Alternative tidal stream offtake routes

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Acronyms

Acronym	Description
AR	Allocation Round (with reference to Contracts for Difference)
CES	Crown Estate Scotland
CfD	Contracts for Difference
DAC	Direct air capture
ESO	Electricity system operator
FiT	Feed-in tariff
HND	Holistic network design
OSW	Offshore wind
PPA	Power purchase agreement
SSEN	Scottish and Southern Electricity Networks
TEC	Tidal energy converters
TNUoS	Transmission network use of system
TRL	Technology readiness level

Executive Summary

Tidal stream energy offers both energy security and resilience. Viable tidal stream energy resources are often situated around remote locations that typically have limited and frequently disrupted National Grid connections, resulting in heavy reliance on diesel generation. This constraint on the availability of electricity has a further impact on local industries by increasing costs and restricting growth. The predictability of tidal stream energy can provide a solution for these communities that other intermittent renewable sources cannot.

Tidal stream technology is now at an early commercial stage but requires commitment from Government if the UK is going to retain its world leading status and maximise UK supply chain content (which has the potential to be greater than 80%) and UK exports of technology and expertise to world markets.

Barriers to deployment include:

- Reliance on revenue support, in particular the relatively small size of the ringfence for tidal in the UK Government's Contracts for Difference auction (£10m in 2024's Allocation Round 6).
- The lack of availability of electricity grid connection capacity in remote locations with good tidal resource.
- The significant time and financial commitment required of (typically small) tidal development companies for the Section 36 planning process for projects of 1 MW+.

Renewable energy projects require an offtake agreement in order to secure finance. Until now, tidal stream generation projects have been small in generation capacity and have focussed on the National Grid as the offtake party when required. An alternative offtake model involves securing different electricity buyers, through direct arrangements such as power purchase agreements, providing a mutually beneficial arrangement for both the energy generators and the local end users by removing the dependence on the National Grid.

This project focused on how implementing an alternative offtake model affects the first two of these barriers to deployment of tidal stream energy generation. It also considered whether that model could contribute to enabling tidal stream projects to achieve industry ambitions of 700MW of installed generating capacity by 2035 with the correct support in place.

Thirty locations of tidal stream resource around Scotland were identified, with 20 offtake industries close enough to be potential end users, the most common being maritime, crofting and farming, tourism, aquaculture, aviation and distilleries. A stakeholder engagement exercise involving generators, local authorities, community groups and local industry representatives was then conducted to understand the opportunities and barriers currently perceived with tidal stream generation and the alternative offtake model. Main opportunities identified were tidal stream being a renewable energy that offered predictability, reduced reliance on National Grid subsea cables and the local employment and community benefits. Main barriers included cost of technology and cables, the risk of new technology reliability, and the financial exposure of being reliant on a single customer for the generator and a single supplier for the offtake party.

The most promising alternative offtake opportunities were then further evaluated to understand the economic viability, the scale of the opportunity and the ability to match supply and demand. Replacement of fossil fuel generators are considered to be financially viable now, although a detailed analysis of local tidal resources is needed to confirm that many of the smaller sites are suitable for tidal stream generation. Potential hydrogen offtake applications for local industry offer a greater impact on deployment targets, although opportunities are limited in tidal areas outwith the distillery industry.

The greatest opportunity identified for the alternative offtake model is the production of synthetic fuels from green hydrogen. Synthetic fuels as an industry is still in the technology demonstration phase, with a technology readiness level (TRL) 6-8 (Ellis et al., 2024), but offers the most feasible opportunity for decarbonising key Scottish industries such as farming and fishing as well as aviation. The dependency of this offtake route on the availability of plentiful, green electricity (for the various chemical processes including electrolysis and CO_2 capture from either air or sea water), its requirement for fuel storage and workforce skills transferrable from oil and gas, make Scotland ideal for establishing this new industry. The industrial scale of this offtake would provide a meaningful route to achieving tidal stream generation ambitions and section 5.5 outlines how this may be established at Flotta oil terminal in Orkney to harness the tidal resource of the Pentland Firth.

Finally, a roadmap and recommendations focus on financial support, resource management, reduced deployment time and risk mitigation for both community scale and larger industrial projects. Key financial recommendations include development of a tidal specific feed-in tariff for smaller projects, and a review of Contracts for Difference including a larger ring fence and non-price evaluation criteria. Resource potential could be maximised by a publicly funded detailed mapping of tidal resource suitable for projects less than 30 MW, to allow identification of smaller industry and community offtake opportunities that could be actively pursued. This can be used alongside a change to the requirement for Section 36 consent for projects with a generation capacity of a certain scale, which is currently prohibitive to smaller projects. Finally, publicly underwritten warranties and insurance can reduce the cost burden associated with risk that is restricting the magnitude of tidal deployment.

1 Introduction

Crown Estate Scotland (CES), Scottish Enterprise and Highlands and Islands Enterprise have commissioned a study to look at alternative offtake routes for tidal stream energy across Scotland and to begin considering the timelines and challenges associated with these. They have contracted the European Marine Energy Centre and Offshore Renewable Energy Catapult to undertake this study.

This study only considers the opportunities presented through the exploitation of tidal stream resource, which henceforth will be referred to as tidal.

1.1 The challenge

Tidal energy has an important role to play in delivering Scotland's net zero ambitions, particularly in terms of energy security and resilience. The predictability of tidal stream enables energy systems to be designed around an understood lower electricity-generation capacity during neap tides, and a clear understanding of how this will increase during spring tides. This predictability can be applied both to designing local energy systems for island communities and large industrial processes. The UK Marine Energy Council is lobbying UK Government to set a 1GW by 2035 target for tidal energy (UK Marine Energy Council, 2023), within which the recommended ambitions for Scottish Waters are:

- 200 MW by 2030 and
- 700 MW by 2035

Due to the location of the tidal energy resource in Scotland, there is an opportunity to create local energy systems and support energy independence for remote and islanded communities. With evidence from the first projects already operating, this sector is directly supporting economic development in coastal communities across Scotland.

Tidal generation provides a predictable energy supply that enable microgrid power systems to be modelled and storage requirements accurately sized to ensure continuity of supply. However, the lack of maturity in the tidal sector as it approaches critical mass means that there remain some significant variables that can only be resolved through experience.

At present, CES operates an open ad-hoc leasing opportunity for tidal energy projects to access seabed development rights. CES can award seabed rights to tidal energy projects with a capacity up to 3 MW for test and demonstration and, where there is sufficient prior experience, larger scale projects with a capacity up to 30 MW.

As part of CES's ongoing review of leasing arrangements for tidal energy, they are seeking to gain a greater understanding of delivery timelines and challenges for tidal energy projects. There is a particular focus on considering alternative offtake routes in comparison to grid connection. Multi-developer as well as multi-offtake models are also explored.

There are several alternative offtake routes being considered by the sector including, but not limited to, electrolytic hydrogen production, community embedded generation, and power for local small-scale industrial demands such as whisky distilleries. The intention is that this project will be used as a market enabler to support future leasing design, evidence deliverability of industry-set targets and identify potential approaches to resolving deliverability constraints.

1.2 The status of tidal generation

The tidal energy sector is considered to be at an early commercial stage. In the past 20 years it has moved on from testing first-of-kind individual technologies to the point where some companies have refined their designs over third or fourth iterations, to the point at which they have proven that their turbines can generate electricity reliably and consistently over long durations. Some companies have also deployed small arrays of tidal turbines to begin to demonstrate how tidal projects can be scaled up to provide utility-scale energy generation.

Scotland is considered a world leader in tidal energy due to the fact that it has installed more technologies than anywhere else in the world and technologies in some of the highest intensity global tidal resources. Furthermore, several of the leading tidal turbine technology developers are based in Scotland and it is home to an indigenous supply chain with unrivalled experience. Currently, approximately 10 MW of tidal capacity is operational in Scotland, with several technologies installed across key sites in the Inner Sound of the Pentland Firth (Caithness), Fall of Warness (Orkney) and Bluemull Sound (Shetland).

Due to its early commercial status, tidal energy costs remain high relative to other forms of low carbon energy generation. To enable costs to come down, the sector needs to scale up such that it can benefit from cost savings achieved via economies of scale and volume, learning by doing and further technology innovation. The importance of setting the 1 GW deployment target is that at this scale it has been estimated that tidal energy will become cost competitive with other low carbon technologies, and notably cheaper than nuclear energy (ORE Catapult, 2022(1)). While tidal would still be more expensive than wind (onshore and offshore) and solar at this scale, the price premium is considered warranted due to the predictability of tidal and the value of this in relation to managing the future energy system. This is similar to how nuclear is considered a dependable energy source that can be relied upon when there is insufficient renewable generation.

Several recent studies have shown that tidal energy could significantly reduce the costs of operating the UK's future energy system (Supergen ORE, 2023), with some estimates suggesting savings of as much as £200m - £600m per year due to savings in future energy infrastructure investment costs and a reduced need to develop expensive low-carbon alternatives, such as carbon capture and storage (ORE Catapult, 2022(2), ORE Catapult, 2023). Furthermore, tidal energy projects are achieving greater than 80% UK local supply chain content spend, compared with approximately 50% in offshore wind. This socioeconomic benefit provides further evidence to warrant a price premium.

Through the Contracts for Difference (CfD) scheme, the UK Government's main mechanism for supporting low carbon energy projects, tidal energy was given a ringfenced budget for the first time in Allocation Round (AR) 4 in 2022. When projects from the subsequent AR5 are included, this has created a pipeline of tidal projects in the UK that currently sits at just under 100 MW, of which 66 MW are planned to be deployed in Scotland. Across the two rounds, these projects are expected to become operational by 2028.

1.3 Bottlenecks to deployment

While the CfD scheme has created a vital pipeline for the tidal sector, based on its current structure, the capacity unlocked on an annual basis will be insufficient to reach 1 GW by 2035. For example, the £10m ringfence announced for tidal in 2024's AR6 is anticipated to unlock less than 20 MW of further capacity (ORE Catapult, 2024(1)). Tidal can be awarded further capacity through the wider emerging technologies pot it sits in (pot 2), but to do so it needs to compete on price with other, more mature technologies, including floating offshore wind. Due to there being no floating offshore wind bids in AR5, this did lead to additional tidal capacity being awarded in 2023. However, this was a unique situation in which the administrative strike price for floating offshore wind was too low to attract bids. The CfD mechanism puts tidal at a competitive disadvantage due to its relative costs compared to the other technologies in its pot. For this reason, the sector is calling for the CfD structure to be reformed to consider the wider benefits of tidal energy, including the aforementioned energy system and socioeconomic benefits. A recent report highlighted the need for both an increase to the tidal ringfence as well as reforming the CfD structure to increase deployment rate, but even in this scenario achieving 1 GW by 2035 is expected to be challenging (ORE Catapult, 2024(2)).

Another significant challenge to meeting deployment ambitions is the slow rate at which projects are developed. In particular, the consenting process is widely viewed as being too time consuming and undefined. This is not strictly unique to tidal, as similar consenting hurdles are being faced in the offshore wind (OSW) sector, but the challenges are arguably far greater for tidal developers because:

- They are typically small companies without significant balance sheets.
- The threshold at which the more complex and lengthy Section 36 consenting process is required is 1 MW for projects within 12 nm of shore (this includes tidal stream projects), compared to 50 MW for projects beyond 12 nm (typically offshore wind), hence even small projects require significant time and resource commitments.

The combination of a long and costly consenting process coupled with the uncertainty of whether consent will be granted means it is often difficult for tidal developers to fund this period of the project. This is particularly so for community projects, where funding is limited and funders' restrictions normally prevent project timescales to extend out this far. A recent industry survey pinpointed the consenting process as being the greatest hurdle to progressing tidal project development (ORE Catapult, 2024(3)).

Lastly, there are widespread concerns within the tidal sector that the grid will be a bottleneck to deployment, both in terms of grid availability and connection timescales. Some of the best tidal sites are located in remote areas where there is insufficient grid capacity. In addition, the transmission network use of system (TNUoS) charges are highest in the three regions where tidal resources are best, and these charges are set to increase more in Scottish zones than any other part of the UK in 2029/30 due to the new high-voltage direct current links (ESO, 2024(1)). This means tidal projects will be subject to the highest level of grid transmission connected generation charges in the UK, and so there are benefits to keeping tidal projects as embedded generation (i.e. connected to the distribution (<132 kV) rather than transmission network and less than 100 MW), where possible. Pursuing alternatives to grid connection is a key motivation for this project in order to identify potential solutions to these challenges and accelerate the route to market for tidal energy.

1.4 The scope of this project

This project identifies and assesses the suitability of alternative offtake models for tidal energy in Scotland. It initially identified the locations of tidal resource around Scotland and each of these was assessed for candidate industries for use of tidal power. A first filter exercise was then completed to understand the most common industries and locations where there were multiple offtake opportunities.

A stakeholder engagement exercise was then conducted to understand the needs of both the tidal industry and potential green energy offtake industries and organisations. This included defining challenges, identifying common threads and sharing lessons learned. A series of business models were evaluated against a range of targets to understand potential impact and a road-mapping exercise was conducted to understand possible routes forward. This work has all then been considered to arrive at the final set of recommendations.

These recommendations focus on the best route for nurturing this home-grown industry to a position of commercial competitiveness over the next ten years by exploiting its ability to provide security to the energy system and deliver wider socioeconomic benefits. This report is intended as a starting point, and each recommendation will require further detailed work in order to propel the tidal industry forward to full commercial deployment.

This report does not consider alternative renewable or carbon-neutral or negative energy sources, e.g. solar, wave, wind or nuclear. Alternative fuels are considered, but only in relation to their use as a potential use/sink (or storage/transportation vector) for renewable energy, that is green hydrogen and e-fuels.

2 Identification of tidal resources and off takers

2.1 Sectoral marine plan and grid network constraints

The Scottish Government used a marine planning approach to develop its draft Sectoral Marine Plan in 2013 (The Scottish Government, 2013). The main areas of tidal resource have been known for a decade or more. A map of these proposed tidal sites is shown in Figure 1, and is also available online via Marine Scotland's National Marine Plan interactive application[1].

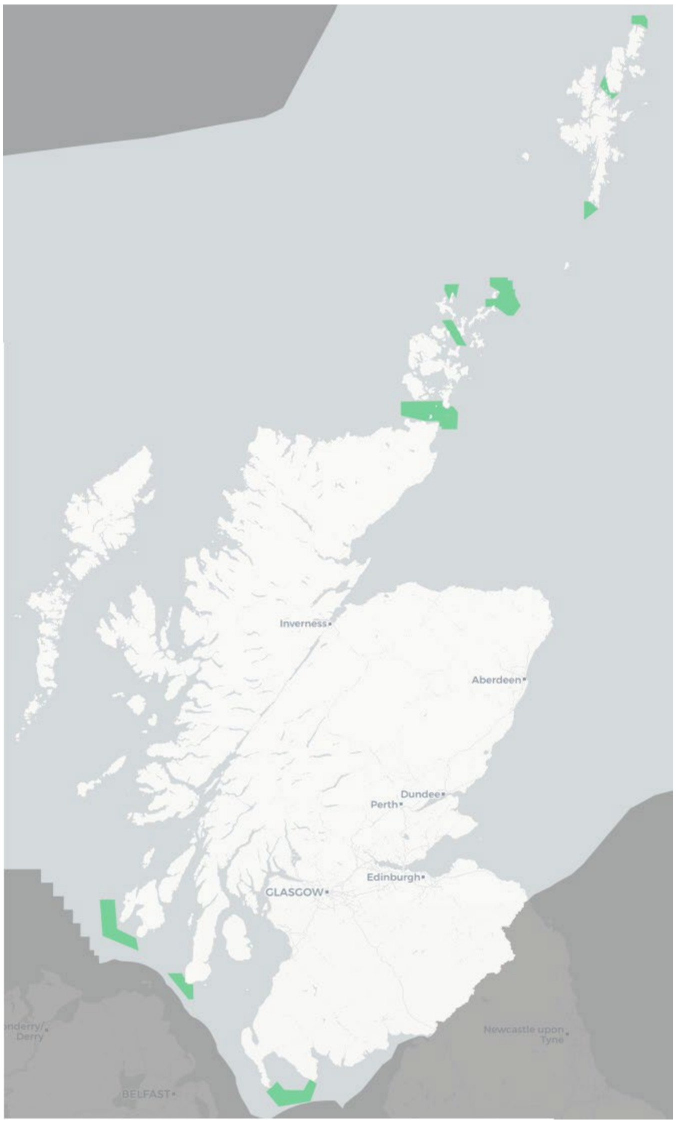

Figure 1 | Target tidal energy locations

This report elaborates upon this previous work to identify target locations for potential tidal energy deployment. However, it was unable to undertake a detailed study of local electricity network constraints at these locations.

It is important to understand the existing grid locations as this will affect where alternative offtake applications are likely to be required. Scottish and Southern Electricity Networks

[1] https://marine.gov.scot/maps/298 [Accessed 21 June 2024]

(SSEN)2 and SP Energy Networks[3] provide maps of the existing grid infrastructure. Information from these, together with the Electricity System Operator's (ESO) Holistic Network Design (HND) and HND Follow Up Exercise for a decarbonised electricity system (ESO,2022. ESO, 2024 (2)) give an overview of how network connections will move forward, as shown in Figure 2.

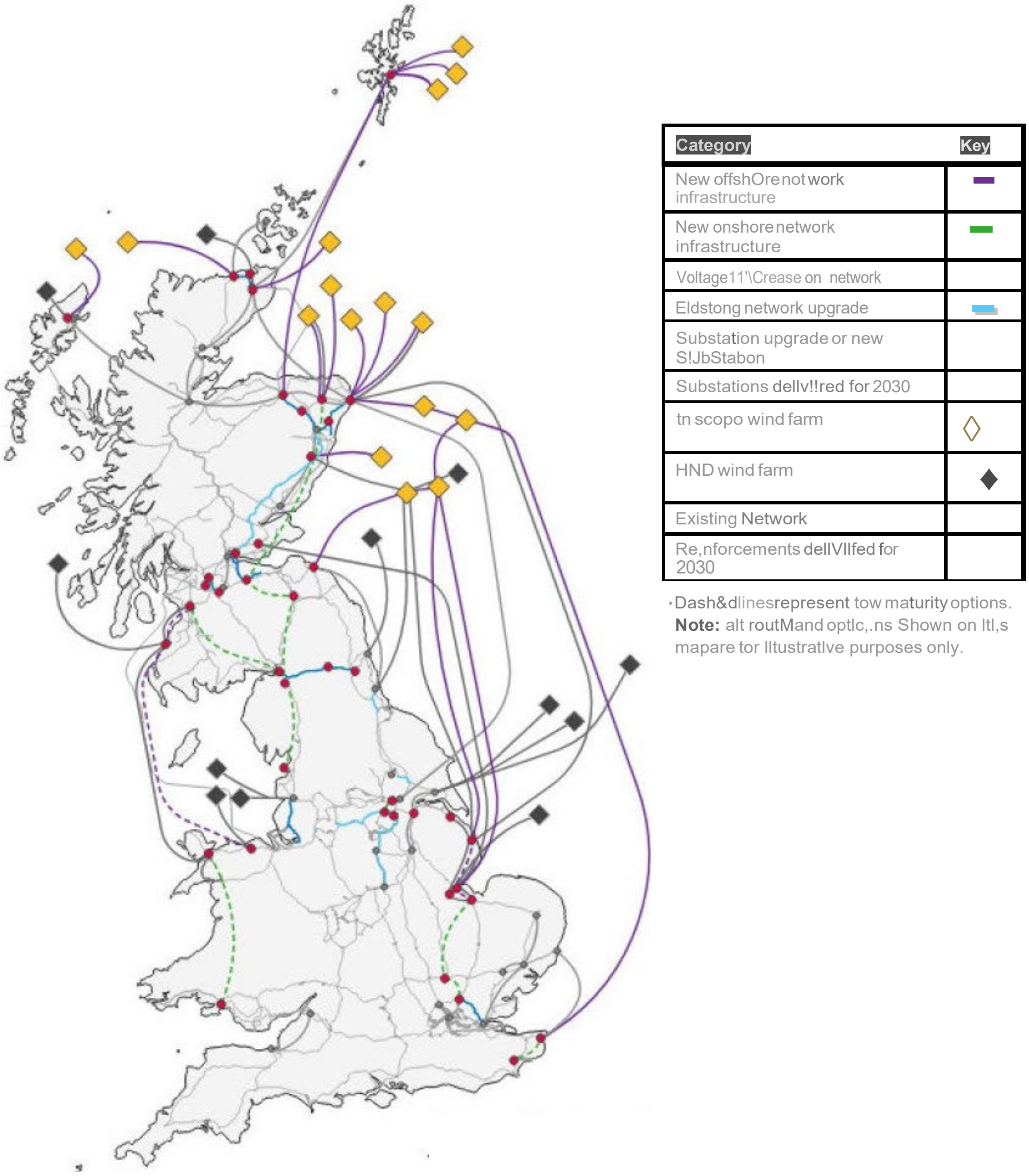

Figure 2 I Map of network infrastructure to be delivered beyond 2030 (ESQ, 2024 (2))

[2] https://new-eonnections ssen.co.uk/eo_web/ (requires registration)

[3] https://www.spenergynetworks.eo.uk/pages/sp_distribution_heat_maps.aspx

These documents indicate that although replacement and additional cables are planned for the grid, these are planned around proposed offshore wind projects and capacity for these is already allocated. This adds another challenge to tidal achieving its ambitious targets by connecting to the transmission network. This further supports that embedded generation or private networks are often the only feasible near-term options available for tidal projects.

The ESO also projects an increase in demand of electricity by up to 65% by 2035 and identifies that there is an 'opportunity to develop large scale strategic or flexible demand closer to sources of generation' to reduce the requirement for additional network infrastructure (ESO, 2024 (2)).

2.2 Tidal stream energy resource

ABPMer have previously characterised the areas around Scotland with high tidal resource yield[4]. From this data, sites were selected based upon flow rates greater than 1.0 m/s at spring tides. This speed was chosen using industry knowledge and supported by research (Lewis M. et al., 2021), as it is the typical cut-in speed for tidal energy converters (TEC),.However, it should be considered that higher flow speeds will generally be required for the current level of technology to achieve economic viability.

The full list of locations is given in Table 1 and their numeric reference is shown on the map in Figure 3.

#	Name	#	Name
1	Annan	**16**	Sound of Shiant
2	Southerness / Solway Firth	**17**	Butt of Lewis
3	Burrow Head	**18**	Cape Wrath
4	Mull of Galloway	**19**	Pentland Firth
5	Mull of Kintyre	**20**	Sound of Hoy
6	Islay	**21**	Fall of Warness
7	Jura / Colonsay	**22**	Papa Westray
8	Firth of Lorn	**23**	North Ronaldsay
9	Coll / Tiree	**24**	Fair Isle
10	Small Isles	**25**	Sumburgh Head / South Shetland
11	Inner Sound	**26**	Foula / West Shetland
12	Barra Head	**27**	Unst / North Shetland
13	Eriskay / South Uist	**28**	Fraserburgh / Rattray Head
14	North Uist	**29**	Inverbervie
15	North Skye & Fladda Chuain	**30**	Firth of Forth

Table 1 | Tidal resource locations in Scotland

It should be noted that some regional data is not available from this analysis (e.g. Firth of Tay, Inverness/Dornoch Firth, Yell Sound) and hence these areas have not been considered in this initial assessment, even though they are understood to have tidal resource potential.

[4] https://www.renewables-atlas.info/explore-the-atlas/

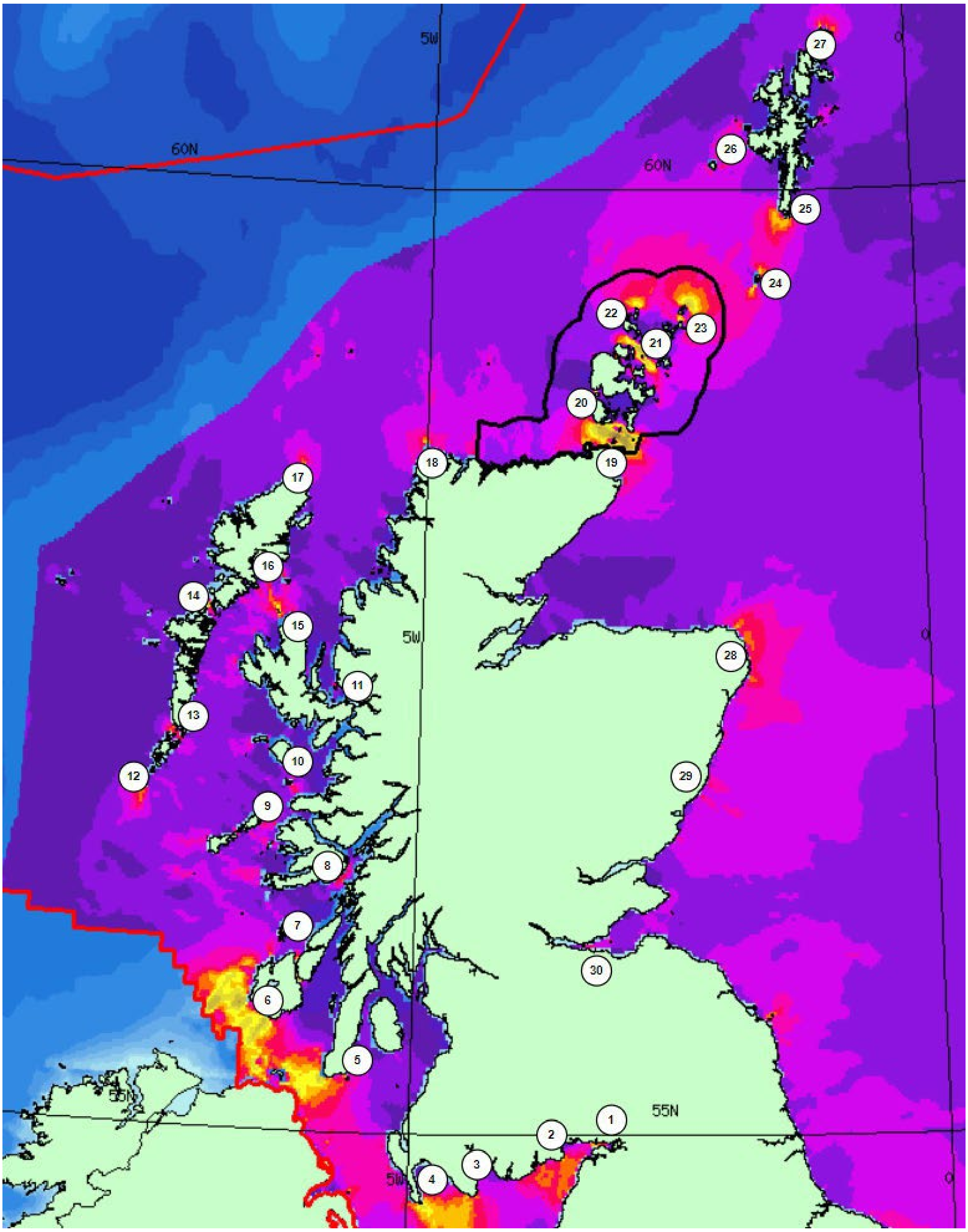

Figure 3 | Map of tidal resource locations in Scotland, based on ABPMer

Consideration of alternative resources, such as wave and wind, was not undertaken during this analysis. TECs of a high TRL are not hybrid devices, and thus in the application of tidal energy in the next 10 years is likely to rely on tidal flow alone at each generation site.

The hierarchical nature of the grid results in infrastructure improvements of the trunk benefiting multiple branches. A more holistic assessment of the renewable energy potential of areas, generally to the north and west of any given point, are likely to show opportunities for the cooperative use of the grid. At a macro scale, regions can appear as 'hybrid' generators with a range of generating sources, whilst at an individual tidal project level they will be single technology specific, at least initially. There may be opportunities for investment at some locations for wave and wind generation as well, but that is beyond the scope of this report.

2.3 Offtake industries

The detailed analysis of individual sites was presented to the funders in an interim report and is available in Annex 1. This includes a corresponding map of each tidal resource hotspot, together with a summary of the candidate offtake industries and other power infrastructure identified at each location. This analysis was used to collate a list of current industries located in the vicinity of tidal resources by location, and these were then ranked according to incidence.

It should be noted that:

- Industries that were within 10 km of a tidal site were given a full score.
- Industries that were at a distance that would require a strong business case to justify a private wire connection, defined as between 10 and 30 km, were given half-scores and defined as "present at distance".
- Defunct industries and planned offtake industries (i.e. those known to be planned and reported in the press only at this stage) were noted but not scored.
- Future industries, or projects that would not consume power (such as local battery storage initiatives) have not been considered.

The summary of this analysis is shown in Table 2. This initial approach gives no consideration to the relative importance of each offtake industry, economic or otherwise. Ranking is achieved purely by the number of incidences of locations where the various industries are present. Further elaboration on the relative importance and priority of potential offtake industries was undertaken after soliciting stakeholder engagement.

Offtake industry	Locations																														Total
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	
Shipping, ferries and ports				X	X	X	X	O	X	O	X	X		X	O				X	X	X	X	X	X	X		X	X		X	19.5
Crofting and farming	X	X	X	X	X			O	X		X		X	X	X				X	X	O	X	X		X			X	X	X	19
Tourism		X	X			X	X	O					X	X	X		X	X		X					X						11.5
Fishing/aquaculture	X					X	X												X	X	O	X			X	O	X	X	O	X	11.5
Aviation					X	X					X								O		X	X	X	X	X	X	O			X	11
Distillery	X				X	X	X	O			X	X							X								X	O	O		9.5
Lighthouses				X												O	X	X	X					X				X		O	7
Community power												X	X						X					X		X			X	O	6.5
Manufacturing	X				D															P								X	X	X	4
Oil & gas/fuels											P								X		P						X	X		X	4
Forestry			X				X																		O						2.5
Military													O															X		X	2.5
Spaceport														P				X									X				2
Road/rail											X																			X	2
Power stations																			O									X		O	2
Brewing															O													O	O		1.5
Bakery																				X											1
Green hydrogen																	P		P		X					P					1
Dairy					D																							X			1
Data/IT																			P		P										0

Key: X Present | O Present at distance | D Defunct | P Potential

Table 2 | Offtake industries, ranked by incidence

A general set of observations about each of these industries is provided in Table 3.

Industry	Observations

Shipping, ferries and ports	• Short routes may be candidates for electrification, but schedule for ferry replacements may need to adjust or individual ferries re-deployed to other routes.
	  ○ Redeployment might not be possible due to local design differences for specific routes (e.g. inter-island in the Outer Hebrides with custom propulsion design).
	  ○ Round-trip routes could be replaced by point to point.
	• There may be alternative fuel options, such as hydrogen or e-fuels including e-diesel or ammonia.

Crofting and farming	• Limited applications for power offtake. • May need hybrid solutions (e.g. transport/electric vehicle (EV) + power for industrial processing). • There is the potential for e-diesel for larger vehicles. Hydrogen refuelling is discounted for this application as it is not currently a mature technology and adoption for small-scale use is unclear due to safety, cost and energy density concerns. • Agricultural waste can be used for biomass. • Further work on decarbonisation of agriculture is understood to be being considered. This is outside the scope of this report.
Tourism	• Generally low power, especially in remote areas: due to focus on nature, wildlife and history rather than energy intensive entertainment options.
Fishing/aquaculture	• Sea farming is prevalent. • Battery/hydrogen/hybrid powered vessels would need to be compelling in terms of cost carrying and safety concerns. • May have other applications not considered here for processing/storage. • Oxygen from electrolysis can be used in this industry. • Biomass/waste may also be generated by this industry for use as a possible carbon source for e-fuels.
Aviation	• Short flights may be candidates for early-stage decarbonisation – either electric or hydrogen. • Support services/infrastructure (e.g. radar, landing lights, ground support, local maintenance) are generally on grid, but could benefit from a decarbonised power supply in some locations. • Operational power needs to be resilient. Backup power storage may be helpful, and some may exist already.

Industry	Observations
Distilling	• Heat is a primary application and requires high temperatures for optimum product quality. • Timing of heat / energy use could be explored against what tidal will produce – it could be possible to avoid energy storage solutions.
Lighthouses	• Low power and generally supplied by existing solar. • *Not a viable offtake.*
Community power	• Avoidance of use of fossil fuels as a backup. • Tidal will add further resilience regardless, as existing projects likely to be wind-based, and therefore less predictable. • Power output would seem to be in the range of existing tidal devices, in the low MW range. Small arrays offer better deployment options and more resilience.
Manufacturing	• Power needs very specific to application. (Not analysed) • *Not considered due to wide variety: diesel generator replacement may be relevant to these locations.*
Oil & gas/fuels	• Stakeholders in Orkney and Shetland (Flotta, Sullom Voe). • Support services are extensive, and include some manufacturing, could be viable offtakes in some locations. • Local e-fuel and hydrogen pathfinder opportunities are already in discussion, with some demonstrated.
Forestry	• Energy usage likely limited to industrial EVs. • Hydrogen/e-fuels could be considered. • *Not considered due to limited use case and power consumption.*
Military	• Specific installations: o MOD Deep Sea Range o RAF Machlinash o RNAS Merganser • Military offtake options have not been explored in this report.
Spaceport	• SaxaVord may be viable (~6 km distant from location of peak tidal flow). • Potential space hub in North Uist. • Sutherland spaceport is at distance (~32 km distant from the main area of tidal flow exceeding ~1.0 m/s). • Unclear what power requirements are. • Could also use oxygen from electrolysis processes.
Road/rail	• Logistics and/or remote fuelling. Limited incidence where viable.

Industry	Observations
	• *Not considered due to limited incidence.*
Power stations	• Existence of large, non-community power generation with high voltage infrastructure, meaning no requirement for offtake opportunity. • Compare this category with community power. • *Not a viable offtake due to transmission grid connection.*
Brewing	• Mostly micro-brewery. • One potential large-scale brewery is present at distance in Aberdeenshire. • Lower heat/power requirements than distilleries, so the amount of energy taken out of the overall energy system will be lower, and this would make breweries a less attractive offtake option than distilleries, even at scale.
Bakery	• Very localised, with low power requirements. • *Not a viable offtake.*
Green hydrogen	• Pathfinder projects only at present, mostly in Orkney. • Several large projects are in planning across Shetland, Orkney and the Western Isles.
Dairy	• One defunct location identified: unlikely to be relevant.
Data/IT	• Remote locations typically having poor data links. (Satellite communication is not currently effective for data centre connectivity.) • Use-case selection would be critical to tolerate spikiness of supply (e.g. crypto-currency vs web hosting).

Table 3 | Notes on offtake industries

An initial prioritisation was then conducted, discounting the non-suitable industries identified above, as well as locations either in local proximity to the transmission grid or with no viable opportunities. These exclusions, and resultant new scores, are shown in grey in Table 4:

Offtake Industry	Locations																														Total
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	
Shipping, ferries and ports				X	X	X	X	O	X	O	X	X		X	O				X	X	X	X	X	X	X		X	X		X	17.5
Crofting and farming	X	X	X	X	X			O	X		X		X	X	X				X	X	O	X	X		X			X	X	X	13.5
Tourism		X	X			X	X	O					X	X	X		X	X		X					X						9
Fishing/aquaculture	X					X	X												X	X	O	X			X	O	X	X	O	X	9
Aviation					X	X					X								O		X	X	X	X	X	X	O			X	10
Distillery	X				X	X	X	O			X	X							X								X	O	O		7.5
Lighthouses				X												O	X	X	X					X				X		O	
Community power												X	X						X					X		X			X	O	5
Manufacturing	X				D															P								X	X	X	
Oil & gas/fuels											P								X		P						X	X		X	3
Forestry			X				X																		O						
Military													O															X		X	1.5
Spaceport																		X									X				**2**
Road/rail											X																			X	
Power stations																			O									X		O	
Brewing															O													O	O		1
Bakery																				X											
Green hydrogen																	P		P		X					P					**1**
Dairy					D																							X			
Data/IT																			P		P										

Key: X Present; O Present at distance; D Defunct; P Potential

Table 4 | Summary of offtakers with initial prioritisation

2.4 Limitations and considerations

Although this approach offers an indication of the industries present in these locations, it does not give a full insight either into the magnitude of the resource in certain areas or the potential of the offtake opportunity. For example, region 19 is the Pentland Firth, which is the largest tidal resource in Europe and many estimates have put its resource potential at multi-GW, e.g. 4.7 GW (Adcock et al., 2011). Also, although shipping/ferries and crofting/farming are the two most prevalent offtake industries, these are challenging to decarbonise on a local basis. In comparison, green hydrogen production ranks much lower in the table, as this industry is in its infancy, but green hydrogen production has a great potential to be a very large offtake opportunity. This is also in line with the latest thinking of the ESO, which has identified the North of Scotland as a region of strategic importance to locate flexible demand in order to avoid network reinforcement. In its 'Beyond 2030' report it stated:

> *For the first time, our offshore network design has included an assumption of major strategic demand being developed in the North of Scotland throughout the 2020s and the early 2030s. This can serve to reduce the requirements for new electricity transmission network build in the 2030s and beyond if the abundant renewable electricity is consumed locally. Solutions such as green hydrogen production (electrolysis) could meet this requirement. All our subsequent recommendations are predicated on stimulating this level of strategic demand within the North of Scotland (ESO 2024, p.51).*

In reality, these large industrial production facilities will require a base level of constant electricity supply to keep equipment operational and prepared to respond to additional supply from intermittent renewables, such as offshore wind. This will avoid lengthy start up procedures, maintain purity of the hydrogen and maximise efficiency from the plant. Local tidal resource can provide an opportunity to satisfy this base load as it can provide a predictable supply, particularly when matched to a suitably sized battery energy storage system.

Hydrogen production sites may be co-located with e-fuel production to minimise hydrogen storage and shipping costs whilst allowing increases in efficiency due to recycling of excess heat from a Fischer Tropsch e-fuel production plant to a hydrogen electrolysis plant, for example. Producing e-fuels such as e-diesel and e-kerosene, for which current systems are already established for distribution and use, provide a path towards decarbonisation for industries such as crofting, farming, maritime and aviation whilst minimising the requirement to replace expensive infrastructure and assets.

It should be remembered that electrification of demand is normally preferential to using hydrogen or hydrogen derived fuels as 20-30% of the input energy is lost during the electrolysis process to produce hydrogen and a further 10% during the compression process. However, hydrogen does offer certain advantages in high-heat applications, such as distilleries and steel production. In these scenarios local production is most cost effective due to the high cost and safety implications associated with moving hydrogen around, particularly to remote locations.

Further energy conversion losses due to the e-fuel production process result in an overall efficiency of less than 50% for e-fuels when compared to direct electrification. These should therefore be used only in the hardest to abate industries. One example of such an industry is the fishing industry, where long ranges are essential and large storage capacity is required for bringing the haul home; hence neither electrification nor less energy dense e-fuels such as methanol are currently considered viable options.

All of this was considered when selecting the stakeholders to discuss the alternative offtake model with. The participants selected included both generators and customers to ensure that the benefits and challenges were fully understood from both sides of the business relationship. In addition, selection was carefully considered to ensure a broad range of geographical location, scale and end use type. Due to the limited timescale of the project, not all industries could be consulted during this engagement, however, the most promising offtake industries could be broadly divided into direct electricity use, conversion to hydrogen and conversion to e-fuels and at least one representative from each was included. Finally, as shipping, ferries and ports is so predominant in tidal regions, representation from this group was included to ensure the sentiments of this key industry is clearly understood.

3 Stakeholder engagement

There have been significant developments in tidal energy projects over recent years. These, together with the island locations that have implemented these projects, have resulted in several innovative offtake projects being trialled in these communities.

A stakeholder engagement exercise was conducted to understand the challenges and benefits that these projects have faced, identify common threads and share lessons learned. The outcomes bring together the latest understanding of how key stakeholders are considering alternative offtake routes versus the grid and identify which alternative routes are considered most favourable. This information has fed into the business modelling exercise, as well as the roadmap and recommendations where appropriate.

3.1 Selecting the stakeholders

A stakeholder list consisting of a mixture of sectors was identified including:

- Tidal developers
- Community energy groups
- Local authorities
- Hydrogen and industrial users
- Ports and harbours

It was important that there was a geographical representation of stakeholders from across the tidal regions. To enable this within the limited timeframe of the project, representatives from different regions were bought together for sector focus group style discussions where possible. This had the advantage of both enabling more stakeholders to be consulted and enabling discussion of ideas between similar stakeholders that may lead to further insights.

3.2 Methodology

The stakeholders were divided into categories based on their sectors and questions were designed that were specific to each sector. The questions were reviewed for bias and sent in advance of the interviews to enable the interviewees to consider their responses. For some sectors there were also some pre-interview quantitative questions that were asked to feed into the modelling exercise.

Careful consideration was given to the structure of the focus group discussions to ensure that all attendees were given a chance to be heard. These sessions were led by an experienced facilitator and questions were divided into related topics.

3.3 Findings

3.3.1 Tidal developers

[redacted] tidal developers were interviewed. A pre-interview questionnaire was provided to gather quantitative data, followed by a list of qualitative interview questions.

3.3.1.1 Achievability of targets

Redacted – EIRs 10(5)(e) Confidentiality of commercial or industrial information

3.3.1.1 Alternative offtake potential

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Case Study: the GHOST project, Shetland

The GHOST (green hydrogen and oxygen supply from tidal energy) project is a feasibility study looking at the generation and potential markets of hydrogen and oxygen powered by tidal energy. The Shetland Islands based project is being led by Nova Innovation with support from the University of Strathclyde, Shetland Islands Council and Ricardo Energy.

This project is investigating whether tidal energy convertors that are planned for deployment near the island of Yell can be used to power the generation of green hydrogen via electrolysis, whilst also capturing the byproduct of oxygen. The project is looking at how these gases can then be utilised best in the local economy and whether this can provide a sound business model. Both transportation and domestic heating are being explored as possible markets for the hydrogen whilst potential customers for the oxygen include the SaxaVord Space Centre for use as rocket propulsion; and the local aquaculture farms, where it's used to keep the fish healthy by reducing the risk of disease outbreaks.

The aim of the project is to understand if green hydrogen can offer an opportunity to bypass electricity grid constraints and thus offer a route to market to enable the growth of tidal energy without the restrictions of local electricity distribution.

The project is expected to report its findings in Summer 2024.

3.3.1.2 Alternative offtake barriers

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3.3.1.3 Industry collaboration

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3.3.1.4 Community partnerships

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Case Study: Flex Marine Power, Islay

Flex Marine Power Ltd. arelooking to enable a network of community embedded tidal (CET) energy projects initially across Scotland, but with global ambitions. These projects will generate local value in the fonn of jobs, business opportunities and green sustainable energy by enabling communities to harness the predictable power in their coastal tidals and estuaries.

Initially based in Islay, Flex Marine Power have developed their 50 KW SwimmerTurbine, which has already seen a **prototype deployed and generating electricity. This machine has been designed to be both affordable for communities and easily maintained using the vessels readily available** in **coastal locations. Their vision is to create many steadily growing sustainable energy projects by facilitating the ownership of these machines by coastal community projects and operating them out of small harbours by redeploying existing underutilised fishing assets. The smaller machine size means projects can benefit from scalable deployment** in **areas where larger machines would be unsuitable, resulting** in **significant long-term growth in regional energy and economic output.**

3.3.2 Community groups

Redacted – EIRs 11(2) Third party personal information

3.3.2.1 Grid challenges

Redacted – EIRs 11(2) Third party personal information

3.3.2.2 Non-grid offtake approaches

Redacted – EIRs 11(2) Third party personal information

A number of barriers to alternative offtake potential were identified including:

- Funding
- Infrastructure and regulation
- Markets

3.3.2.3 Tidal energy and local community deployment

Redacted – EIRs 11(2) Third party personal information

3.3.3 Local Authorities focus group

Redacted – EIRs 10(5)(f) Third party Interests

3.3.3.1 Grid challenges

Redacted – EIRs 10(5)(f) Third party Interests

3.3.3.2 Non-grid offtake approaches

Redacted – EIRs 10(5)(f) Third party Interests

3.3.3.3 Offtake examples

Redacted – EIRs 10(5)(f) Third party Interests

3.3.4 Ports and harbours focus group

Redacted – EIRs 10(5)(f) Third party Interests

3.3.4.1 Decarbonisation plans

Cost was strongly felt to be the main factor currently

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3.3.4.2 Local grid challenges

Redacted – EIRs 10(5)(f) Third party Interests

3.3.4.3 Focus on ferries

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3.3.4.4 Fuel mix and challenges

Redacted – EIRs 10(5)(f) Third party Interests

3.3.5 Industrial applications, hydrogen and synthetic fuels production

Protium were interviewed about their Islay project, which is working with Bruichladdich and other distillers on the island to decarbonise their distillation processes using hydrogen. Conversations also took place with another industrial hydrogen user.

3.3.5.1 Predicted energy requirements for Islay

Protium explained that they are currently commissioning the first of multiple hydrogen production facilities that are lanned for Isla and these will be co-located with clusters of demand on the island.

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Protium were keen to emphasise that they are technology agnostic, but must ensure that all of their energy is sourced from green generation technologies. Idealy, they look to minimise grid connection and use private wire connections a lot of the time as grid connection is not an option in a lot of their locations. The priorities for Protium when considering green energy sources are:

- Green
- Cost effective
- Availability - ideally a flat power curve
- Bankable - have its own funding secured

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3.3.5.2 Community projects

Protium are heavily engaged with local communities and community owned renewable energy providers. [redacted]

3.3.5.3 Grid connectivity

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3.3.5.4 Wider sites and applications

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Case Study: EMEC hydrogen production, Orkney

EMEC has a timetable of multiple tidal developers deploying various devices and arrays at its Fall of Warness site between 2024 and 2030, after which grid connections in Orkney are scheduled to be upgraded. To manage the power until this point, they have carried out modelling to understand the requirement for alternative offtake and whether this can be managed using the existing 1.5 MWh vanadium flow battery and 670 **kW** hydrogen electrolyser that are already installed on site.

The Fall of Warness site has a 4 MW firm allocation with a 3.2 **MW** export allocation subject to active network management **(ANM)** and a future 4.8 **MW ANM** allocation that is agreed. Modelling shows that from 2027 onwards there is a need to implement an alternative offtake model and EMEC are actively considering options in this space to minimise curtailment at its sites, taking into account the impending grid upgrades, which are assumed to reduce the need for offtake.

EMEC produced the world's first green hydrogen using electricity generated from tidal in 2017 and has gained extensive experience of producing, transporting and using hydrogen since. This has shown that the export of hydrogen from the island is uneconomic to pursue on a commercial basis and therefore the hydrogen must be utilised locally when possible, although this can still demand a premium in the current market. One of the most promising use cases for hydrogen is proving to be the production of synthetic fuels, which has the added benefit of offering solutions for difficult to decarbonise local industries such as maritime, farming and aviation.

EMEC is working with several companies in the synthetic fuels space to evaluate potential markets and model possible demonstration and large-scale projects. This modelling includes options to deploy demonstration projects on Eday in the midterm, and these companies are interested in co-locating with a source of predictable, green energy.

3.4 Evaluation

The stakeholder engagement focused on six potential alternative offtake areas: none of these were discounted until this consultation had taken place. Information collected during the stakeholder engagement was then combined with other research to undertake a detailed business modelling exercise. The aim of this was to identify the business models that were best suited for considering for the alternative offtake model and the timescales for deployment for each model. This method and outcome of this modelling is detailed in the next chapter.

4 Potential offtake business models

Through the identification of offtake opportunities in Scotland (chapter 2) and the stakeholder engagement exercise (chapter 3), this chapter evaluates the business model viability of six shortlisted alternative offtake opportunities for tidal stream projects. The six alternative offtakes and the reasoning for further assessment are summarised below:

1. **Small-scale generation** – a potentially large opportunity (in terms of turbine units) for companies targeting this market that needs support that is unique to utility scale tidal stream energy. This model also could tie in with **2.** and **3.**

2. **Fossil fuel generation displacement/replacement** – usage of fossil fuel generators on Scottish islands (permanent and back up) and in industrial settings is still common. The high costs and associated environmental impact of fossil fuel generation make tidal stream an attractive alternative.

3. **Community projects** – considerable appetite for community energy projects was found within the community stakeholder engagement group engaged with. The Scottish Government also has a target of 2 GW of renewable energy to be community or locally owned by 2030.

4. **Hydrogen offtake** – viewed as the largest future alternative offtake opportunity (in terms of energy demand) and relevant stakeholders placed high value on the predictability of tidal stream energy for green hydrogen production.

5. **Hydrogen co-location** – similar reasons to **4.** but this specific model looks at hydrogen being produced alongside a tidal project (not the primary offtake), as a means of preventing generation curtailment when there are grid constraints or if an energy intensive business (connected via private wire) has insufficient demand.

6. **Ports and harbours** – the most prevalent offtake opportunity identified in Chapter 3 and direct stakeholder engagement carried out with this industry.

Some other common offtake industries that were previously identified in Scottish tidal regions are also covered by these business models. For example, an aquaculture offtake could involve replacing or displacing fossil fuel generation, while some distilleries are moving towards hydrogen boilers.

4.1 Alternative offtake business model challenges

4.1.1 Energy demand and storage

Business models for commercially viable offtake not making use of the grid or the CfD for tidal are challenging. The CfD scheme provides revenue support for developing renewable technologies. This revenue support serves two purposes:

1. Provide a route to market for renewable technologies that would be otherwise economically uncompetitive with traditional energy generation technologies.
2. Provide investor confidence. By guaranteeing revenue for 15 years, the CfDs create investor confidence and therefore reduce cost of capital, which is the single biggest cost for renewable technologies.

Projects looking to take advantage of tidal resources are typically in remote locations with no, or limited, grid connections. This is also true of OSW, but the scale of this justifies building a bespoke connection to the site. The same is presently not true for tidal at its current scale, as these projects are typically two orders of magnitude smaller in scale.

Private network CfDs are a potential route to market, provided projects are smaller than 100 MW and are either hybrid or islanded generation[5]. Hybrid generation has access to a grid connection and has a market supply agreement with an onsite customer. Islanded generation has a market supply agreement with an onsite customer but does not have access to a grid connection. Private network CfDs have been awarded 10 times previously[6], including to 4 tidal projects being developed by Orbital Marine Power at EMEC. However, the other 6 projects, a combination of advanced conversion technology and dedicated biomass with combined heat and power projects, were terminated before the start date of the CfD. The private network CfDs will enable power generated by Orbital's O2 devices to produce hydrogen with EMEC's 670 kW electrolyser, as well as to potentially be used in synthetic fuel projects as detailed in the case study on page 26.

At a very high-level, the goal of an alternative offtake is to find a viable route to market, using some form of private (i.e. non-grid connected) offtake. This creates challenges as the grid exists to match supply and demand, or in other words; the grid functions as a coordination tool to connect energy suppliers with energy users. As this happens at a national level there is a smooth and predictable demand profile throughout the day meaning that generators can predictably and consistently sell electricity. This allows a project to achieve as high a capacity factor as is technically possible.

Tidal can predictably generate electricity, but only at specific periods in time. If an offtaker cannot create demand for this electricity to coincide with generation, this will decrease the capacity factor of the project. All things being equal, this will increase the Levelised Cost of Energy (LCOE), as LCOE is all the costs of a project divided by the total usable MWh generated. The relationship between LCOE and capacity factor is shown in Figure 4, taken from ORE Catapult's Cost Reduction Pathway of Tidal report (ORE Catapult, 2022) for a reference 2030 site. Any potential offtake solution will need to match the supply of electricity from a tidal project with demand or will see the LCOE increase.

[5] Other criteria apply. However, for the purposes of this report, these are the relevant criteria

[6] https://cfd.lowcarboncontracts.uk/

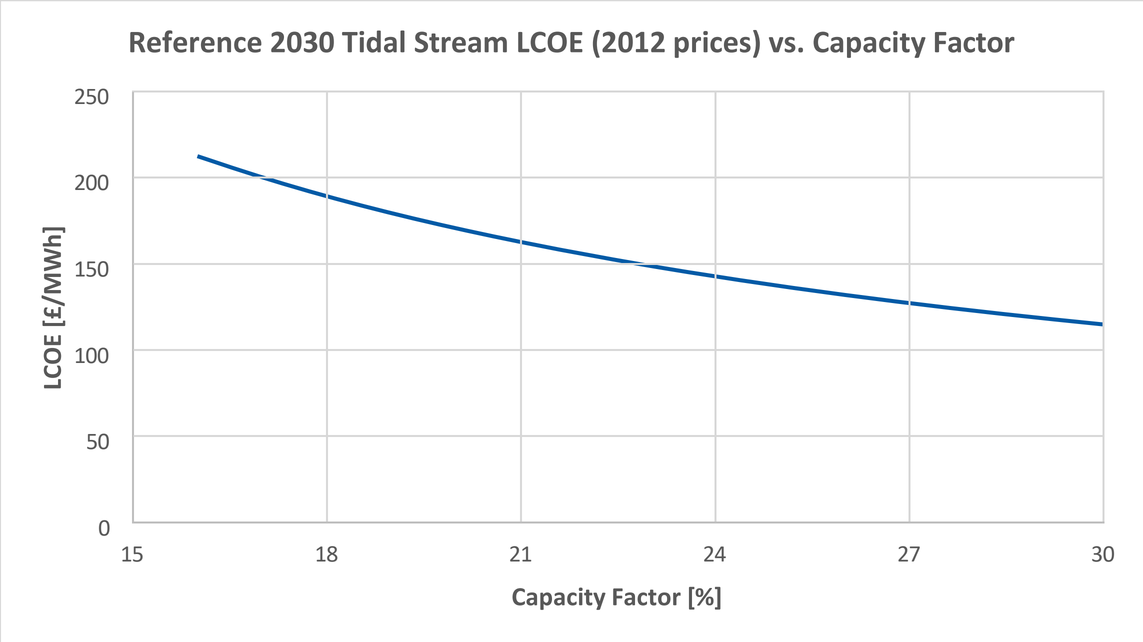


Figure 4 | Tidal stream LCOE vs. capacity factor

Battery solutions provide a partial solution on the demand-side, though they are still relatively expensive (adding capital cost to a project) and only store electricity for short periods of time (Figure 5). They provide a partial solution as the power output of tidal is variable, which is a result of several factors:

- Tides change direction between ebb and flood conditions approximately every 6 hours, and there is a slack water period (typically 30 minutes to 1 hour) which occurs between these two conditions, during which tidal turbines do not produce power as the flow speeds are insufficient to power the turbine.
- Spring and neap tides, which fluctuate approximately every two weeks, exhibit significantly higher power output during the spring tide.

If the costs of tidal and battery storage decrease, some projects have already shown that this could be an attractive combination. For example, with funding from Scottish Government's former Low Carbon Infrastructure Transition Programme, Nova Innovation combined Tesla batteries with its tidal array in Bluemull Sound, Shetland, where it was demonstrated that baseload power could be provided to improve energy security at a local level[7]. Similarly, a study that looked at reducing the reliance of fossil fuel generation on Alderney found that combining tidal with battery storage was much more effective than using onshore wind (Coles D., et al, 2021) due to the predictability of the former and generation continuing during prolonged periods of low winds.

[7] https://www.current-news.co.uk/tidal-plus-tesla-the-scottish-energy-project-providing-baseload-tidal-power/

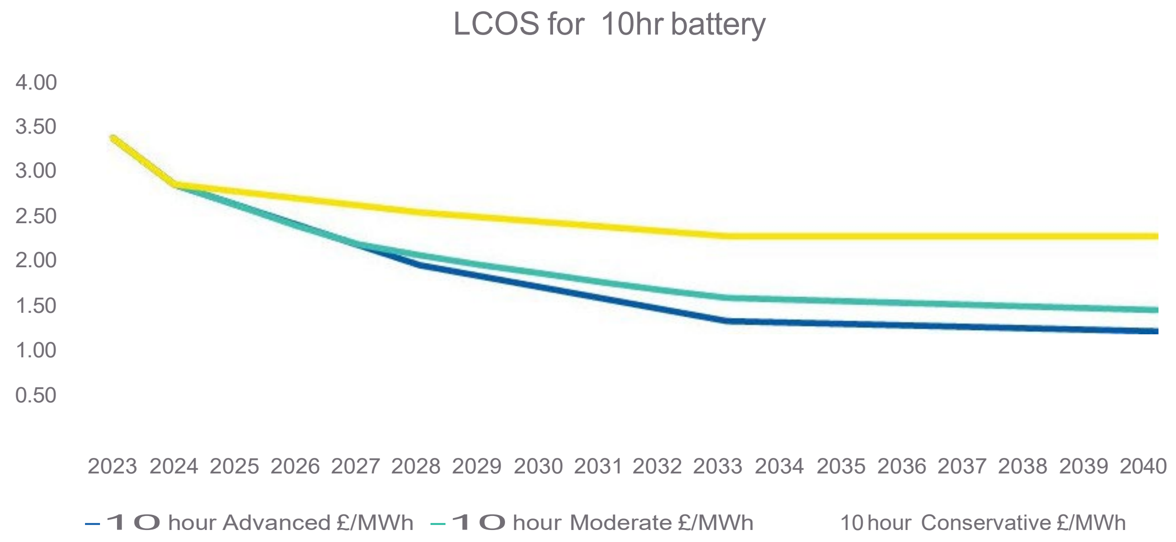


Figure 51 LCOS for 10 hour storage batteries (2022 prices) (NREL, 2022)

Hydrogen could be another possibility in the future, but currently the cost of creating a kilogram of hydrogen from tidal is higher than from other, more established sources of electricity. The levelised cost of hydrogen (LCOH) is highly dependent on the cost of electricity input, as shown in Figure 6. However, transporting hydrogen is challenging and costs are prohibitive for small amounts, as many of the same requirements and costs exist regardless of amounts being transported. From conversations with industry partners, costs are typically around £12/kg of hydrogen, for inter-island transport that will require specialised road and ferry transportation. This means that production of hydrogen on an island using tidal will be cheaper than importing it from a cheaper production source. Figure 5 highlights that the tidal LCOH is competitive with producing hydrogen from offshore wind and shipping it 1000 km, although the actual shipping distance is largely irrelevant due to most of these costs being attributed to handling and loading rather than transportation fuel.

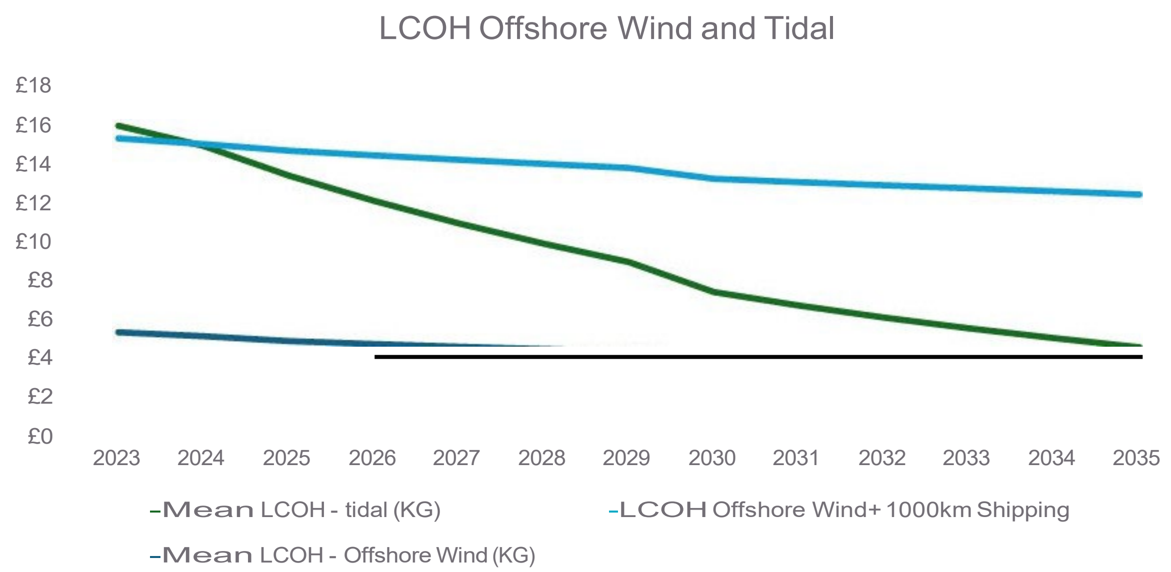


Figure 6 | Levelised cost of hydrogen from offshore wind and tidal, including shipping for wind prices with delivery to remote location

In summary there are two significant challenges any alternative offtake business model must solve:

- Matching demand with supply, both in terms of managing absolute MWs delivered at a specific point in time and managing supply over time.
- High cost of tidal electricity. Due to tidal's early stage of development and therefore high costs, an offtaker will need to either pay a significant premium for tidal generated electricity, find a way to reduce costs significantly in the short term, or will require new subsidy mechanism.

Business models will be assessed against these two criteria, while any regulatory hurdles will be highlighted in each relevant section (Table 5)

Detailed quantification of the business models is not possible as data on how different businesses use electricity, both total demand and demand over time, is not widely available in the public domain. To do this type of assessment data would ideally need to be available in 15 minute increments, as this is the minimum time increment for accurate tidal electricity generation modelling. Different businesses are also more or less sensitive to electricity input costs. Lastly some businesses are more able to pass on electricity costs, so they may be more willing to pay a premium for electricity, even if they are more sensitive to those input costs, as they know they can recover the costs from their sales easily (e.g. hotels are more able to raise room rates than a manufacturer is able to pass on costs to customers).

4.1.2 Multi-project business model

This project has been tasked with understanding how multi-project business models may help address the alternative offtake issue, defined above. Multiple offtake projects are likely a better candidate to address tidal offtake issues. From a purely financial perspective, little changes by combining multiple projects together, as they still have the same development costs, installation costs, etc. The key difference is that by combining multiple technology types and potentially across multiple sites the capacity factor may change due to lower cut in speeds for turbines and different tidal flow patterns. However these changes will be incremental, and some may actually lead to cost increases. For example, if multiple sites require multiple consenting processes. Otherwise, combining multiple projects will simply mean having a combined LCOE and required price per MWh for the project as a whole. If a project of this type were to sell to the grid, it would still sit behind one CfD.

For the purposes of this report, an in-depth financial analysis of a multi-project business model has not been performed, due to time constraints. All business models below can potentially be multi-project business models.

4.1.3 Project finance

The largest issue for all business models will be project finance. In the stakeholder conversations, other barriers were mentioned that were not specific to the business models, but rather to all tidal deployments. The most important was project finance, and specifically project debt covenants and debt servicing covenant ratios (DSCR). Debt covenants are rules put in place by lenders to keep businesses operating within certain boundaries, allowing the lender to manage their risk. DSCRs are form of debt covenants relating to revenue/debt payment ratios. If a revenue/debt payments ratio is breached then the lender can pull their funding. Typically, earnings before interest, taxes, depreciation and amortisation or another measure of ability to service debts is used, meaning surprise costs, due to equipment failure, etc., will impact the DSCR.

The debt payment part of this equation is the interest and principal payments. The revenue part of this equation, particularly for tidal projects, should be straight forward given their access to CfDs and predicable generation. However, given that this is an emerging technology, interruptions to generation are likely. The revenue part of this formula can be thought of as a percentage of availability (given the consistent prices from CfDs). Warrantees and guarantees from suppliers can be used to keep this percentage high, for example if a turbine breaks and is covered by a guarantee to pay all or a percentage of the lost generation, as well as warrantees providing replacement parts.

As it stands, tidal projects need the revenue part of this formula to be a high percentage of total availability (80%+). Obtaining sufficient warrantees and guarantees for this is challenging. One way in which Government can help tidal projects is by underwriting a portion of this risk, ensuring projects do not breach their debt covenants.

This barrier is creating issues for projects that connect to the grid. It will be a larger barrier for alternate offtake agreements, where the counterparty risk is higher than for grid-connected projects, and therefore project financiers will want greater guarantees for debt servicing.

4.2 Potential business models

This section examines the qualitative business cases of the six shortlisted alternative offtake opportunities.

The use of private network CfDs makes the use of any of these business cases significantly more attractive. However, the use of a private network CfD is likely to make the economics of tidal projects utilising alternative offtakers more difficult. This is due to the strike prices for CfDs being set for projects that are able to sell to the grid whenever electricity is generated, as discussed above the lower capacity factors of an alternative offtake project will increase the cost of the project, but to be granted a CfD they will have to compete with projects without this constraint. This is also true of projects with higher counter party risk, and therefore higher costs of capital. Using the CfD removes the ability to be flexible on price and is unlikely to reduce the cost of capital for tidal projects looking to sell to alternative offtakers, as the risk is generated by the high counterparty risk, relative to selling to the grid. For example, an individual business has a risk of ceasing to trade, whereas the grid does not.

4.2.1 Small-scale generation

One potential business model highlighted as a case study in the stakeholder engagement chapter, [redacted] was a model based on small-scale energy production.

This model sees small turbines of approximately 50 kW deployed for use by a single non-energy intensive business (a hotel for example). A turbine of this scale would generate enough electricity for the business when it was operational and the business would continue to draw power from the grid when the turbine was non-operational. A battery could be installed to smooth power supply and create a better synchronisation between supply and demand. This business model would likely require, or will benefit from, FiTs or smart export guarantees for businesses operating these turbines, in a similar way to residential solar installations. While batteries allow the user to shift electricity generation through time, the cost of doing so is high, and economically, in most cases, it makes more sense to draw from the grid rather than deplete batteries.

This model would also address the cost side, though not completely. Tidal generation is expensive for two reasons; high cost of capital, and high capital expenditure per MWh. Small-scale projects can reduce both. Firstly, if businesses are able to fund projects off their balance sheets, or at least significant portions of them, the cost of capital will be lower due to reduced or non-existent borrowing costs, due to lenders views of tidal as a non-bankable technology.

The high capital expenditure per MWh is also addressed, as deployment at this scale does not meet the Environmental Impact Assessment (EIA) threshold and therefore development costs are lower, though there are still consenting requirements. It is unclear how far this will bring down the cost of electricity generation. In the short-term it is likely to make it competitive with diesel electricity generation.

The stakeholder engagement highlighted that "final-mile" connection to offtake was still a challenge, and grants or subsidies would go a long way to making this type of business model more viable.

There are also two key regulatory hurdles constraining this type of business model.

- Lack of FiTs. Without FiTs the business model suffers from supply and demand mismatch outlined earlier. The offtaker will need to draw from the grid when tidal generation is insufficient, or procure excess capacity and store this in batteries/as fuel. Having FiTs requires a grid connection, and therefore the supply and demand mismatch will no longer be a problem.
- [redacted], they highlighted one of the hurdles as being the threshold for EIA creates a gap between small-scale deployment and utility scale deployment, as these costs are largely fixed and render deployment between very small-scale and utility scale projects difficult due to a high ratio of development costs per MWh.

This model has potential to transform the way small remote businesses generate their electricity, however, given the nature of this small-scale deployment this may not have a material impact on reaching industry ambitions of tidal deployment.

4.2.2 Displacement/replacement of fossil fuel generation

This alternative offtake has the most potential to work as a viable business model from an economic perspective, though there is increased counter-party risk due to having only one, or at best, several offtakers.

Diesel generation is expensive compared to buying from the grid, as well resulting in negative externalities. The LCOE of diesel generation is difficult to pinpoint, due to how dependent it is on input fuel costs, however it ranges from £250 - £600/MWh (2012 prices) dependent on a variety of factors. Tidal generation is competitive against this cost, though there would be barriers. Firstly, tidal's variability still poses a challenge, and batteries are required to allow for a consistent supply of electricity. This increases the cost, but not enough to make it uncompetitive with diesel generation. Second is finding businesses with suitable demand profiles for this. Businesses must meet the following criteria:

- Located close to tidal regions
- Require sufficient power to ensure there is adequate demand
- Use fossil fuel generation as their main source of electricity
- Consistent and predictable use of electricity

Finding enough businesses to allow this model to significantly change deployment profiles will be challenging, given that developers will be taking significantly more risk than if they were selling to the grid (if the counter party of the PPA becomes insolvent, etc.), the LCOEs are likely to increase significantly due to higher cost of capital. Potential offtakers may also take a more conservative approach themselves, as receiving power from a technology that is not fully de-risked increases risk within their business significantly. Other barriers include time to develop projects comparative to installing diesel generators and reliance on batteries.

To support this business model, businesses and developers would need assistance managing the increased risk. From the developers' side this can be achieved through insurance products. From a businesses' point of view, further maturing of tidal is the main way in which this risk can be reduced. Faster consenting will also make this more attractive.

4.2.3 Community projects

In stakeholder engagement calls with people working on or with community projects a number of findings came out. Firstly, stakeholders were enthusiastic about renewable energy and were happy to consider tidal as part of their approach/portfolios. Grid constraints meant that significant amounts of electricity came from diesel generation or burning of other fossil fuels in some communities, making them candidates for tidal projects.

However, tidal energy did not always suit the needs of their communities. The main concern was that stakeholders had a low risk threshold and tidal was not seen as a de-risked technology. This is important because communities typically are not able to make more speculative use of available funds, and where they put their money must have a very high likelihood of creating a return.

Other concerns were the imbalance of the scale of tidal projects to community needs. Tidal projects are typically larger than electricity demands of all but the largest remote communities meaning excess electricity needed to be either stored or sold back to the grid. A typical household in the UK uses 8 kWh per day. However, many parts of Scotland, particularly in island and remote settings, are not representative of the average UK household, primarily because they are not connected to the gas network. It is likely that their electricity usage will be higher due to the uptake of air and ground source heating. Furthermore, this is expected to increase further as EVs become more widely used. Small-scale generation is difficult to match with small communities, as coordinating demand and supply across multiple users is challenging. At a national level, supply of electricity is matched to demand; to make this practical at a small-scale, this will need to be flipped so that demand matches supply. Technologies are evolving that will allow this to happen, such as smart appliances, EVs and batteries for domestic use, which can all make this more feasible: though it remains to be seen how flexible demand can be. Energy demand for heating, for example, cannot be flexible, so using electric heating (heat pumps) combined with batteries is one potential solution. However, creating the incentives for this work is beyond the remit of CES.

An additional barrier highlighted was the short application periods for funding make coordination within communities challenging given the comparatively high number of decision makers.

Onshore wind projects have been built successfully on the small-scale generation model, and in these circumstances they overcame the barriers identified above. Grid capacity was available to sell excess electricity, the economics of wind projects are simpler due to the cost of building these projects being more consistent and known. And most importantly wind power is seen as a de-risked, and bankable technology making financing, insuring, etc. simpler.

Provided community projects can get a CfD for their projects, the economics of this business model can work. There are concerns around how practical this is, and much of this will depend on what coordination among energy users is possible and how quickly technologies that allow more flexible energy use are adopted.

4.2.4 Hydrogen offtake

Hydrogen offtake presents a potential business case. There are two broad approaches that can be considered.

- Pure hydrogen offtake model. 100% of electricity generated by a tidal project is used in creating hydrogen.
- Hydrogen co-location. A business, or businesses, are co-located with a hydrogen electrolyser to use electricity when the businesses are unable to.

4.2.4.1 Pure hydrogen offtake

This model is possible from a financial perspective. Hydrogen produced on location will be cheaper than shipping in hydrogen from somewhere where it is produced cheaper, due to how difficult and expensive hydrogen is to transport.

The challenge for this model will be finding the right offtake, which would need to be close to a tidal resource and have sufficient demand for hydrogen. Hydrogen has been used in industrial applications for some time, however, these industries do not typically exist in remote locations due to their energy intensive nature. Offtakers that fulfil both requirements will be limited, however, in these instances a viable business model can be made.

One industry that is keen to adopt hydrogen is the whisky industry, due to the high temperatures that it can achieve when combusted, thus helping to improve product quality. Whisky takes approximately 17 kWh to produce 1 l, and therefore a 7.8 MW[8] array is required to produce 1m litres of whisky, (for reference Ardbeg on Islay produces approximately 1.25m litres per year).

4.2.4.2 Hydrogen co-location

This model would see a business, or businesses, as offtakers for a tidal project co-located with a hydrogen electrolyser. In this model the businesses would replace or supplement their electricity use with the tidal project's output, and when there is no demand from the businesses the electrolyser will run. This hydrogen business model is more difficult financially, as having an electrolyser sit idle while electricity is being used by another source will significantly increase the LCOH, as the capacity factor of the electrolyser will decrease.

4.2.5 Ports and harbours

In speaking with ports, no clear alternative offtake business model was highlighted, but several challenges and barriers were identified. The most pressing of these challenges is technology readiness and appropriateness, which is driven by several factors mainly related to ports being quite conservative in their approach to risk.

Both Shetland and Orkney ports were very keen to use green technologies where possible, but within their operations, which had not already been decarbonised, there were few opportunities to decarbonise their businesses further and provide offtake opportunities for tidal. An example given was the use of tug boats, which often "push-off" large vessels during high winds. This task cannot be performed by an electric tug due to the increased weight and

[8] (1,000,000 x 17) / (1 x (8,760 x 0.25) x 1000)

decreased range/operating time on a single charge. Safety concerns, similar to this are significant concerns for ports, and are barriers to adopting new technologies.

Other options such as offering electricity to ferries to charge batteries was not feasible. Electric ferries were not seen as useful for inter-island use, due to the larger battery requirements and reduced cargo space. For shore power, retrofitting vessels used privately was expensive, and vessel operators were unwilling to take on this cost.

Offering alternative fuels are being constantly reviewed by the ports, however, they are not practical given at this stage it is unclear what technology/fuel type will be the most common.

Lastly, as ports are run as commercial ventures, decisions needed to made to future-proof their businesses. Vessels are expected to be operational for 25+ years, meaning choosing the wrong fuel type will impact long-term finances significantly. Without providing significant sources of funding, ports are unwilling to take the risks required to adopt tidal electricity generation.

4.3 Business model impacts on tidal deployment and recommendations

4.3.1 Impact on deployment

Table 5 shows the impact of the different models assessed across the two identified metrics for creating a successful business case, as well as the impact each business model will have on reaching deployment targets.

Business model	Matching supply and demand	Comparative cost to wholesale prices	Impact on deployment ambitions
Small-scale deployment			
Fossil fuel generation displacement/replacement			
Community projects			
Hydrogen offtake			
Hydrogen co-location			
Ports and harbours			

Table 5 | Review of business models

5 Offtake opportunities for key resource areas

Chapter 4 showed that both the replacement of fossil fuel generation and hydrogen production had the strongest business cases for both matching supply and demand and the comparative cost when compared to wholesale values. Furthermore, hydrogen production has the ability to contribute to the tidal targets, thus removing some of the reliance on the National Grid for the tidal deployment targets.

This chapter evaluates these use cases in more detail. It provides examples of some of the work that is needed to understand how these businesses can implement the offtake model and high level modelling to understand the magnitude of deployment required. This work is conducted at a superficial level for this project and it should be considered that a detailed implementation for each site will involve its own multi-stage project that will span several years.

5.1 The use cases for evaluation

Three scenarios were chosen for detailed evaluation, each building on the previous scenario. These were as follows:

5.1.1 Diesel replacement

The replacement of fossil fuel generation for electricity generation has applications in many remote communities. The diesel generator at Barra and Vatersay was modelled to understand the scale of tidal deployment required and to give an example of some of the factors that need to be considered when making site selection.

5.1.2 Tidal → hydrogen

Hydrogen can be considered for industrial applications: distilling is an early adopter in Scotland with several demonstration projects approaching commissioning in 2025, including the Protium project on Islay. This project was chosen to look at how the alternative offtake model might be applied to this important Scottish industry.

5.1.3 Tidal → hydrogen → synthetic hydrocarbons

Synthetic hydrocarbon technology is currently at an earlier stage of development but is maturing quickly due to investment and its potential to contribute significantly to the decarbonisation of the wider energy system landscape. This final model looks at how the Pentland Firth tidal resource could be connected to a large production facility on Flotta, making use of the facilities that are currently being decommissioned by the oil industry and utilising the skillset of the local workforce to transition to this new green industry.

5.2 Generic turbine model

For the detailed modelling in this section a generic tidal turbine array is referenced, which is used to give indicative quantitative calculations. This is based on the following assumptions:

- 200 kW turbines
- cut-in speed of 0.8 m/s
- rated speed of 1.7 m/s
- a generic cubic power curve matching (to a reasonable degree) currently available technology, as shown in Figure 7
- This results in a rotor radius of approximately 8.3 m

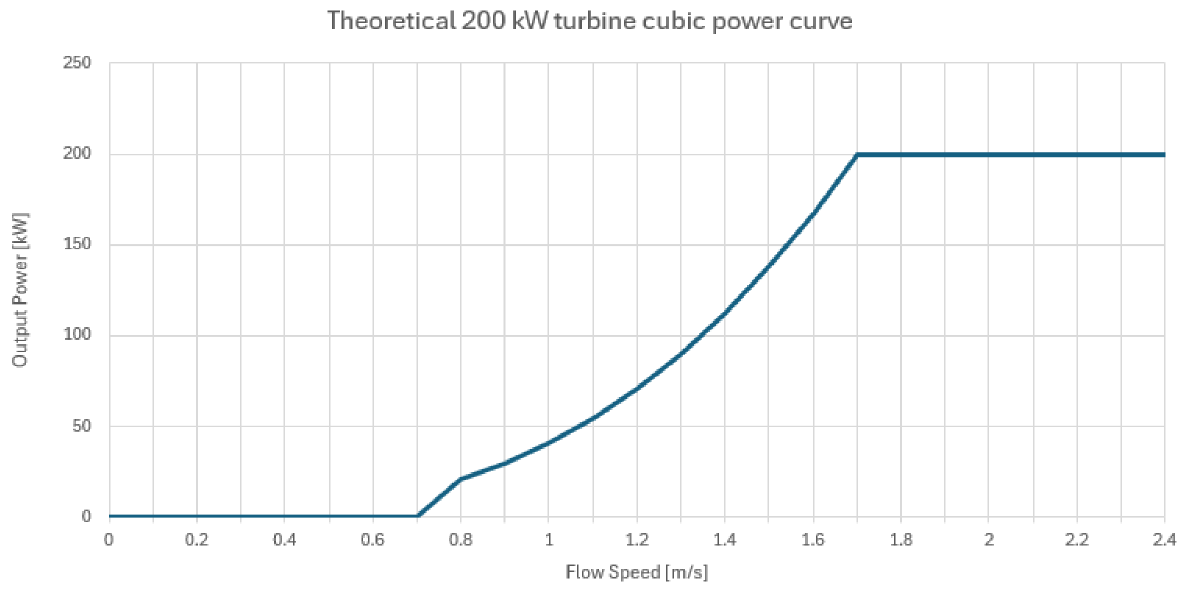


Figure 7 | Theoretical cubic power curve for a 200 kW TEC with cut-in speed of 0.8 m/s, and peak power achieved by 1.7 m/s (i.e. tuned for expected flow)

It should be noted that this power curve is entirely synthetic, but broadly matches smaller tidal devices in existence today. In practice, detailed work would be done to analyse the characteristics of the local tidal resource and then match the tidal generator to these.

5.3 Diesel replacement

Non-grid connected communities exist that have wind and solar generation, with diesel backup. Because of the lack of grid connection, these are clear candidates for use of tidal energy. Many other communities have a single grid connection that is heavily constrained, limiting the viability of adding additional intermittent renewables, and this is backed up by diesel generators. One such example is the circuit to Barra and Vatersay in the Western Isles.

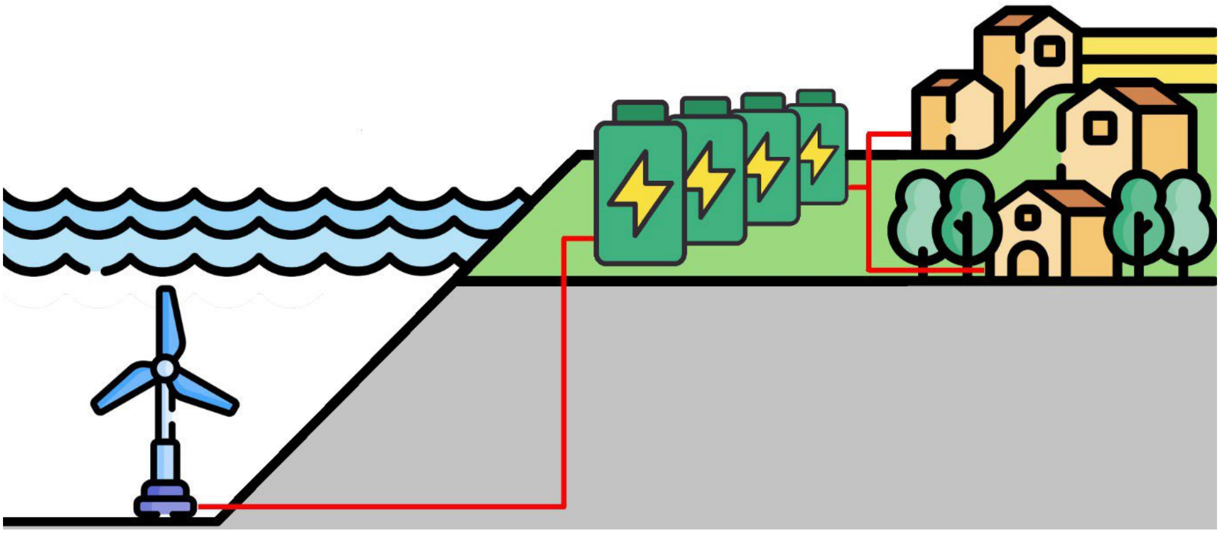


Figure 8 | Diesel replacement: tidal turbine/array + storage as drop-in replacement for local diesel generation

Other locations may have grid connectivity via two connections but retain diesel power generation infrastructure as part of the redundancy component of the network resilience strategy. Kirkwall in Orkney is an example of this.

5.3.1 Example evaluation: Barra and Vatersay

The Barra and Vatersay area has a population of 1,296 (Scottish Government, 2024) and is one of six islands participating in the Community Energy Scotland Carbon Neutral Islands project (MacLeod, 2023). It has an energy plan (Interreg, 2018. Community Energy Scotland, 2018) that details the main source of electricity as an 11 kW circuit that is connected into the grid via a supply point at Loch Carnan, through which supply is lost whenever work is conducted on either the distribution or transmission network. Back-up is provided by the local community power station, which runs on diesel, generating 2.1 MW. There is also a single 900 kW community owned wind turbine, but no other large renewables can be added to the area due to export constraints making projects unviable.

The Barra and Vatersay energy plan identified an action of 'explore community opportunity for collective install of solar PV…Promote other small-scale renewables as suitable for homes/businesses' (p 33, Interrig, 2018). Tidal power was considered, but ruled out at the time due to the CfD being the only means of funding, thus making securing investment difficult and therefore only multi-MW scale projects typically being developed that would be constrained and unviable (pp 27, 36).

SSEN has modelled that all Scottish Island power stations, including Barra, will be decommissioned by 2040 at the latest, with 2035 being targeted. This modelling suggested in the 2022 plan that the diesel power station would ideally be replaced by hydrogen fuelled generation (p.82 SSEN, 2023), however, by the 2023 plan this was replaced by biodiesel run on the same equipment until a study of alternative fuels was complete (p125 SSEN, 2024). One reason for this may be that approximately 50 kg of hydrogen is required to produce 1 MWh of electricity, this would likely require the hydrogen storage to exceed the 5 tonne lower tier limit for control of major accident hazards (COMAH)[9], in order to store enough hydrogen to provide a meaningful level of resilience.

This is the type of community that would be an ideal candidate for tidal to replace diesel generation. Small to mid-sized tidal turbines exist and would be most suitable for this location to give resilience and tidal technology has made significant advancement since the original energy plan was written in 2018. It should also be noted that 11 kV circuits are available as far as Vatersay, which is 17 km from Barra Head, as this may be much closer to a tidal deployment if one were feasible between Vatersay and Sandray.

The local energy plan showed that CO_2 emissions for 2018 were 5,362 + 698 = 6,060 tonnes of CO_2 that could be attributed to electricity generation, as shown in Table 6.

Source	Annual energy use (GWh/yr)	Annual carbon emissions (tCO_{2e}/yr)
Residential, *of which:*	**32.3**	**9,714**
Electricity	13.9	5,362
Heating	10.8	2,487
Transport	7.6	1,865
Non-domestic, *of which:*	**11.0**	**2,968**

[9] At full power 5 tonnes of hydrogen would last 5000/(2.1 x 50) = 47.6 hours, or less than 2 days. In practice, the generator would not run at full capacity, however reserves would need to last substantially longer, and hydrogen presents challenges for transportation.

Source	Annual energy use (GWh/yr)	Annual carbon emissions (tCO_{2e}/yr)
Electricity	1.8	698
Heating	1.3	324
Transport	7.9	1,946
Total (all sources)	**43.3**	**12,682**

Table 6 | Table of Barra & Vatersay energy use and carbon emissions (Community Energy Scotland, 2018)

It is possible that this figure has risen to encompass increased use of electric transport and heat pumps for domestic heating since 2018, but it has not been possible to estimate this with accuracy at this stage. It is reasonable to assume that all vehicles will transition to electric vehicles and heat pump use will increase within the study period, as recommended in the energy plan, thus moving the energy demand from fossil fuels to electricity and increasing electricity consumption on the island. This will not be a direct transfer of MWh from heating and transport to MWh for electricity, as improvements in efficiency and other energy conserving measures could see an overall energy reduction.

A comparison of diesel generation and potential tidal generation is shown in Table 7. However, SSEN has already stated that they are committed to retiring the diesel generator. Replacing this by tidal energy will be expensive, given the additional outlay and ongoing maintenance required, together with the need for battery storage. However, the current SSEN plan to replace the diesel with hydrogen fuelled generation, will not only incur high costs, but may also cause concern in the local community due to the need to establish and maintain a hydrogen COMAH site.

Concern	As-is diesel generation	Potential tidal implementation
Generation hardware	Exists, may have debt outstanding	New, would require finance, and would require significant outlay. Size of equipment needs to be evaluated for tidal resource available, and to cover equivalent diesel operation during neap tides. Timing for eventual removal of the existing diesel plant would need to be confirmed, but would be much reduced, potentially only needed as backup for neap tide conditions or not at all.
Transmission links	Exists, requires maintenance on land, currently budgeted.	In addition to existing links, new sub-sea links would be required to get power to shore. Maintenance and monitoring of these cables would need to be put in place. Marine maintenance can be expensive.
Availability	Fuel availability only.	Tidal cycle only, unless additional storage is implemented. Storage cost will be based upon usage required between tidal cycles.
Storage	Fuel storage only.	Lithium-ion is most mature technology, but remains expensive, and has a relatively short lifetime usually expressed in charge cycles after which it needs to be replaced. This could be required multiple times in a 15-20 year period. Other battery technologies may be more suitable, cost effective, and are evolving

Concern	As-is diesel generation	Potential tidal implementation
		rapidly to meet the challenges of the climate emergency.
Permits	In – place.	Screening/scoping for Section 36 consent (>1 MW) is required including onshore infrastructure. (Cost ~£250,000)

Table 7 | Concerns relating to diesel vs tidal energy

5.3.2 Sizing and location of replacement tidal array

This evaluation is based on replacing the 2.1 MW diesel generator with the generic medium tidal turbines as described in 5.2. A typical capacity factor for tidal power has been assumed based on Verdant Power having reported a capacity factor of 42% in high availability running (Coles et al, 2021(2)) whilst others reported very low capacity factors during testing phases, or did not release them. Using these numbers and current industry knowledge EMEC has assumed the inclusive capacity factor, i.e. with downtime, for pre-commercial turbines as 35%. Using this figure gives the estimation that approximately 6 MW of tidal generation would be required.

It is then possible to take a hydrodynamic modelling approach to the environment around Barra. Using the DHI MIKE Hydrodynamic model[10], with bathymetry from General Bathymetric Chart of the Oceans (GEBCO)[11], and high-resolution coastline from the National Oceanic and Atmospheric Administration datasets[12], a model of the Hebrides can be constructed.

[10] https://www.dhigroup.com/technologies/mikepoweredbydhi

[11] https://www.gebco.net/data_and_products/gridded_bathymetry_data/

[12] https://www.noaa.gov/nodd/datasets

Figure 9 | Modelling domain for the Hebrides, showing boundaries and finite element mesh, close-up on Barra

.

Tidal constituents from the DHI global tide database are used to force the tidal flow at each of the boundaries with node markers 2-6, at the edge of the model. Areas close to Barra power station have limited tidal depth, so selection of the target deployment area for tidal will be key and will also need to consider sedimentology effects.

Initial results, while not formally validated, suggest a peak flow of approximately 0.9 m/s in the channel between Barra and South Uist, north of Fuday and to the east of Lingay. This area is some 9 km from the Barra power station, and approximately 4 km offshore from the nearest point of the local transmission network. The depth of this location is shallow, at between 9 m and 5 m, according to GEBCO. As a result, it is likely that this location may be unsuitable, without a specifically designed tidal device, due to the depth and lower cut-in speed than exists at present. Sediment flow could also pose a concern.

Given the limitations of the tidal resource near the current power station, a wider look was taken for other tidal resources around the island. Alternative resource exists to the south of Vatersay, accessible via Bagh A'Deas, in the channel directly offshore, north of Sandray. According to the UK Hydrographic Office [13], this channel is around 12 m deep, so is unlikely to support turbines of the required size. A larger area of significant flow (approximately 1.2 m/s) is also present in the channel between Sandray and Pabbay, less than 4 km distant,

[13] UK Hydrographic Office, Admiralty Seabed Mapping Service: https://seabed.admiralty.co.uk/selected-items?x=-841672.38&y=7735559.72&z=12.54 – dataset "2012 HI1361 Barra Head to Castle Bay Blk 1-4 2m SB"

offshore. This could be a better location for a tidal array, given marginally faster flow speeds, and bathymetry around approximately 25 m in depth.

EMEC have been unable at this stage to obtain an accurate tidal prediction for the site. However, approximately 0.9 m/s maxima in the area concerned aligns with previous estimates by ABPMer, which were insufficiently detailed to resolve the local flow speeds.

With the theoretical 200 kW turbines modelled, only the remote location between Sandray and Pabbay would be viable and would require an array of up to 30 turbines (at 35% capacity factor) to completely replace the diesel power station, even if local energy storage solutions could be found.

Given the lower flow speeds in this area, a kite style tidal turbine, such as the Minesto[14] which is currently being installed in the Faroe Islands, may be more suitable for the Barra Power Station replacement, pending detailed evaluation and planning.

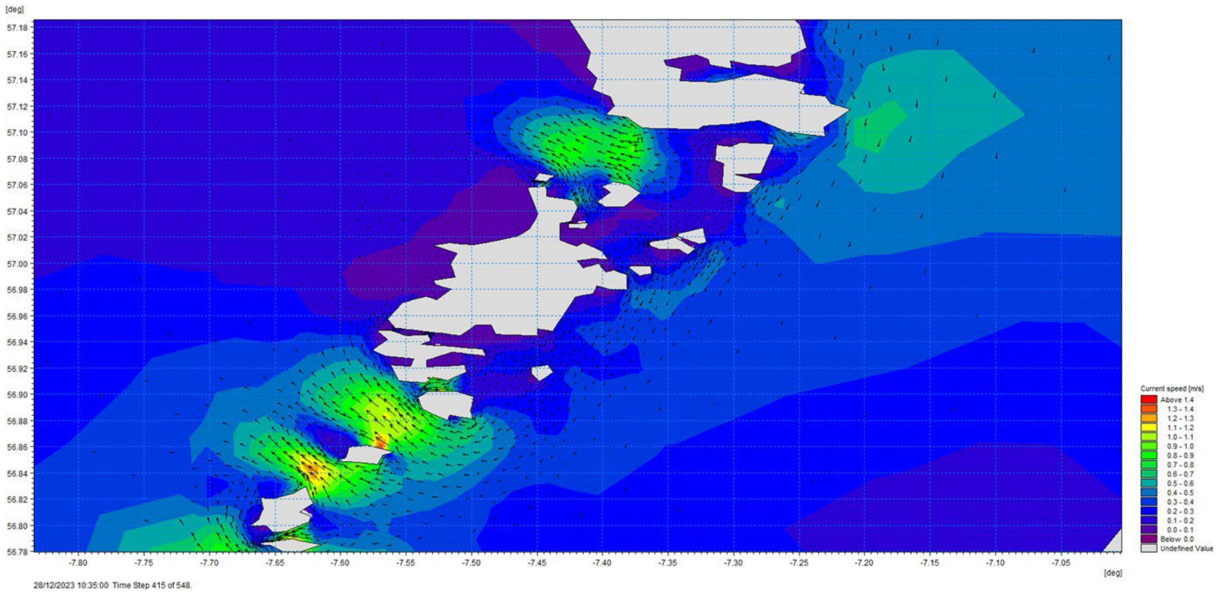


Figure 10 | Ebb flow from an exploratory run of DHI MIKE 21 Hydrodynamic model (EMEC, 2024)

5.3.3 Benefits of modelling

It should be noted that this modelling is preliminary at this stage and is showing anomalous computational effects at the boundaries. However, it does demonstrate how useful this type of modelling is to being able to determine whether suitable tidal resource is located near a potential offtake opportunity, or vice versa.

Further work is clearly required to plan any such tidal deployment. This should include both modelling and device design work, including careful selection of pre-existing devices followed by further optimisation to the flow speeds and water depth at the selected site.

If offtake opportunities are to be identified on this more local basis, then a high-resolution, validated model of the entire Scottish coastline should be prepared for siting purposes, as organisations are unlikely to consider tidal energy without easy access to the available resource. It is advised that this modelling should include detailed assessments of proposed community sites, considering the presence of other renewables (i.e. wind, solar) as well as energy storage. These should consider historical and future energy usage, as well as

[14] https://minesto.com/our-technology/

meteorological and oceanographic variables and modelling. A framework for such assessments could be developed and adopted as a standard for fast-tracking such schemes.

5.3.4 Summary of Barra and Vatersay

From this initial analysis, the following recommendations for further investigation of the viability of deploying tidal energy at this site are made:

- Further investigation of the viability of siting a tidal farm in the channel between Sandray and Pabbay. This should include detailed planning and modelling.
- Investigation of the suitability of smaller tidal devices with lower cut in speeds and greater efficiencies in the range 0.5 m/s – 1.5 m/s.
- Investigation and sizing of new power storage technologies with 10 hour cycles and extended design life such as the vanadium flow batteries that are installed at the EMEC Caldale site.
- A streamlined permitting and consenting approach, up to 6 MW output to facilitate the local community involvement.

Tidal energy remains a potential reliable contributor for complete decarbonisation of remote communities: but will require significant investment, planning and operational readiness activities.

5.3.5 Further notes of larger communities: Kirkwall/Orkney

The other grid connected diesel generators within the SSEN area are listed in Table 8.

Name	Capacity (MW)	Commissioned
Barra	2.5	1986
Bowmore	6.0	1946
Kirkwall	16	1951
Lerwick A and B	65	1953 & 1996
Lerwick back up	6	
Loch Carnan	11.8	1971
Stornoway	23.5	1950
Tiree	2.5	1980

Table 8 | List of diesel generators in SSEN plan (SSEN, 2024)

Kirkwall in the Orkney Islands is an example of where a backup diesel generation plant exists, 16 MW in this case, but the community itself is grid-connected via 2 cables.

The local grid typically draws 15 MW on average, ranging between 6 and 35 MW over the course of a year. A battery to handle any outage of this scale would be cost-prohibitive. While there may remain a requirement for redundancy in the resilience plan, this is more likely to form part of a micro-grid with the significant amounts of renewables already on the islands, of which tidal is playing a growing part, as well as wind, solar and other local micro-generation.

5.4 Hydrogen for industrial applications

There have been efforts to decarbonise the whisky industry resulting in some pilot schemes. One scheme, present on the isle of Islay, has led to the use of hydrogen for generating steam to use as heat in the distillation process, displacing the use of diesel for this purpose.[15]

[15] https://protium.green/bruichladdich-distillery-announces-2-65m-funding-to-partner-with-protium-and-jericho-energy-ventures-on-major-step-towards-decarbonisation-distillation/

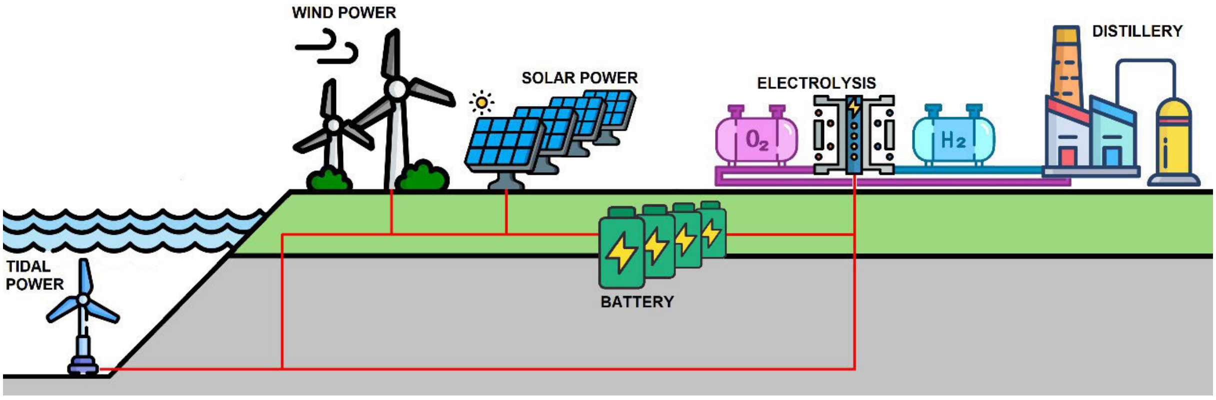
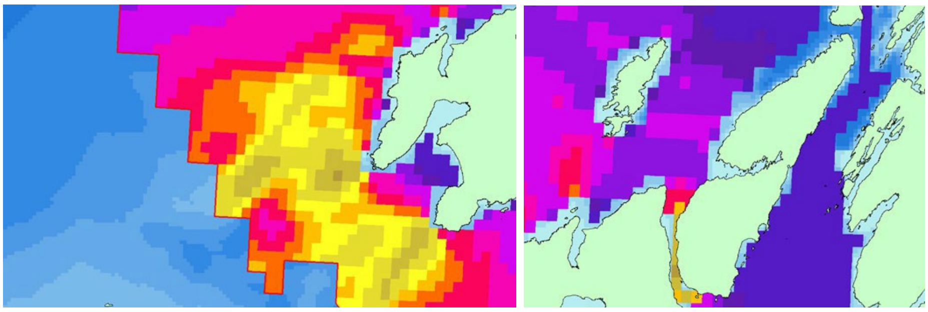


Figure 11 | Decarbonisation of a distillery (e.g. Bruichladdich, Islay)

On Islay, Protium have deployed a heating solution for distilleries that uses hydrogen and oxygen from electrolysis powered from renewables. Electricity for the trial is currently being supplied via a grid supplied renewable PPA, however there are plans to expand this solution to other distilleries on Islay. As a result, Protium are currently considering installing renewables to generate the level of electricity required for their ambitious expansion plans: [redacted] Protium would prefer to not be a generator and so would be interested in using tidal, particularly given the reduced battery capacity and increased predictability. Renewable power can be supplied directly to the electrolysers, or taken from storage, to ensure consistent operation. The hydrogen and oxygen are combusted in a vacuum, thus avoiding NO_x emissions, to generate high temperature hot water and steam in a stoichiometric reaction. Once the water has passed through the heat exchanger tubes, it is collected and then fed back to the electrolysers, thus forming a closed loop system that avoids water purification (Protium, 2020).

Tidal resource on Islay is concentrated to the south-west. There is an area of strong tidal flow to the north-east in the channel between Islay and Jura. There are two consented tidal projects in the channel, but none in the area to the south-west, although a previous lease agreement for 30 MW from CES had been granted to DP Energy Limited, with the stated intention of expanding to a 400 MW West Islay tidal farm[16], although this project has now been handed back to CES.



[16] West Islay Tidal Farm, Scotland (power-technology.com)

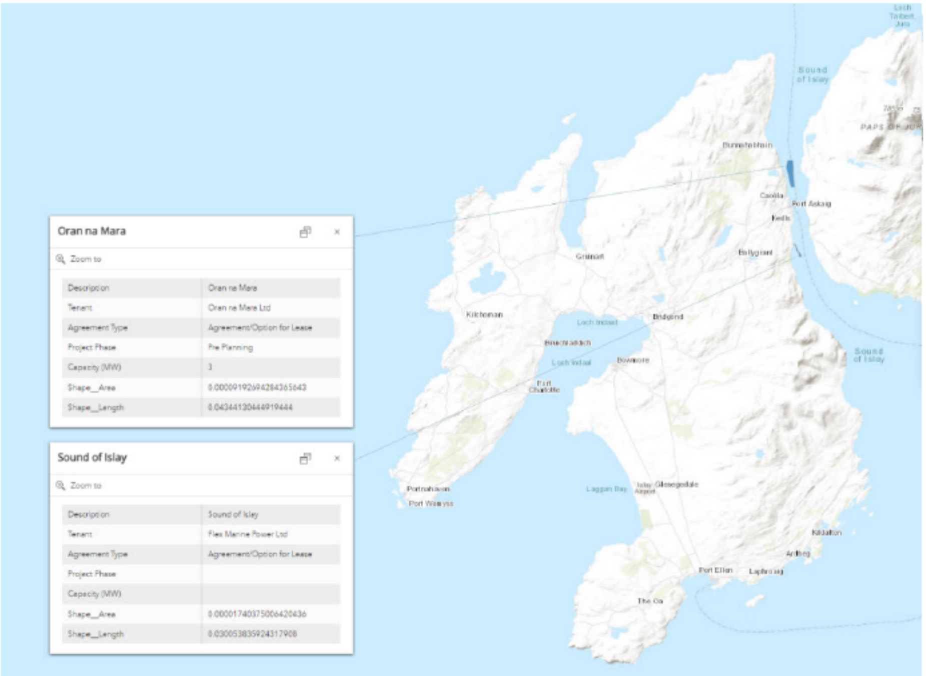


Figure 121 Tidal consented areas (CES) and resource **(ABPMer)**

Redacted – EIRs 10(5)(e) Confidentiality of commercial or industrial information

This power is currently planned to come from either locally generated wind or solar due to grid constraints. [redacted]

Tidal power would assist in reliability of power for the electrolysers. Solar is clearly diurnal in nature and much lower generation during winter months, particularly this far north. Wind is less predictable for systems that rely only on local generation.

It is also worth noting that the intention of this project is to only use renewables as decarbonisation is the intent. Bearing this in mind, tidal would be a good reliable source of baseload to add to the generation mix for their project and would potentially reduce the amount of storage required for smoothing, although solar and wind may be added to reduce risk.

As a result, renewables generation may be split between solar, wind and tidal, although a further exercise would be needed to calculate the ideal mix between solar, wind, tidal and storage to calculate the best balance between cost, reliability of supply and risk.

Connection is thought to be less of an issue, as private wire arrangements are used, although the cost of cabling will be a concern. Survivability will also need to be considered, especially if the high tidal flows to the south-west are chosen.

It would be recommended to perform an exploratory study into how tidal may assist in reducing cost of operations for this project, given the requirement to spread the baseload through the day, and the predictable nature of tidal power.

Other industrial applications do exist. An offtake for the SaxaVord spaceport would look very similar to that on Islay and there may also be opportunities for synthetic fuel production for some maritime applications.

5.5 Hydrogen for synthetic hydrocarbons

5.5.1 Background

The Flotta oil terminal has been a significant part of the UK's success in exploiting North Sea oil. Approximately 10% of oil landed has passed through the Flotta terminal.

Originally designed to handle approximately 470,000 barrels a day of oil, from the Piper field for trans-shipment by tanker, the facilities have gone through several evolutions as fields have matured and handling techniques have altered. The sites now handles approximately 40,000 barrels a day and some decommissioning work has already been undertaken to remove derelict lines.

[redacted]

Having played such a role in the energy past means that there is a legacy of both skills and infrastructure that provide an opportunity to be reused. Specifically the southern shore of the island makes up part of the northern flank of the Pentland Firth. The specific opportunity already identified and outlined in the Flotta Hydrogen Hub (FHH) proposals[17] is for the re-tasking of this infrastructure to produce hydrogen from renewables.

Redacted – EIRs 10(5)(e) Confidentiality of commercial or industrial information

The location of FHH next to the biggest single tidal resource in the UK clearly provides an opportunity to deliver predictable energy to FHH. The advantage to the tidal scheme is that a long grid-based connection will not be required. Given that FHH are already planning for a grid connection to Spittal, the introduction of tidal energy would enable this connection to be used more densely than presently anticipated. The short connection distance between any tidal scheme and the FHH would mean much lower connection costs than would be the case if tidal had to connect to Spittal.

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

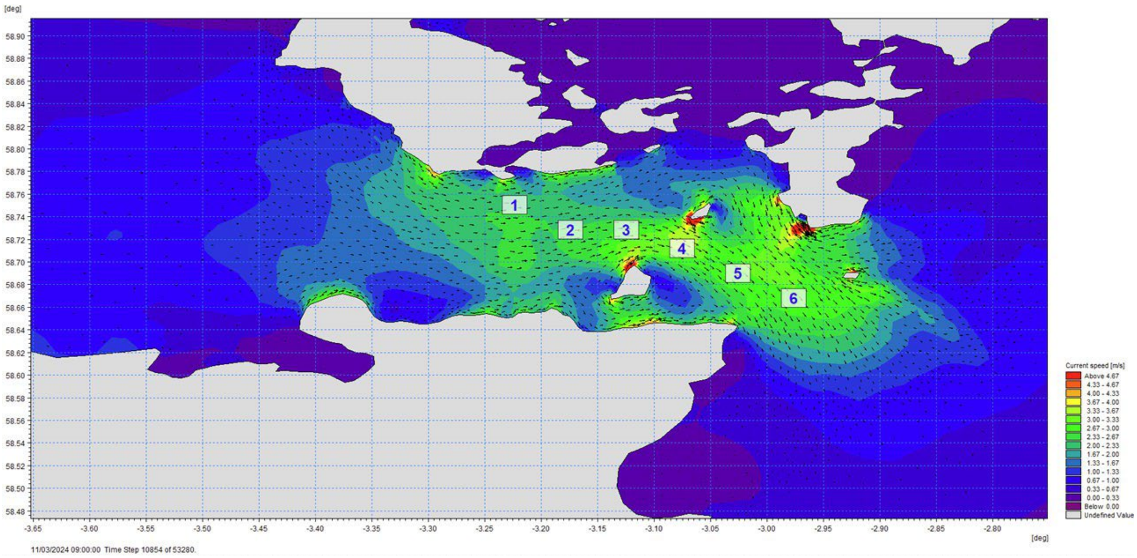


Figure 13 | Tidal resource (spring flood, 11th March 2024 09:00) - DHI MIKE 21 Hydrodynamic model (EMEC, 2024)

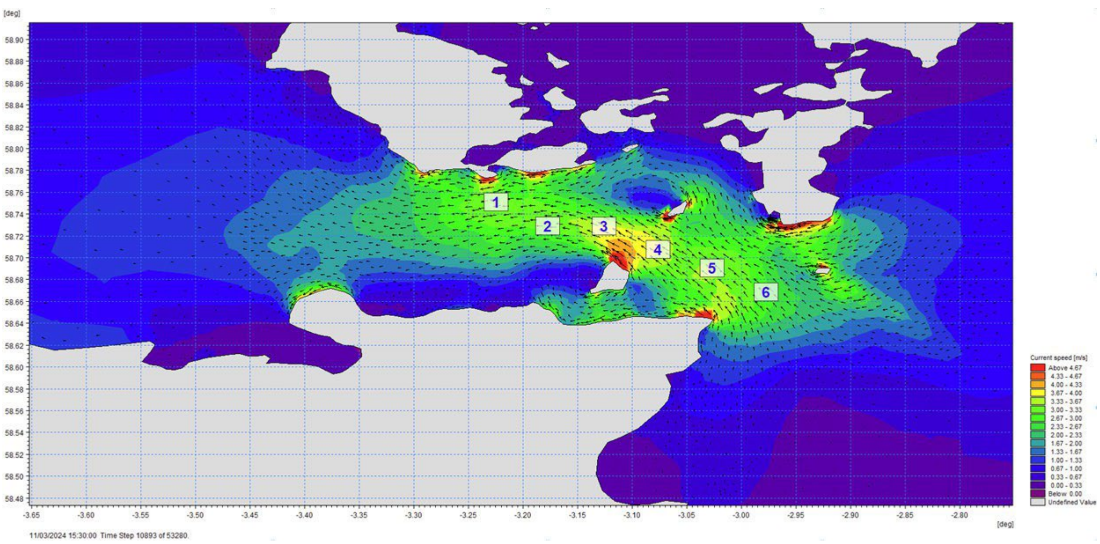


Figure 14 | Tidal resource (spring ebb, 11th March 2024 15:30) - DHI MIKE 21 Hydrodynamic model (EMEC, 2024)

Measurement points, marked 1 to 6, are shown on Figure 13 and Figure 14. These are representative only and chosen solely to demonstrate the magnitude of the main tidal flow in the Pentland Firth. Actual deployment locations for turbines will be adjacent to land, where higher flow magnitudes can be achieved.

Currently leased areas either in planning or operational stages are around the edge of this area, as shown in Figure 15. These have been extracted from the tidal dataset available on Crown Estate Scotland Spatial Hub.[18]

[18] https://crown-estate-scotland-spatial-hub-coregis.hub.arcgis.com/maps/e069d85f344a4d7193389c0adf27855e

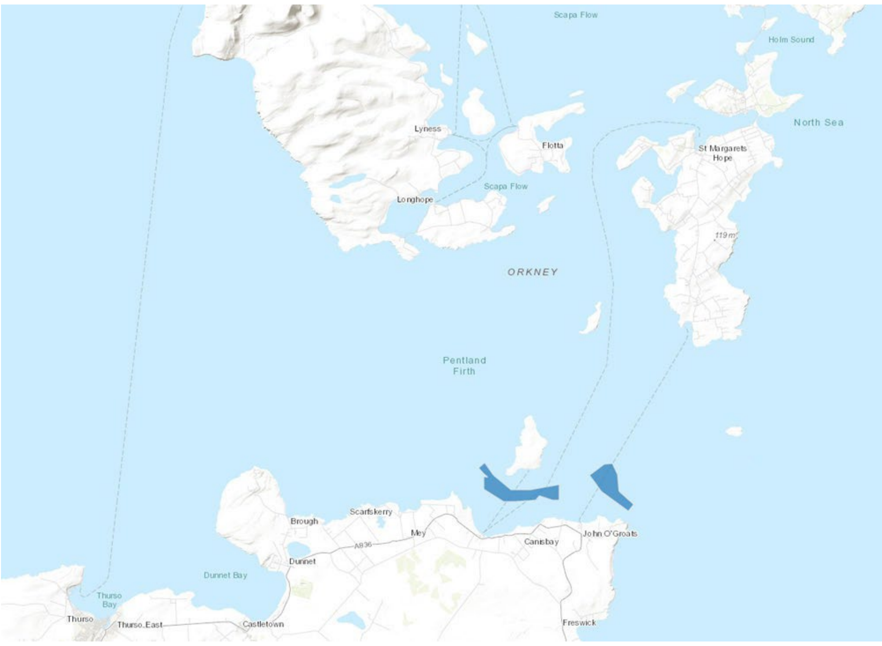


Figure 15 | Tidal consented areas in the Pentland firth (Crown Estate Scotland Spatial Hub, accessed 27 May 2024)

Deployments in the main channel would be challenging, but it is clear there is plenty of resource even outside of the main channel, with similar current speeds. Estimates of the total usable resource of the Pentland Firth vary but have been estimated as high as 4.7 GW (Adcock et al., 2011).

The route of the grid connection from Spittal to FHH is not detailed, however the siting of the link to also allow for connection of tidal power would be beneficial.

Figure 16 | Distance from grid connection point at Spittal to FHH, passing through area of high tidal resource

5.5.2 How much energy?

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There does not appear to be a particular limit to the size of the market and as present limits are more likely driven by available investment and risk appetite than they are technical constraints. However, it is understood that the site on Flotta could accommodate up to 1.SGW of electrolysis.

5.5.3 E-fuels

EMEC's extensive experience of working with hydrogen means that it has a view which is ahead of some contemporary thinking. EMEC's view is now that the use of hydrogen as a gaseous fuel is far more limited than some proponents have and continue to say. However, hydrogen is already a crucial feedstock in a multitude of industries (both local and further afield) and, as EMEC firmly believes, has the potential to become a major part of the feedstock necessary to produce synthetic fuels. Therefore, its production via renewable means is likely to be crucial, regardless of its utility directly as a transport fuel.

EMEC hosted a demonstration project which produced synthetic gasoline from electrolytic hydrogen. This gasoline was supplied to the RAF and used in their first ever fully synthetically fuelled flight. The breakthrough represented by this project arose largely from the far superior volumetric energy density of gasoline, with one litre of the hydrocarbon fuel having more than 17 times the energy content of one litre of gaseous hydrogen at 200 bar.

This increase in energy has significant implications concerning fuel storage and transport. Hydrogen requires high-pressure cylinders, whereas hydrocarbon fuels can typically be stored in non-pressurised containers, and are far simpler to transport via existing infrastructure, thus requiring smaller amounts of support and safety technology. EMEC's experience with liquid fuel synthesis suggests a ratio of 1:1000 should be achievable.

EMEC therefore firmly believes that the scale of the various liquid hydrocarbon markets need to be considered as part of a future study.

5.5.4 Conceptual model

There are two scenarios:

- **(A)** Hydrogen production
- **(B)** Synthetic hydrocarbon production

A is a much-shortened version of B. Therefore A can be considered as being part of B, as depicted below.

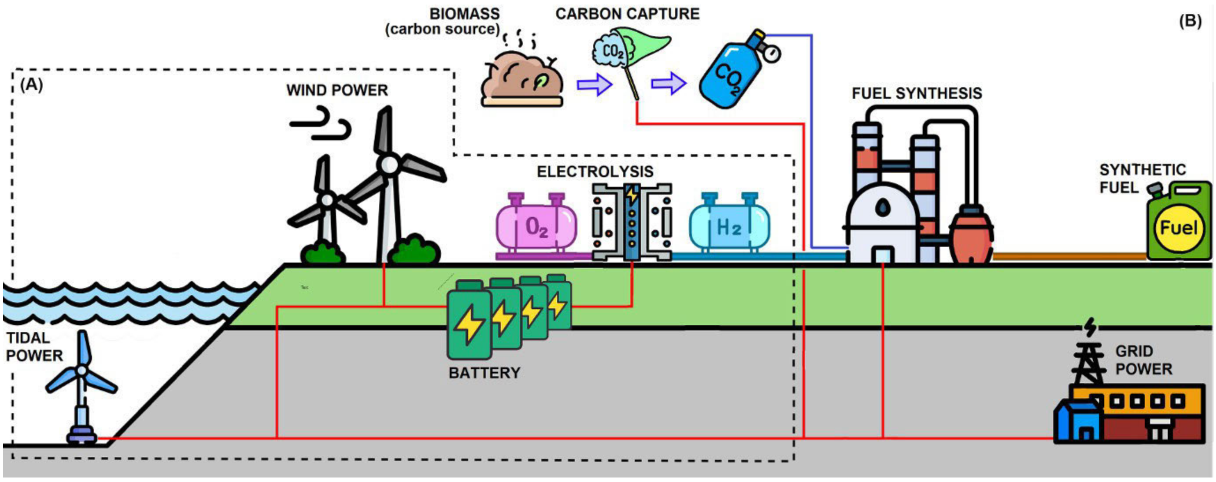

Figure 17 | Hydrogen and fuel synthesis conceptual schematic

Note: The power to carbon capture stage comes from grid – the red line depicting this bypasses the electrolyser, which is not involved, and is powered from battery for smoothing of supply and clean startup/shutdown

- Tidal and wind power are used to power electrolysis, with batteries for smoothing and ensuring supply. Electrolysers are not tolerant of energy supply spikiness and take time to start-up/shut down and reach optimum hydrogen purity.
- Electrolysis needs to be run continuously, provided storage for hydrogen exists (this is needed anyway).
- Various sources of CO_2 are currently being explored including direct air capture (DAC) and collection of CO_2 from sea water during the electrolysis process. When compared to biomass, these provide a longer term solution that is more suitable for colocation with tidal.
- Fuel synthesis and carbon capture can also use renewables when available, with grid power as backup, reducing power demand from grid.
- Excess tidal and wind power can also be returned to grid.
- Hydrogen and oxygen are produced during the electrolysis stage. Oxygen may be useful for specific applications (e.g. space/health industries/aquaculture) but may otherwise be vented.
- Fuel synthesis runs constantly if battery- or grid-connected (although dynamic operation is possible and may be beneficial for some aspects of production). Here, the largest contribution to the overall energy requirement comes from prior reduction of the CO_2 to CO. Due to the thermodynamic stability of CO_2, this is necessary for most transformations (particularly long-chain hydrocarbons) and can be achieved via a reverse water-gas shift reaction of electrochemical reduction of CO_2. As both of these processes require thermal input, heat may be recycled from the highly exothermic fuel synthesis, lessening the energy requirement somewhat.

In this way, batteries are used as an uninterruptible power supply for the electrolysis stage and to bridge times of slack water with little wind. Storage of CO_2 and H_2 are used to drive constant supply to the fuel synthesis stage. This minimises grid demand for fuel synthesis. Remaining renewable power can be supplied back to grid, after other demands from carbon capture and fuel synthesis are met.

Please note that at present, the carbon source will generally be biomass. Direct air capture is clearly desirable but is at a very early technology development stage. As the gasification of biomass yields syngas directly, the requirement for captured carbon and green hydrogen (and therefore the overall energy requirement) is reduced significantly. As well as the reduced energy requirement, the use of biomass in the initial stages also seems to make sense economically due to the local availability of feedstocks from agricultural, fishing, and distilling industries. Additionally, the use of a biomass route mitigates the need to rely too heavily upon lower TRL technologies such as direct air capture or CO_2 electrolysers, which can be incorporated as they reach technological maturity, and operations scale up to meet increasing demand.

5.5.5 High level numerical modelling

A time-based modelling approach can be selected based upon tidal resource models. Pentland Firth tidal flows are generally synchronous, so representative points can be selected for evaluation over a spring-neap period, in 10 minute intervals, in the absence of a wider Pentland Firth development plan. This can then be scaled against the required 500 MW of electrolysis for FHH.

It is noted that this is a very crude approach. Multiple points are selected because there may be marginal gains at the start and end of flood and ebb periods that could be obtained from a distributed set of tidal array developments in the Pentland Firth region. This would potentially extend the period of electrolysis slightly.

A tidal cut-in speed of 1 m/s is assumed, and a cubic power curve reaching maximum power at 2.5 m/s.

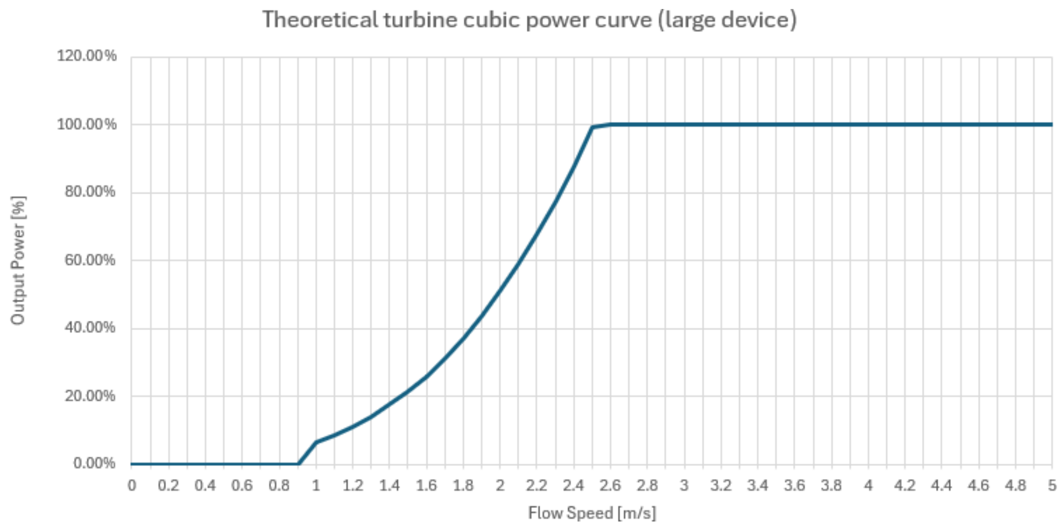

Figure 18 | Theoretical cubic power curve [%] with cut-in speed of 1.0 m/s, and peak power achieved by 2.5 m/s (i.e. typical of a large TEC, existing technology)

EMEC operate an electrolyser at the Fall of Warness grid-connected tidal power test site. This Electrolyser requires approximately 30% of rated power consumption for operation. It can also tolerate up to 10% of rated power change once in operation, per second. However, it is inadvisable to start up and shut down the electrolysis, since it operates optimally at 65% of rated power for continuous production, and optimum equipment lifetime.

Cold starts of the EMEC electrolyser take 300s, but after a cold start, hydrogen purity takes significant time (many days) to reach the 99.9% required. Desiccant in the drying towers needs to reach optimum temperature to work efficiently. Warm starts are quicker taking ~30s.

An assumption of 500 MW of input power is needed at the electrolysers for FHH.

To evaluate the tidal resource, an average of the 6 points in the Pentland Firth identified in Figure 13 and Figure 14 can be used. This can then be scaled to a power yield percentage using the power curve in Figure 18.

It is necessary to ensure constant supply, minus some overhead for carbon capture and fuel synthesis, and add some amount of wind power production as well. Given that all these variables are unknown, they remain inestimable at this point, other than to say that available power is expected to be higher than that from tidal alone, and some amount of power will be required for the carbon capture and fuel synthesis processes.

The tidal resource from points 1-6 can be plotted as depth averaged current speed, with maximum, minimum, and average across the six points selected in the Pentland Firth.

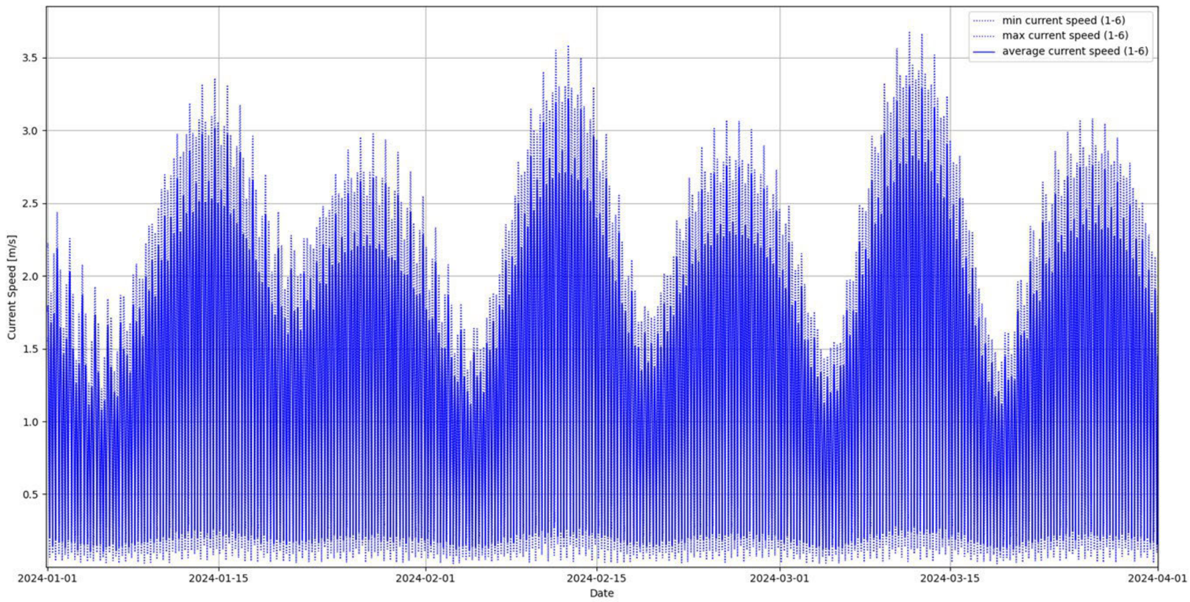

Figure 19 | Current speed maximum, minimum and average for six points in the Penland Firth (January-April 2024)

As a depth-averaged value this is not well aligned to any particular TEC deployment arrangement so is likely lower than expected, but it can be converted to a percentage power value, given the power rating of the TEC considered.

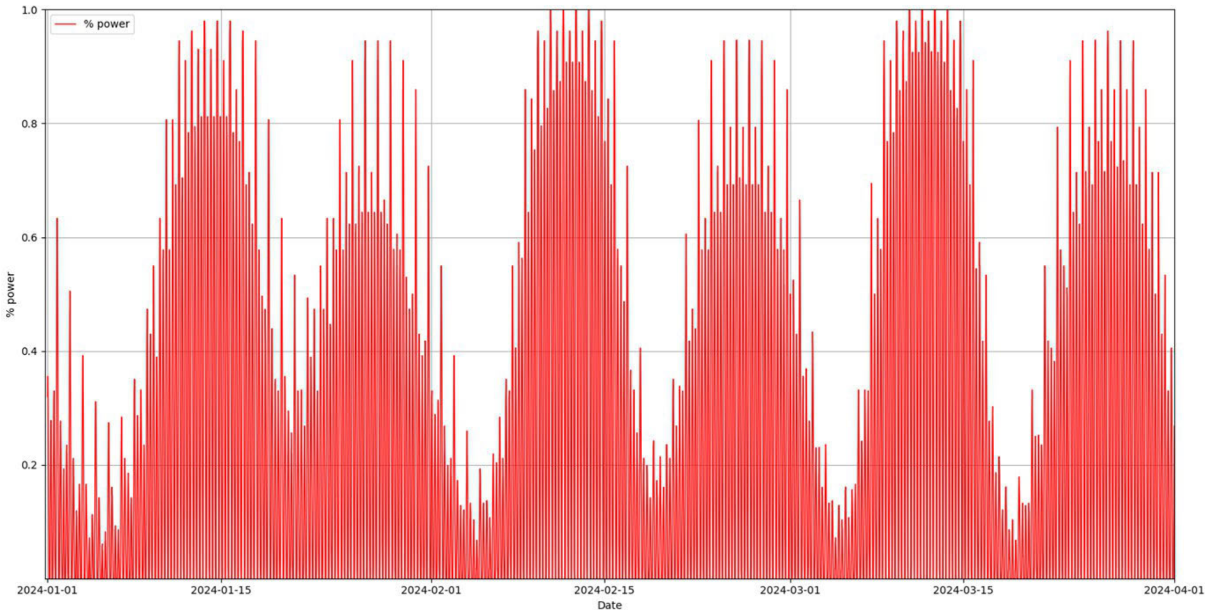

Figure 20 | % power derived from 6 points in the Pentland Firth, using 1.0 m/s cut in with 2.5 m/s rated speed (January-April 2024)

It is clear that a TEC with maximum power achieved at 2.5 m/s is going to be insufficient for constant electrolysis rates: there are periods of several days here where maximum power is less than 20% of the potential. This is driven primarily by the cubic power curve and the disproportionate effect of neap tides.

Considering the power curve of the lighter theoretical 200 kW TEC as in 5.1, then the power output looks much better, while noting this implementation will always require arrays due to high power offtake.

The expected output is very sensitive to the characteristics of the TEC: the lower the cut in speed and speed at which maximum output is achieved, the better: evaluation and modelling of the available resource becomes critical for planning TEC arrays and design/selection of the TECs to be deployed.

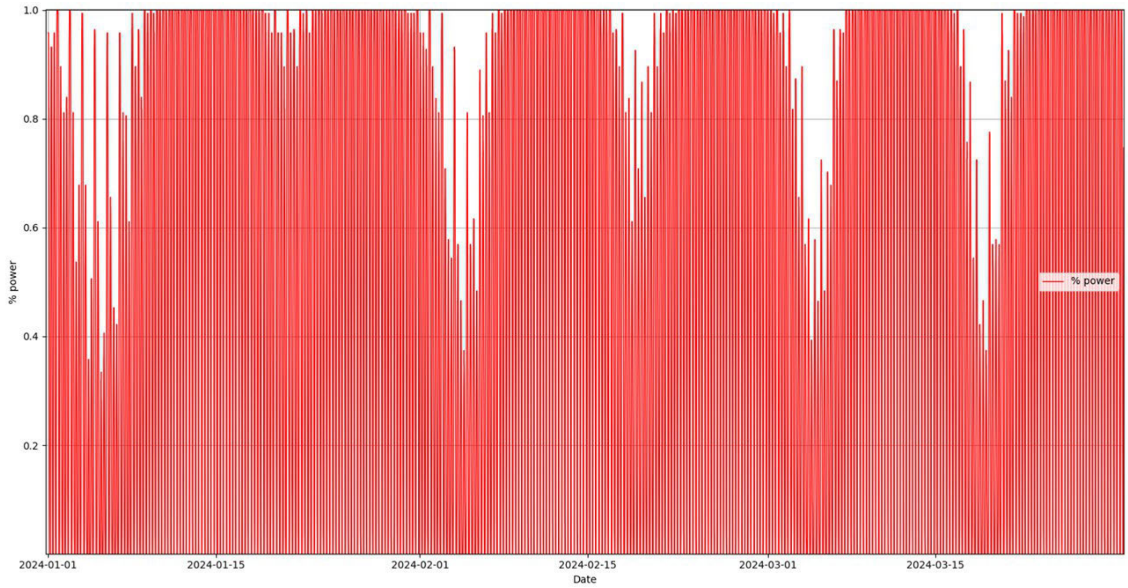

Figure 21 | % power derived from 6 points in the Pentland Firth, using 200kW TECs with 0.8 m/s cut in with rated speed of 1.7 m/s (January-April 2024)

Given that the source data is depth averaged, this could be an achievable level of power, pending detailed modelling with expected TEC power curves, and a clear plan of the expected number of TECs to be deployed.

There is an opportunity to either select TEC devices to maximise power potential, or design specifically to suit particular deployment locations, which would maximise the power yield.

Some gaps in power output will be expected during neap tides, due to the cubic nature of TEC power curves.

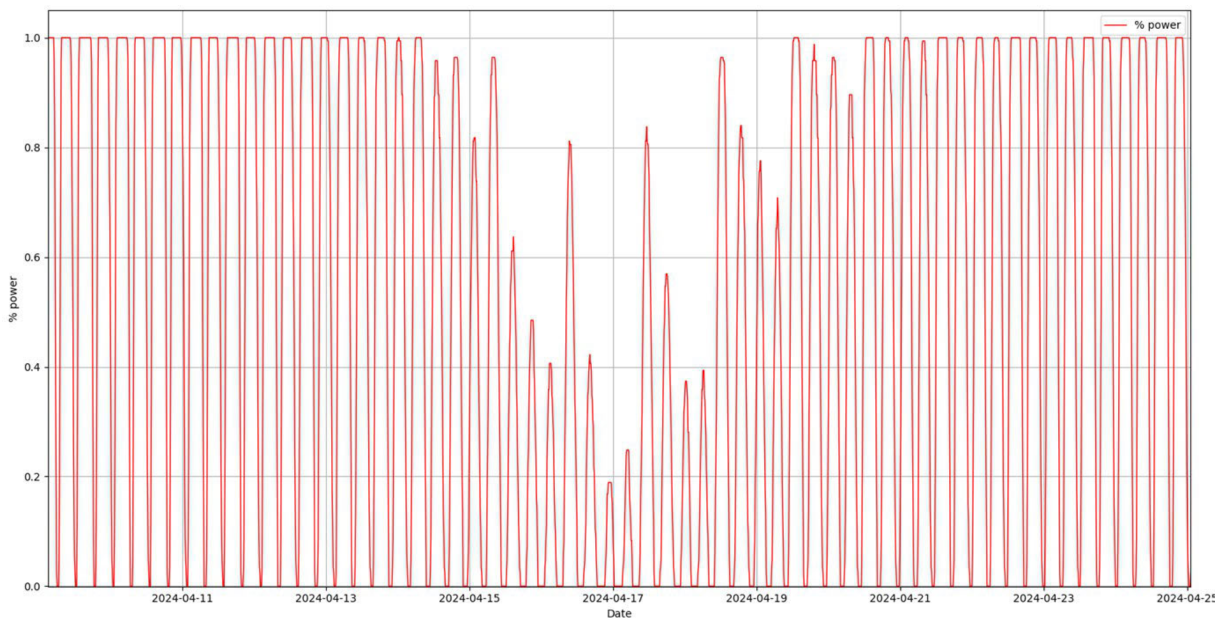

Figure 22 | % power during a neap period in April 2024, for 6 points in the Pentland Firth, 200 kW TECs

Something other than tidal power will be needed to ensure constant operation of the electrolyser, to bridge the neap periods. This could be wind power, solar, grid power or storage of the excess generated tidal power. Use of generated hydrogen to produce electricity to keep the electrolyser running efficiently could be an option, but the losses involved (typically 40%-60%) would be expected to make this non-viable, so it is not considered here.

There are two options here:

- Shut down the electrolyser during neap periods. This option still requires significant outlay in storage to keep the electrolysis running over slack periods.
    - Completely shutting down the electrolyser would mean that it takes a couple of days to achieve acceptable H_2 purity when the electrolyser is restarted.
    - Keep the electrolyser in warm standby during neap periods. This avoids the lag in achieving acceptable H_2 purity but comes at a cost of ~10-20% of electrolyser power being required from elsewhere during the period concerned.
- Perform electrolysis from other renewables or grid. Some analysis would be required as to how much power could be obtained from wind, for example, and large amounts of electrolysis would require a large grid connection if no tidal is available.

Warm standby would seem to be the most effective option for bridging both slack and neap periods, but this should be assessed against the availability of other power such as wind or other renewables, or even in the worst case, grid power.

Energy storage will likely still be needed to "bridge" the slack periods and ensure continuous operation: these values will be large but only needed for a couple of hours at a time.

If 500 MW is assumed to be 40% of output:

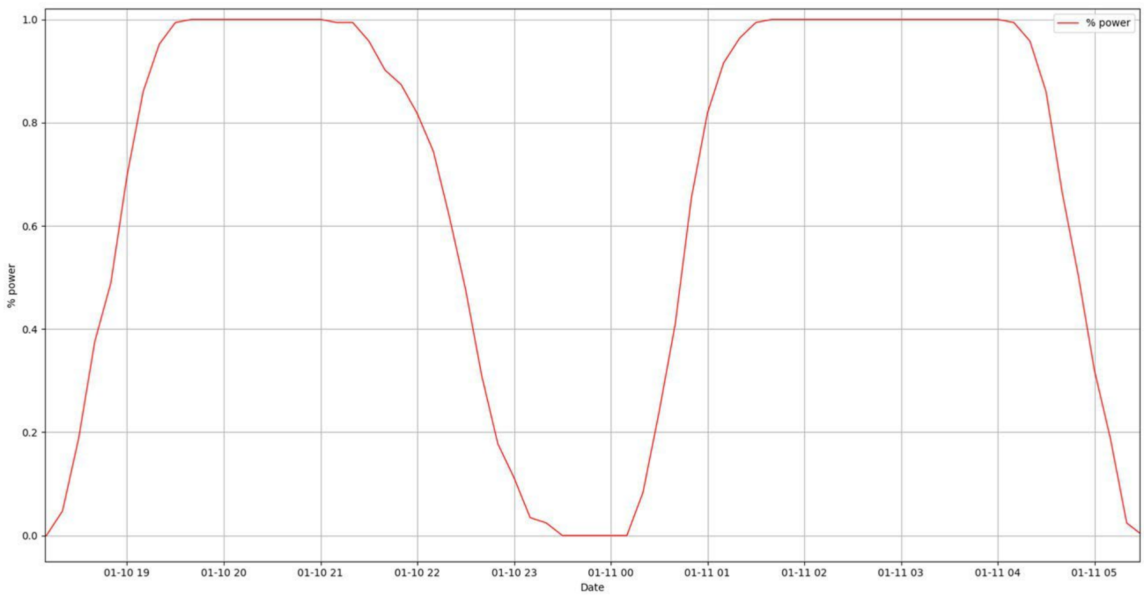

Figure 23 | % power for 6 points aggregated in the Pentland Firth, using 200 kW theoretical TEC (10 Jan 2024 – 11 Jan 2024)

The length of time where the power drops below 40% is approximately 2.5 hours in this case. So storage equivalent to our power output for 2.5 hours is needed: crudely, that is 1250 MWh of storage, if 500 MW electrolysers are used. This is huge, and therefore continuous operation is probably not cost effective.

The alternative to this is to keep the electrolysers running with trace water and heat circulations to avoid a shutdown, but not produce hydrogen during the slack time, known as "warm standby" For example, EMEC's electrolyser at 670 kW rating takes 31 kW to maintain itself in a minimum runnable state, although this would be considered the absolute bare minimum. If this proportion were applied to a 500 MW electrolyser, the required power to "bridge the slack", while not producing any hydrogen would be approximately 60 MWh.

It may also be that with a separate water treatment plant, greater efficiencies could be achieved.

It should be noted that these numbers are extremely sensitive to TEC and electrolyser characteristics and design.

5.5.6 Desalination of water for electrolysis

The availability of fresh water for electrolysis has been an often overlooked potential point of contention.

For small-scale localised offtakes, such as the Caldale facility on Eday, the public supplies have been sufficient. For the industrial uses anticipated on Flotta they will not, and so desalination of either sea-water or saline groundwaters will be required.

It should be noted that desalination is already widely deployed in the potable water supply and although it requires prodigious quantities of energy to support a city's water supply, it is a relatively low energy demand per tonne. Reverse osmosis (RO) is the most widely used means of delivering fresh water at approximately 2 kWh/tonne. Multi Shage Flash desalination is often used where there is excess heat and requires in the order of 3.5 kWh/tonne (Pinto J., 2020).

For electrolysis some additional 'polishing' of the resultant water will be needed to standards above the normal potable supply quality, however this is likely to be a comparatively small energy demand compared to the RO itself. For the purposes of this analysis it is assumed a very conservative final polishing doubles the energy demand to 4 kWh/tonne.

The energy required to electrolyse a tonne of fresh water is of the order of 9000 kWh meaning that the additional energy requirements of the production of hydrogen from sea-water is likely to be of the order of 4/9000 = 0.04% greater than from using fresh water (Environment Agency, 2024).

Some concern has been expressed at the risk to wildlife from the discharge of the brine following desalination however the dispersion characteristics of tidal sites mean that this effect is highly unlikely to be significant if even detectable. It should be noted that the Flotta terminal already has an outfall for the discharge of process water.

5.5.7 Summary

This report has demonstrated the issues that need to be considered as part of planning a viable combined tidal-hydrogen offtake at scale. The available resource in the Pentland Firth is huge, and the benefits of hydrogen production on an industrial scale can play a significant role in the decarbonisation of other industries as well.

Viability will be dependent upon:

- TEC siting and accurate resource assessment.

- TEC characteristics, especially cut-in speed, and the speed at which maximum power is achieved.
- Electrolyser characteristics, especially tolerance to outages, time to achieve required purity of hydrogen.
- Whether the electrolysers would use separate water treatment, and what their standby power arrangements are to keep the electrolyser in a restart-able condition during slack and neap periods.
- Size and cost of energy storage.

There are further unknowns when it comes to fuel synthesis:

- Where is the carbon obtained from? What power is required to obtain CO_2?
- What is the power requirement for fuel synthesis?
- How tolerant to start-up and shut-down events are these processes?

Furthermore, there are operational planning concerns for this site to consider:

- How large is the grid connection for the Pentland Firth, and hence the FHH, as well as the TECs and TEC arrays planned?
- How much energy might be expected from West of Orkney Windfarm?
- Are there potential uses for lower-purity hydrogen than has been generated to date, as this could impact an economic case?

And finally, once these energy budgets have been worked through to establish viability, a matching CAPEX/OPEX budget would need to be derived, for site operation.

This should all be done in collaboration with expected tidal energy developers, West of Orkney windfarm, and FHH, in this instance. A project of this nature could pioneer the methodology for de-carbonisation at scale, while the LCOE of Tidal becomes competitive and safeguards local industries.

6 Roadmapping alternative offtake opportunities

After combining the findings from the stakeholder engagement, business model evaluation and review of offtake opportunities in key tidal resource areas, three alternative offtakes deemed to be the most viable were shortlisted for tidal energy in Scotland, namely small-scale generation, community projects and hydrogen offtake. Roadmaps that highlight the steps required and key actions needed to address market barriers for each of these alternative offtakes are discussed further in this section.

6.1 Small-scale generation

Small-scale generation here relates primarily to privately owned tidal turbines expected to be less than 1 MW in size, analogous to privately owned onshore wind turbines or solar PV installations. Given that the smallest tidal turbines have capacities of the order of 50 kW, which is significantly more than a solar panel or domestic wind turbine, users with the required energy needs will mainly be businesses rather than individual households.

One of the key challenges for this market is that project development costs become prohibitively expensive once there is a requirement for a Section 36 consent, triggered once the generating capacity exceeds 1 MW. Some of the stakeholders interviewed mentioned that the required surveying costs alone made projects unviable. With 1 MW no longer representing a large tidal installation, there is a need to develop the consenting requirements for tidal projects such that they are proportionate to project size. It is recommended that the Section 36 threshold is increased to at least 5 MW to support the small-scale generation market. Other project development enabling actions are discussed in Section 7.

Similarly there is currently no mechanism to sell exported electricity to the grid, in the same way that the Smart Export Guarantee (SEG) pays small-scale generators (<5 MW), including solar PV, wind and hydro, to export to the National Grid. Adding tidal to the SEG would be an easy and quick way of ensuring parity with other small-scale generators.

Given the emerging nature of tidal energy, an enhanced FiT would be a more attractive financial incentive to encourage adoption. The FiT scheme previously available in the UK offered both a generation and export tariff, with the former providing payment for all the electricity produced by the system, irrespective of whether it was used or exported. Some of the FiT rates were initially higher than £0.50/kWh and were guaranteed for a set period, in some cases for as long as 20 years. Rates decreased as the price of the renewable technologies came down. A tidal FiT would need to be similarly designed such that it encourages early adopters taking high risks the opportunity to make high returns after a reasonable payback period, e.g. <10 years.

However, a tidal FiT would need to explicitly serve the small-scale generation market and not become a means for utility scale turbines to distort the market. A clear definition for small-scale tidal generation needs to be developed to make a distinction. This is important as a number of the tidal energy projects awarded CfD to date are less than 5 MW in capacity, in some cases because projects are being developed in phases. The rates in the previous FiT scheme decreased with increasing generator capacity. A similar approach for a tidal FiT would need to be adopted to prevent utility scale developers building multiple small projects eligible for FiT where rates could be higher than CfDs. A tidal FiT could also encourage utility scale developers to develop small-scale devices based on their technologies, helping create competition at this scale. Furthermore, the scheme could be extended to include river current turbines, although the scale of this opportunity in Scotland is beyond the scope of this project.

To address the challenge of cabling costs for small-scale generation, it is recommended that a further review of this issue is undertaken to understand the project scales in which subsea cabling becomes too expensive to make a viable business. This could not be ascertained from stakeholder engagement but it is expected to be a challenge that mostly affects the smallest projects, as a result of cable installation costs not scaling proportionally with turbine capacity or number. Once it has been identified where 'final mile' cabling support is most needed, grants or subsidies should be made available to support these projects. Any financial assistance should be reviewed on a periodic basis as the small-scale generation market develops and technology costs come down, while the amount of support provided would also need to be considered alongside other financial incentives, e.g. a tidal FiT.

Table 9 summarises the key challenges faced by the small-scale generation market, along with the proposed steps and actions required to address these barriers.

Key challenges	Steps required	Actions
• Consenting costs and timescales • No FiTs for tidal • 'Final mile' cable costs prohibitively expensive • High cost of tidal relative to other renewables	• Development of a consenting approach that is proportionate to project size • De-risking of project development process • Develop a clear definition for small-scale tidal • Evaluation of FiT requirements for small-scale tidal generation • Assessment of 'final mile' cabling costs for small-scale projects	• Increase Section 36 project size trigger threshold to at least 5 MW • Add tidal to the list of technologies eligible for SEG tariffs • Establish an enhanced FiT for small-scale tidal projects <5 MW • Introduce grants / subsidies for 'final mile' cabling where support is most needed

Table 9 | Roadmap for small-scale generation projects

6.2 Community projects

Community projects face some of the same challenges as small-scale generation projects, particularly around consenting. Smaller community projects would also benefit from an increase in the Section 36 threshold to at least 5 MW.

Arguably the largest challenge faced by community groups is a low risk appetite for developing projects with unproven technologies. This is difficult to solve in isolation as it is largely dependent on the industry scaling and increasing generation output to demonstrate track record. Some tidal developers have proven consistent generation within recent years and as a first step it is recommended that they engage with communities transparently about their technologies to build support, as well as to explore the wider value of potential projects, e.g. local job creation, spend and investment. This would provide a forum for community groups and tidal developers to understand their respective needs and constraints.

Funding timescales were also highlighted as a challenge for community projects, with the funding that is typically available only being suitable for 'shovel ready' projects. A simple way to solve this challenge is to provide greater visibility of upcoming funding opportunities, through a combination of extending application windows and creating rolling opportunities.

A key technical challenge identified is that some of the communities shortlisted as having high potential for fossil fuel generation replacement do not have strong tidal resources. As shown in Section 5.1.1, this makes it difficult to use conventional tidal turbines at these locations. Further work should explore if tidal technologies designed for low-flow conditions, e.g. kite-based designs, could make projects at these locations viable. This should be combined with developing an increased understanding of the tidal resource potential in Scotland, which is discussed further in Section 7.

Lastly, in order to fully decarbonise communities in which fossil fuel generators still contribute to meeting electricity needs, either in standby or permanent operation, a diverse portfolio of renewable technologies will need to be combined with battery storage to provide energy security. Tidal energy could form the backbone of this, guaranteeing that energy will be available during significant low wind periods, but a detailed evaluation of the energy security requirements across communities in Scotland should be undertaken to identify potential solutions. Setting a date for phasing out fossil fuel generators would significantly help accelerate decarbonisation, while introducing grants or subsidies to support battery installations in community settings would allow tidal projects to competitively bid for private network CfDs in these locations.

Table 10 summarises the key challenges faced by community projects, along with the proposed steps and actions required to address these barriers.

Key challenges	Steps required	Actions
• Consenting costs • Funding call timescales • Low risk appetite in community groups • Low tidal resources • Battery storage required for energy resilience • High cost of tidal relative to other renewables • Unproven nature of tidal	• Development of a consenting approach that is proportionate to project size • Engagement between tidal developers and community groups • De-risking of project development process • Increase understanding of tidal resource potential in Scotland • Assess viability of 'low-flow' tidal technologies in resource limited locations • Evaluate energy security requirements for communities with tidal in generation portfolio	• Increase Section 36 project size trigger threshold to at least 5 MW • Create funding calls with longer / rolling application periods • R&D funding for 'low-flow' tidal technologies • Set a date for phasing out fossil fuel generators • Introduce grants / subsidies to support battery installation in community settings

Table 10 | Roadmap for community projects

6.3 Hydrogen offtake

Hydrogen offtake represents the largest opportunity for tidal energy projects pursuing an alternative to grid connection, although realising it is dependent on a hydrogen economy being developed in Scotland. Due to the scale at which hydrogen offtake projects could be built, they share many of the same challenges as grid-connected, utility-scale tidal projects. This includes limitations within the current CfD mechanism, under the assumption that hydrogen offtake projects are developed by accessing private network CfDs. The existing £10m CfD marine ringfence for AR6 (at time of writing this report), together with tidal being placed at a competitive disadvantage within the wider emerging technologies pot mean that tidal projects will not be able to secure sufficient capacity to meet the needs of large hydrogen offtakes and this could even pose challenges for smaller, nearer-term opportunities, such as hydrogen for distilling. Increasing the CfD ringfence to £30m would help the latter, while a reform of the CfD mechanism to recognise the wider value of tidal will be key in achieving utility-scale levels of deployment. From AR7 onwards, the UK Government will be introducing Sustainable Industry Rewards (SIR) that will provide extra revenue support for projects that add to the economic, environmental and social sustainability of offshore wind projects. There is a need to extend SIRs to include tidal energy while alongside reforming the CfD mechanism further (e.g. to recognise energy systems benefits) in order to support large-scale projects.

As discussed in Section 4.2, securing finance is a key challenge for tidal projects and will only be more difficult for an alternative offtake project. This is particularly true for hydrogen where the technology and its operation are still largely unproven, meaning that there is significant counterparty risk from the possibility of a tidal project being unable to generate revenue because of the hydrogen production facility being non-operational. There is a need for a public body to underwrite the final and least likely portion of availability warranties in these projects to ensure that tidal developers can service their debt requirements. Presenting this as a business case to a prospective public body is one of the next steps required, in which all project risks would need to be comprehensively identified, reviewed and costed.

Similarly insurance is difficult to access in the tidal sector due to technologies being relatively untested and lacking years of uninterrupted performance data, which in turn is discouraging investment and increasing the cost of capital. An interim Protected Cell Company (PCC) captive insurer entity underwritten by a Public Guarantor to cover the high value, low probability risks as a last resort has been proposed to address this challenge (Renewable Risk Advisers, 2022). As with Publicly backed availability warranties, key next steps in the establishment of the proposed PCC insurance entity include quantifying risks and forming an independent risk panel.

In terms of leasing, larger hydrogen offtake opportunities will need the 30 MW ad-hoc lease limit to be increased for tidal projects to be built at sufficient scale to meet required electricity demands, or for another leasing arrangement to be introduced, e.g. competitive leasing. Additionally, developers are presently limited to holding 4 option agreements at one time, which will impact their ability to develop hydrogen offtake projects alongside a pipeline of grid-connected projects. There will, therefore, need to be a review of leasing arrangements in Scotland to support the development of large hydrogen offtake projects, as reported in CES' recent market engagement study (ORE Catapult, 2024(3)).

Lastly, undertaking a detailed review of expected future hydrogen demand in tidal locations in Scotland is a recommended key next step in quantifying the role that tidal energy could play in these projects. This study has mainly identified hydrogen for distilling on Islay and the FHH as key opportunities, but consideration for tidal energy as part of these projects is at an early stage and is currently not a priority, despite stakeholders being receptive to the idea. Further work should be carried out to look at the technical feasibility of tidal energy meeting the energy demands of hydrogen offtake projects. For example, one stakeholder mentioned that typically three times as much solar capacity relative to the electrolyser size is needed to ensure consistent energy supply, combined with battery storage. It was also mentioned that the corresponding ratio for wind is 2:1. A similar analysis should be conducted for tidal energy, while for larger offtakes a technoeconomic study of using multiple green energy sources, e.g. combining tidal energy with offshore wind, should be undertaken to identify generation portfolios that can provide the required energy security.

Table 11 summarises the key challenges faced by hydrogen offtake projects, along with the proposed steps and actions required to address these barriers.

Key challenges	Steps required	Actions
• Project finance • Greater counterparty risk, increased cost of capital • Leasing for utility-scale projects • Hydrogen offtake needs to be located close to tidal resource • Batteries required to ensure consistent energy supply • High cost of tidal relative to other renewables • Unproven nature of tidal • Hydrogen needs to be used locally (high shipping costs)	• Identify and cost project risks intended to be covered by a Public Funder • Review leasing arrangements for tidal projects • A detailed review of expected hydrogen demand in tidal locations • Identify areas where tidal could be combined with other projects, e.g. offshore wind • Establishment of hydrogen economy in Scotland	• Publicly underwrite final portion of availability warranty • Establish a PCC insurance entity backed by a Public Guarantor • Increase 30 MW lease limit and option agreement cap • Increase tidal CfD ringfence annual budget to £30m • Incorporate non-price factors into CfD evaluation process • Undertake feasibility studies to assess potential role of tidal energy in hydrogen offtake projects

Table 11 | Roadmap for hydrogen offtake projects

7 Conclusion and recommendations

This project was tasked with reviewing the current state of the tidal generation market, identifying viable alternative offtake models and assessing their potential impact on deployment targets that have been set for the next 10 years. Key findings from this report include:

1. **Displacement of fossil fuel generation**: Modelling shows that the economic case for displacing fossil fuel generators with tidal generators may now be becoming viable. However, the local tidal resource needs to be accurately modelled to ensure that it is available at sufficient speeds in the necessary locations.
2. **Small-scale generation:** There has been much focus in Scotland on TECs of 100 kW or greater to date. However, with the correct support, smaller TECs offer opportunities for coastal communities to establish energy resilience whilst providing much needed revenue streams if they are community-funded. These would typically be sized to the local grid constraints in arrays of less than 1 MW, but with the ability to be expanded with local demand increase. This will enable the industry to grow in much the same way as smaller turbines in the early days of wind generation.
3. **The potential of e-fuels**: The processing of hydrogen to e-fuels is best co-located with hydrogen production to maximise efficiency and minimise the cost and challenge of transporting hydrogen. E-fuels offer the least disruptive route to decarbonisation for risk averse industries such as maritime, farming and crofting. Early movement in the production of e-fuels offers the opportunity to both satisfy local demand and provide fuel security. Scotland will then be in a position to export this knowledge around the world, as it did in the early days of oil and gas.
4. **Conversion of oil terminals to industrial hydrogen production sites:** Oil terminals such as Flotta and Sullom Voe offer ideal infrastructure and workforce skills for this, whist being ideally located to take advantage of tidal and surplus wind resources.
5. **Not a substitute for grid connection:** The alternative offtake model must be considered as an additional enabler to grid connection opportunities for increasing tidal deployment, not a substitute. This was a key takeaway from the stakeholder engagement activity.
6. **Barriers to alternative offtake**: During this project it became clear that there are barriers to the alternative offtake model, particularly for developers of larger tidal sites, despite it offering a potential solution to the shortage of new grid connections in the areas of greatest tidal resource. These concerns, which are particularly focussed on risk, need to be addressed and the solutions recommended in section 6.3 implemented to incentivise both developers and offtake industries to pursue this avenue where appropriate.
7. **Proactive identification of potential offtake opportunities:** Although tidal could be used to decarbonise industries located close to areas of high tidal resource, outside of the distillery industry there are limited opportunities to achieve this. Those other opportunities that do exist should be actively pursued. As a first step, an accurate modelling exercise should be conducted for all tidal resource locations and this information then used to identify suitable local offtake opportunities. These should then be approached to understand if a mutually beneficial offtake agreement can be agreed.

8. **Exploit the advantages of distribution connection**: Both the scale and location of many tidal stream projects mean that they can only be distribution connected (and not transmission connected). As such, Scotland should look at how best to utilise tidal's predictability to both:

- optimise energy resilience on a local level for remote communities and
- exploit its vast tidal and wind resources and legacy oil assets to deliver transportation decarbonisation and fuel security during the transition to net zero.

7.1 Limitations and recommended further work

This project investigated many aspects of the tidal energy market in a limited time. As such, it could provide only a high-level assessment of tidal resources and offtake opportunities. There was limited quantitative data available for the business model evaluation and the community value of projects was not assessed. The short timeline of the project also resulted in limited engagement with potential offtake opportunities. Recommendations for further work include:

- Detailed modelling of the Scottish coastline, particularly focussed on locations that may be suitable for smaller scale tidal projects and community generation of less than 30 MW. This will identify the best tidal locations and enable planning for the optimal use of resource.
- A detailed review of likely industrial power and hydrogen users within reasonable distance of tidal resource.
- Detailed modelling to understand full project lifetime cost implications of private network versus grid connection for CfD, including a dissemination program.
- A similar exercise to be conducted for wave energy and for other UK regions.

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Appendices

Table 12: Redacted – EIRs 11(2) Third party personal information
Table 13: Redacted – EIRs 10(5)(f) Third party Interests
Table 14 and 15: Redacted – EIRs 10(5)(e) Confidentiality of commercial or industrial information

Table 16: Redacted – EIRs 10(5)(f) Third party Interests and EIRs 11(2) Third party personal information

Table 17 and 18: Redacted – EIRs 10(5)(f) Third party Interests

The European Marine Energy Centre Ltd., The Charles Clouston Building, ORIC, Back Road, Stromness, ORKNEY KW16 3AW
Email: info@emec.org.uk **Web:** www.emec.org.uk **Tel:** 01856 852060
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