Roadmap Study for Tidal Generation with Electrolysis

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Introduction

The Integrating Tidal energy into the European Grid (ITEG) project aims to develop and demonstrate a state-of-the-art energy solution combining a tidal stream turbine with an electrolyser. This report is one of a series of reports from the project. It provides the outcome of the work in Activity LT.1 'Defining Future Opportunities', Deliverable LT.1.1 'Roadmap' which is carried out by Energy Systems Catapult (ESC). This report will be complemented by LT1.2 'Business Case' report delivered by Orbital Marine Power and Elogen.

This activity is an assessment of existing roadmaps for tidal generation and electrolysis technology development and commercial deployment with the associated benefits for North West Europe (NWE). It reviews the current state and outlook for tidal energy technology, electrolyser development and the combination of both technologies into an integrated solution and its potential implementations. This report is a synthesis of previous roadmaps for the individual technologies and the possible deployment of a combined solution.

The global energy system has to undergo a profound transformation to achieve the net zero target set in all countries in NWE in the next decades. Renewable electricity and green hydrogen take part in different proportions in all the future energy scenarios.

Benefits

For hydrogen to play its part in a decarbonised future, renewable electricity and water resources must be made available to feed the electrolysers for production. Tidal energy brings electricity to coastal areas and can be a great consistent source of electricity for electrolysis. Offering a solution integrating a tidal turbine with an electrolyser can offer the electricity and hydrogen required to convert applications relying on fossil fuels. Developed in a coherent and strategic manner, this solution is particularly suited for remote locations and small islands where local skills, services and infrastructure can be used and developed to deliver socio-economic benefits to communities.

Development Drivers

Tidal energy is following a similar technological and commercial pathway as wind and solar energy approximately a decade later. However, tidal not only has to compete economically with fossil fuel alternatives but also with these other more mature and currently cheaper forms of renewable energy. Tidal resources are also limited to coastal areas, limiting the geographical expansion of the tidal energy sector. Nevertheless, in regions where wind or solar is already deployed and has higher priority, tidal energy still has a very important role to play as a complementary source with different patterns to diversify the renewable energy mix. Despite being intermittent, tidal energy is also predictable and repeatable offering the baseload needed for electrolyser efficiency without extra storage requirements.

Electrolyser development in remote locations and islands will be driven by new hydrogen demand, which is currently uncertain. Hydrogen and its derivatives can be used in energy intensive industries (such as distilleries), as fuel for transport (road, marine and aviation), for heating (by combustion or using fuel cells to generate electricity), and as a means for storing renewable energy. Green hydrogen development will be a key enabler to tidal deployment in combination with other renewable sources. If electricity generation exceeds demand and export to the grid is constrained, excess hydrogen production could be exported to neighbouring regions or countries.

Roadmap

Current rapid progress and fast deployment in both of the individual technologies (tidal and electrolyser) will be a key enabler to rapid deployment of a combined solution.

Proving the ITEG technology is a stepping stone in the deployment of an integrated solution where hydrogen demand can (in the near term) be linked to tidal energy potential with matching capacities. In the short term, offering a demonstrated solution could accelerate deployment by reducing planning and installation cost and time in coastal locations.

The location of the electrolyser is of great interest, balancing the distribution costs of electricity or hydrogen to the end use. The system flexibility and connection capability (with other renewable sources and hydrogen demand) for future scenarios is also of particular significance.

In the longer term, an extension to the system would be to integrate it further into the whole energy system by:

- Connection to the electric grid
    - to use tidal generated electricity directly
    - to use grid electricity for electrolysis
- Diversifying hydrogen end use if demand grows
- Adding storage
    - to encourage extra renewable deployment (including tidal)
    - to support grid stability
    - to create a more resilient and independent local energy system
- Developing a multi-vector energy management system to optimise multiple criteria beyond matching supply and demand – such as price control, grid stability, system efficiency, greenhouse gas reduction, asset utilisation, etc.

System stability and resilience rely enormously on digitalisation. Flexibility is built on stability and resilience. They are all interlinked as, for example, electrolyser management control will be critical to integrate more generation from renewables, define storage capacity requirements, satisfy energy demand and develop demand side response in an economical and efficient manner.

The speed and scale of deployment is closely underpinned by policy and regulation development. The regulatory framework to develop an integrated multi vector (hydrogen, electricity, transport, heating etc) system and its supply chain is very complex. Hydrogen and tidal are both nascent and fast-changing areas of energy policy. Identifying needs (capital and revenue support, levers and incentives, supply chain and skills development, strategic decisions etc) and developing demonstrators can support policy makers to prioritise their action to support relevant innovation. With many competing options identified for a low carbon future, the roadmap for an integrated tidal turbine with an electrolyser will closely follow policy and regulations roadmapping.

There are plenty of challenges ahead for this combined solution to be deployed commercially at scale, but the ability to scale up and reduce cost has never been as promising, especially in coastal locations with electricity grid constraints.

This report specifies the detailed development needs, value chain for remote areas and opportunities for technologies and paths to commercial deployment through analysis of existing marine energy road mapping studies. The key enablers and barriers are explored throughout this report.

1 Introduction

Ocean energy and hydrogen are two decarbonisation technologies that have attracted much attention and development in recent years in the future of the energy system.

For the first time, the EU has set deployment milestones for wave and tidal energy: **100 MW by 2025, 3 GW by 2030 and 40 GW by 2050**. According to a 2020 European Commission report [1], Europe has a major opportunity to ramp up renewable power generation, to increase the direct use of electricity for a wider spectrum of end uses and to support indirect electrification through hydrogen and synthetic fuels as well as other decarbonised gases, as illustrated in the energy system integration and the hydrogen strategies. The EU Hydrogen Strategy, in particular, sets an objective of 40 GW of renewables-linked electrolysis capacity in the EU by 2030. Offshore renewable energy (wind, wave and tidal) is among the renewable technologies with the greatest potential to scale up. IRENA [2] estimates that the objective to have an installed capacity of at least 1 GW of wave and tidal energy by 2030, with a view to reach 40 GW of installed capacity by 2050, is realistic and achievable. Achieving these objectives would deliver major gains in terms of decarbonising electricity generation, enable decarbonisation of hard-to-abate sectors with renewable hydrogen as well as deliver major benefits in terms of jobs and growth, thus contributing to the post COVID-19 recovery and positioning the EU as a leader in clean technologies, to the joint benefit of its climate-neutrality and zero pollution goals. Getting 40 GW of installed ocean energy capacity by 2050 means a massive change of scale for the sector in less than 30 years, at a speed unparalleled by the past development of other energy technologies. It means multiplying the capacity for offshore renewable energy by nearly 30 times by 2050. The investment needed to do so is estimated at up to 800 billion Euros.

All other reports analysed estimate tidal and wave energy capacity to be similar or much higher, up to 100GW capacity by 2050 in Europe representing 10% of Europe's electricity consumption according to Ocean Energy Europe in 2020 [3]. The differences between the reports analysed and other aspects are explored in section 3.2.

Europe is the market leader in the ocean energy sector, with a third of the global market in its waters and 50% of the tidal energy companies globally based in the EU. However, the costs of developing this technology becomes disproportionately expensive as the technology moves towards market risking the technology becoming stuck in the "valley of death". Furthermore, whilst the production of electricity from tides has the great advantage of being predictable, this resource is often based on remote areas on the grid infrastructure which limits its uptake potential.

As for hydrogen, all reports reviewed concur (or generally agree,) in the sense that hydrogen has a growing role and opportunities within the energy sector. Current hydrogen production needs to shift from fossil fuels (95% of current hydrogen production is from Steam Methane Reformation (SMR) or coal gasification). Furthermore, hydrogen demand is likely to rise sharply to replace oil and gas especially in areas deemed hard to electrify such as some industry sectors requiring high grade heat, long haul transport, maritime shipping and aviation. As a result, most recent energy scenarios in Europe include green hydrogen as part of the energy mix in varying proportions.

According to the EU Hydrogen Strategy [4], many indicators signal that we are now close to a tipping point. Every week new investment plans are announced, often at a gigawatt scale. Between November 2019 and March 2020, market analysts increased the list of planned global investments from 3.2 GW to 8.2 GW of electrolysers by 2030 (with 57% in Europe) and the number of companies joining the International Hydrogen Council has grown from 13 in 2017 to 81 today.

Going beyond hydrogen as an energy vector, hydrogen can play an important connecting function between energy vector and services such as:

- Renewable electricity can be used to produce hydrogen to supply existing hydrogen intensive users, hard to electrify sectors. Hydrogen end use applications can act as complement of electrification, bioenergy in hybrid systems or direct use.
- Inter-seasonal storage of hydrogen could ease the winter peak demand by using it for heating or converting back to electricity.
- Hydrogen production from intermittent renewable electricity could help limit curtailment and integrate more renewable capacity into the system offering a flexible load and grid balancing services.
- Flexibility can also be beneficial in remote locations and small islands where the electric grid is typically constrained. If hydrogen export becomes economically viable in these regions where renewable energy is often abundant deployment could be maximised. Hydrogen would then become the link between regions with low cost abundant renewables and industrial centres of demand.

Due to the many options and interactions, the long term capacity predictions vary depending on the many recent scenarios and ambitions proposed by different countries and regions. The European Commission estimates 40 GW of installed capacity by 2050 with the possibility to import a further 40 GW. The most optimistic and ambitious water electrolysis dominant scenario from the Fuel Cells and Hydrogen Joint Undertaking (FCH JU) has 95% of hydrogen produced through water electrolysis by 2050 providing 24% of total energy demand (2,250 TWh) [5].

The ambition for the UK was outlined in the UK Hydrogen Strategy [6] published at the end of 2021. Analysis by the UK department for Business, Energy & Industrial Strategy (BEIS) to achieve the target of the Sixth Carbon Budget (CB6) suggests 250-460TWh of hydrogen could be needed in 2050, making up 20-35 per cent of UK final energy consumption .The size of the hydrogen economy in 2050 will depend on a number of factors – including the cost and availability of hydrogen and hydrogen-using technologies relative to alternatives, such as electrification, biomass and use of Carbon Capture, Utilisation and Storage (CCUS). Nonetheless, there is consensus, from the Climate Change Committee (CCC) and others, that we will need significant amounts of low carbon hydrogen on the system by 2050.

The Integrated Tidal Energy in European Grid (ITEG) project introduces energy storage through conversion of renewable electricity to hydrogen, making this technology attractive as a sustainable solution and a possible alternative to upgrades of electricity network infrastructure that could cost millions of euros. The addition of hydrogen production to this will allow further routes for hydrogen based low carbon solutions (e.g. mobility or small local industry) to be used in these regions. ITEG will optimise this process through a control system which enhances how the plant interacts with the grid.

NWE includes some of the most energetic tidal energy sites in Europe and in the world (Ireland, United Kingdom, Northern France and the Netherlands), territories that have already invested a lot in the ocean energy and development of the hydrogen sector (for instance, Normandy invested €100 million in Cherbourg's harbour to adapt its infrastructures to marine energy activities, Ireland , Wales and the Netherlands invested millions in dedicated public agencies and facilities to support ocean energy uptake, Scotland invested €100 million in local infrastructure). NWE also gathers emerging tidal technologies, a world leading marine energy test site and leading R&D centres in the field of energy management and renewable energy development.

Building a cooperation on ITEG within the tidal and hydrogen sectors with a focus on integration and on this territory will:

- Allow synergies amongst the countries involved, since every organisation and region has developed an expertise in a specific field which can either be complimentary or additive. Instead of working as competitors and investing in parallel developments, ITEG will build on each region's and organisation's specific expertise and help gather all experience and information across the NWE area.
- Use and enhance the investments that have already been made locally, in Scotland, Belgium, Ireland and France, since all of the organisations will learn how they can use and upgrade their existing installations and technologies through ITEG (test site at the European Marine Energy Centre (EMEC), R&D installations in Belgium and Ireland, shipyard on the Cherbourg's harbour and turbine for Constructions Mechanical Normandy (CMN)).

A side effect of this project will be to create synergies within the NWE territory by supporting the ocean energy development through expandability and replicability.

1.1 Scope and Objectives of the ITEG Project

This project aims to address energy-related carbon emissions in NWE through the development of a combined solution that includes clean predictable energy generation (tidal energy), safe export to the grid and the storage and delivery of the excess capacity in hydrogen.

The cost of pre-commercial demonstration for Ocean Energy is high and investors are reluctant to invest until the technology has been proven in the sea at scale. This project will drive down these costs (which is the main factor limiting its uptake) through the development of an integrated solution.

Construction of a 1MW floating tidal stream energy generator and deployment of an integrated hydrogen production solution are the main investments envisaged through the ITEG project. Following a thorough demonstration period, business plans will be developed for the construction of further turbines and electrolysis, and will develop opportunities for commercial projects across the North-West Europe region and globally.

1.2 Long-Term Impacts Work Package

The development, deployment and demonstration of these technologies is carried out within the ITEG project 'Investment' and 'Implementation' work packages.

In parallel with this, the ITEG project **'Long Term Impacts' work package (WP LT)** aims:

- to assess in detail the impact and potential benefits of the ITEG solution on the whole energy system, and how it might be rolled out across a range of different energy systems,
- to develop a roadmap and business case, to support the prioritisation of further development as part of a commercially viable marine energy solution,
- to understand the social acceptance aspects associated with the specific technologies, and
- to identify future project opportunities, investors, networks and partners.

The Work Package has gathered data, performed energy system analyses and engaged all project partners to provide robust evidence of the potential impact of the technologies in a local, national and NWE context.

The Work Package will comprise a range of analysis and evaluation and production of associated outputs and reports to support future deployment of the technologies. An energy system model of the Orkneys will be generated and a whole system analysis undertaken to provide insight into the opportunities and barriers facing floating tidal stream energy generator technologies, hydrogen storage and the combined solution. This will inform creation of a roadmap analysis of existing reports supporting development opportunities for tidal energy and green hydrogen production, and the integrated solution within NWE. This roadmap report is an analysis and synthesis of existing roadmaps to help understand the different aspects of an integrated system, the areas of development and the deployment potential for remote locations including small islands. It also provides evidence of how an integrated solution can be modularised and transferred to different territory's energy systems and electricity grid configurations which can be communicated with network operators and other relevant authorities.

1.3 Scope of the Roadmap report

This report is the outcome of Task LT.1.1 'Long Term Impact - Defining Future Opportunities: Roadmap Study'. It is one of two concurrent deliverables to produce detailed specifications of future opportunities and the long term effects of the ITEG project in conjunction with tasks LT1.2, LT.2, LT.3 , and LT.4 of the Long Term work package, as shown in Figure 1-1.

This document addresses and assesses development opportunities for technology deployment from the current status of the ITEG project in Orkney to other locations in the UK and NWE. It focuses on defining suitable areas and end uses for tidal energy, hydrogen, and the value of an integrated solution for other remote locations and islands within the NWE area.

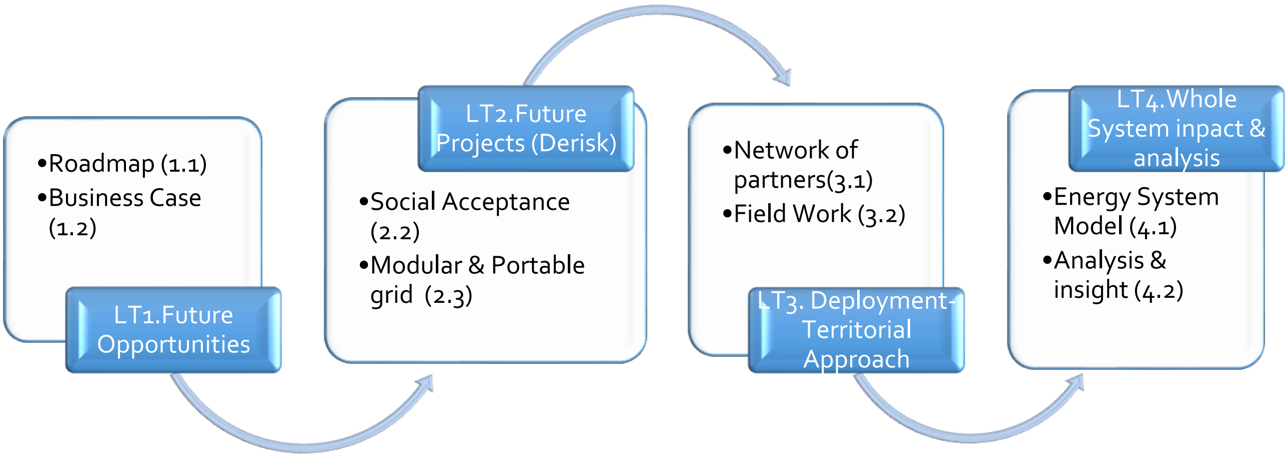

Figure 1-1: List of activities and deliverables within the Long- term Impact WP

1.4 Outline of report

This report specifies the detailed development needs, value chain for remote areas and opportunities for technologies and paths to commercial deployment through analysis of existing marine energy road mapping studies.

The report is laid out as follows:

- Section 2 introduces the technology state illustrated with current and pipeline projects related to:
- tidal energy,
- the hydrogen sector from production to end use, and
- green hydrogen production from renewable including tidal energy.
- Section 3 compiles best practices and analysis of previous roadmaps identifying the different needs and pathways of different aspects. Collecting the different viewpoints and assumptions helps understanding the similarities and discrepancies between the different scenarios and ambitions in the tidal and hydrogen energy sectors and the potential to integrate technologies.
- Section 4 sets out the boundaries and assumptions for this project to define the needs for the development of a roadmap for an integrated tidal turbine with an electrolyser. Different scenarios with various levels of integration within the whole energy system are presented for future deployment in the UK and NWE.
- Section 5 summarises the findings and recommendations for the future of an integrated tidal and electrolyser energy solutions within the rest of the energy system in the context of small islands and remote locations. The conclusion summarises the key enablers and barriers to deployment in the UK and NWE.

2 Technology

This section is a short introduction and review of the current status of tidal energy and hydrogen production technologies.

2.1 Tidal Energy technology

2.1.1 Ocean Energy Introduction

Ocean energy is one of the many renewable sources of electricity that are developing at a fast pace towards decarbonisation of electricity production. Ocean energy technologies comprise five distinctive technologies typically based on the resource used. Technological opportunities will be therefore differ depending on the location. [7]

- **Tidal range** makes use of the tidal range (the actual height difference between high and low tide) and harnesses the potential energy.
- **Tidal stream** makes use of the tidal currents. Tidal energy refers to both technologies unless range and stream is specifically specified.
- **Wave energy converters** harvest the energy that is contained in ocean waves and uses it to generate electricity.
- **Ocean Thermal Energy Conversion** (OTEC) makes use of the temperature difference between the warm surface and the cold deep sea layers (at 800 to 1 000 metres depth) and converts it through a thermal cycle into electricity, heat or cold in a heat cycle.
- **Salinity gradient power generation** makes use of the pressure potential in the difference in the ocean's salt concentration and transforms it into useable energy with the help of membranes.

Ocean energy devices offer clear and potentially substantial benefits for obtaining a renewable energy source and producing low carbon electricity. Apart from wave energy that is weather dependent (mainly wind), ocean energy technologies offer very high predictability, making them suitable to provide steady baseload power, which can be further complemented by wind and solar power.

Tidal stream and wave energy technologies are picking up speed.. This is a very innovative area of renewable electricity generation. According to the International Renewable Energy Agency (IRENA) [2], invention activity in ocean energy technologies has witnessed a surge since the early 2000s, reaching more than 24 000 filed patents by local intellectual property authorities. These technology breakthroughs were accompanied by an annual compound growth rate of 15% between 2007 and 2017. While the fastest growth was driven by wave and tidal technologies, other technologies, such as OTEC and salinity gradient, may become increasingly relevant over longer time horizons and also achieved rapid progress.

For the purpose of this study, amongst the ocean energy technologies, the main focus is on tidal energy as this is the technology of choice for the ITEG project: the development and demonstration of a state-of-the-art energy solution combining a tidal stream turbine with an electrolyser. This is also the dominant technology in terms of worldwide active and projected capacity [7] as well as being suitable for NWE development according to resource attractiveness studies [8]. Wave energy data and development are sometimes combined with tidal energy as the main ocean power sources in roadmaps and are included in this study where appropriate.

Tidal energy technologies are deployed in the EU and worldwide in pre-commercial demonstration projects with the deployment of full scale devices in real sea condition and the technology is approaching commercialisation. [9]

Unlike solar and wind, the potential for tidal energy is limited to regions with significant tidal energy available. Currently, more than half of the worldwide ocean energy active and projected capacity are located in Europe. [7]

Led by the main European pilot farms – Meygen[1], EnFAIT[2] and Oosterschelde[3] - the European tidal stream sector produced close to 12 GWh in 2019. [10]

The main areas with potential are the countries bordering the Atlantic Ocean and the North Sea. The UK, in particular, as a whole, is estimated to have around 50% of Europe's tidal energy. Within the UK, Scotland with its extensive coastline and the number of islands is estimated to have around a third of the UK's tidal stream resources. The Orkney Islands in Scotland have a number of particular distinguishing features, including considerable tidal resources.

2.1.2 Tidal Energy Projects Review

With the concept of tidal energy proven, the growing demand for electrification and progress towards commercialisation, tidal projects and associated test sites are likely to grow in number and capacity in the coming years.

Ocean Energy Europe[4] and EMEC[5] maintain a list of current ocean energy news and projects on their websites. The European Commission[6] also provides a map of projects and test sites in Europe.

For more details, the "UK Marine Energy 2019: A new industry" report from the Marine Energy Council [11] provides more facts about the growing number of marine energy research universities, leading projects in the UK, innovative companies and interest groups from the public and private sectors. The recent report (2021) "Tidal Current Energy Developments

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[1] https://simecatlantis.com/projects/meygen/

[2] https://www.enfait.eu/

[3] https://www.tidalbridge.com/projects/

[4] https://www.oceanenergy-europe.eu/policy-topics/european-projects/

[5] https://www.emec.org.uk/projects/ocean-energy-projects/

[6] https://ec.europa.eu/maritimeaffairs/atlas/maritime_atlas/#lang=EN;p=w;bkgd=1;theme=89:0.75,173:0.75;c=835966.4556538202,6749943.601464724;z=5

Highlights" from Ocean Energy Systems (OES) [9] details the technology highlights of 16 existing and 6 upcoming projects worldwide.

These pioneering projects all bring some technological innovations to the industry. Beyond the technological enhancements, many of the projects have specific area of interest such as gathering data in a real life environment, state of the art tidal turbine concepts, innovation in rotor design, environmental impact, integration within the wider electricity and energy systems... Some projects such as the Tidal Stream Industry Energiser Project, known as TIGER[7] project focus strongly on cooperation between projects, industry partners and academia to share results, integrate findings and accelerate development.

As the scale of each installation and the total number of installations increase around the coastline, the economic and environmental impacts , both positive and negative, will be key determinants to the success and large scale deployment of tidal energy in the UK, in NWE and around the world.

2.2 Hydrogen technology

Hydrogen is an energy carrier element that is not readily available but can be produced, stored and deliver useable energy.

Hydrogen can be produced using diverse processes. Steam reforming of natural gas is currently the primary process of producing hydrogen and the vast majority of hydrogen is produced from fossil fuels (approximately 95%). One fast developing alternative technology is electrolysis of water which can be a carbon free way of producing hydrogen. However, electrolysis of water is a resource intensive process in energy and water.

Hydrogen can be used in different ways: in fuel cells to generate electricity using chemical reactions or to produce heat by combustion, both producing only water and heat as by-products. Hydrogen can be used for mobility (road, railway, waterways, aerospace), for heating (space and water heating) and electricity generation (from portable or stationary fuel cells to hydrogen gas turbines). It is also a widely used chemical feedstock supporting the refinery sector and ammonia production.

For this report, the attention focuses on hydrogen production using renewable electricity. However, a section (2.2.2) on the multiple uses of hydrogen have been highlighted in the context of remote locations which differ from mainland large industrial sites.

2.2.1 Electrolytic processes

The electrolytic process uses electricity to split water (H_2O) into hydrogen (H_2) and oxygen (O_2) using an electrolyser. Electrolysers (commonly designed with an anode, cathode, and electrolyte) can be of different sizes, and types depending on the needs of the application. The four main electrolyser technologies are:

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[7] https://interregtiger.com/

- Polymer electrolyte membrane electrolysers (PEM)
- Alkaline electrolysers
- Solid oxide electrolysers (SOE)
- Anion exchange membrane (AEM)

Alkaline and PEM electrolysers are the most advanced and ready for commercial deployment (TRL 8-9),while SOE and AEM bring promising performance but have lower technological development (TRL 5-6 and 2-3 respectively). Each technology has its own competitive advantage and operational benefits. Alkaline electrolysers have the lowest installed cost, while PEM electrolysers have a much smaller footprint, combined with higher current density and output pressure. Meanwhile, SOE have the highest electrical efficiency. Finally, AEM require no scarce raw materials which can be critical for long term large scale future deployment. Planning and assessment need to take into account the different technological options for the chosen installation with trade-offs between efficiency, durability and costs.

Hydrogen produced via electrolysis can result in zero GHG emissions, depending on the source of electricity used. The embedded emissions related to electrolysers connected to the grid must factor in the amount of fossil fuel required to produce electricity and the associated emitted gasses and particles. However, feeding electrolysers directly from renewable energy electricity sources produces green hydrogen. Furthermore, connecting both renewable sources and the grid to an electrolyser can both benefit the electrolyser in terms of load and support balancing of the electricity to the grid.

In the planning of any electrolyser installation storage is a key consideration to ensure that variable production rates (from intermittent renewable energy sources for example) match the end customer demand. Storage can also help the electrical system resilience and access market prices favourably by directing the produced electricity to the grid or the electrolyser depending on import/export prices and supply/demand forecasts.

2.2.2 Hydrogen use

In order to identify the future of electrolysis and hydrogen production, the local demand and the potential for export need to be identified. Several reports identify multiple uses and their potential in a future hydrogen economy. However, the large scale potential demand, such as building heating and the chemical industry, is unlikely to be required in the context of small islands and remote locations due the absence of gas grids and large industries alongside a low density population.

The most likely uses of hydrogen in this context are listed below by category as well as possible renewable alternatives:

- **Heating**: Hydrogen and fuel cells can play a role in the supply of heat during seasonal peak time without reinforcing the electric power grid. Fuel cells can also be used for combined heat and power. In this configuration hydrogen tanks could replace oil tanks using either combustion or standalone fuel cells. In order to replace fuel oils or gas bottles, heat pumps, biomass boilers, or direct geothermal energy could be used. Current building insulation and retrofit potential need to be accounted for in the decision process.

- Mobility:
- For all types of **short distance travel and small vehicles**, electric vehicles are far more advanced and cost efficient. However, fuel cells offer higher grade power, longer autonomy and faster recharging.
- **Marine applications** include passengers' ferries and marine fleet such as export vessels and vessels used for installation and maintenance of ocean energy assets. Hydrogen can be used directly as a shipping fuel, but its storage poses challenges. Liquids derived from hydrogen such as methanol and ammonia (so-called e-fuels or power fuels) do not face such problems, but their production incurs additional cost and efficiency losses. [2] However, current costs and regulations[8] do not make low carbon alternatives a viable option. However, as the adoption of low carbon technology grows in the mobility sector, technology improves and costs fall across the supply chain, with favourable policies and regulations, hydrogen based fuels are predicted to become competitive in the medium to long term.
- **Road transport**: Fuel cell electric vehicles include both personal vehicles and vehicle fleets. Without significant incentives and the development of recharging infrastructure, electric vehicles are more likely to be the chosen option.
- **Small industries**: Again, this is likely to be used on a small scale compared to large connected industrial clusters. However, hydrogen production can be tailored to the industry demand and co-located production can remove the hydrogen transport difficulties. For high grade heat processes, retrofit is likely to be less extensive than for an electrification alternative. For example, HySpirits 2[9] will deliver the world's first hydrogen fuelled distillery in Orkney switching from fuel oils to green hydrogen.
- **Agriculture**: Large cultivated areas require imported ammonia based fertilisers. Ammonia could be produced using locally produced green hydrogen.
- **Power generation**: Demonstrators of conversion of renewables into hydrogen and storage to then enable green hydrogen electrical generation could support resilience of remote locations, grid stability and counter import price volatility. The value of such a system must account for the very low end-to-end efficiency and the cost of dedicated assets such as storage and electricity power generation.
- **Export:** If an export market develops with lower cost production and rising demand, hydrogen production can be maximised in this scenario. Using existing port facilities

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[8] For more information on regulations that influence hydrogen deployment see the ITEG Hydrogen Handling and Logistics report.

[9] https://www.emec.org.uk/projects/hydrogen-projects/hyspirits/

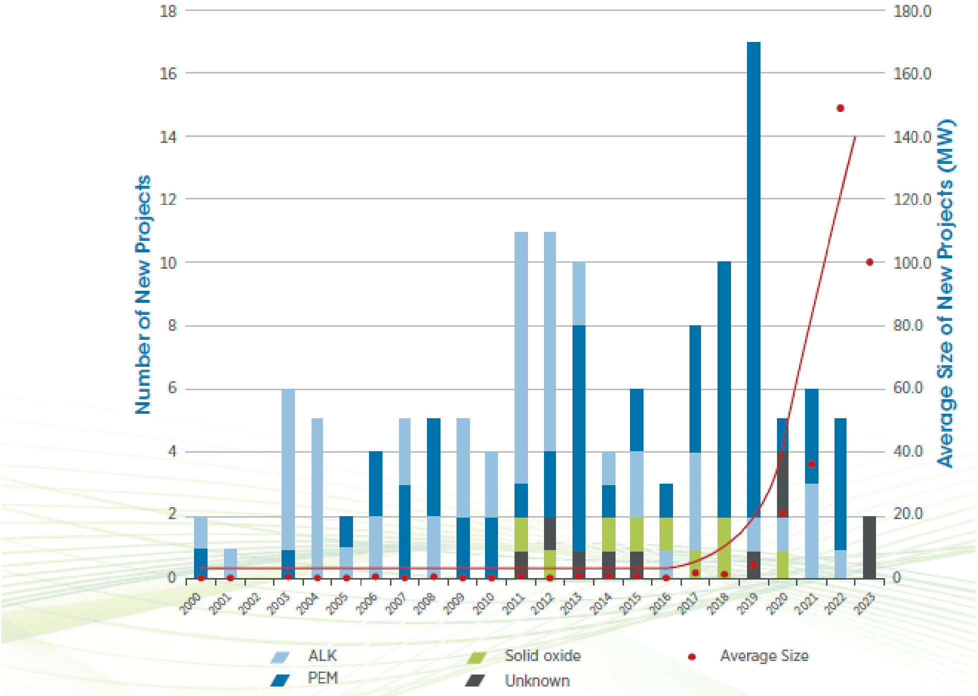
could also support asset, skills and jobs retention. However, the additional cost of hydrogen preparation, storage and transport for the end consumer must remain competitive.

Hydrogen needing electricity to be produced is less energy efficient than using electricity at source. However, their different properties show that they can complement each other. In terms of heating, hydrogen combustion offers similar properties to other fuels in term of grade and responsiveness. Another aspect impacting the supply and demand of hydrogen is the ability to store and transport the energy. Larger quantities of energy can potentially be stored as hydrogen in salt mines. Currently, electric batteries are generally less expensive than hydrogen tanks combined with stationary fuel cells and show better roundtrip efficiencies for equivalent power output [12]. However, hydrogen storage for fuel cells or combustion do not self-discharge allowing for seasonal storage, have a longer asset lifetime and are more temperature and humidity tolerant. Depending on the quantity required for the different applications and the demand profile, it is important to compare the feasibility and cost associated to distribute the required electricity (grid extension, reinforcement) or the hydrogen alternative (pressurised tanks).

2.2.3 Electrolyser Development Projects

Electrolysis is enjoying unprecedented interest and development momentum. With an increasing number of promising policies, investment and the average size of new projects around the world are expanding exponentially as shown in Figure 2-1. Hydrogen isn't a natural resource; its clean production relies on electricity and water resources. However, these are widely available allowing flexibility in terms of both location and scale of electrolyser deployment.

Figure 2: Timeline of power-to-hydrogen projects by electrolyser technology and project scale



Source: Quarton and Samsatli, 2018 and IRENA Database

Figure 2-1: Timeline of power-to-hydrogen projects by electrolyser technology and project scale [13]

Hydrogen from renewable power is technically viable today and is quickly approaching economic competitiveness with other low carbon alternatives especially for transport, and in industrial and power sector applications [14]. The purpose of new projects is now to scale up production from MW to GW scale, to improve the supply chain and to integrate hydrogen within the whole energy system.

An up-to-date database (October 2021) of worldwide hydrogen projects can be downloaded from the IEA website[10]. The database can easily be filtered by country, project status (operational, concept, demo, under construction etc), technology including type of renewable in the case of dedicated renewable source, end use, capacity etc. At European level, the Clean Hydrogen partnership[11] (previously known as the FCH JU) holds a projects repository currently[12] containing 287 projects which can also be filtered and includes links and information for each project (project duration, location, budget, EU contribution etc). The European Network of Transmission System Operators for Gas (ENTSOG)[13] also provides an interactive map of projects from an open source database along the whole hydrogen value chain.

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[10] https://www.iea.org/data-and-statistics/data-product/hydrogen-projects-database

[11] https://www.clean-hydrogen.europa.eu/projects-repository_en

[12] At time of writing (January 2022)

[13] https://h2-project-visualisation-platform.entsog.eu/

2.3 Integrating Tidal Energy with Hydrogen Production

2.3.1 The ITEG Project

As presented in the previous sections, tidal energy and green hydrogen production are at the heart of the decarbonisation strategy of many countries in NWE. The ITEG Project aims to develop and demonstrate a state-of-the-art energy solution combining a tidal stream turbine with an electrolyser (Figure 2-2).

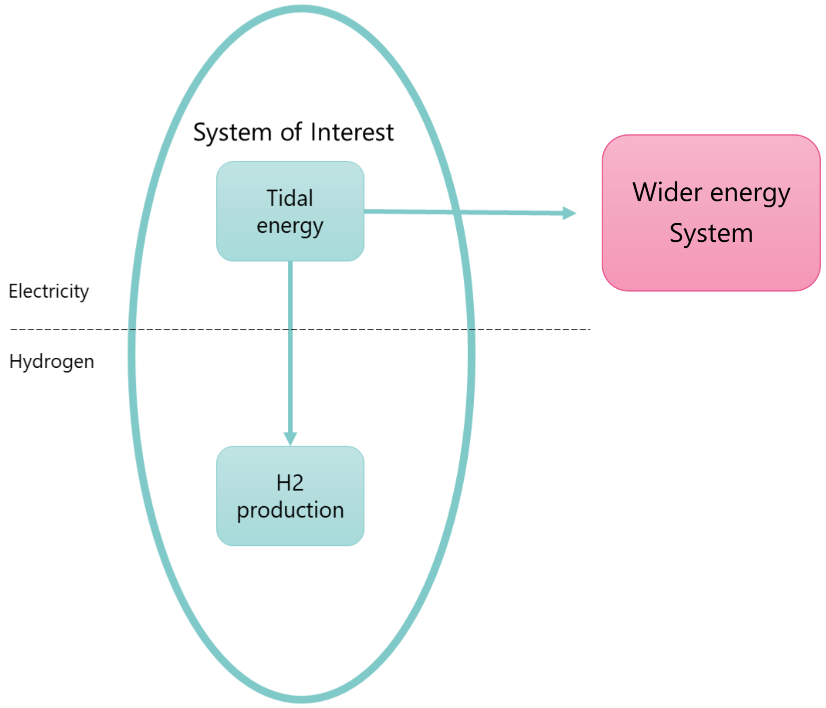

Figure 2-2: ITEG Project System of Interest Diagram

This project is particularly significant due to the increasing focus into the integration of technologies within each energy vector (integrating solar, wind and ocean energy electricity generation) and across vectors (electricity and gas).

For the scope of the ITEG project (see report "Whole Energy System Analysis: Long Term Impacts on the Orkney Energy System"), the tidal generator is assumed to be run to maximise the power output at all times. This maximises the useable energy extracted. Power generated can be fed to the on-site electrolyser or directly onto the grid or split between the two. Unlike a tidal generator, an electrolyser can be run on command at any time and at any level of output within operating parameters. The electrolyser within the ITEG project is set up within the model to run solely from power generated by the tidal turbine, it is not able to take power from the grid. However, the option to power the electrolyser from the grid is also evaluated. Figure 2-3 shows the energy exchanges between the different elements outside the system of interest and the interaction between them.

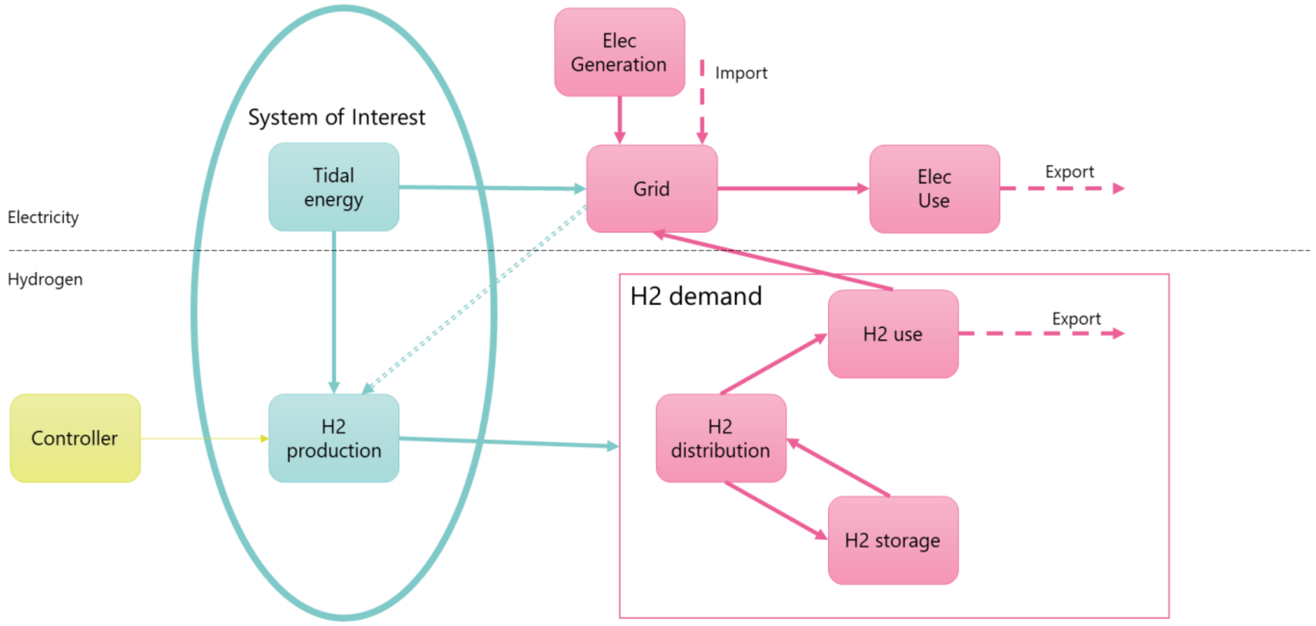

Figure 2-3: ITEG Project System Energy Flow Diagram

Note that the controller can direct the tidal sourced electricity to the grid or the electrolyser for different purposes that can be modelled. The strategies can be defined to operate purely on cost of electricity or to maximise revenue for the operator, to maximise hydrogen output, to increase system resilience following physical, regulatory and commercial constraints.

This integrated system and the development of the controller will be supported by the growing interest in flexibility, storage and digitalisation to develop a decarbonised future for Orkney.

2.3.2 Related Projects Review

Most integration projects for dedicated green hydrogen production use the most widely developed forms of renewable energy: wind and solar energies. Some of the challenges are similar but some differences must be noted:

- Electricity generation from wind and solar energy is intermittent and unpredictable. Tidal energy is very regular and predictable making it much easier to predict and optimise the load factor of the connected electrolysers. Combining electric and hydrogen storage at both ends of the electrolyser can further improve the load factor.
- Any location onshore and offshore has some degree of wind and solar power potential giving the opportunity to install electrolysers close to electricity source and hydrogen demand. The limitation of tidal energy locations limits scale up potential.

However, two other projects are leading the way in integrating tidal energy and electrolysis and are presented in the following section.

2.3.2.1 BIG HIT[14] / Surf'n'Turf[15]

Orkney's existing and developing projects demonstrate an island approach to growing a hydrogen economy, in building block stages.

The initial **Surf 'n' Turf** project delivered a 500 kilowatt (kW) green hydrogen production facility on the Isle of Eday. The hydrogen is produced using tidal power from deployed turbines at the EMEC site, along with 900 kW community wind generation. The hydrogen is stored and transported to Kirkwall harbour, where it is used in a fuel cell to provide electricity to docked ships in the port.

Following this, the Building Innovative Green Hydrogen Island Territories (BIG HIT) project expanded on the idea of whole energy system thinking, at a local level. It aims to demonstrate that the approach can be replicated at other rural locations. Green hydrogen is produced by electrolysers on Eday (0.5 megawatt (MW)) and Shapinsay (1 MW), supplied by onshore wind, and is then stored in tube trailers for transportation to mainland Orkney. Launched in 2018 when fully commissioned 50 tonnes of hydrogen will be produced annually for local buildings and transported to Kirkwall for heat and power of harbour buildings, the marina, vessels and a refuelling station for road vehicles.

From these projects, numerous others have grown and are demonstrating hydrogen demand in ferries (HySeas III[16], HyDIME[17]), aviation (HyFlyer[18]) and distilleries (HySpirits[19]). The Hydrogen Offshore Project[20] on Flotta Island is also considering incorporation of oil and gas infrastructure. Wider energy system integration is being explored through ReFlex[21] which is exploring the potential of both hydrogen and increased electrification alongside smart management of the system to bring more renewable energy online. [15]

2.3.2.2 THyPSO (Tidal Hydrogen Production Storage and Offtake)[22]

Tidal developer HydroWing is creating a floating platform that houses multiple Tocardo horizontal-axis tidal turbines, an electrolyser and storage tanks. The electricity is not delivered to the grid but used to transform seawater into hydrogen, which can be stored on the unit for up to two weeks. Discharge to an offtake vessel moored down-stream of the device, connected via a pressurised delivery hose can be scheduled autonomously by remote communications.

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[14] https://www.bighit.eu/

[15] https://www.surfnturf.org.uk/

[16] https://www.hyseas3.eu/

[17] https://hydime.co.uk/

[18] https://www.emec.org.uk/projects/hydrogen-projects/hyflyer/

[19] https://www.emec.org.uk/projects/hydrogen-projects/hyspirits/

[20] https://www.flottahydrogenhub.com/

[21] https://www.reflexorkney.co.uk/

[22] https://hydrowing.tech/thypso/

The integration of the tidal energy source with hydrogen production and storage aims to overcome some of the challenges faced by each technology alone such as subsea infrastructure and grid connection. An integrated solution also offers accelerated consenting, planning, installation, deployment and decommissioning times. [7]

The development of each element throughout the energy system (renewable generation, hydrogen distribution and demand, electric batteries) and the ability of these demonstrators to integrate within the whole energy system will shape the future of integrated tidal and electrolyser development. The success of these projects, their expandability and replicability can speed up the deployment and scale of future projects.

3 Analysis of Existing Roadmaps

3.1 Roadmap Studies Best Practice

Roadmaps are widely used to provide a structured approach to technology development and support strategic innovation at all levels from national, to sector, to organisation level whilst considering the needs of all the stakeholders in an industry [16]. If successfully implemented, the roadmap is aimed at accelerating understanding of how the sector could develop. In the 2014 UKERC/ETI report [17], technology roadmaps are defined as "tools that provide a framework for stimulating innovation in specific technology areas in order to achieve a long-term vision, target or goal. The aim of this roadmap is to facilitate the establishment of a commercially viable marine energy sector in the UK, supported by an extensive supply chain, thereby building the skills and capacity necessary to enable the sector to make a material and cost-effective contribution to the delivery of the UK's energy and climate change goals".

First developed by Motorola in the seventies, roadmapping has become widely used across most industries to look closely at the future of chosen technologies, strategies or other fields of interest based on consideration of key drivers of change [18]. These roadmapping approaches enable industries to address the key elements that have significant impacts to the sector or the organisation itself. They allow dissemination and communication to help align the market pull (commercial perspective) with technology development.

The various key functions impacting a product/service must be considered when developing a roadmap to maximise its application as innovation comes hand in hand with the competitive position of firms. According to H. Chesbrough [19], companies are moving away from the traditional R&D innovation models to more open and structured approaches that use a combination of internal and external ideas in addition to responding to market needs. These models integrate the needs of the people, the process, the market and the technology as factors of the roadmap.

Roadmaps can be used by organisations to exploit innovation and integrate them into their business planning and/or at a higher level (e.g. national, or sector level) to capture the opportunities, the threats and possible environmental landscape of technologies or applications [20].

Roadmapping is not an activity in its own right happening independently of other strategic plans. A roadmap must be preceded by assessment of the state of the technology and the economic and political landscape. For a roadmap to be successful, it must be supported by action plans and policy statements.

This report compiles data and information from existing roadmaps and ongoing strategies in the ocean energy and hydrogen market sectors and performs a critical review to understand areas of consensus and differences, the challenges and the key aspects relevant to the combination of a tidal stream turbine with an electrolyser.

For the purpose of this report, when the term “short term” is used, it refers to current prospects and planned activities, “medium term” is looking at a 2030/2035 vision becoming dependent on short term development and governmental updates and “long term” refers to a 2050 net zero future.

Many roadmaps and action plans are being developed in parallel and they will interact and impact the development of the energy system in the ITEG context such as climate change plans, economic action plans, transport strategies, heat policies to name a few.

3.2 Tidal Energy Roadmapping studies

With ocean energy abundant in European waters, numerous roadmaps have been developed in recent decades for the Ocean energy sector in the UK and in Europe. These reflect a common vision and identify the challenges facing the sector in its path to commercial readiness.

As presented in section 2.1, among all types of ocean energy, tidal energy technology is advancing steadily and is now approaching commercialisation.

3.2.1 Existing Roadmaps

Thirteen 13 roadmaps and reports related to tidal energy has been reviewed and analysed in this report A summary table of these roadmaps including the key aspects studied and relevant conclusions is available in Appendix 8.1.

The focus of each document varies considerably depending on the area (UK, Europe, Worldwide) and the key aspects of interest. Some roadmaps may primarily focus on the technological or commercial perspective while some integrate both and include some other dimensions such as the environmental, social benefits or policies. As an emerging sector with multiple ocean energy technologies , the focus can also be on the specifics of different development phases.

It is also important to note that many reports include tidal energy within global marine energy. Therefore, for this study, information has to be extracted and conclusions rescaled to a tidal energy perspective.

Each roadmap is based on assumptions to develop one or more potential scenarios. This brings a wide range of ambitions from slow progression to maximising use of natural resources for tidal generation along the NWE coast.

The outcomes have evidently evolved between the earliest roadmap reviewed (from 2008) and the most recent (from 2021) due to rapid technology development, the changing energy and environmental policy landscape alongside, the complexity and uncertain future of the whole energy system. Older roadmaps help understanding of the progression of development and allow assessment of successes and challenges. Comparing them to more recent ones also allows identification of remaining barriers. The conclusions, planning and recommendations will also differ depending on if they relate to the medium term (2030/2035) or long term (2050) outlook.

The next sections identify the current landscape of tidal energy, analyse each aspect covered by the reports and extract key points in the context of the ITEG project.

3.2.2 Roadmaps Analysis / Aspects

Due to the novel and niche nature of tidal energy, most of the authors and participants in these reports are experts in tidal energy and therefore generally agree about main themes.

3.2.2.1 Environment

With net zero objectives set for 2045 or 2050 in all countries in NWE, the increased demand for electrification from renewable sources have been given a boost in recent years including tidal developments. Despite being far behind wind and solar power, the environmental benefits of tidal energy are undeniable:

- Tidal energy has the potential to support the shift from coal, oil and natural gas to electricity. According to a 2018 Offshore Renewable Energy Catapult (OREC) report [21], every kWh of power generated by a wave or tidal saves 394g CO_2 compared to the same power from CCGT (Combined Cycle Gas Turbine Plant), 937g CO_2 compared to coal or 120g CO_2 compared to biomass during operation.
- Compared to wind and solar energy, tidal energy has the added benefit of predictability. The tides can be predicted decades in advance. The different pattern and the predictability make tidal energy a well suited complement to wind and solar energy.
- Combined with energy storage, tidal energy can create the potential for a predictable, dispatchable renewable energy source to support the low-carbon grid.
- It is also worth noting that, in the context of islands and remote locations of communities, oil based fuels are used for heating more often than in urban areas. Electrification could therefore bring an even more important environmental benefit.

To ensure the sustainability of renewables sourced from oceans, benefits must be maximised while addressing potential negative impacts on ocean ecosystems. How the ocean energy technologies, including tidal, are affecting the environment, including marine life, is not clear. Negative impacts could arise in the form of habitat loss, animal-turbine interactions, noise and electromagnetic fields produced by sea cables, which may impact aquatic species. However, research to understand and address these risks is being conducted. Some studies indicate that ocean energy may actually support biodiversity through artificial reefs, fish aggregation devices and marine protected areas. As for any infrastructure project, detailed impact assessment studies and best practices must apply. As understanding of these technologies deepens, we must continue to mitigate any potential risks while maximising the socio-economic and environmental benefits of the various technologies. [2]

The environmental benefits of tidal energy are sometimes just assumed but are not often quantified. It can be difficult to analyse the whole value chain, especially when the end use is unknown. The benefits are different whether tidal generated electricity supports other renewables sources, reduces imports, can be exported, directly replaces fossil fuels sources (for heating or mobility) or indirectly (used to be stored or to produce hydrogen).

Given the relative immaturity of the industry, and the relatively small number and size of devices being installed compared to other renewable technologies, the risk of any significant impacts on the environment is at present very low. However, as scale and number increase around the coastline, both the economical and overall environmental impact will be key determinants. In most roadmaps, the two main parameters identified to define the planned or estimated capacity in the medium and long term are the technological advancement and the economic environment to estimate or plan the capacity.

3.2.2.2 Capacity

The two main recent and quite different capacity forecasts for tidal energy in Europe for 2050 are 40 GW (European Commission strategy [1]) and 100 GW (Ocean Energy Europe [22]). Note both include wave and tidal energy in different proportions. The range shows the most recent European strategy and the most optimistic scenario. With a finite theoretical maximum capacity, the difference also lies in the speed of development more than the ceiling state beyond 2050 (for example, research for the Crown Estate in 2012 [8] reports a value of 32GW for the UK).

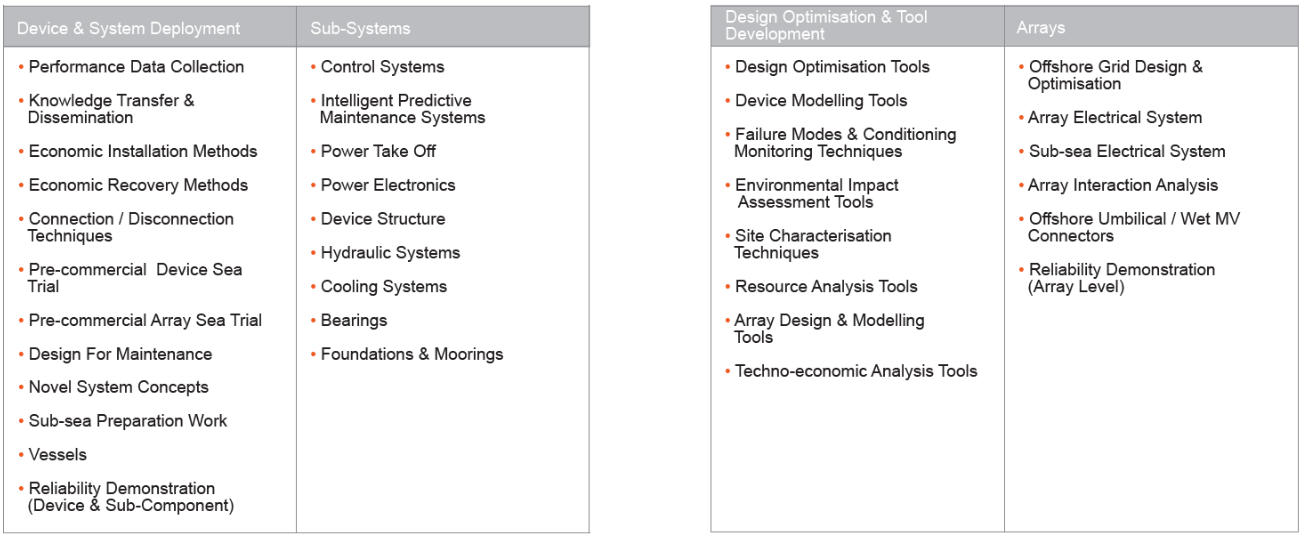
Within Europe, the UK has currently the most installed operational capacity (10MW) with 180MW of tidal energy already planned post 2025 [11]. Offshore Renewable Energy Catapult predicts that in the UK as a whole, 1 GW of tidal energy could be installed by 2030 [21]. However, there is limited visibility in the pipeline of renewable projects beyond 2030.

Technology advancements and the transition to commercialisation can be expected to increase the speed of deployment.

3.2.2.3 Technology

The relative immaturity of the ocean energy industry allows multiple technologies to develop in parallel. Tidal energy is however the most advanced technology getting closer to reaching commercialisation with several tidal arrays in operation across the world.

One of the specific purposes of the “Marine Energy Technology Roadmap 2014” [17] is to identify the specific technological developments and demonstration activities required to progress the marine energy sector. Despite the age of the document, the detailed analysis is still relevant today and the themes presented are found in the other documents as shown in Figure 3-1



Device & System Deployment	Sub-Systems	Design Optimisation & Tool Development	Arrays
Performance Data Collection	Control Systems	Design Optimisation Tools	Offshore Grid Design & Optimisation
Knowledge Transfer & Dissemination	Intelligent Predictive Maintenance Systems	Device Modelling Tools	Array Electrical System
Economic Installation Methods	Power Take Off	Failure Modes & Conditioning Monitoring Techniques	Sub-sea Electrical System
Economic Recovery Methods	Power Electronics	Environmental Impact Assessment Tools	Array Interaction Analysis
Connection / Disconnection Techniques	Device Structure	Site Characterisation Techniques	Offshore Umbilical / Wet MV Connectors
Pre-commercial Device Sea Trial	Hydraulic Systems	Resource Analysis Tools	Reliability Demonstration (Array Level)
Pre-commercial Array Sea Trial	Cooling Systems	Array Design & Modelling Tools	
Design For Maintenance	Bearings	Techno-economic Analysis Tools	
Novel System Concepts	Foundations & Moorings		
Sub-sea Preparation Work			
Vessels			
Reliability Demonstration (Device & Sub-Component)			

Figure 3-1: Development Themes and Activities [17]

The purpose of these activities is to move to the next step of technology readiness by improving performance and cost and integration within the electricity system.

Performance improvement is driven by, but not limited to, the increase of reliability and performance of the design of the turbine itself. Testing and improving the entire device, its subsystems and their components in both real life condition and in controlled environments are needed throughout the different stages of technology development.

Because tidal regions are harsh marine environments, survivability, installation and logistics are also key areas of improvement. Moorings and seabed attachments are integral to the successful deployment, operation and recovery of wave and tidal current devices. Survivability is arguably the most important aspect of the development of any new device. This will benefit from advances in new structural materials, a better understanding of failure modes and component reliability, and the ability to forecast extreme weather events. [23]

With the growing number of real sea operational conditions, models and optimisation tools are being developed to plan and improve techno-socio-economic and environmental outcomes such as:

- Multiple 1D, 2D, and 3D software tools to evaluate the energy potential of tidal currents as reviewed in 2019[23].
- Device energy capture optimisation and energy planning tools such as the open source NEMOH[24] from Ecole Centrale de Nantes and TidalBladed[25] and TidalFarmer[26] from DNV.

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[23] https://www.mdpi.com/1996-1073/12/9/1673

[24] https://lheea.ec-nantes.fr/research-impact/software-and-patents/nemoh-presentation

[25] https://www.dnv.com/Publications/tidal-bladed-23949

[26] https://www.dnv.com/Publications/tidalfarmer-23956

- Techno-economic energy planning and system integration models such as UK Times[27] developed by UCL and BEIS, Energy System Modelling Environment (ESME[28]) and EnergyPath Networks (EPN) from ESC.
- Financial analysis for ocean energy technologies modelling packages such as Exceedence Finance[29], Wave Venture TE™ [30] . These tools focus on assessing and optimising the cost efficiency of deployed ocean energy technologies.
- Design tools for selection, development and deployment of ocean energy systems, aligning innovation and development processes like DTOceanPlus[31] including system performance, energy yield, reliability, availability, maintainability, survivability, social acceptability, and environmental acceptability.

The site selection (including access, load factor and availability), understanding the most appropriate tidal device (types, turbine and array sizes), the conversion from mechanical to electrical energy, the interface with the grid and grid infrastructure upgrade requirements (offshore and onshore) and the end-use of electricity are all critical development points.

3.2.2.4 Levelised Cost of Energy

As for many innovative technologies, the Levelised Cost of Energy (LCOE) from tidal generation is high compared to other renewable technologies. This is mainly due to the high capital expenditure (CapEx) of demonstrators. The objective is for tidal energy technology to become competitive with other renewable sources. Without clarity on the speed of development, it is difficult to agree on a price target against time. However, there is a convergence on the cost reduction against the installed capacity. Recent studies and estimations show that the 0.1£/kWh LCOE target could be achieved in the near future before the installed capacity of tidal energy reaches 1 GW as shown in Figure 3-3 [7]. (Note: conversion rates used 1 USD = 0.9 EUR and 1 USD=0.75 GBP)

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[27] https://www.ucl.ac.uk/energy-models/models/uk-times

[28] https://es.catapult.org.uk/tools-and-labs/our-national-net-zero-toolkit/

[29] https://exceedence.com/

[30] http://www.wave-venture.com/software

[31] https://www.dtoceanplus.eu/Tools/DTOcean

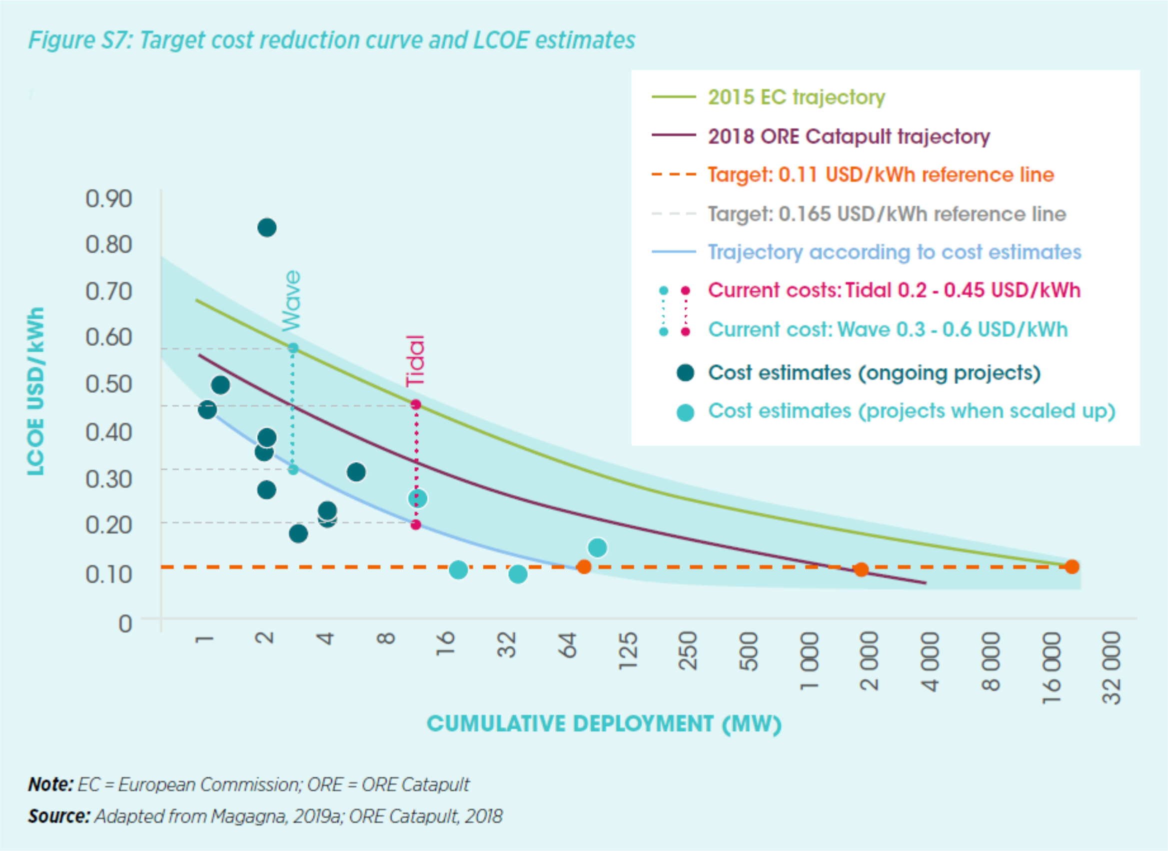


Figure S7: Target cost reduction curve and LCOE estimates

Note: *EC = European Commission; ORE = ORE Catapult*

Source: *Adapted from Magagna, 2019a; ORE Catapult, 2018*

Figure 3-2: Target cost reduction curve and LCOE estimates [7]

For example, as shown in Figure 3-3 from the 2018 OREC report [21], with the right support giving a route to market, we expect significant cost reduction to be achieved in the near-term, followed by ongoing incremental reductions with growth in the industry. Significant cost reduction is expected to be achieved through:

- initial accelerated reductions
- learning by doing and innovation
- and cost of capital.

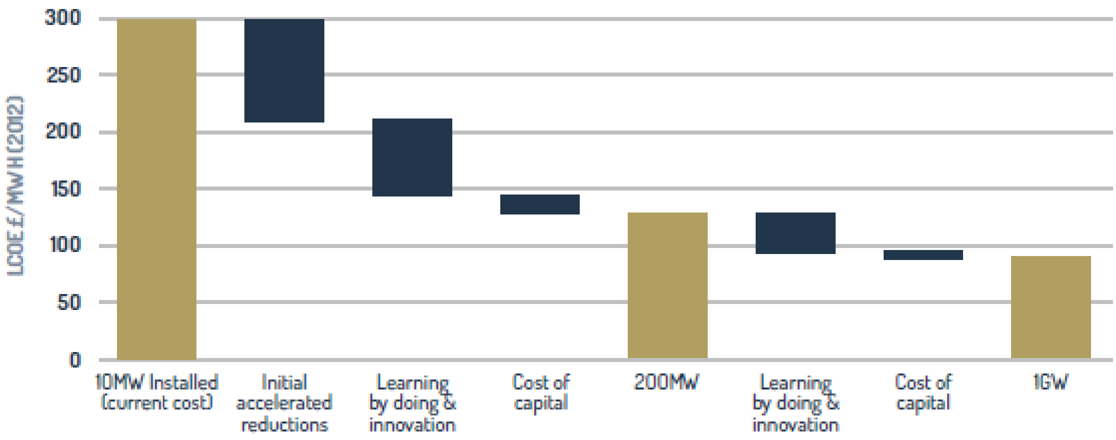


Figure 3-3: Tidal stream LCOE reduction [21]

The LCOE could also be lowered in the context of local generation by sharing infrastructure and avoiding connection fees and grid reinforcement.

Financial instruments to support capital and revenue (e.g. Feed-In Tariffs, Contracts for Difference) similar to those used to promote wind and solar energy uptake are another key aspect for accelerating innovation and deployment leading LCOE reduction towards competitiveness. However, unlike wind and solar, this policy support will compete with more established types of renewable electricity. There is currently a limited pool of potential investors until the technology becomes more mainstream.

3.2.2.5 Policy, Regulation and Standards

Tidal energy is still a niche market sometimes overlooked in preference to wind and solar energy in climate plans and agendas. The next step towards commercialisation will need to be supported with policies that create steady financial support, stable markets and investment incentives to create a positive enabling environment with engaged stakeholders. This should allow tidal energy to establish itself in long term national and local energy roadmaps and action plans. The impact of policy on market development can perform a similar role that was played for offshore wind. The main areas of support from policy and regulation are shown below:

Support financial stability and security

Financing ocean energy technologies can be done through different mechanisms according to the technology stage. In the R&D phase, money is often acquired through capital support schemes such as grants or through special tools such as stage-gate metrics. The same funding instruments are also necessary in the consecutive stages of early testing and demonstration. The phase between demonstration and first commercial deployment, also known as the valley of death, is critical for innovations and start-ups. Large sums of money have been spent but no real revenue has returned at this stage, posing challenges to survivability. This is one of the stages where standardisation can play a significant role in decreasing costs. For all stages of maturity, minimising the perceived risks can help greatly to secure any type of financial support, which can increase a project's viability and help to attract more investment, particularly through private investors and loans. [7]

Some tools and mechanisms that can help balance the equation (reducing costs on the investment side and increasing cash flows on the revenue side) are presented in Figure 3-4.

Table 12: Ways to balance the profit-and-loss equation

Investments: reduce capital costs	Operations: increase income
CAPITAL SUPPORT • Grants • Equity • Loans	**REVENUE SUPPORT** • Power purchase agreements • Feed-in tariffs • Feed-in premiums • Tenders and auction-based instruments • Contracts for Difference • Quota schemes • Certificates, for example renewable obligation certificates or renewable energy certificates

Figure 3-4: Ways to Balance the Profit and Loss Equation [7]

It is worth noting that a single project can mix several mechanisms, from private and public sectors, capital and revenue support etc. Also, some support schemes can be aimed specifically at tidal energy and target remote locations such as islands. For example, Scotland introduced its Energy Investment Fund following the publication of the Scottish Energy Strategy and Climate Change Plan as a tool to mitigate climate change effects.

Policy integration

Many policies and regulations affect tidal energy generation. DTOceanPlus Deliverable D8.5[32] provides a critical evaluation of the ocean energy sector's legal, institutional, and political frameworks with an identification and analysis of barriers and enabling factors for the deployment of ocean energy. Results from this task can provide guidance to future policy instruments and give support to consenting measures to be designed in a more informed and effective manner and to help accelerate the development of the sector. A map linking the barriers to specific areas of policy and regulation for consenting/licensing processes to electricity connections would aid understanding of deployment options.

Tidal generation policies and regulations are related to other marine and climate change policies with renewable electricity generation linking the blue economy to electrification. There is significant scope for utilising existing infrastructure (such as harbours, vessels, power cables, grid connection) and processes (including training, health and safety) from other marine industries. However, a new generation of waterborne and sub-sea solutions is needed to match the specific requirements of ocean energy devices [22].

[3232] https://www.dtoceanplus.eu/Publications/Deliverables/Deliverable-D8.5-Relevant-legal-institutional-and-political-frameworks

Cooperation

Due to their locations, tidal projects tend to be grouped around energy centres. For example, EMEC was established in 2003 for companies to test tidal and wave technology with a mission of reducing the time, cost, and risk to progress innovative sustainable technologies to market, maximising the use of bespoke facilities, industry knowledge, and unprecedented experience. EMEC has exported its knowledge to 18 different countries. Other collaboration programmes such as the TIGER project, promote partnerships to gain design convergence and increased device size to achieve reduced costs and so reach viable commercialisation.

During the transition to commercialisation, it is still important to build on existing marine sector national and international organisations such as IRENA to not only share data, but also best practices and lessons learnt. There is still a need for projects to collect and share real life performance data to allow further investigation. Tidal current energy devices in real sea conditions for long periods of time provide invaluable experience regarding performance, reliability, availability, maintainability, survivability and environmental impact.

With real life operational and weather data, operators can better forecast how frequently inspections and maintenance should take place and develop a proactive O&M strategy which minimises expensive reactive repairs and maximises turbine uptime.

While other marine stakeholders will provide shared supply chain support and experience, there is a risk of conflict in the use of marine resources and space that will require consideration. However, engagement with the different stakeholders and strong communication should support the development of the sector where marine planning has a key role to play.

On the electricity side, a strong collaboration with grid operators and public authorities is paramount to identifying areas and planning where to upgrade and adapt infrastructure to allow ocean energy connection.

Unlike other forms of renewable energy, tidal generation devices cannot be seen or heard from the shore and are more socially accepted. However, increased public engagement can increase the likelihood of a successful consultation outcome and adoption.

Support a stronger value chain

The marine energy supply chain in Europe is at the forefront in terms of activity worldwide. There is a significant opportunity to build on the offshore wind supply chain, for example (mooring, cable supply, vessel operators, offshore contractors, academic research, engineering and consultancy services).

With the confidence in sector growth and a robust supply chain to build on, investments can be unlocked in manufacturing plants and innovation which further supports cost reduction.

Coastal regions should seek to maximise this potential through securing the existing supply chain and economic benefits.

Policies on the demand side, such as long-term planning, regional cooperation and a clear regulatory framework can provide signals and indicate the future volumes that industry and investors could aim for enabling targeted investments to increase manufacturing capacity.

Certification and Standards

As tidal energy generation technology matures and moves towards commercialisation, standardisation will not only reduce cost but also pave the way to certification practices. Certification will, in return, facilitate access to additional commercial financing.

The implementation of such policies would not only reduce cost of electricity but also create a more secure market to obtain further funding and investment.

3.2.2.6 Digitalisation

Digitalisation is a key enabler now that several years of data capture from demonstrators has started acceleration of technology development, connection to the grid and integration within the wider energy system. It also aids the development of models to support future scenarios and foster investors' confidence. Data streams from ever more numerous sensors, new analysis methods such as big data or machine learning, and applications such as digital twins, are expected to become increasingly important. This will particularly be the case for the optimisation of maintenance, as it is applied now in the offshore wind and wider energy sectors. [3]

3.2.2.7 Value

Beyond cost, the added value that tidal energy can bring to communities in remote locations and islands include are:

- Avoided costs of grid reinforcement
- Climate change mitigation
- System stability, security of supply and resilience
- Job creation

It can be difficult to quantify these additional benefits, but they need to be considered as part of the development plan.

3.2.3 Conclusions on Tidal Energy Roadmapping Studies

The benefits of tidal energy are undeniable:

- There is a universal increased demand of renewable electricity.
- Tidal energy is predictable, therefore providing firm capacity. It also complements and can be coupled with other more mature renewable sources such as wind and solar energy.
- Tidal energy is available along coastal areas of remote islands which often suffer from grid constraints and a high level of fossil fuel import in their energy mix.
- Building a supply chain for tidal generation can provide employment opportunities for coastal and island communities.
- Coupled with other energy sources and vectors, tidal energy can promote energy independence for these regions.

- Social acceptance of tidal energy is currently strong. They do not produce any noise and little visual pollution from the shore. Marine environmental assessments are an integral part of the detail design of new projects.

Tidal energy is still a niche technology and relatively immature within the renewable sector. Tidal energy is often overlooked in preference for solar and wind which are more advanced in terms of technology readiness and deployed capacity.

However, tidal energy is experiencing rapid progress and is now transitioning from the demonstration phase to commercialisation. [7] It is difficult to predict the long term deployment of tidal energy. With a breakthrough and increasing acceptance, tidal energy could follow a similar path to offshore wind in recent years. With the right regulatory conditions for development and targeted investment, tidal energy deployment can potentially overtake the current predictions. A global market for tidal energy is still emerging and deployment targets have been set out by different national government and industry groups.

The decision to employ tidal stream devices must take a sustainable development perspective, considering the benefits within a framework of environmental, social and economic impacts. These impacts are a mix of positive and negative influences and their importance in practice will vary according to the location and the scale of development.

The main focus in developing a roadmap for an emerging technology within an industry is firstly to meet cost and performance improvements which are greatly affected by changing policy and regulations. The remaining challenges to overcome include:

- **Economic**: High CapEx requirements call for upfront capital availability and affect the overall LCOE. Economy of volume and scale could accelerate learning and reduce costs.
- **Technical**: Uncertainties inherent to innovative technologies require demonstrators to prove efficiency, lower risks and cost of finance.
- **Regulatory**: There is a lack of supportive policies to encourage tidal energy in the electricity mix. Furthermore, planning and licensing frameworks are required which afford confidence to industry, regulators and stakeholders
- **Investment**: As the marine energy sector is geographically constrained, financing tidal energy in the current energy market is difficult due to the limited pool of potential investors compared to other widespread technologies.

Small islands and remote locations are still well positioned to come at the forefront of tidal energy and become the main beneficiaries.

3.3 Hydrogen Roadmapping studies

As the UK Hydrogen Strategy [6] is introduced: The scale of the challenge is clear: with almost no low carbon production of hydrogen in the UK or globally today, meeting our 2030 ambition and delivering decarbonisation and economic benefits from hydrogen will require rapid and significant scale up over coming years.

There is not only an urgent need to decarbonise current hydrogen but, in all scenarios, demand is expected to increase dramatically by 2050.

Hydrogen is set to be a key energy vector in all main national and international net zero energy scenarios. The potential of hydrogen is well documented and important for the transition from fossil fuel for many reasons detailed below. The description and benefits of the different elements of the hydrogen system is focused for the context of this report on hydrogen generated from tidal electricity, specifically in remote location or small islands:

- **Production**: Hydrogen can be produced in multiple ways meaning it is flexible and not resource constrained. However, the most likely technologies for low carbon hydrogen production in the medium term, are steam methane reforming with high levels of carbon capture and electrolysis. Biomass to hydrogen using microbial processes and solar energy used to split water into hydrogen and oxygen are in their infancy and may play a role in the longer term. This report concentrates on electrolysis and its main challenges of cost reduction alongside access and connection to renewable energy sources.
- **Distribution and Export**: Hydrogen can potentially be distributed through existing polyethylene natural gas pipes and exported by tanker. In this report, the focus is primarily on local use and potentially shipping export.
- **Storage**: Hydrogen can be stored in large volumes for a long time and, if compressed, can be more energy dense and have lower losses than electric batteries. In the context of this report, hydrogen storage is integrated with the production or the intended end use (e.g. within the electrolyser plant, containers for transport shipping, refuelling station etc).
- **Use**: Hydrogen produces no GHG emissions at the point use through combustion or chemical reaction in fuel cells. It also has the ability to generate high temperatures through combustion. However, hydrogen is unlikely to be the main energy vector of choice for final energy demand in the context of this report.

Hydrogen opportunities are often associated with hard-to abate sectors such as heavy industry and transport. However, hydrogen can also be an opportunity for rural areas and islands to harness their renewable energy sources.

3.3.1 Existing Roadmaps

The growing urgency to reduce GHG emissions to reduce the impact of climate change have renewed the interest in hydrogen after many years of slow progress. This interest has been backed by significant and rapidly expanding investments all across the hydrogen supply chain. Literature around the different aspects of hydrogen and roadmaps is extensive and constantly renewed and updated.

For this report, 15 roadmaps and reports related to hydrogen development has been reviewed and analysed with particular attention to electrolysis. A summary table of these roadmaps including the key aspects studied and relevant conclusions is available in Appendix 8.2.

Some reports are used to highlight the current state and provide more details about electrolysis technology within hydrogen developments to support the findings from the roadmaps.

As for the tidal generation roadmaps, the focus of the hydrogen roadmaps varies considerably depending on the area (UK, Europe, Worldwide) and the key aspects of interest. Some roadmaps may primarily focus on the technological or economical perspective while some integrate both and add other dimensions such as environmental considerations, social benefits or policies. As a very fast expanding sector with a huge global market and divergent interest between gas and oil companies and environmental groups, competition is strong, and recommendations can be in conflict.

As well as the differences inherent in the views and intentions of the authors and commissioners of the reports, the ambition and scenarios range from a safe, technologically possible, economically viable perspective to a maximum possible capacity based on ambitions around what might be possible.

Apart from one electrolysis focused report from 2014 [24], all reports are no more than 3 years old and propose roadmaps for 2030 to 2050.

The next sections identify the current landscape of water electrolysis development, analyse each aspect covered by the reports and extract the key points for the context of the ITEG project.

3.3.2 Roadmaps Analysis / Aspects

The development of electrolysers on small islands and remote locations will very much depend on the potential for production of hydrogen from renewable sources, storage and the likely local use and export potential. The development will also be affected by the global evolution of the hydrogen sector in terms of costs, demand, R&D and competition.

3.3.2.1 Environment

Remote locations and small islands rely heavily on fossil fuel for transport, local industries and heating. Their gas networks are often non-existent or limited and their electrical grid is often constrained. With great renewable energy resources, these regions have the potential to take action to replace imported fossil fuels with decarbonised hydrogen improving their resilience and energy independence at the same time.

Unlike natural gas and oil products that have to be imported, hydrogen can be produced either near the source of electricity or near sites of use. Therefore, the electrolyser plant requires careful planning around location depending on the resources required (electricity and water) and the use of hydrogen. It must take into account the supply of electricity and water to the plant and the distribution of hydrogen. Opportunities are likely to be available around port areas for hydrogen storage and fuelling stations for marine, industry and mobility applications.

As described in the previous section, tidal energy adds to developing renewable electricity production whereas hydrogen is a new energy vector. The environmental impact must therefore be assessed as such – where it can replace polluting energy and how it can support the electricity sector (reducing required network capacity and reinforcement).

The environmental impact of hydrogen shouldn't be limited to assessment of the supply chain and the infrastructure. It needs to be compared with the alternatives for the different potential applications (e.g. electrification of heat and mobility or use of biomass heating).

3.3.2.2 Capacity

Low carbon production capacity ambitions sometimes include fossil fuel based hydrogen production with CCUS. For this study only electrolysers are considered.

All roadmaps and predictions see an important increase in electrolyser capacity. The long term capacity forecasts vary a lot depending on the assumed speed of decline of gas and oil and the uncertain demand for hydrogen. It will also depend on the development of hydrogen transmission systems and large scale storage which could favour more centralised large scale production sites.

On a global scale, according to the IEA's Hydrogen Projects Database, with all projects planned, global installed electrolyser capacity is set to reach **54 GW by 2030**.

At European level [4], the strategic objective is to install **at least 6 GW** of renewable hydrogen electrolysers in the EU **by 2024**; then **by 2030 at least 40 GW** with hydrogen becoming an intrinsic part of an integrated energy system. According to the strategy, 40 GW of electrolyser capacity could potentially be installed by 2030 in Eastern Europe and in the Southern and Eastern Mediterranean countries facilitating import.

The UK Hydrogen Strategy [6] projects a **5GW** production ambition **by 2030** and expects hydrogen to help meet the Sixth Carbon Budget and net zero commitments. No further UK objectives have yet been set past 2030.

Scotland has an even more ambitious action plan [25] with a strategic approach to the development of the hydrogen economy and a clear ambition of **5GW** installed hydrogen production capacity **by 2030** and **25GW by 2045**.

The recent report from OREC [26] examines in detail the roadmap and strategy for these regions and provide graphical timelines as shown in the following figures:

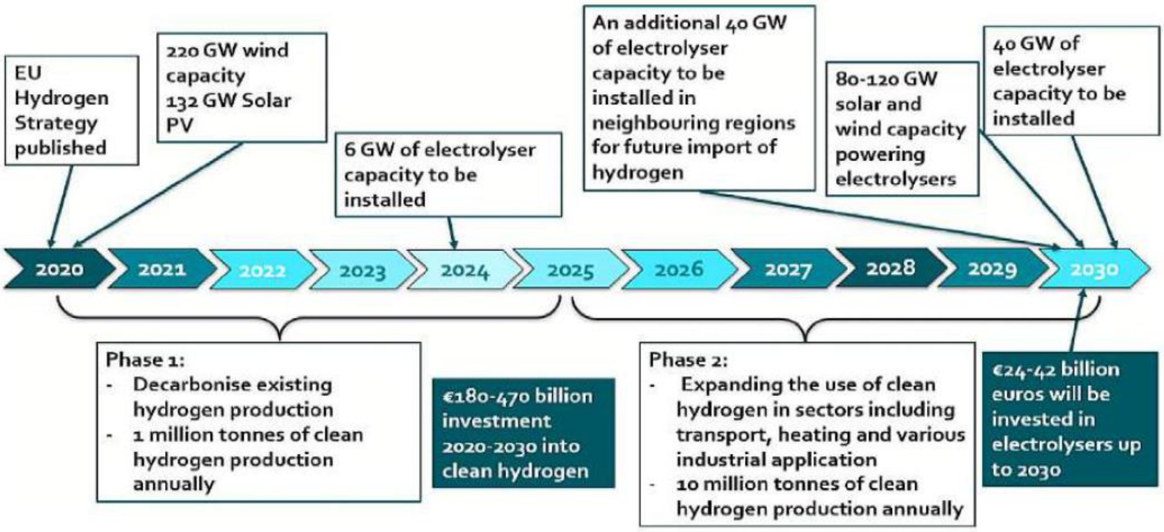


Figure 3-5: Timeline of renewables and clean hydrogen ambitions in the EU [26]

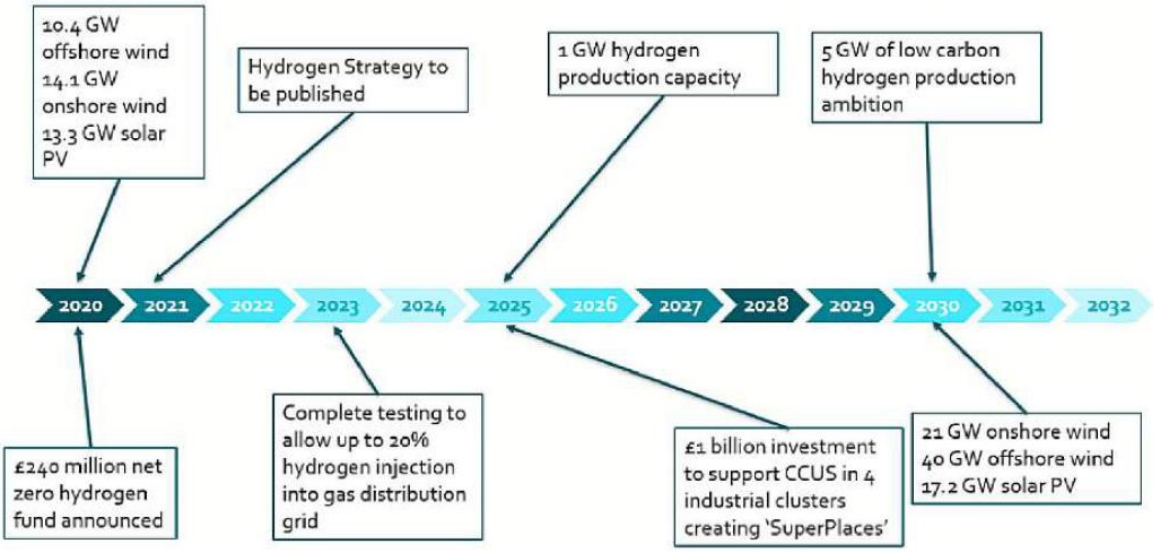


Figure 3-6: Timeline of renewables and clean hydrogen ambitions in the UK [26]

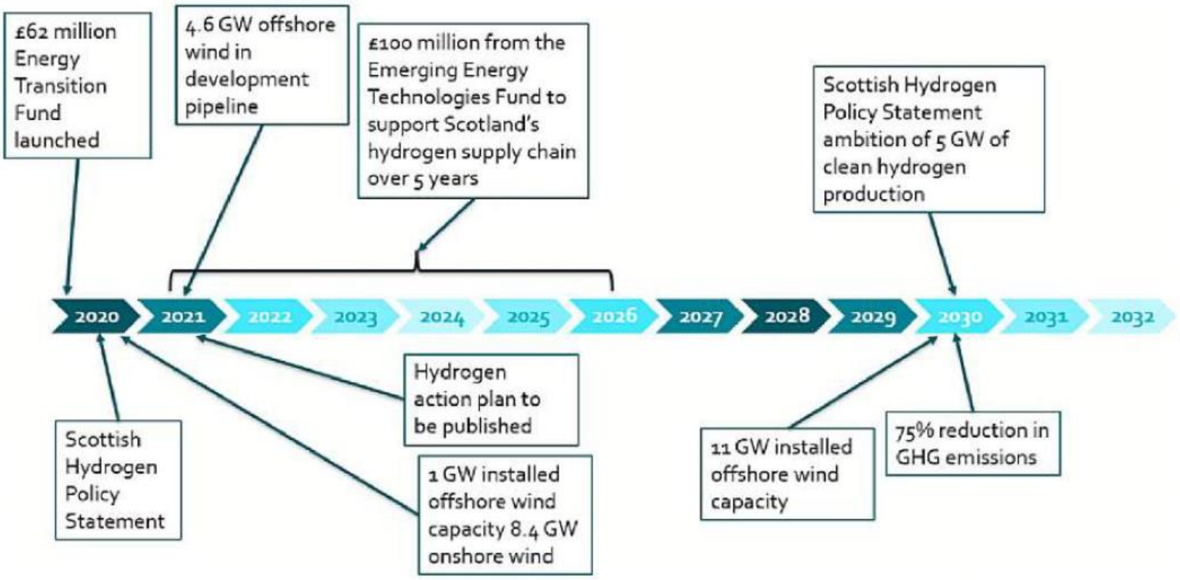


Figure 3-7: Timeline of renewables and clean hydrogen ambitions in Scotland [26]

3.3.2.3 Technology

Electrolyser technology and its supply chain is ready. Hydrogen from renewable power is technically viable today and is quickly approaching economic competitiveness. No real breakthrough is expected in the coming years and gradual progress is expected as technology continues to evolve and become more efficient. Advanced demonstrator developments are moving towards larger scale demonstrators and commercial rollout. A rapid scaling up is now needed to achieve the necessary cost reductions and ensure the economic viability of hydrogen as a long-term enabler of the energy transition.

To achieve further cost reductions in green hydrogen production, technology improvements will be focused on the following areas:

- **Procurement and construction cost**: During scale up, scarce materials can represent a barrier to PEM electrolyser development. The main areas of improvement are the increase in stack production and automation. Furthermore, installation can also be improved by standardisation and best practice for plant design and components.
- **Electrolyser design and construction**: increasing size availability and efficiency and lowering cost. However, the optimal system design will differ between applications depending on location, resources (availability and profile), demand and connectivity.
- **Performance:** Electrolyser plant efficiency is likely to improve from 65% to 76% (average across technologies) by reducing the amount of electricity require to produce one unit of hydrogen. Current systems are designed for high efficiency at their operating design point, at typically close to 100% load, and to run continuously. Intermittent supply and peaky demand are expected to require start-stop and dynamic operation and high efficiency across much of the load curve.

- **Durability:** Research and improvement can also increase the lifetime of the equipment and spread the cost of electrolyser facilities over larger hydrogen production volumes.
- **Control and operation:** The control and operation of the electrolyser within the whole energy system will play a major role in the competitiveness of hydrogen. As electrolyser capacities expand and become more interconnected, how can the system be controlled to send the right quantity of hydrogen to the right place, at the right time, at a viable cost in a safe and reliable manner? Many control strategies are possible to operate electrolysers beyond matching supply and demand especially considering the potential of hydrogen storage. These strategies will be constrained by the type of electrolysers, their operational needs and their purpose (non-mutually exclusive):
- Price based control: Electricity source and operation could be controlled based on real time and forecast electricity prices.
- Emission based control: Prioritise renewable electricity sources with the potential to provide green hydrogen.
- Maximise intermittent renewable energy use: In times of excess electrical production, curtailment can be avoided.
- Inter-seasonal storage: Control to maximise hydrogen production at times of low demand to store sufficient capacity for peak demand.
- Maximise hydrogen production: This could accelerate the transition from oil and natural gas.
- Whole energy system benefit: Electrolysis can support grid balancing services, system flexibility, renewable energy deployment and remote locations resilience.

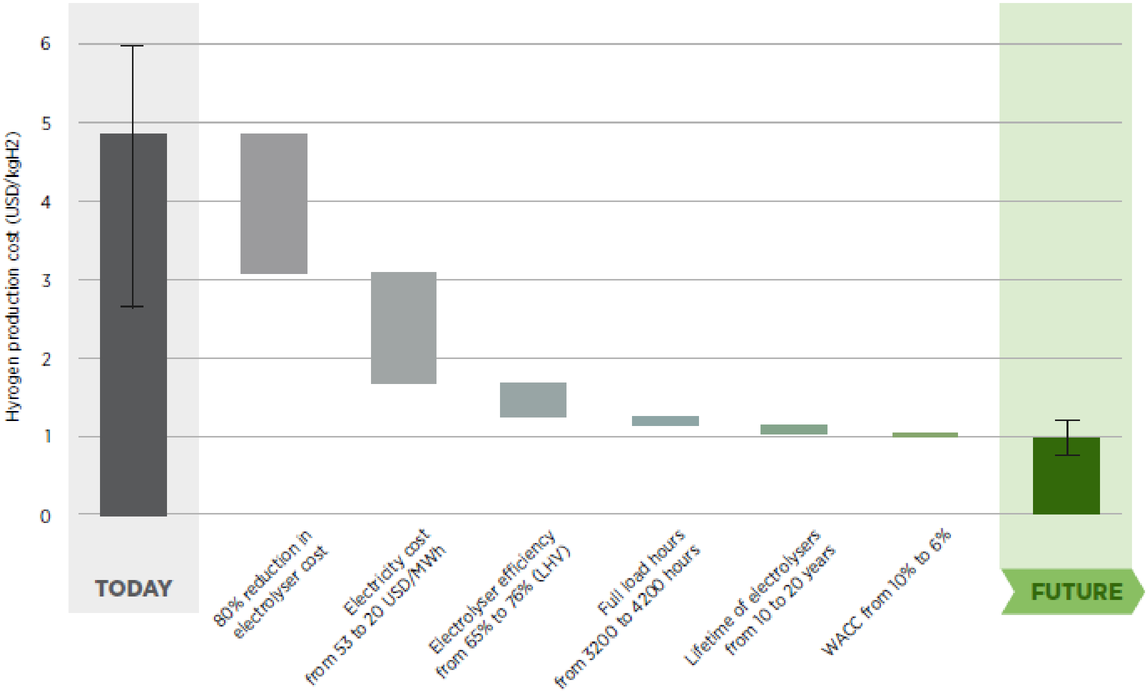
Real world usage data can provide valuable insights into performance and support whole system efficiency. Reducing capital cost while maintaining lifetimes and increasing efficiency are all interlinked and shouldn’t be tackled individually.

3.3.2.4 Levelised Cost of Hydrogen

As conveyed by multiple reports, for competitiveness reasons, renewable hydrogen must generally be produced at less than £2/kg (eq. 60£/MWh) compared to around £8/kg today. It is worth noting that the estimated cost for fossil based hydrogen is currently around 1.5 €/kg for the EU, highly dependent on natural gas prices, and disregarding the cost of CO2. Depending on the development and cost of Carbon Capture, Use and Storage (CCUS), this would mean that green hydrogen could cost even less to produce than fossil based hydrogen with CCUS as well as producing lower GHG emissions. All reports also agree that feedstock electricity accounts for approximately 70% of the total hydrogen cost. The second largest cost is the capital cost of electrolysers.

However, other factors need to be accounted for to assess where hydrogen production can be deployed. First, hydrogen cost must be compared to the current energy costs for the locality including the volatility of electricity prices and mitigation against fossil fuels. The integration of the electrolyser with the electric, water and hydrogen systems (from standalone co-located systems to fully integrated with the electricity grid with multiple hydrogen users) and the potential to use by-products will directly impact the Levelised Cost of Hydrogen (LCOH).

Figure 3-8 shows how up to 85% of green hydrogen production costs can be reduced in the long term by a combination of cheaper electricity and electrolyser CapEx investment, in addition to increased efficiency and optimised operation of the electrolyser [27]. The cost of electricity used for this graph is equivalent to 40 £/MWh to 15 £/MWh for the best conditions (53 $/MWh to 20 $/MWh). Note that the target for tidal energy generation used for this report is 100 £/MWh which should be accounted for in an integrated system.



Note: 'Today' captures best and average conditions. 'Average' signifies an investment of USD 770/kilowatt (kW), efficiency of 65% (lower heating value – LHV), an electricity price of USD 53/MWh, full load hours of 3200 (onshore wind), and a weighted average cost of capital (WACC) of 10% (relatively high risk). 'Best' signifies investment of USD 130/kW, efficiency of 76% (LHV), electricity price of USD 20/MWh, full load hours of 4200 (onshore wind), and a WACC of 6% (similar to renewable electricity today).

Figure 3-8: A combination of cost reductions in electricity and electrolysers, combined with increased efficiency and operating lifetime, can deliver 80% reduction in hydrogen cost. [27]

The dominant factor in the cost of electrolysed hydrogen is the cost of electricity. It can therefore be cost effective to install electrolysers where renewable electricity is abundant, and the grid connection is constrained leading to curtailment. A steady supply of electricity can be provided through multi-source energy vectors or a buffer storage.

However, low electricity cost is not enough by itself for competitive green hydrogen production. The capital cost of electrolysers is the second largest cost so cost reduction and economies of scale are paramount in this area as well as described above in the technology developments.

As well as electricity cost and capital cost, the following considerations need to be accounted for in the LCOH for each hydrogen project:

Electrical connection

Remote locations may have limited or no access to the national transmission network.

However, access to transmission networks is not vital for deployment of renewable energy if energy storage is available to balance intermittent supply with demand. This can be in the form of conversion to hydrogen. The cost of hydrogen supply from renewables has come down in recent years and continues to fall. This is a key contributor to the growth of hydrogen.

However, transmission connection can provide a sustained supply of electricity. Renewable generation can also be traded on the transmission network when prices are high, and electricity can be drawn from the network during periods of low renewable generation. This can both reduce cost and increase electrolyser load factor.

Curtailment or occurrence of negative price due to excess production of electricity may also favour direct connection from renewable energy generation to electrolysers. However, if electrolysis competition develops for the use of this cheaper electricity, this can lead to further dedicated renewable development and the lowest electricity prices are also likely to increase.

Note that the ITEG demonstrator is a hybrid version where the electricity produced by the tidal turbine can be sent to the grid or directed to the electrolyser. Future options for this kind of tidal/electrolyser combination could also include separating the electrolyser and the tidal turbine geographically. Different options have been explored and modelled in report "Whole Energy System Analysis: Long Term Impacts on the Orkney Energy System" .

The UK Hydrogen Strategy [6] developed a table comparing different hydrogen production methods alongside current (2021) estimated carbon intensity and levelised costs shown in Table 3-1. Grid electricity in remote locations is not the ideal source of electricity for electrolysis because:

- grid constraints limit the import of low price electricity
- most of the electricity is generated using technologies that result in greenhouse gas emissions.

However, connecting multiple electrolysers together and creating a local renewable grid to balance direct electricity demand, storage and hydrogen production can reduce the necessary capacity of each element, increase load factors, reduce curtailment, allow more flexibility and improve system balancing.

Production method	Carbon Intensity estimates	Levelised Costs	Role to 2030 / 2050	Next steps
Grid electrolysis	78.4 gCO2e/MJ H2 *	PEM (10MW): 2020: £197/MWh (£6.6/kgH2) 2050: £155/MWh (£5.2/kgH2)	To be determined based on further policy development	Further engagement and analysis required, e.g. via the consultation on the UK Low Carbon Hydrogen Standard
Renewable electrolysis	0.1 gCO2e/MJ H2 (LHV)	PEM (10MW):** 2025: £112/MWh (£4.1/kgH2) 2050: £71/MWh (£2.4/kgH2)	Small projects expected to be ready to build in early 2020s	Scale up technology, reduce costs over time

Table 3-1: Extract from "Overview of selected hydrogen production methods" [6]

** (note this is a blended figure using grid averages to calculate)*

*** (with dedicated offshore wind)*

For consistency, the LCOH has been converted from cost per Lower Heating Value (LHV) referring to the amount of heat liberated during combustion of a unit of fuel to cost per kg of hydrogen using £1/kgH2 is equivalent to £30/MWh H2 (LHV).

Water Supply

It must not be overlooked that electrolysis requires water and the associated costs. Water consumption can vary with the purity of the water feed. Coastal locations can benefit from the proximity and availability of water, but the purification stage and accessibility must not be disregarded.

Hydrogen distribution

Downstream of production, the LCOH for the end users is affected by the transport of hydrogen from the production site to the end use. Hydrogen transport is still problematic and require some preparation (e.g. pressurisation, liquefaction) to allow pipeline or container transport.

Small scale production can be developed close to or co-located with the end use such as an industry, refuelling station.

By-products

Through the hydrogen production process, an electrolyser produces oxygen and heat. Oxygen is safe to be vented into the atmosphere but can also be used for medical purpose, water treatment etc. Any offtake could provide a revenue stream to the hydrogen production facility.

As for the previous point, transport, storage and export need to be accounted for. Waste heat can be used for local space heating, possibly in district heat networks if these already exist.

The cost estimates for electrolysers are rather problematic as they can significantly influence the final cost of hydrogen for end users. Transport (to end use), storage (capital and operation) and preparation (for transport or different end uses) can increase the cost of hydrogen significantly for the end users. Also, the confidential nature of cost data and the desire of suppliers to retain competitive advantage mean that this data can be hard to obtain.

Green hydrogen is predicted to achieve cost-competitiveness with other hydrogen production methods in the near future in locations with high renewable electricity potential. Cost reductions in renewable electricity and electrolysers are likely to continue leading to an increase in the number of installations.

3.3.2.5 Policy, Regulation and Standards

In current policy and regulations, hydrogen is still often characterised as an explosive rather than an energy vector. This leads to a wide range of regulatory barriers that prevent the integration of hydrogen and electrolysers into the grid and to provide grid services such as load shedding.

Clean hydrogen is enjoying unprecedented political and business momentum, with the number of policies and projects around the world expanding rapidly. Further acceleration of efforts is critical to ensuring a significant share of hydrogen in the energy system in the coming decades. [13]

For hydrogen to move to the next stage of development smoothly and at speed, the UK Hydrogen Strategy [6] highlights the challenges of policy and regulatory uncertainty. Industry is looking to government to provide capital and revenue support, regulatory levers and incentives, assurance on quality and safety, direction on supply chains and skills, and broader strategic decisions.

The role and impact of policy on the hydrogen market is similar to tidal and other renewable energy developments. The main areas of support from policy and regulation are provided in the following section:

Financial support

The ambitious targets set to 2030 and beyond couldn't be achievable without financial support.

Alongside cost reductions from economies of scale, R&D is crucial to lower costs and improve performance, including for fuel cells, hydrogen-based fuels and electrolysers. Government actions, including use of public funds, are critical in setting the research agenda, taking risks and attracting private capital for innovation. [14]

Financial support can be in the form of grants or concessional loans that decrease the investment risk for industry and close part of the cost differential with fossil based hydrogen. In 2020 Germany committed €9bn to their hydrogen strategy and France committed €7bn.

To achieve rapid scale-up, a stable and supportive policy framework would be needed to encourage the appropriate private investments. This is the case across the entire supply chain (equipment manufacturers, infrastructure operators, vehicle manufacturers, etc.). [12]

The EU Hydrogen Strategy [4] has developed an investment agenda exploiting synergies and ensuring coherence of public support across the different EU funds and European Investment Bank (EIB) financing, harnessing the leverage effect and avoiding excessive support. Some examples are highlighted below:

- Important Projects of Common European Interest (IPCEI) on hydrogen[33]
- REACT-EU (Recovery Assistance for Cohesion and the Territories of Europe)[34]
- InvestEU programme[35]
- European Regional Development Fund (ERDF) [36]
- the Cohesion Fund [37]

In the UK, the Energy White Paper[38] published in December 2020, which sets out how the UK will clean up its energy system and reach net zero emissions by 2050, reiterates the support for hydrogen defined in the Ten Point Plan[39] with further details. The Ten Point Plan for a green industrial revolution, published in November 2020, sets out the high level approach the British government will take to build back better, support green jobs, and accelerate the path to net zero. This includes more information on technologies relevant to the production of hydrogen and financial commitment. Two key interventions, in the consultation phase, are further set in the UK Hydrogen Strategy [6] that will help to bring down the costs of producing clean hydrogen (including electrolysis) relative to high carbon alternatives:

- **The Net Zero Hydrogen Fund (NZHF)**[40], designed to provide initial co-investment for new low carbon hydrogen production, with the aim of de-risking private sector investment and reducing the lifetime costs of low carbon hydrogen projects.
- **The Hydrogen Business Model**[41], to provide longer term revenue support to hydrogen producers to overcome the cost gap between low carbon hydrogen and higher carbon

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[33] https://ec.europa.eu/growth/industry/strategy/hydrogen/ipceis-hydrogen_en

[34] https://ec.europa.eu/regional_policy/en/newsroom/coronavirus-response/react-eu/

[35] https://ec.europa.eu/growth/industry/strategy/hydrogen/funding-guide/eu-programmes-funds/investeu_en

[36] https://ec.europa.eu/regional_policy/en/funding/erdf/

[37] https://ec.europa.eu/regional_policy/en/funding/cohesion-fund/

[38] https://www.gov.uk/government/publications/energy-white-paper-powering-our-net-zero-future

[39] https://www.gov.uk/government/publications/the-ten-point-plan-for-a-green-industrial-revolution

[40] https://www.gov.uk/government/consultations/designing-the-net-zero-hydrogen-fund

[41] https://www.gov.uk/government/consultations/design-of-a-business-model-for-low-carbon-hydrogen

counterfactual fuels, with the aim of enabling producers to price hydrogen competitively and helping to bring through private sector investment in hydrogen projects.

Policy integration.

Still project developers face hurdles where regulations and permit requirements are unclear, unfit for new purposes, or inconsistent across sectors and countries.

The Hylaw project[42] developed a database of the different regulations, codes and standards that must be met in different jurisdictions and applications for hydrogen technologies[43]. This should support future measures to streamline permitting processes.

Sharing knowledge and harmonising standards is key, including for equipment, safety and certifying emissions from different sources and could help eliminate unnecessary regulatory barriers and harmonise standards.

The Renewable Transport Fuel Obligation (RTFO) in transport, the Capacity Market (CM) in the power sector, or the Industrial Energy Transformation Fund (IETF) in industry are all sector specific policies that can support the use of low carbon hydrogen for particular sectors if updated and adapted. For example, the RTFO currently only covers biofuels but a consultation is in place on the amendments to the scheme to make renewable fuels from non-biological origin used in maritime, rail and non-road vehicles eligible for support. [6] Analysing and reporting sector specific and cross sectors barriers can guide policy makers in designing and implementing policies to support green hydrogen.

Collaboration

The challenge for government is to establish how it can most effectively stimulate the hydrogen economy, both for established energy players and disruptive market entrants. The challenge for the industry is to speak to government with one voice about what is needed. [28]

Stakeholder partnerships and building international co-operation could be significant: Emerging continental economies and islands may be in need of financial resources and business development analysis, both of which could be spurred by cross-water partnerships. Equally important is to strengthen international technology co-operation; policy makers, industry, academia and users of ocean energy technologies should share existing information and collaborate in a more organised manner. Frontrunner countries can encourage knowledge transfer to locations where ocean energy is still at early stages of development. [2]

There is still a need for projects to collect and share real life performance data to allow further modelling of hydrogen within the energy system. Real life operational data allows developers and operators to improve their operation control based on techno-commercial assumptions.

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[42] https://cordis.europa.eu/project/id/735977

[43] https://www.hylaw.eu/database

Qualitative and quantitative evidence from research and development can support evidence based policy development.

On a global scale, between November 2019 and March 2020, market analysts increased the list of planned global investments from 3.2 GW to 8.2 GW of electrolysers by 2030 (of which 57% in Europe) and the number of companies joining the International Hydrogen Council has grown from 13 in 2017 to 81 in 2020. [4] Memberships to similar groups at European level (Clean Energy JU previously FCH JU), UK level (UK HFCA) and Scottish level (SHFCA) have all soared at a similar rate.

As well as industrial and governmental collaboration, consumer engagement will be crucial for hydrogen adoption and demand. Effective communication with consumers needs to be clear around the requirements to change their behaviour to assist in decarbonising transport and heat and use alternative energy sources. [28] The transformation should achieve its objectives while meeting customer preferences, and decarbonized technologies need to provide convenient solutions in order to gain mass appeal.

For example, the peakiest demand for oil is heating for off gas grid areas. When decarbonising heat for domestic, commercial and industrial consumers, awareness, acceptance and informed decision making are crucial for growth. Well informed and engaged consumers can lead to greater uptake and participation. The cooperation between the different stakeholders is crucial for hydrogen to become an integral part of smart local energy systems.

Value chain

For policy and regulation to support the development of electrolysed hydrogen production, it needs to also support distribution, storage, appliances, export, end users and the integration with the electricity system.

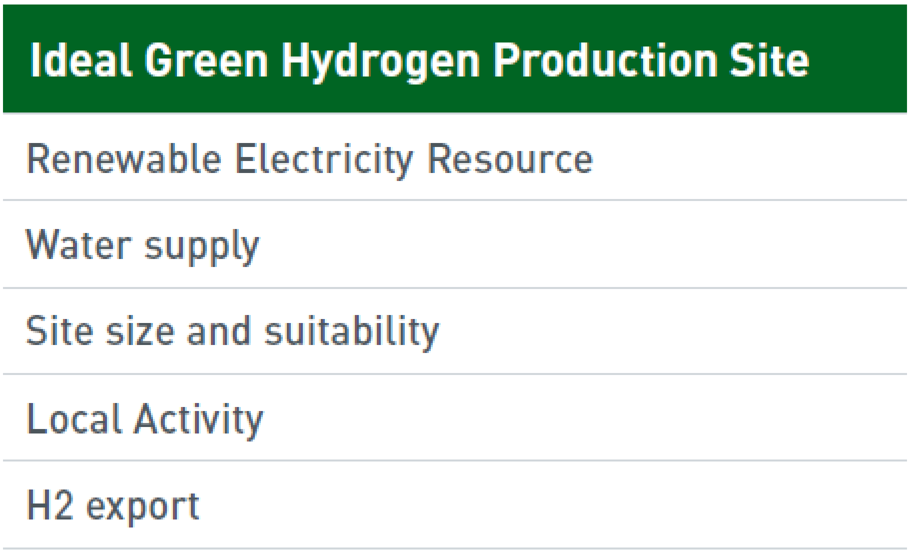
The development and scaling up of each part of the hydrogen value chain will rest on policy frameworks to support the early expansion of a low carbon hydrogen market over the 2020s, and its later evolution to a dynamic, competitive, integrated and liquid market from the 2030s onwards. [6]

On the supply side, as mentioned previously, the availability of feedstock to produce hydrogen, (renewable electricity and water) in the vicinity of the plant will help to define the requirements for best location and connectivity.

However, the development of electrolysers is strongly linked to the expansion of demand. The structure of the supply chain will be primarily influenced by the geographic distribution and nature of the demand. For fuel cell applications, hydrogen produced through electrolysis can be relatively easily configured to meet quality requirements compared to other production methods. However, for combustion applications , the quality is likely to exceed the requirements and other production methods may be more economical.

Green hydrogen hubs are likely to remain at local or regional level of connection. This means establishing clear value chains in individual areas. For remote coastal regions, there is the additional uncertainty of the preferred technology for maritime transport of hydrogen. Ideally, sites with potential demand should promote the scale-up of production and negate the additional cost of potential hydrogen export when it arises.

Island and rural communities are seen to have great potential to aid in the development of a hydrogen production and export market for Scotland due to their access to renewables in the form of offshore wind, coupled with the close vicinity of existing ports and oil and gas facilities, to some of these communities. [26]



Ideal Green Hydrogen Production Site

Renewable Electricity Resource

Water supply

Site size and suitability

Local Activity

H2 export

Figure 3-9: Ideal Green Hydrogen Production Site [26]

There is considerable hydrogen supply chain overlap with elements of parallel sectors, most notably, the oil and gas, offshore wind and subsea engineering sectors. There is a great opportunity to convert skills as energy systems move toward net zero. In areas not connected to the gas grid, introducing hydrogen may require development and import of gas skills and knowledge. Mainland expertise in gas grid project development can set best practice and skills in the installation and maintenance of hydrogen equipment. However, in port areas, the hydrogen economy including export supported by existing skilled workforce can be used to transition from fossil fuel import and retain jobs in the area. For mobility, fuel cell ships are at the demonstration stage in various segments (ferries, shuttles, etc.) and regulatory push is creating the opportunity for more rapid development. Hydrogen fuel cells can also be used to replace on-board and onshore power supply, currently often based on diesel or fuel oil, to eliminate pollutants emissions (NOx, SOx and particulate matter) in harbours, while avoiding expensive installation costs for electrical connections at the harbour. For long-distance ship runs, liquefied hydrogen is now being considered as a potential option to meet the International Maritime Organization's GHG emission reduction target of 50 % by 2050. [12]

Where gaps exist in the supply chain, especially in remote locations, in the areas of design, manufacture and maintenance of hydrogen production, storage and transportation systems, support, including apprenticeships, will be needed to develop indigenous skills and capabilities in these areas. [29]

Hydrogen also provides the opportunity for greater gas and electricity integration capabilities. Electricity grid reinforcement, hydrogen infrastructure installation and electric/hydrogen demands need to progress in a coordinated manner.

From a risk management perspective, investment in new large-scale production capacity has traditionally only been made if a large proportion of the production is sold to a single client (or a limited number of clients) with long-term contracts signed upfront, or if it could be justified by having sufficient equity buffer to cover initial losses or by financial de-risking instruments offered by policy makers. [12]

If remote coastal locations want to capture more of the economic value from hydrogen activities, they need to act quickly and decisively. This could put these regions at the forefront for skills and services and create novel supply chain networks locally. Failing this due to slow deployment, there is a risk that supply chains will be developed elsewhere adding import costs.

Certification and Standards

As each electrolysis technology matures and commences the commercialisation phase, standardisation will not only reduce costs but also pave the way to certification practices. Certification will, in return, facilitate access to additional commercial financing and speed up uptake.

Technology-neutral instruments aimed at final consumers can trigger hydrogen demand and justify investment in infrastructure. Such instruments may include carbon pricing, emissions restrictions (low-emission zones, emissions standards or targets), specific mandates for renewable energy content or carbon pricing in the targeted sectors. [12]

Certificate of origin

Molecules of green hydrogen are identical to those of grey hydrogen. For this reason, once hydrogen has been produced, a certification system is needed that allows end users and governments to know the origin and quality of the hydrogen. [30] This certification framework could be used to underpin international trade

A Low Carbon Hydrogen Standard could help to support the demand for low carbon hydrogen by providing confidence to end users that the hydrogen purchased is a low carbon alternative to existing fuels. [6] This could also be used in time to underpin international trade to allow an export market to be established.

One example in the case of hydrogen is the CertifHy[44] project in the European Union. The scheme issued over 76,000 Guarantee of Origin certificates for green or low carbon hydrogen, out of which 3,600 were used by 2019. This was a pilot project covering less than 0.05% of the total EU hydrogen market and less than 4% of the certificates were actually from renewable energy ("Low carbon hydrogen" certification requires 60% lower GHG emission than the 36.4 gCO2/MJ reference encouraging lower carbon emitting grey hydrogen). [30] Multiple definitions for the guarantee of origin certification of hydrogen exists within Europe and sometimes within a

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[44] https://www.certifhy.eu/

country. Some of the schemes cover multiple hydrogen production technologies, while others focus specifically on green hydrogen. Some also only cover a particular application such as the use in vehicles.

Emission trading / Carbon Pricing

In order to reduce the cost advantage of fossil fuels, the first step is the elimination of subsidies for fossil fuels while providing grants and funding for green energy as well as favourable policies.

Carbon pricing, such as through the European and UK Emissions Trading Schemes, send clear long-term signals that carbon will become an increasing cost for industry, thus promoting investment in low carbon technologies including hydrogen as a route to reducing these costs. [6] International trade policy can avoid market distortions with Europe setting the benchmark for international hydrogen trading.

3.3.2.6 Market

Energy markets and policies have evolved significantly over the past decades in all countries due to globalisation, privatisation and, more recently, environmental considerations.

As much as electrolysis technology is approaching commercialisation, the hydrogen market is in its infancy. Intervening too firmly for first-of-a-kind projects could stifle cost competitive growth as stated in the UK Hydrogen Strategy [6]. The market's legal framework should ensure fair competition, clean and affordable hydrogen and security of supply.

Today, hydrogen producers tend to find specific customers and have bilateral contracts leading to dedicated hydrogen production/end use. Therefore, mitigations must be in place against the single demand risk as the customer may face outage and the producer may face insolvency if the customer switches away from hydrogen or to a different supplier. By 2050, however, hydrogen is expected to follow in the footsteps of established sectors like offshore wind, oil and gas at the heart of the energy markets.

The development of a hydrogen market will be closely linked to the natural gas and electricity markets. The development of a hydrogen and potentially multi-vector energy market will take time and may be hindered by the remaining fossil fuel subsidies for some time.

A clear strategy to focus on the unique properties and strengths of islands such as the use of natural resources, available space and export opportunities, with a clear direction of travel and ambitious targets could increase investors' confidence and give industry a clear signal to accelerate hydrogen development.

3.3.2.7 Value

Beyond techno-commercial considerations, the added value that the production of hydrogen from electrolysis can bring to communities in remote locations and islands include :

- Use of electricity from intermittent renewable sources
- Improved efficiency and stability of the power system
- Security of supply and resilience

- Long-term energy storage options
- Additional flexibility for market and system balancing
- Options in the energy mix for heating and mobility
- Reduction of grid reinforcement requirements
- Climate change mitigation when replacing fossil fuels
- Air quality replacing fossil fuels (e.g. shipping at anchor with generators running, burning fossil fuel for space heating, road mobility in built-up areas)
- Job creation (retaining a skilled workforce in the transition and being at the forefront of new skills required in the supply chain)

It can be difficult to quantify these additional benefits, but they need to be considered as part of the development plan.

3.3.3 Conclusions on Hydrogen Roadmapping Studies

It is a challenge today to develop a roadmap for water electrolysers for hydrogen production without integrating with other forms of hydrogen production and the rest of the hydrogen system (distribution, storage, use). It is also strongly linked to the electricity and water systems.

Some reports have very high ambitions for hydrogen and highlight best case scenarios across the hydrogen supply chain and around future demand potential but can also reflect vested interests from the authors to attract investors and target policymakers to favour the technology against other renewable alternatives.

Hydrogen represents a versatile, clean, and flexible energy vector, which can:

- Enable large-scale renewables integration and power generation
- Reduce the curtailment of intermittent renewable energy
- Distribute energy throughout sectors and regions
- Act as a buffer to increase system flexibility and resilience
- Have multiple usages:
- Decarbonise mobility (road, air and marine sectors)
- Help decarbonise heating and power for buildings
- Decarbonise industrial heat use (e.g. distilleries, ceramics, cement and steel production)
- Serve as a renewable feedstock

Electrolysis from renewable energy sources is ready to scale up and bring down costs to allow hydrogen to become widely used. Many high profile demonstrators and projects under development help:

- democratisation of the technology
- building of information databases

- boost consumer confidence in the technology
- attract new investors

In order to supply cost effective hydrogen to remote customers, further support mechanisms such as green certificates or carbon taxes could support green hydrogen. Providing additional services to grid operators could also bring additional revenue streams and allow electrolytic hydrogen to compete. [24]

However, clean, widespread use of hydrogen in global energy transitions faces several challenges:

- **Techno-economic**: Electrolysers need to directly compete with hydrogen produced from other sources. Further development of electrolyser technology is needed to achieve projected cost and performance targets.
- **Cost**: Electricity price is the main component of the final price of hydrogen ahead of the capital cost of the electrolyser unit.
- **Efficiency:** Energy is lost during each step of the lifecycle. Around 30% of the energy used to produce hydrogen through electrolysis is lost. [30] The total energy loss will depend on transport, storage, preparation options and the final use of hydrogen.
- **Safety:** Hydrogen is sometimes perceived as a dangerously explosive gas. Safety concerns need to be addressed to provide public reassurance and accelerate development.
- **Storage and transport:** Large scale storage and transport of hydrogen is still costly. LCOH must account for transport and storage costs depending on the location of the electrolyser. As a novel energy vector, there is a lack of existing infrastructure.
- **Demand**: Without confidence in the capability of industry to deliver a secure and affordable fuel, consumers and public and private sector buyers will be reluctant to purchase hydrogen products. [28]. As a new energy vector, the technology needs to be accepted.
  The dilemma is to keep increasing supply to meet an uncertain demand in a coordinated and cost effective manner.
- **Hydrogen integration**: The versatility of hydrogen can pose some integration challenges. Different purities and pressures can be required for different applications (heating, industry, mobility, transport). It can then make it difficult for different hydrogen systems to interoperate.
- **Project integration**: As hydrogen development enters its next phase of development with large scale demonstrators and growing private investment, there is a risk of disorganised, disjointed deployment.
- **Regulatory framework**: Hydrogen is more costly than fossil fuels without policy support and carbon pricing. Green certifications and carbon credits must be harmonised to encourage green hydrogen deployment.

Provision of grid services, interfaces to the grid, and deployment in distributed refuelling applications could be impeded by regulatory barriers.[21]

- **Policy development**: The challenge for the industry is to speak to government with one voice about what is needed. [28] There is a complex regulatory, framework, and a lack of clarity of roles in some areas. [15]
- **Market**: Currently hydrogen is mainly traded through long term bilateral agreements between companies. A public hydrogen marketplace needs to be developed and regulated to provide competition.
- **Uncertainty**: The long term role of hydrogen between 2030 and 2050 is very uncertain from production methods to the scale of demand. Hydrogen system development must keep options open from early stage development and be adaptable as the market develops.

Deployment of electrolysers is at its fastest rate ever and hydrogen technology already exists in most segments and is ready for deployment today. Small islands and remote communities can benefit from the co-location of green hydrogen supply and demand, which can accelerate decarbonisation. High fuel costs and constrained infrastructure mean hydrogen projects are more likely to be economically viable and can realise more socio-economic benefits to those communities. They are ideally placed for hydrogen production growth and may also offer opportunities to become hubs for hydrogen export.

3.4 Tidal and Hydrogen Integration

Following the analysis of roadmaps for tidal electricity generation and green hydrogen production in remote locations and islands, the benefits of coupling these two technologies are evident in the decarbonisation pathway. However, integrating two innovative technologies within a fast changing energy system not only brings the challenges posed by each system individually but also their integration.

Coastal areas in NWE hold most of the European tidal resources and, in places, can provide much more electricity than required to meet local demand especially when combined with other renewable sources such as wind and solar. This opens up the possibility of expanding tidal generation beyond electrification with the production of green hydrogen. With the link between declining costs of renewable electricity leading to hydrogen cost reduction, the prospect of export can be envisaged to locations of increased hydrogen demand.

Remote locations and island can also benefit for smaller scale generation to increase their resilience and reduce grid capacity and reinforcement requirements.

This section also focuses on the integration aspects of these two technologies and the integration of this system within the wider energy system (with other renewable sources, the electricity grid, energy storage). As for previous sections, roadmap aspects beyond the technological ones, such as environmental considerations, location, regulatory landscape and value for the community are also investigated.

Progress in the tidal and electrolyser sectors will benefit the development of an integrated solution. Current integrated projects such as ITEG will provide real life data and expertise to allow scaling up and replicating this solution.

3.4.1 Existing Roadmaps

There is a great synergy between renewable electricity and green hydrogen. Four of the marine energy reports have notable mentions of hydrogen and three of the hydrogen related reports have notable sections on tidal energy. For example, the “EU Hydrogen Strategy” [4] sets an objective of 40 GW of renewables linked electrolysis capacity in the EU by 2030.

Also, a further 6 documents have been selected for their focus on the production of hydrogen from renewable electricity. However, most of these existing reports and roadmaps do not include tidal energy but mainly wind and sometimes solar. A summary table of these roadmaps including the key aspects studied and relevant conclusions is available in Appendix 8.3.

Reports focusing on Scotland are of particular interest as they tend to include marine energy as part of the renewable electricity source mix and sometimes have specific observations for small islands and remote locations that can apply for other similar locations in NWE.

3.4.2 Roadmap Analysis / Aspects

None of these reports focus solely on the integration of tidal generation with hydrogen production through electrolysis. A synthesis of findings from roadmaps relating to individual technologies, the integration of electrolysis with other renewable sources and integration with the rest of the energy system is required to understand the possibilities available.

The deployment of such an integrated system will be driven by the interplay between environmental benefits, supply and demand, system costs and value (resilience, stability, energy access).

3.4.2.1 Environment

With similar environmental benefits as wind and solar energy to reduce GHG emissions, tidal energy has the great advantage of being predictable which can offer a reliable baseload for electrolysis.

Coupling electrolysis directly with tidal energy sources guarantees low carbon hydrogen production and high hydrogen purity. If guarantee of origin certificates become widespread and required by consumers, this technology would be ideally placed to set the standards.

3.4.2.2 Levelised Cost of Hydrogen

As previously discussed, many factors can affect the LCOH. In the case of a tidal turbine directly connected an electrolyser for local hydrogen use, the main supply-side costs of green hydrogen are electrolysers, renewable electricity and transportation (of electricity or hydrogen) as shown in Figure 3-10 [31].

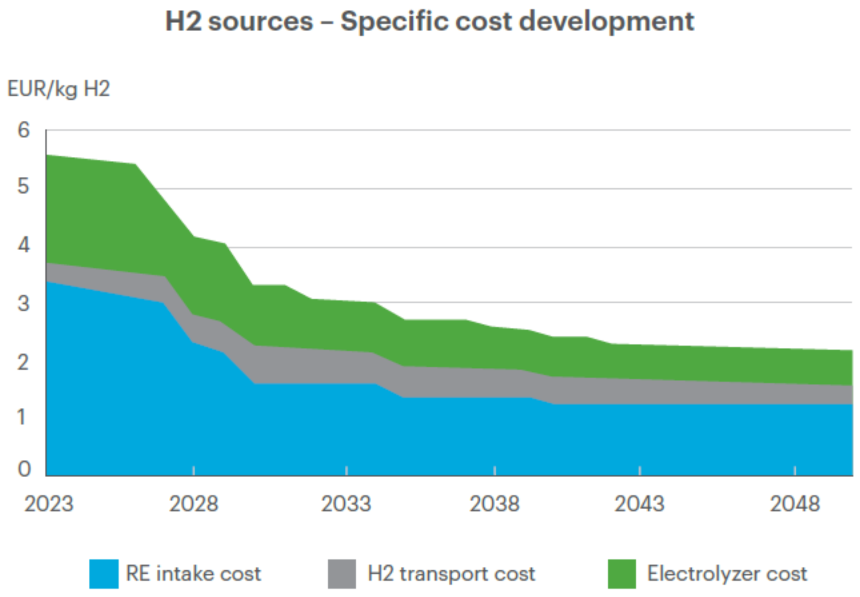


Figure 3-10: Levelised cost of hydrogen split into renewable electricity intake, transport and electrolyser cost [31]

Reduction in tidal electricity production and electrolyser costs individually will have the greatest impact on the cost of the system. The cost of transport is also significant and will depend on system planning to optimise the location of the electrolyser depending of the tidal source (electrical connection) and the hydrogen end use (gas connection). For small applications, it can be envisaged to either collocate the tidal energy production and the electrolyser or the electrolyser with the hydrogen end use.

Another cost can be incurred in preparation of hydrogen for transportation. Producing hydrogen anywhere other than in the exact location where it will be consumed requires a suitable mode of transport. Transport will require the hydrogen to be pressurised or converted to ammonia or another liquid organic hydrogen carrier (LOHC). This also applies for shipping for export. The hydrogen property requirements (form, pressure, quality) also depend on the final use where extra preparation costs could incur.

Another factor affecting the LCOH is the utilisation rate of the electrolyser. An electrolyser solely connected to a tidal source of electricity will have to follow its generation pattern. As much as electrolysers can operate efficiently at lower load, higher capacity would have to be needed for the maximum load. The CapEx component of the LCOH will be directly determined by the load factor of the tidal plant. Also, the effects of dynamic behaviour on the maintenance needs and lifetime of the electrolyser are still under study and can further affect the final LCOH.

However, different integration configurations including connection to other sources of electricity and electricity storage to smooth the electrolyser electrical input could increase the load factor. The LCOH potential should be assessed carefully for each possible production site.

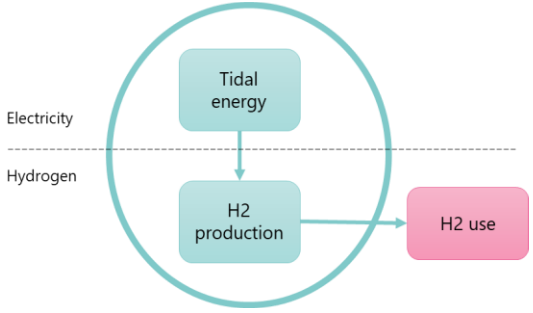
The location of the electrolyser, the end-use requirements (location, quality and profile), the potential connection to an electrical grid (whether renewable electricity or the transmission grid), the use of storage and the potential revenue from heat and oxygen by products will all affect the final LCOH depending of chosen configuration for each development site. A project can also expand and evolve from one configuration to another and multiple projects can merge into one connected system.

3.4.2.3 Integration aspects

As the integration of tidal energy and hydrogen production is suited for remote coastal locations, the replicability and scalability will be limited by suitable sites where tidal energy can be harnessed and hydrogen demand can be created. However, this technology can be integrated within the whole local energy system potentially including import and export. The main factor for maximising tidal development would be exporting surplus in case of the increasing demand for green hydrogen in NWE.

Different configurations and integration aspects are detailed below from an independent energy solution combining a tidal stream turbine with an electrolyser for a single hydrogen use to a fully integrated system including storage and export potential.

Closed System



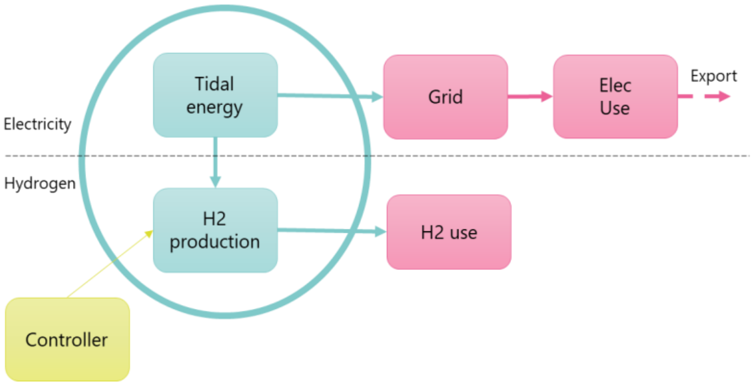
In a closed system, there is no interaction with any other electricity sources and the electrolyser provides hydrogen for a single type of consumer. Examples for this configuration range from refuelling stations for a fleet of vehicles such as bin lorries or council fleet to industrial demand such as a distillery or port activity (industry or ferries).

The advantage of this system is the capacity of the tidal turbine and the electrolyser can be designed for the end demand which, in these examples are reasonably constant throughout the year. However, this configuration wouldn't suit fluctuating demand such as seasonal heating demand without large scale energy storage.

The location of the electrolyser is paramount to the feasibility of the project and the potential for expansion. In the short and medium term, conversion close to tidal source to minimise electrical connection costs or demand side location to minimise hydrogen transport are very relevant to prove the concept prior to scaling up.

The risk of a closed system is the inter-dependence of the assets. Any breakdown or downtime in the system would affect the end use and contingency plans could prove too costly. Also, a reduction in hydrogen demand could leave the tidal generation, electrolyser and their related infrastructure stranded.

Tidal generation controlled between electrolyser and the grid

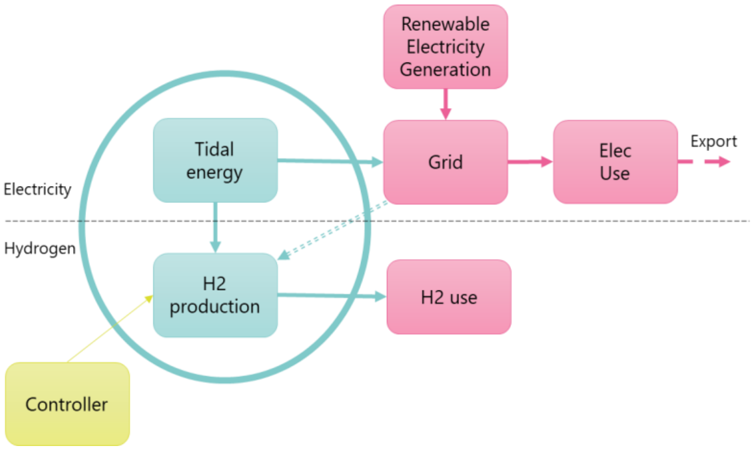


This is the current configuration of the ITEG project in Orkney. Unlike a tidal generator, an electrolyser can be run on command at any time and at any level of output within operating parameters. Numerous control strategies are theoretically possible for the tidal turbine and electrolyser, and various strategies are used in the analysis undertaken by partners within this project in order to explore particular questions (refer to separate ITEG project deliverables).

Depending on the controller strategy, this configuration could maximise the useable energy extracted from the tidal generator and minimise curtailment. In a constrained electricity network, it could also help counterbalance fluctuating electricity prices by using and potentially exporting tidal generated electricity when import prices are high and generate hydrogen when electricity prices are low. For cost based strategies, it is worth noting than electrolysers can operate efficiently dynamically at a wide range of part loads. Other strategies can maximise revenue for the operator, maximise hydrogen output, support energy security and resilience All these different strategies are not mutually exclusive and can converge towards an optimal solution for the overall objectives of the energy system.

The current dominant market for tidal energy is grid connected electricity generation. Connecting tidal generation to both the grid and electrolyser can be a real asset during the transition to decarbonisation when electrification and hydrogen use options are both available.

Mixture of renewable energy source (wind, solar and other marine energy)

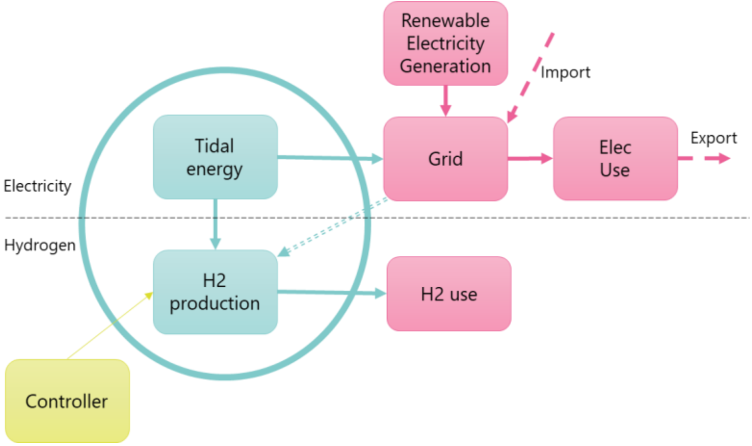


This configuration is an extension of the current ITEG configuration and can be envisaged for a future development of the project.

The system can also accommodate other renewable electricity sources such as additional marine energy, offshore or onshore wind and solar energy to create a renewable electricity grid. Wind, solar and marine energies are complementary. Wind and solar already benefit from large scale, mature technology but suffer from unpredictability Tidal energy is predictable and produce electricity at different time. Connecting multiple sources could provide better possibilities to manage both electricity and hydrogen generation to improve on the outcome described in the previous configuration. Shared infrastructure can also reduce development cost significantly.

This configuration could provide a step up in the development of an integrated renewable electricity and hydrogen market. The synergy between hydrogen and renewable energy could support the deployment of more renewable energy sources and accelerate the transition to hydrogen applications. Electrolysers can also add demand-side flexibility and the potential for energy storage especially in grid constrained areas. One of the conditions for the success of this configuration will remain the cost of both renewable electricity and hydrogen. However, a big driver for deployment in these first three configurations is that both produced electricity and hydrogen are guaranteed to be carbon free.

Full integration with the electric grid



In this configuration, the system is fully connected to the electrical transmission network for both import and export or electricity. This local energy system can be managed at local level and supported by network operators.

This configuration allows extra electrical source options to maximise optimisation control and energy management providing more resilience in the event of malfunction or disruption. Furthermore, increased electrification could be met without investing in expensive transmission infrastructure reinforcement. Additionally, a grid-connected electrolyser can operate close to hydrogen demand, or even on-site, reducing logistic costs significantly.

As in the previous configuration, tidal energy can offer a predictable baseload for electrolysers. Extra demand can be provided by other renewable sources. Electrolysers can absorb excess renewable electricity production at time of low demand. In this configuration, electrolysers can also be used as an ancillary service market for fluctuating electricity prices. Grid electricity can in addition be used to maximise electrolysers' utilisation. This can further encourage new hydrogen demand as supply will be more secure. However, grid electricity and hydrogen cannot be guaranteed to be decarbonised.

Even accounting for grid connection fees and other potential taxes, lower electricity cost and higher electrolyser utilisation should reduce the overall LCOH.

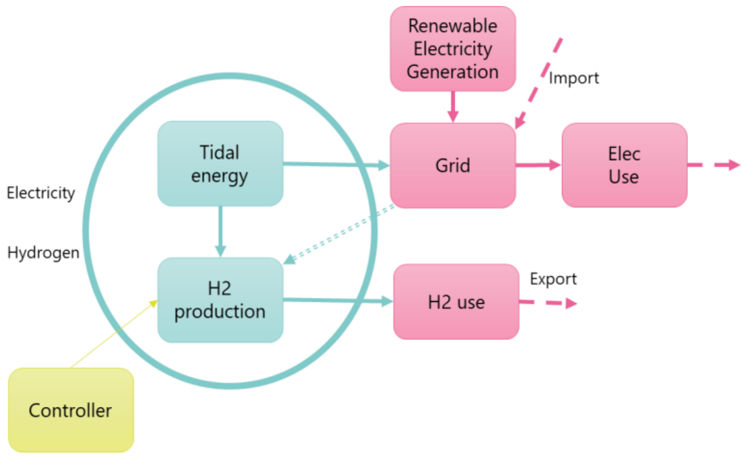
In the longer term, larger scale production could unlock more renewable electricity potential in remote locations and islands in NWE where the wind and marine resources are particularly strong. Renewable electricity combined with hydrogen production could also allow these areas to be more energy independent.

Current and forecast hydrogen and electricity demands should be assessed carefully for each production site as electrical distribution and hydrogen transport infrastructure development have long term cost and environmental implications.

The number of stakeholders and increased complexity of this energy system can lead to divergent and conflicting priorities. This creates a greater need to define the objectives of the energy management system and the electricity source controller possibly assessed by an independent regulator.

In the likelihood of the development of carbon footprint calculations and related regulations for both electricity and hydrogen, the certification of origin for grid electricity can become difficult to prove, assess accurately and maintain.

Hydrogen local use and export



Coastal regions with tidal electricity generation are likely to have other renewable electricity resources. Abundant renewable electricity can be used to produce green hydrogen to help reduce the emissions of historically challenging sectors such as heating, transport and industry.

However, these regions often have low industrialisation and could significantly exceeds their domestic demand for electricity and hydrogen. The disparity between these regions and other regions with higher hydrogen demand could result in an international hydrogen trade development. In this scenario, tidal generation and electrolysis could be maximised to export energy elsewhere by pipeline or ship, avoiding any lack or congested electricity interconnections.

Energy storage integration

In parallel to the configurations presented above, energy storage can have a significant impact on the system. Storage considerations can improve system resilience, increase assets utilisation, access favourable market price, reduce infrastructure reinforcement, reduce peak demand, electrical grid stability… Depending on the application and the desired outcome, the suitability for different energy vectors, scales, charging discharging periods, interconnection issues, efficiency need to be assessed.

Examples of energy storage within the system of interest presented in this report are shown below:

- Electrical batteries. Small scale, short term electrical energy storage can transform end users from consumers into prosumers by reducing supply and demand discrepancies throughout the day and support flexibility and balancing of the local grid. Upstream of the electrolyser, electricity storage can smooth out energy intake, especially for predictable tidal generation and optimise electrolyser capacity, hence reducing size and CapEx.
- Small scale hydrogen storage co-located with the electrolyser can be used directly to balance intermittent electricity supply. Hydrogen tanks are also used to feed fuel cell vehicles, refuelling stations or stationary fuel cells. Hydrogen storage can also support demand fluctuation for industry.
- Large scale hydrogen storage could be used for inter-seasonal peak demand for heating. It could also be used as a reserve for electricity generation. Hydrogen is relatively difficult to store and transport in comparison with petroleum fuels due to its chemical properties: low density requires high compression and molecule size makes it prone to leak and it is highly flammable. The efficiency and cost effectiveness of the process and infrastructure still need to be proven and compared with other options such as increased renewable electricity production and infrastructure reinforcement or alternative storage solutions.
- To a smaller extent, other forms of energy storage such as pumped hydro, liquid/compressed air, heat storage could all play a role.

The value of storage on the whole energy system and on the final energy cost is undeniable but difficult to accurately calculate.

Tidal energy would be an ideal source to reach the sufficient baseload factor for affordable hydrogen. Also, connecting to a decarbonised grid including solar and wind in the mix looks like a promising option when they complement each other in terms of availability. Upfront short term electric battery storage could provide increased and more constant load factor and reduced maximum capacity. Hydrogen storage will be vital to develop a resilient energy system with the potential to develop export.

3.4.2.4 Integrated Policy and Regulation

A lot can be learnt from the evolution of the gas and electricity markets and policies. However, the variety of renewable electricity sources and the infancy of the hydrogen market brings a lot of complexity to develop policy and regulations fit for an integrated system. Reform of energy markets takes time and will be based on the success of demonstrators.

Now that hydrogen is included in most decarbonisation discussion and roadmaps, it is time to plan and boost regulatory schemes for tidal energy as a feedstock for electrolysis in an integrated manner.

As government interventions support different technologies, multiple departments must coordinate their efforts to support concurrent and coordinated creation of supply and demand of both tidal energy and hydrogen. An integrated approach to deliver accelerated deployment, supported by appropriate regulation and policy, targeted research and development, demonstration and large scale validation of new developments, combined with continued tidal and hydrogen cost reduction will support the integration challenge. [32]

For tidal generated hydrogen scale up, regulatory and tariff schemes could push integrated developments to expand and replicate in other locations. Some potential solutions include providing feed-in tariffs for at least 100 MW projects or defining ocean energy tender criteria; the latter is a measure used in the Netherlands. [2]

The Innovation Fund[45] from the European Commission can support the demonstration of innovative clean technologies at commercial scale, such as different ocean energy technologies or projects to couple these with battery storage or hydrogen production. Support could be combined with InvestEU[46] or the Connecting Europe Facility[47] (CEF) funding to increase the viability of such innovative projects and to finance adjacent infrastructure. Furthermore, the Clean Energy for EU Islands[48] initiative provides a long term cooperation framework to promote replicable and scalable projects with funding from private sector investors, relevant EU support instruments, and technical assistance, in order to accelerate clean energy transition on all EU islands. [1]

The roadmap for the integration of tidal energy with electrolysis cannot ignore its interaction with other renewable energy sources, changing energy demands from all sectors and its part and interaction with the different sectors of the blue economy (shipping, port activities).

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[45] https://ec.europa.eu/clima/eu-action/funding-climate-action/innovation-fund_en

[46] https://europa.eu/investeu/home_en

[47] https://ec.europa.eu/inea/en/connecting-europe-facility

[48] https://clean-energy-islands.ec.europa.eu/

3.4.2.5 Socio-economic impact

The integration of tidal energy with electrolysis can provide significant socio-economic opportunities for islands and remote lands with coastal areas, such as job creation, skills development, improved livelihoods, local value chains, resilience and enhance synergies amongst blue economy actors.

Wind and solar energy sectors now have an established workforce while tidal energy and hydrogen are behind in their development stage. Consequently, deployment and jobs are still minor in the sector for the time being. Upscaling will require job creation primarily in installations, integration and the specific supply chain. Given that much of the development is taking place in NWE, the development can lead to growing workforce, expertise and benefits if funding and benefits include development of local skills and supply chain industry. Existing assets as well as marine and gas skills can be converted and upgraded all the way through the new assets' lifecycle (from surveying, planning, installing to operating, maintaining and supporting end of asset life).

Islands and other coastline locations have significant opportunities for tidal energy generation combined with low carbon hydrogen production and use. Its offshore wind and tidal and wave power potential, strong infrastructure networks and ports, research and development strengths, skills base and readily available internal markets provide a platform for deployment of hydrogen and fuel cell technologies under a favourable policy environment.

3.4.3 Conclusions on Integration of Tidal Generation and Hydrogen

From the reviews of tidal energy and electrolyser roadmaps, both technologies are experiencing independently unprecedented interest leading to increased funding and development. However, to combine the technology effectively, development phases and upscaling must be synchronised.

Islands and remote locations usually have land space, coastlines and low density populations leading to the potential to produce significant quantities of renewable hydrogen from tidal resources. The potential for renewable generation can be vastly greater than the local demand.

The production of green hydrogen from tidal energy in these areas can:

- help overcome grid constraints associated with remote locations and small islands
- unlock a clean power generation resource
- integrate with wind and solar energy to use complementary renewable resources
- decouple tidal energy source and consumption through the production of hydrogen
- support decarbonisation by creating a novel clean fuel for industry, mobility and households
- create a highly valuable commodity to supply rapidly growing UK and European markets.

As for any integration project, especially with multiple innovative technologies, the speed of development of all aspects must match or follow each other closely. Further integration within the whole energy system can support discrepancies but also add to the control complexity. For example, tidal generated electricity can be connected to the grid and be combined with other renewable sources or imported electricity. Similarly, if green hydrogen production exceeds local demand, a supply chain for export can be developed.

Hydrogen from renewable electricity is most likely to achieve cost-effectiveness through high electrolyser utilisation rates combined with low-cost renewable electricity. Yet outcomes should be assessed carefully for each possible production site. Large scale, off-grid hydrogen projects directly connected to solar and wind farms in high resource locations may provide low-cost, 100 % renewable hydrogen. However, they will have lower electrolyser utilisation rates than when using tidal generation due to the nature of solar and wind resources, which would increase hydrogen cost. [12]

A strong base for tidal and hydrogen that can be built on in terms of technology, industrial developments, shared existing skills and supply chains with oil and gas industry alongside net zero ambitions.

Early developments such as the ITEG project will give the industry confidence and can pave the way to the next stages. If successful, the closed system can be replicated and adapted to different locations with tidal resources and hydrogen demand. Projects can be scaled up with larger tidal arrays combined with larger electrolyser capacity. Finally, for full deployment, the system can be integrated with local or national electricity grids (for import and export) and the hydrogen system for multiple local applications and potentially export.

4 Development of Roadmap for an Integrated Solution

Hydrogen produced from tidal energy could contribute significantly to the decarbonisation journey to net zero in remote locations and islands in NWE. Many options have been presented for the contribution of hydrogen use between the mobility, industrial and power sectors but the first step must be to scale up green hydrogen production to reduce costs and allow wider use.

Roadmapping is a complex long-term planning instrument that enables setting of strategic goals and estimation of the potential of new technologies, products, and services. Due to the novel and specific aspects of the ITEG project and the wide ranging integration scenarios for the system, a detailed roadmap is not developed in this report. A detailed review of the individual technology roadmaps is followed by the assumptions and needs identification for different development scenarios. This will support the identification of key enablers and barriers to deployment of the different integration scenarios.

4.1 Scenarios and Methodology

The system of interest for this report is the integration of a tidal turbine connected to an electrolyser to produce hydrogen. However, this system is part of the wider energy system of the islands and the deployment of the system goes beyond the technology readiness in terms of cost, performance and reliability. For this reason, some assumptions are reiterated below to introduce this section:

- The area of interest is limited to remote locations and islands in NWE. The characteristics of these regions include high tidal energy and other renewable potential, absence of a gas grid, constrained electricity grids and low density population. The needs and development requirements for these areas are very different to mainland, populated or industrial areas. Development in other areas could support deployment and scaling up projects.
- It is assumed that electricity grid reinforcement in these regions is constrained and is unlikely to be reinforced. This implies that electricity supply and demand to/from the region boundaries are limited to a fixed threshold. Grid reinforcement is another potential future scenario not envisaged in this report.

The integration aspects of the current ITEG system has been presented in section 3.4. Looking at the Orkney energy system (see report "Whole Energy System Analysis: Long Term Impacts on the Orkney Energy System") from the present day until 2050 there is significant uncertainty. The system of the future will be shaped in part by the technologies and options available to it.

The scenarios have been aggregated into three main energy integration options as shown in Figure 4-1:

- (1) Closed system – a tidal turbine and electrolyser for local hydrogen consumption.
- (1/2) Grid connection – renewable and grid connection for both tidal export to the grid and additional electricity source for the electrolyser.
- (1/2/3) Hydrogen export – hydrogen can be used locally and/or exported potentially at scale.

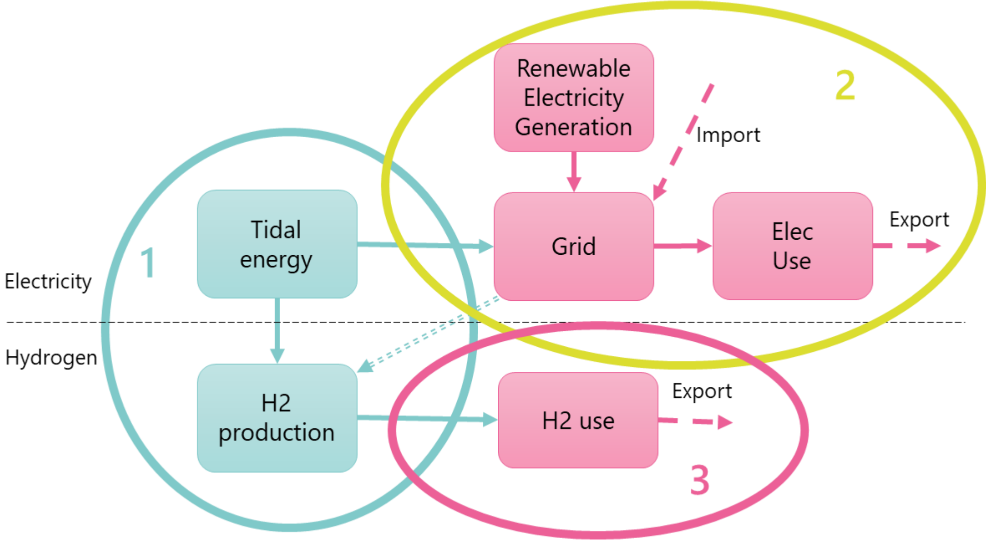

Figure 4-1: System Integration Scenarios

The deployment of the system in other location and at different scales will need to be planned individually for each application depending on the chosen scenario, the tidal energy potential, the hydrogen demand and the existing infrastructure alongside the estimated investment.

The fundamental findings coming from the literature review of individual technologies have helped construct the hypotheses and the different integration scenarios. The feasibility and the proposed outcome follow a scientific method of gathering data, running models and simulations, analysing the test results and interpreting them to form options and conclusions. The results can include electricity price, hydrogen price, infrastructure development costs, carbon saving, curtailment levels etc.

Economies of scale not only benefit end prices but also standards and deployment frameworks (project pipeline, information on capacity planned, start of operation, project lifecycle, expected costs, financial methods). In parallel, additional data becomes available to refine analysis and can further speed up development. Each successful programme will also increase investors' confidence and support future scenarios and energy strategy.

Identifying the needs for deployment of the three different integration scenarios can be the basis for a roadmap to identify future priority opportunities and capability needs. This also allows identifying the key enablers and barriers to deployment at scale.

4.2 Needs identification

In the context of hydrogen produced using electricity from tidal generation in remote locations, the roadmap should not only be technological and economic but also include the environmental impact, the value for the local and whole energy system and the benefits for the local community.

Due to the niche and novel technology of hydrogen produced using electricity from tidal generation, the baseline against which improvements can be measured has to be against competing technologies such as fossil fuels or other renewable sources and end use options. Any target presented should be realistic considering the assumptions and the boundaries of the system of interest.

This section sets out to identify the requirements for the development of these roadmaps in term of:

- The environmental impact
- The technology options
- The economic challenges
- The role of policy and regulation

The different aspects impacting the development of a roadmap are interlinked and progress in one area can set another one back.

4.2.1 Environmental needs

The primary reason for deployment of such system is the decarbonisation targets set in all countries in NWE in the past few years. Every progress in technology advancement or cost reduction must be assessed against the environmental impact towards the carbon emission targets. The environmental impact is not restricted to carbon emission but also include the effect of new installations offshore on marine life and onshore ecosystems.

In small islands and remote locations, fossil fuel is often the main source of heating, mobility (road, marine and air transport) and industrial applications. The role of electrification and the introduction of hydrogen to decarbonise can have a major impact on the local environment.

Assessing the current fossil fuel consumption can support the estimation of the amount of electricity and hydrogen required to achieve net zero by a particular date factoring in the potential for energy efficiency and reduction.

4.2.2 Technology needs

Tidal energy coupled with electrolysers is a major opportunity for NWE, a rich tidal energy region with key hydrogen use potential. [8]

However, tidal energy technology is behind wind and solar and electrolysis behind methane reforming. However, both technologies are growing rapidly and can count on other technology experience and policy support to reach technology readiness for commercialisation and scale up.

Wind and solar electricity generation have grown dramatically because governments provided various forms of financial support for them. Demand was stimulated, and production of turbines and solar panels scaled up. Costs then fell, stimulating more demand, and so on. Hydrogen produced using electricity from tidal generation can follow this path to some extent.

The specific needs for tidal electricity and hydrogen production in remote locations lie in the resources, grid constraints and hydrogen demand:

- **Resources**: The location of tidal turbines and the electrolysers is determined by the availability of resources and demand. Tidal generation is limited to coastal areas. The water requirements for electrolysis could be less stringent due to the coastal nature of the sites but desalination prior to electrolysis is still a challenge.
- **Grid constraints**: The UK's electricity network was originally designed to distribute power from large-scale power stations to the end-user. Optimal tidal turbine locations may be in areas with a low-capacity, or no distribution network leading to curtailment. Current grid constraints can also slow down electrification in these regions. However, hydrogen production can alleviate these constraints by offering an alternative energy vector and acting as a way of storing energy.
- **Hydrogen demand**: demand for hydrogen needs to follow production whether in a closed system for one specific application or a fully integrated system where demand for export is high.

The requirements for electrolyser sites are driven by the understanding of the infrastructure required from the tidal turbine to the hydrogen end use.

Identifying technology needs can support policy makers to prioritise their action to support relevant innovation. Supported demonstration projects to build evidence will be key to additional deployment.

However, focusing solely on technological development might lead to technically sophisticated solutions that lack applicability. Since more mature competing technologies exist for both electricity and hydrogen production, the environmental and economic aspects must be assessed.

4.2.3 Economy

For tidal energy coupled with electrolysis to increase its contribution in the energy mix, the system must be economically viable in the future but with a strong emphasis on the benefits for the local energy system. The cost of hydrogen produced from tidal energy must be competitive with alternatives (other renewable sources or fossil fuel).

The economic needs for the systems are directly linked to the needs of cost reduction of each individual technology to compete in the energy market. **The LCOH is the sum of the LCOE, the electrolyser cost and the transport costs**. Transport costs include electric connection, power conversion, cabling and hydrogen transport and preparation (for example, conversion into ammonia for transportation purposes, and then back into hydrogen for use, or when it is reconverted into electricity in a hydrogen-fuelled power station).

However, in a closed system, the cost is fixed for the small scale system unless unplanned maintenance or failure occurs. The system can be designed to minimise transport costs. In a fully integrated system, LCOH can be driven down by increased utilisation of assets and flexibility but prices are more likely to fluctuate with the global market.

The scale of investment could support greater and faster upscale of hydrogen production using electricity from tidal generation leading to rapidly reach the price target of £2/kg. This is assuming that the targets for tidal LCOE presented in section 3.2.2 and electrolyser LCOH presented in section 3.3.2 are met. However, as the market develops and competition intensifies, assuming that hydrogen demand matches the scale of supply, small islands may become disadvantaged compared to larger producers.

Cost is obviously a key driver, but the value of the system is not limited to it. Tidal generated hydrogen can allow efficient decarbonisation, reduce fuel poverty by allowing better local management of supply and demand and increase local energy autonomy and resilience to imported energy price volatility.

4.2.4 Policy

Roadmapping applied to a green energy technology solution needs to take into account the environmental and techno-commercial needs for the systems. However, the roadmap will closely follow policy and regulations roadmapping.

Clean hydrogen is currently enjoying unprecedented political and business momentum, with the number of policies and projects around the world expanding rapidly. Carbon taxes and targeting the end of fossil fuels subsidies can have a massive socio-economic impact and redirect investment towards green technology.

However, projects tend to focus on one technology (tidal or hydrogen) or even one aspect of each technology (hydrogen production, hydrogen for heating, heat pumps installation). System integration of multiple technologies or multiple vectors projects are more complex and scarcer hence they seem to be less attractive to investors.

Hydrogen policy alone will not determine carbon prices, but support mechanisms will need to take their movements into account. Commercial participants can also do a lot to mitigate the risks, and maximise the upside, of projects similar to the ITEG project.

5 Conclusions

5.1 Key benefits

There is potential for ITEG technologies and the electricity and hydrogen they can produce to play a role in decarbonisation of the Orkney energy system. These combined technologies can support the energy transition in remote locations and islands in the following ways:

- System carbon emissions can be reduced using packages of tidal turbines and hydrogen electrolysers (rolled-out after the ITEG project), and particularly with increased hydrogen demand.
- Primary energy has the potential to be a mixture of wind and tidal generation alongside some solar with some residual oil use and an amount of net imported electricity which varies depending on the scenario investigated.
- Heating of domestic and non-domestic buildings can shift from predominantly oil and some electric resistive heating today, to predominantly heat pumps (ground source and air source) with a mix of other electric and hydrogen heating by 2050 (with the detail varying by scenario and by location).
- For non-domestic buildings hydrogen can play an important role to decarbonise processes that are hard to electrify such as some industrial heat processes.
- Hydrogen could be used (in varying proportions) in fuel cells, non-domestic buildings and domestic buildings as well as for maritime purposes. Potential export markets could develop for remote coastal locations with excess green hydrogen production and limited electricity export opportunities.

5.2 Key enablers to deployment

With the ambitious target of net zero emissions throughout NWE between 2045 and 2050, all scenarios include a significant increase in renewable electricity generation and green hydrogen production. One of the challenges will be to integrate the multiple technologies involved into a safe, reliable and secure energy system.

5.2.1 Individual Technologies

Tidal energy and electrolysis are independently on the way to gain a greater role in energy production. Any progress in each technology’s development and deployment will benefit the potential growth of an integrated system.

- **Tidal** can support both a universal increase of electrification and green hydrogen production.
  Predictability of generation can provide a sound baseload. It also complements and can be coupled with other more mature renewable sources which are widely deployed in similar areas such as wind and solar energy.

There is high availability of tidal resources for islands which often suffer from grid constraints and above average fossil fuel import (land, air and maritime mobility, heating and local industry).

- **Hydrogen** has a major role to play for decarbonising current gas and oil use with potential across all end use applications and storage. Hard to electrify sectors also have potential to switch to hydrogen.
  Green hydrogen production can benefit from low cost electricity from intermittent supply by reducing curtailment. Hydrogen can also provide seasonal storage for heating.

5.2.2 Integrated Tidal Turbine and Electrolyser System

Where tidal resources are abundant, increased electricity production integrated with the potential of turning excess electricity into hydrogen can bring many benefits:

- The undeniable environmental benefits from reducing reliance on fossil fuels.
- The development of the Blue Economy in coastal areas where social acceptance is high and job retention and creation is crucial.
- The accelerated deployment of renewable electricity while reducing curtailment without grid reinforcement.
- The control systems can be adapted to the desired outcomes and benefits (lower cost, increase reliability and resilience, maximise efficiency…)
- The options of different levels of integration within the whole energy system and interaction with other sector (marine, transport…).
- Planning, installation and licensing process can be simplified with a proven and certified integrated solution.

5.2.3 Closed System

A closed system, where the tidal turbine and the electrolyser serve a single hydrogen user can be a stepping stone in the short term and for local hydrogen demand:

- The predictability of tides makes tidal turbines an ideal baseload source of electricity for electrolysis (combined with either electricity or hydrogen storage).
- The ITEG project can demonstrate the feasibility and benefits of producing hydrogen from tidal generation and accelerate the scalability and replicability of this integrated system.
- The relatively small scale of the project could allow rapid replicability in suitable locations and provide rapid benefits. A turnkey solution could be provided where tidal energy is available and new electrical and hydrogen capacity is required.
- The development of these solutions should always be future proofed by factoring in the potential for future further integration into the wider energy system.

5.2.4 Integrated system

In the longer term, integrating tidal energy with other renewable sources, the local or national electric and gas grid for multiple hydrogen usage and users will support the integration of the multiple vectors and technologies.

- Decarbonisation objectives for remote locations and small islands will drive the use of the multiple natural resources to maximise electricity and hydrogen production. The development of a local multi-vector energy system can optimise the capacity of the asset for local demand and potential export.
- Tidal generated hydrogen solutions could provide benefits for the energy system as a whole.

5.3 Key barriers to deployment

Despite definite benefits, fast cost reductions and increased reliability, many barriers still exist in the successful deployment at scale of tidal energy and hydrogen production.

5.3.1 Technical readiness

Both technologies are transitioning from demonstrators to full scale commercial projects. The integration aspect adds an extra layer of complexity in the technology readiness for a combined solution.

- Tidal energy doesn't currently offer the technological maturity of competing wind and solar renewable resources. However, with the right support, tidal energy can provide a predictable, complementary energy source.
- While electrolysis is the more mature technology for low carbon hydrogen production, capital cost and energy efficiency under dynamic operating conditions can still be improved. Integrating hydrogen production with the challenges of transport, storage and usage still needs to be addressed.
- Once the individual technology barriers are tackled, the integrated system efficiency needs to be optimised for specific goals. For example, the electrolyser location and the control management will affect the outcome of short term and long term impacts of the system.
- The risk of stranded assets is currently high without a dedicated hydrogen transport network to deliver hydrogen to the end user or if a co-located customer goes out of business. The potential for a circular economy where assets can be shared or reused is rarely part of project development.

International collaboration, sharing information and best practice, and the development of test centres could help overcome these technical barriers to development.

5.3.2 Cost

The cost associated with both technologies is still high despite fast reductions with growth in installed capacity and technology maturity for both tidal turbines and electrolysers.

- **Cost competitiveness of tidal with solar and wind.** Tidal and other marine energies are behind solar and wind technologies by approximately a decade in terms of capacity and associated technology development and cost reduction. However, tidal resource patterns are predictable and can complement other more mature renewable technologies.
- **Cost competitiveness of electrolysis with blue hydrogen.** Currently, electrolysed hydrogen costs cannot compete with fossil fuel based hydrogen. However, forecast for a net zero future shows that green hydrogen is likely to be more cost effective than fossil fuel based hydrogen with CCUS.
- The current immature market for hydrogen reduces investors' attraction compared to other renewable options. However, successful development of integrated solutions for hydrogen applications could drive investors' interest and boost revenues and accelerate deployment and cost reduction.

Growth in installed capacity can be accelerated with subsidy support leading to cost reduction. By extension, subsidies are indirectly linked to cost reduction for end users.

5.3.3 Policy

The regulatory framework will inform how a tidal turbine combined with an electrolyser can operate and provide transparency on the strategy to give this technology a long term position within the energy sector.

- Net zero ambition and the speed of fossil fuel phase out from both national policies and local energy market choices will greatly impact the speed of deployment of renewable options.
- To the same extend, green policies interventions on market distortion on both energy supply and demand sides will be necessary to reach competitiveness and rapid scaleup.
- Regulatory barriers to the deployment of distributed energy resources need to be addressed. This could incentivise local generation and local market creation. This would empower users to take an active role in the energy transformation and become prosumers.
- Policy and regulation will directly impact financial support, stable markets and investment incentives which could either create a positive enabling environment or barriers to deployment.
- The lack of policy integration between climate and energy objectives could be a barrier to integrated solution deployment. Multiple parties and policies can affect such a system providing support for tidal energy in the electricity mix, encouraging reduction in fossil fuels availability and affordability, and creating hydrogen demand.

The importance of a long term perspective is often overshadowed by shorter term energy or climate concerns and changing political commitments.

5.3.4 Supply chain development

Supply chain development and coordination is vital for this system. Any missing link in the supply chain could impede the commercialisation and deployment at scale.

- The electrolyser supply chain comprises of the electrolyser components (for example for polymer electrolyte and solid oxide technologies), resources (water and electricity), hydrogen storage and offtake, other required new infrastructure etc.
- The tidal generator supply chain includes tidal component manufacturers, foundation and mooring systems, vessels for maintenance, subsea cable installation and maintenance etc.
- Integration of the value chain involves connection between the tidal turbine and the electrolyser, the potential grid connection, hydrogen export potential etc.

The extensive development of the supply chain will be required alongside skills and education in both sectors. There is a scope for cross sector coordination and repurposed skills from marine and fossil fuel existing expertise.

5.3.5 Uncertain evolution of the energy system as a whole

The main barrier to define a confident roadmap for the deployment of an integrated tidal turbine with an electrolyser resides in the highly uncertain direction of energy evolution for the coming years including:

- The future energy consumption per capita and the population density in coastal regions.
- The future mix of electrification and hydrogen use (battery electric vehicles/fuel cell electric vehicles, heat pumps/hydrogen boilers/hybrid systems…)
- The related hydrogen production targets from renewable electricity.
- The local and global end use potential of hydrogen
- The speed of deployment of individual technologies.
- The acceptance and growth in demand for flexibility and demand side response.
- The risk of stranded assets from early demonstrators compared to more mature technology.

6 Glossary

Term	**Acronym**	**Definition / Description**
Anion exchange membrane	AEM	Electrolysis technology using a semipermeable membrane to separate oxygen and hydrogen.
Business, Energy & Industrial Strategy (Department for)	BEIS	Ministerial department
Capital Expenditure	CapEx	Money spent on acquiring or maintaining fixed assets, such as land, buildings, and equipment.
Carbon Capture, Utilisation and Storage	CCUS	Process of capturing carbon dioxide (CO_2) emissions to be either stored or recycled for further usage avoiding them to enter the atmosphere.
European Marine Energy Centre	EMEC	Test and research centre focusing on wave and tidal power development based in the Orkney Islands, UK.
The Fuel Cells and Hydrogen Joint Undertaking	FCH JU	Fuel Cells and Hydrogen Joint Undertaking ceased operations on 29 November 2021. Its successor, Clean Hydrogen JU, was established on 30 November 2021 to take over its legacy portfolio and to continue developing the European value chain for safe and clean hydrogen technologies.
GreenHouse Gas	GHG	Emissions into the earth's atmosphere of any of various gases, especially carbon dioxide, that contribute to the greenhouse effect.
International Energy Agency	IEA	Autonomous intergovernmental organisation
European Territorial Cooperation	INTERREG	Brings people together to share innovative and sustainable solutions to regional development challenges in the EU.
International Renewable Energy Agency	IRENA	Intergovernmental organization mandated to facilitate cooperation, advance knowledge, and promote the adoption and sustainable use of renewable energy.
Integrated Tidal Energy in European Grid	ITEG	Project aiming to develop and validate an integrated tidal energy and hydrogen production solution for clean energy generation to be demonstrated in Orkney.
Levelised Cost Of Energy	LCOE	Methodology used to account for all of the capital and operating costs of producing energy, i.e. the ratio between the lifetime cost of the system by the lifetime energy generation.
Levelised Cost Of Hydrogen	LCOH	Methodology used to account for all of the capital and operating costs of producing hydrogen, i.e. the ratio between the lifetime cost of the system by the lifetime hydrogen generation.
Long Term (effect)	LT	Work package within the ITEG project.
North West Europe	NWE	Geographical scope of the ITEG project.

Term	**Acronym**	**Definition / Description**
Ocean Thermal Energy Conversion	OTEC	Type of ocean energy technology.
Polymer Electrolyte Membrane	PEM	Electrolyser technology where water is electromechanically into hydrogen and oxygen at their respective electrodes.
Solid Oxide Electrolysers	SOE	Electrolyser technology using the reverse process that occurs in a fuel cell.

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8 Appendix

8.1 Tidal Electricity Existing Roadmaps

This list is non exhaustive and presents the roadmaps that have been reviewed for this study. They have been selected for the relevance of the NWE location and the different aspects covered.

#	Area of interest	Year	Roadmapping study	Author / Publisher	**Key Aspects**
1	Europe	2018	Market Study on Ocean Energy [33]	COGEA and WavEC	Identify Financial needs, potential gaps and solutions (Optimistic, medium to Pessimistic scenario cases). Recommendation on funding/investment sources.
2	Europe	2016	Ocean Energy Strategic Roadmap- Building Ocean Energy for Europe (Nov 2016) [22]	Ocean Energy Forum	**6 priority areas**: R&D, Prototype, Demonstrations & validations, dedicated Supply &value chain, suitable Grids & Industrial roll out (standardisation & certification) **Challenges**: technologies, financing, regulatory challenges for each stakeholder (fit-for purpose) **6 Point Action Plan**
3	UK	2008	UKERC Marine (Wave and Tidal Current) Renewable Energy Technology Roadmap [23]	UKERC and University of Edinburgh	Older roadmap(2008) targeting 2GW of wave and tidal energy installed capacity in UK by 2020 with a strategy needing to be in place by 2010. Useful reference for general wave and tidal technology.

#	Area of interest	Year	Roadmapping study	Author / Publisher	**Key Aspects**
4	UK	2014	UKERC Marine Renewable Energy Technology Roadmap 2014. [17]	UKERC and ETI	An update to a 2010 roadmap. Sets targets for device cost and performance through to 2050.
5	Worldwide	2020	Innovation Outlook: Ocean Energy Technologies [7]	IRENA	Report aims to deliver holistic insights into ocean energy and its potential, outlining the steps necessary to reach commercialisation of these innovative power generating technologies and proposes several measures to bridge the commercialisation and economic gaps
6	Europe	2020	2030 Ocean Energy Vision: Industry analysis of future deployments, costs and supply chains [34]	Ocean Energy Europe	Industry analysis which considers the evolution of European tidal and wave technology to 2030. It projects deployments in high and low growth scenarios. The analysis also examines how energy costs will reduce and supply chains grow, as more ocean energy is deployed.
7	Europe	2021	Ocean Energy: Key trends and statistics 2020 [10]	• Ocean Energy Europe	• Summary of state of ocean energy technology deployments by end 2020

#	Area of interest	Year	Roadmapping study	Author / Publisher	**Key Aspects**
8	Europe	2020	Strategic Research and Innovation Agenda for Ocean Energy [3]	Ocean Energy Europe	This Strategic Research and Innovation Agenda for ocean energy outlines the priority research, development and innovation challenges that must be focused upon in the years ahead. It gives guidance to all funders of innovation – industry, EU, national and regional, presenting concrete research and innovation actions that will allow ocean energy to meet its Strategic Energy Technology Plan (SET Plan) targets.
9	UK	2018	Tidal Stream and Wave Energy Cost Reduction and Industrial Benefit [21]	OREC	The aim of this study is to assess the value in further public support for the tidal stream and wave energy industries. Identifies actions under the categories: Initial accelerated reductions Long-term cost reduction potential and shows the advantages that can be gained
10	EU	2020	An EU Strategy to harness the potential of offshore renewable energy for a climate neutral future [1]	European Commission	Include offshore wind but quite a lot of details on wave and tidal as well. Technology assessment, Deployment potential and Scaling up key actions in the following areas: Management of space and resources Grid infrastructure development EU Regulatory framework Investment and funding (EU, national, private) R&D and Supply chain

#	Area of interest	Year	Roadmapping study	Author / Publisher	**Key Aspects**
11	UK	2019	UK Marine Energy 2019: A new industry [11]	Marine Energy Council	State of marine energy in 2019. Details of current projects. Route to market (Inc. revenue support models)
12	Worldwide	2016	International Emerging and Niche Market Research for the Marine Energy Sector [8]	Aquatera Ltd & Caelulum Ltd	Current status of marine energy across the globe. Regional potential for marine energy development and resource attractiveness.
13	Worldwide	2021	Tidal Current Energy Developments Highlights [9]	OES	Details the technology highlights of 16 existing and 6 upcoming projects worldwide.

Table 8-1: Summary of existing tidal energy roadmaps

8.2 Electrolysis Existing Roadmaps

This list is non exhaustive and presents the roadmaps that have been reviewed for this study. They have been selected for the relevance of the NWE location and the different aspects covered.

#	Area of interest	Year	Roadmapping study	Author / Publisher	**Key Aspects**
1	Europe	2020	A hydrogen strategy for a climate-neutral Europe [4]	European Commission	EU document setting out: Current hydrogen situation in Europe A strategic vision of the place for hydrogen in Europe's energy system Investments required Actions required to boost hydrogen demand and production Designing a framework for hydrogen infrastructure and market rules Research and Innovation goals International dimensions
2	Europe	2020	Towards a hydrogen market for Europe [35]	Council of the European Union	EU Council document including a list of actions to support hydrogen developments
3	Europe	2019	Hydrogen Roadmap Europe [5]	FCH JU	Describes an ambitious scenario for hydrogen deployment in the EU to achieve the 2-degree target. The scenario is based on the perspective of the global Hydrogen Council and data from 17 member companies active in hydrogen and fuel cell technologies. Provides an extreme view of the potential for hydrogen.

#	Area of interest	Year	Roadmapping study	Author / Publisher	**Key Aspects**
4	UK	2020	UK Hydrogen Economy [36]	House of Commons Library	UK House of Commons publication prepared ahead of a Westminster Hall debate on the UK hydrogen economy. Provides a high level view of UK government policy alongside some references.
5	Worldwide	2020	Green Hydrogen Cost Reduction Scaling Up Electrolysis To Meet The 1.5°C Climate Goal [27]	IRENA	Key focus is on the cost of hydrogen electrolysers for green hydrogen production. Identifies key strategies to reduce investment costs for electrolysis plants from 40% in the short term to 80% in the long term. These strategies range from the fundamental design of the electrolyser stack to broader system-wide elements
6	Worldwide	2019	Hydrogen: A Renewable Energy Perspective [13]	IRENA	Analysis of the options for hydrogen generation using renewable energy including future hydrogen cost estimates and a proposal for how the Green hydrogen market might grow from sector to sector.
7	UK	2018	Establishing a Hydrogen Economy. The Future of Energy 2035 [28]	Arup	Explores the future of the UK's hydrogen economy, identifies challenges to be overcome and lays out a series of quick wins and longer term actions.

#	Area of interest	Year	Roadmapping study	Author / Publisher	**Key Aspects**
8	Worldwide	2019	The Future of Hydrogen Seizing today's opportunities [14]	IEA	International Energy Agency study which provides an extensive and independent assessment of hydrogen that lays out where things stand now; the ways in which hydrogen can help to achieve a clean, secure and affordable energy future; and how we can go about realising its potential. identifies the most promising immediate opportunities to provide a springboard for the future. **7 key recommendations**
9	Europe	2014	Development of Water Electrolysis in the European Union [24]	FCH JU	Older report focusing on electrolysers. Techno-economic analysis of electrolysers role in energy applications and comparison with other hydrogen production technology. **3 priorities**: energy system, electrolyser system, electrolyser technologies (cost and performance).
10	Scotland	2021	Development of early, clean hydrogen production in Scotland [26]	OREC	Scotland potential for green hydrogen production, export and competitors. Technology and cost reduction opportunities. Production site assessment and Recommendations

#	Area of interest	Year	Roadmapping study	Author / Publisher	**Key Aspects**
11	Worldwide	2020	Green Hydrogen Supply, A Guide to Policy Making [30]	IRENA	Definition of 4 pillars for green hydrogen policy making: National strategies Establish policy priorities for green hydrogen Guarantee of origin scheme Governance system and enabling policies Section on electrolysis (Barriers and policy recommendations)
12	Scotland	2020	Scottish Hydrogen Assessment [15]	Arup and E4tech	Assessment of current hydrogen economy leading to 3 scenarios Integration with Scotland renewable specificities including ocean energy.
13	Scotland	2020	Scottish Government Hydrogen Policy Statement [37]	Scottish Government	In response to the “Scottish Hydrogen Assessment” [15] setting out the policy priorities for Scotland to 2045.
14	Scotland	2021	Draft Hydrogen Action Plan [25]	Scottish Government	Companion document to the “Policy Statement” [37] Ambition of 5GW installed hydrogen production capacity by 2030 and 25GW by 2045 (blue and green). Short term actions to make progress (2025/2026) and route map to 2035 including funding landscape.

#	Area of interest	Year	Roadmapping study	Author / Publisher	**Key Aspects**
15	UK	2021	UK Hydrogen Strategy [6]	HM Government	State of the nation and plan for a plan. Basis for further roadmap and action plan. Link to the Ten Point Plan, Energy White Paper, current projects. Covers all area of the value chain (hydrogen related not specific project).

Table 8-2: Summary of existing hydrogen production energy roadmaps

8.3 Integrated Renewable and Hydrogen Production

The table below presents the documents analysed for the integration of renewable electricity with electrolysis. There are currently no roadmaps specifically detailing the strategy for tidal energy with electrolysis. However, there are multiple reports on the integration of other sources of renewable energy with electrolysis, or looking at multi energy vector integration challenges more generally.

#	Area of interest	Year	Roadmapping study	Author / Publisher	**Key Aspects**
1	Worldwide	2018	Hydrogen from Renewable Power Technology Outlook for the Energy Transition [12]	IRENA	Summary of current technology status and developments for production of hydrogen from renewable energy sources and associated estimates for levelised cost of hydrogen under different development scenarios. Assessment of end-uses for hydrogen and analysis of actions required to develop a hydrogen supply chain and recommendations for policy makers.
2	Scotland	2020	Scottish Offshore Wind to Green Hydrogen Opportunity Assessment [29]	Xodus	Market demand for Green hydrogen (hubs and cost parity) Scotland potential (wind + marine, infrastructure, supply chain, socioeconomic) Cost modelling and policy analysis

#	Area of interest	Year	Roadmapping study	Author / Publisher	Key Aspects
3	UK	2020	Offshore Wind and Hydrogen: Solving the Integration Challenge [32]	OREC	The report examines the potential for hydrogen for flexibility, energy balancing of the UK energy system. Analysis of UK offshore wind capacity (current and potential), industrial base, academic research to develop a green hydrogen industry. Impact on manufacturing and socio economic benefits.
4	Europe	2021	Scaling up Green Hydrogen in Europe [31]	Operis Group Ltd	Development of necessary building blocks to scale up green hydrogen in Europe.
5	Small Islands	2020	Fostering a Blue Economy: Offshore Renewable Energy [2]	IRENA	This discusses the potential of offshore renewables to contribute to achieving the United Nations (UN) Sustainable Development Goals (SDGs), particularly in the ongoing development of islands and coastal territories.
6	Worldwide	2019	Global Energy Transformation: A Roadmap to 2050, [38]	IRENA	IRENA annual energy roadmap to 2050 with not specifically focussed on hydrogen/marine energy. Purpose and aspects of an energy roadmap

Table 8-3: Summary of existing hydrogen from renewable energy roadmaps