energies

MDPI

Review

Towards the Integration of Flexible Green Hydrogen Demand and Production in Ireland: Opportunities, Barriers, and Recommendations

Luciano De Tommasi * and Pádraig Lyons

International Energy Research Centre, Tyndall National Institute, University College Cork, Lee Maltings, Dyke Parade, T12 R5CP Cork, Ireland
* Correspondence: luciano.detommasi@ierc.ie

Abstract: Ireland's Climate Action Plan 2021 has set out ambitious targets for decarbonization across the energy, transport, heating and agriculture sectors. The Climate Action Plan followed the Climate Act 2021, which committed Ireland to a legally binding target of net-zero greenhouse gas emissions no later than 2050, and a reduction of 51% by 2030. Green hydrogen is recognized as one of the most promising technologies for enabling the decarbonization targets of economies across the globe, but significant challenges remain to its large-scale adoption. This research systematically investigates the barriers and opportunities to establishing a green hydrogen economy by 2050 in Ireland, by means of an analysis of the policies supporting the optimal development of an overall green hydrogen eco-system, in the context of other decarbonizing technologies, including green hydrogen production using renewable generation, distribution and delivery, and final consumption. The outcome of this analysis is a set of clear recommendations for the policymaker that will appropriately support the development of a green hydrogen market and eco-system in parallel with the development of other more mature low-carbon technologies. The analysis has been supplemented by an open "call for evidence," which gathered relevant information about the future policy and roles of hydrogen involving the most prominent stakeholders of hydrogen in Ireland. Furthermore, the recommendations and conclusions from the research have been validated by this mechanism.

Keywords: low-carbon hydrogen; hydrogen economy; hydrogen strategy; green hydrogen; electrolyzers

check for updates

Citation: De Tommasi, L.; Lyons, P. Towards the Integration of Flexible Green Hydrogen Demand and Production in Ireland: Opportunities, Barriers, and Recommendations. *Energies* **2023**, *16*, 352. https://doi.org/10.3390/en16010352

Academic Editors: Adam Smoliński and Attilio Converti

Received: 13 November 2022
Revised: 17 December 2022
Accepted: 23 December 2022
Published: 28 December 2022

Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

The objective of the EU's policies on hydrogen is to foster the good operation of the hydrogen market by incentivizing both supply and demand. The policy will have to bridge the cost gap between conventional solutions and renewable and low-carbon hydrogen through appropriate state aid rules. Furthermore, policies and incentives will need to be developed to form a comprehensive support scheme to bridge the gap between market requirements, sustainability and climate requirements, and hydrogen technology development [1].

The policies are designed to increase the EU's support and will stimulate investments when a sustained expansion of the hydrogen market takes place over a brief period [2–4]. The EU's goal is to establish an open and competitive EU hydrogen market by 2030, removing the obstacles to cross-border trade and enabling a truly efficient allocation of hydrogen supply among the sectors.

The EU also regulates several other aspects that may have an influence on hydrogen technology diffusion in its member states and hydrogen EU policy. In fact, the EU has set well-defined targets regarding energy efficiency and/or the share of renewable energy in electricity production. It manages the emission trading scheme and has a central role in the management of European markets for gas and electricity. It also sets minimum levels for

energy taxation and subsidizes energy technologies through its regional funds and research projects. Finally, the EU has developed a policy called Trans-European Networks for Energy (TEN-E), which is focused on linking the energy infrastructure of EU countries [5].

The EU Parliament acknowledged that blue hydrogen has a transition role, even though some members of the Parliament recommend focusing exclusively on green hydrogen. More generally, the importance of carbon capture and storage technologies is recognized on the basis that these technologies can contribute to making heavy industry more sustainable and climate-neutral. Moreover, the EU Parliament recommends that the Commission discloses its legal classification of various types of hydrogen and that a regulatory framework is established such that hydrogen certification, labeling, origin guarantees, and tradability can be readily achieved. The EU Parliament also recognizes the prominent role of hydrogen in the decarbonization of the transportation sector and the related necessity of an adequate refueling infrastructure [6].

The EU strategy determines short-term vs. long-term objectives for hydrogen introduction. Two stages are foreseen; namely, objectives to be achieved from 2020 to 2024 and from 2025 to 2030 [7].

1. The EU's strategic objective from 2020 up to 2024 is to install at least 6 GW of renewable hydrogen electrolyzers in the EU and the production of up to 1 million tons of renewable hydrogen (produced using mainly wind and solar energy).
2. In the second stage, from 2025 to 2030, electrolysis with a capacity of 100 MW next to existing industrial demand centers such as larger refineries, steel plants, and chemical plants will be rolled out. They would ideally be powered directly by local renewable electricity sources. Furthermore, hydrogen refueling stations will be used to support hydrogen fuel-cell buses and, at a later stage, trucks. Electrolyzers will thus also be used to locally supply an increasing number of hydrogen refueling stations.

The EU's strategic objective from 2025 to 2030 is to make hydrogen an intrinsic part of an integrated energy system with the goal to install at least 40 GW of renewable hydrogen electrolyzers by 2030 and the production of up to 10 million tons of renewable hydrogen. Renewable hydrogen will be used to balance the power system with a high penetration of renewables, by transforming electricity into hydrogen when renewable electricity is abundant and cheap and by transforming back hydrogen into electricity when there is a shortage of electrical power from renewables. Hydrogen's use for daily or seasonal storage to provide a load-balancing function will contribute to improving the supply system's security in the medium term.

The relationships between the factors that contribute to determining the consumption of low-carbon hydrogen in a country and the consequent impacts on the decarbonization of the sectors (electricity, buildings, industry, transportation, agriculture, etc.) are complex and are determined by the interaction between demand and supply sides as shown in Figure 1. The challenges that the policymaker needs to address sit on both the demand and supply sides. The assumptions of this paper are that the policy should address the following issues:

- Contribute to increasing the trust of the stakeholders by supporting the demonstration of hydrogen technologies to prove that they met the readiness level required for their deployment.
- Determine which production pathways for low-carbon (green) hydrogen should be prioritized.
- Support the development of the hydrogen infrastructure (production, storage, distribution and delivery, refueling stations, consumption, etc.) by direct or indirect incentivization mechanisms.
- Stimulate the demand of green hydrogen in case the selling price of green hydrogen is too high.
- Establish a certification mechanism for green hydrogen.

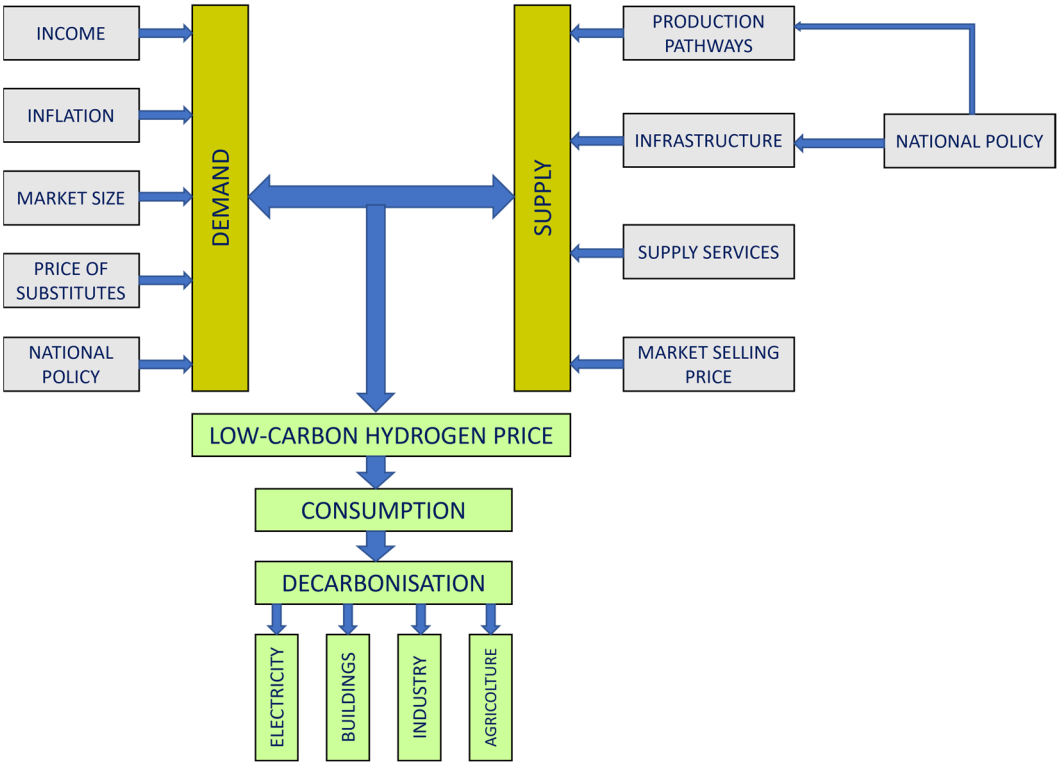


Figure 1. Relationships between the factors that determine uptake of green hydrogen and role of a national policy/strategy.

The policy for hydrogen's part in the decarbonization of the Irish economy in Ireland is discussed in the National Energy and Climate Plan 2021–2030 [7]. The policymaker believes that decarbonization of the Irish energy system requires considering coupling between the electricity, heating/cooling, and transport sectors. The document states the belief that green hydrogen may play a prominent role in sectors such as heavy vehicles and maritime traffic, which cannot be fully decarbonized using other means. There is a realistic potential to produce green hydrogen at scale with a competitive market price using large-scale offshore renewable energy. Furthermore, the plan states that blue hydrogen can only be acceptable in case a full capture and storage of the produced carbon can be demonstrated. In addition, grey hydrogen is likely to be considered not good enough to support the transition of the country to a fully decarbonized energy system. Finally, cooperation with other European countries is required to develop the market rules, the safety standards and the cross-border infrastructure required for the development of the hydrogen economy.

Furthermore, the Climate Action Plan sets out indicative ranges of emissions reductions for each sector of the economy in Ireland as follows:

- Electricity: 62–81%
- Transport: 42–50%
- Buildings: 44–56%
- Industry/Enterprise: 29–41%
- Agriculture: 22–30% reduction
- Land Use, Land Use Change and Forestry (LULUCF): 37–58%

Achieving these targets, cost effectively, safely and reliably, will be challenging and are likely to require changes in how society operates and the introduction of new technologies, which today are considered uneconomic.

At the national level, energy policy has a significant influence on technological diversity, self-sufficiency, and the security of electricity power generation in a country. From a comparative analysis of six EU countries' published hydrogen strategies (from Portugal,

Spain, France, Germany, Netherlands and Norway), it appears that they differ in scale, sophistication, and ambition level. In the longer term, the EU will have to prevent regulatory and competition policy issues because national hydrogen strategies have the potential to create national or regional hydrogen energy markets that could easily damage the EU-wide hydrogen market and lead some of the countries to a dominant position [8].

In countries with high levels of renewable generation, such as Denmark, the policy targets are determining or are likely to determine whether the country will export electricity or hydrogen. In other countries where the main policy target is self-sufficiency, such as Germany, the installed hydrogen capacity should be increased to meet the target. However, there are countries like Bosnia-Herzegovina, which are highly dependent on energy imports, where self-sufficiency would be a target difficult to achieve and are therefore likely to require energy imports in either electrical or hydrogen form in the future [9].

In Spain, green hydrogen seems destined not to play a significant role in the power system's future development. It is envisaged that electricity production from renewables that exceed its exogenous demand will be exported to other countries via electrical infrastructure. The Spanish strategy is to start with electrification and then use renewables to produce hydrogen only for limited use and for power system balancing [10].

Portugal plans to decrease its dependency on energy imports from 78% to less than 20% through an increasing utilization of renewable energy. The country could achieve a 100% RES target by deploying a significant amount of storage and interconnection capacity [11]. However, the preferred electrification pathway in Portugal remains the major decarbonization strategy, thereby discounting the green hydrogen pathway. In addition, there are other economic, societal and technological barriers [12].

France's power generation is currently dominated by its nuclear fleet; therefore, diversification of generation technologies in the long term is one of the main policy targets. Many electricity production facilities are coming to the end of their lives and need sustained investments to be renewed [13]. The need for green hydrogen for the decarbonization of hard-to-abate sectors, such as industry and transport, requires better policy support for the development of renewables, which can provide more low-carbon electricity for green hydrogen production [14].

Italy has the potential to become a hub for the hydrogen trade because of its central location in the Mediterranean, situated between potential major exporters in Africa and the Middle East and consumers in northern Europe. Italian hydrogen strategy will require EUR 10bn of investments between 2020 and 2030 to facilitate the development of a hydrogen-based economy [15]. The goal in Italy is the installation of 5 GW of electrolysis capacity by 2030 and the development of a regulatory framework supporting green hydrogen production. The first experiments regarding the blending of hydrogen in a gas network were conducted in 2019, and they were successful in increasing the percentage of hydrogen by volume to 10% [16].

In the UK, the Government's Hydrogen Strategy plans to attract up to GBP 4bn of private investment by 2030 in blue and green hydrogen generation, storage and usage and create 9000 jobs [17]. Large pilot projects underway demonstrate the commitment of the Government to support technological developments needed to deploy cost-effective hydrogen solutions. The ambition of the UK government is detailed in strategic plans to scale-up hydrogen production and consumption domestically and supply from 20% to 35% of the whole nation's energy consumption using hydrogen by 2050, whereas the global average hydrogen utilization has been forecasted at only 10% by Bloomberg Intelligence.

The construction of a new GBP 12.7m hydrogen transmission network research facility started in 2021, with GBP 9.07m of funding provided by Ofgem's Network Innovation Competition and with the remaining amount coming from the other project partners [18]. The facility will be making use of several decommissioned assets and will be representative of a hydrogen transmission network. The goal of the trial project is to test hydrogen blending up to 100% at transmission pressures. The testing of the facility is due to commence in 2022.

Another large project running in the UK is HyDeploy [19]. The project will demonstrate the injection of up to 20% volume of hydrogen into Keele University's existing natural gas network, feeding about 100 homes and 30 faculty buildings. It is anticipated that this injection can be achieved without requiring any modifications to the existing gas appliances in the homes and faculty buildings.

The remaining part of this paper is structured as follows. Section 2 illustrates the research methodology. Section 3 introduces the characteristics of a national clean hydrogen policy. Section 4 addresses clean hydrogen production. Section 5 covers aspects related to hydrogen distribution and delivery. Section 6 elaborates on the consumption of hydrogen. Section 7 discusses the integration of hydrogen in the power system. Section 8 provides recommendations for the policymaker to establish a green hydrogen economy by 2050. Section 9 discusses the findings of the paper in more depth. Section 10 concludes the paper.

2. Methodology

This paper proposes the generalized methodology for assessing the potential of a country to transition towards a hydrogen society, shown in Figure 1, and it considers Ireland as a case study. The approach comprises six steps. The first step analyzes the opportunities for green hydrogen production [20] since it is assumed that the production of hydrogen without carbon emissions is the final desired state. However, it is generally acknowledged that blue hydrogen may be an attractive alternative in the short term due to its lower production costs, and therefore the second step is to assess whether it could represent a means to stimulate the national demand throughout an initial transition period toward green hydrogen. In [21], it is discussed how in Brazil, the development of a natural gas-based hydrogen industry equipped with CO_2 capture could monetize natural gas remaining resources, mitigate CO_2 emissions, and facilitate the transition to green hydrogen. The third step is to consider the efforts required to establish a transportation and distribution/delivery infrastructure to supply diverse consumers with clean hydrogen. Such an infrastructure needs to consider that hydrogen can be delivered either in gaseous or liquid form or using a material-based hydrogen carrier [22]. The fourth step is to assess the potential and the benefits of utilization of green hydrogen for home heating, followed by the assessment of competing technologies (such as heat pumps etc.) [23]. Although a certain amount of carbon emissions may be avoided when blending hydrogen with natural gas used for residential heating, this would lead to an increase in energy price between 1 and 2% [24]. Finally, the last step should consider the certification of green hydrogen to guarantee that only zero-carbon hydrogen is sold on the market as green hydrogen, whereas other low-carbon hydrogen should not be labeled as "green". A certification scheme needs to specify what hydrogen is certified against, reference emissions thresholds, and carbon accounting system boundaries [25].

An extensive literature review linked to the steps in Figure 2 has been performed to establish the knowledge about state of the art, which is preliminary to policy analysis and recommendations. After that, a "call for evidence" was launched, which used a structured questionnaire to gather relevant information from the most prominent Irish stakeholders of low-carbon/green hydrogen. The objectives of the survey were to:

- Support the development of a low-carbon hydrogen policy in Ireland;
- Collect evidence on the challenges and opportunities associated with the production of low-carbon hydrogen in Ireland;
- Collect evidence on the challenges and opportunities associated with the distribution and delivery of low-carbon hydrogen in Ireland;
- Collect evidence on the challenges and opportunities associated with the consumption of low-carbon hydrogen in Ireland;
- Revise the recommendations to the policymaker previously formulated.

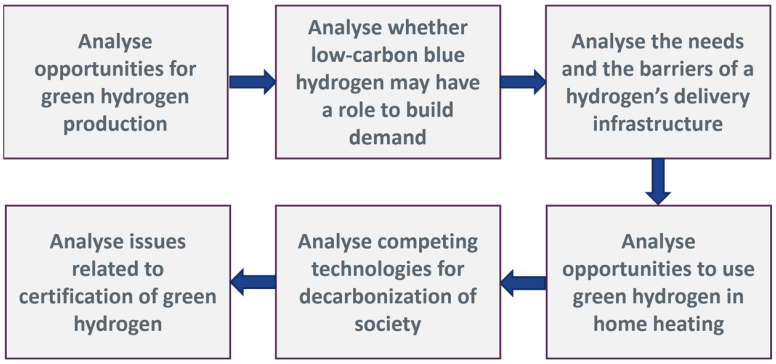


Figure 2. Methodology for assessing the potential for transition towards a low-carbon hydrogen society.

The call for evidence was open for two weeks and closed at 5pm Friday, 4 February 2022. The stakeholders who responded are listed in Table 1 and have been anonymized in this paper.

Table 1. Stakeholders involved in the call for evidence.

Stakeholder Number	Type of Organization
1	National association for hydrogen
2	Distribution System Operator
3	Manufacturer of electrolyzers
4, 5	Academic institution

3. A Hydrogen Policy in Ireland

A hydrogen market already exists in Ireland. The country is importing hydrogen from the UK, Algeria, France, Belgium and the Netherlands (Figure 3a) and is exporting it to the UK, Germany, Saudi Arabia, Spain and Belgium (Figure 3b). Ireland was the worldwide 52nd exporter of hydrogen in 2019, with 5.015 M€ exported. In the same year, Ireland was the 40th largest importer of hydrogen at 22.216 M€ imported [26]. Note that hydrogen has several applications in different types of industries, such as metals [27,28], steel [29], chemical [30,31], oil refining [32], food [33], glass [34,35], and electronics [36]. A policy about green hydrogen should promote the fulfillment of the current demand for hydrogen using zero-carbon (green) hydrogen, where grey hydrogen produced through the steam reforming process (which emits CO_2) is still used. This would be consistent with the strategy set by the European Commission of replacing the 8 Mt grey hydrogen demand currently consumed in the EU as feedstock by 2030 with green hydrogen, which would require around 400 TWh of renewable electric power per annum [37].

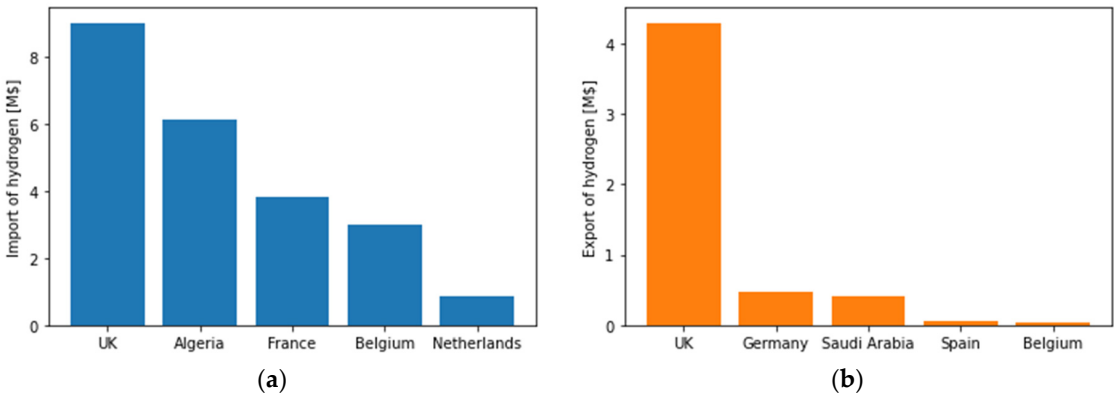


Figure 3. (**a**) Ireland imports of hydrogen from other countries, and (**b**) Ireland exports of hydrogen to other countries.

Although Ireland may show some specific conditions with respect to the other European Countries in relation to the forthcoming hydrogen economy, the national policy on hydrogen should follow the overarching EU strategy on energy sector integration. The applications of hydrogen to be prioritized in Ireland should be determined considering the EU hydrogen strategy [4]. The document addresses the European Commission's ambition for hydrogen and provides good indications regarding the policy and potential end-uses of hydrogen. According to the European Commission, "hydrogen can be stored in the local gas grid and used for decarbonizing domestic heating". The gas network of Ireland comprises 14000 km of pipeline throughout the country, and it is connected to the wider markets of the UK and Europe via Scotland.

The plan-do-check-act process (Figure 4) is a useful tool that may be used to determine a strategic direction for the decarbonization of the sectors in Ireland by means of green hydrogen projects [38].

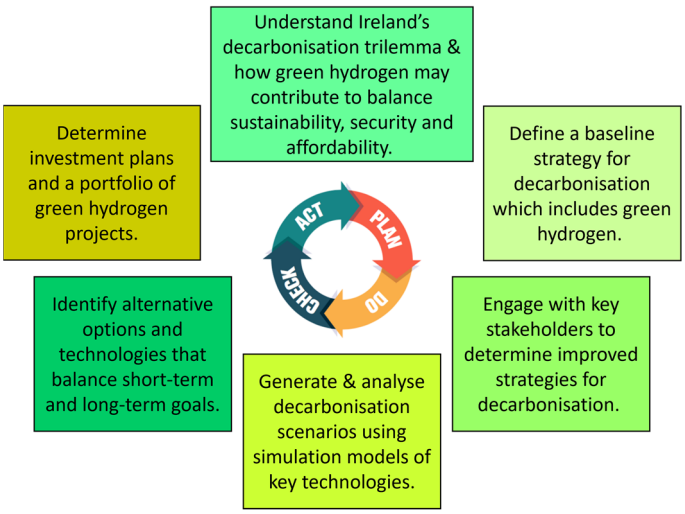


Figure 4. Process to determine a decarbonization strategy based on green hydrogen.

The injection of hydrogen into the Irish gas grid surely brings an opportunity to use existing and new infrastructure, enabling the distribution of clean gas. Mixing green hydrogen with natural gas to supply conventional gas combustion boilers for domestic heating systems is a potential approach to reducing CO_2 emissions from gas-heated homes in Ireland [5]. This requires a careful evaluation of the type of burner used and the materials used in its construction due to the different flame temperatures of hydrogen with respect to that of methane in the air [39]. Moreover, the long-term impact of hydrogen on materials and equipment needs to be carefully assessed because hydrogen may cause embrittlement of metallic and non-metallic materials [40,41]. In addition, to maintain the same thermal load, the fuel flow with hydrogen blending must be increased up to more than three times, and this affects the designs of the fuel/air mixer and gas valve [6]. The stakeholders did not agree on the fact that the Irish policy should prioritize the blending of green hydrogen into the gas grid. In fact, direct electrification using heat pumps is considered a potentially more efficient and cost-effective solution. However, it should be considered that, besides being used to supply heat to 710,000 households and businesses in Ireland, natural gas is also used to power 51% of electricity demand [42]. Industry customers and gas turbine customers might be the focus of use for low-carbon hydrogen due to their high-temperature needs. Air Source Heat Pumps are the technology that will have the lowest impact values in primary energy demand, freshwater eutrophication, photochemical oxidant formations and ozone depletion by 2050 [43]. The utilization of green hydrogen for heating may result in similar CO_2 emission reductions with respect to heat pumps, but greater investments will be required to establish a hydrogen gas grid; therefore, economic profits will be lower [44]. Such costs of conversion of gas networks to hydrogen may result in consumer heating

bills being even 50% higher when using hydrogen for heating than when using electric heat pumps [45]. According to stakeholder 2 (a Distribution System Operator), hydrogen blending into the gas network could be seen as 'wasting' precious green hydrogen, which could be better deployed to other sectors. Furthermore, some concerns arise for the gas quality in the Irish gas network when using only curtailed renewable electricity during a period with excess renewable power generation and despite using multiple injection points [46]. The use of curtailed wind power to produce green hydrogen will become increasingly viable as the installed capacity of renewable generation increases further, resulting in larger and more frequency mismatches between available generation and demand. At the point when the production of green hydrogen becomes very cost-effective and supply chains exist to decarbonize a few sectors of the economy, the use of dedicated plants for green hydrogen production may become viable and appropriate [47]. However, the assumption of using only curtailed wind electricity using to produce green hydrogen is not accurate because hydrogen will be produced by a mix of curtailed, constrained waste and dedicated electrical sources. In Ireland, an investment of €200 million by 2025 will enable the building of a wind farm at Firlough (northeast Co. Mayo), which will generate the electrical power to supply 45,000 homes and a plant that will convert electricity into hydrogen [48].

Another concern was expressed by one of the stakeholders and related to a possible economic challenge posed by the high degree of seasonality that characterizes the heat demand profile. This would require, as a buffer, large amounts of underground hydrogen storage if heating systems rely mainly on hydrogen. Moreover, the European Commission has indicated that direct electrification and energy efficiency will have a prominent role and will be leading drivers of the decarbonized European economy. The strategy addresses three main complementary concepts: a more circular and efficient energy system, greater direct electrification of end-use sectors, and the use of renewable and low-carbon fuels, including hydrogen, for end-use applications where direct electrification is not feasible [49]. The policy should promote the use of green hydrogen in Ireland, especially in the sectors where electrification is not possible, such as in heavy transport, e.g., using heavy-goods vehicles (HGV) [48,50,51], shipping [52], and aviation [53], in industrial high-temperature heat supply [5], and as a chemical feedstock in the industry [54]. In Ireland, road transport is responsible for most of the CO_2 emissions from the transport sector. This represents about 94% of all transport sector emissions, corresponding to 10.3 Mt CO_2 equivalent in 2021 [55]. It is worth noting that the costs of the infrastructure rollout for both hydrogen refueling and battery recharging technologies are similar for low market penetration levels (up to a few hundred thousand vehicles) [56]. The development of adequate and sustainable business models for the market of hydrogen-fueled vehicles will likely require cost-sharing between the government and industry, especially for the delivery of the first thousand hydrogen stations [57]. In aviation, besides the direct use of hydrogen as a CO_2-neutral fuel, synthetic kerosene may also be effectively used to decarbonize aviation using hydrogen and to keep the existing aviation infrastructure. It can be produced by various CO_2 sources such as biogenic point sources (biomass power plants, biogas upgrading, fermentation to alcohols), fossil point sources, i.e., industry/power sector emissions (gas power/CHP plant emissions, cement and steel plant emissions), or Direct Air Capture (DAC) from the atmosphere [58–60]. One of the stakeholders considered applications such as long-distance aircraft and maritime vessels considered feasible but still a long way off. The government policies, regulations and funding mechanisms in Ireland should consider the technology and manufacturing readiness levels. The use of hydrogen as an industrial feedstock is considered of low value. Its availability is essential for making certain important chemicals and fertilizers, though. Therefore, not using it is not an option.

Moreover, hydrogen can be used as a zero-carbon energy storage means and for zero-carbon dispatchable power generation by producing, storing, and reconverting it to electricity on-site [61,62]. It could be used to export renewable energy from Ireland (either using green hydrogen or green ammonia). Ireland has a significant amount of

hydrogen and electricity export, respectively, 85 TWh/annum and 95 TWh/annum [63]. Obviously, the potential of hydrogen is higher in those applications where the price gap between green hydrogen and the fossil alternative is limited. The price gap between conventional fuels such as natural gas, petrol, grey hydrogen, and green hydrogen will be completely overcome before 2050 [64]. The policy should also add hydrogen production to national incentives, such as the inclusion of synthetic fuels produced from green hydrogen as "eligible for credits," as affirmed by the Policy Statement from November 2021 on Renewable Fuels for Transport [65]. Moreover, Gas Networks Ireland may need to be ready for the receipt of hydrogen blended with natural gas through the Great Britain interconnectors since the UK Government's "hydrogen policy calendar 2022" suggests that [66].

Hydrogen engines and hydrogen fuel cells offer complementary use cases. Internal combustion engines tend to be more efficient under high loads: these range from heavy-duty trucking to construction. On the other hand, vehicles that frequently operate without any load (tow trucks or concrete mixer trucks) may be more efficient using a fuel cell. Green hydrogen may effectively support the decarbonization of heavy polluting industries such as chemicals and oil refineries in Ireland.

4. Hydrogen Production

The main types of hydrogen are their production processes are summarized in Table 2 [67–73]. Currently, the most important technologies for producing green hydrogen by means of electrolysis are the Alkaline cell, the proton exchange membrane (PEM) cell and the solid-oxide electrolysis cell (SOEC), which are schematized in Table 3. A comparison of the three technologies is included in Table 4 [74–76]. Furthermore, another remarkable pathway to produce green hydrogen is the thermochemical process using the heat rejected from a nuclear reactor (Figure 5).

Table 2. Types of Hydrogen.

Type of Hydrogen	Production Process	Advantages	Disadvantages	Cost
Grey	Steam Reforming Stage 1: high temperature (700–1100 °C) endothermic reaction: $CH_4 + H_2O \rightarrow CO + 3\ H_2$ Stage 2: low temperature (360 °C) exothermic reaction: $CO + H_2O \rightarrow CO_2 + H_2$	The production process is well-established and cheap compared to other types of hydrogen	10 kg CO_2/kg Ten tons of CO_2 are generated as waste per ton of hydrogen produced [67]	1.5 €/kg [68,69]
Blue	Steam Reforming with capture and storage of the produced CO_2 or carbon capture and conversion	Low carbon emissions when compared to Grey, cheaper than Green 1	Residual emissions of CO_2 and fugitive methane are present.	2–3 €/kg [68]
Turquoise	Methane Pyrolysis the natural gas is broken down into hydrogen and graphite or carbon granules	The production process is carbon-free (no CO_2 production at all)	Turquoise technology is promising but at the development stage [87].	Not
Green	Electrolysis of water $2H_2O$ + electricity + heat $\rightarrow 2H_2 + O_2$ Electricity and heat needed for the chemical reaction to happen are generated from renewable sources.	The production process is carbon-free (no CO_2 production at all)	Production requires a renewable plant, solar or wind. Costs are currently higher than Blue.	3.5–6 €/kg [68] Predicted in 2030: 0.7–1.8 €/kg [70]
Pink	Electrolysis is powered by nuclear energy or thermochemical process using very high temperatures from nuclear reactors.	CO_2 free production process but producing radioactive toxic waste in the long term	Non-circular and unsustainable production pathway; nuclear wastes are dumped in the oceans, where they remain a potential biological hazard for an extremely long time.	2.3–2.5 €/kg [71]

Table 2. *Cont.*

Type of Hydrogen	Production Process	Advantages	Disadvantages	Cost
From biomass gasification (no color)	Biomass gasification $C_6H_{12}O_6 + O_2 + H_2O \rightarrow CO + CO_2 + H_2 +$ other species Water shift reaction $CO + H_2O \rightarrow CO_2 + H_2 +$ heat	Low net carbon emissions, offsetting the CO_2 released from producing hydrogen with its consumption from plants' growth process [72]	High capital cost of equipment. High biomass feedstock costs.	4.7–6 €/kg [73]

Table 3. Most important electrolyzers technologies.

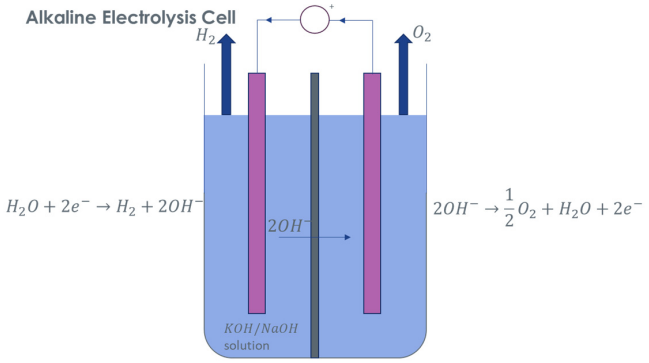
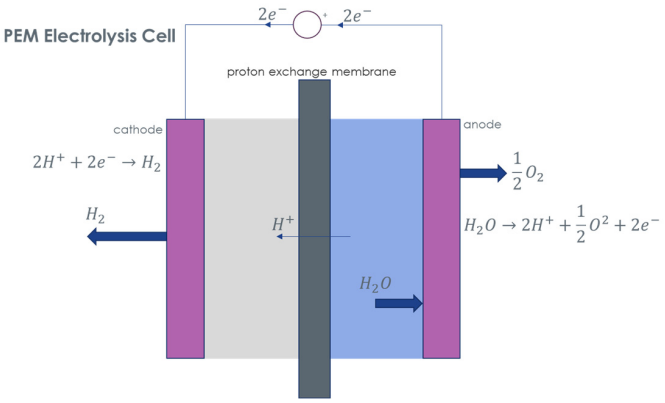
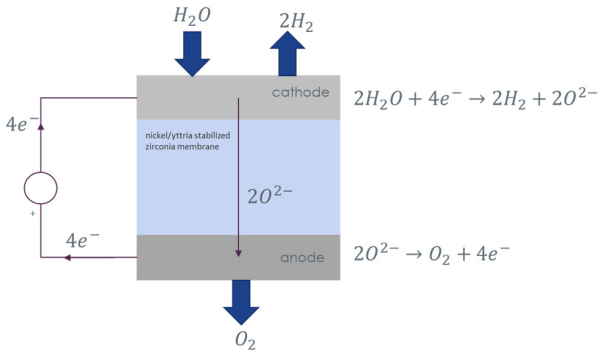
Type of Electrolysis Cell	Notes
Alkaline Electrolysis Cell 	• Introduced by Troostwijk and Diemann in 1789 • Operates at lower temperatures such as 30–80 °C • The electrolyte is an aqueous solution (KOH/NaOH) with a concentration of ~20% to 30%
PEM Electrolysis Cell 	• Idealized by Grubb in the early 1950s and developed in 1966 by General Electric Co. • compact design • high current density (>2 A/cm^2), high efficiency (~80%) • fast response • operates under lower temperatures (20–80 °C) • produced ultrapure hydrogen and oxygen as a by-product • Low current densities (<400 mA/cm^2), low operating pressure (~3.2MPa) and low energy efficiency (up to 73% for commercial units)
Solide Oxide Electrolysis Cell 	• Introduced by Donitz and Erdle in the 1980s • operates at high pressure and high temperatures of 500–850 °C • utilizes the water in the form of steam • some issues related to lack of stability and degradation • efficiency > 90% • not a commercial product yet

Table 4. Comparison between electrolyzers technologies [76].

	Alkaline Electrolysis	**PEM Electrolysis**	**Solid Oxide Electrolysis**
State of development	Commercial	Commercial	Laboratory
H_2 production in m^3/h (STP, per system)	<760, 2 MW	up to 450, 1.6 MW	-
Electrolyte	Alkaline solution	Solid polymer membrane	ZrO_2 ceramic doped with Y_2O_3
Charge carrier	OH^-	H_3O^+/H^+	O^{2-}
Cell temperature in °C	40–90	20–100	800–1000
Cell voltage in V	1.8–2.4	1.8–2.2	0.91–1.3
System power consumption (current) in kWh/m^3 H_2	5.4–8.2	4.9–5.2	-
System power consumption (future) in kWh/m^3 H_2 (HS)	4.3–5.7	4.1–4.8	-
Cold start time	Minutes–hours	Seconds–minutes	-
Advantages	Available for large plant sizes, cost, lifetime	No corrosive substances, high power densities, high pressure > 100 bar, good dynamics	High electrical efficiency, integration of waste heat possible
Disadvantages	Low current density, maintenance costs (the system is highly corrosive)	Expensive, fast degradation	Limited long-term stability of the cells, not suited to fluctuating systems, expensive

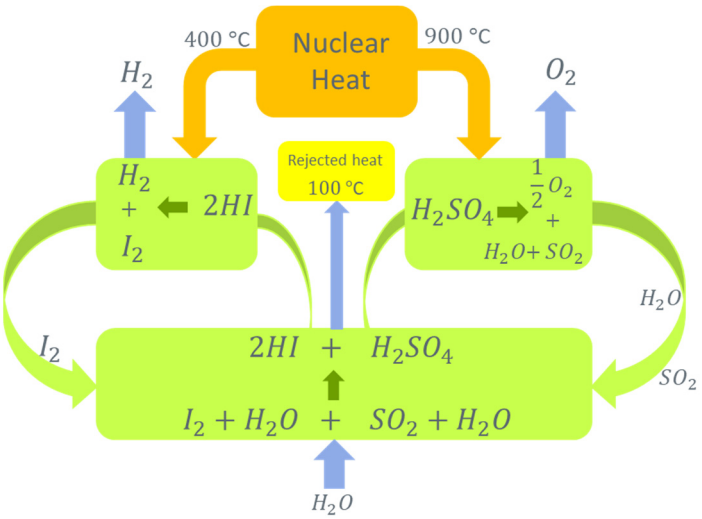


Figure 5. Thermochemical process to produce hydrogen using the heat rejected from a nuclear reactor.

The call for evidence addressed multiple aspects of hydrogen production in Ireland. It was asked whether blue hydrogen is currently produced in Ireland, and the stakeholders answered that, to their best knowledge, it is not produced in Ireland. The policy should not incentivize the production of blue hydrogen in Ireland because the country is heavily reliant on the import of natural gas. Blue hydrogen would not contribute to improving the energy security of the country. There are concerns about the effectiveness of technologies for carbon capture and sequestration (CCS). Existing CCS plants show that they might not be able to operate at the high capture rates that modelers assume in their future projections for blue hydrogen production. Literature has shown that several assumptions about the CCS model are possible, which result in different amounts of cumulative CO_2 captures. There is significant uncertainty around CCS deployment projections [77]. The stakeholders believe that to make blue hydrogen cost-effective in Ireland, if net zero is the goal to be

achieved, large subsidies might be required from the government, and large amounts of emissions capture are required to counteract the residual emissions of upstream methane and CO_2. Cost-effective blue hydrogen production would greatly depend on negotiating long-term contracts to secure low natural gas prices and reduce emission abatement costs. These could be achieved by converting captured CO_2 into high-value chemicals such that the volume of CO_2 to be stored would also be reduced, and the revenue from retailing the chemical by-products would offset blue hydrogen production costs [78]. A German study has reported that without additional policy measures, the production of green hydrogen using grid electricity is more expensive than blue hydrogen production even when electricity prices are low, and gas prices are high [79]. However, it must be considered that Germany has no potential for large-scale offshore wind compared to Ireland. The stakeholders consider low carbon hydrogen not a good solution for Ireland because recent literature reported that the GHG footprint of 'blue hydrogen' is so high that the enormous investment in infrastructure required for the production of 'blue' hydrogen would eventually not fulfill Ireland's decarbonization ambitions [80]. It is therefore suggested that green hydrogen produced using Ireland's vast offshore wind resource (at least 75 GW) would improve Ireland's energy security as it would be indigenously produced. Furthermore, it is believed that the utilization of solar PV could contribute to increasing the capacity factors of electrolyzers because the PV panels' production profile is somewhat complementary to wind turbines [81]. In addition, the levelized cost of solar PV is falling, and this could reduce the production cost of green hydrogen [82]. However, there are some technical and social barriers to the integration of green hydrogen into Ireland's energy systems. On the technical side, a known barrier with respect to green hydrogen production in Ireland is the lack of adequate offshore wind and hydrogen supply chains [83]. In countries like Japan, South Korea, China, and Germany, the creation of a supply chain has also helped to reduce the cost of the whole hydrogen value chain, making it globally an appealing resource for the decarbonization of society [84]. Other barriers are the lack of regulations for green hydrogen guarantee (Ireland could follow the example of many EU member states that are seeking to align their guarantee of origin with the EU-wide CertifHy [25]), lack of infrastructure to deploy green hydrogen [20] (there is a suggestion of using the existing gas network to deliver hydrogen, initially with blends of hydrogen up to 20% and then transitioning to a 100% hydrogen gas network), need for an upgrade of boilers to work either with a blend of hydrogen and natural gas or with pure hydrogen. In fact, the gas network might be broken into segregated sections, some with bio-menthane, others with blends of hydrogen and others with pure hydrogen. In the future, most sections could be segregated with pure hydrogen. The stakeholders do not seem concerned about the high cost of green hydrogen injected into the Irish gas network, which is 9–11 €/kg (and will drop to 6–8 €/kg soon), although it has been shown that 84% of the hydrogen supply potential in Ireland is located not farther than 100 km from the nearest injection point [85]. The policy should create demand for green hydrogen by setting ambitious targets for CO_2 reduction, especially in the transport sector. Heavy-goods vehicles (HGV) transport can be a starting point to create a hydrogen market, thereby enabling the scale-up of green hydrogen production over time [20]. Moreover, the policy should create market signals for zero carbon dispatchable generation, which can effectively use green hydrogen. This would be aligned with the EU goal of improving the electricity markets to attract investment in technologies that can compensate for the variable electricity production of renewable energies, like energy storage (this may include storage of green hydrogen) [86]. Moreover, exportation opportunities of green hydrogen should be considered to allow potential customers to contribute to the funding of a large-scale production and storage infrastructure in Ireland [63].

5. Hydrogen Distribution and Delivery

The stakeholders think that green hydrogen produced from offshore wind farms could be a second energy vector to ensure the security of supply [88]. Hydrogen transmission and

distribution networks will have to be deployed to allow large-scale adoption of hydrogen and displacement of fossil fuels. Forthcoming policies are expected to play a crucial role in removing non-economic barriers and fostering a higher acceptance of economic risk from public funding, which is required for the deployment of hydrogen infrastructures [89]. The existing natural gas infrastructure could be upgraded to enable the transportation of hydrogen. However, the long-term impact of hydrogen on materials and equipment needs to be assessed [40]. In Ireland, transmission pipes are constructed from steel, whereas most of the distribution pipes are nowadays constructed from polyethylene (PE) [90]. The replacement of old ductile and cast iron mains and services with PE pipes in the Irish distribution network has made them compatible with hydrogen. Hydrogen pipelines are expected to be more efficient and less expensive than most of the conventional long-distance electricity transmission lines, perhaps with the only exception of some high-voltage Direct Current transmission lines [91].

The roll-out of renewable gas, such as a mixture of bio-methane and hydrogen, might reduce the reliance on Carbon Capture and Storage (CCS) and contribute at the same time decarbonization of the heat and transport sectors. Bio-methane is expected to play a role in the decarbonization of the heat sector in the short term because it is chemically more similar to natural gas and, therefore, easier to blend than hydrogen [92]. Moreover, while the blending of 20% of H_2 by volume in natural gas is considered tolerable for most appliances, it can be foreseen that 30% of the appliances may not cope well with this quantity of hydrogen [93].

In the UK, the effectiveness of the blending of natural gas and hydrogen is going to be demonstrated, and a proposal on a Regulation for Alternative Fuels Infrastructure establishes an obligation for the Member States to ensure a minimum coverage of refueling points for hydrogen, dedicated to heavy and light-duty vehicles, by 31 December 2030 [94]. Purchasing incentives for FCEVs should be part of the policy until the costs of FCEVs are as low as those of petrol and diesel vehicles. A national hydrogen refueling network is expensive, and the project developers need to see a firm and stable demand for several years to be incentivized to invest in such an infrastructure. Similarly, the market success of electrolysis to produce green hydrogen requires the establishment of an adequate demand [95]. Customers need to see a cheap and resilient fuel supply to be incentivized to quit the abundant and convenient fossil fuels. The use of a surplus of intermittent renewables to produce green hydrogen can effectively reduce its cost and make hydrogen fuel cell vehicles more competitive with conventional vehicles [96]. Finally, Ireland has enough wind capacity to produce green hydrogen to fulfill its demand and for exportation; therefore, the policy should not incentivize the import of green hydrogen from neighboring countries (the UK and France). A green hydrogen supply and delivery infrastructure for refueling stations are schematized in Figure 6.

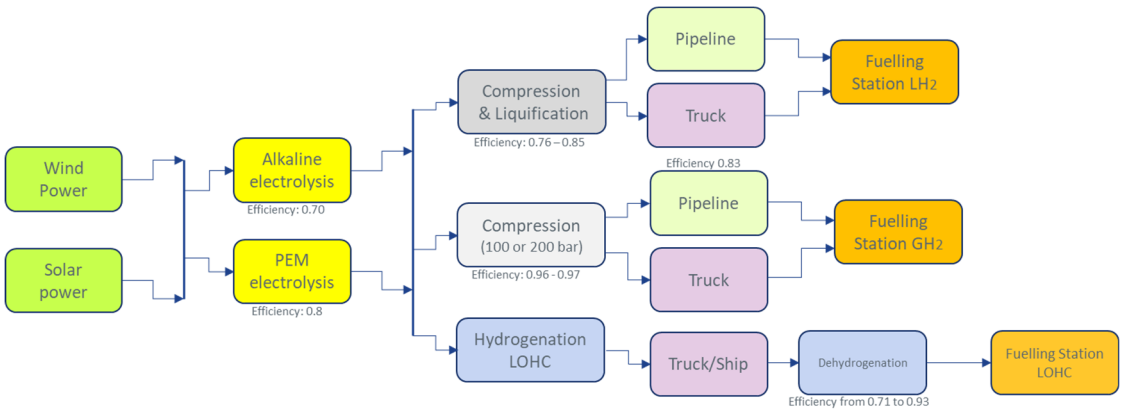


Figure 6. Pathways for green hydrogen production, transport, and consumption by fueling stations.

6. Hydrogen Consumption

Most of the hydrogen produced in Europe is consumed at the point of production. In Ireland, centers of production should be built around hydrogen demand clusters (e.g., coastal industrial sites near offshore wind farms) [97]. Clusters of industries related to chemical products, power generation, production technology, oil and gas, and automotive and aerospace technology may foster the development of hydrogen technologies nearby [98]. In the transport sector, vehicles that can be powered by green hydrogen include cars, buses, coaches, trains, ferries, ships, boats for inland waterways, and regional airplanes [99]. Green hydrogen is seen as a means for indirect electrification of vehicles that are not particularly suitable for batteries, for example, long-distance heavy-duty trucks. They would require a very large battery capacity. The weight of the batteries would reduce the effective capacity of the truck to carry goods, the cost of the vehicle would be very high, and the charging time would be too long [100]. The recent literature showed that there are concerns in relation to batteries used in electric vehicles regarding the high requirement of energy and high level of carbon emissions throughout their fabrication process, their usage for their whole lifetime, and their disposal and recycling process [101]. Fuel cells powered by green hydrogen would overcome many problems of the utilization of batteries in electric vehicles [102]. The Lighthouse initiative showcased the smart integration of transport and power sectors, i.e., "wind to wheel" via green hydrogen [103]. In Ireland, a hydrogen transport hub is going to be developed and demonstrated at the Port of Galway in the GH2 project to produce green hydrogen fuel and to supply public and private vehicles, such as buses and trucks initially, followed by maritime and aviation. The plan is to connect electrolyzers to the national grid at the Galway 110 kV grid substation and to supply them with green electricity through a renewable energy Power Purchase Agreement supported by a guarantee of origin [104]. Galway's hydrogen valley will significantly contribute toward demonstrating Ireland's potential as a significant hydrogen producer and exporter [105]. In the transport sector, green hydrogen has the potential to significantly reduce greenhouse gas emissions. Stakeholders who responded to our call for evidence are aware that fuel cell electric vehicles (FCEVs) require less energy to travel the same distance with respect to conventional petrol/diesel vehicles [106]. In fact, tank-to-wheel efficiencies are between 40 percent to 45 percent for vehicles based on internal combustion engines and approximately 50 percent for FCEVs [107]. Moreover, an FCEV fueled by hydrogen obtained from a fossil-based production pathway (via SMR of natural gas) exhibits between 5% to 33% lower well-to-wheels (WTW) fossil-energy use and 15–45% lower WTW GHG emissions than a gasoline conventional internal combustion engine vehicle [108]. Highly resistant and cost-effective hydrogen fuel tanks can be manufactured [109], even though the volume of the tanks is sometimes deemed unsatisfactory with respect to the desired utilization of the vehicles [110].

One of the stakeholders reported a cost of 12 £/kg for green hydrogen (including VAT 20%) for the UK's market. It is believed that such cost will fall to 4–5 £/kg soon if the electricity sector embraces it and then to 2–3 £/kg by 2030 when its national demand will become significant. In 2050 it is foreseeable that green hydrogen will be used to power more heavy vehicles (both road and non-road) and those light vehicles that require rapid refueling.

In the domestic sector, blending hydrogen in natural gas to supply households' heating systems is considered technically achievable but with limited potential of achieving a significant GHG reduction. Replacement of a conventional natural gas-fired boiler with a new hydrogen-fired boiler is also considered straightforward because it does not require any upgrades to the wet central heating and hot water system. In addition to direct flame combustion boilers, green hydrogen could also be used for domestic heating to power fuel cell micro-CHPs, catalytic boilers and gas-powered heat pumps [5].

The industries that should be incentivized by the policy to consume green hydrogen are refineries as well as ammonia and methanol producers. However, it was observed that in contrast to renewables that can readily replace fossil fuel power, green hydrogen

might require investment by the end-users to replace equipment using natural gas. For this reason, tax credits for green hydrogen production may not be sufficient, and an investment incentive for the end users may be required [111]. Indeed financial incentives for green hydrogen uptake already introduced by 20 countries include incentives for investment in hydrogen technology, incentives for the use of renewable green hydrogen in industry, financial incentives for vehicle manufacturers, and purchase and building hydrogen refueling stations [112].

Furthermore, the policy should incentivize the consumption of hydrogen to generate electric power for covering periods of very low wind and solar production. In [113], a 'Green Hydrogen' scenario was formulated, where 1600 MW of hydrogen electrolysis capacity installed in Ireland would produce 3.9 TWh of hydrogen from 5.6 TWh of electricity at an average cost of electricity used for electrolysis of around 15 €/MWh. Then all the green hydrogen produced would be utilized for electricity generation by 900 MW of retrofitted fossil gas-fired capacity in the Republic of Ireland and 300 MW in Northern Ireland. In such scenario the hydrogen-fired generation units would be dispatched when day-ahead prices are greater than 80 €/MWh, thereby displacing fossil gas-fired generation during such hours.

7. Integration of Hydrogen in the Power System

In Ireland, the Transmission System Operator (TSO) envisages that many existing peat, heavy oil and coal plants will close over time and will be replaced by gas-fired generation, which currently already plays a fundamental role in meeting the adequacy needs of the country. The Government considers its policy of prohibiting the exploration for and extraction of coal, lignite, and oil shale as fundamental to achieving the implementation of a circular economy and has included it as part of the Circular Economy Bill 2021 [114]. In response to these and other changes, to support economic development and energy security, the development of lower carbon gas-fired generation is a priority set out by the Government's policy on the security of electricity supply, and the need to deliver about 2 GW of such generation by 2030 is recognized in the National Development Plan 2021–2030 and the Climate Action Plan 2021 [115]. As these fossil fuel-based units are still likely to be significant GHG emitters, it will be important to look for ways to decarbonize their operation and reduce their importance to the electrical power system in the long term. CCS technologies could be helpful in the decarbonization of the gas-fired generation fleet as they will be gradually refurbished, and the decisions of large investments in new technologies will likely also consider the goal of achieving deep decarbonization [116].

There is also an opportunity to retrofit existing gas-fired generation to use hydrogen, the installation of hydrogen turbines and use them as backup systems for intermittent renewable sources and use fuel cells to generate electricity [7]. Fuel cells have the potential to have the highest efficiency in terms of conversion of hydrogen to electrical energy but are currently very expensive at this scale (e.g., in comparison with battery storage) [117]. In this context, a study found that CCGT (Closed Cycle Gas Turbine) technology in conjunction with the HVDC cables for electricity transport has been evaluated to be the most cost-effective pathway for hydrogen electricity reconversion, followed by the Solid Oxide Fuel Cell (SOFC) technology for net zero carbon scenarios for Germany in 2050 [118].

Green hydrogen could also help to integrate elevated levels of variable generation into the electricity system by creating a variable electricity demand that utilizes the renewable sources not used to supply other loads to produce green hydrogen, which can be stored in the local gas grid and used for decarbonizing domestic heating, transport, and industry sectors. In fact, curtailment of renewable generation can be alleviated using congestion management methods that exploit flexibility options alternative [119], such as an optimized operation of controllable generation units and green hydrogen production.

Figure 7 shows the integration of green hydrogen production in the electric grid using electricity that would otherwise be curtailed to supply electrolyzers. The produced hydrogen can be stored and distributed to various consumers when demand occurs. In

power systems dominated by variable renewable generation supplying both firm and flexible electricity loads, green hydrogen production can act as a new flexible load that can effectively contribute to better utilization of the generation assets. When excess generation capacity is available during most of the hours of the day, flexible loads (especially the small ones) can operate at high-capacity factors.

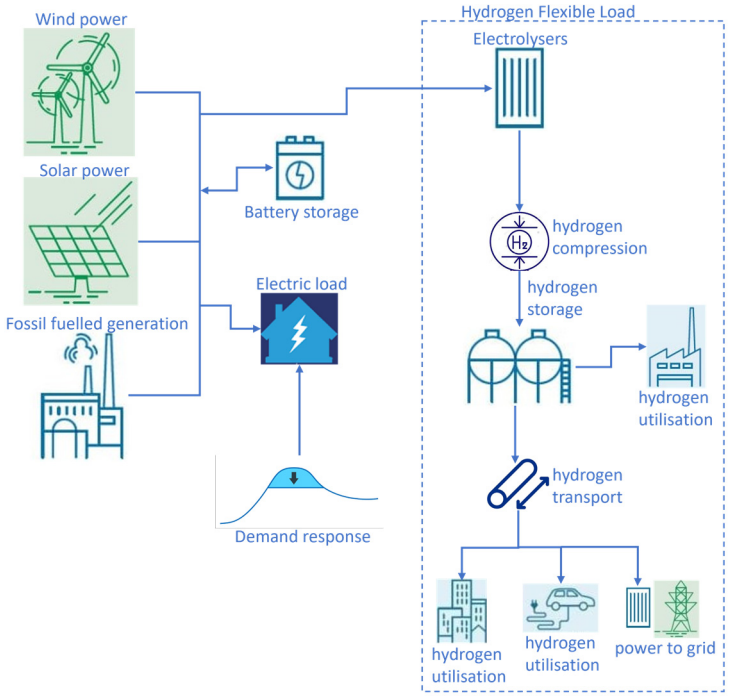


Figure 7. Hydrogen production is integrated into the electrical grid as a flexible load.

Flexible loads such as electrolyzers for hydrogen production could contribute to reducing the average cost of electricity by allowing better exploitation of the generation capacity that was installed for the supply of firm loads. In fact, the electricity that is used to supply the electrolyzers would be lost if not used for hydrogen production; on the other hand, the produced hydrogen can be stored and converted back to electricity when needed. In many system configurations, the variable renewable electricity assets supplying firm loads at current energy costs could supply about 25% or more additional flexible loads with 10% or less capacity expansion, at the same time reducing average electricity costs by 10–20% [120]. The electrolyzers used for hydrogen production can be seen as an additional flexible load that could be added to the combination of load-following generators, energy storage, expansion of grid transmission, and other flexible loads to effectively fill the gaps existing between non-dispatchable generation and inflexible demand [120,121].

The design of an energy system, including hydrogen production using potentially curtailed renewable power, has some challenges, however. For example, if power curtailment occurs only for short periods of time, the electrolyzers would work as low-capacity factors when only absorbing the spikes of excess power, potentially reducing operational efficiency and reducing revenues under existing business models. An approach to mitigate this risk is additional storage to better manage excess generation, resulting in higher equipment costs or new business models that provide appropriate financial recognition for this demand side flexibility and the production of low carbon hydrogen when electrolyzing when the entire power system is being powered by high levels of renewables. Moreover, if hydrogen generation plants are installed close to areas with high wind power production, then the need for grid reinforcement may be reduced [122].

A model for estimating the amount of green hydrogen which can be produced from dispatched-down wind power considering a grid-connected electrolyzer system was proposed in [123]. The model can be easily extended, including a battery energy storage system

operating as an energy buffer between the wind farm and the electrolyzer system. The battery is charged with the dispatched-down wind energy when that is not used for the supply of the electrolyzer. An electrolyzer requires at least a certain fraction of its rated power to work stably, normally 25% of the rated power [123]. Note that the hydrogen production cost of an electrolysis plant is marginally affected by the capacity factor. In fact, an electrolysis plant with a 25% capacity factor has approximately 11% higher production cost than an electrolysis plant with a 95% capacity factor [124]. Equations (1)–(3) show the model, including a battery storage system, using the same notation that was used in [123]. The meaning of the symbols used in Equations (1)–(3) is explained in Table 5. The model assumes that time is discretized in 10 min intervals.

$$E_{H_2} = E_b + E_{grid} \tag{1}$$

$$E_b = P_e \cdot T_{\Delta P_{t,b} \geq P_e} + \sum \Delta E_{t,b_{\Delta P_{t,b} < P_e}} \tag{2}$$

$$E_{grid} = \left(25\%P_e - \sum \Delta P_{t,c_{\Delta P_{t,b} < 25\%P_e}}\right) \cdot T_{\Delta P_{t,b} < 25\%P_e} \tag{3}$$

Table 5. Legend of symbols.

Symbol	Meaning
E_{H_2}	wind energy used for electrolyzer system
E_b	dispatched-down wind energy used for electrolyzer system using battery storage
E_{grid}	grid electricity used for electrolyzer system
P_e	electrolyzer rated power
$\Delta P_{t,c}$	average wind farm dispatched-down power in 10 min. used by the battery-electrolyzer system at time t
$\Delta E_{t,b}$	battery energy in 10 min. used by the electrolyzer at time t
$T_{\Delta P_{t,b} \geq P_e}$	total time when $\Delta P_{t,b} \geq P_e$
$\Delta E_{t,b_{\Delta P_{t,b} < P_e}}$	wind farm dispatched-down wind energy in 10 min at time t when $\Delta P_{t,b} < P_e$
$\Delta P_{t,c_{\Delta P_{t,b} < 25\%P_e}}$	average wind farm dispatched-down power in 10 min. at time t when $\Delta P_{t,b} < 25\%P_e$
$T_{\Delta P_{t,b} < 25\%P_e}$	total time when $\Delta P_{t,b} < 25\%P_e$

The energy consumed by the electrolyzer system over a certain period of time (e.g., one year) is delivered partially from the grid and partially from the battery (1). The energy supplied by the battery to the electrolyzer is the sum of two terms (2). The first term of the sum in (2) is the total energy supplied by the battery when its state of charge is sufficient to supply the rated power P_e to the electrolyzer, for the time period T (when $\Delta P_{t,b} \geq P_e$). The second term of the sum in (2) represents the energy supplied by the battery to the electrolyzer when the state of charge of the battery is not sufficient to supply the rated power. The battery will supply the energy that is stored in it, whereas the remaining energy will be supplied by the grid. The grid supplies the energy required to ensure that the electrolyzer can be continuously powered with the minimum power required, e.g., $25\%P_e$ for the whole time period T when the battery is not sufficiently charged to supply that minimum power (3).

System sizing is of fundamental importance for an accurate estimation of deployment costs of wind-electrolyzer and wind-battery-electrolyzer systems and for the policymaker to make effective decisions on whether and how to incentivize green hydrogen production from curtailed wind power. If the size of the electrolyzer is too small compared to that of the wind farm, a large percentage of curtailed wind power will not be used to produce green hydrogen and will be wasted. Moreover, the size and utilization of the battery storage system used as a buffer for maximizing the harvested curtailed wind power will depend on the size of the electrolyzer as well. A too-large battery will not be necessary to supply a small electrolyzer. The results of the analysis of the potential performance of electrolyzer plants of various capacities with respect to the potential daily green hydrogen production using curtailed power under current Irish electrical system scenarios are shown

in Figure 8. Figure 8a shows that the amount of hydrogen produced increases with the installed capacity of the electrolyzers. In order to operate the system exploiting a high amount of curtailed energy, the electrolyzers must be coupled with a storage system. The peak size of the storage grows with the size of the chosen electrolyzer capacity as shown in Figure 8b. However, larger electrolyzer capacities lead to better exploitation of available storage capacity as well, with a maximum storage daily utilization that grows with the size of the installed electrolyzer capacity (Figure 8c). Also, the unused curtailed power decreases when the system size increases (Figure 8d,e). Finally, Figure 8f shows that utilization factors of electrolyzers decrease when the system capacity increases.

Note that the current demand for hydrogen in Ireland is only 2000 tons per year which may be fulfilled by the full-year production of a 12 MW electrolyzer [125]. If the current hydrogen demand were entirely supplied by electrolyzers powered by curtailed wind power, less than 10% of the curtailed wind power would be used. On the positive side, electrolyzer utilization would be higher than 25% enabling quite cost-effective production of hydrogen. Figure 8 provides information on the system operation when the demand will increase from the current 5.5 t/day up to 30 t/day. Data show that increased hydrogen demand up to 5.5 times higher than the current demand could be entirely fulfilled by curtailed wind power. The Levelized Cost of Hydrogen (LCOH) using curtailed wind power was evaluated for different wind farms in Ireland, and it was found to be very high (greater than 13 €/kg and up to 23–24 €/kg) [85].

There is clearly a trade-off between electrolyzers and hydrogen storage implementation costs and the benefits associated with higher hydrogen production using more curtailed power from renewables. The size of the hydrogen production plant should be determined considering the desired payback time of the investment.

Furthermore, in addition to large electrolyzer plants that use wind power to produce green hydrogen, the future Irish power system (wherein both electricity and hydrogen are needed) might include some prosumers owning grid-connected PV-hydrogen systems, which will allow for addressing interesting use cases accounting for the building and transport sector coupling [126].

Prosumers that will adopt hybrid renewable energy systems, including solar-powered electrolysis and a hydrogen storage unit, will obtain several benefits, such as increased system reliability and flexibility, reduced CO_2 emissions and energy costs.

Finally, it is worth noting that electricity can be generated from wastes by means of different technologies, such as anaerobic digestion (using a gas engine), gasification (using a gas turbine), pyrolysis (using a gas turbine), incineration (using a steam turbine) [127]. The electricity output of waste-to-energy plants may be used to produce green hydrogen, especially the amount that would be otherwise curtailed because of low demand or high renewable generation (as these plants continue to incinerate waste even when their electricity output is curtailed) [128].

In order to maximize its effectiveness, the policy should support hydrogen production from both curtailed wind power, curtailed power from waste-to-energy plants, grid power (with GHG emissions lower than the well-to-tank threshold of 24.5 gCO_2e/MJH_2 [104]), and congested power. The latter is the power that can be consumed by power-to-hydrogen conversion systems to reduce congestion in the grid in case of a high level of penetration of renewables [129].

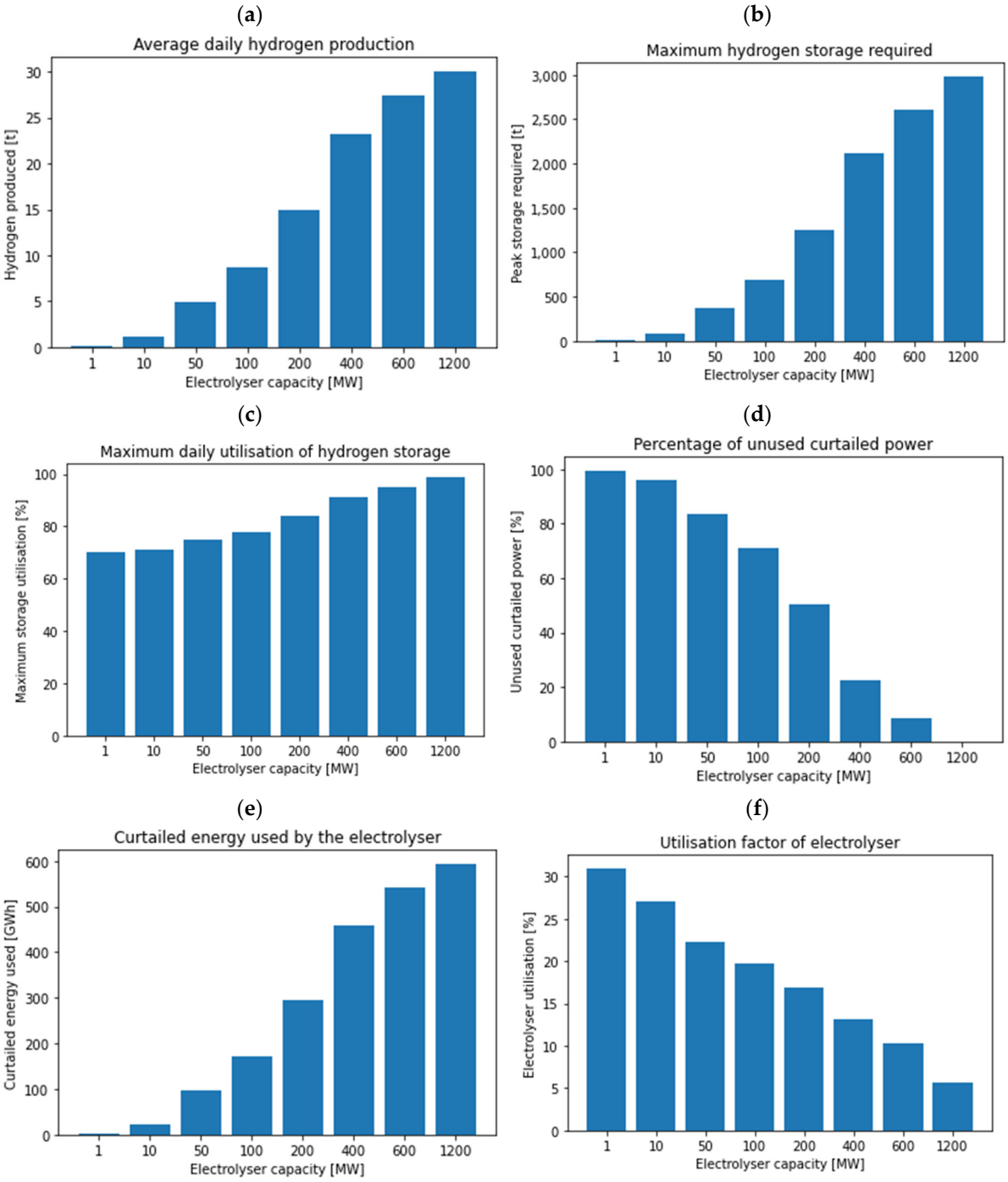


Figure 8. Potential hydrogen production using curtailed wind power in 2020 (EirGrid data). (**a**) Average daily hydrogen production; (**b**) maximum hydrogen storage required; (**c**) maximum daily utilization of hydrogen storage; (**d**) the percentage of unused curtailed power; (**e**) curtailed energy used by the electrolyzer, and (**f**) utilization factor of electrolyzer.

8. Recommendations

The analysis of hydrogen opportunities in Ireland leads to some recommendations regarding the development of a hydrogen policy to promote the use of hydrogen and its benefits [130].

8.1. Recommendation 1: Demonstrate the Use of Green Hydrogen in Road Transportation

The demonstration of green hydrogen in road transportation has already started with fuel-cell buses in Dublin (the operational cost parity between diesel and hydrogen-fueled buses is expected by 2030 [131]). Private, public and industrial vehicle demand might even saturate hydrogen production capacity while delivering reduced operational costs and GHG emissions [132]. Existing road vehicles include cars (Toyota and Hyundai), buses (Wrightbus, a manufacturer based in Ballymena, CaetanoBus), vans (Renault and LDV), trucks (Hyundai, Nikola), Refuse Collection Vehicles (FAUN), which are all almost unknown to local communities. These demonstrations should be extended to prove the reliability of the technology and its benefits such that the technology will be considered mature for adoption when the price of green hydrogen is close to that of gasoline [133]. In addition, an adequate infrastructure of refueling stations and incentivization mechanisms should be considered to support the envisaged penetration of FCEVs. Risks associated with the storage of both liquid hydrogen and compressed hydrogen must be carefully evaluated [134].

8.2. Recommendation 2: Build-Up Additional Renewable Energy Sources for Green Hydrogen Production and Provide Support for Green Hydrogen Production Using Curtailed Renewable Power When Applicable

Green hydrogen is the preferred type of hydrogen because it does not emit any carbon. The Renewable Electricity Support Scheme (RESS) will provide support financed by the PSO Levy to incentivize private capital investment toward the achievement of the target of generating up to 80 percent of our electricity from renewable sources by 2030 [135]. Such a policy will also facilitate the construction of new facilities to produce green hydrogen from renewables and supply part of the demand in a cost-effective manner. An example of this is the project for the first green hydrogen plant in County Mayo, which has recently received approval [48,136]. The plant will make use of 13 turbines and an electrolyzer plant. At the same time, there are cost-effective opportunities to use part of the excess electricity produced by existing renewable power plants to supply power to electrolyzers which should be exploited to fulfill part of the green hydrogen demand.

8.3. Recommendation 3: Incentivize the Production of Green Hydrogen by Introducing Quotas for Green Hydrogen to Drive Demand in Case Its Selling Price Is Too High and Allow Auctions for Hydrogen Production Using Electricity from Renewables

In the long term, green hydrogen is the most acceptable technology. It is recommended to investigate the barriers that prevent the price of green hydrogen from being closer to the price of steam-methane reforming hydrogen, including the imported "grey" hydrogen. If the price of green hydrogen does not decrease by 2030, thanks to the adoption of cheaper electrolyzers and the achievement of scale economies, production can be incentivized by introducing quotas, a measure that is already under consideration by the European Commission. In addition, the policymaker should identify the opportunities for the communities (such as industries, heat users, cement factories, data centers, etc.) to participate directly in green hydrogen production projects through auctions, to make the technology mix of renewable energy projects broader, including electrolyzers, and to increase system security and sustainability while ensuring that cost-effective solutions can be implemented, as recommended by the Renewable Electricity Support Scheme RESS2. In addition, the policy could introduce an incentive for prosumers that want to produce, store and consume green hydrogen using renewable energy to power electrolyzers (e.g., solar energy).

8.4. Recommendation 4: Demonstrate the Use of Hydrogen as a Flexibility Provider to Perform Power System Balancing

Reduced scale experiments could show how hydrogen storage can be used as an alternative to batteries for balancing fluctuations of loads and renewables. Operation of small-size electrolyzers and fuel cells can be first demonstrated in relatively small power systems, such as microgrids. Electrolyzers for hydrogen production can be seen as a flexible

load that can help the TSOs (Transmission System Operators) to manage the variability of wind power generation and to maintain the system stability and security. The DS3 program "Delivering a Secure, Sustainable Electricity System" (or a successor of it) could be updated to enable electrolyzers to provide system services. Moreover, if larger green hydrogen production sites (e.g., electrolyzer plant larger than 100 MW) would be made bidirectional, they could be given the same status as energy storage in DS3.

8.5. Recommendation 5: Investigate and Demonstrate the Blending of Hydrogen into the Existing Gas Network

A feasibility investigation, performing experiments aiming at demonstrating the safe and reliable operation of residential end-user devices connected to the Irish gas network over the range between 2% and 20% hydrogen blending, has already been performed by Gas Networks Ireland and University College Dublin (UCD) Energy Institute [137]. The plan of blending 20% to 50% of hydrogen in the existing gas network should be actuated progressively. Currently, it is not clear whether the Irish gas network, which is almost fully made of polyethylene, would allow it to blend 50% hydrogen in volume into natural gas and operate the network, ensuring its safety and reliability. Therefore experimentation should continue testing of higher than 20% hydrogen blends, up to 100% hydrogen. In the long term, opportunities and costs to convert portions of the existing distribution network to a pure hydrogen network should also be evaluated. Low-cost green hydrogen boilers are now arriving, which are more suited to deliver energy to existing buildings with simple upgrades, requiring only minimal home improvements. A revision of the applicable legislation may be required to achieve this objective.

8.6. Recommendation 6: Investigate the Feasibility of Low-Carbon Hydrogen Using Carbon Capture and Storage Technologies Applicable to Geological Basins and Structures in Ireland

The cost of low-carbon hydrogen (blue hydrogen) is currently lower than the cost of green hydrogen, and blue hydrogen is considered a viable opportunity by the European Commission and in several European countries. Reforming natural gas into hydrogen with CCS to produce blue hydrogen is considered the most competitive process also in Ireland. Ireland has commenced research and demonstration activities on CCS at the Whitegate oil refinery in the Cork harbor. It is recommended to continue with a reduced-scale demonstration of CCS technologies and to investigate their applicability to hydrogen production because they could be a cost-effective alternative to green hydrogen in the medium term. Storage of carbon dioxide (CO_2) in geological basins and structures is technically simpler than storage of hydrogen and might be appealing in the short term. In fact, hydrogen is about 22 times less dense than CO_2. Therefore, more space and pressure will be required for hydrogen to store the same mass amount of gas. Hydrogen's lower viscosity and molecular weight could result in its leakage because its diffusivity is higher compared to CO_2, and, therefore, hydrogen storage will require a higher capacity sealing system than CO_2 [138]. In the UK, the H2Teesside project aims to produce 1GW of CCUS-enabled blue hydrogen from 2027. The project will capture and send for storage up to 2 million tons of CO_2 per year, equivalent to capturing the emissions from the heating of one million UK households [139]. In Ireland, further geological and engineering studies are needed to determine actual CO_2 storage capacities of onshore and offshore geological basins and structures. The island of Ireland has a theoretical capacity for CO_2 storage in natural structures of 93115 Mt. A thorough geological assessment based on deep geological data is needed for each basin or structure to determine the exact amount of theoretical and effective capacities. More geological data should be obtained from drilling exploration wells from the existing platforms, and the data should be used to conduct reservoir simulations to investigate the effect of CO_2 injection on the structure stress and to identify possible leakage points.

8.7. Recommendation 7: Robustly Evaluate the Feasibility of Large-Scale Hydrogen Storage in Salt Caverns

In the North of Ireland, there are a few underground salt layers that could be used to build hydrogen storage facilities. Seven salt caverns located at Islandmagee in County Antrim (Northern Ireland) will be used to store up to 500 million cubic meters of gas in the salt beds 1500 meters below Larne Lough [140]. These caverns could also be used to store hydrogen. Feasibility of hydrogen storage in salt caverns is required to prove that hydrogen can be used in the future as a flexible resource to balance the fluctuations of renewables, given the 2030 scenario where the expected installed capacity of intermittent renewable sources will be three times higher than the forecasted average load. In the US, salt caverns have been used for decades to store hydrogen on the Gulf Coast. Big companies such as Mitsubishi Power and Siemens are looking for partnerships to convert large natural gas reserves in giant underground salt caverns into hydrogen storage sites in both the eastern and western parts of the country. The policymaker should promote a similar process in Ireland to support decarbonization through large-scale hydrogen production and storage and to identify opportunities for using salt caverns and aquifers for hydrogen storage.

8.8. Recommendation 8: Establish a Greenhouse Gas Emissions Standard for Low-Carbon Hydrogen That Meets Multiple Relevant Criteria

Low carbon hydrogen, obtained through well-understood chemical processes, is currently cheaper to obtain than green hydrogen obtained from the electrolysis process. Without any prejudice toward the path towards full utilization of electrolyzers for green hydrogen production, the policymaker should carefully consider the possible advantages of other technology pathways to produce green hydrogen. Following the UK example, it is recommended to establish a GHG emission standard meeting relevant criteria such as: neutral with respect to technology, accessible, cost-effective, user-friendly, transparent, compatible with other schemes in the energy sector and with other countries' standards: ambitious, accurate, robust, including penalties for fraud, and predictable [141].

8.9. Recommendation 9: Demonstrate Storage and Conversion Technologies Such as Power-to-Gas and Gas-to-Power Conversion in Microgrids

Irish microgrids such as those installed in Cork, Sligo, or Galway can be used to demonstrate a "Power-to-Power" storage and conversion system based on hydrogen, comprising an electrolyzer converting electricity into hydrogen (Power-to-Gas) and a fuel cell system converting the hydrogen stored back to electricity (Gas-to-Power). The different configurations of storage in microgrids, battery-based, hydrogen-based and hybrid combinations of battery-hydrogen-based, should be evaluated and compared against each other to identify the one enabling the highest exploitation of renewable generation and eventually the most cost-effective solution for the Irish market.

9. Discussion

A comparison of low-carbon hydrogen strategies of EU countries reveals that the countries have different objectives with respect to the production, consumption and transport of hydrogen (Table 6). In contrast to other European countries, Ireland does not have a national strategy on hydrogen yet (Figure 9). The Government of Ireland has recently run a consultation process to gather the views of stakeholders and interested parties to inform the development of a hydrogen strategy for Ireland. The consultation has now been closed, and strategy might be available shortly. It has been recognized in the Climate Action Plan 2021 that green hydrogen has the potential to support decarbonization across several sectors and that it could play a significant role in sector coupling, i.e., the increased integration of energy supply and end-use sectors and minimize the overall cost of decarbonization across all sectors. A hydrogen strategy for Ireland is one of the key priorities of the National Energy Security Framework to ensure the current and long-term security of affordable energy supply. The main outcomes of the study presented in this paper are the nine recommendations of Section 9. They have been derived from a thorough analysis of a

detailed literature review and a survey of key stakeholders of clean hydrogen in Ireland, as explained in Section 2. Furthermore, the main findings of the performed study have been further analyzed using the framework proposed in Figure 1. The findings are also matched with some of the most important key comments or questions that the Irish government provided in their consultation document (Table 7).

Table 6. Comparison of low-carbon hydrogen strategies of EU countries.

Countries	Production	Consumption	Transport
Italy [15]	Electrolyzer capacity installation target of 5 GW by 2030 (12.5% of the European target).	Dedicated pipelines and adapted natural gas ones could likely accommodate half of the hydrogen trade, while the other half could be mainly transported on ships as synthetic fuels.	Prevalent consumption envisaged is blended with natural gas and injected into the natural gas network.
Germany [142]	Green hydrogen is produced by electrolysis from renewable electricity. Blue hydrogen is obtained from natural gas by means of steam reforming using the carbon capture and storage (CCS) process.	Transport network connecting ports and wind parks by using (to some extent) already existing infrastructure such as pipelines and waterways. Pipelines currently still used for transporting low-calorific gas could be transformed and integrated into a hydrogen network.	Industrial sectors, as well as heating and transport.
Poland [143]	Low-carbon hydrogen will be produced using steam reforming of hydrocarbons with CO_2 capture and storage (CCS) or CO_2 capture and use (CCU), coal gasification with CCS or CCU, biomass gasification with CCS or CCU, electrolysis using electricity from renewable energy sources, electrolysis using electricity from conventional sources with CCS or CCU, pyrolysis, and chemical processes that produce hydrogen as a by-product, including separation of hydrogen from coke oven gas.	Transmission of electricity to the place of hydrogen production, hydrogen transmission, SNG transmission with the existing gas network, or hydrogen transmission through dedicated pipelines.	Transport, industry, power generation, and heating
UK [66]	Steam methane reformation (SMR) or autothermal reformation (ATR) with carbon capture, grid electrolysis, renewable electrolysis, low-temperature nuclear electrolysis, high-temperature nuclear electrolysis, bioenergy with carbon capture and storage, thermochemical water splitting, methane Pyrolysis (turquoise hydrogen).	Blending of hydrogen into the gas grid; development of a dedicated hydrogen grid extending up to tens or hundreds of kilometers that may include hydrogen converted and distributed as ammonia for use as a shipping fuel.	Agriculture, industry, residential, services and transport sectors
France [144]	Electrolysis of water using decarbonized or renewable electricity.	Liquid H_2, reuse in the gas network.	Industry (e.g., steel industry for the reduction of iron ore, or in the chemical industry for the manufacture of fertilizers), heavy-duty mobility (e.g., aircraft and ships).

Table 6. *Cont.*

Countries	Production	Consumption	Transport
Spain [145]	Electrolysis to produce renewable hydrogen (using renewable energy).	Hydrogen pipelines and public access hydrogen stations.	All industries use hydrogen. Transport (fuel cell buses, light and heavy-duty fuel cell vehicles for freight transport), power sector (consumption of previously produced and stored hydrogen).

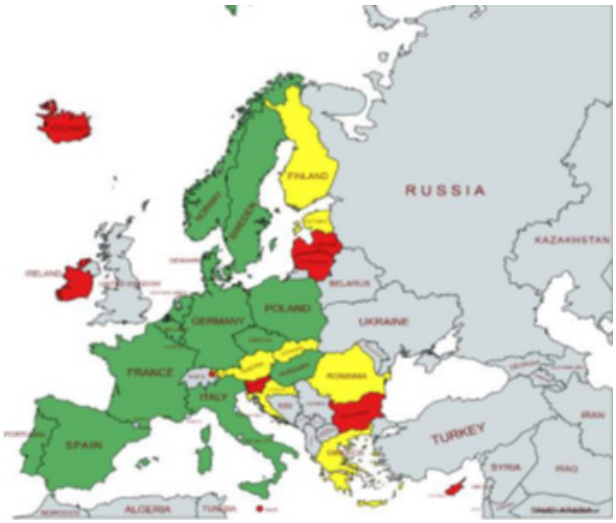


Figure 9. National strategies for hydrogen in Europe (red = do not have a national green hydrogen strategy, green = have a national hydrogen strategy, drafting or in the process of approving a national hydrogen strategy, yellow = in the process of approving or launching a strategy).

Table 7. Questions/comments of the Irish Government consultation addressed by this paper [146].

	Questions/Comments of Irish Government Consultation Document	Findings of this Paper
Opportunities for green hydrogen production	• What is the renewable electricity potential that does not have a route to market from conventional grid connections? Could this be used for green hydrogen production? • What are the most cost-effective ways of utilizing potentially curtailed renewable electricity output for hydrogen production?	Green hydrogen should be produced using mainly offshore wind, with a possible contribution of photo-voltaic production. A renewable electricity potential that does not have a route to market is curtailed energy. There is a concern regarding the usage of curtailed renewable energy to produce green hydrogen in relation to the possible very high costs. Electricity storage systems may add flexibility to the wind-electrolyzers systems, enabling a better harvesting of the curtailed energy, and must be studied in future research projects.
Role of blue hydrogen	"There will also be other competing technologies to meet medium and high-temperature heat use, including electric technologies, biomass and carbon capture, utilization and storage (CCUS) on sites with significant process emissions"	Possibly there will be no role for blue hydrogen due to a lack of trust in technology for carbon capture and storage (residual emissions might be too high) and concerns about Ireland's dependence on imported natural gas. "Blue hydrogen in the short term" is considered a high-risk strategy and inconsistent with EU policy.

Table 7. *Cont.*

Hydrogen infrastructure	Determining factors in identifying economic solutions include the available volume of hydrogen and the extent to which it could meet demand, the length of time it would need to be stored, site location, whether any existing infrastructure can be used or adapted, and the potential end-use application, in addition to the need to satisfy any regulatory and statutory criteria which may be put in place.	• Infrastructure must cover at least delivery to industry and heavy-duty transport. • The Irish gas network could, in the long term, become a hydrogen network. • The deployment of a hydrogen refueling infrastructure faces some barriers, such as the high CapEx required, the fact that the investors cannot see a stable demand for a few years, the customers cannot see a secure, resilient fuel supply and a cost subsidy to incentivize their change from current abundant and cheap fossil fuel. Battery Electric Vehicles might sometimes be perceived as better alternatives to Hydrogen Fuel Cell Vehicles.
Hydrogen in domestic heating	• Are hydrogen blends injected into the gas network considered to be a good use of green hydrogen? • Would hydrogen blends in the gas network be a viable way to underpin investment and ensure lack of demand risk is mitigated in the event that hydrogen demand fails to adequately materialize in end-use sectors? • Should there be a long-term plan for a transition of the natural gas network to 100% green hydrogen? How much of the network should be repurposed (should it be the transmission pipelines only or include some of the distribution network)? Should the existing gas grid will be broken up into smaller segregated sections to carry 100% hydrogen in some areas? How would this meet needs of end-use sectors? What should be the timeline for this?	• Adoption of green hydrogen as a fuel for domestic heating systems can avoid the costs of the upgrades required for a shift to all-electric heating. It could be supplied by oil, gas and solid fuel suppliers. • The effectiveness of blending low percentages of hydrogen in natural gas is considered questionable in terms of CO_2 reductions achievable. Generally, it is not considered a good use of green hydrogen. The maximum proportion of H_2 that could safely be burned in current domestic boilers is 20% H_2. It can reduce greenhouse gas emissions by only 6–7% because hydrogen's heating content is lower compared to natural gas. • Yes, part of the natural gas network should be repurposed to 100% green hydrogen by broking it up into smaller segregated sections carrying 100% hydrogen in some selected areas.
Other technologies for the decarbonization of society	How does hydrogen compare to competing technologies (direct electrification and other decarbonization options) for each of these end-uses?	Heat pumps are the most efficient option, which comes with rather high installation costs. Blending green hydrogen into the natural gas grid risks being a 'waste' of precious green hydrogen, which could be used for different applications because direct electrification using heat pumps is more efficient and cost-effective.
Green hydrogen certification	The options to produce renewable/green hydrogen will need to be examined in the context of the proposed changes to the Renewable Energy Directive (recast as RED III as part of the EU's 'Fit for 55′ package), particularly any requirements around co-location with new/existing generation and additionality. Certification will need to be examined to ensure the sustainability of hydrogen produced in Ireland.	Concerns arose from the additionality requirement of RED II in relation to green H_2 production. Green H_2 projects might be delayed if H_2 production from the electrolyzer requires the commissioning of a new renewable asset to produce the electricity to power the electrolyzer. Moreover, green hydrogen might be very expensive if it could only be produced from curtailed renewable energy.

10. Conclusions

Ireland is in the process of establishing a national strategy for zero-carbon hydrogen. It is expected that the strategy will prioritize green hydrogen production from renewable sources, especially offshore wind power. The goal of the paper is to determine a set of recommendations for the policymaker in Ireland, which aim to promote a green hydrogen economy by 2050 and the decarbonization of the country using green hydrogen. The recommendations were derived from a critical review of the literature and from a survey involving the key stakeholders.

The policy should support green hydrogen production from curtailed wind power, curtailed power from waste-to-energy plants, grid power (with associated GHG emissions lower than an appropriate threshold) and grid-congested power. These options should be compared in terms of their complementarity, costs and flexibility. The policymaker should consider investment costs and hydrogen demand when determining the appropriate support to kick-start such a production pathway in Ireland. The applications of such green hydrogen will be in industry, heavy-duty transport, and, later, domestic heating. It is expected that green hydrogen will be used initially blended with natural gas, and after that, the infrastructure and equipment will be updated, and parts of the gas network will be repurposed to carry pure hydrogen. In the road transportation sector, hydrogen needs to be incentivized by the policy to stimulate the appetite of the consumers to abandon the current fossil fuels, thereby fostering the development of the refueling infrastructure. A certification for green hydrogen will need to be established considering the requirements of the Renewable Energy Directive (and the changes introduced in the RED III as part of the EU's 'Fit for 55′ package), such as any requirements in relation to the co-location with new or existing generation and additionality. The study presented in this paper has preceded the national consultation on green hydrogen recently announced by the Irish government and is already significantly contributing to the national debate on green hydrogen in Ireland.

Author Contributions: Conceptualization, L.D.T. and P.L.; methodology, L.D.T. and P.L.; validation, L.D.T.; formal analysis, L.D.T.; investigation, L.D.T.; resources, P.L.; data curation, L.D.T.; writing—original draft preparation, L.D.T.; writing—review and editing, L.D.T. and P.L.; visualization, L.D.T.; supervision, P.L.; project administration, P.L.; funding acquisition, P.L. All authors have read and agreed to the published version of the manuscript.

Funding: This work was funded as part of the "Energy Policy Insights for Climate Action" project, which has received funding from the Department of Environment, Climate, and Communication, Government of Ireland [grant agreement number R19097]. The funding body was not involved in conducting the research and its associated publications.

Data Availability Statement: Not applicable.

Acknowledgments: The authors thank EirGrid for providing the data concerning the potential hydrogen production using curtailed wind power.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Bleischwitz, R.; Bader, N. Policies for the transition towards a hydrogen ecoomy: The EU case. *Energy Policy* **2010**, *38*, 5388–5398. [CrossRef]
2. Trans-European Networks for Energy, The European Commission. Available online: https://ec.europa.eu/energy/topics/infrastructure/trans-european-networks-energy_en (accessed on 14 October 2021).
3. Available online: https://www.catf.us/2021/05/european-parliament-hydrogen-strategy/ (accessed on 16 August 2021).
4. European Commission. A Hydrogen Strategy for a Climate-Neutral Europe. 2022. Available online: https://ec.europa.eu/commission/presscorner/api/files/attachment/865942/EU_Hydrogen_Strategy.pdf (accessed on 22 December 2022).
5. Dodds, P.E.; Staffell, I.; Hawkes, A.D.; Li, F.; Grünewald, P.; McDowall, W.; Ekins, P. Hydrogen and fuel cell technologies for heating: A review. *Int. J. Hydrog. Energy* **2015**, *40*, 2065–2083. [CrossRef]
6. Schiro, F.; Stoppato, A.; Benato, A. Modelling and analyzing the impact of hydrogen enriched natural gas on domestic gas boilers in a decarbonisation perspective. *Carbon Resour. Convers.* **2020**, *3*, 122–129. [CrossRef]

7. The Government of Ireland. Ireland's National Energy and Climate Plan 2021–2030. 2021. Available online: https://www.gov.ie/en/publication/0015c-irelands-national-energy-climate-plan-2021-2030/ (accessed on 4 June 2022).
8. Machado, J.T.M.; Flynn, B.M.; Williamson, I. The national shaping of Europe's Emerging Hydrogen Strategies: Coop-erative or Competitive Hydrogen politics? In Proceedings of the 10th FSR Annual Conference, Infrastructure investment challenges: Reconciling competition, decarbonisation and digitalisation, Online, 10–11 June 2021.
9. Sasanpour, S.; Cao, K.-K.; Gils, H.C.; Jochem, P. Strategic policy targets and the contribution of hydrogen in a 100% renewable European power system. *Energy Rep.* **2021**, *7*, 4595–4608. [CrossRef]
10. Ministry for the Ecological Transition and the Demographic Challenge. Hydrogen Roadmap European Gas Regulatory Forum. 2020. Available online: https://commission.europa.eu/system/files/2020-10/02.03.02_mf34_presentation-spain-hydrogen_roadmap-cabo.pdf (accessed on 22 December 2022).
11. Fernandes, L.; Ferreira, P. Renewable energy scenarios in the Portuguese electricity system. *Energy* **2014**, *69*, 51–57. [CrossRef]
12. Khatiwada, D.; Vasudevan, R.A.; Santos, B.H. Decarbonization of natural gas systems in the EU—Costs, barriers, and constraints of hydrogen production with a case study in Portugal. *Renew. Sustain. Energy Rev.* **2022**, *168*, 112775. [CrossRef]
13. Maïzi, N.; Assoumou, E. Future prospects for nuclear power in France. *Appl. Energy* **2014**, *136*, 849–859. [CrossRef]
14. Shirizadeh, B.; Quirion, P. Long-Term Optimization of the Hydrogen-Electricity Nexus in France: Green, Blue, or Pink Hydro-gen? Available online: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4169441 (accessed on 22 December 2022).
15. Pastore, L.M.; Basso, G.L.; Sforzini, M.; de Santoli, L. Technical, economic and environmental issues related to electrolysers capacity targets according to the Italian Hydrogen Strategy: A critical analysis. *Renew. Sustain. Energy Rev.* **2022**, *166*, 112685. [CrossRef]
16. The Italian Hydrogen Strategy. Available online: https://www.wfw.com/articles/the-italian-hydrogen-strategy/ (accessed on 20 August 2021).
17. UK Hydrogen Strategy Published, with Government Targeting £4bn of Private Investment by 2030. Available online: https://www.edie.net/uk-hydrogen-strategy-published-with-government-targeting-4bn-of-private-investment-by-2030 (accessed on 22 December 2022).
18. Ofgem Gives Green Light to £12.7m Hydrogen Trial Project. Available online: https://www.nationalgrid.com/30-november-ofgem-gives-green-light-ps127m-hydrogen-trial-project (accessed on 4 June 2022).
19. HyDeploy: UK Gas Grid Injection of Hydrogen in Full Operation. Available online: https://itm-power.com/news/hydeploy-uk-gas-grid-injection-of-hydrogen-in-full-operation (accessed on 22 December 2022).
20. Laguipo, J.; Forde, C.; Carton, J.G. Enabling the scale up of green hydrogen in Ireland by decarbonising the haulage sector. *Int. J. Hydrogen Energy* **2022**, *47*, 26812–26826. [CrossRef]
21. dos Santos, R.M.; Szklo, A.; Lucena, A.F.; de Miranda, P.E.V. Blue sky mining: Strategy for a feasible transition in emerging countries from natural gas to hydrogen. *Int. J. Hydrog. Energy* **2021**, *46*, 25843–25859. [CrossRef]
22. Moradi, R.; Groth, K.M. Hydrogen storage and delivery: Review of the state of the art technologies and risk and reliability analysis. *Int. J. Hydrogen Energy* **2019**, *44*, 12254–12269. [CrossRef]
23. Gaur, A.S.; Fitiwi, D.Z.; Lynch, M.; Longoria, G. Implications of heating sector electrification on the Irish power system in view of the Climate Action Plan. *Energy Policy* **2022**, *168*, 113136. [CrossRef]
24. Longoria, G.; Lynch, M.; Curtis, J. Green hydrogen for heating and its impact on the power system. *Int. J. Hydrogen Energy* **2021**, *46*, 26725–26740. [CrossRef]
25. Cheng, W.; Lee, S. How Green Are the National Hydrogen Strategies? *Sustainability* **2022**, *14*, 1930. [CrossRef]
26. Hydrogen in Ireland. Available online: https://oec.world/en/profile/bilateral-product/hydrogen/reporter/irl (accessed on 19 September 2021).
27. Okolie, J.A.; Patra, B.R.; Mukherjee, A.; Nanda, S.; Dalai, A.K.; Kozinski, J.A. Futuristic applications of hydrogen in energy, biorefining, aerospace, pharmaceuticals and metallurgy. *Int. J. Hydrogen Energy* **2021**, *46*, 8885–8905. [CrossRef]
28. Burkin, A.R. PRODUCTION OF SOME METAL POWDERS BY HYDROMETALLURGICAL PROCESSES*. *Powder Met.* **1969**, *12*, 243–250. [CrossRef]
29. Bhaskar, A.; Assadi, M.; Somehsaraei, H.N. Decarbonization of the Iron and Steel Industry with Direct Reduction of Iron Ore with Green Hydrogen. *Energies* **2020**, *13*, 758. [CrossRef]
30. Modak, J.M. Haber process for ammonia synthesis. *Resonance* **2011**, *16*, 1159–1167. [CrossRef]
31. Khademi, M.; Rahimpour, M.; Jahanmiri, A. Differential evolution (DE) strategy for optimization of hydrogen production, cyclohexane dehydrogenation and methanol synthesis in a hydrogen-permselective membrane thermally coupled reactor. *Int. J. Hydrogen Energy* **2010**, *35*, 1936–1950. [CrossRef]
32. Ramachandran, R.; Menon, R.K. An overview of industrial uses of hydrogen. *Int. J. Hydrog. Energy* **1998**, *23*, 593–598. [CrossRef]
33. Reddy, S.Y.; Nalinakshi, M.; Chetana, R. Fully hydrogenated vegetable oil as a stabilizer for low fat butter spreads. *J. Food Lipids* **1999**, *6*, 245–259. [CrossRef]
34. Zier, M.; Stenzel, P.; Kotzur, L.; Stolten, D. A review of decarbonization options for the glass industry. *Energy Convers. Manag. X* **2021**, *10*, 100083. [CrossRef]
35. Prieto, M.; Díaz, J.; Egusquiza, E. Analysis of the fluid-dynamic and thermal behaviour of a tin bath in float glass manufacturing. *Int. J. Therm. Sci.* **2002**, *41*, 348–359. [CrossRef]
36. Chevallier, J. Hydrogen and doping issues in wide band gap semiconductors. *Mater. Sci. Eng. B* **2000**, *71*, 62–68. [CrossRef]

37. Belmans, R.; dos Reis, P.C.; Vingerhoets, P. Electrification and Sustainable Fuels: Competing for Wind and Sun (Complement to the Policy Brief), Working Paper Containing Calculations and Assumptions in Support of the Accompanying Policy Brief with the Same Title, European University Institute, Robert Schuman Centre for Advanced Studies, Florence School of Regulation. Available online: https://cadmus.eui.eu/bitstream/handle/1814/71402/RSC%202021_55.pdf (accessed on 12 September 2021).
38. Gidey, E.; Jilcha, K.; Beshah, B.; Kitaw, D. The plan-do-check-act cycle of value addition. *Ind. Eng. Manag.* **2014**, *3*, 2169-0316.
39. Flame Temperatures Table for Different Fuels. Available online: https://www.thoughtco.com/flame-temperatures-table-607307 (accessed on 12 February 2022).
40. Panasyuk, V.; Andreykiv, O.; Gembara, O. Hydrogen degradation of materials under long-term operation of technological equipment. *Int. J. Hydrogen Energy* **2000**, *25*, 67–74. [CrossRef]
41. Material Considerations When Working with Hydrogen, HySafe—Safety of Hydrogen as an Energy Carrier. Available online: http://www.hysafe.org/download/1002/BRHS%20Chap3%20-%20material%20consideration-version%201_0_1.pdf (accessed on 12 February 2022).
42. Gas Networks Ireland. Network Development Plan. 2021. Available online: https://www.gasnetworks.ie/docs/corporate/gas-regulation/GNI-2021-Network-Development-Plan.pdf (accessed on 22 December 2022).
43. Slorach, P.C.; Stamford, L. Net zero in the heating sector: Technological options and environmental sustainability from now to 2050. *Energy Convers. Manag.* **2021**, *230*, 113838. [CrossRef]
44. European Climate Foundation. Modelling the Socioeconomic Impacts of Zero Carbon Housing in Europe. 2022. Available online: https://europeanclimate.org/wp-content/uploads/2022/03/modelling-the-socioeconomic-impact-of-zero-carbon-housing-in-europe-final-technical-report-march2022.pdf (accessed on 22 December 2022).
45. Quarton, C.J.; Samsatli, S. How to incentivise hydrogen energy technologies for net zero: Whole-system value chain optimisation of policy scenarios. *Sustain. Prod. Consum.* **2021**, *27*, 1215–1238. [CrossRef]
46. Ekhtiari, A.; Flynn, D.; Syron, E. Investigation of the Multi-Point Injection of Green Hydrogen from Curtailed Re-newable Power into a Gas Network. *Energies* **2020**, *13*, 6047. [CrossRef]
47. European Environmental Bureau. Face to Face with Hydrogen. The Reality behind the Hype. An EEB Position Paper for a Bet-ter-Informed Approach to Hydrogen. Available online: https://mk0eeborgicuypctuf7e.kinstacdn.com/wp-content/uploads/2021/05/EEB-Hydrogen-Position-Paper-FINAL.pdf (accessed on 12 September 2021).
48. Mercury Renewables Plans €200m Wind and Hydrogen Plant, The Irish Times (2021). Available online: https://www.irishtimes.com/business/energy-and-resources/mercury-renewables-plans-200m-wind-and-hyrdogen-plant-1.4752258 (accessed on 22 December 2022).
49. European Commission. Powering a Climate Neutral Economy: Commission Sets Out Plans for the Energy System of the Future and Clean Hydrogen. 2020. Available online: https://ec.europa.eu/commission/presscorner/detail/en/ip_20_1259 (accessed on 22 December 2022).
50. Cunanan, C.; Tran, M.-K.; Lee, Y.; Kwok, S.; Leung, V.; Fowler, M. A Review of Heavy-Duty Vehicle Powertrain Technologies: Diesel Engine Vehicles, Battery Electric Vehicles, and Hydrogen Fuel Cell Electric Vehicles. *Clean Technol.* **2021**, *3*, 474–489. [CrossRef]
51. Valente, A.; Tulus, V.; Galán-Martín, Á.; Huijbregts, M.A.; Guillén-Gosálbez, G. The role of hydrogen in heavy transport to operate within planetary boundaries. *Sustain. Energy Fuels* **2021**, *5*, 4637–4649. [CrossRef] [PubMed]
52. Atilhan, S.; Park, S.; El-Halwagi, M.M.; Atilhan, M.; Moore, M.; Nielsen, R.B. Green hydrogen as an alternative fuel for the shipping industry. *Curr. Opin. Chem. Eng.* **2021**, *31*, 100668, Erratum in **2021**, *34*, 100775. [CrossRef]
53. Dincer, I.; Acar, C. A review on potential use of hydrogen in aviation applications. *Int. J. Sustain. Aviat.* **2016**, *2*, 74. [CrossRef]
54. Nicita, A.; Maggio, G.; Andaloro, A.; Squadrito, G. Green hydrogen as feedstock: Financial analysis of a photovoltaic-powered electrolysis plant. *Int. J. Hydrogen Energy* **2020**, *45*, 11395–11408. [CrossRef]
55. Transport, Environmental Protection Agency. Available online: https://www.epa.ie/our-services/monitoring--assessment/climate-change/ghg/transport/ (accessed on 11 November 2022).
56. Robinius, M.; Linßen, J.F.; Grube, T.; Reuß, M.; Stenzel, P.; Syranidis, K.; Kuckertz, P.; Stolten, D. Comparative Analysis of Infrastructures: Hydrogen Fueling and Electric Charging of Vehicles; Energie & Umwelt/Energy & Environment Band/Volume 408; 2018; ISBN 978-3-95806-295-5. Available online: http://www.smartenergyportal.ch/wp-content/uploads/2018/04/Energie_Umwelt_408_NEU.pdf (accessed on 22 December 2022).
57. Isenstadt, A.; Lutsey, N. Developing Hydrogen Fueling Infrastructure for Fuel Cell Vehicles: A Status Update, Briefing of the International Council of Clean Transportation. 2017. Available online: https://theicct.org/wp-content/uploads/2021/06/Hydrogen-infrastructure-status-update_ICCT-briefing_04102017_vF.pdf (accessed on 16 February 2022).
58. Haglind, F.; Hasselrot, A.; Singh, R. Potential of reducing the environmental impact of aviation by using hydrogen Part I: Background, prospects and challenges. *Aeronaut. J.* **2006**, *110*, 533–540. [CrossRef]
59. FAQ: The What and How of E-Kerosene. A Briefing of Transport and Environment. 2021. Available online: https://www.transportenvironment.org/wp-content/uploads/2021/02/FAQ-e-kerosene-1.pdf (accessed on 22 December 2022).
60. Decarbonisation Potential of Synthetic Kerosene. E4tech (UK) Ltd for Ministerie van Infrastructuur en Waterstaat. 2021. Available online: https://assets.website-files.com/6144857e3aac5ad07ebf212f/615c3cb88f7f25a651a66e2f_2021_E4tech_Decarbonisation%20potential%20synthetic%20kerosine.pdf (accessed on 22 December 2022).

61. Zhang, F.; Zhao, P.; Niu, M.; Maddy, J. The survey of key technologies in hydrogen energy storage. *Int. J. Hydrogen Energy* **2016**, *41*, 14535–14552. [CrossRef]
62. Li, P.; Wang, R.; Xia, S.; Zhang, F. Low-carbon economic dispatch of power system based on mobile hydrogen storage. *J. Physics Conf. Ser.* **2022**, *2276*, 012007. [CrossRef]
63. Caglayan, D.G.; Heinrichs, H.U.; Robinius, M.; Stolten, D. Robust design of a future 100% renewable european energy supply system with hydrogen infrastructure. *Int. J. Hydrogen Energy* **2021**, *46*, 29376–29390. [CrossRef]
64. Schnuelle, C.; Wassermann, T.; Stuehrmann, T. Mind the Gap—A Socio-Economic Analysis on Price Developments of Green Hydrogen, Synthetic Fuels, and Conventional Energy Carriers in Germany. *Energies* **2022**, *15*, 3541. [CrossRef]
65. Government of Ireland. Renewable Fuels for Transport. Policy Statement November 2021. 2021. Available online: https://assets.gov.ie/205285/331035ce-e45c-493d-99be-7b8bad6a9ba8.pdf (accessed on 22 December 2022).
66. HM Government. UK Hydrogen Strategy. 2021. Available online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1011283/UK-Hydrogen-Strategy_web.pdf (accessed on 22 December 2022).
67. Why Green Hydrogen—But Not Grey—Could Help Solve Climate Change. Available online: https://theconversation.com/why-green-hydrogen-but-not-grey-could-help-solve-climate-change-162987 (accessed on 30 March 2022).
68. van Renssen, S. The hydrogen solution? *Nat. Clim. Change* **2020**, *10*, 799–801. [CrossRef]
69. Gas Price Spike Puts Green Hydrogen at Cost Parity with Fossil Fuels. Available online: https://www.spglobal.com/commodity-insights/en/market-insights/latest-news/electric-power/102221-european-green-hydrogen-costs-already-competitive-with-fossil-fuels-say-producers (accessed on 30 March 2022).
70. Vartiainen, E.; Breyer, C.; Moser, D.; Medina, E.R.; Busto, C.; Masson, G.; Bosch, E.; Jäger-Waldau, A. True Cost of Solar Hydrogen. *Sol. RRL* **2021**, *6*, 2100487. [CrossRef]
71. Martens, P.; Vandezande, B. What Is Pink Hydrogen, and Does It Have a Future in Belgium? 2022. Available online: https://www.agoria.be/en/climate-environment-energy/energy-climate/renewable-energy/what-is-pink-hydrogen-and-does-it-have-a-future-in-belgium (accessed on 17 August 2022).
72. The U.S. Department of Energy. Office of Energy Efficiency & Renewable Energy. Hydrogen Production: Biomass Gasification. Available online: https://www.energy.gov/eere/fuelcells/hydrogen-production-biomass-gasification (accessed on 17 August 2022).
73. National Renewable Energy Laboratory. Hydrogen Production Cost Estimate Using Biomass Gasification. Report NREL/BK-6A10-51726. 2011. Available online: https://www.hydrogen.energy.gov/pdfs/51726.pdf (accessed on 17 August 2022).
74. Guo, Y.; Li, G.; Zhou, J.; Liu, Y. Comparison between hydrogen production by alkaline water electrolysis and hydrogen production by PEM electrolysis. *IOP Conf. Series: Earth Environ. Sci.* **2019**, *371*, 042022. [CrossRef]
75. Götz, M.; Lefebvre, J.; Mörs, F.; McDaniel Koch, A.; Graf, F.; Bajohr, S.; Reimert, R.; Kolb, T. Renewable Power-to-Gas: A technological and economic review. *Renew. Energy* **2016**, *85*, 1371–1390. [CrossRef]
76. Gondal, I.A. Hydrogen integration in power-to-gas networks. *Int. J. Hydrogen Energy* **2019**, *44*, 1803–1815. [CrossRef]
77. Koelbl, B.S.; van den Broek, M.; Faaij, A.P.C.; van Vuuren, D.P. Uncertainty in Carbon Capture and Storage (CCS) deployment projections: A cross-model comparison exercise. *Clim. Change* **2014**, *123*, 461–476. [CrossRef]
78. Khan, M.H.A.; Daiyan, R.; Neal, P.; Haque, N.; MacGill, I.; Amal, R. A framework for assessing economics of blue hydrogen production from steam methane reforming using carbon capture storage & utilisation. *Int. J. Hydrogen Energy* **2021**, *46*, 22685–22706. [CrossRef]
79. George, J.F.; Müller, V.P.; Winkler, J.; Ragwitz, M. Is blue hydrogen a bridging technology?—The limits of a CO2 price and the role of state-induced price components for green hydrogen production in Germany. *Energy Policy* **2022**, *167*, 113072. [CrossRef]
80. Howarth, R.W.; Jacobson, M.Z. How green is blue hydrogen? *Energy Sci. Eng.* **2021**, *9*, 1676–1687. [CrossRef]
81. Papadopoulos, V.; Desmet, J.; Knockaert, J.; Develder, C. Improving the utilization factor of a PEM electrolyzer powered by a 15 MW PV park by combining wind power and battery storage—Feasibility study. *Int. J. Hydrogen Energy* **2018**, *43*, 16468–16478. [CrossRef]
82. Sustainable Energy Authority of Ireland. Community Energy Resource Toolkit. Solar PV. 2021. Available online: https://www.seai.ie/publications/Community-Toolkit-Solar-PV.pdf (accessed on 22 December 2022).
83. O'Hanlon, Z.; Cummins, V. A comparative insight of Irish and Scottish regulatory frameworks for offshore wind energy—An expert perspective. *Mar. Policy* **2020**, *117*, 103934. [CrossRef]
84. Abdin, Z.; Zafaranloo, A.; Rafiee, A.; Mérida, W.; Lipiński, W.; Khalilpour, K.R. Hydrogen as an energy vector. *Renew. Sustain. Energy Rev.* **2020**, *120*, 109620. [CrossRef]
85. Gunawan, T.A.; Singlitico, A.; Blount, P.; Burchill, J.; Carton, J.G.; Monaghan, R.F.D. At What Cost Can Renewable Hydrogen Offset Fossil Fuel Use in Ireland's Gas Network? *Energies* **2020**, *13*, 1798. [CrossRef]
86. European Commission. Electricity Market Design. 2022. Available online: https://energy.ec.europa.eu/topics/markets-and-consumers/market-legislation/electricity-market-design_en (accessed on 22 December 2022).
87. Diab, J.; Fulcheri, L.; Hessel, V.; Rohani, V.; Frenklach, M. Why turquoise hydrogen will Be a game changer for the energy transition. *Int. J. Hydrogen Energy* **2022**, *47*, 25831–25848. [CrossRef]
88. Noussan, M.; Raimondi, P.P.; Scita, R.; Hafner, M. The Role of Green and Blue Hydrogen in the Energy Transition—A Technological and Geopolitical Perspective. *Sustainability* **2020**, *13*, 298. [CrossRef]

89. Garcia, D.A. Analysis of non-economic barriers for the deployment of hydrogen technologies and infrastructures in European countries. *Int. J. Hydrogen Energy* **2017**, *42*, 6435–6447. [CrossRef]
90. Gas Networks Ireland. Safety Advice for Working in the Vicinity of Natural Gas Pipelines. Guideline No: HSQE/GU/016 Rev 2. 2020. Available online: https://www.gasnetworks.ie/docs/business/safety-in-the-business/Safety-Advice-for-working-in-the-vicinity-of-Gas-pipes-2021_.pdf (accessed on 22 December 2022).
91. Andrews, J.; Shabani, B. The role of hydrogen in a global sustainable energy strategy. *WIREs Energy Environ.* **2014**, *3*, 474–489. [CrossRef]
92. Cavana, M.; Leone, P. Biogas blending into the gas grid of a small municipality for the decarbonization of the heating sector. *Biomass-Bioenergy* **2019**, *127*, 105295. [CrossRef]
93. Quintino, F.M.; Nascimento, N.; Fernandes, E.C. Aspects of Hydrogen and Bio-methane Introduction in Natural Gas Infrastructure and Equipment. *Hydrogen* **2021**, *2*, 301–318. [CrossRef]
94. Smith, C.; Mouli-Castillo, J.; van der Horst, D.; Haszeldine, S.; Lane, M. Towards a 100% hydrogen domestic gas network: Regulatory and commercial barriers to the first demonstrator project in the United Kingdom. *Int. J. Hydrogen Energy* **2022**, *47*, 23071–23083. [CrossRef]
95. Wind Energy Ireland. Hydrogen and Wind Energy. The Role of Green Hydrogen in Ireland's Energy Transition. 2022. Available online: https://windenergyireland.com/images/files/final-hydrogen-and-wind-energy-report.pdf (accessed on 22 December 2022).
96. Moriarty, P.; Honnery, D. Prospects for hydrogen as a transport fuel. *Int. J. Hydrogen Energy* **2019**, *44*, 16029–16037. [CrossRef]
97. Andrews, J.; Shabani, B. Re-envisioning the role of hydrogen in a sustainable energy economy. *Int. J. Hydrogen Energy* **2012**, *37*, 1184–1203. [CrossRef]
98. Madsen, A.N.; Andersen, P.D. Innovative regions and industrial clusters in hydrogen and fuel cell technolo-gy. *Energy Policy* **2010**, *38*, 5372–5381. [CrossRef]
99. Hosseini, S.E.; Butler, B. An overview of development and challenges in hydrogen powered vehicles. *Int. J. Green Energy* **2020**, *17*, 13–37. [CrossRef]
100. Kalghatgi, G. Running Heavy-Duty Transport on Batteries. 2020. Available online: https://www.realclearenergy.org/articles/2020/08/11/running_heavy-duty_transport_on_batteries_501650.html (accessed on 22 December 2022).
101. Sanguesa, J.; Torres-Sanz, V.; Garrido, P.; Martinez, F.; Marquez-Barja, J. A Review on Electric Vehicles: Technologies and Challenges. *Smart Cities* **2021**, *4*, 372–404. [CrossRef]
102. Umicore. Fuel Cells vs. Batteries: What's the Difference? 2022. Available online: https://www.umicore.com/en/newsroom/news/fuel-cells-battery-difference/ (accessed on 22 December 2022).
103. Hydrogen Europe. Lighthouse Initiative. 2022. Available online: https://hydrogeneurope.eu/lighthouse-initiative/ (accessed on 22 December 2022).
104. Abad, A.V.; Dodds, P.E. Green hydrogen characterisation initiatives: Definitions, standards, guarantees of origin, and challenges. *Energy Policy* **2020**, *138*, 111300. [CrossRef]
105. SSE Renewables. DETAILS OF GALWAY HYDROGEN HUB (GH2) ANNOUNCED. 2022. Available online: https://www.sserenewables.com/news-and-views/2022/06/details-of-galway-hydrogen-hub-gh2-announced/ (accessed on 22 December 2022).
106. Wang, J.; Wang, H.; Fan, Y. Techno-Economic Challenges of Fuel Cell Commercialization. *Engineering* **2018**, *4*, 352–360. [CrossRef]
107. McKinsey & Company. How Hydrogen Combustion Engines Can Contribute to Zero Emissions. 2021. Available online: https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/how-hydrogen-combustion-engines-can-contribute-to-zero-emissions (accessed on 22 December 2022).
108. Liu, X.; Reddi, K.; Elgowainy, A.; Lohse-Busch, H.; Wang, M.; Rustagi, N. Comparison of well-to-wheels energy use and emissions of a hydrogen fuel cell electric vehicle relative to a conventional gasoline-powered internal combustion engine vehicle. *Int. J. Hydrogen Energy* **2019**, *45*, 972–983. [CrossRef]
109. Hydrogen Tank. Available online: https://www.doosanmobility.com/en/products/hydrogen-tank/ (accessed on 30 March 2022).
110. Sandí, G. Hydrogen storage and its limitations. *Electrochem. Soc. Interface* **2004**, *13*, 40. [CrossRef]
111. Bartlett, J.; Krupnick, A. Decarbonized Hydrogen in the US Power and Industrial Sectors: Identifying and Incentivizing Opportunities to Lower Emissions. 2020. Available online: https://media.rff.org/documents/RFF_Report_20-25_Decarbonized_Hydrogen.pdf (accessed on 22 December 2022).
112. Dong, Z.Y.; Yang, J.; Yu, L.; Daiyan, R.; Amal, R. A green hydrogen credit framework for international green hy-drogen trading towards a carbon neutral future. *Int. J. Hydrog. Energy* **2022**, *47*, 728–734. [CrossRef]
113. Turner, M.; Palmer, A.; Granville-Willet. End Game. A Zero-Carbon Electricity Plan for Ireland. 2021. Available online: https://windenergyireland.com/images/files/20210629-baringa-endgame-final-version.pdf (accessed on 22 December 2022).
114. The Government of Ireland—New legislation to Implement a Circular Economy. Press Release from Department of the Environment, Climate and Communications, 15 June 2021. Available online: https://www.gov.ie/en/press-release/65f5e-new-legislation-to-implement-a-circular-economy/ (accessed on 22 December 2022).
115. Natural Gas Grid, Dail Eireann Debate, Tuesday—14 December 2021. Available online: https://www.oireachtas.ie/en/debates/question/2021-12-14/28/ (accessed on 18 February 2022).

116. Tomorrow's Energy Scenarios, 2019 Ireland. Planning our Energy Future, EirGrid, October 2019, EirGrid-TES-2019-Report.pdf. Available online: Eirgridgroup.com (accessed on 18 August 2021).
117. Mayyas, A.; Chadly, A.; Amer, S.T.; Azar, E. Economics of the Li-ion batteries and reversible fuel cells as energy storage systems when coupled with dynamic electricity pricing schemes. *Energy* **2022**, *239*, 121941. [CrossRef]
118. Welder, L.; Stenzel, P.; Ebersbach, N.; Markewitz, P.; Robinius, M.; Emonts, B.; Stolten, D. Design and evaluation of hydrogen electricity reconversion pathways in national energy systems using spatially and temporally resolved energy system optimisation. *Int. J. Hydrog. Energy* **2019**, *44*, 9594–9607. [CrossRef]
119. Schermeyer, H.; Vergara, C.; Fichtner, W. Renewable energy curtailment: A case study on today's and tomorrow's congestion management. *Energy Policy* **2018**, *112*, 427–436. [CrossRef]
120. Ruggles, T.H.; Dowling, J.A.; Lewis, N.S.; Caldeira, K. Opportunities for flexible electricity loads such as hydrogen production from curtailed generation. *Adv. Appl. Energy* **2021**, *3*, 100051. [CrossRef]
121. Frew, B.A.; Becker, S.; Dvorak, M.J.; Andresen, G.B.; Jacobson, M.Z. Flexibility mechanisms and pathways to a highly renewable US electricity future. *Energy* **2016**, *101*, 65–78. [CrossRef]
122. González, A.; McKeogh, E.; Gallachóir, B. The role of hydrogen in high wind energy penetration electricity systems: The Irish case. *Renew. Energy* **2004**, *29*, 471–489. [CrossRef]
123. Zhang, G.; Wan, X. A wind-hydrogen energy storage system model for massive wind energy curtailment. *Int. J. Hydrogen Energy* **2014**, *39*, 1243–1252. [CrossRef]
124. Mason, J.; Zweibel, K. Centralized Production of Hydrogen using a Coupled Water Electrolyzer-Solar Photovoltaic System. In *Solar Hydrogen Generation*; Springer: New York, NY, USA, 2008; pp. 273–313. ISBN 9780387728094.
125. Energy Ireland. Developing Ireland Hydrogen's Potential. 2021. Available online: https://www.energyireland.ie/developing-irelands-hydrogen-potential/ (accessed on 22 December 2022).
126. Mokhtara, C.; Negrou, B.; Settou, N.; Bouferrouk, A.; Yao, Y. Design optimization of grid-connected PV-Hydrogen for energy prosumers considering sector-coupling paradigm: Case study of a university building in Algeria. *Int. J. Hydrogen Energy* **2021**, *46*, 37564–37582. [CrossRef]
127. Khan, I.; Kabir, Z. Waste-to-energy generation technologies and the developing economies: A multi-criteria analysis for sustainability assessment. *Renew. Energy* **2019**, *150*, 320–333. [CrossRef]
128. Mona, S.; Kumar, S.S.; Kumar, V.; Parveen, K.; Saini, N.; Deepak, B.; Pugazhendhi, A. Green technology for sus-tainable biohydrogen production (waste to energy): A review. *Sci. Total Environ.* **2020**, *728*, 138481. [CrossRef]
129. Ghaemi, S.; Li, X.; Mulder, M. Economic feasibility of green hydrogen in providing flexibility to medium-voltage distribution grids in the presence of local-heat systems. *Appl. Energy* **2023**, *331*, 120408. [CrossRef]
130. Opportunities for Hydrogen Energy Technologies Considering the National Energy and Climate Plans. Fuel Cells and Hy-drogen 2 Joint Undertaking (FCH 2 JU) Study on Opportunities Arising from the Inclusion of Hydrogen Energy Technologies in the National Energy & Climate Plans. Available online: https://www.fch.europa.eu/publications/opportunities-hydrogen-energy-technologies-considering-national-energy-climate-plans (accessed on 4 September 2021).
131. Gunawan, T.A.; Williamson, I.; Raine, D.; Monaghan, R.F. Decarbonising city bus networks in Ireland with re-newable hydrogen. *Int. J. Hydrog. Energy* **2021**, *46*, 28870–28886. [CrossRef]
132. Butturi, M.A.; Gamberini, R. The potential of hydrogen technologies for low-carbon mobility in the urban-industrial symbiosis approach. *Int. J. Energy Prod. Manag.* **2022**, *7*, 151–163. [CrossRef]
133. Olabi, A.G.; Wilberforce, T.; Abdelkareem, M.A. Fuel cell application in the automotive industry and future per-spective. *Energy* **2021**, *214*, 118955. [CrossRef]
134. Hansen, O.R. Hydrogen infrastructure—Efficient risk assessment and design optimisation approach to ensure safe and practical solutions. *Process Saf. Environ. Prot.* **2020**, *143*, 164–176. [CrossRef]
135. Government of Ireland. National Development Plan 2021–2030. 2021. Available online: https://www.gov.ie/en/publication/774e2-national-development-plan-2021-2030/ (accessed on 22 December 2022).
136. Dail Eireann Debate. Thursday, 14 July 2022. Volume 1025 No. 5. Green Hydrogen Strategy Bill 2022: Second Stage [Private Members]. Available online: https://www.oireachtas.ie/en/debates/debate/dail/2022-07-14/52/ (accessed on 22 December 2022).
137. Gas Networks Ireland. Testing of Blends of Hydrogen and Natural Gas. 2022. Available online: https://www.gasnetworks.ie/docs/hydrogen-blend.pdf (accessed on 22 December 2022).
138. Muhammed, N.S.; Haq, B.; Al Shehri, D.; Al-Ahmed, A.; Rahman, M.M.; Zaman, E. A review on underground hydrogen storage: Insight into geological sites, influencing factors and future outlook. *Energy Rep.* **2022**, *8*, 461–499. [CrossRef]
139. Hydrogen Projects in Teesside. Available online: https://www.bp.com/en/global/corporate/what-we-do/gas-and-low-carbon-energy/h2teesside.html (accessed on 27 February 2022).
140. Salt Cavern Gas Storage Project at Islandmagee in County Antrim, Northern Ireland. Available online: https://www.islandmageeenergy.com/ (accessed on 27 February 2022).
141. UK Hydrogen Policy Takes Shape: Defining "Low Carbon Hydrogen". Available online: https://www.lexology.com/library/detail.aspx?g=9ac6c040-7336-4045-808a-0d7b835743ed (accessed on 29 September 2021).
142. Westphal, K.; Dröge, S.; Geden, O. The International Dimensions of Germany's Hydrogen Policy. 2020. Available online: https://www.swp-berlin.org/10.18449/2020C32/#:~{}:text=It%20contains%20plans%20to%20build,additional)%20renewables%2Dbased%20electricity (accessed on 22 December 2022).

143. Gawlik, L.; Mokrzycki, E. Analysis of the Polish Hydrogen Strategy in the Context of the EU's Strategic Documents on Hydrogen. *Energies* **2021**, *14*, 6382. [CrossRef]
144. Government of France. National Strategy for the Development of Decarbonised and Renewable Hydrogen in France. 2020. Available online: https://www.bdi.fr/wp-content/uploads/2020/03/PressKitProvisionalDraft-National-strategy-for-the-development-of-decarbonised-and-renewable-hydrogen-in-France.pdf (accessed on 22 December 2022).
145. Bernad, A.; Zarzuela, M.; Férriz, A.M.; Floristean, A.; HyLaw. National Policy Paper—Spain. 2019. Available online: https://www.hylaw.eu/files/2019-02/HyLAW_%20National%20policy%20Paper_ENG_Final.pdf (accessed on 22 December 2022).
146. Government of Ireland. Consultation on Developing a Hydrogen Strategy for Ireland. 2022. Available online: https://www.gov.ie/en/consultation/5c087-consultation-on-developing-a-hydrogen-strategy-for-ireland/ (accessed on 22 December 2022).

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.