Opportunities for Roll-Out of Tidal Generation with Electrolysis Across North West Europe

Benefits, Impacts, Configuration and Potential Sites for Maximum Value

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Executive Summary

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. They are deployed at the EMEC site on Eday in Orkney. This report examines how tidal generation with electrolysis could best be deployed into a wide range of energy systems, as well as the potential impacts on those systems. It then investigates what potential there is for this combination of technologies to be scaled up and rolled out to achieve these added benefits in other parts of North-West Europe.

The benefits of deploying these technologies in different areas will depend considerably on the specific characteristics of the energy systems in those areas. However, they will be valuable additions to most energy systems, with benefits including:

- predictable electricity generation that provides diversity, resilience and security of supply
- hydrogen for use in hard to decarbonise sectors,
- avoidance of curtailment of local electricity generation through hydrogen production
- support to an integrated electricity and hydrogen market
- potential to store tidal energy as hydrogen over daily and seasonal time periods
- revenue generation potential through hydrogen export

The added benefits arise from increased utilisation of the tidal turbine by feeding power to the electrolyser when the turbine would otherwise be curtailed because of capacity constraints on the electrical network, and subsequent use of the hydrogen in the local energy system to achieve deeper decarbonisation than might otherwise be possible. Three factors are therefore seen to be necessary to achieve benefits from the combined deployment. These are:

- practically accessible tidal stream resources;
- constraints on exporting power from the site; and
- potential demand for the hydrogen produced.

These three criteria are examined in turn and used to identify sites and regions where a combined deployment of tidal stream turbine and electrolyser might be particularly advantageous.

<u>Tidal Resource</u>

Tidal resources in North-West Europe are primarily to be found in north-western France, the Netherlands and the UK, notably both sides of the Irish Sea, off the north of Scotland and in the Orkney and Shetland islands.

<u>Electrical Transmission Constraints</u>

To assess the likelihood of electrical transmission constraints causing curtailment of generation from the tidal stream turbines, a map of the European high voltage transmission network was analysed and a literature search carried out. More detailed information was not readily available. Many of the sites with potential for tidal generation, including all those on mainland Europe,

were found to be well-connected to the electrical network, or very likely to be well-connected shortly as new interconnectors are built.

The sites which showed promise (from the perspective of achieving additional value in overcoming constraints) were clustered around the Irish Sea, The Orkneys, The Faroes and possibly a site on the Isle of Wight.

Hydrogen Demand

To assess the potential for consumption of the hydrogen produced within the locality, emissions inventories were examined to identify significant sources of carbon dioxide which are likely to indicate requirements for heat on an industrial scale. Available literature was then searched for more information.

Application of Criteria to Co-Located Plants and Remotely Located Installations

Two plant options are considered:

1. Co-located packages of a tidal generator and an electrolyser (or scaled up tidal array and electrolysis plant but remaining co-located) were first considered.
2. Following the findings of the modelling work (Deliverable LT.4.2) that there are sometimes benefits in locating the electrolysis close to the hydrogen demand rather than close to the electricity generation, such installations with electrolysis located elsewhere within the local energy system were then considered.

Applying the three criteria above firstly to co-located packages, the locations where the packaged ITEG solution of tidal generation plus electrolyser is deemed most likely to offer some additional benefit are: around Islay and the Mull of Galloway off the western coast of Scotland, the Isle of Wight if local network constraints continue to present a capacity constraint, and the Faroe Islands. Between them the potential tidal resource in those areas totals around 1GW. The likely hydrogen demand has not been quantified.

Applying the same criteria secondly to installations more separated from each other, a number of regions were found which may benefit from the presence of both technologies. Orkney as a whole is one of those, the north of Scotland is another – with abundant tidal stream resource in the Pentland Firth and a constraint on transmission of electricity south of Beauly. Brittany might be another such region if a regional hydrogen hub develops there, and the hydrogen hub being developed in the Netherlands under the HEAVENN project ("H_2 Energy Applications in Valley Environments for Northern Netherlands") might be another.

These locations (shown here) represent potential high-value, sweet-spots for early deployment of the combined solution, as they may be able to provide additional value return on the investment.

Feasibility studies are therefore recommended for these locations.

1 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 aims to overcome technical and commercial challenges associated with the use of abundant renewable energy resources in regions with weak or constrained electricity grids, and to use hydrogen to capture this green energy and enable decarbonisation of the wider energy system and the many domestic and commercial users of energy. The turbine and electrolyser are deployed at an EMEC site on Eday in the Orkneys.

The contribution that tidal stream turbines and electrolysers could make to the Orkney energy system was modelled and extensively reported in deliverable LT4.2 “Whole Energy System Analysis: Long Term Impacts on the Orkney Energy System”[1].

This report investigates the potential benefits and impacts of deploying these technologies and what potential there is to achieve similar added benefits by combining tidal stream turbines with electrolysers in other parts of North-West Europe.

2 Benefits and Impacts of Deployment

2.1 Benefits of Deployment

The benefits of deploying tidal generation, hydrogen, and specifically the combination of these technologies, into the Orkney energy system are set out in detail in Deliverable LT.4.2 "Whole Energy System Analysis: Long Term Impacts on the Orkney Energy System". This provides a detailed case study of the unit deployed at Eday, and of potential larger scale deployment of these technologies in Orkney, setting out a number of scenarios as to how the Orkney Archipelago could achieve net zero and what the contributions, benefits and impacts of these technologies could be.

At a European scale a range of estimates of the potential for ocean energy have previously been produced ranging from 40 GW (European Commission strategy for offshore renewable energy[2]) to as much as 100 GW (Ocean Energy Europe[3]). Whilst these include both wave and tidal energy, these figures indicate the scale of potential for tidal generation. Similarly, the European Commission Hydrogen Strategy[4] has an objective to install at least 6 GW of renewable hydrogen electrolysers in the EU by 2024 with at least 40 GW by 2030 and with hydrogen becoming an intrinsic part of an integrated energy system.

The benefits of deploying these technologies in different areas will depend considerably on the specific characteristics of the energy systems in those areas – although they are generally expected to be valuable additions to most energy systems. Benefits could include:

- Provision of flexible, low carbon hydrogen for use in hard to decarbonise sectors such as industrial processes, heavy duty transport and, potentially, aviation as well as space heating of buildings.
- Predictable, low carbon electricity generation that provides additional diversity and increased resilience and security of supply when combined with other less predictable low carbon generation such as wind and solar.
- The ability to avoid curtailment of local generation due to network constraints through local use of electrolysis to produce hydrogen.
- Supporting the development of an integrated electricity and hydrogen market where the synergy between tidal generation and hydrogen production allows options to match supply and demand across both energy vectors.
- The option to store energy produced using tidal stream turbines as hydrogen over both daily and seasonal time periods.
- The opportunity for revenue generation through export of low carbon hydrogen from areas with significant tidal resources.

For electricity distribution network operators, the combined technologies can provide a source of flexibility to help in managing local supply and demand, reducing problems with network constraints and so diminishing or removing the need for expensive network reinforcement. In addition, the predictable nature of tidal generation can help in forecasting the timing and scale of flexibility services that may be required. With increasing electrification of heat and transport, it can be expected that demand for electricity will increase. This may alleviate current constraints on export of electricity in places such as Orkney, as more local generation will be used locally rather than exported.

Where there are pre-existing gas networks there is a possibility to re-purpose these to distribute hydrogen rather than natural gas. Combining local tidal generation and hydrogen electrolysis could provide a local supply of low carbon hydrogen to feed these networks. Whilst this locally-produced hydrogen could be mixed with hydrogen imported to the local area, there is also a possibility for local, islanded gas networks to be created. These would not be connected to a wider hydrogen transmission network and would meet all their hydrogen demands through local production. This opportunity is probably limited to a relatively small number of locations with existing gas networks and significant renewable energy resources, but could have significant cost benefits through removing the need for new hydrogen transmission networks.

2.2 Other Impacts of Deployment

In addition to the benefits summarised above, there may be additional impacts from deploying these technologies in other areas and, again, these will depend considerably on the specific characteristics of the energy systems in those areas. Some of these impacts, including a few points which are sometimes raised as questions by stakeholders, are briefly addressed below.

Increasing use of local energy production is likely to result in reverse flows in energy networks that were originally designed to work 'top down' with large, central energy production sites connected to transmission and distribution networks. These networks have their largest capacities closest to their energy production sites. Producing large quantities of energy at the distribution end of networks can cause problems where energy production exceeds the capacity of local networks to carry that energy to sources of demand. This can lead to restrictions on local energy production even when local demand is available.

In order to maximise the opportunities for local energy production, network operators (both gas and electricity) will need to have a good understanding of the specific characteristics of each local area including:

1) The types, sources and scales of energy demands
2) The likely influence of efficiency improvements (e.g. building fabric upgrades) on energy demand
3) The options for, and likely scale of change to, low carbon energy services (e.g. electric vehicles or heat pumps) and how these will influence energy demand (both within day demand profiles for different seasons and total annual demands)
4) The capacities of existing energy networks
5) The potential types and scales of energy production
6) The opportunities to match supply and demand in the most effective way
7) The options for control of energy demand and production and the associated technical and financial routes to implementation
8) The opportunities for energy storage (both within day and between seasons)

Given the significant differences between local energy systems in all these respects it is unlikely that a single solution will be found that is suitable for all local areas. It follows, therefore, that network operators and other local stakeholders will need to work collaboratively to understand the challenges and opportunities for each location separately. Energy Systems Catapult has pioneered development of a process for such collaborative, evidence-based Local Area Energy Planning (see https://es.catapult.org.uk/tools-and-labs/our-place-based-net-zero-toolkit/local-area-energy-planning/).

Although a full Local Area Energy Plan has not been developed for Orkney, the ITEG project has delivered a detailed case study for how local characteristics can influence the most appropriate local solutions, which is presented in Deliverable LT.4.2 “Whole Energy System Analysis: Long Term Impacts on the Orkney Energy System”.

Alongside technical aspects of energy system integration, other impacts of deploying tidal stream turbines linked to hydrogen electrolysers include:

1) Consideration of how hydrogen can be stored and transported and the associated, complex regulatory environment (see Deliverable LT.4.3 “Hydrogen Handling and Logistics”
2) Factors associated with social acceptance of new energy technologies and related environmental and safety concerns (Deliverable LT.2.2 “Social Acceptance Study”)
3) Commercial and regulatory arrangements for energy producers and network operators:
    a. to provide access to energy networks for producers to allow them to sell their products to consumers
    b. to create means through which energy producers can provide flexibility services to network operators in ways that appropriately benefit all stakeholders (including energy consumers)
4) Consideration of the impacts of new technologies on vulnerable or fuel poor customers.

3 Configuration and Modularisation

The combination of tidal generation and hydrogen electrolysis can potentially be configured in different ways to suit different applications, different energy systems, different territories and different requirements. It can thus be replicated and rolled out in a manner which maximises the value achieved from its deployment.

As discussed in section 2.2 the characteristics of each local area will influence the most appropriate configuration for that area and specific application. Knowledge of the local hydrogen and electricity demand profiles through the year is likely to be required. For example, if winter hydrogen demands are significantly higher than at other times of year then sizing of tidal generation and hydrogen electrolysis may need to be considered in terms of the relative costs and benefits of seasonal hydrogen storage compared to installing plant to meet peak demand and having excess production capacity for much of the year, although opportunities for hydrogen export may provide an alternative demand at these times.

It may be possible to implement some simple modularisation of the solution, in order to increase the degree of standardisation, and thus reduce capital and operating costs or to improve deployment times, etc.

Tidal stream turbines are expected to be limited in rating to approximately 2.5MW, due to the required blade size and the limited water depth in coastal areas with maximum tidal velocities. It is therefore likely that most manufacturers will develop a relatively small number of standardised unit sizes and specifications up to this limit.

Some manufacturers are developing small modular clusters of turbines with some common infrastructure (e.g. sub-sea cabling systems). Ultimately, turbine array sizes could be as high as tidal resource permits in an area, in some cases multiple GWs, though it is important to integrate these into the whole energy system design, and optimum system benefits may be achieved in some cases by array sizes lower than that resulting from the resource potential alone.

Similarly, electrolysers are being developed by manufacturers in a range of standardised unit sizes and specifications. Relatively small units and potentially clusters of such unts will be ideal for configuration to suit specific local applications of modest scale.

There is, however, a more fundamental split in how units can be 'packaged' – with units rated in the low MW range typically being packaged into shipping containers or equivalent (such as those in Orkney on Eday and Shapinsay), and units rated in the GW range being installed instead into bespoke buildings (which along with other cost drivers enables significant economies of scale). These much larger installations will be ideal for configuration to suit more centralised electrolysis facilities, often serving a wider part of the energy system over a larger area; One such installation is under consideration at Flotta on Orkney.

When considering a combined deployment of tidal generation and electrolysis technologies, however, the generation and electrolysis may be modularised, it is also possible to deploy capacity in defined modules of each technology. In addition to optimising manufacturing costs, this enables the ratio of tidal electricity generation and hydrogen production to be optimised to suit the specific application, energy system and particular commercial circumstances. Similarly, as mentioned above, the capacity of hydrogen storage can be optimised relative to electricity generation and hydrogen production capacities dependent on the area and application.

Some of these issues have been studied during the ITEG project, with several deliverables exploring different potential objectives (such as prioritisation to maximise hydrogen production, or avoid turbine curtailment, or manage with various network constraints, or achieve optimum revenue dependent on relative market prices for hydrogen and electricity and dependent on ownership of each asset, etc). Each of these (and others) may lead to different solution configurations.

One key consideration can be the range over which the electrolysers operate most efficiently, and the minimum turn-down rating, as maintaining operation in the optimum zone will improve operating efficiency and avoid the need to switch off and then restart the electrolyser later, which can be a time-consuming and expensive procedure. This can drive selection of both the total electrolysis power rating and the ratings of individual electrolyser units (e.g. switching off some modules in order to retain others at peak operating point).

Similarly, it will often be desirable to ensure that the electrolysis is driven solely or predominantly from local green (renewable / zero carbon) electricity. In order to achieve this, the ratio of green electricity supply (tidal and other generation or infeed) and electrolysis capacities has to be studied carefully, along with the availability of other network flexibility provision (such as battery storage, demand-side management systems, etc).

Finally, the location of the electrolysis can be critical. Deliverable LT.4.1 explores this in detail on Orkney, setting out the case both for small/medium co-located units (such as that at Eday), and for larger installations of generation and electrolysis located in different places (such as the proposed electrolysis installation at Flotta).

That report is accompanied by Deliverable LT.4.3 “Hydrogen Handling and Logistics” which sets out some of the practical considerations for transporting hydrogen, particularly in an archipelago or other remote setting. These considerations in many cases will lead to the optimum location being as close as possible, not to the electricity generation, but to the hydrogen demand – as this enables the electricity to be moved instead of the hydrogen. Our studies have shown that even with significant electricity system constraints, this is often a more cost-effective whole-system solution, and that other changes in the energy system such as domestic heating electrification can provide a means to overcome a significant degree of network constraints.

Large installations are more likely to be managed as an entire tidal array and a separate large electrolysis plant and may have different but complementary system and commercial objectives.

4 UK and European Contexts

4.1 UK National

4.1.1 National Scenarios

To study the energy system of the Orkneys in a relatively high level of detail for the ITEG project Energy Systems Catapult's (ESC) detailed 'EnergyPath Networks' (EPN) model was appropriate. That model was used for long-term energy system modelling within ITEG. ESC also has a UK national model, ESME (Energy Systems Modelling Environment) which covers the whole of the UK energy system but in much less spatial detail. ESME cannot give any indication of the most promising locations for tidal generation, or electrolysis units, or the combined package. However, it does give some indication as to the likely role and extent of tidal stream and electrolysis technologies in a future net-zero UK energy system optimised for cost.

The numbers below are drawn from ESC's report 'Innovating to Net-Zero' and are for the year 2050[5]. In that report two alternative scenarios are examined: Clockwork and Patchwork. In Clockwork, coordination from central Government drives long term investment in strategic energy infrastructure. In Patchwork, central Government takes less of a leading role, resulting in a patchwork of regional low carbon strategies. There are other more detailed differences consistent with those two paradigms (as detailed in the 'Innovating to Net-Zero' report).

4.1.2 Role of Tidal Stream Generation

Electrification of heating, transport and industry lead to greatly increased demand for electricity in both scenarios: 524 TWh/year in Clockwork and 700 TWh/year in Patchwork (up from 300TWh in 2015). In both scenarios very significant deployment of nuclear plant and offshore wind are required to meet these levels of demand, but other renewable technologies play their part too. The ESME model finds that it is economic to deploy around 2GW of tidal stream generation in the Clockwork scenario. In the Patchwork scenario the model deploys all the tidal stream generation that is available to it, a much more challenging 16 GW, and might have deployed more if it were available.

4.1.3 Role of Electrolysis

Hydrogen plays a significant role in both scenarios with 250 TWh/year being consumed by 2050 in Clockwork and 185 TWh/year in Patchwork. Hydrogen is used to decarbonise industry, space heating and heavy-duty transport and also to provide carbon-free flexible power generation to help meet peak demands in the year.

In Clockwork it is assumed that carbon capture and storage (CCS) facilities are available with the capture technology achieving 99% capture rate. It is also assumed that direct air carbon capture (DACC) technologies are available to deploy. Use of these technologies allows hydrogen to be produced by steam reformation with CCS and biomass gasification. These technologies are favoured over electrolysis in this scenario, due to the configuration of the whole energy system and consequent whole-system costs (rather than being due to the respective technology costs for the electrolysis and SMR themselves).

The situation changes in the Patchwork scenario. In this case CCS plant is assumed to achieve only a 95% capture rate and DACC is not available. In the Patchwork scenario the model chooses to produce the majority of hydrogen by electrolysis, a total of 110 TWh/year.

4.2 European

A 2015 report[6] on scenarios implemented in the JCR-EU-TIMES model also found a significant role for hydrogen produced by electrolysis using power from renewable sources. The JCR-EU-TIMES model operates in a similar fashion to ESC's ESME model. The model covered what was then the EU28 countries plus Switzerland, Iceland and Norway under two different scenarios reflecting different levels of carbon reduction ambition. In the less onerous scenario, inflow to electrolysers in 2050 was estimated at 50 TWh/year, and in the more ambitious scenario at 200 TWh/year.

Electrolysers were found to play a role in managing the intermittency of renewable power generation to maintain the reliability of the electricity system. The hydrogen produced was found to be used in sectors with limited low-carbon alternatives, notably transport and industry.

The report does not comment on the role of tidal stream generation.

Similarly, the hydrogen strategy published by the European Commission in 2020[7] sees a major role for hydrogen and explicitly for hydrogen produced by electrolysis. This report sets a target for deployment of 40 GW of renewably powered hydrogen electrolysers by 2030. It sees the development of hydrogen valleys as part of the pathway to achieving this vision.

5 Criteria for Evaluation of Potential Locations

This study sets out to evaluate the potential for a combined package of tidal stream generation and electrolysis in the same local area. It is not evaluating the potential for either technology on its own. Both technologies clearly need to be feasible at a location, but there also needs to be a real benefit to the energy system from the combination. This benefit is most likely to come from avoiding curtailment of generation when the excess over local demand exceeds the capability of the electrical network to export it.

With this in mind, the following criteria were considered when evaluating the suitability of locations for the ITEG solution of tidal stream generation coupled with electrolysis on the same site, or nearby:

1. Clearly there must be a tidal stream resource offshore;
2. There should be a potential hydrogen demand locally. This could be in industries with processes currently using fossil fuels for which options to convert to electricity are either unavailable or uneconomic, or some other hydrogen demand (such as transport fuelling or space heating), or a hydrogen export facility;
3. There should be constraints on the export of electrical power from the area so that, all other things being equal, new tidal generation is likely to be curtailed at times. This is not an essential criterion for either tidal generation or electrolysis to be able to provide benefit to the energy system; however, it can be a key constraint on renewable deployment and consequently the presence of such constraints is indicative of a high likelihood that the combination of ITEG technologies may provide strong additional value to the plant operators and to the whole system.

The first of these criteria is clearly necessary in order to deploy a tidal stream turbine or array. The other two criteria are not necessary for there to be a sound business case but, if met, mean that the combination of ITEG technologies offers additional benefits over and above separate deployment of tidal generation at one site and an electrolyser at another site possibly in another part of the country. This report is concerned primarily with the case for the packaged solution, not with the case for each of the two technologies separately.

If there is very little local hydrogen demand our modelling suggests that it may be more economic to export excess energy as electricity and place the electrolyser nearer centres of hydrogen demand even if that requires some upgrade to the electrical network. The decision reduces simply to the value or otherwise of tidal stream generation in that location.

If there is no constraint on export of electrical power, then the coupled tidal generator and electrolyser solution no longer has the additional benefit of increasing utilisation of the generator (even if the hydrogen is useful locally to decarbonise demand). The investment might still be sound but deployment of the tidal generator and of the electrolyser should be treated as two separate decisions.

The modelling of the Orkney energy system which ESC undertook and which is reported in Deliverable LT.4.2 supports the use of these criteria. When the model was given freedom to site electrolysers wherever it chose it tended to choose sites close to the demand for hydrogen rather than close to the source of generation. These sites were, perforce, still on Orkney and local power distribution was found to have the capacity to support this[1]. Taken at a larger scale, deployment of both electrolysers and tidal generation on Orkney did help to overcome limited capacity to export power to mainland Scotland.

In practice, data which would allow evaluation against criteria two and three and which was readily available was found to be scarce. It is hoped that the evaluations offered are, nonetheless, useful in themselves and as an illustration of the potential scale of the opportunity as well as providing a possible evaluation process.

[1] This modelling considered a future, decarbonised Orkney energy system. In this system significant electrification of building heat increases local demand for local renewable generation and so frees up parts of the network which are currently export constrained.

6 Tidal Resources

6.1 Location

North-West Europe has an estimated 150TWh/year of tidal energy resource[8] of which the great majority is in UK or French waters. Ireland and the Netherlands have lesser but significant resources and there are a few other areas with much lower tidal energy. In 2020 there was reported to be 25MW[9] of tidal stream generating capacity in Europe producing close to 12 GWh[10] annually.

Sites for possible tidal stream arrays in north-western Europe have been identified from literature and are shown in the Figure 1.

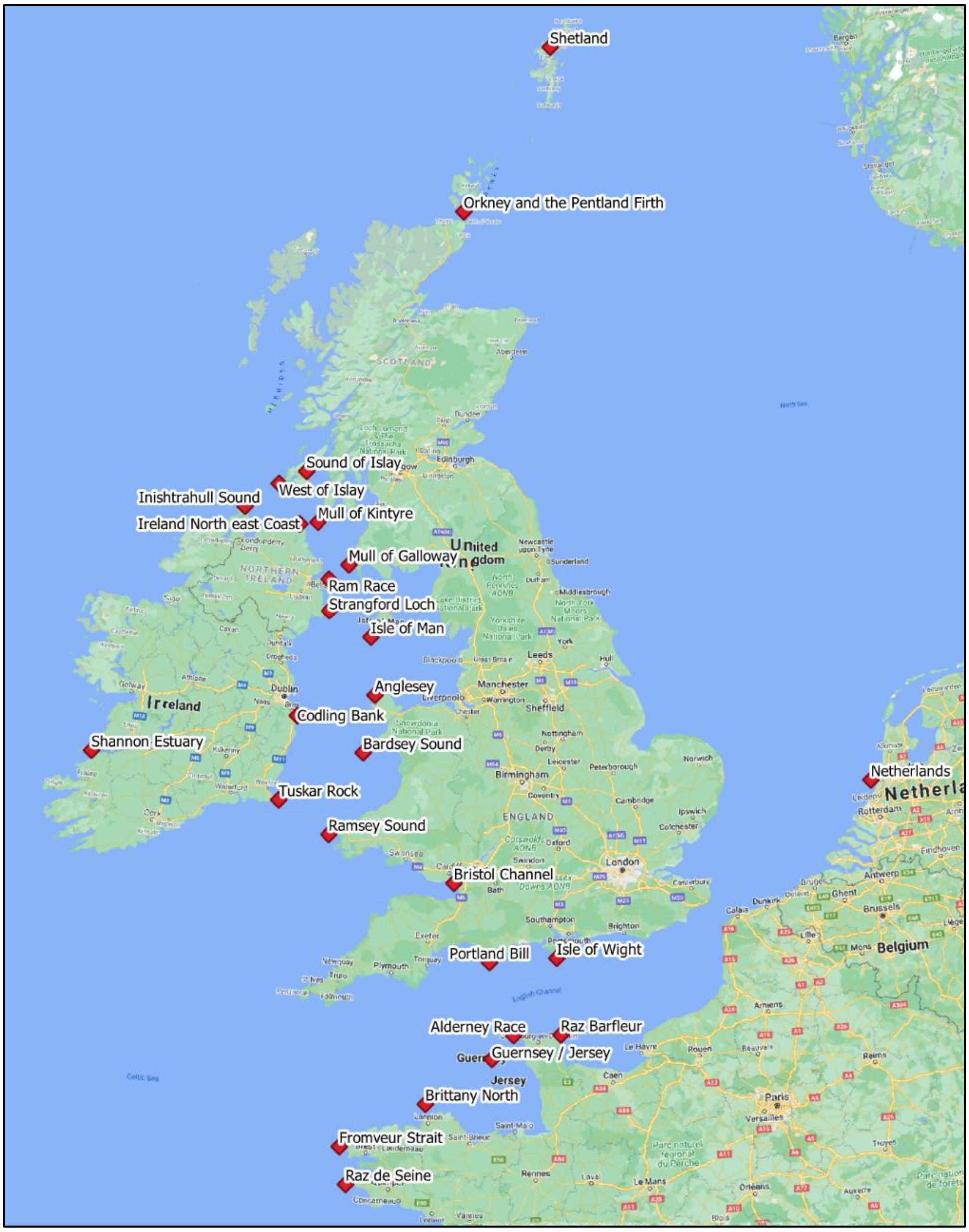

Figure 1 - Tidal stream resources

6.2 Potential Power

Table 1 gives estimates of the potential power accessible at each site on the map above (Figure 1).

Table 1 - Potential power of tidal stream sites

Site	Potential power
Netherlands	100 MW
Raz de Sein, Brittany	266 MW
Fromveur strait, Brittany	282 MW
Raz Barfleur, Normandy	1057 MW
Brittany North (Paimpol-Bréhat)	246 MW
The Alderney Race	608 MW
Guernsey and Jersey	1589 MW
Isle of Wight	120 MW
Portland Bill	12 MW
Bristol Channel	265 MW
Ramsey Sound	204 MW
Bardsey Sound	9 MW
Anglesey (Carmel Head)	519 MW
Mull of Galloway	84 MW
Mull of Kintyre	120 MW
Sound of Islay and West of Islay	591 MW
Strangford Lough	76 MW
Ram Race	15 MW
Codling banks	8 MW
Tuskar Rock	20 MW
SW Ireland	40 MW
Ireland North East Coast	80 MW
Orkney and the Pentland Firth	3,850 MW
Shetland Isles	18 MW
Faroe Isles	200 MW [11]

For the UK sites the potential average power is estimated from the high estimate (as opposed to base and low estimates) of practical annual energy potential in the Carbon Trust report (Carbon

Trust, 2011 [12].) A load factor of 38% is used to convert from annual energy to average power; that load factor was taken from ESC's national modelling assumptions. This estimate is also used in ESC's national modelling using ESME for a net zero UK energy system; more details of this modelling are given in Section 5.

A more recent estimate of the practical UK tidal stream resource made by Coles et al.[13] gave a total of 11.5 GW, 30% less than the 16 GW in the Carbon Trust 2011 report. That is more in line with the base estimate in the Carbon Trust report and may therefore represent a less optimistic estimate. The precise numbers are not crucial to what follows here and the higher numbers were chosen as they are consistent with assumptions in other ESC UK national modelling [14].

The estimates for French sites were taken from a 2021 report under the EU funded ELEMENT project[15]. The estimates for the Irish sites were taken from a 2007 SEAI report[16] and that for the Netherlands from a 2021 report by DNV[17]. According to DNV, suitable locations for tidal stream technologies in the Netherlands are the Oosterscheldekering, the drainage shafts of the Afsluitdijk, the Westerschelde, and the Waddenzee.

The Raz Barfleur is on the opposite side of the Cotentin peninsula to the Alderney Race so transmission connections and opportunities for supplying hydrogen locally will be much the same at both locations. This site is not considered separately in the rest of this report.

7 Electrical network

7.1 Criterion

Part of the rationale for the ITEG combination of tidal turbine and electrolyser is to increase the utilisation of the turbine, or array of turbines, where electrical network constraints would otherwise curtail output. At those times excess electrical power can be fed to the nearby electrolyser. For that reason, one of the criteria suggested above for evaluation of suitable sites is the strength of the electrical connection with the rest of the grid.

7.2 Analysis of Transmission Networks

Detailed information on power flows was not readily available, nor information which would enable them to be estimated even crudely. However, information is available on the routing of transmission lines[18]. Figure 2 shows the total length of transmission lines per 20km polygon; areas with greater density of transmission lines are darker red, those with no transmission lines are white. Tidal sites identified in section 2 are located at red diamonds.

A number of sites have no transmission lines nearby, or very few, and will be considered further as those most likely to have limited electrical connection options. All the sites in Western Ireland, France and Netherlands have transmission lines near likely sites for landfall of cables from tidal stream turbines. That does not guarantee that additional generation could be connected and exported; further investigation would be required to ascertain that.

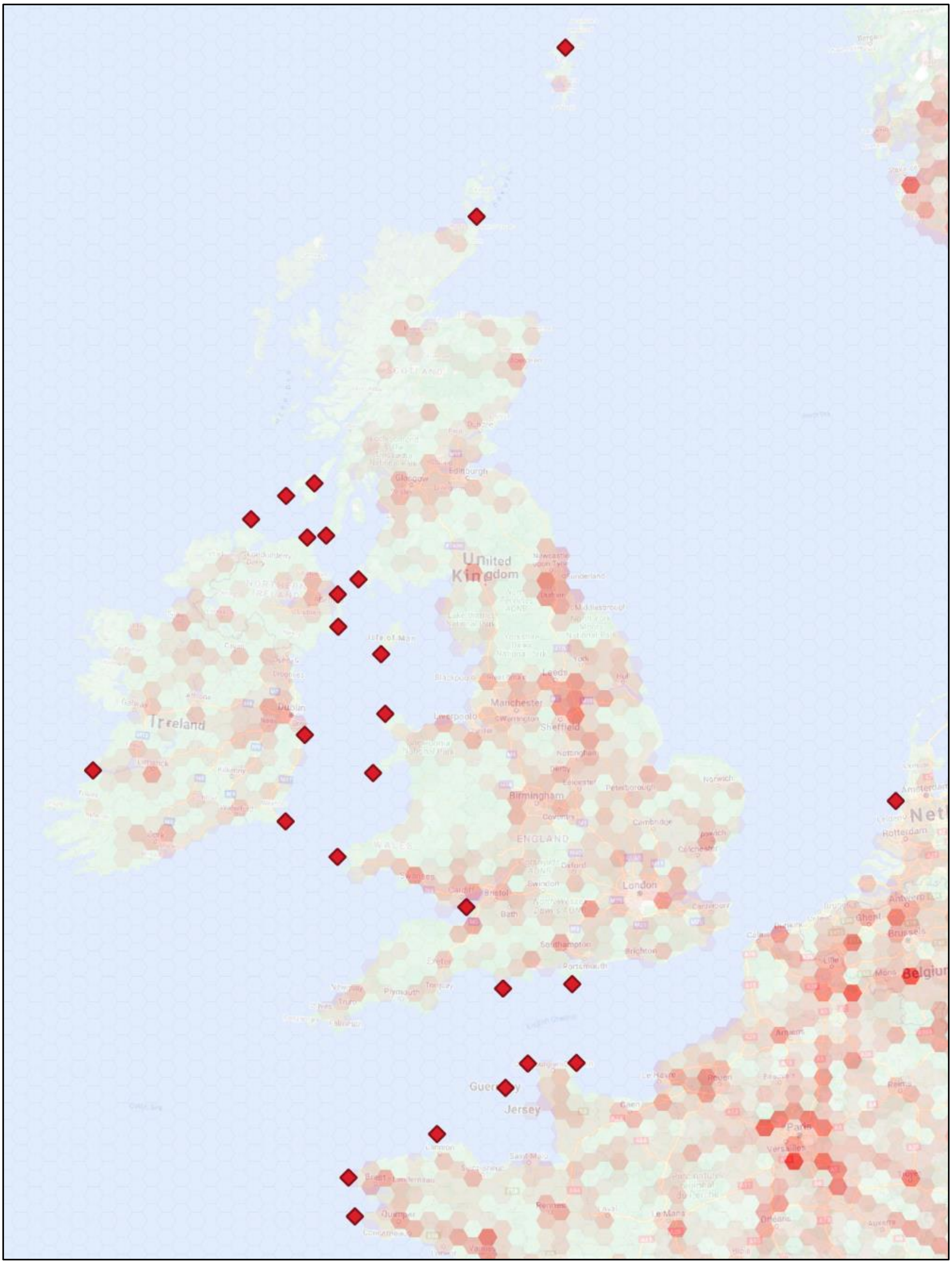

Figure 2 - Electrical Transmission Density (darker red = more dense, with tidal stream sites in red diamonds)

7.3 Network Notes on Selected Areas

7.3.1 Alderney Race and The Channel Islands

The Cotentin peninsula in France has a strong transmission network but has the Flamanville nuclear power station at one end of it. Once that is fully operational it may be that the network is fully loaded and the 2019 French Transmission Plan[19] does show a potential constraint on lines from this area towards Paris if investment is not made. However, a new interconnector between GB and France is planned to link Alderney to both systems and would provide ample export capacity for tidal schemes in the area. This project is currently awaiting regulatory approvals.

Guernsey and Jersey are well connected to the French grid and import the vast majority of their power so tidal generation schemes there would, in the first place, reduce imports and not be at risk of curtailment for power network reasons[20].

7.3.2 Brittany

Power flows are predominantly into Brittany[21], not out of it, so additional generation there will offset those inflows. The French Transmission Development Plan of 2019 does not show any constraints on flows into or out of Brittany. Any new tidal stream schemes connecting into that part of the network should therefore not face curtailment due to transmission level constraints. It is, of course, still possible that more local issues arise on lower voltage parts of the network.

7.3.3 Netherlands

The transmission system owner in The Netherlands, Tennet, are building a high voltage offshore grid to facilitate connection of renewable generation. They say this is likely to be completed in 2023[22]. From the map shown on their website it appears this may benefit connection of any tidal stream generation in the western part of the country [23].

Elsewhere there are some indications of network capacity constraints becoming evident and preventing connection of new projects, especially in the northern part of the country [24]. It is not clear how this may impact on connection of tidal stream generation.

7.3.4 Shetland, Orkney and Pentland Firth

At present Shetland is not connected to the GB transmission network but a project is underway to install a 260km, 600MW HVDC link directly from Shetland to Noss Head in Caithness, Scotland. This will allow export of additional renewable generation from Shetland.

As is well documented in Deliverable LT.4.2, the current connection between Orkney and mainland Scotland does not have capacity for any significant additional export of power from the islands, and existing generation is often curtailed because of network constraints. An upgrade is proposed but not agreed.

There is a further potential network limitation on development of renewable generation in this area. The lines connecting this Northern part of Scotland, north of Beauly, to southern Scotland and England and Wales can currently cope with exports of up to 1.15GW[25]. Investment proposals quoted in the Ten Year Statement would alleviate this constraint to a degree. Deployment of electrolysers in this area and development of a hydrogen economy might allow a reduced level of investment in the transmission network and give a net cost saving for the UK energy system.

7.3.5 Islay and Mull of Kintyre

According to Coles et al[26] the capacity of the transmission network to export power from an area including the tidal stream sites around Islay and the Mull of Kintyre is limited to 0.43 GW. The tidal generation capacity noted above is 0.71 GW so full exploitation of this resource could result in some curtailment due to transmission restrictions. This constraint does not feature in the Electricity Ten Year Statement; However, the Scottish Government's hydrogen policy statement notes the Western Isles as the weakest part of the Scottish electricity transmission network [27].

7.3.6 Isle of Man

Although no transmission network showed up on the data used for the map above, there is in fact a 65MW AC link between Manx Utilities network and the UK National Grid. Excess power from the Manx system is exported to the UK. Generation on the island is from a mixture of gas-fired CCGT and renewables. Additional renewable generation in the form of tidal stream turbines could, therefore, firstly displace gas and any excess be exported to the UK up to the capacity of the existing link.[28]

7.3.7 Isle of Wight

There may be features of the lower voltage electrical network which limit the capacity of tidal schemes to export their generation. According to a 2011 report for the Isle of Wight Council such limitations applied at the time there and major reinforcement work would be required to accommodate the full 100MW capacity of a tidal stream generator that was proposed. It is not known whether that is still the case.[29]

7.3.8 Faroe Islands

The Faroe Islands are not connected to any other electrical network so must supply all their own power[30]. Their maximum demand is around 60MW and currently 50-60% of their electricity is generated from renewable sources. Adding hydrogen to the energy system may allow them to increase this further. To do so would probably require adoption of hydrogen-fuelled marine vessels as this makes up much of their industry[31].

7.4 Conclusions on applying the Transmission Criterion

The sites which appear most promising for the ITEG combined package on this very approximate test are as follows, with tidal resource shown in brackets:

- Around Islay and the Mull of Kintyre (711 MW)
- Anglesey (519 MW)
- Ramsey Sound (204 MW)
- Mull of Galloway (84 MW)
- Bardsey Sound (9 MW)
- Strangford Lough (76 MW)
- NE coast of Ireland (80 MW)
- Orkneys and Pentland Firth (3850 MW)
- Faroes (200 MW)
- Isle of Wight (120 MW).

It should be noted that, on the western side of the Irish Sea there are sites, notably Ram Race, Tuskar Rock and Carnsore Point, where there are both significant tidal stream potential and local transmission lines. A tidal generation developer might find it more economic to develop one of those sites rather than deploy a turbine and electrolyser package at one of the Irish sea sites listed above.

8 Potential Hydrogen Demand

8.1 Sites with High Carbon Dioxide Emissions

One way of locating potential sources of hydrogen demand is to find existing sites with high emissions of carbon dioxide as this will usually be from combustion of fossil fuels. Not every case will be suitable for switching to hydrogen but it provides a starting point for further investigation. Data was used from the European Pollutant Release Register[32] which identifies point sources of emissions. Those which are within 30km of a tidal resource are shown on the map below as orange dots. Potential tidal stream generation sites are shown as red diamonds as in the maps above.

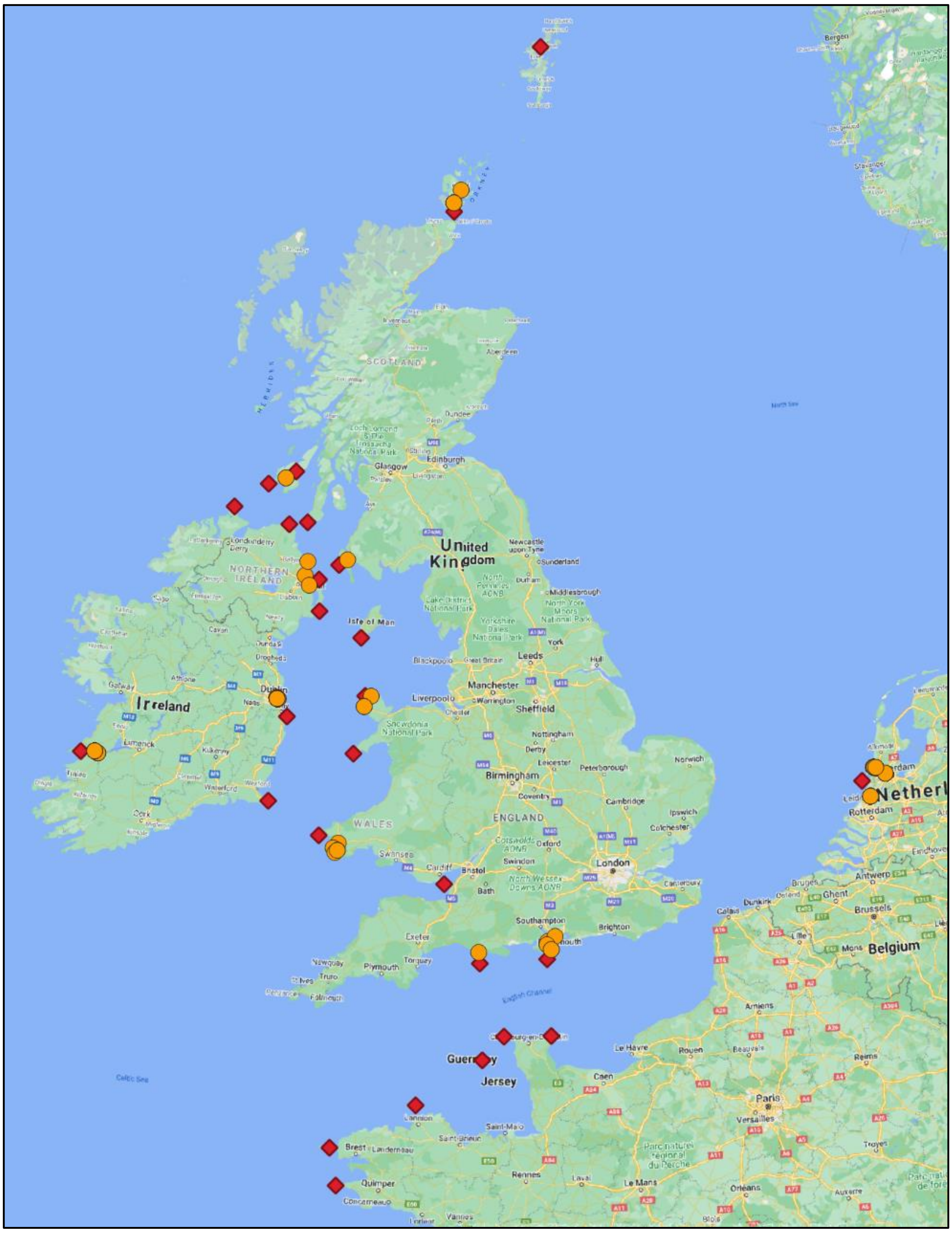

Figure 3 - Sites with High Carbon Emissions (orange circles), with tidal sites (red diamonds)

8.2 UK Industrial Fuel Switching

In the UK a number of areas in which there are industrial demands which may be suitable for switching to hydrogen were identified in a report for BEIS on industrial fuel switching [33]. Those which coincide with tidal stream resources are:

- Pembroke and Ramsey Sound (mostly from the power and gas sector but some food processing too according to the UK National Atmospheric Emissions Inventory (NAEI)[34])
- Stranraer and the Mull of Galloway (the point source emission is from a cheese maker[35])
- Belfast area of Ireland and Ram Race and Copeland Island tidal resource.

Of these only the second, Stranraer, is in an area with relatively weak transmission links.

8.3 Netherlands and 'Hydrogen Valleys'

Although not a good candidate for the combined electrolyser and tidal stream turbine package because of the relatively good transmission connections, The Netherlands are worth further discussion. The point sources in The Netherlands are all in the Rotterdam / Amsterdam area. This area is well connected to the rest of the electricity transmission grid and, furthermore, contains two of the connection points for the offshore grid which is being developed so electrification of processes or heating is unlikely to be prevented by electricity supply constraints.

However, there is a project currently running, HEAVENN[36] ("H_2 Energy Applications in Valley Environments for Northern Netherlands"), which will develop a "Hydrogen Valley" in northern Netherlands, reckoned to be the first in Europe. This aims to harness wind power but one of the areas of tidal stream resource, in the Ems estuary, is in the vicinity. The project aims to facilitate a local hydrogen economy comprising renewable electricity generation, electrolysis, hydrogen storage and hydrogen use in industry, heating and transport.

So called 'Hydrogen Valleys' like this are part of the Dutch and EU strategy for development of a hydrogen[37] economy and the Dutch government has an ambition to see 3-4GW of electrolysis deployed by 2030[38]. Hydrogen valleys are candidates for the ITEG solution if there are tidal stream resources nearby, whether or not electrical transmission links are strong. The HEAVENN project website lists a number of 'follower territories' for future roll-out of this model for development of a hydrogen economy; Ireland is one of these. With the wealth of tidal stream resources around its coast, Ireland could be a good candidate for a 'hydrogen valley' with tidal stream powered electrolysis.

8.4 Scottish Hydrogen Strategy

In their statement of hydrogen policy[39] in December 2020 the Scottish Government set out a vision to utilise Scotland's abundant renewable resources and energy engineering capabilities to become both a significant user and also an exporter of hydrogen. They set an initial ambition to see 5GW of renewable and low-carbon fuelled hydrogen production in Scotland by 2030 and to become the lowest cost producer of hydrogen in Europe by 2045.

Part of the mechanism envisaged for facilitating this transformation is the development of 'Hydrogen Hubs', similar to the EU concept of 'Hydrogen Valleys'. Such a hub is already being developed in Aberdeen with support from a variety of Interreg projects (Smart-Hy-Aware, HyTrEc2, Hector, FCCP [40]) and direct funding from the Scottish Government. The policy statement supports the establishment of hydrogen hubs within island communities.

Further north, but still on the East Coast, the partners of the North Scotland Hydrogen Programme are planning another hydrogen hub based around the Cromarty Firth. This is envisaged to include facility for refuelling international shipping burning hydrogen fuel. It also envisages a future space port.[41]

Other potential locations for hydrogen hubs identified in the draft hydrogen action plan[42] include the Argyll Islands, which include Islay where there is tidal resource. Shetland and Orkney are also identified as potential locations for hydrogen hubs.

8.5 French Hydrogen Strategy

The French hydrogen strategy, as set out in 2020, is to facilitate the deployment of 6.5 GW of electrolysers by 2030 powered by a mix of nuclear and renewable electricity; decarbonised hydrogen rather than renewable hydrogen [43] [44]. Priorities for the use of the hydrogen are decarbonisation of hydrogen already used in industry and heavy-duty transport. This will be encouraged by the creation of regional hydrogen hubs. Brittany has ambitions to become one of those regional hubs [45]. If this ambition is realised, then there may be scope for tidal generation and electrolysers both to be deployed in the region but the evidence found here suggests sites for each are better chosen independently and the power transmitted between them. The tidal power might be competing with nuclear power from elsewhere in the country.

8.6 Examination of Identified Sites

In this section each of the potential tidal sites with point source emissions of carbon identified in the vicinity are examined briefly, together with any other sites with tidal resource which appear to offer possibilities.

8.6.1 Isle of Wight

The major point sources on the Isle of Wight are from heat and power generation sites and a hospital, which may also be a local combined heat and power unit. There may be opportunity to convert these to a hydrogen fuel cell or other hydrogen fuelled solutions.

8.6.2 Portland Bill

The major point source is a power producer, a 45MW gas-fired embedded power station at Chickerell[46]. This is not a good candidate for converting to hydrogen. Unless there is a strong local network constraint a hydrogen fired power turbine could be located anywhere in the country if it is needed as part of decarbonisation of the electricity supply system.

8.6.3 Ramsey Sound

The point sources here are from gas and oil processing and Pembroke power station. This is not likely to be a good candidate for switching to hydrogen.

8.6.4 Anglesey

The historic point source here is from Wylfa power station and was only 24.5 tonnes of carbon per year. This is not a candidate for switching to hydrogen.

8.6.5 Mull of Galloway

There are sites at Stranraer and Girvan, both in the food and drink industry (information from the UK National Atmospheric Emissions Inventory) with combined emissions of 4,500 tonnes of carbon per year. If this is from burning gas then that indicates a thermal capacity of 10-20MW depending on the load factor. There may be scope for switching to hydrogen here.

8.6.6 Islay

The point source here is labelled as a power producer in the NAEI but is at the site of a whisky distillery so is probably a CHP plant. Emissions recorded in the NAEI are only 90 tonnes of carbon per year so the plant will be small, less than 1MW thermal capacity. The NAEI shows very low levels of carbon emissions from the rest of the island of Islay and from neighbouring Jura. There may, therefore, be some small opportunity for fuel switching to hydrogen locally.

However, the Bruichladdich Distillery is aiming to achieve net zero carbon emissions by 2025 and has recently won funding to install a hydrogen boiler [47].

8.6.7 Ram Race and Copeland Island

There are many sources of carbon emissions a little way inland from this potential tidal stream generation site in and around Belfast, but the electricity transmission and distribution network is likely to be adequate to allow switching to electrical solutions. The analysis above of transmission network density supports this finding.

8.6.8 Codling Bank and Shannon Estuary

More details about sites with high carbon emissions in Ireland were not found to be readily available. However, the sites near the Codling Bank site are in the Dublin area so there is likely to be lots of industry there but also strong electrical networks. A map of the Irish electricity network from EirGrid[48] shows a thermal power station at the location of the point emission source near the Shannon Estuary and strong transmission links in the area.

8.6.9 Orkney and Pentland Firth

As hydrogen hubs develop in northern Scotland there may be scope for tidal generation from the Pentland Firth to power electrolysers producing hydrogen for those hubs. However, as has already been noted, the detailed modelling for Orkney already reported within ITEG found that it was more beneficial to site electrolysers close to the hydrogen demands and transport power to them than to site them close to the tidal generation and transport the hydrogen. It is highly likely that the same will be true for the north Scotland region, north of the electricity transmission congestion point at Beauly.

9 Conclusions

Important Roles for Tidal Generation and for Electrolysis

Both tidal stream generation and electrolyser technologies separately have important and sizeable roles to play in a North-West European net zero carbon energy system. Whole system models seeking to minimise the total energy system cost consistently find both technologies attractive.

Potential for 'Premium' Value

Tidal stream generation technology can, by its nature, be deployed only where there are suitable and accessible tidal currents. Electrolysers can be deployed anywhere, and in most of the areas considered for this report the electricity transmission network is likely to be adequate to transport power to those electrolysers. Modelling carried out by ESC within the ITEG project showed that, within the Orkney energy system, larger scale electrolysis is better sited close to the hydrogen demand it is serving.

The ITEG concept was originally to co-locate electrolyser and tidal generation to minimise the load on the electricity network. Based on the analysis of opportunities for European roll-out above, co-locating on the same site or within very close proximity to each other, there are relatively few sites where this package would offer additional value from the combined package (compared to the value from separate deployment). Decisions to deploy the two technologies are therefore best made independently, as far as location is concerned. It should be noted, however, that in this roll-out analysis the electrical network was only examined at the transmission level; there may still be capacity limits on lower voltage parts of the network which mean co-location is of benefit at other sites not identified in the current analysis.

The 'sweet-spot' locations which best appear to meet the criteria used here for selecting sites are those at which the packaged/combined ITEG solution of tidal generation plus electrolyser (or scaled-up tidal array and electrolysis plant located nearby) are deemed most likely to offer some additional 'premium' value by helping to overcome network constraints, enabling greater deployment and utilisation of the technologies.

It is important to note that the sweet-spot locations identified and filtered by the use of these criteria are by no means the only suitable locations for deployment of either tidal generation or electrolysis; (The tidal stream capacity in the UK alone is estimated at 10-15GW). Rather, they are the locations offering 'premium' value return on the investment. They could therefore be regarded as potential high value locations for early deployment of the combined solution, especially before anticipated (volume-related) capital cost reductions have been achieved. It is therefore recommended that full feasibility studies should be conducted for these areas as an early priority.

Potential High Value, Sweet-Spot Locations Identified

The sweet-spot locations discussed above are shown in Figure 4 and itemised below it.

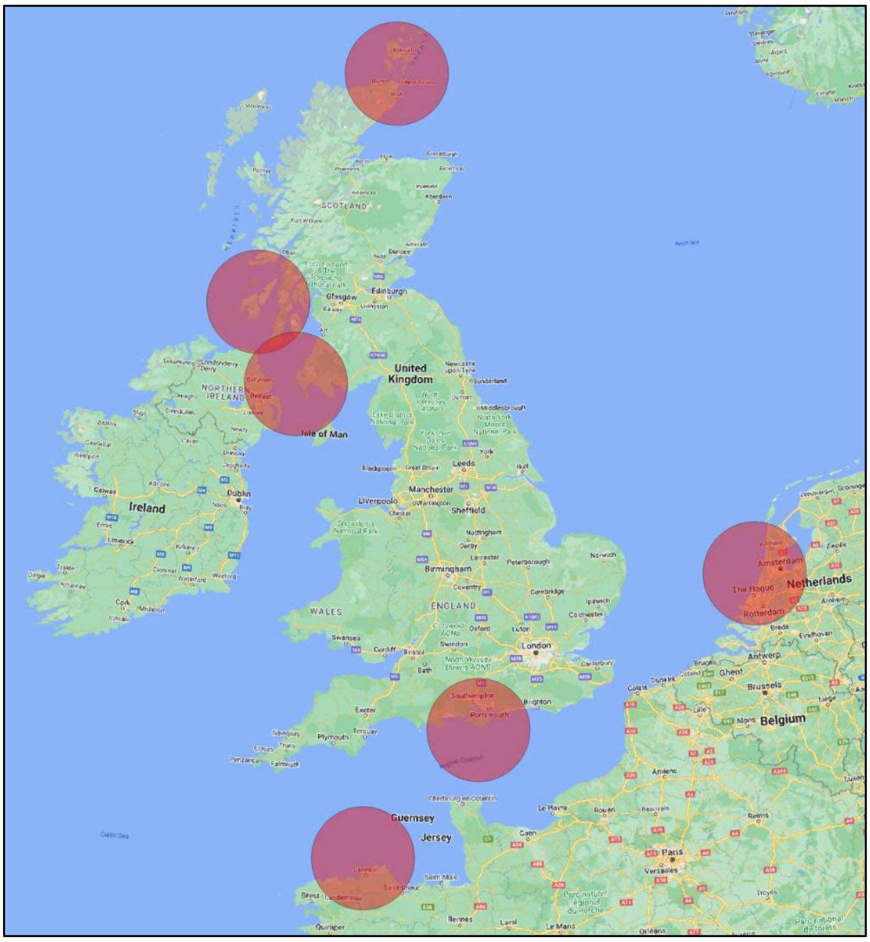

Figure 4 – Potential High Value, Sweet Spot Locations for Combined Deployment of Tidal Generation with Electrolysis

Firstly, the analysis carried out has identified the following potential high value, sweet-spot locations for co-located packages of a tidal generator and an electrolyser (or scaled up tidal array and electrolysis plant but remaining co-located):

- around Islay and the Mull of Galloway off the western coast of Scotland;
- the Isle of Wight if local network constraints continue to present a capacity constraint; and
- the Faroe Islands (not shown in the figure).

Between them the potential tidal resource in those areas totals around 1 GW.

Secondly, the analysis has further identified the following potential high value, sweet spot locations for installations with electrolysis located elsewhere within the local energy system close to the hydrogen demand:

- The Orkneys as a whole is one of those; the presence of electrolysers and a developing hydrogen economy allowing a greater capacity of tidal stream and other renewable generation to be connected than would otherwise be the case because of the limited capacity of the link to mainland Scotland.

- The north of Scotland is another such region with abundant tidal stream resource in the Pentland Firth and a constraint on transmission of electricity south of Beauly.
- Brittany might be another such region if a regional hydrogen hub develops there.
- The hydrogen hub being developed in the Netherlands under the HEAVENN project might be another.

Adding these additional locations brings the total to around **6 GW** of tidal stream capacity.

The likely hydrogen demand has not been quantified, and the findings are subject to a requirement for detailed feasibility studies for each site.

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