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Energy analysis for hydrogen transport methods

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1. Abstract

A comparative energetic study between liquid hydrogen and e-methanol as hydrogen vectors for large-scale transport of hydrogen at sea has been performed. The objective of this study is to gain insight on which one of the energy vectors compared is the best option for transporting renewable energy and obtain hydrogen at destination. The alternatives covered include the seaborne transport of liquid hydrogen or methanol with the reconversion to hydrogen at the destination through methanol electrolysis or a steam-reforming process. Three different production mass flow rates of hydrogen at the origin are explored: 100 kt/y, 1 Mt/y, and 10 Mt/y. The findings of this study suggest that liquid hydrogen is the best alternative in terms of energy vector. However, if methanol electrolysis technology improves, lower electricity consumption and lower energy losses are achieved, the alternative based on methanol electrolysis may compete with the transport of liquefied hydrogen.

2. Introduction

There is an increasing importance of renewable energies in the global power sector. However, the renewable energy sources may not be close to the place of energy consumption, which makes it necessary to transport this energy to its destination. In addition, some of them, such as wind and solar energy, have stochastic and intermittent nature due to their dependence on weather conditions. A possible solution consists of the storage and transport of this energy to adapt its consumption to the needs of existing energy grids. Renewable electrical energy could be stored in the form of chemical energy of a fuel, such as green hydrogen [1].

Green hydrogen can be generated through water electrolysis with electricity from renewable sources and then transported to the destination [2]. However, due to the low energy density of hydrogen (the energy per volume of hydrogen gas is 12.7 MJ/Nm^3, merely 1/3000 of oil) the seaborne transport of this fuel is carried out in tankers that transport liquefied hydrogen (LH_2). Regarding the safety, LH_2 induces hydrogen embrittlement and well-designed vessel and containment facilities must be designed to contain this fuel. Besides, a small release or leakage of LH_2 potentially results in explosion.

A fuel that can be obtained from green hydrogen and that is easier to handle than a gaseous fuel is methanol (MeOH), as it is a liquid chemical compound at ambient conditions. Methanol has lower impact than conventional hydrocarbon fuels if leaked into the environment due to the fact that it dissolves readily in water. Furthermore the International Bulk Chemical Code does not classify it as a toxic substance if it is onboard cargo. Once at destination, this methanol can be used as fuel or converted into hydrogen. In this way, one of the applications of methanol as an energy vector arises, being an energy transport option that could constitute a way of transporting clean energy from its origin to its place of consumption. The methanol obtained through

captured CO_2 and hydrogen from renewable sources, e-methanol, is neutral in carbon emissions. For the conversion of e-methanol into hydrogen there are different possibilities, among which steam reforming and electrolysis stand out [3].

In this work the energy analysis of three alternatives for seaborne transport of hydrogen is presented. The first one is based on LH_2 transport and the other two options are based on MeOH transport.

The alternative based on the transport of liquefied hydrogen includes water electrolysis plant, hydrogen liquefaction plant, storage at origin, transport, storage at destination and hydrogen regasification plant.

Alternatives based on the transportation of methanol include water electrolysis plant, methanol synthesis plant, storage at origin, transportation and storage at destination. The difference within methanol-based alternatives is established in the process to obtain hydrogen at destination. In one of them the electrolysis of methanol is carried out and in the other the methanol steam reforming is studied.

Three different mass flow rates of hydrogen produced are studied: 100 kt/y, 1 Mt/y and 10 Mt/y. The distance analysed corresponds to seaborne transport between Brazil and Spain. Brazil is one of the main methanol producers, and its low electricity cost makes green hydrogen production attractive. Spain has been selected as green fuel importer as there is an increasing demand for carbon-neutral fuels in Europe, and Spain can be an important hydrogen distribution point in the Mediterranean Sea.

3. Methods

In this study, an energetic analysis of the sea transport of energy from renewable sources using hydrogen and e-methanol as vectors is made. The route proposed is Pecem (Brazil) - Algeciras (Spain), a distance of 5629 km.

Hydrogen is obtained from water with an electrolysis process consuming electricity from renewable sources, and this hydrogen is liquefied and transported as liquefied hydrogen or transformed into e-methanol through a synthesis process for transporting e-methanol by ship.

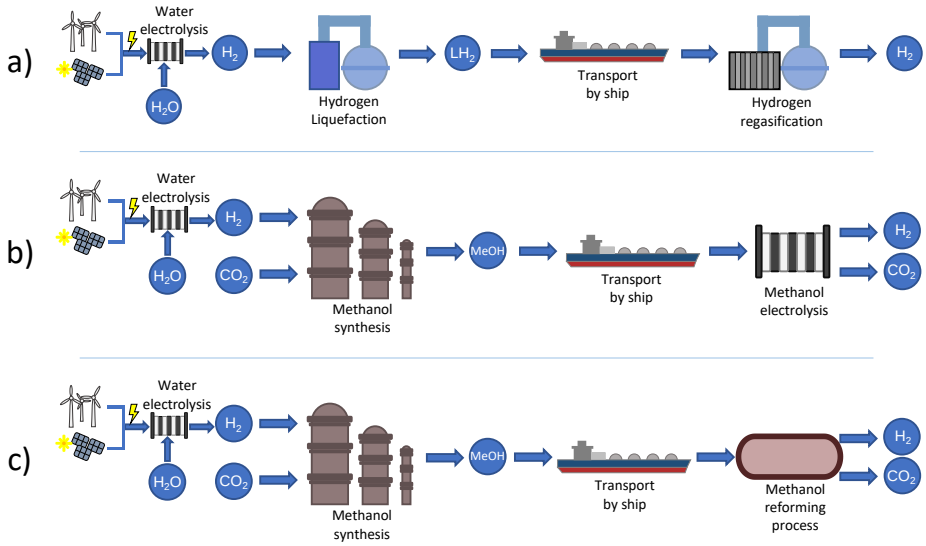

Figure 1. Diagram of the hydrogen transport process using as a vector: a) liquefied hydrogen (LH_2); b) methanol (MeOH) with electrolysis process; c) methanol (MeOH) with reforming process.

In this study, three alternatives are analysed, presented in Figure 1: one based on the transport of liquefied hydrogen (Figure 1.a) and two on the transport of e-methanol. The alternatives based on the transport of e-methanol differ from each other when obtaining hydrogen at destination, from an electrolysis process (Figure 1.b) or a reforming process (Figure 1.c). To carry out this study, the mass flow of hydrogen available at the place of origin is established (100 kt/y, 1 Mt/y and 10 Mt/y). The three alternatives proposed in this work are presented in Subsections "3.1. Hydrogen power link", "3.2. Methanol power link with electrolysis process" and "3.3. Methanol power link with reforming process".

The initial energy flow of the analysis of this work is the electricity supplied to the electrolyser to obtain hydrogen from water, that is part of the hydrogen production process of each alternative. Its characteristics are presented below.

Water electrolysis plant. In this facility, hydrogen and oxygen are produced using renewable electricity and water. To develop this model, the efficiency of the water electrolyser has been set at 80 % [4]. From this parameter and the desired hydrogen mass flow rate, the mass flow rates of necessary water, $\dot{m}_{H_2O}$, and oxygen produced, $\dot{m}_{O_2}$, during the process and the electric power consumed, $\dot{W}_{ext,electrol}$, have been calculated using Eq. 1 and 2, respectively.

$$H_2O \rightarrow H_2 + 1/2\ O_2 \quad \text{(Eq. 1)}$$

$$\dot{W}_{ext,electrol} = \frac{\dot{m}_{H_2} \cdot h_{H_2} + \dot{m}_{O_2} \cdot h_{O_2} - \dot{m}_{H_2O} \cdot h_{H_2O}}{\eta_{electrol}} \quad \text{(Eq. 2)}$$

where $\dot{m}_{H_2} = M_{H_2}/M_{H_2O} \cdot \dot{m}_{H_2O}$; $\dot{m}_{O_2} = M_{O_2}/M_{H_2O} \cdot \dot{m}_{H_2O}/2$, and h_i is the the enthalpy of the different substances present in the reaction that is calculated as:

$$h_i = \Delta h^0_{f_i} + [h_i(T,p) - h_i(T^0,p^0)] \quad \text{(Eq. 3)}$$

where $\Delta h^0_{f_i}(T^0,p^0)$ is the enthalpy of formation of the substance i at (T^0,p^0), and $[h_i(T,p) - h_i(T^0,p^0)]$ is the enthalpy increment of the substance i from (T^0,p^0) to (T,p).

3.1. Hydrogen power link

Hydrogen can be transported by sea under different conditions, such as liquefied and compressed hydrogen by ship. Due to the low energy density of the on-board compressed hydrogen storage system compared to liquefied hydrogen, the last option is chosen for comparison purposes with the methanol vector within this study. Figure 1.a shows a diagram of this alternative.

The characteristic facilities of this alternative are:

Hydrogen liquefaction plant. This facility liquefies the hydrogen obtained from electrolysis to transport it more easily. The electrical energy needed for the transformation of hydrogen into a liquefied state is calculated by multiplying the mass of the produced hydrogen by the specific work for hydrogen liquefaction (22.0 MJ/kg)[5].

Liquid hydrogen storage facilities. The storage of liquid hydrogen after and prior to its transport is an important facility within the power link. The size of the tanks of the export terminal is adapted to that of the tanks of the ship that will transport the liquefied hydrogen. The size of the installation prepared for import is dependent upon the number of ships, voyages, and mass of hydrogen that they deliver. The electricity consumption within this installation is related to re-liquefaction energy of the boil-off of the stored hydrogen. A daily boil-off rate of 0.1 % of the total mass of hydrogen contained in the tanks is considered [2]. The energy needed for the re-liquefaction process is calculated with the specific work for hydrogen liquefaction.

LH_2 carrier ship. Currently there is no fleet of hydrogen transport vessels, but there are vessels that can undertake this operation [6]. Nevertheless, there is insufficient data regarding these types of ships in order to create a model and it has been decided, due to the similarities they present, to use data from LNG transport fleets, thereby adapting them for purposes of creating a transport model of liquefied hydrogen. Regarding fuel consumption, in this work, ships that transport hydrogen as cargo are assumed to consume part of the hydrogen cargo for propulsion with a power plant based on fuel cells. Therefore, the consumed cargo during the round trip will be considered in the energy analysis. The consumed mass of hydrogen m_C is estimated by means of:

$$m_C = 2 \cdot \frac{l}{s_V} \cdot cr_C + \left(\frac{V_H}{\dot{V}_L} + \frac{m_{OL}}{\rho_l^0 \cdot \dot{V}_{OL}} \right) \cdot cr_{L,OL} \quad \text{(Eq. 4)}$$

where l is the distance between ends, s_V is the speed of the vessel, cr_C is the consumption rate of hydrogen during navigation, V_H represents the volume of the holds inside the ship, $\dot{V}_L$ is the loading flow rate of the liquefied hydrogen, m_{OL} is the offloaded mass of hydrogen, ρ_l^0 represents the saturation density of liquid hydrogen at 1 bar, $\dot{V}_{OL}$ represents the off-loading flow rate of the liquefied hydrogen and $cr_{L,OL}$ is the consumption rate of hydrogen during loading and offloading.

The mass flow rate of hydrogen consumed during cruising, cr_C, can be calculated according to the cubic rule [2]:

$$cr_C = \frac{\dot{W}_{nom}}{\eta_{FC} \cdot LHV} \cdot \left(\frac{s_V}{s_{V\,nom}} \right)^3 \quad \text{(Eq. 5)}$$

where $\dot{W}_{nom}$ is the power developed at cruise speed; η_{FC} is the fuel cell efficiency; LHV is the Lower Heating Value of hydrogen and $s_{V\,nom}$ the nominal cruise speed of the ship.

Table 1 contains the baseline assumptions used for the calculations of the energy consumed within hydrogen power link.

Table 1. Assumptions for the LH_2 transport facility.

Parameter	**Value**
Ship capacity (t_{H2})	12,760
V_H (m^3)	180,000
Nominal pressure (bar)	1
Min pressure (bar)	1
$s_{V_{nom}}$ (kn)	20
$s_{V_{nom}}$ (m/s)	10.29
$\dot{W}_{nom}$(sailing) (MW) [7, 8]	35
$\dot{W}_{nom}$ (Loading and offloading) (MW)	2
Power plant efficiency η_{FC} (based on LHV_{H2})	0.55
$\dot{V}_L$ (m^3/h)	12,000
$\dot{V}_{OL}$ (m^3/h)	12,000

Hydrogen regasification. Some facilities of this type use heat exchangers to obtain hydrogen under conditions suitable for storage in vehicles. The thermal energy required to evaporate the liquefied hydrogen in those heat exchangers is calculated from the enthalpy difference of the liquefied hydrogen and hydrogen at standard conditions of pressure and temperature.

3.2. Methanol power link with electrolysis process

This power link raises the possibility of using e-methanol as a hydrogen vector. It is based on the transport of this fuel obtained using green hydrogen and CO_2 as feedstocks, and subsequently, obtaining hydrogen at destination by carrying out a methanol electrolysis process. Figure 1.b shows a diagram of this alternative.

The characteristic facilities of this alternative are:

Methanol synthesis plant. Within this facility methanol is obtained through a synthesis process from renewable hydrogen and CO_2. The ratio between hydrogen and methanol mass flow rates and CO_2 and methanol mass flow rates needed in this facility are fixed (1.397 kg_{CO2}/kg_{MeOH}, 0.192 kg_{H2}/kg_{MeOH}) [9]. Electricity needed within this facility is also related to the mass flow rate of methanol produced, 0.175 MWh/t (630 kJ/kg) [9].

Methanol carrier ship. There are ships designed to transport methanol nowadays, however, not enough data have been collected to develop a reliable model. For this reason, the model developed for hydrogen transport has been used, adapting the input data to that of a tanker ship due to the similarities between ships presently transporting methanol and this type of ships. As in the case of hydrogen transport, methanol is intended to be used as fuel for propulsion, in this case in an internal combustion engine. Table 2 contains the baseline assumptions used for the calculations of the energy consumed within methanol power link.

Table 2. Assumptions for the methanol transport facility.

Parameter	Value
Ship capacity (t_{MeOH})	95,040
V_{MeOH} (m^3)	120,000
$s_{V_{nom}}$ (kn)	15.4
$s_{V_{nom}}$ (m/s)	7.92
$\dot{W}_{nom}$(sailing) (MW)	15
$\dot{W}_{nom}$ (Loading and offloading) (MW)	2
Power plant efficiency η_{FC} (based on LHV_{H2})	0.35

Methanol electrolysis plant. In this facility hydrogen is obtained using renewable electricity and e-methanol. The model developed in this work is based on the efficiency of a methanol electrolyser, set at 34 % [10]. The mass flow rate of hydrogen obtained at the destination and the electric power needed for this process, $\dot{W}_{ext,MeOH\ electrol}$, are calculated using Eqs. 6 and 7, respectively:

$$CH_3OH + H_2O \rightarrow CO_2 + 3H_2 \quad \text{(Eq. 6)}$$

$$\dot{W}_{ext,MeOH\ electrol} = \frac{\dot{m}_{H_2} \cdot h_{H_2} + \dot{m}_{CO_2} \cdot h_{CO_2} - \dot{m}_{H_2O} \cdot h_{H_2O} - \dot{m}_{CH_3OH} \cdot h_{CH_3OH}}{\eta_{meth-electrol}} \quad \text{(Eq. 7)}$$

where $\dot{m}_{H_2} = \frac{M_{H_2}}{M_{H_2O}} \cdot \dot{m}_{H_2O} \cdot 3$; $\dot{m}_{CO_2} = M_{CO_2}/M_{H_2O} \cdot \dot{m}_{H_2O}$; $\dot{m}_{CH_3OH} = M_{CH_3OH}/M_{H_2O} \cdot \dot{m}_{H_2O}$; and the enthalpies are obtained with Eq. 3.

3.3. Methanol power link with reforming process

This power link shares the characteristics of the case 3.2 previously described. The difference lies in the method for hydrogen production from methanol. In this case, hydrogen is obtained by means of a methanol-reforming process. The characteristics of the processes of this power link are the same as in the previous case, thereby exchanging the methanol electrolysis plant for a methanol-reforming one. Figure 1.c shows a diagram of this alternative.

Methanol-reforming plant. During this process, an input of thermal energy is needed to obtain hydrogen from e-methanol. To provide this thermal energy a portion of the transported e-methanol is burned. Due to this, the emission from the e-methanol combustion is added to the CO_2 emission produced during the reforming process, which is more difficult to capture than the CO_2 produced from electrolysis. However, this way of obtaining the necessary thermal energy makes the process independent from the electrical grid. The mass flow rate of methanol necessary to carry out the reforming process is obtained from the data of the efficiency of a methanol reforming reactor:

$$\dot{m}_{MeOH_{Combustion}} = \dot{m}_{MeOH}\left(1 - \frac{\frac{LHV_{MeOH}}{LHV_{H_2}} \cdot \eta_{reform}}{r_{conv}}\right) \quad \text{(Eq. 8)}$$

where $\dot{m}_{MeOH}$ represents the mass flow rate of methanol that arrives at the facility in kg/s, LHV represents the lower heating value of methanol and hydrogen in MJ/kg, η_{reform} represents the efficiency of the methanol reforming reactor, set at 85 %, and r_{conv} represents the mass ratio of hydrogen converted to methanol in the reforming process (0.189 kg_{H2}/kg_{MeOH}) [11].

4. Results

Figures 2-4 show the process energy flow diagram for an annual produced hydrogen of 100 kt, 1 Mt and 10 Mt, respectively. From left to right: hydrogen power link, methanol transport and electrolysis alternative, methanol transport and reforming alternative. To develop these diagrams, the value of 100 is assigned to the electricity from renewable sources necessary to conduct the water electrolysis in each case. The energy contained in the e-methanol and hydrogen vectors has been obtained with the LHV of each fuel.

Figure 2 shows the processes that require a higher electricity consumption, without considering the production of hydrogen from water: methanol electrolysis and hydrogen liquefaction. The processes that involve the greatest energy losses are the methanol electrolysis process, the synthesis of this fuel and the reforming of methanol to obtain hydrogen.

Figure 3 shows that for a mass flow rate of 1 Mt/y the methanol electrolysis alternative can provide better results in terms of hydrogen mass flow rate obtained at destination. However, the electricity consumption for the electrolysis process is greater than the electricity needed for hydrogen liquefaction. Thus, despite obtaining a slightly greater mass flow of hydrogen with methanol electrolysis alternative, hydrogen liquefaction still remains the best option in terms of energy.

Figure 4 shows the increase in methanol consumption with respect to the total electrical energy supplied at the source when the mass flow rate of hydrogen produced increases to 10 Mt/y. However, this figure also shows a decrease in the percentage of energy supplied for the methanol electrolysis and also in the energy losses of the processes for transforming hydrogen into methanol.

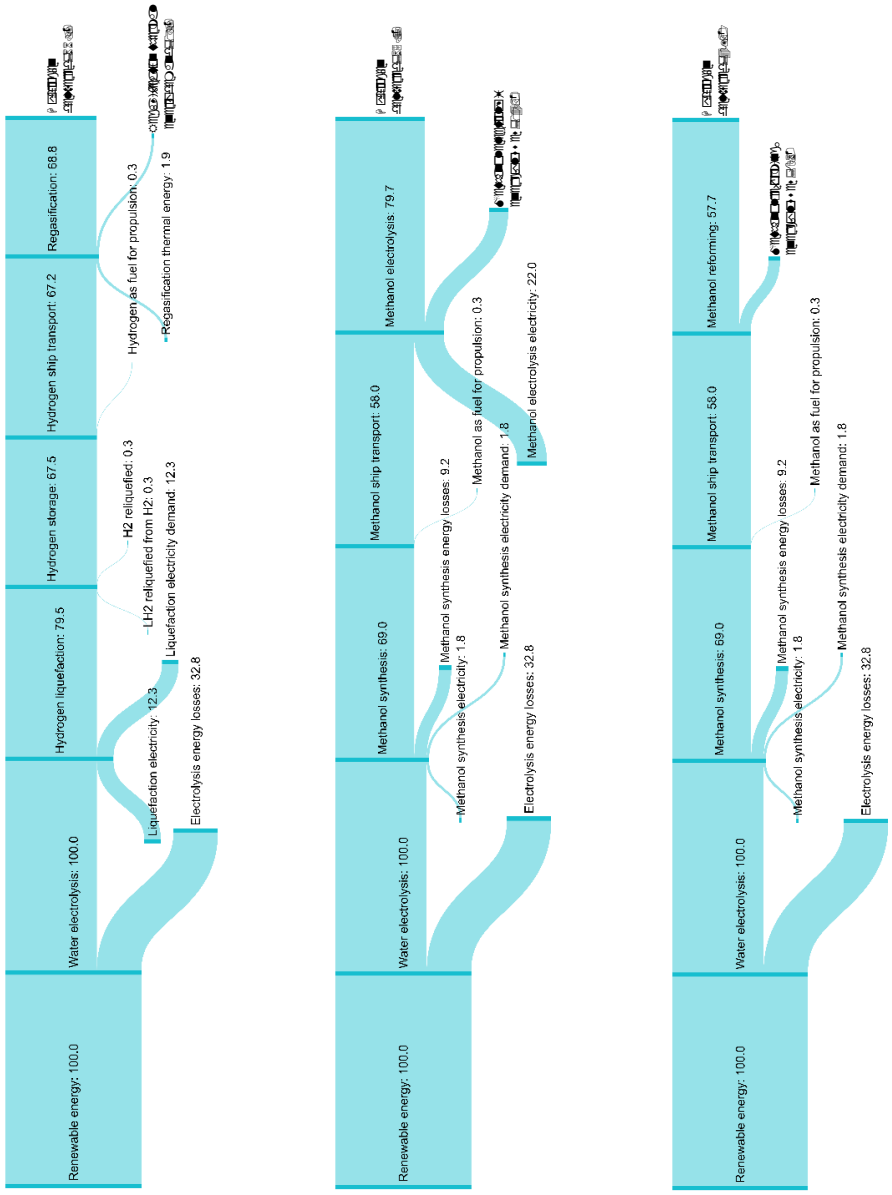

Figure 2. Process energy flow diagram for an annual production of 100 kt of hydrogen. From left to right: hydrogen power link, methanol transport and electrolysis alternative, methanol transport and reforming alternative. 17,870 TJ/y is set at an index value of 100.

In in Figures 2-4, the energy that reaches its destination in the form of hydrogen presents similar values between the alternatives based on liquefied hydrogen and on methanol electrolysis, with a maximum variation of 1.2 %. The energy that reaches the destination for the alternative based on steam reforming is 16.6 % lower that the obtained with methanol electrolysis alternative. This difference is due to the consumption of methanol to obtain the necessary thermal energy during reforming. Thus, to compare methanol electrolysis and methanol reforming alternatives, the electricity consumption of the methanol electrolysis must be considered.

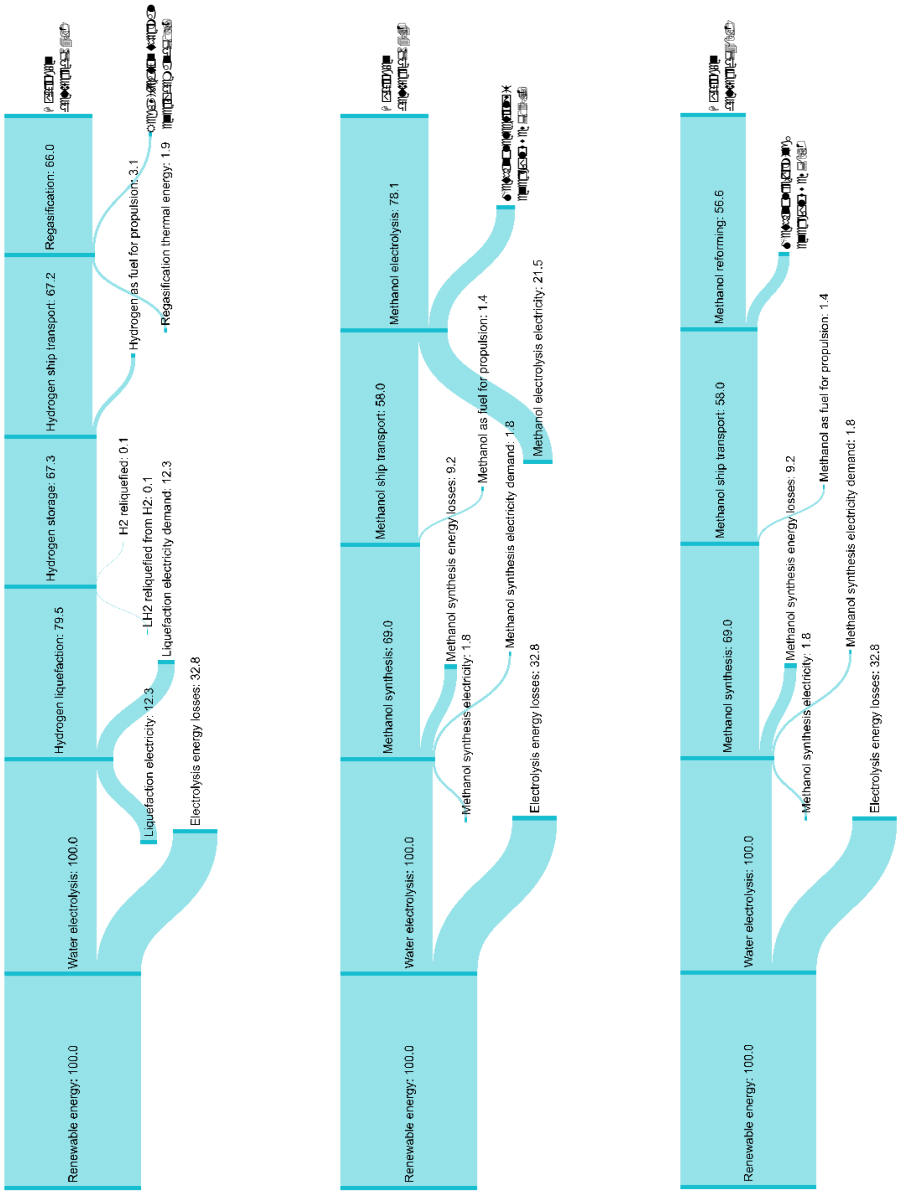

Figure 3. Process energy flow diagram for an annual production of 1 Mt of hydrogen. From left to right: hydrogen power link, methanol transport and electrolysis alternative, methanol transport and reforming alternative. 178,700 TJ/y is set at an index value of 100.

Figures 2-4 show that by increasing the hydrogen mass flow rate, the consumption of methanol and hydrogen for propulsion of the ships increases in relation to the electricity supplied for the electrolysis of the water in each power link. Besides, hydrogen consumption for propulsion represents a higher percentage of the renewable energy supplied at the beginning of the chain, resulting the hydrogen transport by ship in higher energy consumption than transporting methanol.

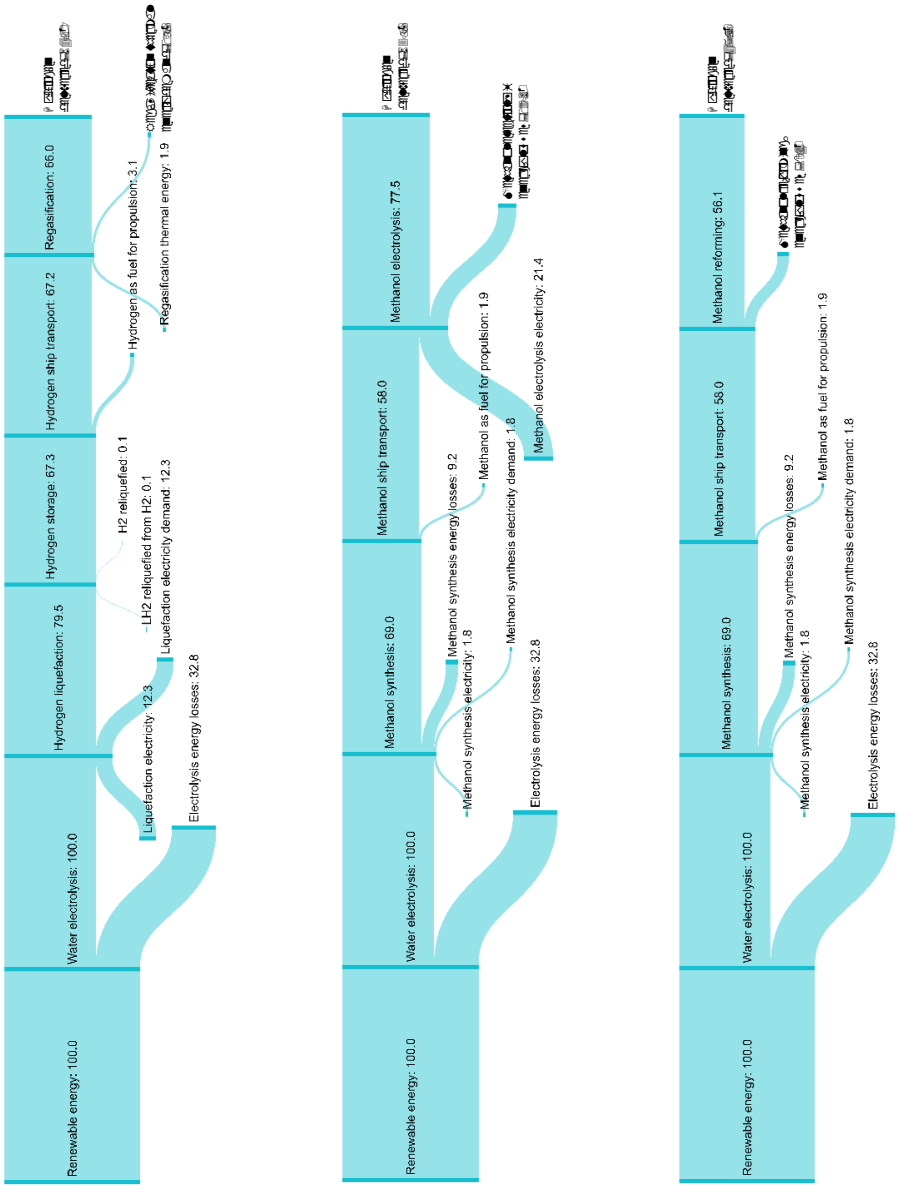

Figure 4. Process energy flow diagram for an annual production of 10 Mt of hydrogen. From left to right: hydrogen power link, methanol transport and electrolysis alternative, methanol transport and reforming alternative. 1,787 PJ/y is set at an index value of 100.

5. Conclusions

This work presents an energy study comparing three alternatives for transporting renewable energy under the form of fuels, delivering hydrogen at destination. The first alternative is based on the use of liquefied hydrogen as an energy vector. The second is based on the use of methanol as hydrogen vector, with a subsequent electrolysis process to obtain hydrogen at the destination. The third one also considers the methanol vector, but a methanol reforming process is used to obtain hydrogen. This work considers three mass flow rates of hydrogen produced: 100 kt/y, 1 Mt/y and 10 Mt/y, to make the comparison between the alternatives presented.

Comparison of the results obtained for the three power links show that the most interesting alternative in terms of energy is the transport of liquefied hydrogen. Transformation of H_2 in MeOH (methanol synthesis) and the subsequent reconversion of MeOH into H_2 (methanol electrolysis or reforming processes) implies more inefficiencies than liquefaction or regassification of H_2, so the alternative based on the transport of liquefied hydrogen is the one that allows receiving a greater mass flow rate of hydrogen at destination with the lowest energy losses.

Comparing the power links based on methanol as hydrogen vector, the alternative that provides the greatest mass flow rate of hydrogen at destination is the electrolysis of methanol, due to the electricity consumed at destination. However, despite obtaining a smaller mass flow rate of hydrogen, the methanol reforming process is more independent of the electrical grid at destination.

Considering the electrical energy necessary at destination for the methanol electrolysis facility, it can be seen that research in this process could facilitate its development and produce a decrease in the energy consumption. This would modify the results shown, and the electricity demand and energy losses of this alternative could be closer or better to the ones obtained through the alternative of transporting liquid hydrogen.

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