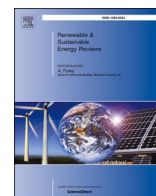


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A diffusion model approach to forecast multi-sector demand growth for green hydrogen generated from offshore wind power

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ABSTRACT

Green hydrogen, generated from renewable electricity, offers a means of decarbonising energy demand currently met by liquid and gaseous fossil fuels. However, this will require the roll-out of new technologies in diverse and distributed energy demand sectors. Therefore, the growth of hydrogen demand will depend on the rate of technological uptake in each sector. A bottom-up analytical method based on the Bass diffusion model is used to predict future hydrogen demand from the industrial, transport, power generation, and residential sectors. This is coupled with a dynamic model of green hydrogen supply based on offshore wind energy. Three scenarios for hydrogen demand in Ireland are developed and analysed as a case study. By 2050, Ireland's annual hydrogen demand is projected to reach approximately 500,000 tonnes, 950,000 tonnes, and 1,480,000 tonnes under low, medium, and high demand scenarios, respectively. To meet this demand solely through offshore wind-powered electrolysis, respective wind capacities of 5.2 GW, 9.8 GW, and 15.2 GW would be required. Future hydrogen demand is expected to mainly come from industry and zero-carbon power generation. The levelised cost of hydrogen will decline significantly as the first 500 MW of wind capacity is installed, driven by increased production scale. A sharp increase in hydrogen demand is predicted after 2030, highlighting the importance of timely infrastructure development and supportive policy frameworks. This approach highlights the gap between policy ambitions and the pace of technology diffusion, showing the potential to develop new large-scale demand sectors such as production of ammonia and sustainable aviation fuel.

Abbreviations

A	Wind turbine rotor swept area
BEV	Battery electric vehicle
Car_{FC}	Number of fuel cell private cars
$COWF_{his}$, $COWF_{2030}$	Cumulative capacity of offshore wind farm in year his , and in 2030, respectively
C_p	Power coefficient
DRI	Direct reduced iron
E_{EL} , E_{hps}	Energy used by the electrolyser and by the other parts of the plant, respectively, to produce 1 kg of hydrogen.
E_H^{res} , E_H^{pg}	Energy demand in form of hydrogen in residential, and in power generation sectors, respectively
ϵ_{con}	Energy conversion efficiency
FC	Fuel cell
H_{ref} , H_{SAF} , H_{tran} , H_{res} , H_{pg}	Hydrogen demand in oil refining, SAF, transport, residential, and power generation sectors, respectively

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(continued)

H_d , H_g , H_k , H_f , H_l	Hydrogen demand for diesel, gasoline, kerosene, fuel oil and liquefied petroleum gas (LPG) production, respectively
HCV_{FC}	Number of fuel cell heavy commercial vehicles (HCV)
LCV_{FC}	Number of fuel cell light commercial vehicles (LCV)
L_r	Learning rate
LCOH	Levelised cost of hydrogen production
NZE	Net Zero Emissions (by 2050)
n_{tur}	Number of turbines
O_d , O_g , O_k , O_f , O_l	Output of diesel, gasoline, kerosene, fuel oil and LPG, respectively (unit: tonne)
OWF	Offshore wind farm
P_{rate}	Power rate of turbine
PM_{tt}	Potential market for all types of engines
SAF	Sustainable Aviation Fuel
U_d , U_g , U_k , U_f , U_l	Unit hydrogen consumption per tonne of diesel, gasoline, kerosene, fuel oil and LPG, respectively (unit: kg/tonne)

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(continued)

$U_{car}, U_{LCV}, U_{HCV}$	Annual hydrogen consumption per vehicle (private car, LCV, HCV)
ρ_H^E	Energy density of hydrogen (unit: MJ/kg)
ρ_{air}	Density of air (unit: kg/m ³)
V	Wind speed (unit: m/s)
$V_{cut-in}, V_{rate}, V_{cut-out}$	Cut-in, rated, and cut-out wind speeds of turbine, respectively (unit: m/s)
$wake_{loss}$	Energy loss due to wake effects (unit: %)

1. Introduction

Hydrogen is increasingly recognised as a versatile energy carrier with potential applications across various sectors. With its advantages of flexibility and storage capacity, hydrogen has the potential to serve multiple energy demand sectors, ranging from highly distributed end users to large energy users. Green hydrogen, produced from renewable resources, is an energy carrier with zero direct carbon emissions [1]. Given these characteristics, green hydrogen plays an essential role in the global energy transition, particularly in the decarbonisation of key sectors such as transportation, industry, power generation, and residential heating. Several countries have implemented policies to encourage the use of hydrogen on a commercial scale [2].

Under the net zero-emissions scenario developed by the International Energy Agency (IEA) [3], the global demand for hydrogen will be more than 500 million tonnes (Mt) in 2050. The applications of low-carbon hydrogen are forecasted to expand in many fields rapidly after 2030. The proportion of low-carbon hydrogen in total hydrogen production will increase from the recent level of 5 %–10 % [3,4] to 98.5 % in 2050 [3], where the majority of low-carbon hydrogen will come from water electrolysis powered by renewable energy. The three sectors that are expected to use 94 % of total hydrogen consumption in 2050 are transport, industry and electricity generation [3].

In the transport sector, besides battery electric vehicles (BEVs), fuel cell (FC) electric vehicles are emerging as another option to replace conventional vehicles using fossil fuels [5]. Compared to conventional vehicles, FC vehicles release between 31 % and 80 % fewer greenhouse gases and consume between 29 % and 66 % less energy [6]. FC vehicles use hydrogen as a fuel and oxygen from the air to generate electricity and only release heat and water. The main advantages of FC vehicles over BEVs are that they have shorter refuelling times than battery charging and are lighter than BEVs for the same driving range [6]. Shemin et al. [7] investigated the performance of the FC and battery-powered powertrains used in buses and light-duty vehicles. The results showed that the battery is the best option for light-duty vehicles. However, FC can compete if production costs are reduced and more hydrogen fuelling stations are installed. In addition, FC is also identified as the optimal choice for buses and trucks where battery BEVs may not be practical due to weight and range limitations. Today, there are many different types of fuel cell technology. Each technology offers unique advantages that enable fuel cells to be used in a wide range of applications [8]. Mekhilef et al. [9] compared different fuel cell technologies and found that although PEM FC has lower efficiency than Alkaline FC, with its advantages, PEM FC is still commonly used in manufacturing FC vehicles. The European hydrogen industry has developed a roadmap for the future use of hydrogen [10]. In the European roadmap report, the target of the transport sector for 2030 is 45,000 fuel cell (FC) trucks and buses, 500,000 FC light commercial vehicles (LCV), 3.7 million FC private cars and around 570 FC trains. According to the Hydrogen Council [11], the number of hydrogen refuelling stations operating worldwide is more than 1100, and about 70 % of them are installed in the Asia-Pacific region and about 22 % are installed in the Europe and Middle East region. To expand the FCEV market, in addition to infrastructure deployment, automakers also face major challenges related to hydrogen production, distribution, and storage [12]. Hydrogen can be used directly as a clean fuel or as a feedstock to produce hydrogen-based fuels

such as methanol, ammonia, and sustainable aviation fuels (SAF), offering a promising solution for decarbonising shipping, rail, and aviation. To fully realise the potential of hydrogen and overcome existing challenges, it is essential to continue research into their technological, economic, policy, and other relevant aspects within the transport sector.

One of the biggest sources of greenhouse gas emissions comes from the industrial sector. Currently, more than 99 % of hydrogen demand comes from traditional industrial applications, including ammonia and methanol production, oil refining, and the direct reduced iron (DRI) process in steelmaking [13]. In the oil refining industry, hydrogen can be used in various processes. For example, in the hydro-desulphurisation process, hydrogen removes sulphur and nitrogen by converting them into hydrogen sulphide (H₂S) and ammonia (NH₃) [14]. The traditional source of hydrogen used in a refinery is typically produced through steam reforming of natural gas. According to global hydrogen review report published by IEA, about 33.4 % of global hydrogen was used to produce ammonia in 2023 [13]. Besides its applications in industry, ammonia has the potential for long-distance hydrogen transportation [15]. Currently, ammonia is synthesised mainly through the Haber-Bosch process [16]. Nitrogen from air separators and green hydrogen from electrolyzers are synthesised into ammonia [16]. Cui and Aziz analysed the techno-economic aspects of hydrogen transportation in the form of methanol and ammonia [17]. According to the results, the transportation cost of hydrogen in the form of ammonia was lower than for methanol [17]. The research considered eight systems: four with hydrogen at end-users, two with methanol at end-users, and two with ammonia at end-users. In the case of ammonia used by the end-user, the levelised cost of energy transmission was the lowest at \$10.1/GJ [17]. Negro et al. [18] discussed the challenges and opportunities of using ammonia as means of hydrogen storage and transport. The research examined various aspects, such as technical feasibility, economic viability, and environmental impacts [18]. The research also highlighted the potential benefits of utilising ammonia directly in applications [18]. Recently, Shahabuddin et al. [19] investigated the challenges and techno-economics of integrating hydrogen into the steelmaking process. By using an electric arc furnace and hydrogen in the DRI process, it represents a cleaner alternative to traditional coal-based steelmaking and can cut off up to 95 % of CO₂ emissions. The transition to hydrogen-based steelmaking depends largely on the competitiveness of green hydrogen cost, which is currently too expensive, but the integration of hydrogen is expected to become viable as its cost falls below \$2.0/kg. Green hydrogen, when used as a feedstock, can support industrial decarbonisation in two main ways [20]. First, its production can be made low-carbon by using renewable electricity for electrolyzers. Second, it can replace carbon delivered from fossil resources as a reducing agent in steelmaking and serve as an alternative feedstock in the chemical industry by combining hydrogen with captured CO₂, thus significantly reducing emissions from fossil fuel feedstock. Therefore, green hydrogen holds significant potential to transform the industrial sector by decarbonising across various industry processes, paving the way for a more sustainable and low-carbon future.

In the context of increasing the ratio of renewable energy sources (RES) in the power system, their variability creates challenges for grid stability, highlighting the need for suitable energy storage solutions [21]. Hydrogen is increasingly being recognised as an important component in the power systems. Ge et al. [22] conducted a comprehensive review about the role of hydrogen in modern power systems. One of the key characteristics of hydrogen in power systems is its long-duration energy storage, helping to balance supply and demand [22]. Hydrogen also plays a key role on the source side by reducing wind and solar curtailment and stabilising the fluctuations of renewable energy sources. By producing hydrogen from excess wind and solar energy and storing it for later use, power systems can improve economic efficiency, enhance grid stability, and enable better integration of renewables [22]. On the grid side, hydrogen can serve several functions, such as energy storage for peak load management, adjusting frequency and

voltage, and congestion relief [23]. Hydrogen can be used in standalone power systems in off-grid or remote areas because of its long-term storage capability with cost-effectiveness, providing a clean and reliable energy source where grid connection is not possible [24]. The study by Viteri et al. [25] offers a comprehensive assessment of green hydrogen technologies in off-grid systems, highlighting both their potential and limitations. Currently, studies investigating the techno-economics of on-grid and off-grid systems integrated with hydrogen are also being carried out [26,27]. Overall, hydrogen stands out as a potential solution for contributing to supporting a more stable, efficient, and decarbonised power system and unlocking the full potential of clean energy systems.

In addition, hydrogen also can be a solution to decarbonise the residential and building sectors, particularly in heating, electricity, and energy storage. However, the high cost of heating from hydrogen technologies in comparison to alternative options like heat pumps will have a significant impact on its role in building energy systems [28]. Low efficiency is a major drawback of using green hydrogen for heating in comparison to heat pumps [28]. Hydrogen could be blended into existing natural gas networks, with blend levels of 20 % achievable, however it has been cautioned that hydrogen blending represents a suboptimal use of this valuable energy carrier, especially while production is ramping up and there is likely to be significant demand from large energy users [29]. Additionally, hydrogen has the potential to be used as seasonal storage, which is especially advantageous in colder climates where seasonal energy storage is very important due to high winter heating demand. In general, heat pumps are likely to remain the preferred heating solution for buildings due to their high efficiency and green hydrogen is likely to be utilised in buildings only in specific regions with low hydrogen price [28].

Ireland has set targets for future emissions reduction, and the government plans to halve emissions by 2030 and achieve net zero by 2050, [30,31]. Renewable gases have been identified as necessary in supporting emission reductions in various sectors to achieve that national target. Martins et al. [32] recently published research assessing the potential role of green hydrogen for emissions reduction strategies in Ireland. According to the study, Ireland can quickly and effectively decarbonise with the help of green hydrogen. Besides current industrial applications, the study also recommended promoting the expansion of hydrogen applications in the transport, heat, and power sectors, focusing on energy storage and heavy transport areas. A techno-economic evaluation study was also carried out for FC buses used in Irish cities [33]. The study estimated the total annual hydrogen required for FC bus operation in six cities to be about 13.7 kilo tonnes. Besides application studies, green hydrogen production in Ireland has also been explored. The operation of electrolyzers combined with wind-generated electricity was studied by Gunawan et al. [34]. Gunawan et al. showed that in order to achieve the lowest levelised cost of hydrogen (LCOH); the electrolyser must be operated at full capacity. They also pointed out that using curtailed electricity is not economically viable.

Ishaq et al. [35] conducted a research review of hydrogen production methods in order to provide an overview of hydrogen production. Green hydrogen is produced using electricity from renewable energy sources to electrolyse water and is therefore a zero carbon emissions process [36]. There have been investigations of the possibilities of producing hydrogen using solar [37,38], biomass [39,40], and wind [41,42] power sources. The possibility of hydrogen production from offshore wind energy is receiving significant attention, as the global installed capacity of offshore wind is expected to increase in the coming decades [43]. This may result in further significant cost reductions. Calado et al. [44] reviewed the current technologies and models viable for producing hydrogen from offshore wind farms (OWFs). The study discussed the advantages of two hydrogen production models corresponding to two electrolyser locations (offshore and onshore). The small losses of hydrogen by pipeline transmission is the main advantage of the offshore

electrolyser model, while flexibility is the main advantage of the electrolyser onshore.

The only currently-feasible options for long-term bulk storage of renewable energy are green hydrogen or derived fuels. Dinh et al. [45] developed an analytical model to evaluate using the total electricity output from an OWF to produce hydrogen. The study evaluated the economics of different underground hydrogen storage capacities. Research results suggest that a storage facility sufficient for a short storage period (2–7 days) should be preferred because of its low investment cost. Song et al. [46] evaluated the potential for hydrogen production using offshore wind energy in China and investigated the potential for exporting hydrogen to the Japanese market. Three vectors of hydrogen transport (ammonia, methylcyclohexane, and liquid hydrogen) were economically assessed. The study defined that the methylcyclohexane mechanism with a levelised cost of hydrogen for delivery is 2 €/kg, which is more economical than ammonia (2.3 €/kg) and liquid hydrogen (3.0 €/kg) transport methods by 2030. In addition, the study also identified potential hydrogen production areas based on a map of levelised cost of hydrogen. Lucas et al. [47] proposed a hydrogen production concept using electricity from a floating wind farm called Windfloat Atlantic. The research initially described the critical technologies for a project that uses wind energy to produce hydrogen. Following that, the research conducted an economic analysis of two case studies for hydrogen generation from a 25.2 MW wind farm based on 2019 costs and a large-scale 150 MW wind farm in 2050. In these case studies, hydrogen was assumed to be transmitted through a pipeline system. The study predicted a decrease in LCOH by 2050 of c. 50 %, the exact reduction depending on the cost of electricity.

Large-scale production of green hydrogen is currently in an early stage of development. It is therefore necessary to study the projected growth of both hydrogen demand and supply in order to properly plan for this development. Huang et al. [2] developed a system dynamics model to forecast China's hydrogen demand. In that model, hydrogen demand comes from three sectors: transportation, the ammonia industry and the petroleum industry. Ma et al. [48] studied a system dynamics model that integrates parameters of each sector (energy consumption intensity, hydrogen share of energy consumption, and the percentage of total GDP) to estimate hydrogen demand in China. Hydrogen demand in Australia and global demand were forecasted for 2021–2050 by combining dynamics and thinking systems [49]. The study of Yusaf et al. [49] assumed hydrogen growth scenarios based on historic global hydrogen demand data (historical values from 1990 to 2019). Korea is currently one of the leading markets in the use of hydrogen in the transport sector and several studies [50,51] have been carried out to forecast the future hydrogen demand for this market. In Germany, hydrogen demand in the industrial sector has been studied [52]. The required total annual hydrogen demand for the energy intensive industries in Germany is 326 TWh. The annual demand for hydrogen could range between 482 and 534 TWh if non-energy-intensive industries are taken into account. However, market studies have focused only on predicting future hydrogen demand without considering any hydrogen supplies.

The literature to date shows that the studies on modelling the hydrogen market, including demand and production, are still few and often focused on one particular aspect or demand sector. In addition, most studies consider a specific market or production technology. Therefore, a hydrogen market model including distributed demand and supply components is developed in this paper. The model is built in a modular structure, therefore it is convenient to adapt to different markets and supply sources. The modelling approach is bottom-up, which reflects real-life trajectories of uptake of new distributed technologies. This is an important contrast to other techno-economic modelling studies which take a top-down approach, starting with government-mandated decarbonisation targets and use mathematical optimisation methods to identify feasible solutions. The market model is applied to several distributed energy use sectors within the Irish market. Hydrogen

production is from offshore wind in order to provide insight into future green hydrogen supply and demand in Ireland. The model developed in this paper is used to answer the following three research questions: How large will hydrogen demand be in Ireland from distributed end use sectors? How much dedicated offshore wind capacity will be required to serve distributed green hydrogen demand in the Irish market? And how does the value of the levelised cost of hydrogen change over time from 2030 to 2050?

2. Literature review

Understanding the market for products is important for planning the development strategy of those products. Research on market models in the energy sector is being carried out in various aspects.

2.1. Examples from liquid fuel markets

Oil is a globally traded fuel with important markets in North America, Europe, Asia, and the Middle East. Understanding the characteristics of the oil market is critical for making informed decisions in the energy and related sectors. Kilian and Lee [53] looked into how crude oil inventories affect global market prices. To estimate the price of oil, the authors developed statistical tools based on the historical real price of oil. According to the findings, in the middle of 2008, speculative demand drove up the oil price in the market. Their results also demonstrated the impact of inventories on the oil market between 2003 and 2012. Dées et al. [54] modelled the global oil market using an econometric model. The model structure included three components: prices, supply, and demand. The model performed well, with projections closely matching historical data from 1995 to 2000. The model could project prices, demand, and supply variables in the global oil market. Recently, Bornstein et al. [55] used a general equilibrium model to model the global oil market. One of the research objectives was to examine the impact of fracking on the price of oil. The world output characteristics and volatility of oil prices were considered in the research. In the case of fracking, the oil price was lower by 46 %, which could increase world output by 5 % [55].

2.2. Examples from natural gas markets

Currently, natural gas plays an essential role in the energy system. Studies on the natural gas market are also being carried out. Lochner and Bothe [56] conducted a prediction of the global natural gas supply using a global gas market model. The model was used to estimate supply costs in the future in three regions: Japan, the US, and Europe. For the US market, Canada is an external gas supplier with the lowest costs [56]. Egging et al. [57] developed a natural gas market model, considering different market players. Four scenarios were created for evaluating the natural gas market in Europe. In addition, the research modelled the natural gas supply chain. Rubaszek et al. [58] used the structural vector autoregression method to model the natural gas market in the US. The effect of structural shocks on the US market was analysed in the research. The results showed that demand shock had a more significant influence on price fluctuations than other factors. Shao et al. [59] improved the classic commodity model from considering two factors to three factors. The improved model was used to analyse the natural gas market in the US. The seasonal risk was also investigated in the research. The peak and trough times of seasonal risk during the year could be obtained from the model [59]. In the Turkish market, Melikoglu used semi-empirical models to forecast natural gas demand [60], biogas generation [61], and electricity consumption [62]. A semi-empirical model was developed by combining statistical and econometric parameters [60]. Both linear and logistic models were used to predict the demand for natural gas. For forecasting the medium term, the linear model demonstrated suitability [60]. For long-term forecasting, the logistic model was suggested [60]. In Refs. [61,62], exponential empirical

models were used to forecast biogas production and electricity consumption. In Bangladesh, Wadud et al. [63] projected the natural gas demand using a dynamic econometric model. The loglinear Cobb-Douglas model was applied with three variables: price, GDP, and population. The model was applied on different levels, from national to sectoral, such as the power sector and industry [63]. Shaikh and Ji [64] developed logistic models to project the natural gas market in China. The model parameters were estimated using the Levenberg–Marquardt algorithm, which helped improve the precision of forecast results. The projected medium- and long-term demand was consistent with results from international and national organisations [64]. Suganthi and Samuel [65] reviewed various models from simple to complex methods that can be used to forecast energy demand.

2.3. Examples from electricity markets

The electricity market exhibits fluctuating characteristics and is influenced by many factors. Therefore, accurately forecasting electricity demand is a primary challenge. Forecasting demand from short-to long-term plays a necessary role in system operation and planning. Aneiros et al. [66] forecasted the electricity demand for the next day and the price change over various durations. Several regression models have been combined with data from 365 previous days to predict the electricity market in Spain. Al-Musaylh et al. [67] applied three regression models (ARIMA, SVR, and MARS) to forecast Queensland's electricity market in the short term. The four-year historical demand dataset with a 0.5-h time step was used as input for forecasting models. Regarding forecasting for 0.5 and 1 h ahead, the results indicated that MARS was the most accurate model. As for forecasting with a 24-hour horizon, the SVR model gave better results. High errors in the short-term forecasting of the ARIMA model were shown in the research [67]. Yang et al. [68] based three single models (diff-SARIMA, ANFIS and BP) to develop a novel combined forecasting model. The drawbacks of single models were overcome in a combined model. The combined model could work well with different types of data (seasonality, linearity, and non-linearity). The results of three statistical metrics confirmed the accuracy of the proposed model in the research.

Long-term demand projections are often performed for long forecast horizons, typically over a year. The usual purpose of long-term demand forecasting is to support countries' energy system planning activities. Gebremeskel et al. [69] recently used a bottom-up model (LEAP) to forecast the electricity and energy demand in Ethiopia in the long term. The research developed six scenarios for forecasting in the 2018–2050 period. Overall, electricity demand in all sectors was identified as having an increasing trend [69]. The LEAP model was also applied to the long-term forecast of the electricity market in Pakistan [70]. Three scenarios were developed based on electricity generation technologies in the Pakistani market. The demand supply situation in the electricity market from 2011 to 2030 was projected [70]. Torrini et al. [71] forecasted the demand for electricity in the Brazilian market over the 2014–2030 period. The research used a fuzzy logic model and proposed structures suitable for sectors in the market. The future demand of each subsystem was estimated by using a top-down technique [71]. Jin Oh et al. [72] developed a model to forecast electricity consumption for the cooling building sector in Singapore from 2014 to 2030. The two approaches (top-down and bottom-up) were used in the forecasting model. The bottom-up technique was used to determine the total demand for the 2002–2013 period from three different building types. In the next step, a top-down technique was used to project annual electricity demand. According to the findings, nearly one-third of total electricity could be required to cool Singapore's buildings [72].

2.4. Hydrogen markets

Due to the growing demand for clean and sustainable energy sources, hydrogen demand could grow significantly in the coming years. With

the continuous development of technology and government support, a comprehensive understanding of the green hydrogen market is necessary. Several recent studies have been conducted to forecast the future hydrogen market. Lane et al. [73] forecasted the future market share of green hydrogen production technologies. Global hydrogen demand was forecasted by using a logistic model. Gasifiers and PEM electrolyzers were two hydrogen production technologies considered in the research. Based on the findings, the technology projected to hold the majority of the market share in the early stages was biomass gasifiers [73]. A declining trend in future renewable electricity prices will push the market share of electrolyser technology in the long term [73]. Odenweller et al. [74] used the logistic diffusion model to analyse the expansion of electrolyser capacity in the future. Because the green hydrogen market is emerging, the research decided to show the volume change over time instead of the market share. The results mentioned that the electrolyser capacity targets (global, European Union) in 2024 and 2030 would not be achieved [74]. The paper suggested that policy support could foster the growth rate of electrolyser capacity [74]. Bhandari [75] projected the amount of hydrogen required in the transport and electricity sectors in Niger. Electricity, diesel, and gasoline demand were forecasted using the moving average method. The hydrogen required was estimated based on future electricity, diesel, and gasoline demand. The result indicated that to supply green hydrogen from solar energy for two sectors, Niger would use 5 % of its land area for solar farms [75]. Houghton and Cruden [76] developed and applied a forecasting model to predict hydrogen deployment in the Scottish market. Four development scenarios were created to evaluate the deployment of hydrogen. The hydrogen production in cases of centralised and decentralised models was investigated [76]. The hydrogen market is in the early stages of development but has the potential for tremendous growth in the future.

In forthcoming years, there will likely be a significant increase in demand for hydrogen, which will promote the hydrogen trade. Research on potential export markets and hydrogen transportation methods is also being studied. Hjeij et al. [77] recently conducted an investigation into the competitiveness of hydrogen exports across all countries.

Twelve experts participated in a survey and interview to quantify the competitiveness of hydrogen exports. The research considered 21 indicators in four aspects. The results listed the top 10 countries as contenders in the hydrogen economy [77]. Eicke and De Blasio developed geopolitical potential maps for three applications (steel, methanol and ammonia production) of hydrogen [78]. In all four industrial applications, the United States was predicted to become a frontrunner. Ireland was identified as a potential green hydrogen exporter [78].

In summary, the global energy market is undergoing a significant transformation driven by policy, technological innovation, and increasing climate concerns. With the integration of renewables, electricity markets are changing quickly, requiring system optimisation and flexibility. Meanwhile, hydrogen is emerging as a versatile energy carrier with the potential for long-duration storage and decarbonising energy systems. However, the development of a competitive and scalable hydrogen market depends on overcoming cost, infrastructure, and policy barriers. Projecting future hydrogen demand is crucial for guiding infrastructure development, investment decisions, and policy planning to support the transition toward a low-carbon energy system.

3. Market model

The diagram in Fig. 1 shows the structure and processes of the market model. The modular structure can be seen in the demand and supply parts. Other hydrogen applications or end uses can be easily added to the model in order to investigate new scenarios. A diffusion model is used in the demand part to estimate demand size and is described in the following subsection. Overall, the process includes three main steps.

Step 1 Forecast hydrogen demand in multiple distributed demand sectors

Firstly, the model identifies hydrogen demand across several distributed sectors: industry, transport, residential, and power generation. In Ireland's industry, the oil refining sector is currently the main

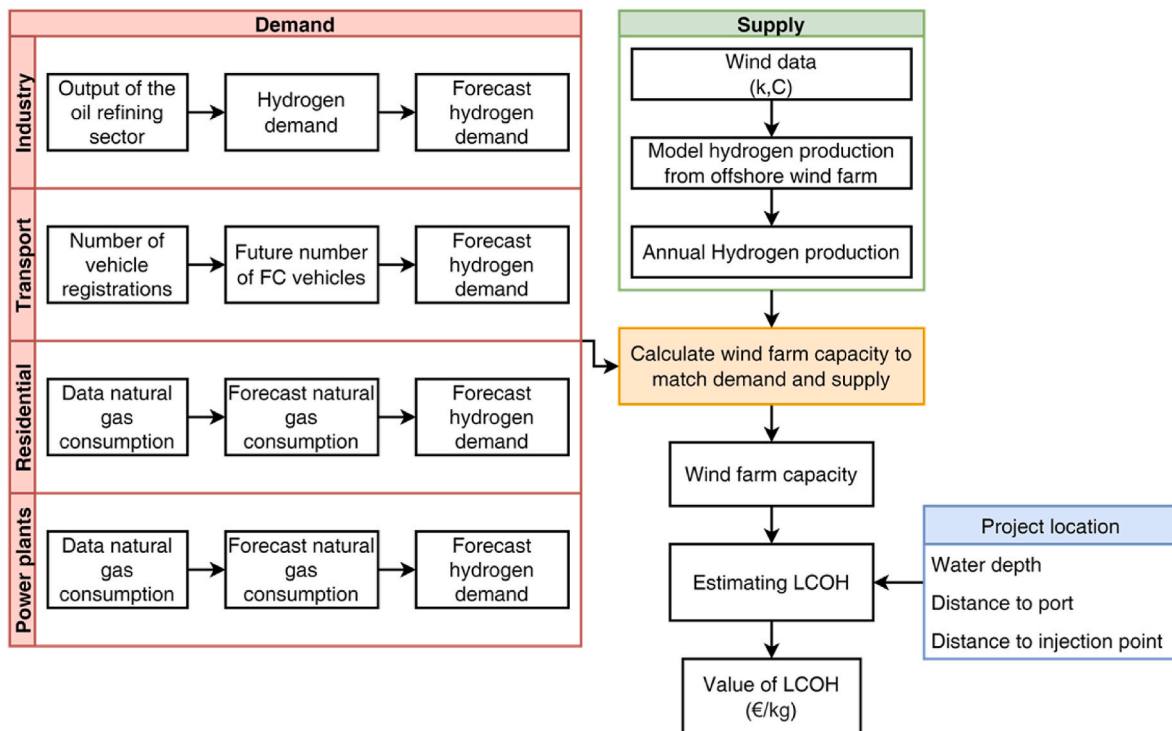


Fig. 1. Diagram of the market model for distributed hydrogen demand and production from offshore wind.

consumer of hydrogen. Hydrogen is required for the production of hydrotreated vegetable oil, a low-carbon diesel replacement. This component of industrial hydrogen demand is therefore estimated based on the output of the oil refining sector. In the future, the production of SAF is expected to be a significant application of hydrogen in the industry sector in Ireland. For the transport sector, hydrogen demand is estimated based on the annual hydrogen consumption of several FC vehicle types. In the residential sector, hydrogen can be injected into the natural gas network to provide residential heating. Hydrogen also has the potential to replace natural gas in the power generation sector to provide zero-carbon dispatchable generation during periods when wind or solar generators are not productive, as fuel cells and gas turbines for 100 % hydrogen combustion are either available or close to market [79]. Next, the market model combines several methods with assumptions to forecast future distributed hydrogen demand.

Step 2 Combine with modelled hydrogen production from wind energy

The hydrogen supply component of the model is derived from hydrogen production from offshore wind energy. The required wind farm capacity is calculated based on information on hydrogen demand, the hydrogen production model, and wind characteristics.

Step 3 Calculate Levelised Cost of Hydrogen

In this step, the required wind farm capacity obtained from step 2 is combined with parameters representing the project location to calculate LCOH value.

3.1. Diffusion model for predicting roll-out of distributed hydrogen technologies

A type of social change known as diffusion occurs when the acceptance or rejection of an invention leads to changes in the structure and operations of the social system [80]. The Bass diffusion model, which describes the diffusion curve of new items by an S-shaped curve with important characteristics such as the innovation and imitation factors, is the most common model to predict project market penetration of new products [51,81]. Anna et al. [80,82] used the Bass diffusion model to analyse the current usage of electric cars and zero-emission buses and to predict their future trends in the European market. In China, Liu et al. [83] also applied the Bass model to forecast the market of new vehicle technologies (including fuel cell vehicles, hybrid electric vehicles, plug-in hybrid electric vehicles, battery electric vehicles) in the road transport sector. Hydrogen demand in transport and industry in Germany has been forecasted by Simonas et al. [84] using the Bass model. Diffusion models have also been used in studies to forecast hydrogen demand in the Korean transport sector, which currently has the largest number of FC vehicles (FCVs) in the world [50,51,85]. In Spain, a diffusion model has been used to forecast natural gas consumption [86]. In India, Reddy [87] analysed the movement of renewable energy technologies by using the Bass diffusion model. As the Bass diffusion model has been adopted by several relevant studies, it has been used in this study to analyse the current situation and forecast future green hydrogen demand.

The Bass diffusion model is represented in differential equation form [81] (see Eqn. (1)). In the model, potential consumers are assumed to come from two groups (imitator and innovator groups). Consequently, there are two parameters: the imitation factor and the innovation factor, represented by q and p in the equation. Besides, the potential market parameter (M) is also essential in determining the number of products consumed. The function $f(t)$ is the probability distribution function and the function $F(t)$ is the cumulative distribution function, representing the amount of product consumed at time t , and the total product accumulation up to time t , respectively.

$$f(t) = \frac{dF(t)}{dt} = \left[1 - \frac{F(t)}{M} \right] [Mp + qF(t)] \quad (1)$$

Eqns. (2) and (3) are the analytical solutions obtained by solving Eqn. (1) in combination with the initial condition $F(0) = 0$. For a new product at the time of launch ($t = 0$), the cumulative number of that product on the market is zero ($F = 0$). The analytical solutions are shown as follows [80,82,88]:

$$f(t) = M \frac{e^{-(q+p)t} \times (q+p)^2}{p \times (1 + q \times e^{-(q+p)t} / p)^2} \quad (2)$$

$$F(t) = M \frac{-e^{-(q+p)t} + 1}{1 + q \times e^{-(q+p)t} / p} \quad (3)$$

The parameters q and p are obtained using the nonlinear least squares method based on fits to historical data. Potential market value can be estimated or assumed. The following sections will explain specific values for the product categories in the study.

3.2. Distributed hydrogen demand

3.2.1. Industry – refining of liquid fossil hydrocarbons and sustainable aviation fuel

In the industry sector, this model considers hydrogen demand in both oil refining and sustainable aviation fuel production. The model hypothesizes that the output of the refining sector consists of five fuels, as shown in Fig. 2. Therefore, the hydrogen demand in oil refining is calculated as the total hydrogen consumed to produce the five fuels. Hydrogen demand in the refining sector (H_{ref}) can be estimated according to Eqn. (4). Then, the Bass model is applied from annual historical data to determine the future trend of hydrogen in this sector.

$$H_{ref,t} = H_{d,t} + H_{g,t} + H_{k,t} + H_{f,t} + H_{l,t} \quad (4)$$

The indices d, g, k, f, l represent the outputs of final fuels which are diesel/biodiesel, gasoline, kerosene, fuel oil, and liquefied petroleum gas (LPG), respectively. The symbol O in Eqn. (5) represents the amount of final fuel output. The amounts of hydrogen required to produce one-tonne of the final fuels are $U_d = 4.69 \text{ kg/tonne}$, $U_g = 2.35 \text{ kg/tonne}$, $U_k = 1.59 \text{ kg/tonne}$, $U_f = 0.71 \text{ kg/tonne}$, $U_l = 2.79 \text{ kg/tonne}$ [89]. The amount of hydrogen consumed to produce each fuel type is calculated according to Eqn. (5).

$$H_{i,t} = O_{i,t} \times U_i \text{ with } i = d, g, k, f, l \quad (5)$$

For estimating hydrogen demand for SAF production (H_{SAF}), this study assumed that its imitation and innovation parameters are the same as those in oil refining. This assumption is based on the similar technological requirements and the critical role hydrogen plays in both applications. Therefore, the total hydrogen demand estimate for the industry sector includes hydrogen demand in oil refining and SAF production applications.

3.2.2. Distributed transport

Fig. 3 presents the groups of road vehicles and the process of calculating hydrogen demand in the transport sector. Road transport vehicles are divided into three groups: private cars, light commercial vehicles (LCVs), and heavy commercial vehicles (HCVs). Therefore, FCVs are divided into three groups: FC car; FC LCV; and FC HCV. The Bass model is applied to predict the number of FCVs in the future. The hydrogen demand in the transport sector (H_{tran}) is the total hydrogen consumption of the three FCV groups, and it is calculated by Eqn. (6).

$$H_{tran,t} = U_{Car} \times Car_{FC,t} + U_{LCV} \times LCV_{FC,t} + U_{HCV} \times HCV_{FC,t} \quad (6)$$

FC vehicles are still very new in the Irish market, and no local data on hydrogen fuel consumption by FCVs in Ireland is available. Thus, this study assumes that the annual hydrogen consumption per vehicle of FC

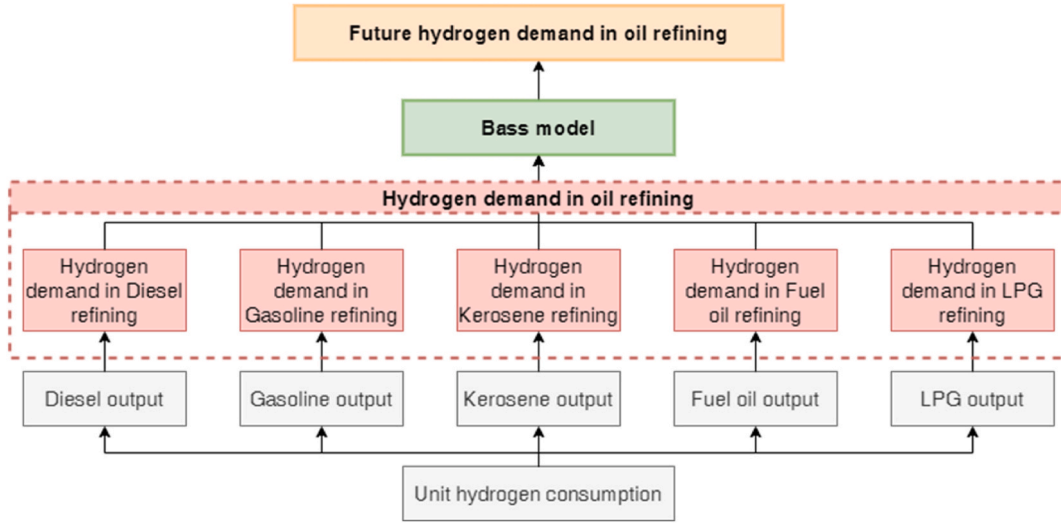


Fig. 2. Diagram illustrating hydrogen demand in the oil refining sector – including liquid fossil fuel hydrocarbons and biodiesel.

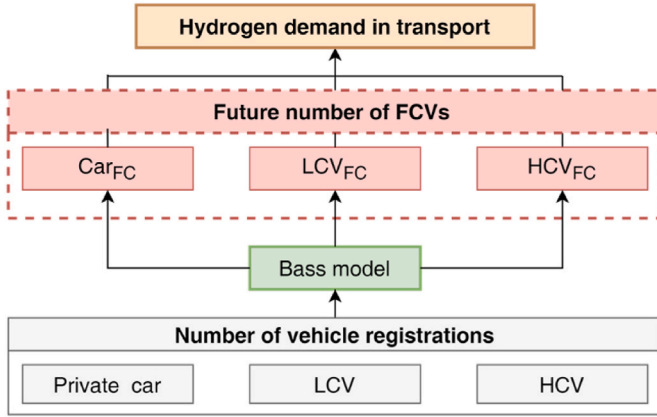


Fig. 3. Diagram showing hydrogen demand in the transport sector.

private cars (U_{car}) and FC HCVs (U_{HCV}) is similar to that of Korea, for which data is available. The annual amount of hydrogen consumed by passenger cars and trucks in Korea [50] is estimated at 0.15 tonnes/vehicle and 5 tonnes/vehicle, respectively. The average annual journey of LCV (vans) in Ireland has been estimated to be 25,925 km/LCV [90]. The amount of hydrogen needed for a van to travel 100 km is estimated at 0.9 kg by 2050 [91]. The annual hydrogen consumption per LCV (U_{LCV}) is calculated to be 0.233 tonne.

3.2.3. Distributed residential and utility power generation

The hydrogen demand in the residential and power generation sectors is approximated based on their energy needs in the form of hydrogen. In the calculation, this research considers the hydrogen characteristic parameters by its lower heating value. Eqn. (7) and Eqn. (8) show how hydrogen demand is calculated for the residential and power generation sectors, respectively.

$$H_{res,t} = E_{H,t}^{res} \times \rho_H^E \quad (7)$$

Where $E_{H,t}^{res}$ is the energy demand in the form of hydrogen fuel in the residential sector at time t , ρ_H^E is the hydrogen energy density defined by its lower heating value ($\rho_H^E = 120 \text{ MJ/kg}$).

$$H_{pg,t} = E_{H,t}^{pg} \times \rho_H^E \quad (8)$$

where $E_{H,t}^{pg}$ is the energy demand in form of hydrogen fuel in the power

generation sector in time t .

3.3. Green hydrogen supply from offshore wind farms

The model uses the Weibull distribution function to represent the wind speed (V) at the wind farm location, as defined in Eq. (9). The shape parameter (k) describes the convergence around the average wind speed, and the scale parameter (C) demonstrates whether the area has strong or weak wind resources.

$$f_{Weibull}(V) = \frac{k}{C^k} V^{k-1} \times e^{-(V/C)^k} \quad (9)$$

The electrical energy obtained depends not only on the wind characteristics but also on the turbine technology used. Within wind farms, downwind turbines will be affected by the upstream turbines, resulting in energy losses known as wake loss (defined as $wake_{loss}$). Wake loss accounts for at least 10 % of the annual energy production of the wind farm, with the exact amount depending on the local wind characteristics and the array layout [92,93]. Combined with the parameters of the turbine used for the wind farm, the annual energy production (AEP) is calculated using Eqn. (10).

$$AEP = \left(T \times n_{tur} \times \int_{V_{cut-in}}^{V_{cut-out}} P(V) f_{Weibull}(V) dV \right) \times (1 - wake_{loss}) \quad (10)$$

$$\text{With } P(V) = \begin{cases} 0.5 \times V^3 \times A \times \rho_{air} \times C_p, & V_{cut-in} \leq V < V_{rate} \\ P_{rate}, & V_{rate} \leq V \leq V_{cut-out} \end{cases}$$

A wind turbine starts generating electricity when the wind speed reaches the cut-in wind speed (V_{cut-in}). The turbine works at rated power (P_{rate}) when the wind speed is greater than or equal to the rated wind speed (V_{rate}). The turbine will stop working when the wind speed is higher than the value of the cut-out wind speed ($V_{cut-out}$). A and C_p represent the rotor swept area and power coefficient of turbine, respectively.

The mass of hydrogen produced is estimated based on the energy required to produce 1 kg of hydrogen. The energy required to produce 1 kg of hydrogen comes from two components, the electrolyser (E_{EL}) and the other parts of the plant (E_{hps}). The efficiency of converting (ϵ_{con}) electricity to hydrogen is an essential parameter of an electrolyser, the computation thus requires it. The annual mass of hydrogen produced (AHP) is therefore calculated according to Eqn. (11).

$$AHP = \frac{AEP}{\frac{E_{EL}}{e_{con}} + E_{hps}} \quad (11)$$

3.4. Calculation of levelised cost of hydrogen production

The levelised cost of hydrogen production (LCOH) is the average net present cost of producing hydrogen over the project lifetime. It is a useful indicator for assessing the economics and competitiveness of various methods for producing hydrogen. Eqn. (12) expresses the value of LCOH as the total expenditure required over the lifetime of the project (lp) divided by the total amount of hydrogen produced.

$$LCOH = \frac{\sum_0^{lp} NPV(CAPEX) + \sum_0^{lp} NPV(OPEX) + \sum_0^{lp} NPV(DECEX)}{\sum_0^{lp} NPV(AHP)} \quad (12)$$

Where $CAPEX$, $OPEX$ and $DECEX$ are capital, operational and decommissioning expenditures, respectively. Net present value (NPV) represents the present value of cash flows.

$$CAPEX = Capex_{OWF} + Capex_{H_plant} + Capex_{pipeline} \quad (13)$$

As this study looks at hydrogen supply from offshore wind energy, the concept of combining the OWFs with electrolyzers to produce hydrogen is included in the market model. All the electricity generated from the off-grid OWF is supplied to the offshore centralised electrolyser plant. The hydrogen produced is then compressed and delivered onshore via subsea pipelines. As shown in Eq. (13), the capital cost for hydrogen production from offshore wind power in this study is composed of three main components (offshore wind farm, hydrogen plant and subsea pipeline). Operating and decommissioning costs of components are estimated to be proportional to their capital costs. Location characteristics of OWFs significantly influence the investment cost. In the location characteristics considered in this study, water depth is a decisive factor in choosing the foundation technology to use, distance between the OWF site and the port impact on the installation cost of a project, subsea pipeline cost depends on the distance from the offshore electrolyser plant (assumed to be within the OWF site) to the onshore landing point [94]. The cost calculation formulas can be found in the Appendix section.

According to a report by the International Energy Agency, by 2030, the cost of producing green hydrogen may decline by 30 % [15]. The scaling up of hydrogen production, along with the lower cost of renewable energy, is predicted to bring the cost of green hydrogen down. This study calculates the cost of hydrogen production for the year 2030. The costs of components are projected for 2030, according to Eqn. (14), based on the historic observed learning rate of offshore wind energy projects [94].

$$Cost_{2030} = Cost_{his} \left(\frac{COWF_{2030}}{COWF_{his}} \right)^{\frac{Log(1-Lr)}{Log(2)}} \quad (14)$$

In which Lr is learning rate of the OWF part of the system [95], the cumulative capacity of OWF in the world in 2030 and year his are $COWF_{2030}$ and $COWF_{his}$ [96,97], respectively.

4. Case study: selected distributed end uses of green hydrogen in Ireland

4.1. Scenarios

Low, medium, and high demand scenarios were developed for each of the distributed green hydrogen demand sectors outlined. This study uses refining output data from Ireland's energy data for 1990–2023 published by the Sustainable Energy Authority of Ireland (SEAI) [98]. Currently, many countries are co-operating to reduce emissions by

reducing the use of fossil fuel sources and therefore the consumption of products from fossil fuels tends to decrease sharply in the future [99]. In the oil refining sector, this study develops three potential scenarios for green hydrogen demand in this sector in Ireland. Based on actual historical data, an analytical method is used to directly predict the hydrogen demand in this sector, and this forecast result is selected as the target for the high scenario. According to the results from the Bass model, hydrogen demand in the refining sector in 2050 will be 73 % lower than in 2023, and this value is used as the target for the medium scenario. In the low scenario, nearly all fossil fuel sources are expected to be eliminated by 2050; therefore, hydrogen demand in oil refining of fossil fuels is assumed to be zero. The low scenario is also consistent with the commitment of the Irish government to achieve net zero emissions by 2050. The target in 2050 under the high scenario is assumed to be double that of the medium scenario.

According to the national hydrogen strategy [31], there are two scenarios for hydrogen use in aviation by 2050. In the low scenario, hydrogen demand is estimated to be 13 TWh. This scenario expects that SAF will account for 35 % of aviation fuel demand. The high scenario projects hydrogen demand to reach 26 TWh, representing 70 % of aviation fuel demand. Based on the low and high scenarios outlined in the national hydrogen strategy, this study selects the medium scenario, which is positioned at the midpoint between those scenarios. The government of Ireland has demonstrated a strong commitment to supporting SAF, which can reduce emissions from the aviation sector. The establishment of the Sustainable Aviation Fuel Task Force in December 2023 marks a significant step forward [100].

In 2021, the Irish government released its Climate Action Plan (CAP21) [30]. The plan provides guidance on actions to reduce emissions by 50 % by 2030 and achieve net-zero emissions by 2050. The transport sector accounts for about 20 % of total emissions in Ireland [30]. The report sets specific goals for this sector by 2030, including 845,000 private electric cars, about 95,000 electric vans (LCVs), and about 3500 low emission trucks. The targets remain unchanged in the Climate Action Plan that was released in 2024 [101]. Based on these targets, this study has developed a medium scenario for fuel cell vehicles (FCVs) in Ireland, assuming that FCVs will begin commercial sales in 2030.

For FC cars and FC LCVs, the high scenario is assumed to account for 5 % more market share than the medium scenario, and the low scenario accounts for 5 % less than the medium scenario. For FC HCVs, there is still a lack of specific information and targets for low-emission truck types in Ireland. However, in Germany – a fellow European Union member state alongside Ireland – the percentage of FC trucks in the truck market is predicted to be 25 %, 50 %, or 75 % by 2050 according to the low, medium, and high deployment scenarios [84], respectively. In the high scenario outlined in the national hydrogen strategy, up to 50 % of HCVs are projected to use hydrogen [31]. Therefore, the market share of FC HCV under the low, medium, and high scenarios in this research is assumed to be 5 %, 25 %, and 50 %, respectively.

In 2022, the Sustainable Energy Authority of Ireland published a comprehensive and rigorous report on emission reductions for Ireland's heating and cooling sector [102]. The report developed five scenarios for energy demand and CO₂ emissions in heating and cooling. The Baseline scenario will not reach net-zero emissions by 2050, and the remaining four scenarios (Rapid Progress, Balanced, Decarbonised Gas, High Electrification) will achieve net zero. The use of green hydrogen for heating was also explored in the report. Before the 2030s, green hydrogen probably will not be widely accessible to the heating sector [102] apart from quantities potentially blended into natural gas imported via the interconnectors with Great Britain, which will not be considered further in this study. Regarding heating in the residential sector, hydrogen technology is expected to be available on the commercial market by 2035 in Ireland [102]. Hydrogen demand for heating in the residential sector in 2050 under the SEAI scenarios is shown in Table 1.

Hydrogen is currently very new to heating applications, whereas

Table 1

Hydrogen annual demand for heating in the residential sector from SEAI scenarios.

Heating fuel	Hydrogen demand in 2050		
Sector	Residential		
Year available	2035		
Unit	TWh		
Scenarios	Baseline	Balanced	Decarbonised Gas
	High Electrification		
	Rapid Progress		
SEAI [102]	0	1.43	5.5

natural gas is already widely adopted. In the types of heating fuel used, hydrogen is highly similar to natural gas, such as the auto-ignition temperatures of natural gas and hydrogen are 539.4°C and 585°C, respectively. The mass density of hydrogen in gaseous and liquid form is equal to 1/10 and 1/6 that of natural gas respectively [15]. The energy density of hydrogen is equal to 1/3 of natural gas [15]. Thus, this study assumes that the innovation and imitation characteristics of these two fuels are the same. The three scenarios in the study build upon the three levels of hydrogen demand under the SEAI scenarios combined with innovation and imitation factors of natural gas in the residential sector.

Recently, the Irish government published a national hydrogen strategy that identified two scenarios for hydrogen demand in the power generation sector: low and high. Hydrogen demands in this sector in 2050 are projected to be 3.6 TWh under the low scenario and 13.3 TWh under the high scenario [31]. Table 2 presents hydrogen annual demand for power generation in 2050 under national hydrogen strategy scenarios. These values correspond to the low and high scenarios of the model in this study, with the medium scenario set between them. The national hydrogen strategy expects hydrogen to play a critical role in flexible power generation and long-duration energy storage, which are essential for integrating high levels of variable renewable energy and ensuring system security. The likely market entry timeframe for these applications is set between 2030 and 2035 [31], aligning with the broader goals of the strategy. One of the methods for converting hydrogen into electricity is the fuel cell. In addition, low-emission hydrogen and ammonia could be co-fired at coal and natural gas-fired power plants to reduce the power plant emissions, with this co-firing model expected to start in 2025 and expand in the late 2020s [103]. Therefore, this study conservatively assumes that hydrogen use in the power generation sector in Ireland will begin in 2030. In the power generation sector, the long-term vision of Gas Networks Ireland is to support hydrogen production from renewable energy that can be used when required [104]. The Bord Gais Energy recently announced plans to construct two new gas-fired power plants of total 200 MW capacity that can be converted to 100 % hydrogen combustion [105]. This will pave the way for future hydrogen use in Ireland's power generation sector.

4.2. Offshore wind resource

For sustainable energy development in Ireland, Offshore Renewable Energy Development Plan (OREDP) was created a framework for offshore renewable energy development [106]. The report divided the Irish coastline into six assessment areas to reflect the potential of tidal,

Table 2

Hydrogen annual demand for power generation from national hydrogen strategy scenarios.

	Hydrogen demand in 2050	
Sector	Power generation	
Likely market entry timeframe	2030–2035	
Unit	TWh	
Scenarios	Low	High
National hydrogen strategy [31]	3.6	13.3

wind, and wave resources. The total development potential of floating offshore wind is significantly larger than that of fixed wind [106], which makes floating wind technology a key focus for future development. Consequently, this study uses the characteristics of floating offshore wind as the basis for a case study.

To assess the wind energy potential, the Weibull function was used to model offshore wind characteristics. The spatial variation of Weibull parameters of wind speed distributions in Ireland has been mapped by SEAI [107]. The average values for the shape and scale parameters ($k = 2.1$, $C = 11.7$ m/s) in the OREDP assessment zone are used to calculate the generated wind energy. In calculating LCOH, the characteristics of the project site are taken into account, and therefore this study needs to select a representative site. The majority of the area off the coast of Ireland (exclusive economic zone) has a water depth greater than 60 m [94], and the Irish Sea (off the east coast) is where most of the offshore wind power development is planned [108]. To calculate investment costs for hydrogen production from OWFs, the study assumes the project location will be the same as that mentioned in Ref. [94] with a water depth of 83 m, 47 km from the port, and 47 km the injection point. In the context of continuously developing turbine technology, this study assumes the use of 15 MW turbines for OWF, as detailed in Ref. [109].

5. Results and discussion

This study presents a novel approach by combining diffusion modelling with scenario analysis to forecast green hydrogen demand across multiple distributed end-use sectors in Ireland, including power generation, residential heating, transport, and refining. Moreover, it uniquely combines hydrogen demand forecasts with offshore wind capacity requirements and LCOH, providing a comprehensive framework for assessing the feasibility of large-scale green hydrogen deployment. The model's modular structure allows for easy extension and adaptation to various hydrogen supply sources and end-use sectors, making it suitable for a wide range of technology deployment scenarios and case studies.

This study uses two data sources: the National Energy Balance 1990–2023 published by SEAI [98] and National Vehicle Statistics published by Society of the Irish Motor Industry (SIMI) [110]. According to data on hydrogen demand in Europe published by the Fuel Cells and Hydrogen Observatory (FCHO) [111], hydrogen demand in Ireland was 7662 tonnes in 2020, with the refining sector accounting for 7269 tonnes (95 %). In comparison, the hydrogen consumption in the refining sector, as estimated by Eq. (4) incorporating SEAI data, was 7328 tonnes in 2020. This verifies that the calculation method used in the study is appropriate for estimating hydrogen demand in oil refining. Fig. 4 compares the results obtained from the Bass model (blue solid curve) with historical data (orange dashed curve) from the oil refining, residential, and power generation sectors. Table 3 provides values of innovation and imitation factors, estimated from historical data using the least-squares method.

In the transport sector, 2009 was selected as the starting year for fitting the model to historic data as the financial boom of the early 2000s followed by 2008–2009 crisis, caused an abrupt drop in new vehicle registrations. Using data from the period 2009–2021, the parameters of the Bass model were estimated and are presented in Table 4. The R-squared (R^2) value for the Bass model, which indicates the accumulation of registered vehicle, is very close to 1. This suggests that the model fits the actual data extremely well. The potential market for each vehicle type, including all types of engines, is represented by the parameter PM_{tt} . The future vehicle market share of BEVs and FCVs is estimated based on PM_{tt} . Combined with the targets set in CAP21, the Bass model for BEVs has been fitted. The model parameters fitted to historical data and statistical goodness-of-fit measures are presented in Table 4 and are illustrated by Fig. 5. Currently, HCVs primarily use internal combustion engines, which represent a high potential future market for FCVs.

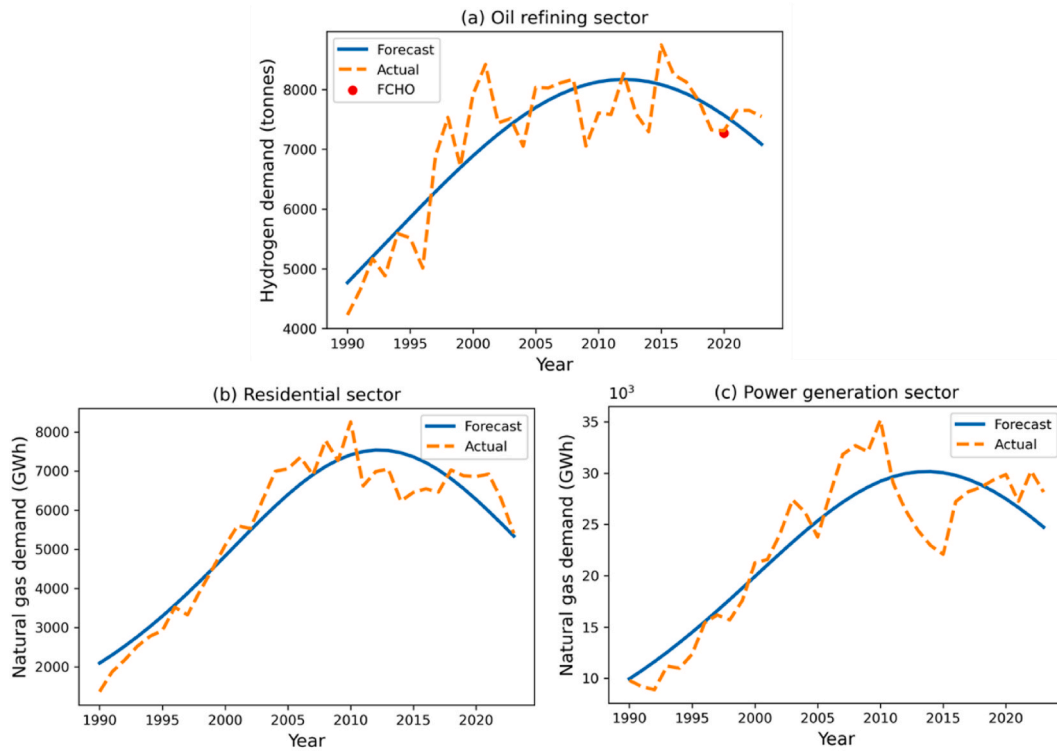


Fig. 4. Comparison of historical data and the Bass model for oil refining (a), residential (b), and power generation (c).

Table 3

Innovation factor and Imitation factor of sectors estimated from data.

	Commercial sale	p	q	R^2	Ref.
Oil refining	2030	0.0117	0.058	0.78	
Residential	2035	0.0076	0.1051	0.91	
Power generation	2030	0.0081	0.0892	0.81	
Transport	2030	0.0037	0.3454		[51,112]

Table 4

Parameters of the Bass model fitted to vehicle registration data since 2009 in Ireland.

Engine type	Vehicle type	p	q	Potential market PM_{it} (10 ³)	R^2
All	Private car	0.0257	0.214	1859	0.9925
	LCV	0.0148	0.2362	397.63	0.9889
	HCV	0.0188	0.2162	41.31	0.9915
Engine type	Vehicle type	p	q	Potential market (%) PM_{tr}	R^2
BEV	Private car	3.17×10^{-6}	0.598	62	0.9004
	LCV	8.47×10^{-6}	0.473	60	0.9495
		10^{-6}			

Table 5 presents the projected FCVs market share in Ireland under three different scenarios.

The probability distribution function ($f(t)$) is applied for forecasting demand in oil refining, SAF production, residential, and power generation sectors while the cumulative distribution function ($F(t)$) is used to estimate future hydrogen demand for the transport sector in the distributed market model. Green hydrogen is prioritised for early use in existing and high-value hydrogen markets. Fig. 6 shows the change in hydrogen demand, and the corresponding variation in OWF capacity required to meet that demand. Fig. 6 shows forecasted total hydrogen demand under three scenarios for green hydrogen use in the oil refining

and SAF production applications. Firstly, it can be seen that hydrogen demand in this sector is expected to decrease significantly in the future. Secondly, Ireland's refining industry might require 4042 tonnes of green hydrogen annually by 2050. The hydrogen demand for SAF production is projected to be a major consumer of hydrogen in the industry sector. With estimates ranging from 390,000 to 780,000 tonnes by 2050, SAF production is set to play a significant role in driving hydrogen demand. Fig. 7 shows the total hydrogen demand in the industrial sector, which includes oil refining and SAF production, as well as the offshore wind farm capacity required to generate hydrogen to satisfy this demand. The demand for hydrogen in the industry sector is significantly driven by its application in SAF production. This high demand highlights the essential role that SAF production will play in shaping the future hydrogen market. To supply hydrogen for the industry sector in 2050, the required offshore wind farm capacity varies across three scenarios: 4020 MW in the low scenario, 6045 MW in the medium scenario, and 8070 MW in the high scenario.

The transportation sector is a high potential market for green hydrogen. Fig. 8 shows the change over time of hydrogen demand for FCVs in the transport sector across three scenarios. Overall, Fig. 8 shows that the hydrogen demand in the transport sector increases sharply during the period 2035–2050, after which it will be relatively stable. This market has significant potential demand for hydrogen; in the low scenario, total hydrogen demand in 2050 is about 9726 tonnes, while in the high scenario, it is about 132,256 tonnes. Across all three scenarios, it can be seen that the main consumer in this sector is FC HCVs. Furthermore, hydrogen consumption for FC cars is slightly higher than for FC LCVs. Fig. 9 illustrates total hydrogen demand and the OWF capacity required to produce hydrogen for the transport market. In general, the cumulative capacity curve follows the same trend as the demand curve, which can be explained by the fact that as market demand increases, production capacity needs to be increased to meet this demand. By 2050, the required OWF capacity to produce hydrogen for the transport sector in Ireland is expected to range from 105 MW to 1365 MW.

According to this study's scenarios of future hydrogen applications in

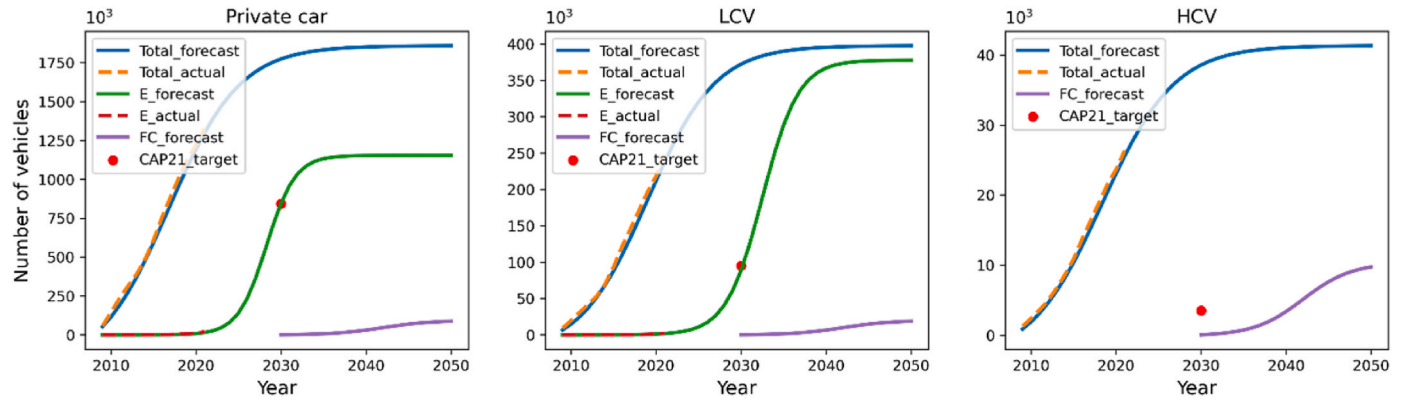


Fig. 5. Cumulative private car, LCV, HCV registrations and the corresponding Bass model forecasts in the medium scenario (Total_forecast: total number of vehicle from Bass model, Total_actual: total number of vehicle from historical data, E_forecast: number of BEV from Bass model, E_actual: number of BEV from historical data, FC_forecast: number of FCV from Bass model).

Table 5

Parameters of Bass model for three scenarios of FCV deployment.

Scenarios	FCV	Commercial sale	Innovation factor p	Imitation factor q	Potential market (%PM _{tr})
Low	Private car	2030	0.0037	0.3454	0
	LCV				0
	HCV				5
Medium	Private car	2030	0.0037	0.3454	5
	LCV				5
	HCV				25
High	Private car	2030	0.0037	0.3454	10
	LCV				10
	HCV				50

the Irish market, hydrogen use in the power generation sector will start in 2030. The amount of hydrogen used annually for power generation can reach 400,000 tonnes by 2050, equivalent to 4110 MW of dedicated wind capacity producing hydrogen, while the required wind farm capacity under the low and medium scenarios is 1125 MW and 2610 MW, respectively. The high scenario predicts hydrogen demand for power generation in 2050 to be equivalent to the high range value in the government's hydrogen strategy, the latter prediction based on the IEA's assessment of 15 % of generation being met by zero-carbon dispatchable sources such as green hydrogen, which could also include bioenergy

[31]. Fig. 10 illustrates the hydrogen demand and required OWF capacity in the power generation sector.

The use of hydrogen in residential heating is forecast to begin later than in power generation according to the constructed scenario, starting in 2035. Under the high and medium scenarios, the annual hydrogen demand in the residential sector is about 165,000 tonnes and 43,000 tonnes, respectively. The change in hydrogen demand and the required wind farm capacity in the residential sector over the years is shown in Fig. 11. However, current government policy supports the immediate decarbonisation of residential heating by electric heat pumps rather than by hydrogen. Therefore, the most likely future heating demand is likely to be closest to the 'low' scenario presented here.

The market share of four sectors in the Irish market during the period 2030–2050 under three scenarios are shown in Fig. 12. The industry sector consistently accounts for the largest share of hydrogen demand, and SAF production is expected to share most of this demand. The power generation sector is expected to have the second highest demand for hydrogen in Ireland. Although the oil refining sector is the largest user of hydrogen today, it will become almost insignificant in the future market. The annual hydrogen demand in Ireland in 2050 under the low, medium, and high scenarios is about 508,226 tonnes, 950,446 tonnes, and 1,481,672 tonnes, respectively. These figures largely align with the projected demand ranges in the Irish government's hydrogen strategy of between 19.8 and 74.6 TWh [31].

Fig. 13 presents the changes in required OWF capacity over time under three scenarios and the variation in LCOH with wind farm capacity. The total required OWF capacity for the low, medium, and high scenarios is 5.2 GW, 9.8 GW, and 15.2 GW, respectively. Hydrogen

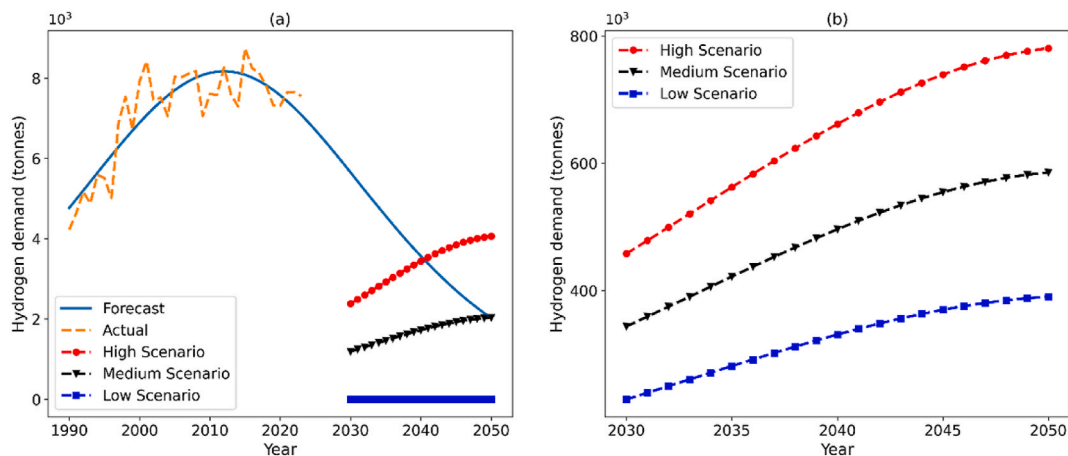


Fig. 6. Hydrogen demand in the industry sector: oil refining (a), and SAF production (b).

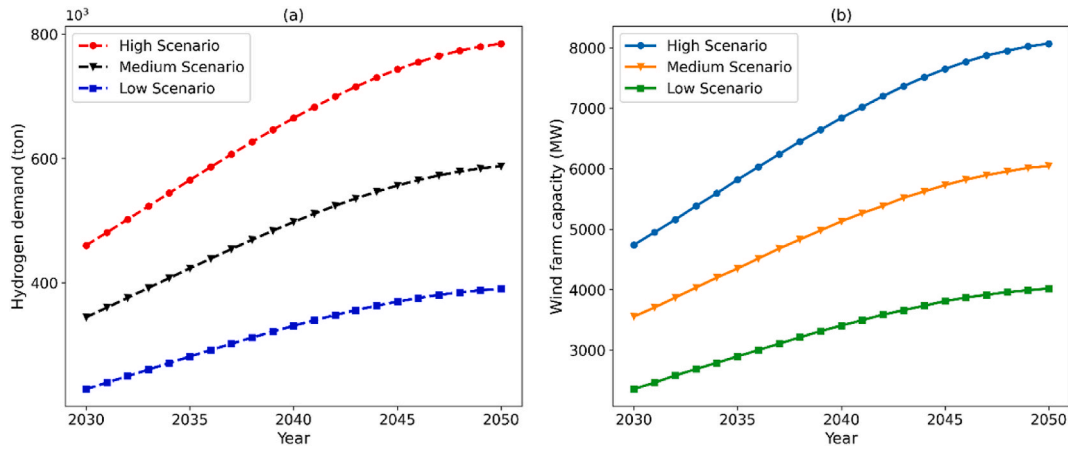


Fig. 7. Industry sector requirements: total hydrogen demand (a); and OWF capacity (b).

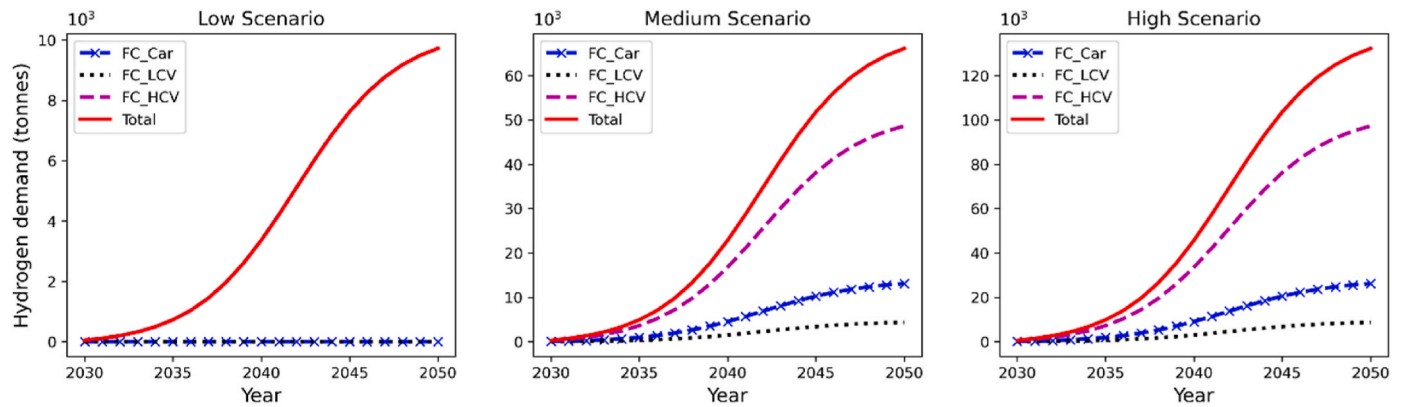


Fig. 8. Change over time of hydrogen demand in transport across fuel cell cars and fuel cell light and heavy vehicles.

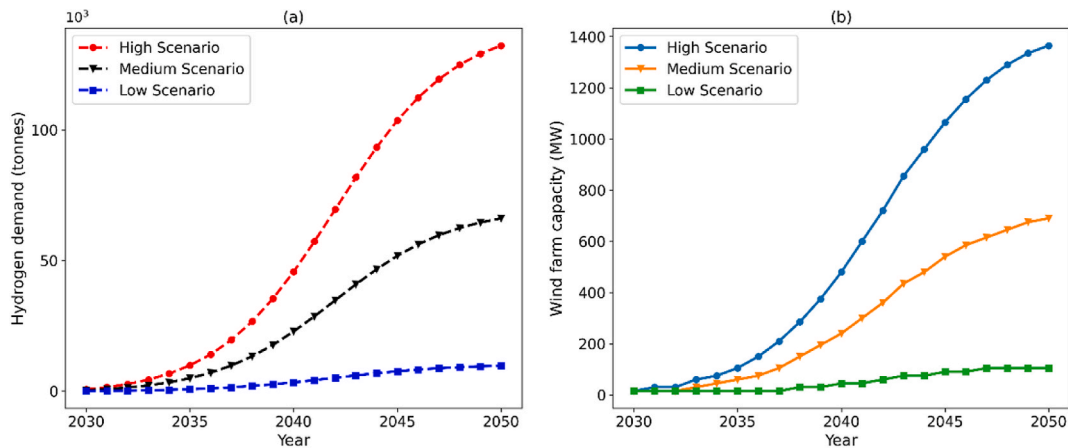


Fig. 9. Transport sector requirements: hydrogen demand (a); and OWF capacity (b).

consumption is expected to increase sharply from 2035. Fig. 13b examines the relationship between OWF capacity and the LCOH. The plot indicates that as OWF capacity increases, the LCOH decreases. Moreover, the LCOH value is projected to drop significantly when OWF capacity reaches 500 MW. This inverse relationship highlights the potential cost benefits of expanding OWF capacity to support hydrogen production. Fig. 14 provides an overview of each sector's required wind farm capacity in 2050 under the three scenarios. The figure highlights again that the main consumers of hydrogen are the industry and the power generation sectors. It should also be noted that the transport

sector is a market with the highest-value application of hydrogen among the four sectors considered. However, it also faces complex infrastructure requirements.

A strength of the diffusion modelling approach taken in this paper is its ability to predict time-lines for technological roll-out and public and industry acceptance of distributed energy technologies. However, these time-lines may be affected by additional mandated changes such as government-imposed bans on ICE vehicles or gas boilers, and policies such as carbon taxes, grants, or subsidies aimed at diverting the different sectors away from fossil fuel use. A limitation of the diffusion model

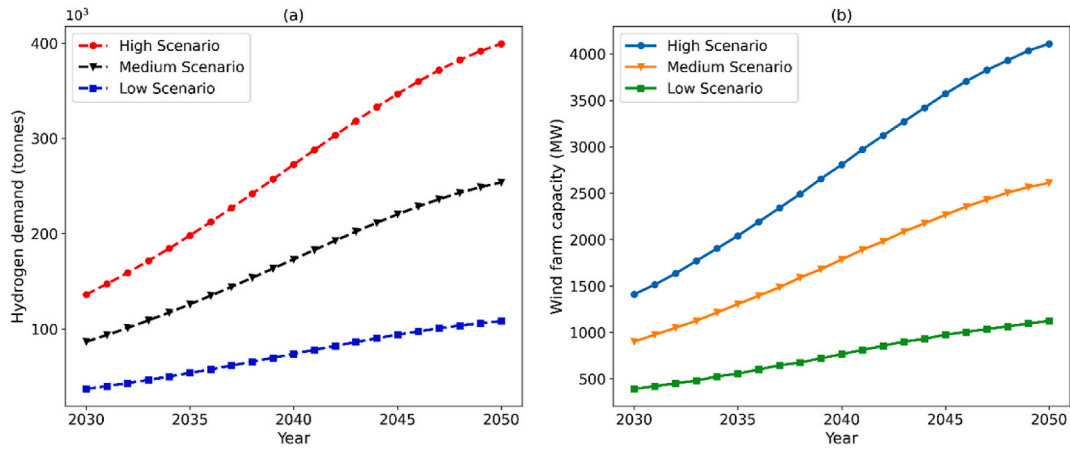


Fig. 10. Power generation sector requirements: hydrogen demand (a); and OWF capacity (b).

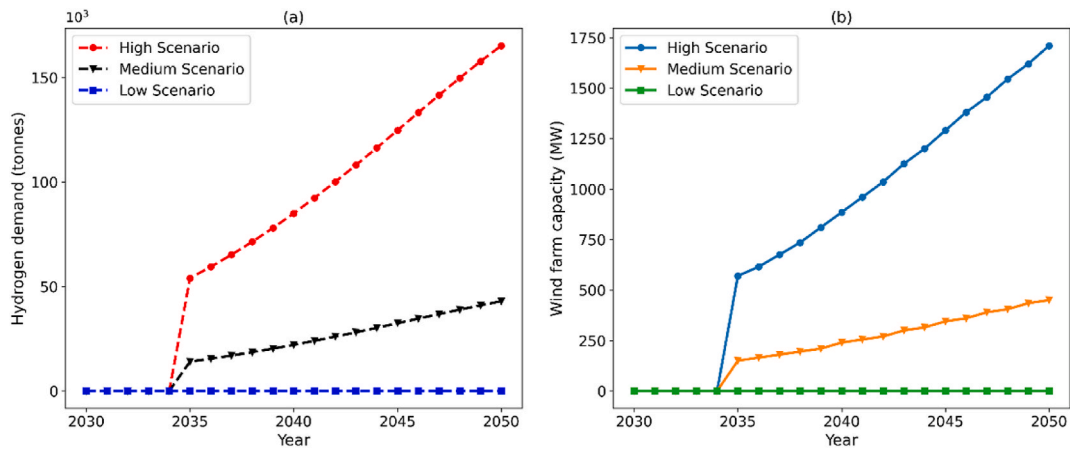


Fig. 11. Residential sector requirements: hydrogen demand (a); and required OWF capacity (b).

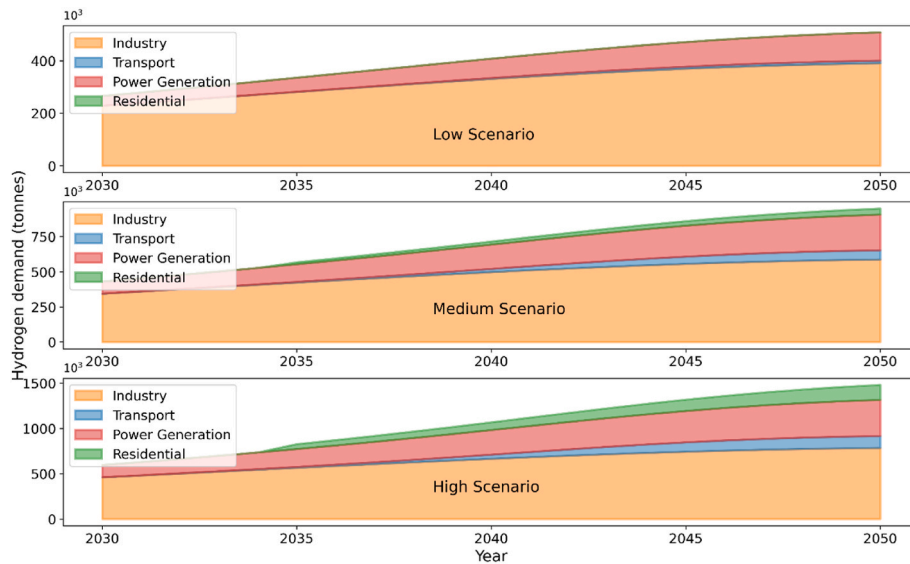


Fig. 12. Changes over time for hydrogen demand in the distributed sectors of the domestic Irish market.

approach is that it is not well-suited to predict roll-out of disruptive new technologies for which no present-day analogues exist, or for large-scale non-distributed end use categories concentrated in a small number of centralised installations, for example ammonia production or other

energy-intensive processes such as steel manufacturing, or for processes with large demands for high-temperature heat energy.

Important insights into opportunities for new hydrogen end uses can be drawn by examining the gap between the demand predictions for

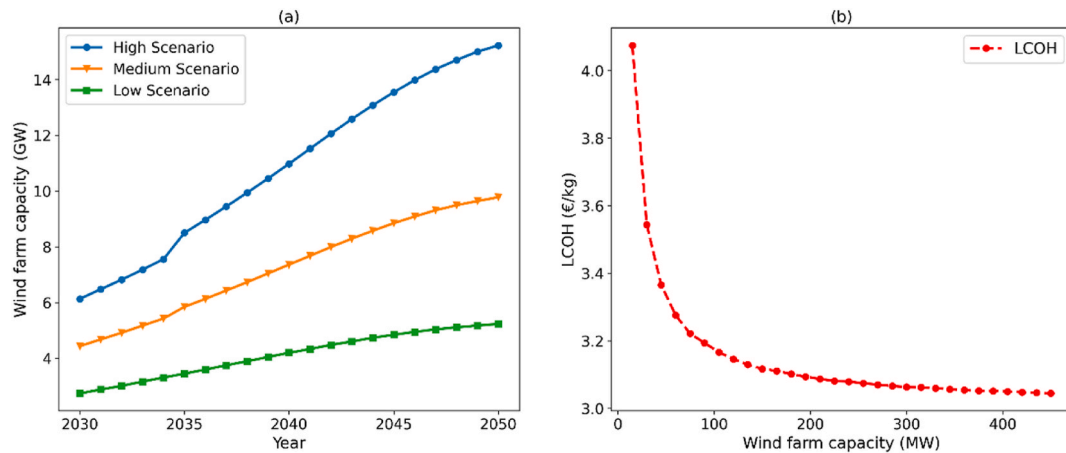


Fig. 13. Changes over time for required OWF capacity to serve green hydrogen demand (a); and LCOH variation with OWF capacity (b).

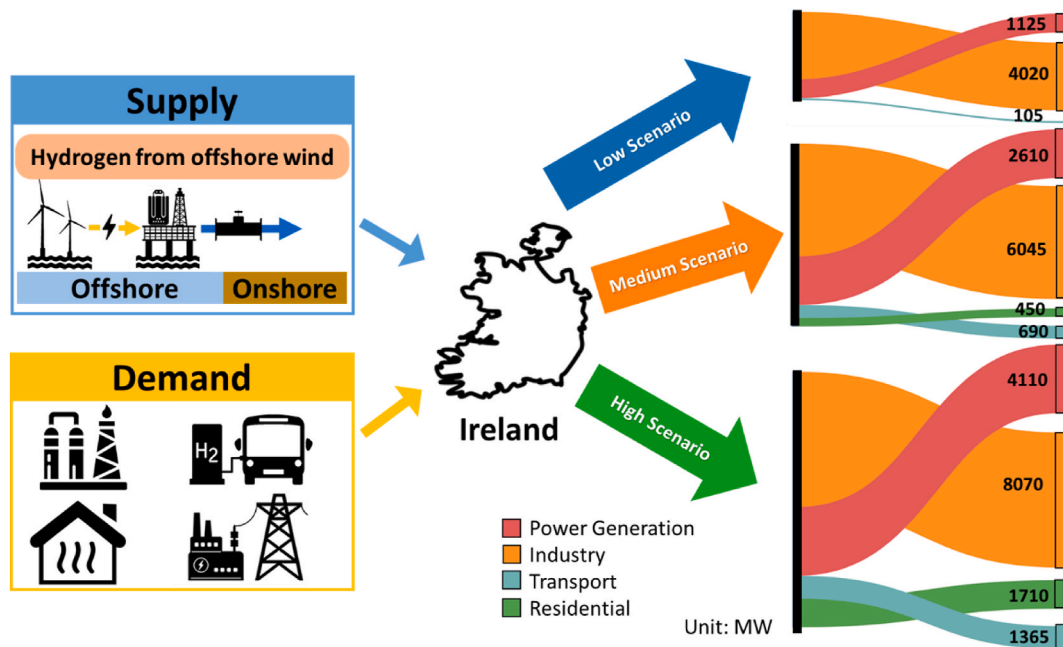


Fig. 14. Wind farm capacity required to serve several different green hydrogen demand sectors according to three scenarios in 2050.

mass distributed applications, as developed in this study, and the size of the potential green hydrogen resource from offshore wind in Irish waters. The gap between the two estimates gives the potential for developing new large-scale hydrogen domestic demand such as low-carbon ammonia or steel production, and for developing export opportunities to larger green hydrogen markets.

The Irish government's Climate Action Plan aims to commence hydrogen production from dedicated OWFs in 2030 [31], the start date of green hydrogen production is assumed in this study to be 2030. Before 2030, green hydrogen supply may come from other potential production sources, such as onshore wind farms. The gap between model prediction and the target indicates that policy measures and incentives to support demand would be needed order to generate sufficient demand by 2030; relying on "organic" technology diffusion will not be sufficient. However, it should also be noted that additional sectors such as high temperature heat energy and large industrial energy users, outside the scope of this modelling study, have the potential to create significant extra demand, particularly beyond 2030. Examining the predicted hydrogen demand for 2050, the domestic distributed demand sectors examined in this paper will be sufficient to absorb the output equivalent to almost

15.2 GW of dedicated OWF capacity (Fig. 13). It is interesting to place this figure in the context of the overall wind resource and the likely OWF capacity required to deliver net zero by 2050. It has been predicted that the installed OWF capacity required to contribute to domestic electricity demand in 2050 will be up to 15 GW [113]. Up to 30 GW of total OWF deployment has been projected by the government considering the technical potential of the wind resource in Irish waters [114]. Therefore, with OWF capacity potential above the requirements for direct electricity generation and the green hydrogen demand sectors considered here, it is clear that huge potential exists for green hydrogen export and for new domestic industrial end use sectors to be developed, for example ammonia production.

6. Conclusion

This study provides an overview of the growth trajectory of green hydrogen demand across various sectors, highlighting its increasing importance as a versatile energy carrier in the transition to a low-carbon energy system. A detailed literature review was conducted, focusing on the fuel markets for oil, natural gas, electricity, and hydrogen. This

review provided the basis for projecting changes in fuel demand in the future.

A market model was developed to project hydrogen demand across different sectors. Using an analytical approach, a dynamic distributed green hydrogen market model was created consisting of two parts: demand and supply. The market sectors with significant hydrogen demand examined within the scope of this study were industry, transport, residential, and power generation. All hydrogen supply was assumed to be from dedicated offshore wind farms (OWFs) coupled with electrolyser plants.

The application of the market model to the Irish market is an original contribution of this study. Potential scenarios for sectors of the future Irish energy market for green hydrogen were based on national targets and policies. In the Irish market, the findings show that while the refining sector remains the largest current consumer of hydrogen, its role will be insignificant in the future hydrogen market, with SAF production and power generation emerging as the major consumers of hydrogen. The total hydrogen demand in Ireland by 2050 is projected to range from approximately 500,000 tonnes under the low scenario to 1,480,000 tonnes under the high scenario. The required OWF capacity to meet this demand will increase over time, with total OWF capacity in 2050 estimated to reach as high as 15 GW under the high scenario. The findings of this study provide a foundation for guiding future research and supporting effective policymaking.

The modular structure of the model makes it convenient to extend and adapt to different supplies and other hydrogen end uses as they emerge in future. Therefore, it can be readily applied to other technology deployment scenarios in Ireland or in other countries in order to predict the scale of future distributed green hydrogen demand, the required wind generation capacity and the levelised cost of hydrogen achievable based on the size of the market sectors.

The model approach also allows insights to be drawn on (1) potential future additional large-scale centralised end uses of green hydrogen such as ammonia production, which can be more rapidly developed than the

relatively slow public acceptance and diffusion of existing, distributed, technologies, and (2) the gap between decarbonisation targets and diffusion and roll-out of hydrogen technologies, which is useful in order to develop new policy measures to ensure decarbonisation targets are achieved.

CRediT authorship contribution statement

Quang Vu Dinh: Conceptualization, Methodology, Visualization, Validation, Investigation, Writing – original draft, Writing – review & editing. **Van Nguyen Dinh:** Conceptualization, Methodology, Supervision, Writing – review & editing, Funding acquisition. **Paul G. Leahy:** Conceptualization, Methodology, Supervision, Writing – review & editing, Funding acquisition.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Paul G. Leahy, one of the co-authors of this paper, is Senior Editor of RSER. He was blinded during the review process and the paper was handled by another Editor.

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

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Appendix

The unit of currency used is million euros. The symbol C_i represent the cost of component i (i = D&C, Turbine, Foundation, Installation, Substation, Cable, Electrolyser, Compressor, Stack replacement)

$$Capex_{OWF} = C_{D\&C} + C_{Turbine} + C_{Foundation} + C_{Installation} + C_{Substation} + C_{Cable}$$

$$\begin{cases} C_{D\&C} = 0.188 \times S_{OWF} \\ C_{Turbines} = \left(1.6 - \frac{1.9}{S_T}\right) \times (S_{OWF})^{0.9984}, \text{ with } S_T \geq 2 \\ C_{Substation} = 0.14 \times S_{OWF} \\ C_{Cable} = 0.41 \times S_{OWF} \end{cases}$$

$$C_{Foundation} = \begin{cases} 0.336 \times S_{OWF}, \text{ Monopile} \\ 0.442 \times S_{OWF}, \text{ Jacket} \\ 0.84 \times S_{OWF}, \text{ Floating} \end{cases}$$

$$C_{Installation} = 0.15 \times Time_{rent}$$

With size of offshore wind farm is S_{OWF} , size of turbine is S_T , total time rent vessel is $Time_{rent}$.

$$Capex_{H_plant} = C_{Electrolyser} + C_{Compressor} = 0.6 \times S_{El} + 0.0126 \times \left(\frac{P_{com}}{10}\right)^{0.9}$$

With size of electrolyser is S_{El} , power consumed by the compressor is P_{com} .

$$Capex_{pipeline} = \left(16 \times \frac{S_{El} \times EL_{rate}}{\rho \times \nu \times \pi} + 1.2 \times \sqrt{\frac{S_{El} \times EL_{rate}}{\rho \times \nu \times \pi}} + 0.329\right) \times D$$

With electrolyser production rate is EL_{rate} , mass density and velocity of hydrogen in pipeline is ρ and ν , respectively. Distance from the offshore electrolyser plant to the onshore landing point is D (unit: km).

$$OPEX = Opex_{OWF} + Opex_{H_plant} + Opex_{pipeline}$$

$$\left\{ \begin{array}{l} Opex_{OWF} = 0.03 \times Capex_{OWF} / \text{year} \\ Opex_{H_plant} = \frac{0.02 \times Capex_{El} + 0.03 \times Capex_{compressor}}{\text{year}} + C_{Stack_replacement} \\ Opex_{pipeline} = 0.02 \times Capex_{pipeline} / \text{year} \end{array} \right.$$

$$DecEX = Decex_{OWF} + Decex_{H_plant}$$

$$\left\{ \begin{array}{l} Decex_{OWF} = 0.05 \times Capex_{OWF} \\ Decex_{H_plant} = 0.02 \times Capex_{H_plant} \end{array} \right.$$

Data availability

Data will be made available on request.

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