohydride.

(a) Gravimetric Ragone plot



(b) Volumetric Ragone plot

**Fig. 4.** Ragone plots of ammonia borane.

shows a higher energy density, while the GT shows a higher power density. The volumetric Ragone plot (Fig. 5(b)) is different. The SOFC has the highest power and energy density. As the SOFC is clearly the best performer based on the volumetric Ragone plot, and also scores relatively well on the gravimetric Ragone plot, it is chosen to be the representative case for NEC in the remainder of this study.

Finally, Fig. 6 shows the Ragone plots of DBT. Similarly as to NEC, the gravimetric Ragone plot (Fig. 6(a)) shows a trade-off between

power and energy density. The GT achieves a higher power density, while the SOFC achieves a (significantly) higher energy density. The volumetric case (Fig. 6(b)) shows similar results; however, the difference in power density between the SOFC and GT is significantly smaller than their respective difference in energy density. So, the SOFC overall outperforms the GT, and the DBT-SOFC combination will be regarded from now on. Table 3 gives an overview of all casestudies that will be considered.

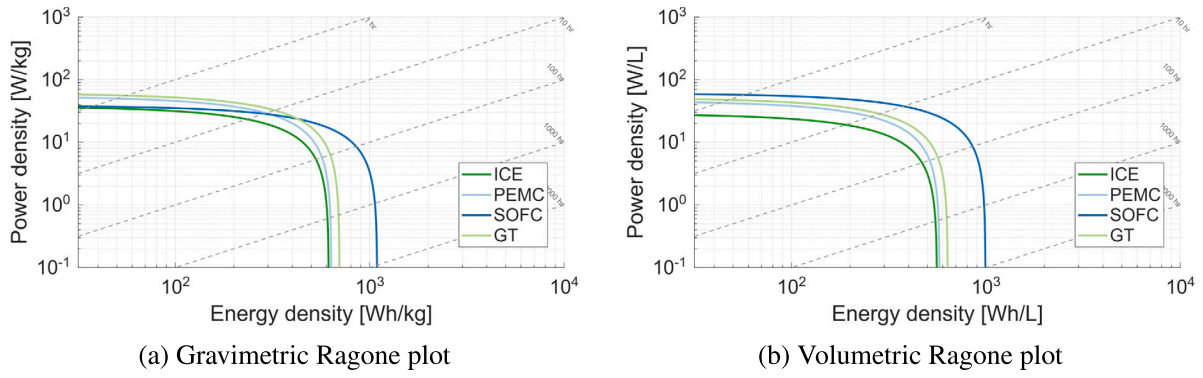


Fig. 5. Ragone plots of NEC.

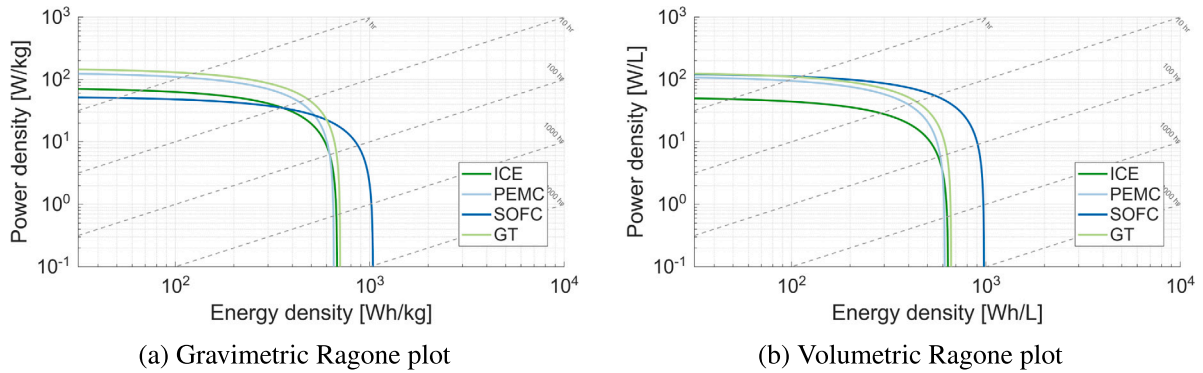


Fig. 6. Ragone plots of DBT.

Table 3

Case studies and names.

| Case name | Hydrogen carrier   | Energy converter |
|-----------|--------------------|------------------|
| SB_PEM    | Sodium borohydride | PEMFC            |
| AB_ICE    | Ammonia Borane     | ICE              |
| NEC_SOFC  | N-Ethylcarbazole   | SOFC             |
| DBT_SOFC  | Dibenzyltoluene    | SOFC             |
| MDO_ICE   | Marine Diesel Oil  | ICE              |
| LH2_PEM   | Liquid Hydrogen    | PEMFC            |
| NH3_SOFC  | Ammonia            | SOFC             |
| MeOH_ICE  | Methanol           | ICE              |

### 3.2. Specific case studies and their uncertainty

This section presents the case studies for each hydrogen carrier, examining how data availability and consistency influence the results. In addition to the cases specified in Section 3.1, a fifth case of DBT combined with a GT is chosen to be represented here; this way, the uncertainty of the GT and its influence on the results is visible as well. The GT is combined with DBT because this combination (visible in Fig. 6) showed better compatibility than the GT with NEC (Fig. 5). Figs. 7 and 8 display the gravimetric and volumetric energy densities of SB and AB, respectively, with uncertainty bands representing the range of available data. These figures also illustrate the impact of spent fuel by including additional plots showing energy density calculations based solely on spent fuel mass.

Fig. 7 shows the gravimetric and volumetric energy densities of SB and its spent fuel in combination with a PEMFC. The gravimetric range (Fig. 7(a)) exhibits substantial variation in fuel-cell power density, spanning from 30 W/kg to around 500 W/kg, with values distributed relatively symmetrically around an average of approximately 140 W/kg. The gravimetric energy densities highlight the mass penalty associated with the spent fuel: the spent fuel-to-fuel ratio is roughly

2.7, reflected in average energy densities of about 1200 Wh/kg for the spent fuel and 3200 Wh/kg for the fuel.

The volumetric plots (Fig. 7(b)) reveal a different pattern. Owing to the low bulk density of SB itself and the considerably higher density of the spent fuel, the volumetric energy densities of fuel and spent fuel partially overlap. The spent fuel density may be lower than shown, as it is unclear whether this density is the bulk or particle density. Both fuel and spent fuel cluster around approximately 1800 Wh/L, though the spent fuel range is noticeably wider due to greater uncertainty in the underlying data. The volumetric power density also spans a broader interval than its gravimetric counterpart, ranging from 12 W/L to 645 W/L.

Fig. 8 presents the case of AB combined with an ICE. Here, the lower bound of the energy density assumes hydrogen-only utilisation and PEMFC waste heat integration, representing a conservative operation. The gravimetric power density exhibits considerable variability, as indicated by the broad uncertainty band in Fig. 8(a) (60–115 W/kg). This reflects the strong sensitivity of the gravimetric metric to variations in reported engine mass. The gravimetric energy density also reveals the mass penalty associated with spent fuel; however, both fuel and spent fuel ranges are wider and partially overlap, reflecting the higher data uncertainty for AB compared with SB.

The volumetric power density displays a much narrower uncertainty interval (47–63 W/L), consistent with lower variability in reported volumetric parameters. For the volumetric energy density, the spent fuel exhibits higher values than the fuel. This follows from the relatively low spent-to-fuel mass ratio (around 2) combined with the substantial difference in material densities (approximately 400 kg/m<sup>3</sup> for the fuel and 1435 kg/m<sup>3</sup> for the spent fuel), which shifts the volumetric metric in favour of the spent fuel.

Fig. 9 presents the power and energy density characteristics of NEC combined with an SOFC. The gravimetric power density exhibits a wide uncertainty band, ranging from 6 to 80 W/kg, with a skewed distribution that favours lower values, around 33 W/kg. The gravimetric energy

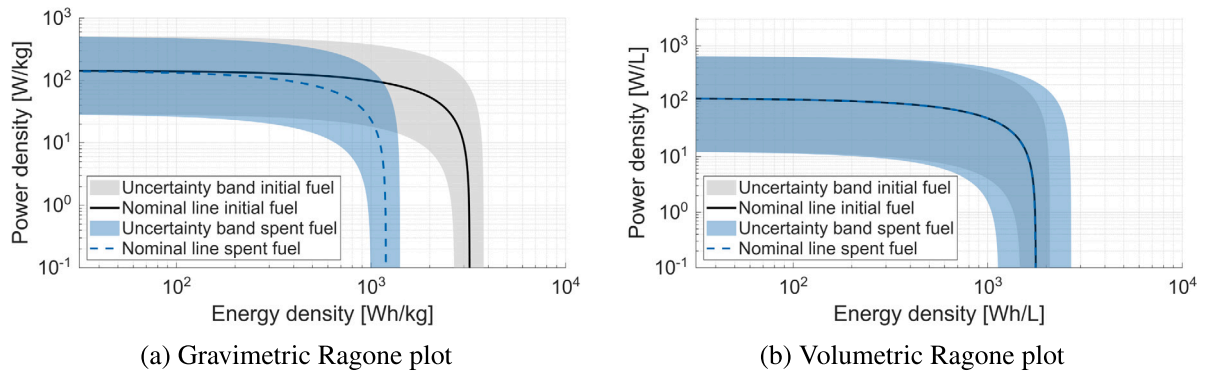


Fig. 7. Ragone plots of SB combined with a PEMFC.

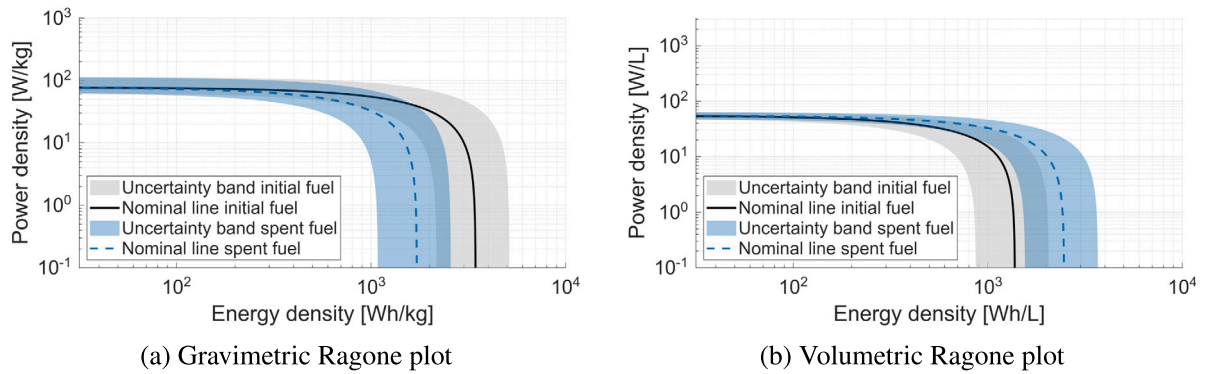


Fig. 8. Ragone plots of AB combined with ICE.

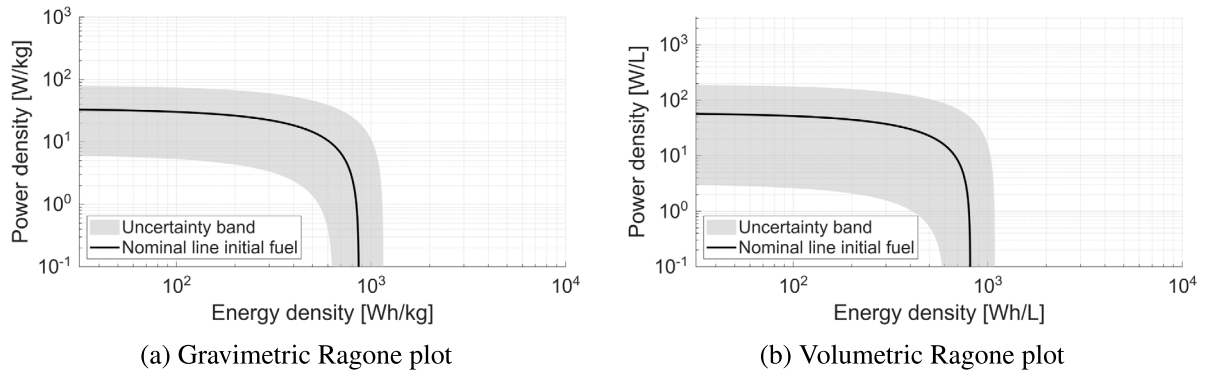


Fig. 9. Ragone plots of NEC combined with an SOFC.

density is centred around approximately 900 Wh/kg, and the associated uncertainty band is relatively broad.

The volumetric power density (Fig. 9(b)) covers an even wider range than the gravimetric case, extending from 3 to 190 W/L, again with a clear concentration of values (midline being around 56 W/L) near the lower boundary. The volumetric and gravimetric energy densities are similar, reflecting the high material density of NEC (approximately 940 kg/m<sup>3</sup>).

Fig. 10 provides an overview of the performance of DBT when coupled with an SOFC. The gravimetric power density (Fig. 10(a)) exhibits a slightly narrower uncertainty range (6 to 50 W/kg) compared with NEC. This likely reflects the larger and heavier reactor and heat-exchanger components required for DBT, which shift the system towards lower gravimetric power densities and reduce variability. The gravimetric energy density shows a broader spread than in the NEC case, ranging from approximately 400 to nearly 900 Wh/kg.

The volumetric plot (Fig. 10(b)) displays a similar pattern: while the uncertainty range remains substantial (3–80 W/L), it is smaller than that of NEC yet still wider than the gravimetric equivalent. This again stems from the system-level mass and volume contributions of the reactor and ancillary components associated with DBT processing. Similar to NEC, the volumetric and gravimetric energy densities lie close to each other; DBT also has a density of approximately 910 kg/m<sup>3</sup>.

Fig. 11 shows the performance of DBT in combination with a gas turbine. The gravimetric and volumetric power-density bands (Figs. 11(a) and 11(b)) are very narrow, ranging from 45 to 75 W/kg and 40 to 65 W/L, respectively. Both the magnitude and the limited spread reflect the small number of data sources available for GT systems and the fact that the reported values lie within a constrained region. This case is included primarily to illustrate the comparatively low uncertainty associated with the GT data relative to the fuel-cell cases discussed elsewhere in the paper.

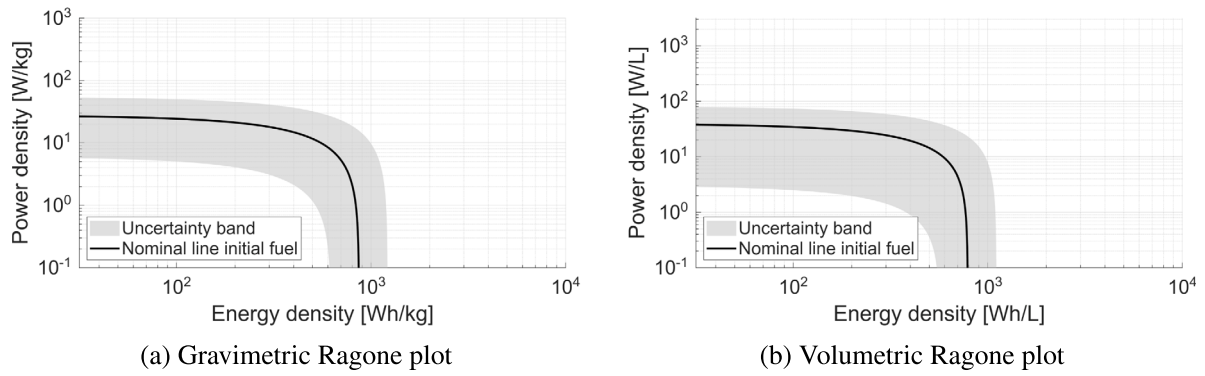


Fig. 10. Ragone plots of DBT combined with a SOFC.

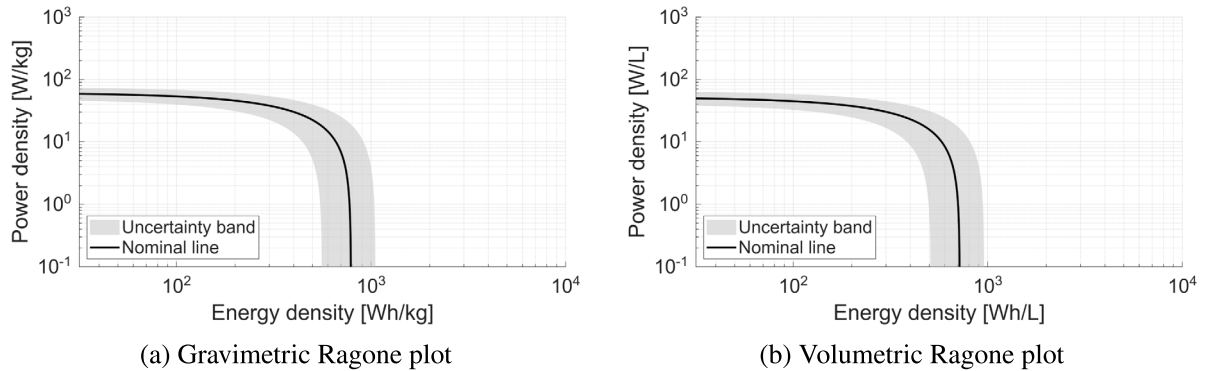


Fig. 11. Ragone plots of DBT combined with a gas turbine.

### 3.3. Reference cases

Fig. 12 provides a comparison of all reference cases, with each case presented through both gravimetric and volumetric analyses. The liquid hydrogen case (Figs. 12(c) and 12(d)) exhibits the only significant uncertainty band for the power density. The bandwidth of the power density is slightly different from that of SB. For the LH2 case, it ranges from 40 W/kg up to 820 W/kg, and from 15 W/L up to 1500 W/L. The energy density of liquid hydrogen shows narrow uncertainty bands. Because the midline is the geometric mean of the bounds, the apparent kink arises from the logarithmic scaling and does not reflect a physical discontinuity.

All other reference cases demonstrate very narrow uncertainty bands. For marine diesel oil shown in Figs. 12(a) and 12(b), the uncertainty bands range from 45 W/kg up to 71.5 W/kg, for example. The methanol and ICE cases exhibit the same narrow uncertainty bands, as these have the same background data for the internal combustion engine. The NH<sub>3</sub>-SOFC case study (Figs. 12(e) and 12(f)) also shows narrow uncertainty bands, from 25 W/kg up to 35 W/kg, and from 50 W/L up to 77 W/L.

### 3.4. Comparison of case studies

To enable comparison across all fuel systems despite varying data quality and availability, the midlines of the uncertainty bands are used for each technology combination. These midlines represent the geometric mean of the upper and lower bounds established in the preceding analysis. Figs. 13 and 14 show all hydrogen carrier and reference cases in gravimetric and volumetric form, respectively. Solid lines denote the hydrogen carrier case studies, while dashed lines represent the reference cases.

Fig. 13 gives an overview of the gravimetric energy and power density of all cases; hydrogen carrier and reference cases. The plot shows

the high power density of PEMFCs. The power density of a PEMFC with only liquid hydrogen is higher than that when combining it with SB, as SB requires heat exchangers and, most significantly, a release reactor and separator system to provide the hydrogen, thereby reducing the overall system's power density. However, the energy density of SB is considerably higher than that of LH<sub>2</sub>. SB-PEM may therefore be advantageous in applications where energy density is the primary constraint. AB-ICE demonstrates a significantly higher power density than most alternative fuels, including NH<sub>3</sub> and MeOH, except for LH<sub>2</sub>-PEM and SB-PEM. The power densities of MeOH-ICE and MDO-ICE are essentially equivalent, with the power density of ammonia borane surpassing them both. When considering energy density, AB-ICE and SB-PEM are the alternative fuels that come closest to MDO, however the difference is still large; around 3200 Wh/kg for the hydrogen carriers and almost 4700 Wh/kg for MDO. When both energy and power density matter, SB-PEM might potentially, if the stated assumptions are correct, surpass MDO.

In Fig. 14, all three ICE cases show nearly identical volumetric power densities. The main differences therefore appear in the volumetric energy density, where the ordering is clear: MDO-ICE has the highest values, followed by AB-ICE, with MeOH-ICE lowest. These differences are substantial and reflect the underlying fuel volumetric energy densities rather than differences in converter performance.

When examining the SOFC-based systems, the ammonia case shows slightly higher power densities than the hydrogen carrier cases with NEC or DBT, mainly due to the large amount of additional equipment the latter require. In terms of energy density, ammonia remains much higher than both NEC and DBT. Compared with SB and AB, NEC and DBT both exhibit relatively low energy densities. In the LOHC cases, DBT has lower power density and slightly lower energy density than NEC in both gravimetric and volumetric terms. Although DBT-SOFC is the lowest-performing in the SOFC group, it still represents a functioning hydrogen carrier option in the overall comparison.

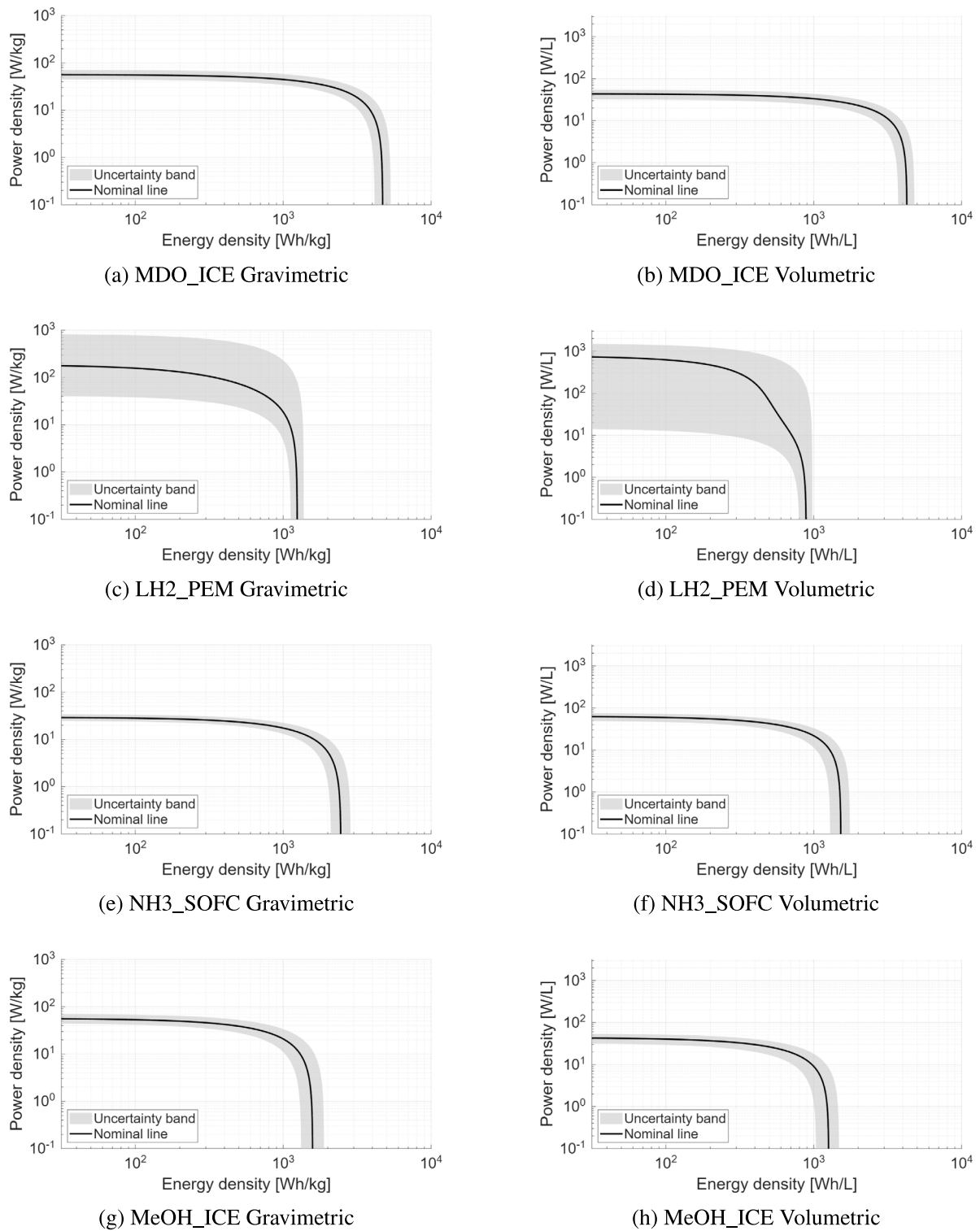


Fig. 12. Ragone plots of reference cases.

#### 4. Research implications

The analysis presented in the preceding section demonstrates that all hydrogen carrier case studies exhibit performance metrics within a similar order of magnitude as the reference cases. Each case study remains relevant for further interpretation, as shown in Section 4.1. Their possible practical implications are discussed in Section 4.2. However, the results should be interpreted with caution. The many assumptions

necessary to do the calculations will influence the overall outcome. The influence of these assumptions is discussed in Section 4.3.

##### 4.1. Interpretation of results

Analyses and interpretation of the Ragone plots reveal several recurring patterns across the different fuel–converter combinations. These patterns provide insight into the relative maturity of technologies,

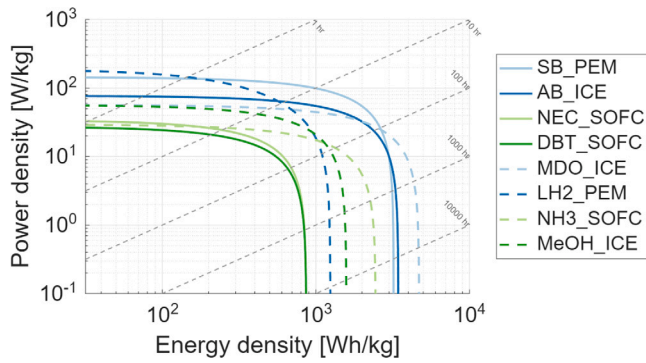


Fig. 13. Gravimetric Ragone plot of all cases.

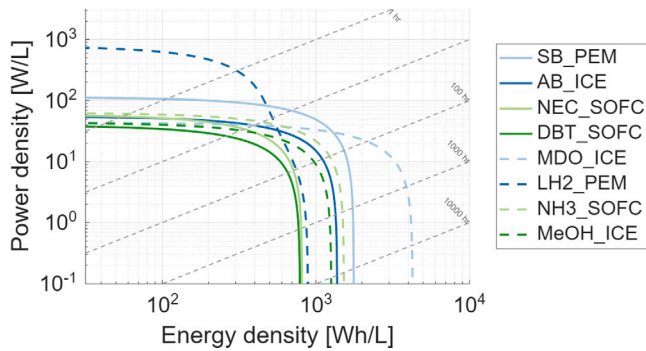


Fig. 14. Volumetric Ragone plot of all cases.

the influence of system integration, and the key drivers behind the observed performance ranges.

First, several cases show a skew towards a lower or higher power-density values within their uncertainty ranges. This is particularly visible for the PEMFC-based cases (SB\_PEM and LH2\_PEM) and for the SOFC-based hydrogen cases (NEC\_SOFC and DBT\_SOFC). In these cases, most reported values cluster towards one end of the gravimetric and volumetric power-density ranges, with fewer data points broadening the uncertainty band. Despite appearing to make data less reliable, a large distribution with a skew towards higher estimates indicates a certain maturity to the technology. First of all, there is sufficient data to form such a wide band; secondly, there is even enough data to have a distinct skewer; finally, the technology is likely to be researched, with continuous improvements regarding the power density.

A second observation concerns the shape of the midlines. In some cases, especially visible in Fig. 12(d), the upper and lower bounds have markedly different curvatures, resulting in midlines that show mild non-monotonic behaviour. This effect arises from the averaging procedure: when power-density bounds diverge strongly while energy density bounds converge to similar magnitudes, the midline reflects the mathematical interpolation between two distinct performance envelopes. The phenomenon is most evident in cases where the underlying datasets differ widely in system inclusion (e.g., balance-of-plant assumptions), but it does not indicate physical discontinuities in the underlying technology.

By contrast, the internal combustion engine results exhibit consistently narrow uncertainty bands. In the MDO\_ICE case, this is explained by the high maturity of the technology. It is assumed that methanol engines do not differ greatly from MDO engines, resulting in the same narrow band. Hydrogen ICEs do differ from MDO engines, as compression ignition is not an option for hydrogen. Hydrogen ICEs also exhibit relatively narrow ranges: although their combustion characteristics differ from those of diesel engines, commercially available hydrogen

engines have similar volumetric power densities, while gravimetric values differ only modestly.

The gas turbine case likewise shows a narrow uncertainty band, but for a different reason. Publicly available data for hydrogen-fuelled GTs remain limited, and the existing values cluster tightly. As a result, the DBT\_GT case displays consistent but data-sparse performance envelopes.

The energy density behaviour differs across the hydrogen carriers and reflects their underlying chemistry. For AB, the fuel releases both hydrogen and ammonia; if both species can be utilised in the energy converter, the effective energy density is substantially higher than when only hydrogen is used. However, the use of ammonia is not straightforward, as it readily dissolves in water and may require additional separation steps before it can be supplied to the converter. Both AB and SB also require significant amounts of water for hydrolysis, although this can be largely mitigated by recycling the water produced when hydrogen is converted to useful energy. This reduces the net amount of additional water that must be supplied. In the case of SB, some studies report energy densities that include the mass of the required water; however, in this work, the energy density based solely on the hydrogen content of SB is used to represent the lower bound, allowing for consistent comparison across all carriers.

For LOHCs (NEC and DBT), the energy density is more strongly influenced by the degree of heat integration, as their endothermic dehydrogenation requires substantial thermal input. When heat can be integrated effectively from the energy converter, the usable energy density increases accordingly. This explains the broader energy density bands observed for NEC and DBT in Figs. 9 and 10.

Together, these findings underline the importance of evaluating complete fuel-converter value chains rather than isolated components. Although the hydrogen carriers differ substantially in chemistry, handling requirements, and heat-integration demands, the system-level Ragone framework provides a consistent basis for comparing their effective gravimetric and volumetric power and energy densities. This system-integrated perspective is essential for assessing the suitability of alternative fuels for maritime applications, where the converter, reactor, heat exchangers, and storage all contribute to the overall performance.

#### 4.2. Practical implications for maritime vessels

The respective energy and power densities of hydrogen carriers vary from each other and from other reference fuels, as visible in Figs. 13 and 14. Combined with the well-known notion that there will likely not be a one-size-fits-all solution for alternative fuels and energy converters on ships [70], it is interesting to look at different ship types, their relevant power requirements and range or days of autonomy, and see which fuel-converter combination would be fitting for each ship type. Table 4 gives an overview of the typical ship types used in this study. The power, required energy or size of the fuel tanks, size and volume of each of a typical example of these vessels has been estimated. The space and weight current fuels (MDO) as well as a standard ICE take up (thus, not the size of the engine room), is then compared to each of the case studies. The results of the energy density are in Figs. 15 (gravimetric) and 16 (volumetric). Figs. 17 and 18 give an overview of the minimum required engine weight and space compared to the overall ship weight (DWT) and (cargo) volume, respectively.

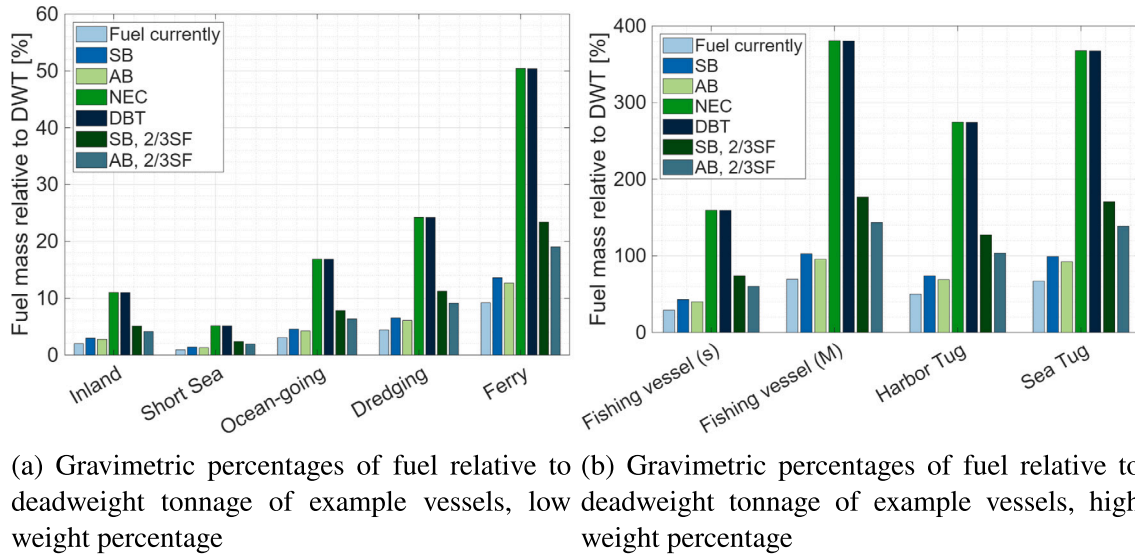
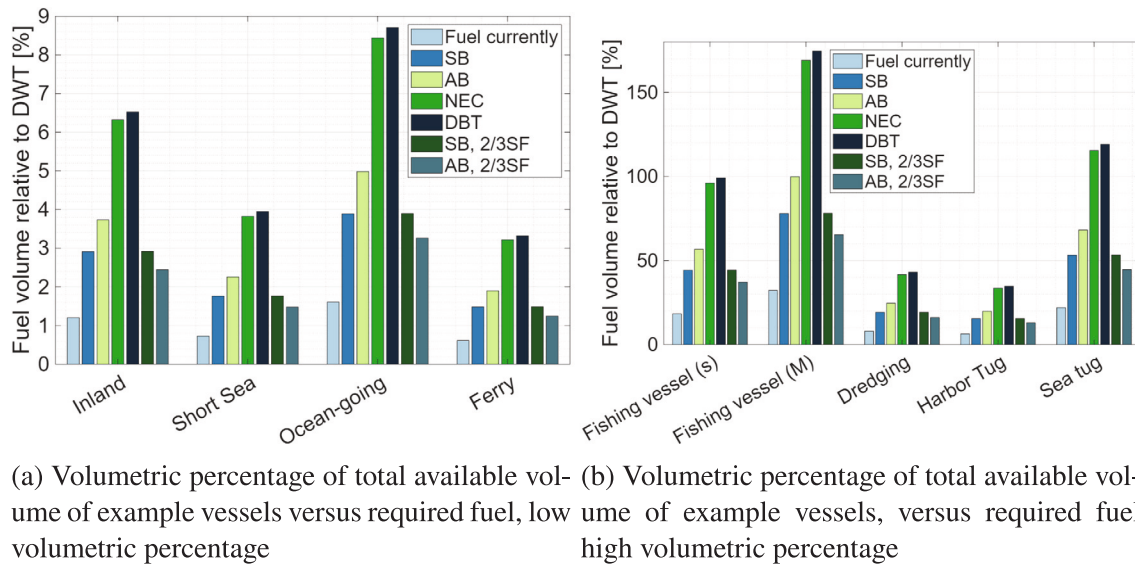
##### 4.2.1. Inland ships

Inland ships require relatively little power but operate with medium to long autonomy. The choice of hydrogen carrier, therefore, has a strong impact on their bunkering arrangements. Although frequent refuelling is considered a feasible business case [75], it is generally undesirable. For these vessels, energy density becomes particularly relevant. Depending on the cargo, inland ships may be weight- or

**Table 4**

Typical ship types, power and days of autonomy.

|                            | Power       | Time of autonomy | Notes                                                       | Source  |
|----------------------------|-------------|------------------|-------------------------------------------------------------|---------|
| Inland ship                | 250–840 kW  | 5–15 days        | Trade off bunker frequency and space or weight requirements | [71]    |
| Coaster                    | 700–3000 kW | around 10 days   | Trade off bunker frequency and space or weight requirements | [70]    |
| Ocean-going                | 2.5–10 MW   | over 30 days     | Space requirements to have sufficient energy                | [70]    |
| Short-range fishing vessel | 300–600 kW  | 5–6 days         | Relatively small for the amount of energy required          | [72,73] |
| Dredger                    | 8–15 MW     | 15 days          | Relatively large amount of power and energy required        | [70]    |
| Tug                        | 2–5 MW      | 2 days           | Relatively small for the amount of power required           | [70]    |
| Short-range ferry          | 1–3 MW      | 50–180 min       | Volume limited, safety important                            | [74]    |

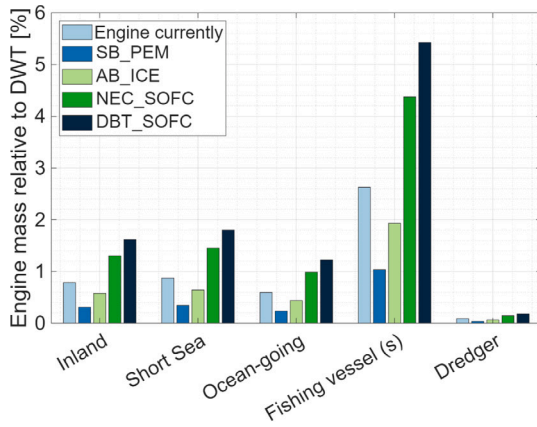
**Fig. 15.** Gravimetric percentages of fuel relative to deadweight tonnage of example vessels.**Fig. 16.** Volumetric percentage of total available volume of example vessels, versus required fuel.

volume-limited: light cargo typically leads to volume limitations, while dense cargo results in weight restrictions. In Figs. 15(a) and 16(a) an inland container barge is taken as the example vessel; this vessel is likely volume-limited. SB\_PEM and AB\_ICE are both suitable options, with SB\_PEM being more attractive if volumetric energy density is extremely important. For weight-limited ships, it may be possible that no change in operational patterns can be achieved, while for volume-limited ships, some operational changes would have to be made. Regarding engine size and weight (Figs. 17(a) and 18(a)), it appears that SB\_PEM and

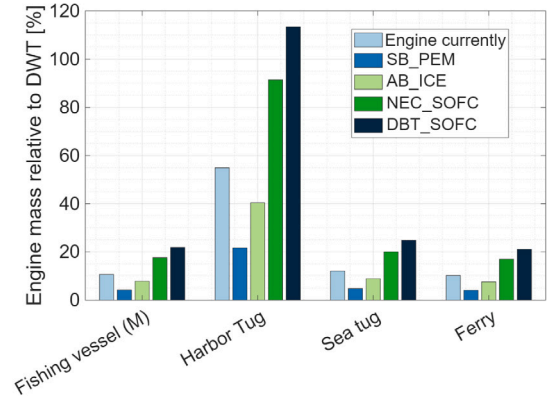
AB\_ICE are likely to fit in the current engine rooms, because of their high efficiencies and high power densities.

#### 4.2.2. Coasters

Coasters, or short sea vessels, have medium power requirements and similar autonomy to inland ships. Bunkering frequency directly influences the required onboard storage volume; while more frequent bunkering reduces storage needs, it is generally avoided for operational convenience. These vessels, like inland ships, may be either weight- or

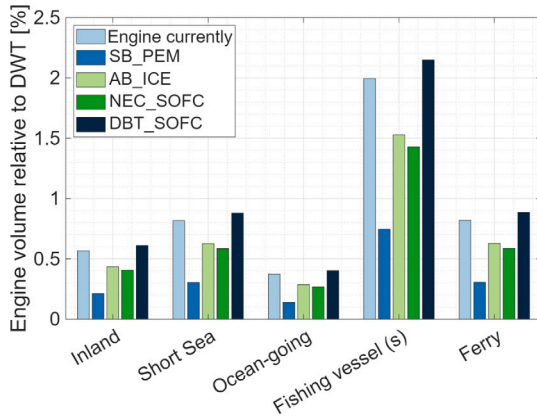


(a) Gravimetric percentages of deadweight tonnage of example vessels versus weight of energy converter, low weight percentage

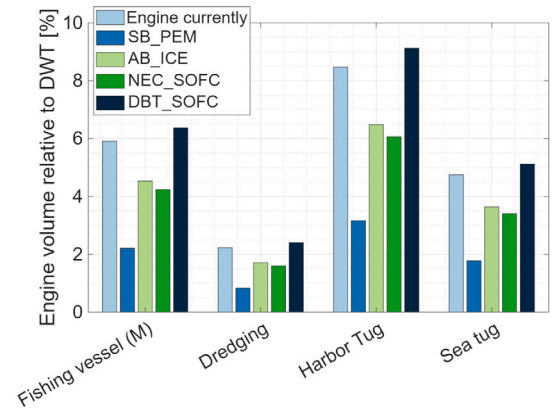


(b) Gravimetric percentages of deadweight tonnage of example vessels versus weight of energy converter, high weight percentage

Fig. 17. Gravimetric percentages of deadweight tonnage of example vessels versus weight of energy converter.



(a) Volumetric percentage of total available volume of example vessels versus required energy converter space, low volumetric percentage



(b) Volumetric percentage of total available volume of example vessels versus required energy converter space, high volumetric percentage

Fig. 18. Volumetric percentage of total available volume of example vessels versus required energy converter space.

volume-limited depending on their cargo. The reference coaster vessel currently has a very small amount of space and weight dedicated to its fuels (Figs. 15(a) and 16(a)). Similarly to inland vessels, both SB\_PEM and AB\_ICE emerge as relevant options. If the vessel is unlikely to refuel often and is volume limited, AB\_ICE might be a better option than SB\_PEM, due to the lower volume its spent fuel occupies. When looking at power, again, it is estimated that both options will possibly fit in the current engine room. So, SB\_PEM and AB\_ICE again emerge as relevant options, providing high power density while supporting operationally meaningful ranges.

#### 4.2.3. Ocean-going vessels

Ocean-going vessels require substantial power and very large autonomy, frequently exceeding 30 days [70]. Depending on the type of cargo and vessel layout, they may be either volume- or weight-limited. The reference vessel, an LNG tanker, often uses at most 2/3 of its maximum energy usage [31]. For weight-limited applications, Fig. 15(a) shows that AB\_ICE is slightly favourable over SB\_PEM, due to its higher

energy density, combined with a gravimetric power density sufficient to sustain large propulsion loads over long periods. Additionally, its spent fuel is lighter, which becomes increasingly relevant as storage capacity increases. For volume-limited vessels, Fig. 16(a) shows that SB\_PEM offers a higher energy density and a similar spent fuel density as AB\_ICE. Thus, both AB\_ICE and SB\_PEM could be suitable options for ocean-going vessels.

#### 4.2.4. Fishing vessels

Fishing vessels vary widely in size and operational profile. This study focuses on shorter-voyage vessels operating for 5 to 6 days, which typically require modest power but have very limited space onboard. There are two reference vessels: a small Dutch vessel and a slightly larger Norwegian fishing vessel. The fuel energy density percentage of both are depicted in Figs. 15(b) and 16(b). A major issue with these fishing vessels is the very limited space and weight available for fuel. Current fuel already accounts for a large share of their DWT and volume. Of all hydrogen carriers, only SB\_PEM and AB\_ICE could

possibly fit on both fishing vessels. However, a major issue of these fishing vessels is that they cannot currently contain both fuel and fish at the same time; heavier spent fuel is thus problematic and operational parameters need to be changed. However, using SB\_PEM and AB\_ICE may enable fishing vessels to continue operating within ecologically protected areas without causing environmental harm, even if they have to refuel more often. The engine room appears to not be the limiting factor.

#### 4.2.5. Dredging vessels

Dredging vessels exist in two types: long-range vessels with an autonomy of around 15 days, and shorter-range vessels with an autonomy of 3 to 7 days. Here, the focus is on the long-range vessels. These vessels have greater autonomy than most ship types in this study; yet, their power requirements are extremely high, making it essential to achieve a high power density. However, the overall size and weight of the current engine (estimated), does not appear to be limiting for the example vessel. Depending on the vessel's specific power demand, range, and weight- or volume-related constraints, SB\_PEM, AB\_ICE, and NEC\_SOFC can all be viable options. SB\_PEM offers the highest gravimetric power density. NEC\_SOFC and AB\_ICE exhibit high volumetric power densities as well. For the example vessel, the total fuel volume appears to be more limiting than the weight for the fuel. The gravimetric percentage the fuel takes up (Fig. 15(a)) is significantly smaller than the volumetric one (Fig. 16(b)). As a dredging vessel gets heavier over time, AB\_ICE would likely be the best option for the example vessel; its spent fuel takes up less space than SB's and is also lighter. However, SB\_ICE would also be possible, as well as NEC\_SOFC. The latter would be less desirable due its higher volumetric energy density. It additionally appears all would fit in the current engine room.

#### 4.2.6. Tugs

Tugs have relatively high power requirements for their size, but typically limited onboard space and relatively short autonomy. As tugs do not carry cargo, the concept of weight or volume limited is less relevant; instead, volumetric power density and endurance are the key constraints. In this paper, two tugs are regarded: a harbour tug (lower endurance and higher power density) and a sea tug (higher endurance and lower power density). Especially for the harbour tug, the gravimetric power density appears to be limiting (Fig. 17(b)). This can be improved by using LH<sub>2</sub>. However, the amount of fuel both tugs need to bring, given their own weight and size, is relatively high. For both tugs, it appears that none of the hydrogen carriers can be used without compromising operational demands. The spent fuels, specifically, are too heavy for the tugs (Fig. 15(b)); the volume appears to be less limiting (Fig. 16(b)). For the sea tug, it is slightly worse than for the harbour tug.

#### 4.2.7. Ferries

Ferries exist in many configurations, with operational profiles ranging from extremely short river crossings to medium-range sea routes. This study focuses on short-range ferries, such as those serving the Dutch islands [74], with an example ferry also operating between the Dutch coast and the island of Ameland. Ferries generally require high energy densities and are typically volume-limited. Quiet operation is also desirable, and the fuel needs to be safe for the passengers. AB\_ICE is not considered, due to the presence of (toxic) ammonia. SB\_PEM, NEC\_SOFC and DBT\_SOFC appear to be good fits for these vessels, offering a balance of power, energy density, and silent operation. These options would theoretically fit on the ferry, although the weight of DBT and NEC would likely influence the operational profile of the ferry, as seen in Fig. 15(a). The latter becomes especially evident when taking into account the estimated size of the engine; a larger engine room is possibly required, especially for DBT\_SOFC. As with all other ship types, the optimal choice ultimately depends on the vessel's detailed operational profile.

#### 4.2.8. Broader applicability

Table 5 summarises the relevant power and energy requirements and the case study combinations capable of meeting them. Although this analysis focuses on maritime applications, the underlying characteristics of hydrogen carriers, including high energy density, high power density, silent operation, and zero emissions, may also be beneficial in other sectors such as road transport, construction, and aviation. However, the results cannot be transferred directly to these sectors. Both AB and SB require large amounts of water during hydrolysis, which is not an issue for maritime applications but may be problematic elsewhere unless water is readily available.

#### 4.3. Reflection on modelling assumptions

The apparent consistency of certain technology combinations masks underlying assumptions that may not reflect real-world performance variability. This subsection examines how key assumptions in data treatment, system boundaries, and technology projections influence the results and their interpretation and how future research can improve the overall results.

From the energy density perspective, the bulk density, the treatment of fuel and spent fuel, and the heat requirements of each carrier strongly influence the outcome. The bulk densities of SB and AB used in this research are based on experimental data, yet they remain sensitive to the measurement method. SB exists as both powder and granulate, while AB is available only as a powder. These materials can be compressed to some degree, which increases bulk density, but excessive compression may hinder flowability and is therefore not always desirable. Bulk density can deviate significantly from particle density, with reported values as low as half of the true material density. In this research, the bulk density of SB is regarded as 65% of the particle density of SB, namely 550 kg/m<sup>3</sup>. For AB, no data is available on bulk density. After in-house, unpublished testing by the authors, the bulk density appears to be less than SB and is estimated to be around 400 kg/m<sup>3</sup>, although this value depends strongly on the packing state (e.g., loose or compressed). Because volumetric energy density scales directly with bulk density, this assumption introduces uncertainty into the volumetric performance of AB. The reported volumetric energy density values should therefore be interpreted as estimates within a realistic range rather than precise values. The gravimetric energy density is not influenced by this. Further research on the bulk density and a sensitivity study on how it influences the volumetric energy density is still advisable.

The distinction between fuel and spent fuel is also important. Figs. 7 and 8 clearly show this, as well as Figs. 15 and 16. For safety reasons, ships are not operated with empty tanks, so energy density estimates based solely on spent fuel are not representative. That is why the specific mixture is chosen when evaluating the feasibility for different ship types. For gravimetric energy density, the effect of the spent fuel may be significant for weight-limited ships. These distinctions, while important at the ship-integration level, are not shown directly in the Ragone plots.

Heat integration assumptions further affect the energy density of LOHC systems. Proper waste-heat recovery can improve the overall energy density by up to about 30% [14], and this has been included by using the average expected improvement in the comparison figures. However, the practical achievable degree of heat integration depends strongly on system layout, operational profiles, and thermal-management constraints.

Beyond energy density considerations, several assumptions regarding power density calculations influence the comparative results. The technology to convert hydrogen into useful power (e.g. electrical or mechanical) is in various stages of maturity. The PEMFC are the most mature. Substantial data is available for PEM, yet the range of these technologies may be improved. The other converters are less mature, yet have much smaller data bandwidths. In this research, all the data is

**Table 5**

Overview of possible hydrogen carrier and energy converter combinations suitable for different ship types and operations.

|                                      | Inland | Short Sea | Ocean-going | Fishing | Dredging    | Tug         | Ferry        |
|--------------------------------------|--------|-----------|-------------|---------|-------------|-------------|--------------|
| Power requirement                    | Small  | Medium    | High        | Small   | High        | Medium      | Medium       |
| Autonomy                             | Medium | Medium    | Long        | Medium  | Long        | Medium      | Short        |
| Case study                           | SB, AB | SB, AB    | SB, AB      | SB, AB  | SB, AB, NEC | LH2, SB, AB | SB, NEC, DBT |
| Operational changes likely necessary | No     | No        | No          | Yes     | Maybe       | Yes         | Maybe        |

assumed to be of a comparable level of performance characterisation. This assumption may make less-developed technologies appear more consistent than they are in practice, potentially underestimating their future improvement potential as well as their present uncertainty. This affects comparative conclusions, as emerging technologies may seem either more predictable or less promising than their true developmental trajectory suggests.

The reactor, separator and heat exchangers influence the power density as well. Because the separator size is determined by the reactor, reducing the reactor size significantly affects the power density. The reactor itself is strongly influenced by the choice of catalyst and type of reactor, but the throughput time also plays an important role. In this research, experimental data is taken as a basis, and it is assumed that these experiments can be easily scaled up. However, scaling up a reactor may influence its power density. Additionally, as these are emerging technologies, the throughput time of the reactor may still be reduced, which strongly influences its size and thus the power density. This scaling assumption is particularly significant given that most experimental data comes from laboratory-scale systems, while marine applications require industrial-scale reactors. Furthermore, as especially the DBT reactor is operated at temperatures very close to DBTs degradation temperature, intermediate heat exchangers were added to avoid overheating of the reactor of DBT and of NEC. These heat exchangers are of considerable size and strongly influence the power density of the overall system. Even though these intermediate heat exchangers were assumed necessary based on thermal limits, alternative reactor designs, improved thermal management, or improved overall energy management could potentially remove this requirement.

Mass-flow and heat-flow integration are also critical. In this work, ideal mass-flow matching is assumed, meaning that flow rates between components are perfectly aligned without practical constraints such as control limitations or pressure-drop penalties. Real systems will experience such constraints, potentially lowering power density. Similarly, waste-heat utilisation improves energy density, but may influence power density depending on the level of integration. Without heat integration, a hydrogen burner is required, which simplifies the system but increases hydrogen demand. This reduces both the energy density and, by increasing reactor throughput requirements, the power density. In this research, the net effect of heat-integration assumptions on power density is assumed negligible, although deviations from ideal integration could alter this balance.

Finally, more advanced integration strategies could further improve system performance. Internal reforming of NEC or DBT within an SOFC could reduce heat-exchanger requirements substantially. Likewise, the use of liquid cooling could reduce heat-exchanger size because liquid-liquid units are typically more compact than liquid-gas systems. These options were not considered here due to limited research availability, meaning the current approach may overestimate system size and underestimate power-density potential for future integrated designs.

The assumptions discussed above influence different performance metrics to varying degrees. Power density is dominated by converter data and reactor sizing assumptions, with heat-integration choices playing a comparatively minor role. Energy density, on the other hand, is more sensitive to heat-integration assumptions and spent fuel effects, and these factors may alter comparative outcomes significantly.

The potential for future optimisation varies significantly as limitations may be physical or technological in nature. Certain energy converter efficiencies, such as those for ICE and GT, are fundamentally

limited by thermodynamics, specifically by the Carnot efficiency. On the other hand, reactor technologies and catalyst selections are largely technologically limited, resulting in possible optimisation as emerging technologies mature.

Finally, the logarithmic scaling used in the plots inherently reduces the visual impact of small performance differences. This results in emphasis on meaningful performance differences, while minor variations are not emphasised. In turn, small data discrepancies or measurement uncertainties are rightfully minimised, ensuring the focus lies on substantial performance distinctions, rather than small differences which will not likely influence practical design decisions.

#### 4.4. System-level constraints beyond energy density

This research focusses exclusively on gravimetric and volumetric power and energy density. However, power and energy density are only two of a large variety of values that have to be considered when assessing the suitability of alternative fuels. Other values are, for example, availability, safety, technology readiness level (TRL), material handling, stability of fuel, renewability of fuel, economic impact, sustainability [7,8].

- **Availability:** New and alternative fuels are not always easily available in the large quantities which are often needed when using fuels.
- **Safety:** Several hydrogen carriers and alternative fuels exhibit toxicity (to either humans or marine life), corrosivity or flammability [76]. These properties may influence ship design and impose additional system requirements.
- **TRL:** The TRL of the hydrogen carriers discussed in this research is relatively low [7]. Significant technical uncertainties remain, as most concepts remain at laboratory or early pilot scale [7,8].
- **Material handling:** the handling of fuels that are not liquid, such as SB and AB, makes material handling onboard as well as bunkering more complex, especially when combined with the fact that these fuels should not come into touch with water, so also not with humid air [24].
- **Stability of fuel:** some of the fuels (and reference cases) are not perfectly stable under the standard operation conditions. LH2, for example, experiences boil-off, while both LOHCs lose a bit of their total fuel during dehydrogenation because they are not perfectly stable.
- **Renewability of fuel:** A major advantage of hydrogen carriers is their renewability; empty hydrogen carriers can be reloaded with hydrogen again. For LOHCs, this is more straightforward than for SB or AB, which are fairly complex to regenerate [8,77].
- **Economic impact:** alternative fuels are generally more expensive than MDO. The price of hydrogen is relatively high [78]. Additionally, for hydrogen carriers, there are the additional cost of the carrier and the hydrogenation.
- **Sustainability:** The overall environmental impact of hydrogen carriers depends on lifecycle emissions, including hydrogen production and carrier regeneration. The associated energy demand and upstream processes may significantly influence net greenhouse gas performance.

The choice for an additional fuel depends on how these values (and power and energy density) are evaluated and valued in turn. The results presented in this work therefore represent an energetic comparison only and do not constitute a comprehensive feasibility assessment.

## 5. Conclusion

Alternative fuels, particularly hydrogen carriers, represent a promising approach for reducing greenhouse gas emissions from ships. Given the substantial variation in power and energy density among alternative fuels, no single solution is likely to be universally applicable across all vessel types.

This study compared several alternative fuels and energy converters using Ragone plots and evaluated their suitability for seven distinct ship types. The analysis revealed that AB paired with an ICE and SB combined with PEMFC have the greatest potential across a broad range of vessels, including inland, short-sea, and ocean-going ships. For tugboats and fishing vessels, however, the investigated hydrogen carriers cannot meet current operational requirements. The relative fuel mass and volume are already significant compared to vessel size, and the additional weight and storage requirements of hydrogen carriers exceed feasible onboard limits. For dredgers and ferries, implementation appears technically possible, although increased fuel mass and volume may substantially affect vessel layout, payload capacity, or operational flexibility, potentially requiring design adaptations.

Because the calculated system mass and volume per unit of power and unit of energy depend only on the intrinsic properties of the carriers, converters and their integration, and not on the vessel considered, these characteristics are expected to hold for other ship types. The resulting feasibility, however, varies strongly between vessels, since ships differ widely in how much mass and volume they can accommodate relative to their power and energy demand. Notably, the outcomes span the full range: for some ship types the systems are comfortably feasible, while for others they are entirely infeasible.

This analysis relies on component efficiencies and property data from the literature rather than on experimental measurements. Its value as a screening tool is therefore twofold: it identifies the carrier-converter combinations and vessel categories that warrant experimental demonstration, and those for which likely no additional evidence is needed, since they are unlikely to fit. Experimental investigation can accordingly focus on the promising combinations, such as AB-ICE and SB-PEMFC, in the vessel segments where the analysis indicates feasible operation. The results confirm that no universal solution exists while simultaneously showing that hydrogen carriers can serve as effective alternative. For certain applications, they may achieve energy and power density performance comparable to or exceeding conventional fuels such as MDO and other alternatives including ammonia, methanol, and LH<sub>2</sub>. Notably, this holds for the fuel-converter combinations rather than for hydrogen carriers as a class: the choice of converter proves as decisive as the choice of carrier.

While this analysis focused primarily on power and energy density considerations, other critical factors, such as fuel availability, fuel renewability, safety, and sustainability, require further evaluation. Nevertheless, the analysis establishes that hydrogen carriers can be technically feasible for maritime propulsion under appropriate operational conditions, demonstrating that ships can operate for extended periods on hydrogen-based fuels while achieving zero tank-to-wake CO<sub>2</sub> emissions and substantially reducing harmful exhaust emissions.

## CRedit authorship contribution statement

**E.S. van Rheenen:** Writing – original draft, Visualization, Validation, Methodology, Investigation, Data curation, Conceptualization. **A.A. Kana:** Writing – review & editing, Resources, Investigation, Data curation. **K. Visser:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **J.T. Padding:** Writing – review & editing, Data curation, Conceptualization.

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## Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Erin van Rheenen reports financial support was provided by Netherlands Enterprise Agency. Specifically, the work was supported by the project SH2IPDRIVE: Sustainable Hydrogen Integrated Propulsion Drives, funded by the RvO under grant MOB21013. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

The data used for this research paper can be found in [10.4121/95ae4238-b9f1-4ba0-a40c-e661d1611cff](https://doi.org/10.4121/95ae4238-b9f1-4ba0-a40c-e661d1611cff).

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