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Review

Superconductivity and Hydrogen Economy: A Roadmap to Synergy

Masih Mojarrad [1,*], Sana Farhoudian [2] and Pavlo Mikheenko [1]

[1] Department of Physics, University of Oslo, 0371 Oslo, Norway
[2] Faculty of Engineering and Natural Sciences, Tampere University, 33100 Tampere, Finland
* Correspondence: masih.mojarrad@fys.uio.no; Tel.: +47-96725565

Abstract: Hydrogen as an energy carrier is a promising alternative to fossil fuels, and it becomes more and more popular in developed countries as a carbon-free fuel. The low boiling temperature of hydrogen (20 K or −253.15 °C) provides a unique opportunity to implement superconductors with a critical temperature above 20 K such as MgB_2 or high-temperature superconductors. Superconductors increase efficiency and reduce the loss of energy, which could compensate for the high price of LH_2 to some extent. Norway is one of the pioneer countries with adequate infrastructure for using liquid hydrogen in the industry, especially in marine technology where a superconducting propulsion system can make a remarkable impact on its economy. Using superconductors in the motor of a propulsion system can increase its efficiency from 95% to 98% when the motor operates at full power. The difference in efficiency is even greater when the motor does not work at full power. Here, we survey the applications of liquid hydrogen and superconductors and propose a realistic roadmap for their synergy, specifically for the Norwegian economy in the marine industry.

Keywords: superconductors; liquid hydrogen; hydrogen economy; marine industry; MgB_2

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1. Introduction

Hydrogen is zero-emission fuel. However, the energy consumed for hydrogen production is bigger than the energy that could be obtained from it. This is why hydrogen is known as an energy carrier, not an energy source [1]. Hydrogen would serve as a replacement for fossil fuels. The latter has been providing the majority of energy in the world. However, deposits of fossil fuels are limited, and they strongly contribute to global warming [2]. The strong policy in some countries forces industries to reduce CO_2 emissions. Norway is going to diminish its carbon emission by 40% by 2030 compared with emission in 1990, and this still needs to be decreased by 85–90% by 2050 according to the Paris agreement in 2015 [3]. Some companies in Norway, such as Equinor, aim to have zero carbon emission by 2050 [4], and it is projected that hydrogen will provide 24% of all energy needs in the world by this year. Although the amount of pure hydrogen is extremely small on Earth, fossil fuels and water have a large amount of hydrogen in their bonds [5], some of which could be released and used with the following advantages:

- Water is the only by-product of hydrogen combustion. It produces no pollutants [5,6];
- Hydrogen has a wide range of uses in transportation and industries [5];
- The excess of the energy/electricity can be saved in the form of hydrogen, thus utilizing it as storage for the grid [1,5,7];
- Companies can produce hydrogen almost everywhere in the world since the variety of energy sources is ubiquitous, and it would not be the exclusive source for only a few countries [5,8];
- Hydrogen has the highest gravimetric energy density of 120 MJ/kg, which is 2.75 times bigger than in hydrocarbons [1,6,9,10].

Despite all the mentioned benefits, one needs to take the downsides of hydrogen into consideration:

- Its production can release CO_2 as a by-product in case fossil fuels are used as the feedstock [6];
- It has very low volumetric energy density of 0.01 MJ/L [6];
- It can be explosive possessing a high flammability range; therefore, safety is one of the main issues in the handling of hydrogen.

Some of the discussed drawbacks could be compensated by using hydrogen in its liquid form. However, liquid hydrogen (LH_2) has its own challenges. On the positive side, LH_2 has three times higher energy density than the compressed hydrogen gas at a pressure of 350 bar. Due to this advantage, more LH_2 can be loaded to tracks in comparison with compressed hydrogen gas (CGH_2), which results in cost-reduction in the transport and storage [10]. The energy density of LH_2 is 8.50 MJ/L, which is 850 times higher than the energy density of hydrogen in gas form at normal conditions and almost two times higher than that of compressed hydrogen at 700 bar and 25 °C. This energy density is also a bit higher than the heating value of methane, which is 8.39 MJ/L at 200 bar and 15 °C [1,6,11]. Furthermore, liquefaction of hydrogen leads to freezing out impurities, which prevents contamination during combustion [12].

Although it is generally believed that the low boiling temperature of LH_2 (about 20 K [1]) is a downside and a barrier for its applications, it can be one of the main advantages since it allows to be a coolant for superconductors. Superconductors, in their turn, can make hydrogen very efficient, especially what is called type II superconductors. The superconductors in this group have typically higher critical magnetic field (H_c) and critical temperature (T_c) than others, which make them useful for applications [13,14]. Type II superconductors with T_c higher than the boiling point of LH_2 have considerable potential for synergy with LH_2.

Compactness, loss-free energy transfer, high efficiency, and other unique features of superconductors make them superior compared with conventional conductors [15]. Magnesium diboride (MgB_2) seems to be the best material for LH_2 economy: its critical temperature is twice the boiling point of LH_2, it is light and processed easily, and it is least expensive than other appropriate superconductors. High temperature superconductors (HTS) are another option, but a significant decrease of critical current density at grain boundaries of HTS bulks and a higher cost of producing HTS without grain boundaries make them inferior in comparison with MgB_2 [15–18].

The wide range of uses for superconductors is already recognized. In most cases, the high cost and challenges of cooling are restricting their applications in the industry. Availability of LH_2 seems to be able to solve this problem. However, this case is rarely examined in studies. Since the LH_2 industry has rapidly been developing in recent years, it seems to be a proper time to reintroduce superconductivity to relevant industries. Here we assess the possibility of the synergy of LH_2 and superconductors, and how this synergy could contribute to both sectors.

2. Hydrogen Economy

Hydrogen has the potential to be the cost-effective substitution for fossil fuels because of the abundance of element hydrogen in the universe, the highest energy content, and its sustainability and environmentally friendly features—unlike hydrocarbons [2]. We examine hydrogen economy in categories of production, storage, distribution, and applications.

Hydrogen can be produced using sustainable sources of energy like hydro, wind, solar or from fossil fuels. The latter release CO_2 emissions that need to be counterbalanced by the carbon capture and storage (CCS) procedures [3]. In the production of green hydrogen from water, the price of electrolyzers influences the capital cost [19], and the high electricity demand is another issue. Hydropower produces about 91.5% of electricity in Norway. Generating electricity in this way not only avoids carbon emissions but used to be also low in price, which was about 33–50 Øre/kWh (100 Øre = 1 NOK ≈ 0.1 € ≈ $0.1) in the first quarter of 2021 before the energy crisis happened in Europe. However, the price of electricity is still low in the northern part of Norway. In addition, there has been an exemption for the state electricity tariffs since 2019 for the companies producing hydrogen by electrolysis in Norway. The progress in the efficiency of electrolyzers also results in the cost-reduction [3]. As a result, while most of hydrogen in the world is extracted from fossil fuels [11], climate conditions in Norway offer a special advantage in the supply of green hydrogen at the lowest possible price and without environmental side effects. Fees for hydrogen production from water by electrolysis in terms of energy are estimated to be about \$20/GJ (with the electricity price of \$0.036/kWh), which is three times higher than when it is generated from natural gas with CCS (\$6.9/GJ) [20]. Although the price of hydrogen obtained from natural gas currently seems to be more reasonable economically, fossil fuel sources will not last forever. Moreover, hydrogen produced from water by electrolysis becomes more and more inexpensive over time. While recent studies in Norway reveal that the cost of hydrogen production can reach \$3.6–4.9/kg, Norwegian NEL company plans to produce green hydrogen at the cost of \$1.5/kg by 2025, which is equivalent to \$12.5/GJ [21]. Another investigation by DNV-GL projects the price of hydrogen produced in Norway by electrolysis to be in 2030 at the level of \$2–6/kg [22]. Technically, the larger amount of hydrogen is generated, the less it would cost [2]. However, the effect of electricity price could not be neglected. Figure 1 depicts how the electricity price and the scale of hydrogen production affect its final cost in the USA.

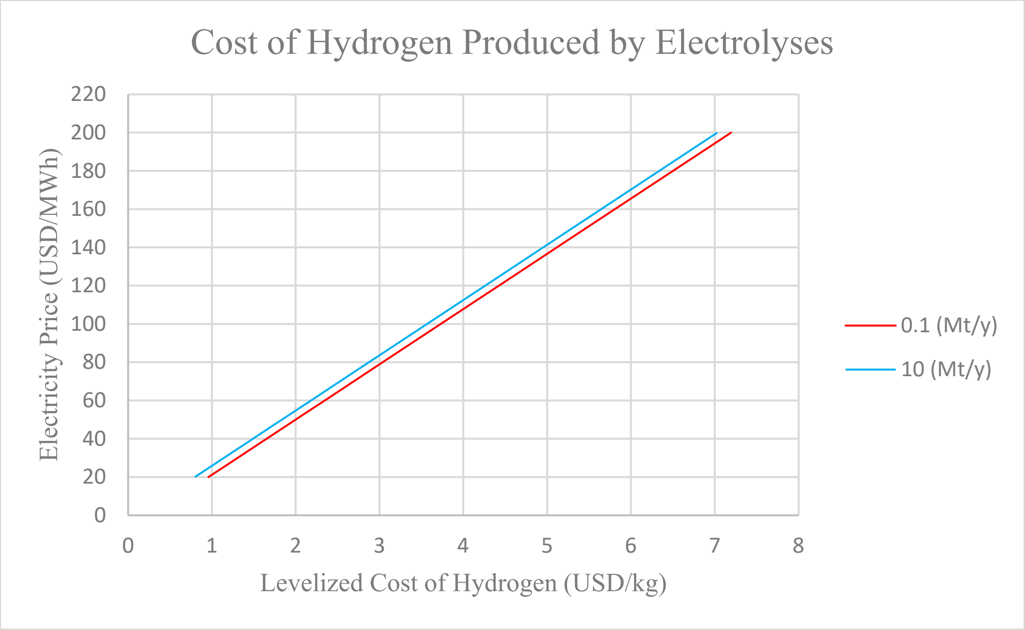

Figure 1. Levelized cost of hydrogen as a function of price for electricity (data from [23]).

Liquefication and storage are other processes that determine hydrogen production cost. The specific energy quadruples when the hydrogen gas at 250 bar converts to LH_2 at 1 bar, but one-third of the energy content of hydrogen is consumed by liquefication. This makes LH_2 expensive. Therefore, neither the capacity of liquefaction is considerable in Europe (only 20 tons/day), nor it is produced in Norway [3], although some companies start investing in LH_2 production. The relatively small size of current LH_2 plants is also responsible for the high price. If larger LH_2 plants are constructed, about 67% of additional cost reduction would be possible. The high price of LH_2 production could be compensated to some extent in other sectors, like in transportation [3,12]. In the storage sector, preparing the proper insulation is the main issue. While the amount of boil-off during the transportation is estimated to be about 0.2% per day [24], NASA claims that the boil-off could be reduced to zero by an internal heat exchanger [7,22]. In any case, the issue of boil-off gas could be lifted in the maritime shipping sector by using it in the propulsion system [23].

In 2050, 31,000–60,000 TWh/year of hydrogen is expected to be produced according to the EU scenario, while only a fraction of this amount will be transported [25]. Thus, hydrogen storage is a critical factor in its use. Generally, hydrogen is stored at high pressure, up to 700 bar, but about 12% of energy content has to be consumed in the storage process [2]. In addition, refueling the high-pressure hydrogen tanks is challenging due to a negative Joule–Thomson coefficient and embrittlement of the walls of the tanks [6,26]. Liquefication of hydrogen is another method to store it: LH_2 is more compact and is kept in low-pressure vessels, which helps to transmit more hydrogen by the trailers in safer conditions [2]. Trucks can transport up to 4000 kg of LH_2, while it is typically 1000–1500 kg for the compressed hydrogen gas [3,27]. Therefore, transportation of hydrogen in cryogenic form is a cost-efficient method for long distances and large loads of hydrogen [1,12]. As an example, the transportation cost of LH_2 is almost four times lower than that of compressed hydrogen in terms of price per distance in Germany [28]. In contrast, high energy demand for liquefication and difficulties in the insulation of the vessels restrict this application and increase the cost [2]. However, in large plants, the cost-reduction in LH_2 distribution more than compensates for the cost imposed by LH_2 production [1].

Hydrogen applications also play role in its cost-efficiency. Storing electricity is challenging, but, instead, excess electricity can be used to produce hydrogen from water. It then could be easily stored and later used to produce electricity by fuel cells [20]. In transportation, batteries as storage of electricity might be a proper option for a short distance, but they do not have enough capacity for long journeys. Due to higher energy density in hydrogen fuel cells, they can replace batteries in the storage of energy [19,29]. Norway projects that, in 2030, about 23% of total hydrogen in the country would be consumed in the transportation sector [4], where relevant industries can implement hydrogen fuel cells. Norway has already constructed factories to produce fuel cells to convert hydrogen to electricity. Due to compact volume of liquid, vehicles could use LH_2 as fuel both in internal combustion engines and fuel cells. Although hydrogen fuel cells consume hydrogen in gas form, LH_2 still can be considered as the storage option and primary source of gas. In this case, the amount of evaporation becomes crucial since its high rate may cause overpressure in the vessels, while low evaporation rate means a lack of fuel [9,10]. Overall, hydrogen fuel cells can provide the best energy efficiency in vehicles without carbon emissions. In addition, such vehicles can compete economically with gasoline and hybrid ones on a cost per kilometer both in urban and rural areas [27,30]. Hydrogen fuel cells can have stationary applications too [12].

Fuel cell electric vehicles (FCEVs) are competitors for plug-in electric vehicles (PEVs), and they have the potential to compete with internal combustion engine vehicles (ICEVs). A fuel cell stack costs approximately \$100/kW, while a lithium-ion battery values on average \$270/kWh. If the retail price of hydrogen is reduced to \$8/kg (\$0.24/kWh)—which is cheaper than the electricity cost in most places—and governments set a high price (or restriction) for carbon emissions, FCEVs can even dominate ICEVs. The absence of carbon emission, low weight and lack of hazardous materials are other advantages of FCEVs over PEVs and ICEVs [30,31].

3. Superconductivity Applications

Due to unique features of superconductors, among them loss-free energy transfer, they can be used in a variety of sectors: transportation, electrical and mechanical devices [32], medicine [32,33], and distribution of energy [33,34].

Wires and coils are important in the distribution sector, but they are also responsible for energy losses. Superconducting cables/wires could compensate electromagnetic fields around sensitive devices; help to avoid losses of energy; occupy less volume than conventional conductors; and are stable in various weather conditions such as strong wind, snow, and ice [34]. Production of long HTS wires is challenging and costly, but MgB_2 wires have a reasonable price and are easy to produce—costing about one-tenth compared with HTS wires. The higher critical temperature is the main advantage of HTS wires since the cost of a cryogenic cooler also affects the total price [34]. Low AC losses in MgB_2 wires are another advantage [35]. Whenever the available coolant (such as LH_2) is appropriate for both cases, MgB_2 would be the first candidate for the superconducting wires. Wires/cables are used not only in most of the electrical devices but also for the distribution of electricity. Superconducting wires can pass electrical current with a density of 10–100 times higher than in conventional (Cu) wires with the same cross-section area [33]. Hence, superconducting wires provide very high efficiency in the transmission of electricity.

Superconductors can be used in motors with a wide range of applications in vehicles and industrial devices. They can provide light weight, smaller size, low energy consumption and high-efficiency of the motors [32,36,37] by making stronger magnetic fields that rotate rotors with stronger force, lead to a reduction of the amount of iron used in the motor, increase the torque and reduce the motor size [33,38]. In large-scale vehicles, such as a ship, superconductors can save space and considerably reduce noise [33]. The torque density of a superconducting ship propulsion motor can reach 28 kN/m^3, while it is only 10 kN/m^3 for conventional motors [34].

The superconducting generators can also provide a good solution for ever increasing electrical demands [17]. Terao et al. [39] compared superconducting generators with conventional ones for 10 MW wind turbine generators. In their study, the fully superconducting generators (FSCG) with yttrium barium copper oxide (YBCO) and MgB_2 coils were used instead of permanent magnets and copper coils, as in the conventional one known as a permanent magnet synchronous generator (PMSG). FSCG had two advantages compared with PMSG: the weight of the generator was reduced from 231.7 to 63.6 tons, and the copper energy loss was omitted. Copper causes 4% of the total energy loss in the PMSG, and its total efficiency is less than 90%. In contrast, FSCG had no copper loss, yet it suffered from AC losses in multifilament MgB_2 wires that were about 2%. In wind turbines, a superconducting generator allows for removing the gearbox, decreasing the size and weight, and reducing the cost [40,41]. The cooling system of such generators consumes negligible energy compared with its total loss [36]. However, the cooling system still needs to be optimized by choosing a proper heat exchanger [42].

Some mechanical devices, such as a bearing one, can also take advantage of superconductors. Superconductors can provide quasi-permanent magnetic flux [32]. Therefore, the permanent magnet can be replaced by a superconducting magnet resulting in a magnetic levitation (maglev) unit [43]. The superconducting bearings can stabilize and suspend flywheel rotors avoiding wearing and friction between them, which means having low energy loss [36,44]. These mechanical devices exist both in motors and generators.

Superconductors can completely change transportation providing high efficiency and low emission in vehicles [34]. It was already pointed out that energy-loss-free characteristics of superconducting wires, electrical, and mechanical devices will benefit all kinds of vehicles: trains, planes, ships, and spaceships [17]. However, there are many possibilities to increase the use of superconductors in transportation. For instance, the flux pinning in superconductors allows one to use them for maglev trains. The speed of maglev trains could reach 1000 km/h [44]. Since a high magnetic field has to be generated to levitate a heavy train, long and large coils are required. Therefore, once again, MgB_2 seems to be the best option for this application because of its low cost [35].

Berger et al. [45] demonstrated that transformers could also operate more efficiently by using superconductors. In this study, the authors replaced the copper in the coils with YBCO, while the core remained to be iron. In this case, the efficiency increased from 99.6% to 99.9%, while the main loss of the superconducting transformer still stemmed from the iron core—67.2% of the total loss. Superconducting transformers could avoid up to 81% of energy loss per year. Other researchers have also investigated the development of superconducting transformers in several studies [46–48].

The most successful commercial application of superconductivity has been in medical diagnostics, namely in magnetic resonance imaging (MRI) in which over 70% of the MRI scanners are using superconductors—mainly niobium-titanium (NbTi). The critical temperature of NbTi is about 10 K, so liquid helium (LHe) is the only proper coolant for it, but the price of LHe significantly increased in the last decade. The solution is to develop the next generation of MRI using HTS (including YBCO, other rare-earth barium copper oxides and bismuth strontium calcium copper oxides) or MgB_2. The critical temperature of MgB_2 (39 K) is lower than that of HTS (90–110 K), but the affordable price, availability of wire, and simplicity of making joints between the bulks make MgB_2 a superior option for this application [49–51].

Superconductors can deliver a prominent outcome, but for most applications, the high price of the cooling deters commercial investments and hinders their development. Increasing the popularity of using LH_2 in the industries and decreasing its cost could lift this barrier. It seems it is time to reconsider use of superconductivity in industrial applications taking into account the large-scale production of LH_2.

4. Synergy of Superconductivity with LH_2

LH_2 use becomes more and more popular in many countries. The unique characteristics of superconductors are well known. However, industrial applications are still limited because of technological challenges and the high cost of cooling. On the other hand, since the electricity sector is one of the main sources of carbon emission [52], superconductors can reduce pollution. Moreover, industries consume more LH_2 nowadays, so cooling a wide range of superconductors is not a serious issue anymore. The traditional coolants for the superconductors are either liquid nitrogen or liquid helium. Unlike LH_2, neither of them is a fuel. The latter is a strong argument in considering the potential and outlook for the synergy of superconductors with LH_2.

Hydrogen is an energy carrier, and at the same time, it could be a coolant for superconductors when it is in the form of liquid. For vehicles, hydrogen could be a fuel for the engine or a feedstock for fuel cells to generate electricity. Some types of vehicles have a liquid hydrogen tank that can cool superconducting motors, generators, bearings, and wires in the vehicle before its consumption. It allows for using less fuel (hydrogen), having higher performance, and avoiding energy loss. This can be introduced in all transportation sectors like maritime, trains, cars, trucks, buses, and in the aviation industry. For example, Airbus is endeavoring to construct zero-emission aircraft by 2035, while the company is planning to use hydrogen in liquid form [53]. It could be a good solution for Airbus to use superconducting devices to reduce the costs by saving both energy and fuel.

MgB_2 superconducting tapes are not over expensive, being comparable in price with the conventional conductors. The HTS wires cost about $100/kAm, which is more expensive than competing copper with the cost of tens of $/kAm [54]. In contrast, MgB_2 wires could be produced and sold cheaper in the USA, according to the Hyper Tech Research company (private communication). Since wires exist in all electrical devices such as generators or motors, implementing MgB_2 tapes is more reasonable wherever LH_2 is available or can be adopted.

HTS superconductors allow for constructing economical generators. The superconductivity results in omitting ohmic resistivity, which leads to lower energy consumption. The amount of energy saved during the lifetime of an HTS generator can compensate for its initial cost [55]. Replacing HTS with MgB_2 would probably reduce the cost even more. Other electrical and mechanical components or devices, such as cables, motors, fuel cells, and bearings, could also take advantage of superconductors to diminish energy loss. In all these cases, LH_2 can cool the superconductors before it is used as a feedstock or fuel. For instance, a very recent study has demonstrated how LH_2 chills a generator, and the evaporated hydrogen runs a turbine afterwards [56].

All kinds of vehicles have the potential to use superconducting devices and LH_2 as both a fuel and coolant. Almost all electrical and some mechanical parts could be built from superconductors. For example, in [38], the fully superconducting motors were tested while LH_2 was served as a coolant. Since LH_2 becomes more and more popular as a storage of fuel in vehicles, it could cool the superconductors first and then feed the fuel cells. This can result in economical and highly-efficient vehicles. For example, Nam et al. [57] have investigated the possibility of replacing a turbine-based propulsion system with a hydrogen fuel cell while LH_2 cools the superconducting motor before it feeds the fuel cells. This proposed system helps to increase efficiency by about 15% simultaneously decreasing the amount of polluting gases and noise. The same could be implemented in other vehicles as well: the first LH_2 fuel-cell ship is already projected to operate in Norway in 2023. For this purpose, LH_2 in the tank should be evaporated first to be able to initiate fuel cells [58]. However, as mentioned earlier, it could be designed more efficiently. If the superconducting devices are used in this project, LH_2 would first cool the superconductors while LH_2 boils off during this process. The produced hydrogen gas would further be used as a feedstock for fuel cells or hydrogen internal combustion engines.

Pipelines are one of the applications that can merge superconductors with liquid hydrogen. The need for power transmission increases more and more [18], and it could be tackled by superconducting pipelines. Nowadays, mainly vehicles distribute LH_2, while pipelines only distribute hydrogen in gas rather than liquid form [3]. The reason is probably the high cost of insulation and stabilization of temperature. If MgB_2 pipelines were built, at the same time, a considerable amount of hydrogen and electricity would be passed through. Pipelines could provide fuel and electricity for a whole city. The MgB_2 pipelines have few pros [59]: the connections between the pipes are not that challenging compared with other superconductors; the weight is three times lower than that of stainless steel; the current that can be passed through the pipeline is considerable because of high critical current density and a bigger cross-section than in the cables. Simultaneously with electricity distribution via pipelines, LH_2 inside them can provide the fuel for households and industries or be the coolant for other end-users such as hospitals, which need it for medical diagnostics.

The superconducting railways that can levitate trains could be combined with the pipelines delivering LH_2 to the consumers. The electricity distribution via superconducting pipelines may practically compensate for the cost of LH_2. The compactness of LH_2 compared with hydrogen gas is another advantage that can be taken into consideration when building superconducting pipelines.

After LH_2 cools the superconducting devices, it can be used for other purposes. Since LH_2 evaporates after cooling the devices, as already mentioned, it is a proper feedstock for fuel cells. Fuel cells can generate electricity on demand. Thus, the electricity can run or pass through the superconducting devices that are already cooled by LH_2.

The potential and possibilities of combining LH_2 with superconductivity have been considered in different sectors. Figure 2 illustrates the general perspective and purpose of the synergy between LH_2 and superconductivity described in the paper. Among all possible sectors, the combination of superconductors and LH_2 is more likely to happen in the maritime industry first. Norway has a prominent infrastructure for producing and implementing LH_2 in the maritime sector [22,60], and it targets shifting to zero-emission passenger ferries in ten years while hydrogen, as a green energy carrier, is considered one of the options for this purpose [61]. However, unfortunately, the role and effect of superconductors could be missed from the consideration. Using superconductors, one could develop the LH_2 industry in marine technology, make it more economical than in the currently planned state, and help to create more environmentally friendly and highly efficient society. In the next section, it is discussed in detail how superconductivity would affect the LH_2 industry in the maritime shipping sector.

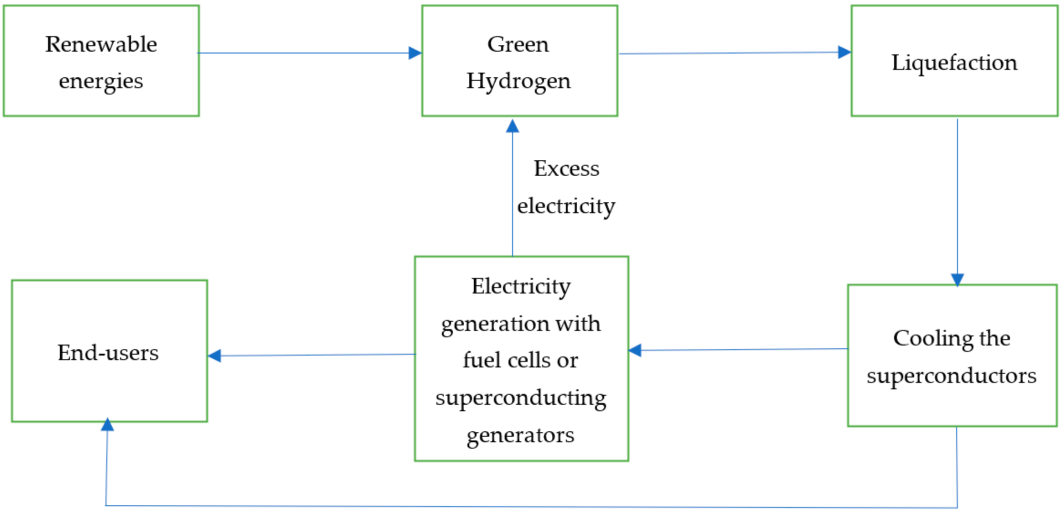

Figure 2. Outlook of the synergy between superconductors and liquid hydrogen.

5. Introducing Superconductivity into the LH_2-Based Marine Industry

The maritime shipping industry is responsible for 7–8% of carbon greenhouse gas emissions in the world [11], and it will increase 50–250% by 2050 if the current trend remains the same [62]. Therefore, International Maritime Organization (IMO) decided to reduce the emission by 50% by 2050 compared with that in 2008. There, LH_2 could play a key role as its use could reduce emissions by 40% and 70% by the years 2030 and 2050, respectively [7].

Safety is one of the main concerns for each technology. This applies to LH_2 as well. LH_2 is a non-toxic fuel; however, its high concentration could lead to asphyxiation [11]. The wide concentration range of flammability presents a considerable risk of fire. However, hydrogen could be considered a safer fuel in terms of explosion compared with fossil fuels in case the container is settled in an unconfined area. The reason is that hydrogen disperses in the environment quite quickly and does not reach the critical concentration to explode even if it is ignited [63]. Nevertheless, it seems that it is not documented well, and the LH_2 industry suffers from a lack of standards. The Norwegian Directorate for Civil Protection (DSB) suggested imposing the same standards for LH_2 as for Liquid Natural Gas (LNG) in bunkering [61], but more regulations are needed in this sector.

Besides safety, probably the most important barrier for the production and implementation of LH_2 is its high cost compared with conventional fuel in the maritime shipping industry, i.e., diesel. Table 1 shows that, besides the high cost of production, storage cost imposes substantial expenditure on the LH_2 option. Moreover, LH_2 has a lower volumetric energy density, which means that more space should be assigned in the ships for the fuel tank compared with that of a diesel one. On the other hand, the weight of hydrogen is considerably lower than that of diesel, which is considered to be a big advantage since the deadweight is a critical parameter for designing a ship—especially for the small size of vessels. As an example for comparison, in Norway, a vessel with a length of 30–40 m has a diesel tank with a capacity of 6000 to 12,000 L weighing 5000 to 10,000 kg. To have the same amount of energy for the same size of vessel operating with LH_2, the vessel requires 25,000–50,000 L of LH_2 weighing 1700–3500 kg.

Table 1. Diesel and LH2 costs and properties.

Fuel	Production Cost (USD/kg)	Onboard Fuel Storage Cost for Haulage (euro/MJ Stored)	Volumetric Energy Density (GJ/m^3)	Specific Energy Density (MJ/kg)	Density (kg/m^3)
LH_2	4–12 * [11]	2.87 [62]	8.5 [11]	120 [7]	70.8 [61]
Diesel	0.96 [64]	0.07 [62]	36.3 [7]	43.25 [7]	837 [7]

* Depending on the method of production.

LH_2 could not compete with diesel and other fossil fuels in terms of price, but using a superconducting propulsion system in the maritime sector could compensate for this to some extent. Using a superconducting propulsion system, rather than a conventional one, offers higher energy efficiency; compact volume, which could partly compensate for the high volume of LH_2 tank; less weight; abatement in the maintenance and operational cost [65]. Moreover, superconducting propulsion system does not need a gearbox to adjust the rpm of the motor. The gearbox in a conventional propulsion system is responsible for 1–5% of total loss [66]. A superconducting propulsion system has already been developed by the US navy, but the coolant is currently gas helium (private communication). Table 2 shows the comparison between a superconducting motor and a conventional one in a propulsion system in terms of efficiency.

Table 2. Efficiencies of conventional and superconducting motors in different ranges of power *.

	Full Power	30% to 50% of Power
Efficiency of Conventional motor	95%	30–75%
Efficiency of Superconducting motor	98%	97%

* The data are provided by American Superconductor.

Figure 3 shows how LH_2 and a superconducting propulsion system could be implemented in a marine vessel. First, LH_2 is used to cool the superconducting propulsion system. During this process, LH_2 absorbs some heat, and it might be evaporated. However, its temperature is still low to be able to use in the fuel cells. Therefore, a heat exchanger is needed to increase the temperature of hydrogen to the minimum operating temperature of the fuel cells. Fuel cells have two important outputs: electricity and heat. The electricity would run the superconducting propulsion system, while obtained heat could be used to heat up the hydrogen fed to the fuel cells. The other solution for heat is to use it for warming the deckhouse, and instead use the seawater to warm the initial hydrogen.

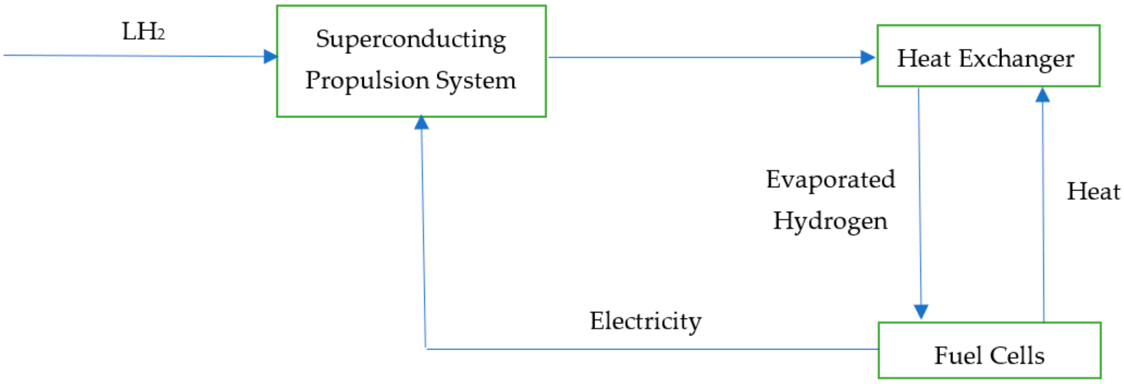

Figure 3. Synergy of LH_2 and superconductivity in a marine vessel.

To summarize, on one hand, there is a high cost of LH_2, but on the other hand, superconductivity reduces the cost by consuming less energy. As a trade-off, having an appropriate economic evaluation by considering both operating and investment costs seems essential for adopting environmentally friendly LH_2.

6. Conclusions

The recent state of the hydrogen economy and the developments in the field of superconductivity has been reviewed. Their applications are addressed both separately and together. The potential of synergy between superconductors and liquid hydrogen is discussed showing how it can evolve technically and economically. The roadmap of this synergy is illustrated in an example of a marine vessel, and it is explained how LH_2 and a superconducting propulsion system could influence this sector. Moreover, this review describes a general perspective of the roadmap in the other sectors i.e., other forms of transportation, generating electricity, and distribution of fuel and energy. The amount of research in this area is, however, not large, and it requires more attention and bigger investments. Specifically, some countries, such as Norway, have adequate infrastructure for implementing liquid hydrogen, especially in the maritime shipping industry. These countries have additionally great potential to invest and develop the roadmap to synergize liquid hydrogen and superconductivity.

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References

1. Gupta, R.; Basile, A.; Veziroglu, T.N. *Compendium of Hydrogen Energy: Hydrogen Storage, Distribution and Infrastructure*; Woodhead Publishing: Swaston, UK, 2016.
2. Abe, J.O.; Popoola, A.; Ajenifuja, E.; Popoola, O. Hydrogen energy, economy and storage: Review and recommendation. *Int. J. Hydrogen Energy* **2019**, *44*, 15072–15086. [CrossRef]
3. Damman, S.; Sandberg, E.; Rosenberg, E.; Pisciella, P.; Johansen, U. Largescale hydrogen production in Norway-possible transition pathways towards 2050. *SINTEF Rapp.* **2020**. Available online: https://hdl.handle.net/11250/2649737 (accessed on 14 February 2020).
4. Hamborg, E.S.; Gulbrandsen, T.H.; Steeneveldt, R.; Svenes, S.; Berggren, H.; Kvarsvik, S.; Pettersen, J. Norwegian Hydrogen Value Chain Demonstration Based on Decarbonized Natural Gas. In Proceedings of the 15th International Conference on Greenhouse Gas Control Technologies, Abu Dhabi, United Arab Emirates, 15–18 March 2021.
5. Van de Graaf, T.; Overland, I.; Scholten, D.; Westphal, K. The new oil? The geopolitics and international governance of hydrogen. *Energy Res. Soc. Sci.* **2020**, *70*, 101667. [CrossRef] [PubMed]
6. Preuster, P.; Papp, C.; Wasserscheid, P. Liquid organic hydrogen carriers (LOHCs): Toward a hydrogen-free hydrogen economy. *Acc. Chem. Res.* **2017**, *50*, 74–85. [CrossRef] [PubMed]
7. Van Hoecke, L.; Laffineur, L.; Campe, R.; Perreault, P.; Verbruggen, S.W.; Lenaerts, S. Challenges in the use of hydrogen for maritime applications. *Energy Environ. Sci.* **2021**, *14*, 815–843. [CrossRef]
8. Moreno-Benito, M.; Agnolucci, P.; Papageorgiou, L.G. Towards a sustainable hydrogen economy: Optimisation-based framework for hydrogen infrastructure development. *Comput. Chem. Eng.* **2017**, *102*, 110–127. [CrossRef]
9. Petrescu, R.V.V.; Machin, A.; Fontánez, K.; Arango, J.C.; Marquez, F.M.; Petrescu, F.I.T. Hydrogen for aircraft power and propulsion. *Int. J. Hydrogen Energy* **2020**, *45*, 20740–20764. [CrossRef]
10. Stroman, R.O.; Schuette, M.W.; Swider-Lyons, K.; Rodgers, J.A.; Edwards, D.J. Liquid hydrogen fuel system design and demonstration in a small long endurance air vehicle. *Int. J. Hydrogen Energy* **2014**, *39*, 11279–11290. [CrossRef]
11. Atilhan, S.; Park, S.; El-Halwagi, M.M.; Atilhan, M.; Moore, M.; Nielsen, R.B. Green hydrogen as an alternative fuel for the shipping industry. *Curr. Opin. Chem. Eng.* **2021**, *31*, 100668. [CrossRef]
12. Cardella, U.; Decker, L.; Klein, H. Roadmap to economically viable hydrogen liquefaction. *Int. J. Hydrogen Energy* **2017**, *42*, 13329–13338. [CrossRef]
13. Jha, A.K.; Matsumoto, K. Superconductive REBCO thin films and their nanocomposites: The role of rare-earth oxides in promoting sustainable energy. *Front. Phys.* **2019**, *7*, 82. [CrossRef]
14. Seidel, P. *Applied Superconductivity: Handbook on Devices and Applications*; John Wiley & Sons: Hoboken, NJ, USA, 2015.

15. Mikheenko, P.; Yurchenko, V.; Cardwell, D.; Shi, Y.; Johansen, T. Magneto-optical imaging of superconductors for liquid hydrogen applications. *J. Supercond. Nov. Magn.* **2013**, *26*, 1499–1502. [CrossRef]
16. Arvapalli, S.S.; Miryala, M.; Jirsa, M.; Sakai, N.; Murakami, M. Pinning behavior in bulk MgB_2 prepared using boron powder refined via high-energy ultra-sonication. *J. Supercond. Nov. Magn.* **2021**, *34*, 1297–1301. [CrossRef]
17. Mikheenko, P. Superconductivity for hydrogen economy. *J. Phys. Conf. Ser.* **2011**, *286*, 012014. [CrossRef]
18. Vysotsky, V.S.; Nosov, A.A.; Fetisov, S.S.; Svalov, G.G.; Kostyuk, V.V.; Blagov, E.V.; Antyukhov, I.V.; Firsov, V.P.; Katorgin, B.I.; Rakhmanov, A.L. Hybrid Energy Transfer Line With Liquid Hydrogen and Superconducting MgB_2 Cable—First Experimental Proof of Concept. *IEEE Trans. Appl. Supercond.* **2013**, *23*, 5400906. [CrossRef]
19. Ball, M.; Weeda, M. The hydrogen economy–vision or reality? *Int. J. Hydrogen Energy* **2015**, *40*, 7903–7919. [CrossRef]
20. Demirbas, A. Future hydrogen economy and policy. *Energy Sources Part B Econ. Plan. Policy* **2017**, *12*, 172–181. [CrossRef]
21. Norway's NEL Targets $1.5/kg Green Hydrogen Cost by 2025. Available online: https://www.spglobal.com/platts/en/market-insights/latest-news/electric-power/012121-norways-nel-targets-15kg-green-hydrogen-cost-by-2025 (accessed on 21 January 2021).
22. Norwegian Future Value Chains for Liquid Hydrogen. Available online: https://maritimecleantech.no/wp-content/uploads/2016/11/Report-liquid-hydrogen.pdf (accessed on 21 August 2022).
23. Meca, V.L.; d'Amore-Domenech, R.; Crucelaegui, A.; Leo, T.J. Large-Scale Maritime Transport of Hydrogen: Economic Comparison of Liquid Hydrogen and Methanol. *ACS Sustain. Chem. Eng.* **2022**, *10*, 4300–4311. [CrossRef]
24. Wijayanta, A.T.; Oda, T.; Purnomo, C.W.; Kashiwagi, T.; Aziz, M. Liquid hydrogen, methylcyclohexane, and ammonia as potential hydrogen storage: Comparison review. *Int. J. Hydrogen Energy* **2019**, *44*, 15026–15044. [CrossRef]
25. Ishimoto, Y.; Voldsund, M.; Nekså, P.; Roussanaly, S.; Berstad, D.; Gardarsdottir, S.O. Large-scale production and transport of hydrogen from Norway to Europe and Japan: Value chain analysis and comparison of liquid hydrogen and ammonia as energy carriers. *Int. J. Hydrogen Energy* **2020**, *45*, 32865–32883. [CrossRef]
26. Mojarrad, M. Simulation of Hydrogen Tank Refuelling. Master's Thesis, University of South-Eastern Norway, Notodden, Norway, May 2020.
27. Paster, M.D.; Ahluwalia, R.K.; Berry, G.; Elgowainy, A.; Lasher, S.; McKenney, K.; Gardiner, M. Hydrogen storage technology options for fuel cell vehicles: Well-to-wheel costs, energy efficiencies, and greenhouse gas emissions. *Int. J. Hydrogen Energy* **2011**, *36*, 14534–14551. [CrossRef]
28. Reuβ, M.; Dimos, P.; Léon, A.; Grube, T.; Robinius, M.; Stolten, D. Hydrogen Road Transport Analysis in the Energy System: A Case Study for Germany through 2050. *Energies* **2021**, *14*, 3166.
29. Nerheim, A.R.; Æsøy, V.; Holmeset, F.T. Hydrogen as a Maritime Fuel–Can Experiences with LNG Be Transferred to Hydrogen Systems? *J. Mar. Sci. Eng.* **2021**, *9*, 743. [CrossRef]
30. Rosenberg, E.; Fidje, A.; Espegren, K.A.; Stiller, C.; Svensson, A.M.; Møller-Holst, S. Market penetration analysis of hydrogen vehicles in Norwegian passenger transport towards 2050. *Int. J. Hydrogen Energy* **2010**, *35*, 7267–7279. [CrossRef]
31. Brandon, N.; Kurban, Z. Clean energy and the hydrogen economy. *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.* **2017**, *375*, 20160400. [CrossRef]
32. Durrell, J.H.; Ainslie, M.D.; Zhou, D.; Vanderbemden, P.; Bradshaw, T.; Speller, S.; Filipenko, M.; Cardwell, D.A. Bulk superconductors: A roadmap to applications. *Supercond. Sci. Technol.* **2018**, *31*, 103501. [CrossRef]
33. Kitazawa, K. Superconductivity: 100th anniversary of its discovery and its future. *Jpn. J. Appl. Phys.* **2011**, *51*, 010001. [CrossRef]
34. Nishijima, S.; Eckroad, S.; Marian, A.; Choi, K.; Kim, W.S.; Terai, M.; Deng, Z.; Zheng, J.; Wang, J.; Umemoto, K.; et al. Superconductivity and the environment: A roadmap. *Supercond. Sci. Technol.* **2013**, *26*, 113001. [CrossRef]
35. Tomsic, M.; Rindfleisch, M.; Yue, J.; McFadden, K.; Phillips, J.; Sumption, M.D.; Bhatia, M.; Bohnenstiehl, S.; Collings, E.W. Overview of MgB_2 superconductor applications. *Int. J. Appl. Ceram. Technol.* **2007**, *4*, 250–259. [CrossRef]
36. Plakida, N. *High-Temperature Cuprate Superconductors: Experiment, Theory, and Applications*; Springer Science & Business Media: Berlin/Heidelberg, Germany, 2010.
37. Baik, S.; Kwon, Y.; Park, S.; Kim, H. Performance analysis of a superconducting motor for higher efficiency design. *IEEE Trans. Appl. Supercond.* **2013**, *23*, 5202004. [CrossRef]
38. Terao, Y.; Seta, A.; Ohsaki, H.; Oyori, H.; Morioka, N. Lightweight design of fully superconducting motors for electrical aircraft propulsion systems. *IEEE Trans. Appl. Supercond.* **2019**, *29*, 1–5. [CrossRef]
39. Terao, Y.; Sekino, M.; Ohsaki, H. Comparison of conventional and superconducting generator concepts for offshore wind turbines. *IEEE Trans. Appl. Supercond.* **2012**, *23*, 5200904. [CrossRef]
40. Abrahamsen, A.B.; Mijatovic, N.; Seiler, E.; Zirngibl, T.; Træholt, C.; Nørgård, P.B.; Pedersen, N.F.; Andersen, N.H.; Østergaard, J. Superconducting wind turbine generators. *Supercond. Sci. Technol.* **2010**, *23*, 034019. [CrossRef]
41. Qu, R.; Liu, Y.; Wang, J. Review of superconducting generator topologies for direct-drive wind turbines. *IEEE Trans. Appl. Supercond.* **2013**, *23*, 5201108.
42. Furuse, M.; Fuchino, S.; Okano, M.; Natori, N.; Yamasaki, H. Development of a cooling system for superconducting wind turbine generator. *Cryogenics* **2016**, *80*, 199–203. [CrossRef]
43. Del-Valle, N.; Sanchez, A.; Navau, C.; Chen, D.X. Magnet guideways for superconducting maglevs: Comparison between Halbach-type and conventional arrangements of permanent magnets. *J. Low Temp. Phys.* **2011**, *162*, 62–71. [CrossRef]
44. Werfel, F.N.; Floegel-Delor, U.; Rothfeld, R.; Riedel, T.; Goebel, B.; Wippich, D.; Schirrmeister, P. Superconductor bearings, flywheels and transportation. *Supercond. Sci. Technol.* **2011**, *25*, 014007. [CrossRef]

45. Berger, A.; Cherevatskiy, S.; Noe, M.; Leibfried, T. Comparison of the efficiency of superconducting and conventional transformers. *J. Phys. Conf. Ser.* **2010**, *234*, 032004. [CrossRef]
46. Dai, S.; Ma, T.; Qiu, Q.; Zhu, Z.; Teng, Y.; Hu, L. Development of a 1250-kVA superconducting transformer and its demonstration at the superconducting substation. *IEEE Trans. Appl. Supercond.* **2015**, *26*, 1–7. [CrossRef]
47. Glasson, N.; Staines, M.; Buckley, R.; Pannu, M.; Kalsi, S. Development of a 1 MVA 3-phase superconducting transformer using YBCO Roebel cable. *IEEE Trans. Appl. Supercond.* **2010**, *21*, 1393–1396. [CrossRef]
48. Vysotsky, V.S.; Fetisov, S.S.; Zubko, V.V.; Zanegin, S.Y.; Nosov, A.A.; Ryabov, S.M.; Bykovsky, N.V.; Svalov, G.G.; Volkov, E.P.; Fleishman, L.S.; et al. Development and test results of HTS windings for superconducting transformer with 1 MVA rated power. *IEEE Trans. Appl. Supercond.* **2016**, *27*, 1–5. [CrossRef]
49. Baig, T.; Al Amin, A.; Deissler, R.J.; Sabri, L.; Poole, C.; Brown, R.W.; Tomsic, M.; Doll, D.; Rindfleisch, M.; Peng, X.; et al. Conceptual designs of conduction cooled MgB_2 magnets for 1.5 and 3.0 T full body MRI systems. *Supercond. Sci. Technol.* **2017**, *30*, 043002. [CrossRef] [PubMed]
50. Iwasa, Y. Towards liquid-helium-free, persistent-mode MgB_2 MRI magnets: FBML experience. *Supercond. Sci. Technol.* **2017**, *30*, 053001. [CrossRef] [PubMed]
51. Parizh, M.; Lvovsky, Y.; Sumption, M. Conductors for commercial MRI magnets beyond NbTi: Requirements and challenges. *Supercond. Sci. Technol.* **2016**, *30*, 014007. [CrossRef]
52. Lazarou, S.; Makridis, S. Hydrogen storage technologies for smart grid applications. *Challenges* **2017**, *8*, 13. [CrossRef]
53. Airbus Reveals New Zero-Emission Concept Aircraft. Available online: https://www.airbus.com/newsroom/press-releases/en/2020/09/airbus-reveals-new-zeroemission-concept-aircraft.html (accessed on 21 September 2020).
54. Rey, C. *Superconductors in the Power Grid: Materials and Applications*; Elsevier: Amsterdam, The Netherland, 2015.
55. Latest Developments in Superconducting Motors. Available online: https://www.machinedesign.com/motors-drives/article/21828530/latest-developments-in-superconducting-motors (accessed on 1 August 2000).
56. Hara, S.; Iwami, Y.; Kawasaki, R.; Matsumoto, T.; Shirai, Y.; Shiotsu, M.; Kobayashi, H.; Naruo, Y.; Nonaka, S.; Inatani, Y.; et al. Development of Liquid Hydrogen Cooling System for a Rotor of Superconducting Generator. *IEEE Trans. Appl. Supercond.* **2021**, *31*, 1–5.
57. Nam, G.D.; Sung, H.J.; Lee, S.J.; Park, M. Conceptual Design of an Aviation Propulsion System Using Hydrogen Fuel Cell and Superconducting Motor. *IEEE Trans. Appl. Supercond.* **2021**, *31*, 1–7. [CrossRef]
58. World's First Liquid Hydrogen Fuel Cell Cruise Ship Planned for Norway's Fjords. Available online: https://www.rechargenews.com/transition/world-s-first-liquid-hydrogen-fuel-cell-cruise-ship-planned-for-norway-s-fjords/2-1-749070 (accessed on 5 February 2020).
59. Mikheenko, P.; Johansen, T.H. Smart superconducting grid. *Energy Procedia* **2014**, *58*, 73–78. [CrossRef]
60. Torvanger, A. Hydrogen for shipping–Opportunities for Norway. *CICERO Rep.* **2021**. Available online: https://hdl.handle.net/11250/2755909 (accessed on 20 May 2021).
61. Hansen, O.R. Liquid hydrogen releases show dense gas behavior. *Int. J. Hydrogen Energy* **2020**, *45*, 1343–1358. [CrossRef]
62. Gray, N.; McDonagh, S.; O'Shea, R.; Smyth, B.; Murphy, J.D. Decarbonising ships, planes and trucks: An analysis of suitable low-carbon fuels for the maritime, aviation and haulage sectors. *Adv. Appl. Energy* **2021**, *1*, 100008. [CrossRef]
63. So Just How Dangerous Is Hydrogen Fuel? Available online: https://hydrogen.wsu.edu/2017/03/17/so-just-how-dangerous-is-hydrogen-fuel/ (accessed on 3 July 2017).
64. Zang, G.; Sun, P.; Elgowainy, A.A.; Bafana, A.; Wang, M. Performance and cost analysis of liquid fuel production from H_2 and CO_2 based on the Fischer-Tropsch process. *J. CO_2 Util.* **2021**, *46*, 101459. [CrossRef]
65. Ross, R.; Meijer, C.G.; Hunik, R. Maritime superconductivity perspectives. *IEEE Trans. Appl. Supercond.* **2013**, *23*, 3601405. [CrossRef]
66. Shi, W.; Grimmelius, H.; Stapersma, D. Analysis of ship propulsion system behaviour and the impact on fuel consumption. *Int. Shipbuild. Prog.* **2010**, *57*, 35–64.