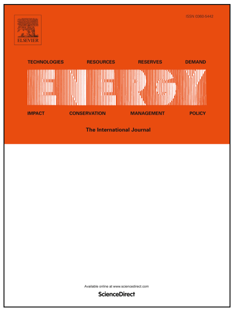

Power-to-Ships: Future electricity and hydrogen demands for shipping on the Atlantic coast of Europe in 2050

Rafael Ortiz-Imedio, Dilara Caglayan, Alfredo Ortiz, Heidi Heinrichs, Martin Robinius, Detlef Stolten, Inmaculada Ortiz

PII: S0360-5442(21)00909-9

DOI: https://doi.org/10.1016/j.energy.2021.120660

Reference: EGY 120660

To appear in: *Energy*

Received Date: 19 November 2020

Revised Date: 23 March 2021

Accepted Date: 14 April 2021

Power-to-Ships: Future electricity and hydrogen demands for shipping on the Atlantic coast of Europe in 2050

Rafael Ortiz-Imedio [a], Dilara Caglayan [b,c], Alfredo Ortiz [a], Heidi Heinrichs [b], Martin Robinius [b], Detlef Stolten [b,c], Inmaculada Ortiz [a]*

[a] Chemical and Biomolecular Engineering Department, University of Cantabria, Av. Los Castros 46, 39005, Santander, Spain

[b] Institute of Energy and Climate Research – Techno-Economic Systems Analysis (IEK-3) Forschungszentrum Jülich GmbH, 52425 Jülich, Germany

[c] RWTH Aachen University, Chair for Fuel Cells, Faculty of Mechanical Engineering, Kackerstraße 9, D-52072 Aachen, Germany

*Corresponding author: ortizi@unican.es

Abstract

The Atlantic coast of Europe has very high demand for maritime transport, with important commercial ports and tourist areas that emit significant amounts of greenhouse gas emissions. In an effort to address this, the impact of electric and H_2 ships for freight and passenger transport along the Atlantic coast on the European energy system in 2050 is analyzed. An optimized energy supply model is applied, which envisions a cost-optimal infrastructure with 100% renewable energy across all of Europe, employing hydrogen as an energy vector. To achieve this target, a minimization of the total annual costs to supply electricity and hydrogen demands is carried out. The obtained results indicate that Ireland will play a key role as a hydrogen supplier as ship demand rises, increasing onshore and electrolyzer capacities, mainly due to comparable low-cost renewable electricity production. The preferred supply routes for Irish hydrogen will be pipelines through the United Kingdom and France to export energy to continental Europe. An increase in salt cavern storage capacity in the United Kingdom, central Europe and Spain is observed. H_2 and electricity are shown to be essential for the deployment of more sustainable maritime transport and related activities on the European Atlantic coast.

Keywords

Energy system model, hydrogen, ship demand, renewable energy, electricity

1. Introduction

Climate change, caused by the increase in anthropogenic greenhouse gas emissions (GHGs) over the last few centuries, has prompted governments and societies to change their environmentally-harmful policies and behaviors in favor of more sustainable pathways of energy consumption and generation. As a result, many roadmaps in individual countries or groups have been developed [1–6]. The increasing contribution of variable renewable energy sources (VRES) to the energy system is the prevailing decarbonization route for current systems, and this increased globally by 50% in the five years between 2013 (1563 GW) and 2018 (2351 GW) [7]. However, the intermittent character of VRES necessitates the use of energy vectors to store the energy over long periods of time and balance the electrical grid [8,9]. Hydrogen is currently receiving significant attention as a potentially suitable energy carrier by many country roadmaps and studies [10], as it can be cleanly generated by means of electrolyzer technology [11–13] or recovered from industrial hydrogen-rich waste streams using separation techniques [14]. H_2 fuel can be used for transportation [15–18], as raw material in industries (chemical, metallurgical [19,20] and refineries), injected in the natural gas network [21,22] or to balance the electric grid [23,24], allowing the coupling of different sectors [25]. Although this vector has a low volumetric energy density, it can be stored, in liquid form, in metal or chemical hydrides [26–28] and in gaseous form (vessels, salt caverns or the gas grid). Furthermore, H_2 can be transported in liquid form in trucks, large containers and ships and in gaseous form via pipelines or trucks [29–31].

High investment and a number of challenges must be addressed in order to achieve the established targets. For this reason, energy system models, as well as the simulation and analysis of optimal possible future scenarios, are playing an important role in helping policy-makers and companies make decisions in order to tailor their actions and investments in an optimal way. Several system models have addressed the deployment of a high-penetration renewable energy scenario at the European level, investigating the influence on renewable shares and costs in the cases of isolated or interconnected countries [32–35]. Child et al. [32] highlighted the importance of an interconnected European scenario with a 100% VRES power system to reduce the storage capacity and the total annual costs (TAC). In turn, other models have considered the coupling of renewable energy with the transport and heating sectors [17,36–38]. Cebulla et al. [38] realized that sector coupling reduced the requirement for electrical energy storage. Moreover, short-term storage was more suitable for regions with frequent periods with an excess of VRES. However, aviation, shipping and pipeline transport have not been considered thus far. In contrast, other studies have focused on decarbonizing the energy system by utilizing H_2 as an energy vector at different regional levels and accounting for diverse generation technologies and demands, as described in the following.

An energy study for Europe with different shares of VRES and assuming a power demand for 2050 was assessed by Gils et al. [39]; however, H_2 was considered only as a storage resource and solely becoming important at high solar contributions. On the other hand, an H_2 deployment scenario was cost-optimally designed by Samsatli et al. [40], satisfying a 100% penetration assumption for fuel cell-electric vehicles (FCEVs) as domestic transport demand across Great Britain, with onshore wind turbines for generation. Pressurized vessels, underground salt caverns, as well as depleted oil and gas fields, were considered as storage solutions and H_2 pipelines and electricity lines for transmission. In Robinius et al. and Welder et al. [25,41], a hypothetical energy system for Germany in 2050 was developed. In the former study, an H_2 transmission and distribution pipeline grid was created to cover future demand of FCEVs with surplus energy from diverse renewable energy sources (RES). In the latter work, only eligible onshore wind was used, but with consideration of both mobile and industrial H_2 demand. Additionally, a new hydrogen transmission pipeline infrastructure was designed on the basis of compressed natural gas pipelines, highways and railways and utilizing salt caverns and gas pipe as storage. In the study by Guandalini et al. [42], a power-to-gas system was applied to Italy in 2050, producing an amount of H_2 equivalent to 5-6% of all natural gas consumption, or 6-8% of the total transportation fuel supply. With a different target year of 2035, Tlili et al. [43] assessed the potential of generating H_2 in France with RES and nuclear energy. In an isolated countries scenario, the available surplus energy for producing H_2 was higher than in a highly interconnected case but with a lower nuclear capacity factor.

Finally, Caglayan et al. 2021 [44] designed a European hydrogen infrastructure to supply electricity and H_2 in a 100% renewable energy scenario for 2050. The electricity was based on the e-Highway “100% RES” project [45] but substituted electric vehicles with FCEVs. Underground salt caverns were used for storage [46], as well as different conversion technologies, with electrical grids and hydrogen pipelines conducting transmission.

Despite all the interesting system models developed, none of them have included the maritime sector in their analysis, which accounted for 2.6% of global CO_2 emissions in 2012 [47]. In 2018, the International Maritime Organization (IMO) established the target of reducing total annual GHG emissions in the sector by 50% or more by 2050 against 2008 to align with the 2015 Paris Climate Agreement goals [48,49]. Moreover, and beyond GHG emissions, a link between particulate matter (PM) emissions from global shipping and health effects was evaluated, with around 60,000 premature deaths estimated annually [50]. For these reasons, many scientific studies and projects are being developed to achieve the target established by the IMO for 2050 using more bio-friendly systems and fuels to decarbonize the sector [51–55]. Fuel cells have gained much attention in ships and submarines as they can be used as power auxiliary units or for propulsion depending on the ship power requirements [53,56–59]. In addition, fuel cells can be also used as an alternative to cold ironing, reducing the emissions at ports [60]. Other projects are focused on hybrid power systems to enhance the transition to cleaner fuels reducing emissions in comparison to original engines [52,61–63]. Furthermore, some companies are developing liquefied H_2 carriers to promote the transport and use of hydrogen in different countries [30,31,64].

On the other hand, the Atlantic coast of Europe is characterized by many important ports, with intensive cargo ship traffic for trading with other countries and is a notable tourist area with many passenger ships. This high volume of ships implies a significant amount of GHGs and other harmful emissions being secreted in the region [65,66]. In this sense, projects have been launched in this area to promote hydrogen [67–70] and some companies have developed fuel cell ships [71,72] or use hydrogen as a fuel or as auxiliary support, combined with renewable energy technologies [73]. These investigations and developments prove that electricity and hydrogen could be used as cleaner sources of propulsion for ships.

The previous aforementioned studies and projects focus on hydrogen performance and storage in ships. However, none of the previous energy systems models have considered the implications of maritime transport despite being the main mode for goods transport. Hence, the impact of the new hydrogen and electric demand for shipping on the future European energy system as a whole has yet to be addressed.

The main novelty of this work is the study of the impact of a futuristic electric and hydrogen maritime sector on the European energy system in 2050 for a scenario with 100% renewable energy sources. This impact has been considered including the estimated electrical and hydrogen demand of ships from the ports of the Atlantic coast of Europe in 2050. The transport activities of freight and passenger ships in the main ports of this coast that have been registered in the Eurostat database [74] have been included. The optimizer energy model minimizes the TAC of an interconnected European system based on an electrical and H_2 infrastructure that selects the most adequate technologies and capacities in each region. The model provides an optimal design of the infrastructure of the energy system across Europe to satisfy the electric and H_2 demands in all of the regions. Furthermore, the hourly operation time series of all of the technologies through the year 2050 are calculated for every region. In this way, a snapshot of the 100% renewable energy system configuration required in 2050 with a high penetration of eco-friendly ships is shown to promote its transition by the corresponding policy agents.

In this work, the technologies and the electrical and hydrogen demands included as input for the energy system model are first described. Then, a discussion of the results is conducted in terms of TAC, technology capacities, the state of charge, the operation of some technologies and the electrical and hydrogen balance in two regions. Finally, the main conclusions of the work are drawn.

2. Methodology

This section briefly describes the energy system model and the boundaries employed in this work. Then, the main technologies considered in each region for optimization are provided. Ultimately, a detailed explanation of the methodology employed to calculate ship electricity and hydrogen demands is presented.

2.1 Program

The optimized design of the energy system discussed herein is based on a program developed in the Python language named Framework for Integrated Energy System Assessment (FINE) [75], which is explained in detail in Welder et al. [41]. This program minimizes the TAC of the energy system, selecting and adjusting the capacity of the optimal renewable energy sources as well as the conversion, transmission and storage technologies in each region. An interconnected electric and hydrogen infrastructure between regions across Europe is designed, with each region represented as a node of a network and transmission between them by edges. The system enables the exchange of electricity and hydrogen commodities and the deployment of specific technologies and capacities in each region in accordance with their specific characteristics. The techno-economic parameters of each technology are defined as input for the optimization problem. In this way, the system is able to satisfy the expected hourly electricity and hydrogen demand across all regions and at all times in 2050. In terms of temporal resolution, the model employs an hourly time series for that year.

2.2 System definition

The energy system definition employed here is the same as in the work of Caglayan et al. 2021 [44], where it is explained in detail; therefore, a brief description of their energy system concept is presented here.

For the regional boundaries of Europe, 96 regions were considered in accordance with the e-Highway project [45]. In each region, energy carriers can be generated, consumed, converted or stored using the same technologies as proposed in Caglayan et al. 2021 [44], as is shown in Fig. 1. The same values of specific investments of all technologies are taken, and are considered constant for all regions except in the case of onshore and offshore wind, with variable costs according to the size and location of the turbines, as discussed in Ryberg et al. and Caglayan et al.

[76,77]. In these studies, the maximum capacity was calculated through diverse land eligibility constraints.

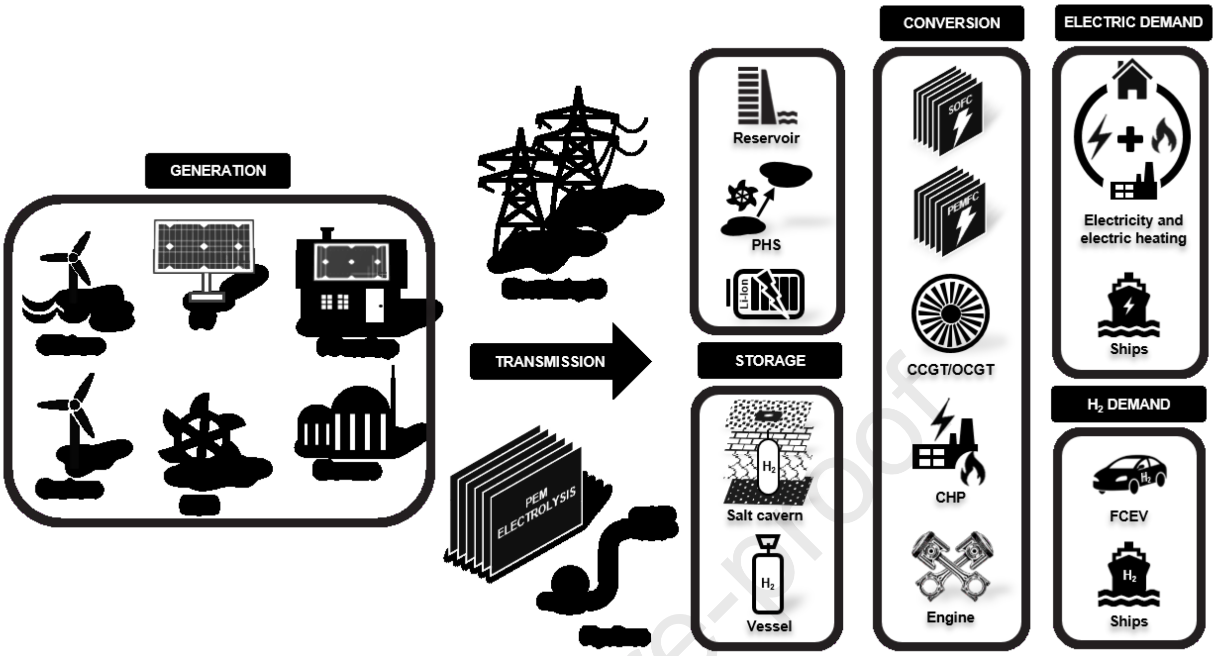

Fig. 1. Generation, transmission, conversion and storage technologies considered in the model.

In their study, only RES generation technologies were considered, including onshore, offshore, photovoltaic (PV) fixed or with sun tracking in open fields, as well as PV on rooftops, biomass and run-of-river (ROR) hydropower [44]. The renewable feed-in time series for onshore, offshore and PV were created with the weather dataset, Modern-Era Retrospective Analysis for Research and Application, Version 2 (MERRA-2) [78] and the simulation tool, RESKit [76,79]. The capacities of ROR and hydropower were assumed to be fixed respect to 2015. In addition, biomass was treated as a commodity that could be acquired when needed to generate electricity with heat and power (CHP) technology [44].

To convert H_2 from electricity by means of a clean process, polymer electrolyte membrane (PEM) electrolyzers were considered to be the best option [80]. Regarding the conversion from H_2 to electricity, five technologies were taken into account: PEM fuel cells, solid oxide fuel cells (SOFCs), hydrogen open cycle gas turbines (OCGTs), hydrogen combined cycle gas turbines (CCGTs) and hydrogen gas engines [44].

For energy storage, electricity was expected to be stored by using lithium-ion (Li-Ion) batteries, which have a fast and steady response time and small self-discharge rate (less than 0.3%) [81], and by using pumped hydro storage (PHS) and hydro reservoirs systems with fixed capacities [44]. In the case of hydrogen storage, thin-bedded structures and salt domes were considered with the technical capacity in each region defined from the study of Caglayan et al. 2020 [46]. Both salt caverns have the benefit of being very gastight and inert with H_2, while possible reactions between hydrogen and microorganisms or mineral constituents in depleted fields and aquifers can occur [82]. However, as not all of the regions feature salt caverns, vessels were also included in the model that could be used as alternative hydrogen storage media [44].

With respect to energy transmission, the electricity was transmitted through high-voltage direct current (HVDC) and high-voltage alternating current (HVAC) lines, which are considered fixed and carrying zero investment costs. For H_2 transmission, pipelines were considered to be the best and most economical method for transporting hydrogen on a large scale and across significant distances (greater than 200 km) due to their lower operational costs in demand-intensive scenarios [83,84]. The shortest path for pipelines between regions was extracted combining the existing infrastructure of roads, railways and natural gas pipelines.

Finally, for electricity demand, the estimated value for 2050 from the e-Highway project [45] was used, which included a large share of electrified heat demand for space and water heating in residential and non-residential places. However, instead of considering electric vehicles as electricity consumers, a 75% penetration of FCEVs was assumed for the hydrogen demand. In this study, the expected market penetration for 2050 was reduced to 50% [85].

2.3 Ship electricity and hydrogen demands

In this study, a special emphasis is placed on the Atlantic coastal regions of France, Spain, Ireland, the United Kingdom and Portugal, estimating and including the electricity and hydrogen demand for ships making use of the ports of these regions in 2050.

These estimated marine transport demands provide an insight into the shipping decarbonization in 2050 to reduce GHGs and other harmful emissions along the coast and ports of the Atlantic area of Europe. This area is characterized by intensive ship traffic for both trade and leisure. Furthermore, this work provides a study of the potential of the hydrogen vector in the area in a bid to encourage policy-makers and companies to use environmentally-friendly fuels and transports.

For this purpose, the methodology shown in Fig. 2 is employed to estimate the electricity and hydrogen demands for ships in 2050, with values in 2015 from the detailed database Eurostat [74] and growth estimations derived from Khalili et al. [86].

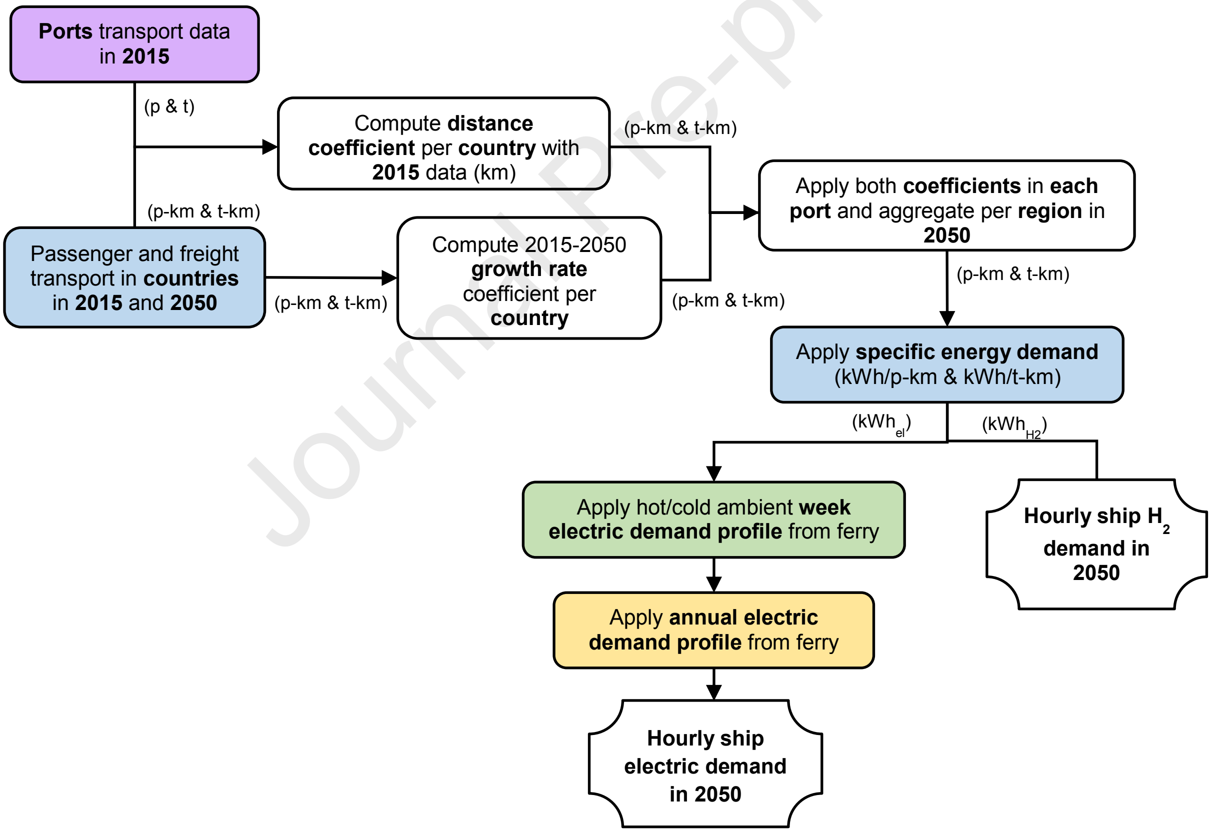

Fig. 2. Flow chart of the methodology to calculate ship demand. Data: Khalili et al. [86] (blue); Eurostat [74] (pink); Rivarolo et al. [87] (green); and Baldi et al. [88] (yellow).

The marine operations of freight and passenger transport from ports in the United Kingdom, Ireland, France, Spain and Portugal in the region under study (see Fig. 4) and registered in the Eurostat database [74] for the year 2015 were identified. These activities are expressed in terms of the annual gross weight of goods transported (in tonnes, t) and passengers transported (in passengers, p) for each port. However, to attain a projection of marine activities for 2050 for each port, the values from 2015 for each country from Khalili et al. [86] for both marine freight (in million t-km) and passengers (in million p-km) modes were collected. As is apparent, both data sources have different units for each of the transport modes (freight and passenger) because, in Khalili et al. [86], the weight of the goods or passengers is multiplied by the distance traveled. To find an equivalence in units between both data sources, an average "distance coefficient" (t-km/t and p-km/p) is calculated for each country in 2015. In this way, the data from the Eurostat database [74] can be multiplied by the "distance coefficient" to obtain the same values as in Khalili et al. [86] for the year 2015 and in the same units. The "distance coefficient" is employed for all the ports of each country, assuming that the average distance traveled is the same for all of them (Table 1).

Once the marine transport values of all ports have been calculated for 2015 using the units of Khalili et al. [86], the "growth ratio" for each country between 2050 and 2015 for the same reference is attained. This is accomplished by dividing the transport estimated value in each country in 2050 by the value in 2015 (Table 1). Furthermore, it is assumed that all the ports in each country grow at the same pace as the country itself from 2015 to 2050, computing the "growth ratio" in each transportation mode for all of the ports in their respective countries. The coefficients calculation can be found in the Supplementary Material.

Table 1. Average "distance coefficient" and "growth ratio" between 2050 and 2015 for each country.

Country	Average distance coefficient		Growth ratio 2015-2050 (-)	
	Freight (t-km/t)	Passengers (p-km/p)	Freight	Passengers
UK	4230	251	2.1	5.2
Ireland	4140	190	1.4	1.1
France	6744	238	1.6	2.9
Spain	2942	170	1.3	1.6
Portugal	2552	1089	1.2	1.1

Once the freight and passenger transportation activity values for the year 2050 in each port are quantified, the annual electric and H_2 demands for shipping are calculated with the corresponding specific energy demand estimations for 2050 [86]. These values are 0.02 kWh_{el}/t-km and 0.029 kWh_{H2}/t-km for freight mode and 0.325 kWh_{el}/p-km and 0.461 kWh_{H2}/p-km for passenger mode [86]. The ship demands calculated by each port are added up to compute the regional demands for each commodity. The detailed annual electricity and hydrogen demands calculations by regions can be found in the Supplementary Material.

The temporal resolution of the model used in this study is hourly, and for that reason, these annual values must be disaggregated by the hour. As there is a lack of data on hourly electric energy demand in ports, the electric consumption profiles for hotel services and related services from a cruise ship during a typical week of operation, from Rivarolo et al. [87], is employed. These vessels can offer an insight into the electrical variability required in ships with high energy demand for non-propulsion processes. The normalized week electrical demand profile from Rivarolo et al. [87] in cold ambient is repeated cyclically in the months between October and April and the warm ambient week in the months between May and September. Moreover, to better represent the energy demand evolution along the year because of differences in ambient temperature, the normalized daily electric power demand profile of a cruise ship, from Baldi et al. [88], is also applied. The resulting ship electricity demand for ships in the region of the northeast of France is represented in Fig. 3. Electrical power demand is higher in ships during the summer months due to heat, ventilation and air conditioning needs than in the winter months, while ferry operations see an increase due to tourism [88]. However, the total electricity demand during summer is lower due to a reduced electricity demand for the rest of applications (heating, lighting, etc.), as can be seen in Fig. 3.

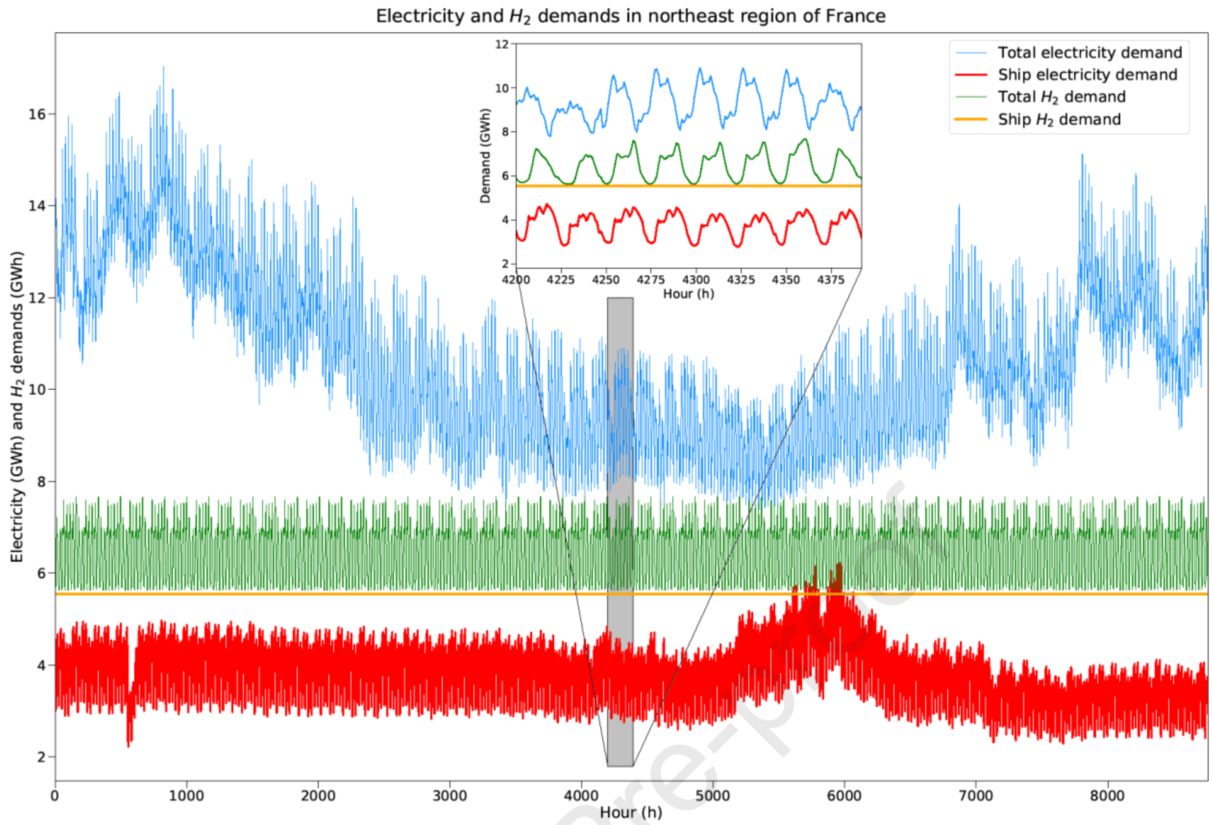

Fig. 3. Total and ship hourly electricity and H_2 demands (GWh) in the northeast region of France

H_2 fuel is expected to play a dominant role in 2050 for marine passenger and freight transport. H_2 could be used to reduce emissions [6,86,89], as an auxiliary power supply system [6,90], as a hybrid fuel with biofuels and synfuels [91–93], or to support the high energy demand of auxiliary engines and boilers for the on-board operations of large ships in berth [47,60,94]. However, the ship H_2 demand profile is considered constant throughout the year because there is no data from hydrogen refueling stations dedicated to marine vessels or the use of this fuel in the maritime setting in the first place, as it is still in the research stage. Nevertheless, due to the dense marine traffic between ports and regions, the fact that maritime trade is usually regular throughout the year and the energy demanded by ships during operation at berth [47,95,96], an average value of H_2 demand can be considered a good approximation. Therefore, the average annual hydrogen demand is divided by the number of hours of a year to obtain an average hourly H_2 demand per region. In Fig. 3 the total and ship H_2 demands for the northeast region of France are represented. The ship H_2 demand is constant throughout the year with the previous assumption considered and the variable profile of the total H_2 demand corresponds to the hourly profile of a fueling station for the FCEV [44].

Fig. 4a shows the total annual ship electricity demand (TWh/y) in each of the regions studied on the European Atlantic coast. Its contribution to total electricity demand in each region and along the Atlantic coast is represented in percentage values in black and red, respectively. As can be observed, a high contribution of ship electricity demand is expected in 2050 in each region, especially in the United Kingdom and northeast of France, reaching a third of the total electricity demand in some of those regions. In total, the electricity demand from all the ships on the Atlantic coast would be around 4.26% of the total electricity demand in Europe. This contrasts with the nearly zero electricity demand currently and the important development that must be carried out in the electric marine sector to achieve these values by 2050.

In Fig. 4b, the total annual ship H_2 demand (TWh/y) in each of the regions along the Atlantic coast studied is plotted and its contribution to the total H_2 demand of each region is represented in percentage values in black. The share of regional ship H_2 demand to the total Atlantic coast H_2 demand is depicted in red. As can be seen, the ship H_2 demand generally predominates over FCEV demand in all of the regions, highlighting the role of maritime transport on the Atlantic coast of Europe and the efforts that must be addressed in this sector to achieve this high H_2 demand compared to the null current hydrogen demand.

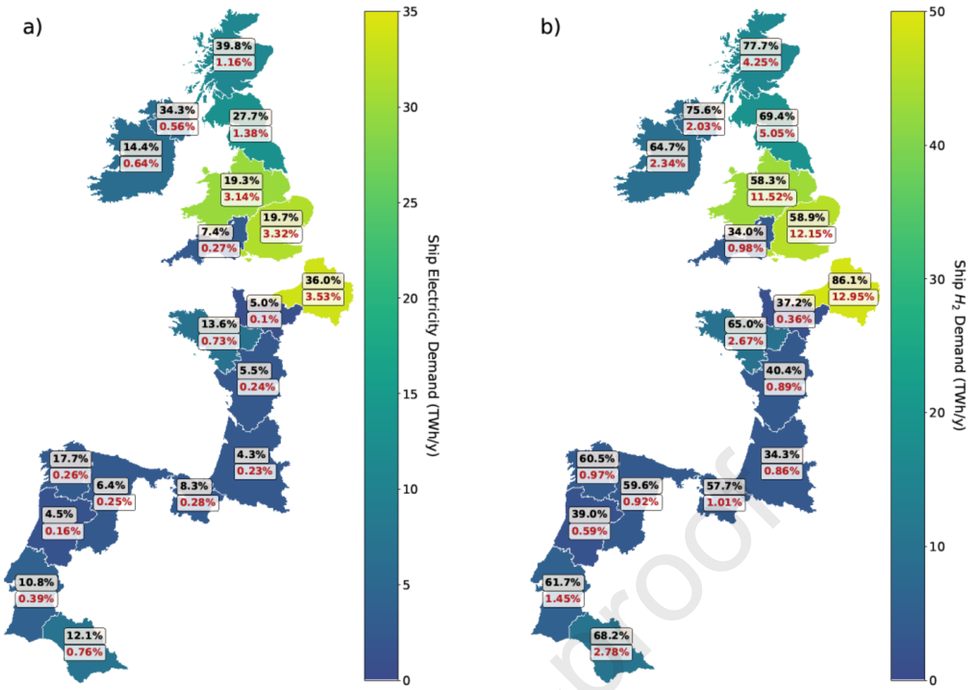

Fig. 4. Annual ship demand (TWh/y) and its contribution (%) to regional demand (in black) and to total Atlantic coast demand (in red) in terms of electricity (a) and H_2 (b) in each of the regions of the Atlantic coast of Europe considered.

2.4 Scenarios

As this work is an estimation of the future consumption of electricity and H_2 for freight and passenger transport ships in 2050, the real values could differ. Therefore, different penetration scenarios of ship H_2 demand are simulated to analyze its effect on the model. The electricity demand of ships is maintained constant with the value calculated previously in order to be able to emphasize the influence of H_2 as an energy vector for maritime transport. Furthermore, the electricity demand derived from the e-Highway project [45] and the H_2 demand for the FCEV also remained constant in all scenarios.

The range of variation of ship H_2 demand spans from 0% of the values calculated previously, considered the reference case (S0), up to 160% (S160), implying an increase of 60% with respect to the calculated values. This overestimation allows observing the impact if the calculated values are underestimated with respect to reality in 2050. Scenario S100 is the case in which the ships use 100% of the values of H_2 calculated previously (Fig. 4). Intermediate steps of 20% are included to track the evolution of costs and capacities in the energy system.

These penetration scenarios enable an analysis of the impact of less polluting vessels for freight and passenger transport concerning the Atlantic area and their requirements in a transition to a more sustainable European energy system.

3. Results and discussion

The results obtained in this study using the methodology previously discussed are described in this section in order to analyze the economic and technical impact of the additional ship H_2 demand on the European energy system. Then, a study of the energy system behavior in scenario S100 is conducted in order to better understand the relationships between the different technologies considered.

3.1 Impact of ship H_2 demand

Fig. 5a shows the TAC (10^9 €/y) of the main technologies and storage systems across all of Europe with respect to the scaled ship hydrogen demand scenarios. The generation technologies with the highest TAC values in 2050 will be onshore wind, PV fixed and offshore. As the ship H_2 demand increases, the TAC of the technologies rises linearly. However, in the case of electrolyzer and onshore technologies, a steep slope is produced between scenarios 0% (S0) and 160% (S160), increasing a 49.4% and 16.7%, respectively. For the remaining technologies, the slope is very slight. These results can be explained with the capacities of generation, conversion and transmission technologies and storage systems that will be installed in 2050, which are shown in Fig. 5b. Electrolyzer and onshore technologies have variations in capacity values of 49.4% and 17.3% between 0 and S160, respectively, similar to the TAC case, because capacity and TAC are directly related. Therefore, onshore technology will be the main renewable source of electricity to generate hydrogen as the demand from ships increases.

It can be noted that fixed PV will have a high installed capacity with a lower variation than onshore wind (5.7%) between the extreme scenarios. Thus, PV is a very important technology for electricity generation, compensating for the wind fluctuations, but with little dependence on ship H_2 demand. On the other hand, offshore technology will have a smaller installed capacity but make a relatively high contribution to the TAC.

The capacity of H_2 pipelines is defined as the product of the mass flow rate (g/s) and lower heating value (LHV, in MJ/kg) of H_2. HVAC and HVDC have zero TAC values, as they are defined exogenously, without investment costs or expansion. However, a highlighting fact is the high contribution of the H_2 pipeline to the capacity but with very little impact on the TAC, with values lower than 0.4% of the TAC for each scenario, demonstrating the importance and feasibility of the use of pipelines for H_2 transport in 2050 with low investment.

In terms of storage capacities, the largest installed systems will be salt caverns and hydro reservoirs, with the former accounting for around 54% of the total installed storage capacity. These systems will be used for long periods and with an increase of 7% for salt cavern capacity between the S0 to S160 scenarios, remaining constant for hydro reservoirs due to the capacity being considered to be fixed [44]. This 7% variation in salt cavern capacity means 13 TWh, while ship H_2 demand has increased from 0 TWh in scenario S0 to 383 TWh in S160. This result highlights the slight increase in storage requirement when a high amount of H_2 demand is added and the reduced impact on the TAC (Fig. 5a).

Therefore, the deployment of hydrogen ships in the Atlantic area to promote cleaner transport of freight and passengers requires the reinforcement of the European energy system and its technologies with a relatively low additional TAC (11%) between scenarios S0 and S160.

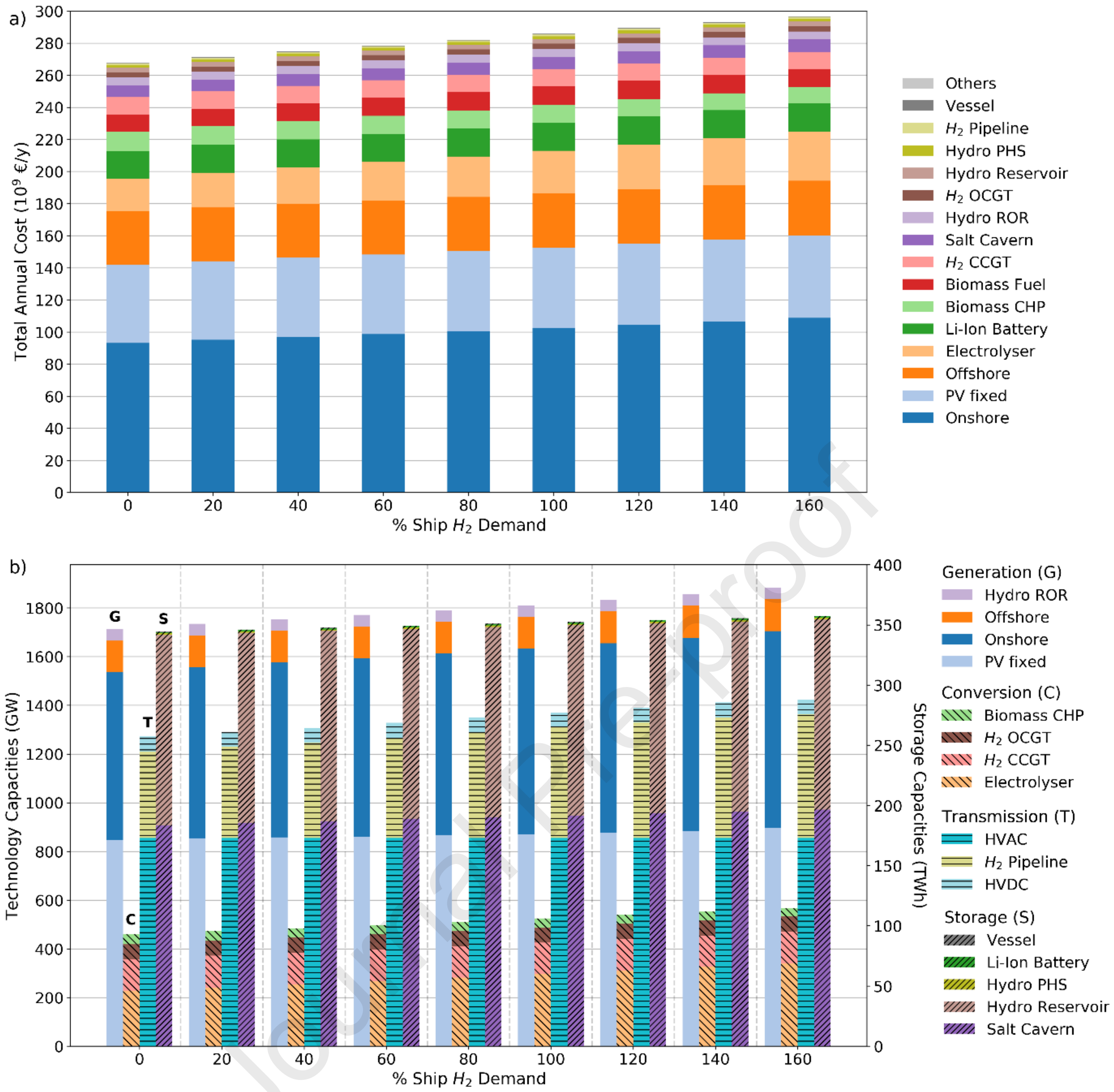

Fig. 5. a) Variation of total annual costs (TAC, in 10^9 €/y) and b) main generation, conversion and transmission technology capacities (GW) and storage capacities (TWh) versus percentage of ship H_2 demand across all regions of Europe.

To determine the impact of ship H_2 demand across the regions of Europe, Fig. 6a shows the difference in the capacity of the main RES technologies, H_2 pipelines and salt caverns between scenarios S160 and S0. On the other hand, Fig. 6b displays the layout of the capacities that would be required in 2050 in scenario S160. The total storage capacity is increased from 184 TWh to 197 TWh from the S0 scenario to the S160 case, mainly increasing in Northern Ireland (7 TWh), the southern region of Scotland (3 TWh) and the southwestern United Kingdom (2.7 TWh), but decreases by around 2 TWh in the Wales-Midlands area of the United Kingdom and in the west of Germany. Minor variations are also produced in other regions of Europe.

Analyzing the optimal VRES capacities in the two scenarios, a combination of different generation technologies is observed in the center and north of Europe, with the dominance of onshore, while in the southwest PV without tracking predominates, as explained in Caglayan et al. [44]. The main increases are produced for onshore (123 GW) and PV fixed technologies (53 GW). Onshore capacity is mainly increased in Ireland (72 GW) and lower variations are produced in the London area and the Netherlands. On the other hand, the capacity of fixed PV in the field is increased in Scotland, southeast of Spain and the Netherlands. Offshore technology only increases by 4 GW between extreme scenarios, varying only in Wales-Midlands and the north of Germany.

With respect to the H_2 pipelines, an important growth in the capacities of Ireland, the United Kingdom and the interconnection with France can be observed in Fig. 6a. The low cost of electricity generation in Ireland and the United Kingdom and the high full load hours (FLH) of onshore technology favor the conversion from electricity to hydrogen via electrolyzers and transportation with high-capacity pipelines to continental Europe [44]. As the H_2 pipeline between southern Ireland and the south of Scotland achieve the maximum established capacity (48 GW), a reinforcement of the pipeline route southern Ireland – Northern Ireland – southern Scotland is proposed.

Furthermore, the pipelines primarily reinforce their capacities in regions where hydrogen demand has increased, in this case, in the areas along the Atlantic coast where ship H_2 demand has been varied in the studied scenarios. However, the pipelines of other European regions also increase their capacities, as in the case of southeastern Norway or the north of Germany, to support the additional ship H_2 demand with cheaper commodity production.

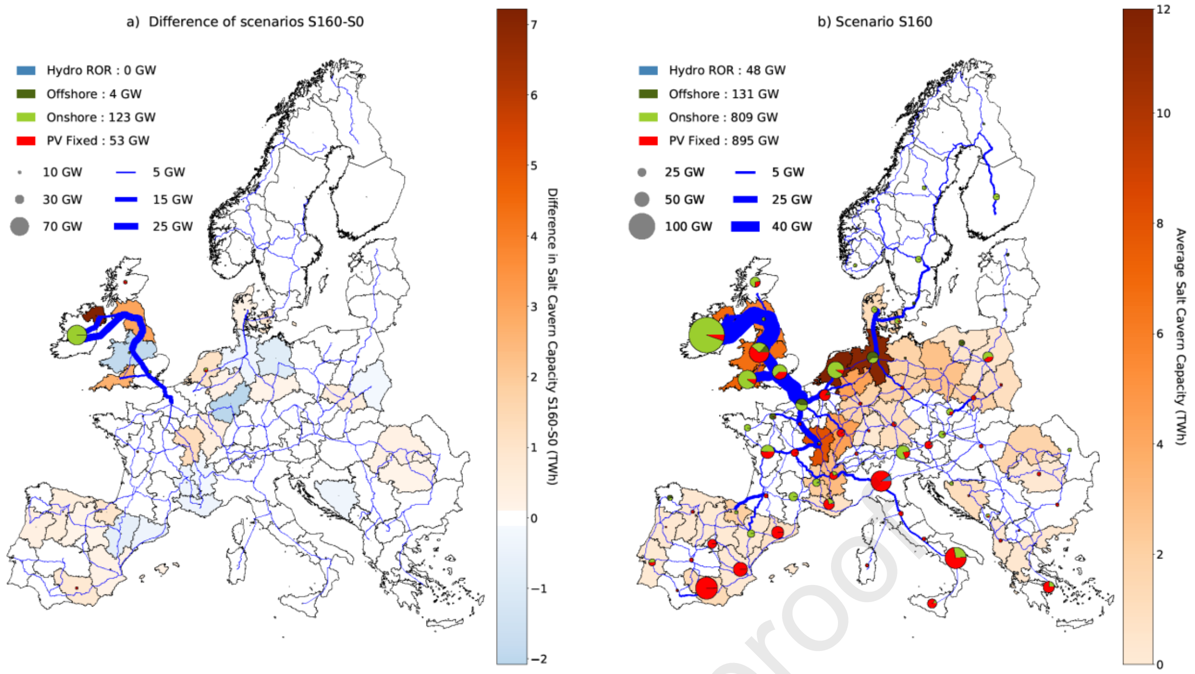

Fig. 6. a) Difference in salt cavern capacity, RES technologies and H_2 pipelines across regions of Europe between scenarios S160 and S0; b) Capacity distribution in scenario S160.

The increase in the installed capacities (GW) between scenarios S0 and S160 of onshore and fixed PV RES technologies previously discussed can be better observed in Fig. 7a and Fig. 7b. Ireland, with an increase of 72.3 GW for onshore, is plotted in green and out of scale so as to be able to appreciate the variation in the remaining regions, as in the case of London, Wales-Midlands and the Netherlands. However, small variations would be required in many other regions in the central and northern Europe to support the production of electricity for H_2 production in the S160 scenario. A decrease in onshore capacity is observed in the southwest of the Iberian Peninsula and is replaced by fixed PV. This latter technology, along with the main increases in Scotland, southeastern Spain and the Netherlands, also requires minor variations in other regions in the center and south of Europe (Fig. 7b). Furthermore, a small reduction in the fixed PV installed capacity is produced in Ireland or other regions because the model assumes that electricity can be produced more economically with onshore technology or in adjacent regions.

Regarding conversion technologies, scenario S160 would require installing additional 63.8 GW of electrolyzers in Ireland (Fig. 7c). This value is close to the onshore increase in the same region, confirming Ireland to be the main supplier of H_2 for ship

H_2 demand in the Atlantic area. Moreover, electrolyzer capacity would also need to grow in the other regions, where onshore and fixed PV are further deployed to produce H_2 from renewable electricity, as in the case of Scotland, London, Wales-Midlands, the Netherlands and southeastern Spain. Finally, as ship H_2 demand increases, a small variation in the capacity of hydrogen gas turbines (CGT) is required (Fig. 7d). The capacity increases in the south of Scotland, the Netherlands and in the London area because a higher amount of H_2 is generated with electrolyzers and stored in salt caverns and converted again into electricity with H_2 turbines. On the other hand, the installed capacity decreases in the S160 scenario in Scotland, Wales-Midlands and central Europe. This can be explained because more electricity is produced directly with the reinforcement of RES technologies.

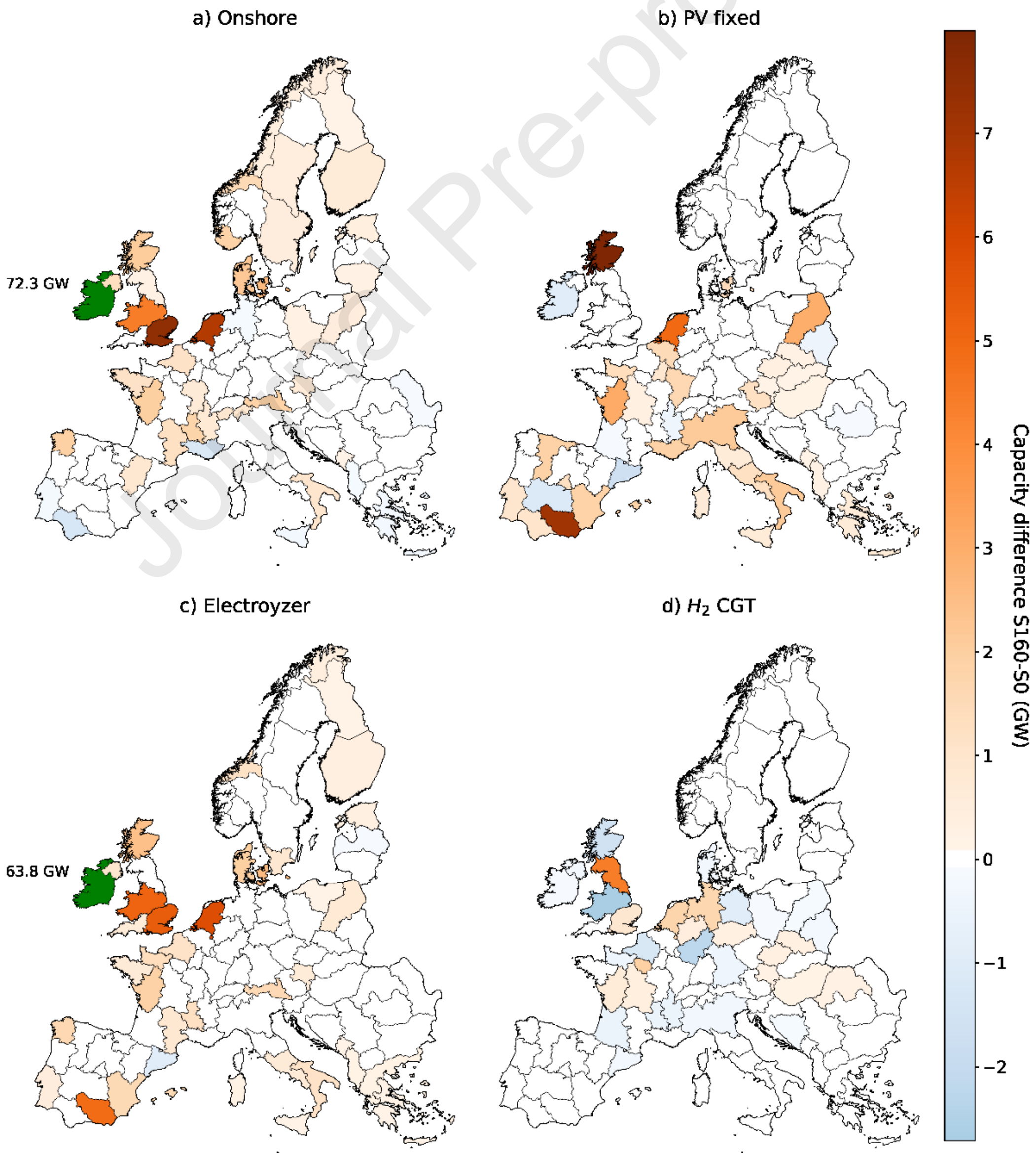

Fig. 7. Difference in installed capacity (GW) of: a) onshore, b) fixed PV, c) electrolyzers and d) H_2 CGT (CCGT+OCGT) technologies across the regions of Europe between scenarios S160-S0.

3.1 Analysis of scenario S100

In order to better understand the energy system, an analysis of scenario S100 in terms of the operation of different technologies in one region (Fig. 8), the state of charge of salt caverns in another region (Fig. 9) and electric and H_2 balance in two other regions (Fig. 10) is carried out.

In Fig. 8, operation in the region of London in scenario S100 for the year 2050 for the onshore, fixed PV, electrolyzer and Li-Ion batteries technologies are graphed. With regard to RES, higher electricity generation with onshore technology compared to PV can be observed during fall and winter, despite the daily fluctuations. A soft "eye shape" shadow (slightly wider than the PV fixed generation) of lower operation can also be perceived because wind is driven by sun energy, originating boundary layers and turbulences due to the thermal effect on land and the creation of transitions between day and night [97].

On the other hand, electrolyzers harness electricity from both onshore and fixed PV following their characteristic generation patterns throughout each day and during the year. Electrolyzers work at maximum capacity most of the time because the model has optimized their capacities to increase their FLH; however, only a small part of the energy generated is used by them, as electricity is also used to supply demand in the London area, as well as being exported to neighboring regions.

In the case of the state of charge (SOC) of Li-Ion batteries, intra-day changes are displayed with large transitions throughout the day, evincing their use for short-term storage in order to balance electrical and hydrogen demand. In the early hours of the morning, batteries start to be discharged to supply electricity demand and are charged again after midday with energy coming from the sun, which is collected with PV. This cycle is repeated almost every day; however, during the first and last days of the year, the pattern is more irregular, in line with the months that have lower sun irradiance, as indicated in the fixed PV graph with the "eye shape" operation. There are some days on which batteries remain charged, as energy can be directly supplied from other sources.

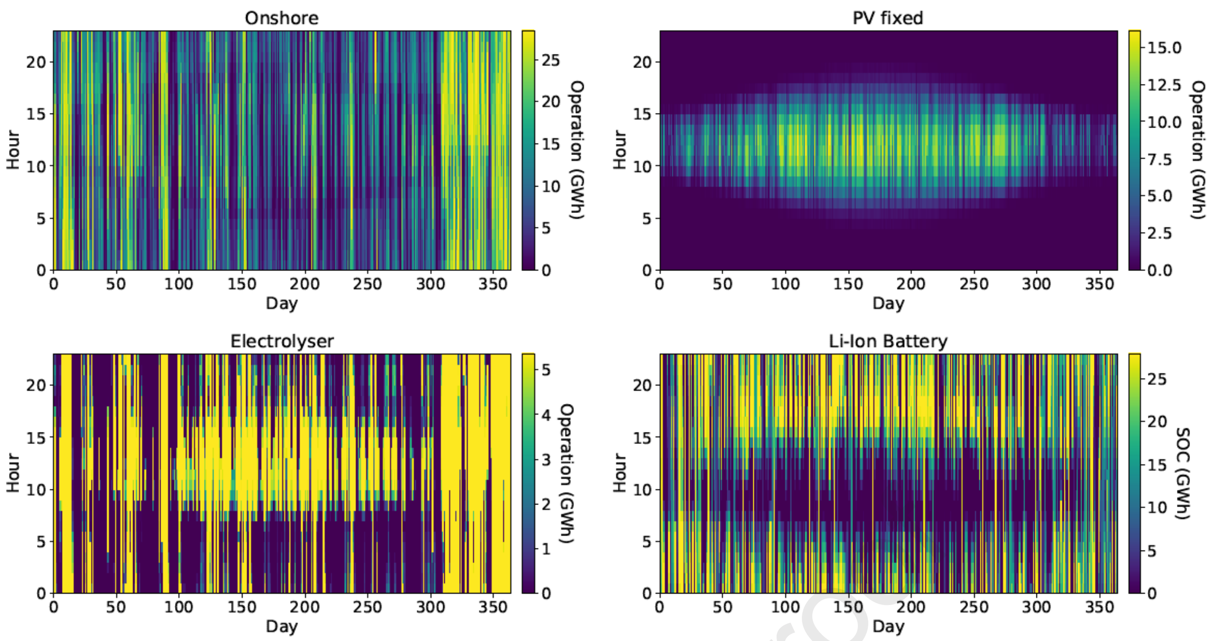

Fig. 8. Operation of onshore, PV fixed, electrolyzer and SOC of Li-Ion batteries in GWh in the S100 scenario from the region covering London for the year 2050.

In order to analyze the energy use of salt caverns, Fig. 9 shows the evolution of the SOC throughout the year 2050 in the S100 scenario in the regions i) Basque Country – Navarre (Spain), ii) Northern Ireland and iii) The Netherlands. In Fig. 9a, the SOC in terms of energy values (TWh) indicates the energy stored on each day of the year, while Fig. 9b shows the percentage of the salt cavern capacity that is filled. As can be observed, the energy stored diminishes during the spring season and the beginning of fall, due to a reduction in the energy generated with onshore and PV fixed technologies. On the contrary, at the end of the spring and during summer, the electric demand is lower (Fig. 3) and energy generation with PV is increased (Fig. 8), charging the salt caverns for the rest of the year. Additionally, at the end of the year, onshore generation is increased and the electric demand is still not at maximum values, enabling the storage of more H_2 for winter and spring.

In the case of (i), the energy stored is lower than in other regions, because the maximum capacity is nearly 4 TWh (see Fig. 6); however, during the months of summer and fall, it is nearly at full capacity with values around 100%, confirming the reasons exposed. The system designs the capacities of salt caverns in small regions in accordance with their own demands and from neighboring regions to prevent overcapacities and over costs. For that reason, the Spanish region (i) gets filled up during long periods, to cover mainly their necessities and for a few nearby regions. In the case of Northern Ireland (ii), there is a higher installed capacity of salt caverns (11.3 TWh), but the periods with full storage are shorter than in the Spanish region, exporting the H_2 to other regions with lower capacities and which are not self-sufficient, as can be seen from the pipelines distribution in Fig. 6. Finally, the Netherlands (iii) salt caverns have the highest storage capacity (23.6 TWh) in Europe, reaching around the 80% of the total capacity at the beginning of winter, as can be seen in Fig. 9b. This region mainly exports H_2 to the rest of regions and provides an extra storage capacity in the center of Europe for the years with higher energy generation and lower demand, avoiding excessive curtailments.

Therefore, a good optimization and distribution of the salt caverns across Europe enable the exchange of H_2 between regions to fulfill the high number of sustainable ships estimated in 2050. This fact reinforces the importance of an interconnected Europe to harness the higher energy generation from regions with favorable conditions and support the regions with higher demands and lower generation capabilities.

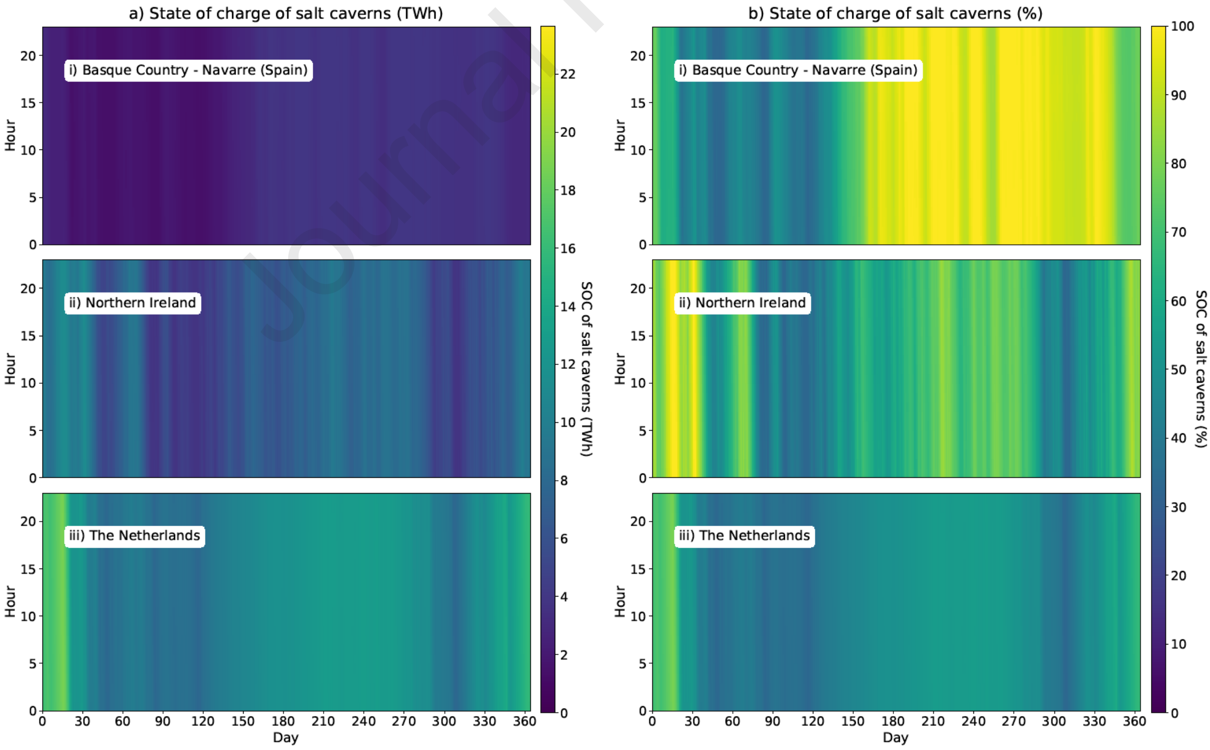

Fig. 9. SOC of salt caverns in the regions of i) Basque Country - Navarre (Spain), ii) Northern Ireland and iii) The Netherlands in terms of TWh (a) and percentage (b) in the S100 scenario for the year 2050.

To analyze the balance of energy production and demand, the model can calculate the hourly operation time series of all technologies in every region in terms of electric and H_2 balances throughout the year 2050. In Fig. 10, the balances of the regions of Wales-Midlands (United Kingdom) (a) and Ireland (b) during the last days of May and the first ones of June are shown as examples of the operation of individual technologies. Positive values mean the generation, production or import of electricity or H_2, while negative values indicate their consumption or export to other regions.

In Wales-Midlands (a), in the case of electricity, the demand is usually covered with onshore, offshore and fixed PV in the field. Nevertheless, there are some periods that utilize backup electricity production from hydropower, H_2 CCGT or OCGT, or from Li-Ion batteries. In addition, import from neighboring regions is necessary and more economically-beneficial to balance the demand. There are periods in which energy generation with RES is higher than the demand, taking advantage of the energy surplus to export electricity to the neighboring regions, charge Li-Ion batteries or PHS systems or convert to H_2 through electrolyzers. However, excess electricity is sometimes curtailed.

Analyzing the H_2 balance, the commodity is imported through pipelines, possibly from Ireland (Fig. 10b), and used to fulfill H_2 demand and store the surplus in salt caverns. As the import of gas is highly variable, salt caverns must be discharged to satisfy the demand when imports are scarce and to export it to other regions (Fig. 9). H_2 produced with electrolyzers is stored in salt caverns or used to supply the demand. At certain times, imported H_2 or that from salt caverns is employed to generate electricity with CCGT and OCGT technologies, assisting the electricity demand. At a glance, during this period in this region, H_2 is primarily imported in order to increase the state of charge of the salt caverns to be used as a backup for other periods of the year.

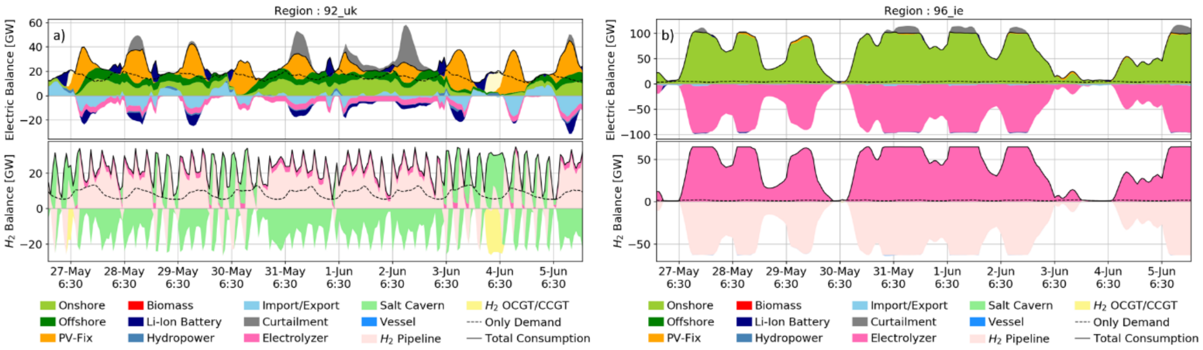

Fig. 10. Electric (upper) and hydrogen (lower) balance with the operation of individual technologies in the: a) Wales-Midlands (United Kingdom) and b) Ireland regions with the S100 scenario.

In Ireland (Fig. 10b), the predominant generation of electricity with onshore wind energy is apparent, with the limited addition of PV technology on some days. This energy generation is mainly used to supply own demand and is converted to H_2 with electrolyzers. As this region lacks salt caverns, the H_2 is exported to many of the European regions, making it one of the main suppliers of this commodity.

Curtailments can be observed when the H_2 produced with electrolyzers reaches the maximum capacity of the pipeline and vessels, which is demonstrated as flat caps in the H_2 export profile. However, these capacities and the overall system were optimized by the model to achieve the minimum value of TAC, therefore providing the most feasible energy system based on RES and H_2 for the year 2050. In this way, electricity and H_2 demanded by ships on the Atlantic coast of Europe can be fulfilled, facilitating the transition to a more sustainable energy system.

To summarize, Europe should reinforce the current energy system to achieve in 2050 a sustainable maritime transport of freight and passengers based on electricity and hydrogen. To achieve this goal, an optimal infrastructure of hydrogen pipelines between countries should be installed creating an interconnected network to cover all regions and ports. This would enable the transport of this gas from countries with higher RES (especially Ireland, the United Kingdom and north of Europe) to the countries with higher demands and less renewable resources. In addition, electrolyzers will be very relevant for the generation of H_2 with electricity from RES. In this work, the region of Ireland is highlighted as the main producer of H_2 through onshore wind and electrolyzers and the main exporter to Europe of this commodity. Additional PV installation will offer support to the electricity generation with RES when the ship demand is increased, especially in summer. Furthermore, the creation of salt caverns through Europe will be the key step to the use of H_2 as an energy vector, storing the energy for long periods and being supplied again when it is required. In this way, the electricity and hydrogen demands in all the countries and in the ports will be fulfilled saving energy and avoiding the emissions of pollutants from fossil fuels.

4. Conclusions

This study analyzed the impact of ship electricity and H_2 demands on the European energy system in 2050. To achieve this goal, an estimated ship electricity demand in 2050 and different penetration scenarios of ship H_2 demand from freight and passenger marine transport along the Atlantic coast of Europe were considered to visualize the infrastructure that should be deployed. The energy model formulated was based on the work of Caglayan et al. [44].

A predominance of H_2 demand from maritime transport compared to FCEV can be observed on the Atlantic coast in 2050 in most of the regions, highlighting the importance of developing the marine sector to reduce pollutant emissions. On the other hand, the higher ship electricity demand during summer has a low impact over the total electricity demand in each region. Increasing hydrogen demand for shipping results in higher total annual costs and installed capacities. The main technology expansion occurs in Ireland, increasing the onshore and electrolyzer capacities by 72 GW and 64 GW, respectively. Fixed PV technology also increases its capacity in some regions to support the high H_2 demand from ships, especially during summer, when there is an increase of passenger transport with ferries. In contrast, the capacity of offshore technology is very low influenced by the penetration of ship demand, varying only 4 GW between scenario S0 with zero ship H_2 demand and scenario S160 with 160% of the estimated ship H_2 demand.

A reinforcement of salt cavern storage, mainly in the United Kingdom, is required when the ship H_2 demand increases between the S0 and S160 scenarios to extend the capability of balancing the energy system with higher H_2 demand. Salt caverns are discharged during winter and spring when the demand is high and the generation is low, and charged again in summer to support the rest of the year.

Pipelines mostly increase their capacities in Ireland, the United Kingdom and the interconnection with France, which strengthens their position as the leading suppliers of energy to Europe, with low costs and high FLH for electricity generation. However, additional minor expansion in the pipeline capacities in the regions of northern Europe is required with the higher demanding scenarios for additional H_2 supply for ships at a lower cost.

Many studies and projects about fuel cells and storage applied to ships are on development to increase the energy power density and autonomy, especially for the long distance transport. Therefore, an appropriate infrastructure for H_2 generation and supply across Europe should be deployed to enable the transition to more sustainable ships in 2050, with a relatively low cost but with a high positive impact on the environment.

Further work will be necessary to adopt more realistic electrical and hydrogen demand curves throughout the year according to the different types of ships that travel within the region under study. This will enable the further quantification of hydrogen demand for maritime operations and its impact on the energy system in Europe in 2050.

Acknowledgments

This research was supported by the Project, “HYLANTIC”- EAPA_204/2016, co-financed by the European Regional Development Fund within the framework of the Interreg Atlantic program and the Spanish Ministry of Science, Innovation and Universities (Project: RTI2018-093310-B-I00). The IEK-3 is supported by the Helmholtz Association via the Joint Initiative, “EnergySystem 2050: A Contribution of the Research Field Energy”. Rafael Ortiz-Imedio is grateful to the Concepción Arenal postgraduate research grant from the University of Cantabria.

Nomenclature

CCGT	Combined cycle gas turbine
CHP	Combined heat and power
FCEV	Fuel cell electric vehicle

FLH	Full load hours
GHG	Greenhouse gas emissions
HVAC	High-voltage alternating current
HVDC	High-voltage direct current
IMO	International Maritime Organization
JCR	Joint Research Centre
LCOE	Levelized cost of energy
Li-Ion	Lithium-ion
OCGT	Open cycle gas turbine
PEM	Polymer electrolyte membrane
PHS	Pumped hydro storage
PM	Particulate matter
PV	Photovoltaic
RES	Renewable energy sources
ROR	Run-of-river
SOC	State of charge
SOFC	Solid oxide fuel cell
TAC	Total annual cost
VRES	Variable renewable energy sources

References

[1] European Commission. Roadmap 2050. A practical guide to a prosperous, low-carbon Europe. 2010. doi:10.2833/10759.

[2] IRENA International Renewable Energy Agency. Global Energy Transformation: A Roadmap to 2050. 2019.

[3] Fuel Cells and Hydrogen 2 Joint Undertaking. Hydrogen Roadmap Europe. A Sustainable Pathway for the European Energy Transition. Belgium: 2019. doi:10.2843/249013.

[4] Greenpeace. Energy [R]evolution. A Sustainable World Energy Outlook. Brussels: 2015.

[5] DECC Department of Energy & Climate Change. UK Renewable Energy Roadmap - Update 2013. London: 2013.

[6] Hydrogen Council. Hydrogen Scaling Up. A sustainable pathway for the global energy transition. 2017.

[7] IRENA International Renewable Energy Agency. Renewable capacity statistics 2019. Abu Dhabi: 2019.

[8] Gahleitner G. Hydrogen from renewable electricity: An international review of power-to-gas pilot plants for stationary applications. Int J Hydrogen Energy 2013;38:2039–61. doi:10.1016/j.ijhydene.2012.12.010.

[9] Ban M, Yu J, Shahidehpour M, Yao Y. Integration of power-to-hydrogen in day-ahead security-constrained unit commitment with high wind penetration. J Mod Power Syst Clean Energy 2017;5:337–49. doi:10.1007/s40565-017-0277-0.

[10] Hanley ES, Deane JP, Gallachóir BPÓ. The role of hydrogen in low carbon energy futures–A review of existing perspectives. Renew Sustain Energy Rev 2018;82:3027–45. doi:10.1016/j.rser.2017.10.034.

[11] Carmo M, Fritz DL, Mergel J, Stolten D. A comprehensive review on PEM water electrolysis. Int J Hydrogen Energy 2013;38:4901–34. doi:10.1016/j.ijhydene.2013.01.151.

[12] Winkler-Goldstein R, Rastetter A. Power to gas: The Final Breakthrough for the

Hydrogen Economy? Green 2013;3:69–78. doi:10.1515/green-2013-0001.

[13] Gandía LM, Oroz R, Ursúa A, Sanchis P, Diéguez PM. Renewable Hydrogen Production: Performance of an Alkaline Water Electrolyzer Working under Emulated Wind Conditions. Energy & Fuels 2007;21:1699–706. doi:10.1021/ef060491u.

[14] Yáñez M, Ortiz A, Brunaud B, Grossmann IE, Ortiz I. Contribution of upcycling surplus hydrogen to design a sustainable supply chain: The case study of Northern Spain. Appl Energy 2018;231:777–87. doi:10.1016/j.apenergy.2018.09.047.

[15] Sharaf OZ, Orhan MF. An overview of fuel cell technology: Fundamentals and applications. Renew Sustain Energy Rev 2014;32:810–53. doi:10.1016/j.rser.2014.01.012.

[16] Verhelst S. Recent progress in the use of hydrogen as a fuel for internal combustion engines. Int J Hydrogen Energy 2014;39:1071–85. doi:10.1016/j.ijhydene.2013.10.102.

[17] Ruhnau O, Bannik S, Otten S, Praktiknjo A, Robinius M. Direct or indirect electrification? A review of heat generation and road transport decarbonisation scenarios for Germany 2050. Energy 2019;166:989–99. doi:10.1016/j.energy.2018.10.114.

[18] Rose PK, Neumann F. Hydrogen refueling station networks for heavy-duty vehicles in future power systems. Transp Res Part D Transp Environ 2020;83:102358. doi:10.1016/j.trd.2020.102358.

[19] Remus R, Roudier S, Aguado Monsonet M a., Sancho LD. Best Available Techniques (BAT) Reference Document for Iron and Steel Production. vol. BREF-IS. 2013. doi:10.2791/97469.

[20] Otto A, Robinius M, Grube T, Schiebahn S, Praktiknjo A, Stolten D. Power-to-steel: Reducing CO2 through the integration of renewable energy and hydrogen into the German steel industry. Energies 2017;10. doi:10.3390/en10040451.

[21] Dodds PE, Demoullin S. Conversion of the UK gas system to transport hydrogen. Int J Hydrogen Energy 2013;38:7189–200.

doi:10.1016/j.ijhydene.2013.03.070.

[22] Nastasi B, Lo Basso G. Hydrogen to link heat and electricity in the transition towards future Smart Energy Systems. Energy 2016;110:5–22. doi:10.1016/j.energy.2016.03.097.

[23] Sherif SA, Barbir F, Veziroglu TN. Wind energy and the hydrogen economy-review of the technology. Sol Energy 2005;78:647–60. doi:10.1016/j.solener.2005.01.002.

[24] Grüger F, Hoch O, Hartmann J, Robinius M, Stolten D. Optimized electrolyzer operation: Employing forecasts of wind energy availability, hydrogen demand, and electricity prices. Int J Hydrogen Energy 2019;4:4387–97. doi:10.1016/j.ijhydene.2018.07.165.

[25] Robinius M, Otto A, Heuser P, Welder L, Syranidis K, Ryberg DS, et al. Linking the power and transport sectors - Part 1: The principle of sector coupling. Energies 2017;10. doi:10.3390/en10070956.

[26] Simón J. HyUnder - Assessment of the potential, the actors and relevant business cases for large scale and seasonal storage of renewable electricity by hydrogen underground storage in Europe 2015. http://hyunder.eu/ (accessed March 6, 2020).

[27] Steward D, Saur G, Penev M, Ramsden T. Lifecycle Cost Analysis of Hydrogen Versus Other Technologies for Electrical Energy Storage. 2009.

[28] Clegg S, Mancarella P. Storing renewables in the gas network: Modelling of power-to-gas seasonal storage flexibility in low-carbon power systems. IET Gener Transm Distrib 2016;10:566–75. doi:10.1049/iet-gtd.2015.0439.

[29] Sherif SA, Barbir F, Veziroglu TN. Towards a hydrogen economy. Electr J 2005;18:62–76. doi:10.1016/j.tej.2005.06.003.

[30] First liquid hydrogen carrier. Mot 2014. https://www.motorship.com/news101/ships-and-shipyards/first-liquid-hydrogen-carrier (accessed December 3, 2019).

[31] Liquefied Hydrogen Bunker Vessel Designed. Marit Exec 2019. https://www.maritime-executive.com/article/liquefied-hydrogen-bunker-vessel-

designed (accessed December 3, 2019).

[32] Child M, Kemfert C, Bogdanov D, Breyer C. Flexible electricity generation, grid exchange and storage for the transition to a 100% renewable energy system in Europe. Renew Energy 2019;139:80–101. doi:10.1016/j.renene.2019.02.077.

[33] Schlachtberger DP, Brown T, Schramm S, Greiner M. The benefits of cooperation in a highly renewable European electricity network. Energy 2017;134:469–81. doi:10.1016/j.energy.2017.06.004.

[34] Schlachtberger DP, Brown T, Schäfer M, Schramm S, Greiner M. Cost optimal scenarios of a future highly renewable European electricity system: Exploring the influence of weather data, cost parameters and policy constraints. Energy 2018;163:100–14. doi:10.1016/j.energy.2018.08.070.

[35] Rodriguez RA, Becker S, Greiner M. Cost-optimal design of a simplified, highly renewable pan-European electricity system. Energy 2015;83:658–68. doi:10.1016/j.energy.2015.02.066.

[36] Victoria M, Zhu K, Brown T, Andresen GB, Greiner M. The role of storage technologies throughout the decarbonisation of the sector-coupled European energy system. Energy Convers Manag 2019;201:111977. doi:10.1016/j.enconman.2019.111977.

[37] Brown T, Schlachtberger D, Kies A, Schramm S, Greiner M. Synergies of sector coupling and transmission reinforcement in a cost-optimised, highly renewable European energy system. Energy 2018;160:720–39. doi:10.1016/j.energy.2018.06.222.

[38] Cebulla F, Naegler T, Pohl M. Electrical energy storage in highly renewable European energy systems: Capacity requirements, spatial distribution, and storage dispatch. J Energy Storage 2017;14:211–23. doi:10.1016/j.est.2017.10.004.

[39] Gils HC, Scholz Y, Pregger T, Luca de Tena D, Heide D. Integrated modelling of variable renewable energy-based power supply in Europe. Energy 2017;123:173–88. doi:10.1016/j.energy.2017.01.115.

[40] Samsatli S, Staffell I, Samsatli NJ. Optimal design and operation of integrated wind-hydrogen-electricity networks for decarbonising the domestic transport

sector in Great Britain. Int J Hydrogen Energy 2016;41:447–75. doi:10.1016/j.ijhydene.2015.10.032.

[41] Welder L, Ryberg DS, Kotzur L, Grube T, Robinius M, Stolten D. Spatio-temporal optimization of a future energy system for power-to-hydrogen applications in Germany. Energy 2018;158:1130–49. doi:10.1016/j.energy.2018.05.059.

[42] Guandalini G, Robinius M, Grube T, Campanari S, Stolten D. Long-term power-to-gas potential from wind and solar power: A country analysis for Italy. Int J Hydrogen Energy 2017;42:13389–406. doi:10.1016/j.ijhydene.2017.03.081.

[43] Tlili O, Mansilla C, Robinius M, Syranidis K, Reuss M, Linssen J, et al. Role of electricity interconnections and impact of the geographical scale on the French potential of producing hydrogen via electricity surplus by 2035. Energy 2019;172:977–90. doi:10.1016/j.energy.2019.01.138.

[44] Caglayan DG, Heinrichs HU, Robinius M, Stolten D. Robust design of a future 100% renewable european energy supply system with hydrogen infrastructure. Int J Hydrogen Energy 2021. doi:10.1016/j.ijhydene.2020.12.197.

[45] Bruninx K, Orlic D, Couckuyt D, Grisey N, Betraoui B, Anderski T, et al. e-Highway 2050. D 2.1 Data sets of scenarios for 2050. 2015.

[46] Caglayan DG, Weber N, Heinrichs HU, Linßen J, Robinius M, Kukla PA, et al. Technical potential of salt caverns for hydrogen storage in Europe. Int J Hydrogen Energy 2020;45:6793–805. doi:10.1016/j.ijhydene.2019.12.161.

[47] Smith TWP, Jalkanen JP, Anderson BA, Corbett JJ, Faber J, Hanayama S, et al. Third IMO Greenhouse Gas Study 2014. London: 2014. doi:10.1007/s10584-013-0912-3.

[48] Nations U. The Paris Agreement. 2015.

[49] UNCTAD. Review of Maritime Transport 2019. New York: 2019.

[50] Corbett JJ, Winebrake JJ, Green EH, Kasibhatla P, Eyring V, Lauer A. Mortality from ship emissions: A global assessment. Environ Sci Technol 2007;41:8512–8. doi:10.1021/es071686z.

[51] Liu J, Duru O, Law AWK. Assessment of atmospheric pollutant emissions with

maritime energy strategies using bayesian simulations and time series forecasting. Environ Pollut 2021;270:116068. doi:10.1016/j.envpol.2020.116068.

[52] Trillos JCG, Wilken D, Brand U, Vogt T. Life cycle assessment of a hydrogen and fuel cell ropax ferry prototype. Sustain Prod Life Cycle Eng Manag 2021:5–23. doi:10.1007/978-3-030-50519-6_2.

[53] Perčić M, Vladimir N, Fan A. Life-cycle cost assessment of alternative marine fuels to reduce the carbon footprint in short-sea shipping: A case study of Croatia. Appl Energy 2020;279. doi:10.1016/j.apenergy.2020.115848.

[54] Pratt JW, Klebanoff LE. Feasibility of the SF-BREEZE: a Zero-Emission, Hydrogen Fuel Cell, High-Speed Passenger Ferry. 2016.

[55] Fuel cell technology in ships (FCSHIP) 2004. https://cordis.europa.eu/project/id/G3RD-CT-2002-00823 (accessed February 24, 2021).

[56] Tronstad T, Hogmoen Astrand H, Petra Haugom G, Lagnfeldt L. Study on the Use of Fuel Cells in Shipping. 2017.

[57] De-Troya JJ, Álvarez C, Fernández-Garrido C, Carral L. Analysing the possibilities of using fuel cells in ships. Int J Hydrogen Energy 2016;41:2853–66. doi:10.1016/j.ijhydene.2015.11.145.

[58] Rivarolo M, Rattazzi D, Lamberti T, Magistri L. Clean energy production by PEM fuel cells on tourist ships: A time-dependent analysis. Int J Hydrogen Energy 2020;45:25747–57. doi:10.1016/j.ijhydene.2019.12.086.

[59] GEV, Ballard Developing Hydrogen Fuel Cell-Powered n.d. https://www.marinelink.com/news/gev-ballard-developing-hydrogen-fuel-485145 (accessed February 24, 2021).

[60] Sembler WJ, Kumar S, Palmer D. Fuel cells as an alternative to cold ironing. J Fuel Cell Sci Technol 2009;6:0310091–03100911. doi:10.1115/1.3006305.

[61] Yuan Y, Wang J, Yan X, Shen B, Long T. A review of multi-energy hybrid power system for ships. Renew Sustain Energy Rev 2020;132:15. doi:10.1016/j.rser.2020.110081.

[62] Roh G, Kim H, Jeon H, Yoon K. Fuel Consumption and CO2 Emission Reductions of Ships Powered by a Fuel-Cell-Based Hybrid Power Source. J Mar Sci Eng 2019;7:230. doi:10.3390/jmse7070230.

[63] Hornblower Hybrid: The World's First Hydrogen Hybrid Ferry n.d. https://www.marineinsight.com/future-shipping/hornblower-hybrid-the-worlds-first-hydrogen-hybrid-ferry/ (accessed February 24, 2021).

[64] NYK Steps into the Future with Super Eco Ship 2050. World Marit News 2018. https://worldmaritimenews.com/archives/264771/nyk-steps-into-the-future-with-super-eco-ship-2050/ (accessed December 13, 2019).

[65] Eyring V, Isaksen ISA, Berntsen T, Collins WJ, Corbett JJ, Endresen O, et al. Transport impacts on atmosphere and climate: Shipping. Atmos Environ 2010;44:4735–71. doi:10.1016/j.atmosenv.2009.04.059.

[66] Buhaug Ø, Corbett JJ, Endresen O, Eyring V, Faber J, Hanayama S, et al. Second IMO GHG Study 2009. 2009.

[67] Ortiz A. HYLANTIC - Atlantic Network for Renewable Generation and Supply of Hydrogen to promote High Energy Efficiency 2018. http://hylantic.com/ (accessed February 24, 2020).

[68] Pang E. HySeas III - Realising the world's first sea-going hydrogen-powered RoPax ferry and a business model for European islands 2019. https://www.hyseas3.eu/the-project/ (accessed February 24, 2020).

[69] Arguedas Ortiz D. How hydrogen is transforming these tiny Scottish islands. BBC Futur 2019. https://www.bbc.com/future/article/20190327-the-tiny-islands-leading-the-way-in-hydrogen-power (accessed February 24, 2020).

[70] Mikkola J. FLAGSHIPS - Clean waterborne transport in Europe 2019. https://flagships.eu/ (accessed March 6, 2020).

[71] Singh J. Auriga Energy - Developing efficient hydrogen fuel cell products and solutions. Auriga Energy 2019. http://www.auriga-energy.com/ (accessed February 24, 2020).

[72] Nemo H2: The First Ecofriendly Electrical Boat | Join the EcoLuxury Revolution! n.d. https://ecoluxuryrevolution.wordpress.com/2009/12/19/nemo-

h2-the-first-ecofriendly-electrical-boat/ (accessed February 24, 2021).

[73] Erussard V, Delafosse J. Energy Observer. Energy Obs 2019. http://www.energy-observer.org/en/#hydrogene (accessed December 13, 2019).

[74] Eurostat Database. Your key to European statistics. Eur Comm n.d. https://ec.europa.eu/eurostat/data/database (accessed November 25, 2019).

[75] Welder L, Heinrichs H, Linßen J, Robinius M, Stolten D. FINE - Framework for Integrated Energy System Assessment. GitHub 2018. https://github.com/FZJ-IEK3-VSA/FINE (accessed February 24, 2020).

[76] Ryberg DS, Caglayan DG, Schmitt S, Linßen J, Stolten D, Robinius M. The future of European onshore wind energy potential: Detailed distribution and simulation of advanced turbine designs. Energy 2019;182:1222–38. doi:10.1016/j.energy.2019.06.052.

[77] Caglayan DG, Ryberg DS, Heinrichs H, Linßen J, Stolten D, Robinius M. The techno-economic potential of offshore wind energy with optimized future turbine designs in Europe. Appl Energy 2019;255:113794. doi:10.1016/j.apenergy.2019.113794.

[78] Gelaro R, McCarty W, Suárez MJ, Todling R, Molod A, Takacs L, et al. The Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2). J Clim 2017;30:5419–54. doi:10.1175/JCLI-D-16-0758.1.

[79] Ryberg DS, Caglayan DG, Schmitt S, Linssen J, Stolten D, Robinius M. RESKit - Renewable Energy Simulation toolkit for Python. GitHub Repos 2019. https://github.com/FZJ-IEK3-VSA/RESKit (accessed August 21, 2020).

[80] Vincent I, Bessarabov D. Low cost hydrogen production by anion exchange membrane electrolysis: A review. Renew Sustain Energy Rev 2018;81:1690–704. doi:10.1016/j.rser.2017.05.258.

[81] Javed MS, Zhong D, Ma T, Song A, Ahmed S. Hybrid pumped hydro and battery storage for renewable energy based power supply system. Appl Energy 2020;257:114026. doi:10.1016/j.apenergy.2019.114026.

[82] Crotogino F, Donadei S, Bünger U, Landinger H. Large-Scale Hydrogen

Underground Storage for Securing Future Energy Supplies. 18th World Hydrog. Energy Conf. 2010 - WHEC 2010, vol. 78, Essen: 2010, p. 37–45. doi:10.1109/INTMAG.2015.7157557.

[83] Reuß M, Grube T, Robinius M, Preuster P, Wasserscheid P, Stolten D. Seasonal storage and alternative carriers: A flexible hydrogen supply chain model. Appl Energy 2017;200:290–302. doi:10.1016/j.apenergy.2017.05.050.

[84] Reuß M, Welder L, Thürauf J, Linßen J, Grube T, Schewe L, et al. Modeling hydrogen networks for future energy systems: A comparison of linear and nonlinear approaches. Int J Hydrogen Energy 2019;44:32136–50. doi:10.1016/j.ijhydene.2019.10.080.

[85] Fuel Cells and Hydrogen Joint Undertaking. A portfolio of power-trains for Europe: a fact-based analysis. The role of Battery Electric Vehicles, Plug-in Hybrids and Fuel Cell Electric Vehicles. 2010.

[86] Khalili, Rantanen, Bogdanov, Breyer. Global Transportation Demand Development with Impacts on the Energy Demand and Greenhouse Gas Emissions in a Climate-Constrained World. Energies 2019;12:3870. doi:10.3390/en12203870.

[87] Rivarolo M, Rattazzi D, Magistri L. Best operative strategy for energy management of a cruise ship employing different distributed generation technologies. Int J Hydrogen Energy 2018;43:23500–10. doi:10.1016/j.ijhydene.2018.10.217.

[88] Baldi F, Ahlgren F, Nguyen T-V, Thern M, Andersson K. Energy and exergy analysis of a cruise ship. Energies 2018;11:1–41. doi:10.3390/en11102508.

[89] MariGreen - Perspectives for the Use of Hydrogen as Fuel in Inland Shipping. A Feasibility Study. 2018.

[90] ITF. Decarbonising Maritime Transport. Patways to zero-carbon shipping by 2035. 2018.

[91] Lloyd’s Register, UMAS. Zero-Emission Vessels 2030. How do we get there? 2017.

[92] Samadi S, Lechtenböhmer S, Schneider C, Arnold K, Fischedick M, Schüwer

D, et al. Decarbonization Pathways for the Industrial Cluster of the Port of Rotterdam. 2016.

[93] Smith T, Raucci C, Hosseinloo SH, Rojon I, Calleya J, Fuente SD La, et al. CO2 Emissions from International Shipping: Possible reduction targets and their associated pathways. vol. October. 2016. doi:10.1002/yd.20075.

[94] Abbasov F, Earl T, Calvo Ambel C, Hemmings B, Gilliam L. Roadmap to decarbonising European shipping. Transp Environ Rep 2018:22.

[95] Marine Traffic 2020. www.marinetraffic.com (accessed May 11, 2020).

[96] Eyring V, Isaksen ISA, Berntsen T, Collins WJ, Corbett JJ, Endresen O, et al. Transport impacts on atmosphere and climate: Shipping. Atmos Environ 2010;44:4735–71. doi:10.1016/j.atmosenv.2009.04.059.

[97] Stull RB. An Introduction to Boundary Layer Meteorology. vol. 13. Dordrecht: Springer Netherlands; 1988. doi:10.1007/978-94-009-3027-8.

Highlights

- Impact of electrical and hydrogen demand of ships on the Atlantic coast of Europe
- Cost-optimal energy system with a 100% renewable energy European scenario in 2050
- Ireland has a key role as hydrogen supplier with onshore turbines and electrolyzers
- H_2 from Ireland and United Kingdom supplied to continental Europe through pipelines
- Salt caverns reinforced to balance the energy system with higher hydrogen demand

Author Contributions

Rafael Ortiz-Imedio: Conceptualization, Investigation, Formal analysis, Writing – Original Draft, Visualization

Dilara Caglayan: Conceptualization, Methodology, Software, Validation, Investigation, Writing – Review & Editing, Visualization

Alfredo Ortiz: Conceptualization, Resources, Writing – Review & Editing, Project administration, Funding acquisition

Heidi Heinrichs: Conceptualization, Methodology, Writing – Review & Editing, Supervision

Martin Robinius: Resources, Writing – Review & Editing, Supervision, Project administration

Detlef Stolten: Supervision, Funding acquisition

Inmaculada Ortiz: Conceptualization, Writing – Review & Editing, Supervision, Project administration, Funding acquisition

Declaration of interests

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

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: