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OFFSHORE GENERATION, ENERGY STORAGE & SYSTEMS FEASIBILITY STUDY

An Everoze report commissioned by Crown Estate Scotland
December 2018

Crown Estate Scotland
Oighreachd a' Chrùin Alba

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PROJECT OVERVIEW

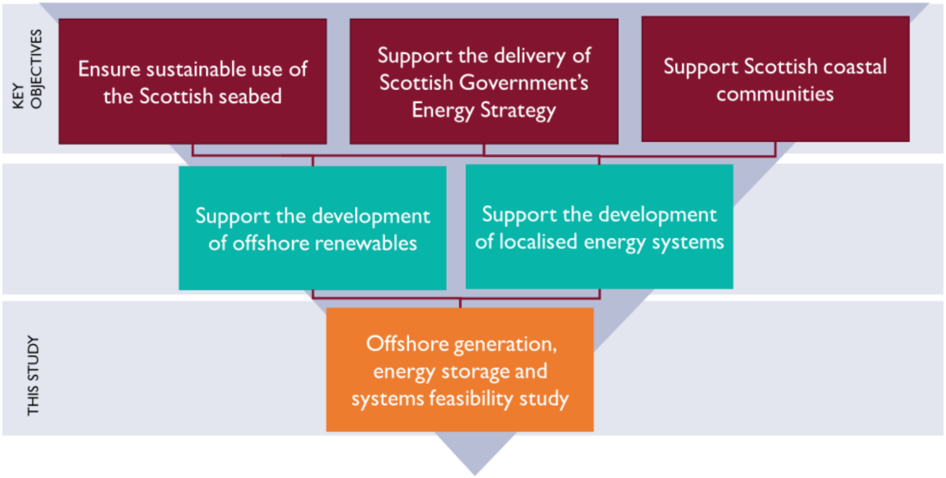
CROWN ESTATE SCOTLAND

This study has been commissioned by Crown Estate Scotland. Crown Estate Scotland is a public corporation which manages land and property to benefit businesses, communities and families across Scotland. All revenue profit generated is returned to the Scottish Consolidated Fund. Crown Estate Scotland:

- is responsible for managing a range of rural, coastal and marine assets, as well as some commercial property
- leases land and property to 2000 individuals and businesses
- supports aquaculture, farming, forestry, tourism and offshore renewables through leasing, research and other activities
- invests in marine leisure facilities to support coastal communities

WHY IS CROWN ESTATE SCOTLAND INTERESTED IN A STUDY ON ENERGY SYSTEMS FOR OFFSHORE RENEWABLES?

This study draws together two delivery paths which could potentially deliver on three of Crown Estate Scotland's core aims:



AIM OF THIS STUDY

The aim of this study is to deliver an initial high-level investigation as to how integration of offshore renewables into a localised energy system can support the pathway to commercial viability of offshore renewable projects, whilst benefiting coastal communities through improved local energy solutions.

SCOPE

The project looks at six hypothetical scenarios that represent challenging offshore renewables deployment opportunities in high resource areas. The study makes an initial determination of the potential benefits of developing these integrated systems and outlines the key barriers to deployment.

The study looks at potential future scenarios and is not a detailed techno-economic review of current commercial viability of these systems. It deliberately does not address a specific development timeline at this stage. As such, it makes some assumptions that technologies that are still under development, are fully commercially available.

For the purposes of this study, offshore renewables includes floating wind, tidal and wave energy. It does not consider conventional offshore wind (fixed bottom), as a key objective of the study is to look at the potential to support emerging offshore energy technologies. For the purposes of this work, conventional offshore wind is considered to be a mature technology.

THIS IS THE FIRST STEP IN AN ONGOING PROCESS

For identified systems that are shown to be theoretically beneficial and viable in the short- to mid-term, further, more detailed work will be carried out to identify potential communities where projects may be delivered. A review will then be undertaken to determine how Crown Estate Scotland can best support these.

A GUIDE TO THIS REPORT

For each scenario the following review was undertaken.

1. FRAMING

Situation: Defining and assessing representative geographies, grid constraints and energy use profiles to determine situational requirements.

Options: Scoping energy systems which have the potential to deliver value to stakeholders.

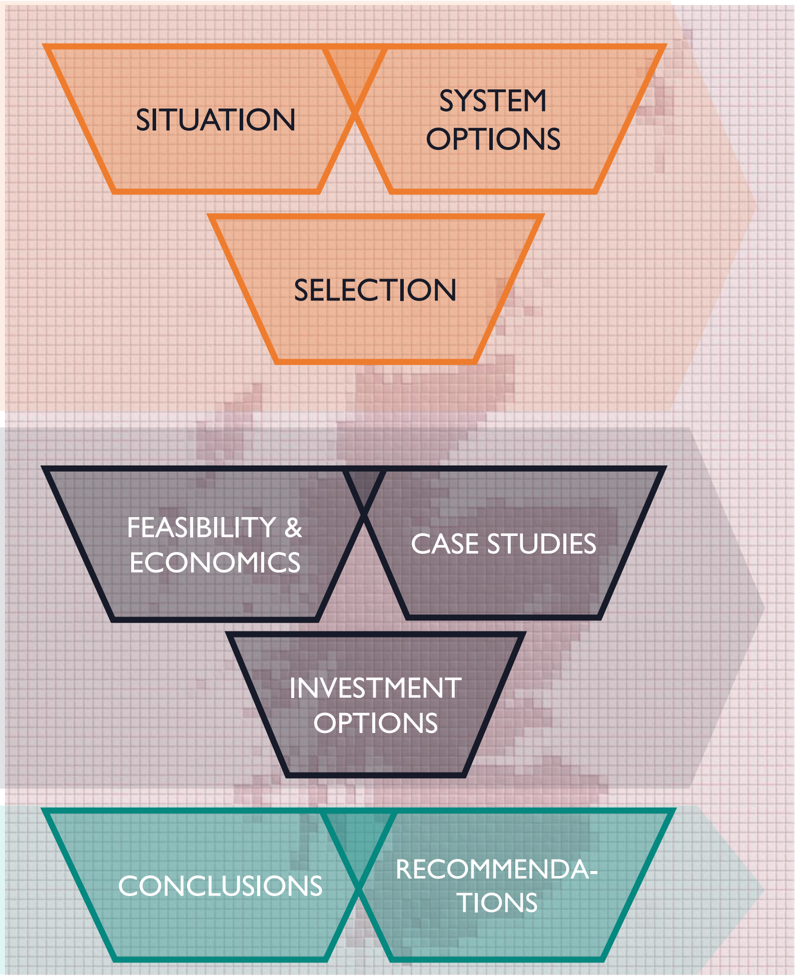
Selection: Preliminary assessment to identify the most promising energy systems.

2. ASSESSMENT

Techno-economic modelling to evaluate potential commercial viability. This, combined with a review of **case studies, regulatory issues** and **investment options,** allows a picture of emerging **barriers & opportunities** for each scenario.

3. RECOMMENDATIONS

Defining specific actions to unlock the potential value of the energy system for relevant stakeholders.



The approach for this study is based on the following principles:

- REPRESENTATIVE SCENARIOS – The study focuses on six scenarios, representative of potential development opportunities for offshore renewables. This allows a relevant level of depth for the study as well as ensuring a broad width of options are included.
- SIMPLIFIED ENERGY SYSTEMS – The study is based on energy system elements i.e. generation, storage, conversion and end use options, combined into simplified systems. Both those commercially available and those in later stages of development were considered. It was assumed that those still under development would become commercially available.
- STAKEHOLDER INPUT – A workshop and a review of case studies were carried out to ensure lessons learnt in the development and deployment of relevant systems was captured in the work.
- MODELLING – Techno-economic modelling of the specific scenarios were carried out, including sensitivity analyses to the key techno-economic drivers. This reduces the limitations of modelling specific scenarios. Due to the forward looking nature of the report, many assumptions within the report are predictions based on, or derived from, industry data and reports. These are outlined in Appendix I.
- BARRIERS AND OPPORTUNITIES – In addition to the techno-economic drivers for development, there is a range of more qualitative benefits and challenges to deployment of these systems. These are recognised within this report.

LIMITATIONS OF APPROACH

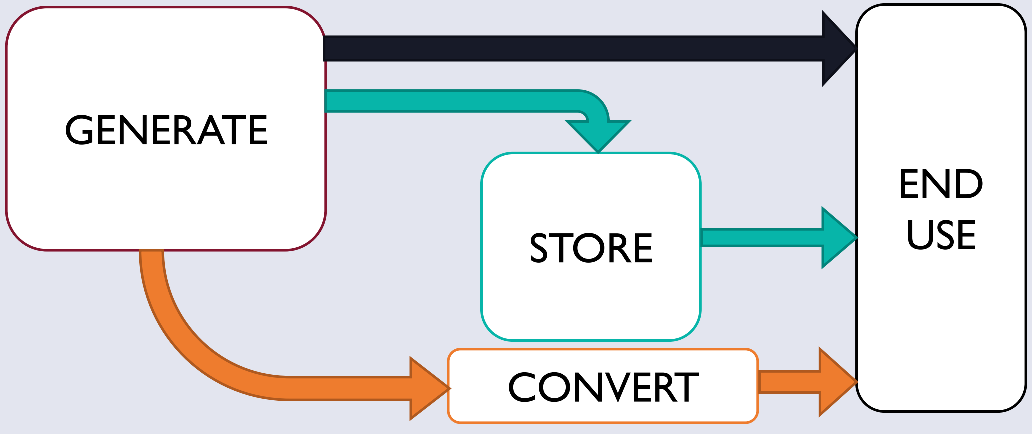
This study is an initial top level review of a wide variety of current and future energy system options. The scenario based approach taken within this study has its limitations:

- Not all viable combinations of energy system have been analysed.
- Although some sensitivity analysis has been carried out, the results are only representative for the scenarios presented. Projects should be assessed on a case by case basis.
- Some significant assumptions have been made about the viability and future costs of techno-logies still in development. The results are therefore subject to high levels of uncertainty.
- Potential revenue from ancillary services (e.g. frequency response) is not included.

DEFINITION OF AN ENERGY SYSTEM

OVERVIEW OF AN ENERGY SYSTEM

- An 'energy system' can be interpreted in a wide variety of ways.
- Like all systems, it can be broken down to a discrete set of interconnected elements. This simplified model helps to conceptualise the energy system. These sub-elements are energy generation, storage, conversion and use.
- In some scenarios we just focus on generation => end use (with no storage or conversion), in others we have generation => storage => end use.
- The systems we propose do not work in isolation, with the scenarios considering what the 'base case' generation and end use mix is. The analysis therefore assesses the potential benefit of adding new offshore renewable generation assets and storage or conversion technology against the 'base case'.
- For clarity, the elements of the energy system considered within this study are outlined in the next pages.



SCHEMATIC SHOWING ELEMENTS OF AN ENERGY SYSTEM

HOW WERE THE ENERGY SYSTEMS FOR THIS STUDY SELECTED?

DEVELOP TOPOGRAPHICAL SCENARIOS

Developed in discussion with Crown Estate Scotland and based on selection of locations in Scotland that are subject to a wide range of development and grid issues.

SYSTEM REQUIREMENTS FOR EACH SCENARIO

DEFINE ENERGY SYSTEM OPTIONS

Potential elements of the systems were identified based on:

- Generation
- Storage
- Conversion
- End use

PERFORMANCE PARAMETERS FOR ENERGY SYSTEM OPTIONS

SHORTLISTING OF POTENTIAL ENERGY SYSTEMS

At this stage based on:

- Scale
- Maturity
- Locational requirements

ENERGY SYSTEM SCENARIOS

In order to develop scenarios for more detailed assessment, initial energy systems were selected in order to meet the requirements of the topographical scenarios.

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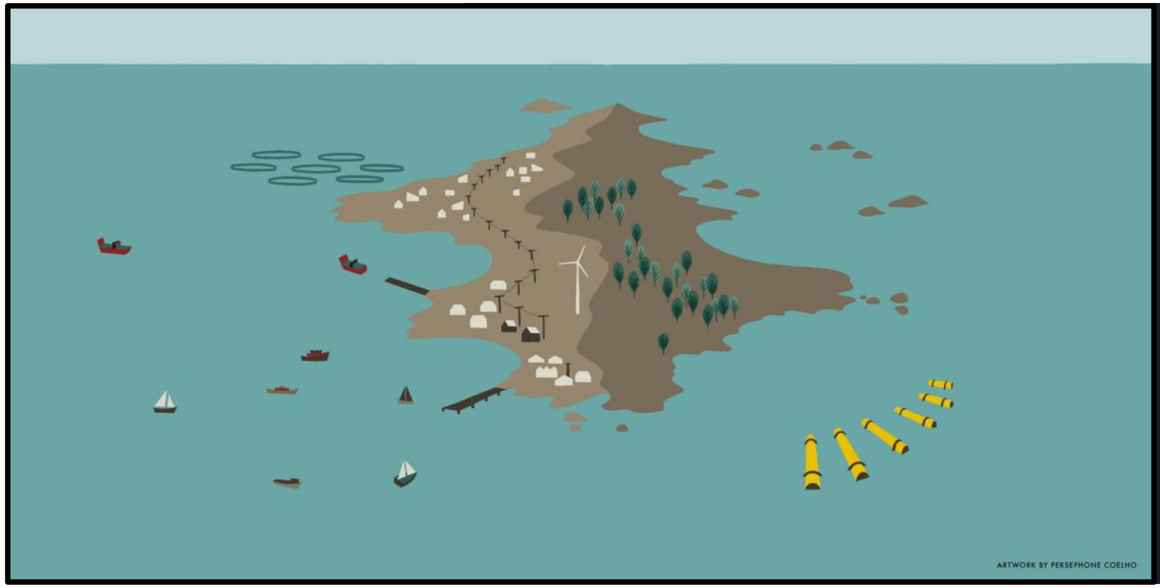


SCENARIO 1A:

SMALL WAVE CONNECTING TO REMOTE ISLAND WITH PRIVATE NETWORK

WHAT COULD BE DONE IN THIS SITUATION?

SCENARIO 1a: SMALL WAVE CONNECTING TO REMOTE ISLAND WITH PRIVATE NETWORK

SITUATION

This situation was chosen as it is representative of the scale, location and potential connection typical of niche deployment of wave devices

- Small remote island (~100 houses) which has a private network
- Wave developer is seeking to connect 200 kW device to this private network
- No electrical or gas connection to the mainland

REQUIREMENTS

Needs to reduce diesel generation enough to provide viable business case for the island

PROPOSED ENERGY SYSTEM OPTION

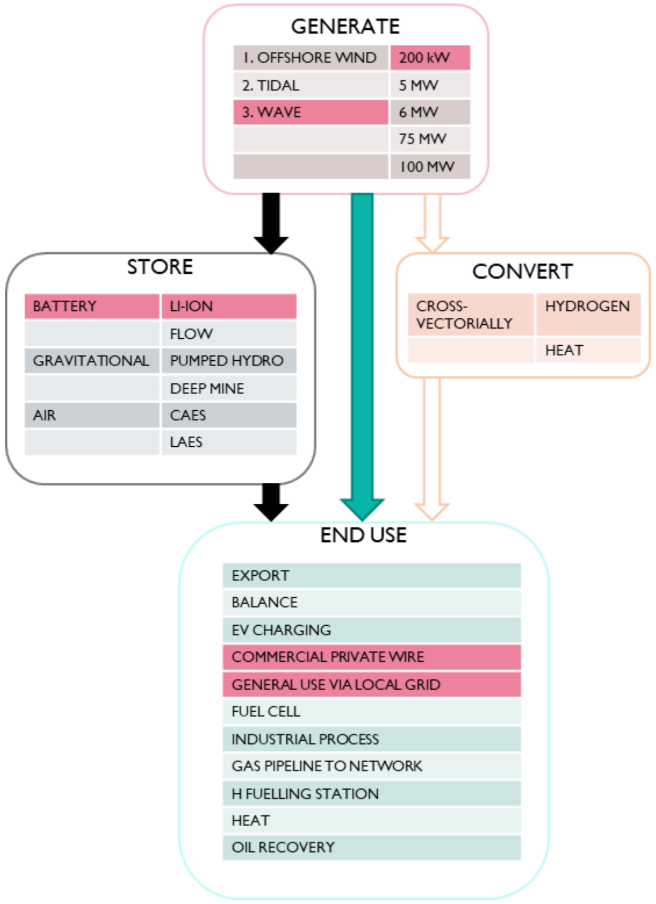
Everoze reviewed potential storage and cross vector options. This concluded that a private wire to the private network, potentially with a battery was the best option as:

- No locations on island are suitable for pumped hydro, CAES or deep mine
- Likely to be too small scale for LAES
- Hydrogen is an option but is covered under other scenarios
- Heat is potentially of interest but assume housing stock is poorly insulated and therefore not well suited to heat pumps
- Batteries can be deployed but will be secondary consideration within modelling

SYSTEM ELEMENTS	Deployable in this location	Appropriate storage capacity	Viable use of stored energy
Electric Vehicles	Potentially viable	Potentially viable	Viable
Li-ion battery	Viable	Viable	Viable
Lead-acid battery	Viable	Viable	Viable
Flow battery	Viable	Viable	Viable
Pumped hydro	Potentially viable	Unlikely to be viable	Potentially viable
Deep mine	Unlikely to be viable	Viable	Potentially viable
CAES	Unlikely to be viable	Unlikely to be viable	Potentially viable
LAES	Viable	Potentially viable	Potentially viable
Hydrogen	Viable	Viable	Viable
Heat	Potentially viable	Viable	Viable
Private wire	Viable		

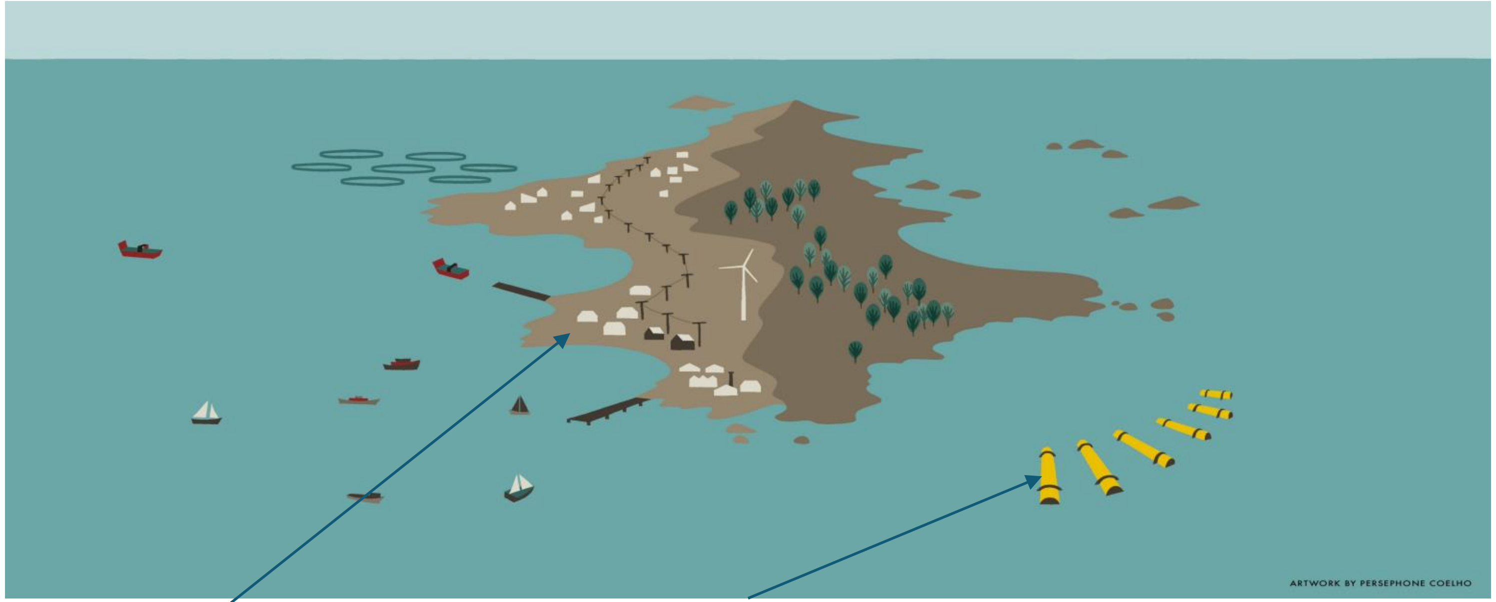
KEY: Unlikely to be viable; Potentially viable; Viable

SUMMARY OF PROPOSED ENERGY SYSTEM



WHAT MIGHT IT LOOK LIKE?

The initial analysis allows the development of an overall proposed energy system for Scenario 1a.



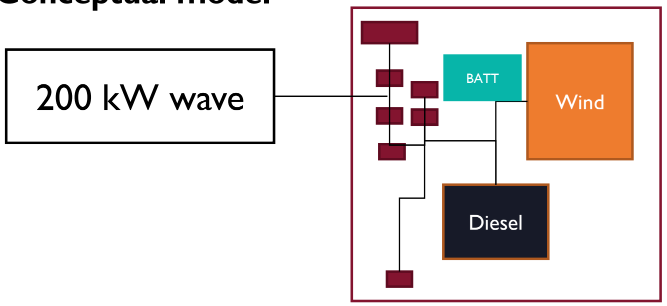
i) Island has existing diesel generators and wind farm

ii) Wave device connects directly to island private network

iii) This helps displace diesel generation

How would the proposed system work?
The island has an existing private network, with diesel and onshore wind generation capacity.
Through connecting wave device, the generation capacity on the island is increased. We assume the wave energy is used to offset diesel. However more energy generation capacity could mean more MWh can be consumed, potentially boosting economic activity. A battery can be added to help reduce diesel. use further.

Conceptual model



THEORETICAL POTENTIAL BENEFITS OF THIS ENERGY SYSTEM AND WHICH STAKEHOLDERS COULD POTENTIALLY BENEFIT		Wave developers	Local community
Access to higher prices for the power	The island has a high cost of electricity ~20-25p/kWh. This is much higher than a wave developer could access connecting into the mainland.	x	
Access to community grant funding	Schemes of this type can access community funds, aiding investment case for wave developer and reducing cost to local community.	x	x
Increased economic activity on islands	Power can be a limit to economic activity on small islands (i.e. new farm may not be able to connect due to insufficient generation capacity). Increasing local generation could therefore help boost growth.		x
Reduction in diesel generation	The island is seeking to reduce diesel generation to i) support move towards 100% renewables island and ii) provide additional resilience in winter when diesel supplies can fail.		x

The viability of realising these benefits are assessed in the following section of this report.

WHAT CAN WE LEARN FROM ELSEWHERE?

This page provides some examples where elements of this system have been or are being deployed. Lessons learnt from these have been taken into account during assessing potential energy systems.

LESSONS LEARNT

EVIDENCE

A RANGE OF WAVE DEVICES HAVE BEEN DEPLOYED TO DATE - THESE RANGE FROM 5KW TO 600KW BUT ARE GENERALLY STILL IN THE TESTING AND PROTOTYPING STAGE

- 600 kW Wello Oy device has been deployed at EMEC in Orkney since March 2017.
- A range of devices are being tested at EMEC, WaveHub FaBTest and elsewhere.


Source: Wello

PRIVATE NETWORKS ALREADY COMMON AND PROVIDING BENEFIT TO REMOTE SCOTTISH ISLANDS

Examples of Scottish islands that have developed localised networks include those on Eigg, Muck, Rhum, and Fair Isle. In 2018, the Fair Isle community delivered a project to ensure 24hr access to electricity by developing a localised energy system. The island was reliant on intermittent generation from wind and diesel and the 55 residents had limited access to electricity after 11pm. The project consists of wind turbines (180KW), solar array (50KW) and a battery system.


Source: Wind and Sun

REMOTE ISLAND NETWORKS HAVE NOT USED WAVE DEVICES TO DATE

Solar, wind, hydro, diesel generators and batteries have all been used to date. For example, Eigg has 87 inhabitants and until 2007 the island was not served by mains electricity, most properties were supplied by diesel generators. This changed when the Isle of Eigg Electrification project sought to supply a reliable and mainly renewable 24 hour supply. This led to installation of 9.9 kWp PV system, three hydro systems (totalling 112 kW), 24 kW wind farm supported by diesel generator and batteries. These were connected to demand using three phase distribution system. System was later extended with solar panels in 2010.


Source: HI-Energy

CONCLUSION

Development of remote island networks is feasible, as shown in various Scottish islands. It is however uncertain how many more Scottish islands need this solution. Whilst wave technology at the right scale is demonstrated it is yet to be proven in this context.

Sources:

- Eigg - : http://www.windandsun.co.uk/case-studies/islands-mini-grids/isle-of-eigg,-inner-hebrides,-scotland.aspx#.W-BfTpP7TD5

IS THE SYSTEM VIABLE?

Having established a proposed system conceptual model, an economic model were developed to assess the economic and technical viability of the scenario.

TECHNO-ECONOMIC VIABILITY — Medium

HYPOTHESIS: Can wave displace diesel generators on a remote island? Does this provide a viable niche business case for wave energy?

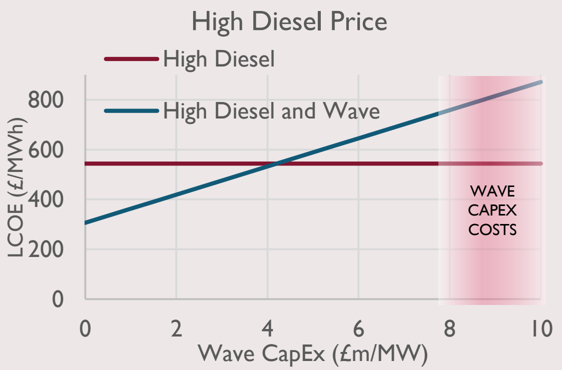
RESULT:

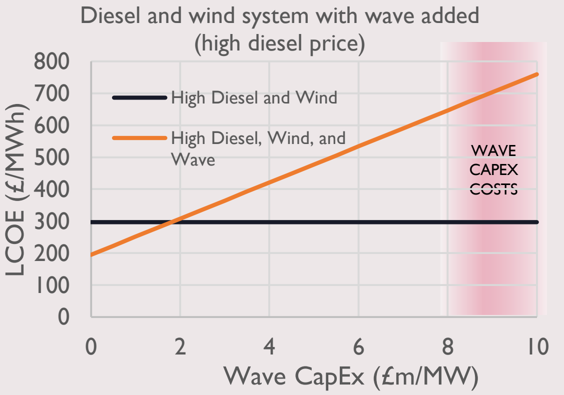
- If we consider that the island is supplied just from diesel generators (top graph), then costs are initially £540/MWh under high cost diesel scenario. Wave system has to be cheaper than ~£4.25m to reduce system costs.
- If we consider central case diesel costs and that the island is supplied initially from diesel generators and wind (bottom graph), then wave would have to have a capex less than £2m/MW.
- 40% of renewable energy generated is spilled in the system which incorporates wave and diesel.
- Wave generation alone is only likely to be cost competitive against diesel generation following significant deployment.

RATIONALE:

- Remote islands have high base-line energy costs due in part to reliance on imported diesel.
- Scenario base case deployment of renewables provides ~80% of islands energy needs.
- Capturing the spilt energy alone does not make an economic case for lithium-ion battery storage in any of the scenarios modelled.
- Therefore there is a vast amount of spilt energy, significantly increasing the cost of supply.
- The LCOE of the modelled wave device alone, with no spilt energy, at a CapEx of £4.25m/MW is £293 / MWh. According to IRENA's Wave Technology Energy Brief this is at the lower end of deployment costs for 10 MW demonstration projects.
- Significant cost reduction required before small scale sites can reach this cost.

IMAGE :
The images below show system supply costs for a range of technologies, how these are affected by wave costs and diesel prices.





REGULATORY VIABILITY — Good

- Private networks are not subject to the same regulatory conditions as projects connecting to the mainland network.
- This means that the project will need to meet requirements of the network it is connecting into and this can be determined on case by case basis. These are not expected to be onerous.
- Regulatory requirements (cost and liabilities) for decommissioning offshore assets will be a challenge.
- Overall the regulatory viability is expected to be good.

OTHER POTENTIAL CHALLENGES — Medium

- Matching of supply and demand on small network is challenging.
- Wave is not fully commercially available and the cost of deployment is currently significantly above the assumed cost in the model.
- There is currently no incentive for the community to chose wave over another form of generation that is more mature and cheaper e.g. wind or solar.
- Many islands already have island networks and localised generation in place, limiting how many other islands this system can be deployed at.
- Capability/enthusiasm is needed within the community to take ownership of offshore generating assets and network.

CONCLUSIONS & RECOMMENDATIONS

CONCLUSIONS

Wave could play a role within energy island systems, alongside other generation technologies, if the costs of development and operation were substantially reduced. The scenario is ambitious in its attempt to decarbonise 80% of the island's electricity demand. There is therefore a significant amount of excess energy, driving up the cost of supply. The economic case for deployment could be improved by reducing the installed capacity and creating responsive cross-vector demand (e.g. EVs or hydrogen production). If additional revenues for energy storage were available this could support the case for battery deployment.

Localised private energy network systems with local generation sources can offer multiple benefits to island communities. This scenario also potentially offers a niche opportunity for wave developers to access higher island electricity prices. However, there is currently little incentive for communities to adopt wave, an expensive, immature technology, when other more mature technologies such as wind and solar are available.

LEVEL OF BARRIERS TO DEVELOPMENT

BARRIER	CURRENT	MEDIUM-TERM
Technical	MEDIUM	
Economic	HIGH	MEDIUM
Regulatory	LOW	
Other	MEDIUM	

SCENARIO LIMITATIONS

Scenario focused on offsetting diesel generation as opposed to benefits from increasing generation capacity on island. Benefits of increased economic activity could be more attractive.

The results and conclusions of the modelled scenario are heavily reliant on a range of scenario assumptions and fixed technical parameters. Scenario limitations which may have a material impact on real life projects are:

- Site specific wave & onshore wind resources and community specific energy consumption.
- No mainland electrical grid connection.
- No additional revenue streams available within the local market for energy storage (i.e. costs only remunerated through reducing amount of spilt renewable energy generation).
- No secondary use for spilt energy. In reality this could be monetised through cross vector processes.
- Performance and cost of system elements.

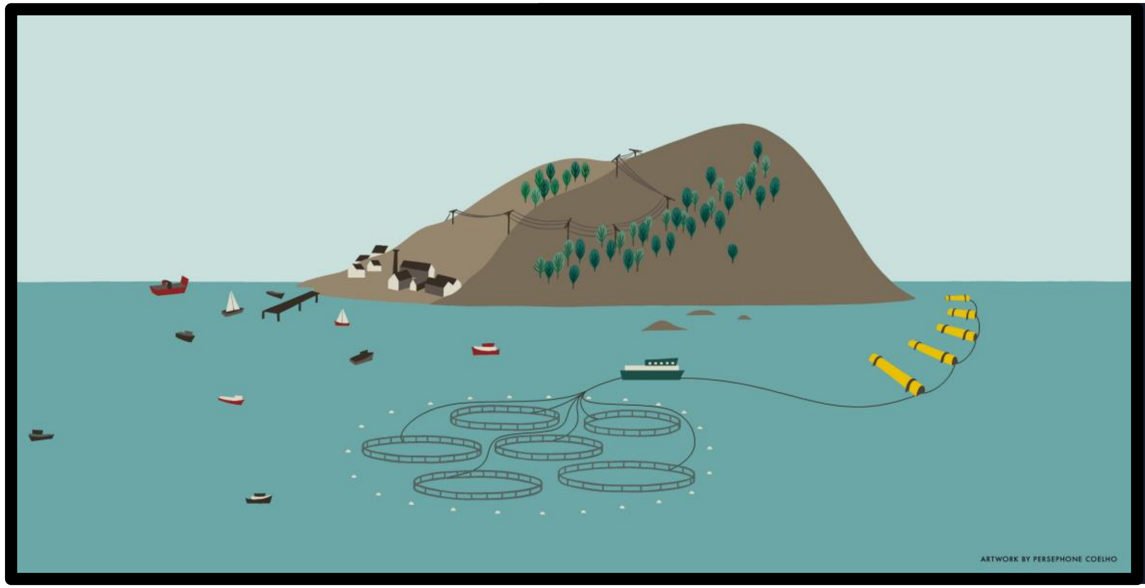
RECOMMENDATIONS

WHAT NEEDS TO BE DONE TO REALISE THIS SCENARIO

- The cost of wave energy needs to be significantly reduced and wave energy needs technology needs to become more mature.
- In the mid-term, wave will not become competitive with onshore wind for most Scottish island communities and onshore wind offers many of the same benefits. Therefore, communities considering wave devices need to be give a significant incentive to chose wave over wind or solar generation.
- The energy system requirements, generation sources and resource availability of the Scottish islands are very variable and therefore, in reality the viability of this type of energy systems must be assessed on a case by case basis and with a mid-term outlook.
- Island communities need to be engaged.

WHAT COULD THE PUBLIC SECTOR DO?

- Support further development and demonstration of wave devices in a non-commercial environment to prove viability and cost reduction potential of the technology.
- Review potential island systems on a case by case basis to determine outline feasibility for this type of system.
- Consider incentive mechanism for communities to adopt wave (or tidal) technology – likely to need to be a financial incentive and a mechanism for reducing project development and operational risk.



SCENARIO 1B:

WAVE TO AQUACULTURE

WHAT COULD BE DONE IN THIS SITUATION?

SITUATION

This situation was chosen as it is a typical scenario being explored by wave developers as they seek to find niche applications for deployment

- This is the same island scenario as 1a except the focus this time is on supply to a local commercial enterprise
- Aquaculture was selected as a widespread coastal energy user that may be located in remote islands
- An off-grid aquaculture site off the island was selected
- Wave developer is seeking to connect 200 kW device

REQUIREMENTS

Provide economic alternative to diesel generators on the aqua-culture farm

PROPOSED ENERGY SYSTEM OPTION

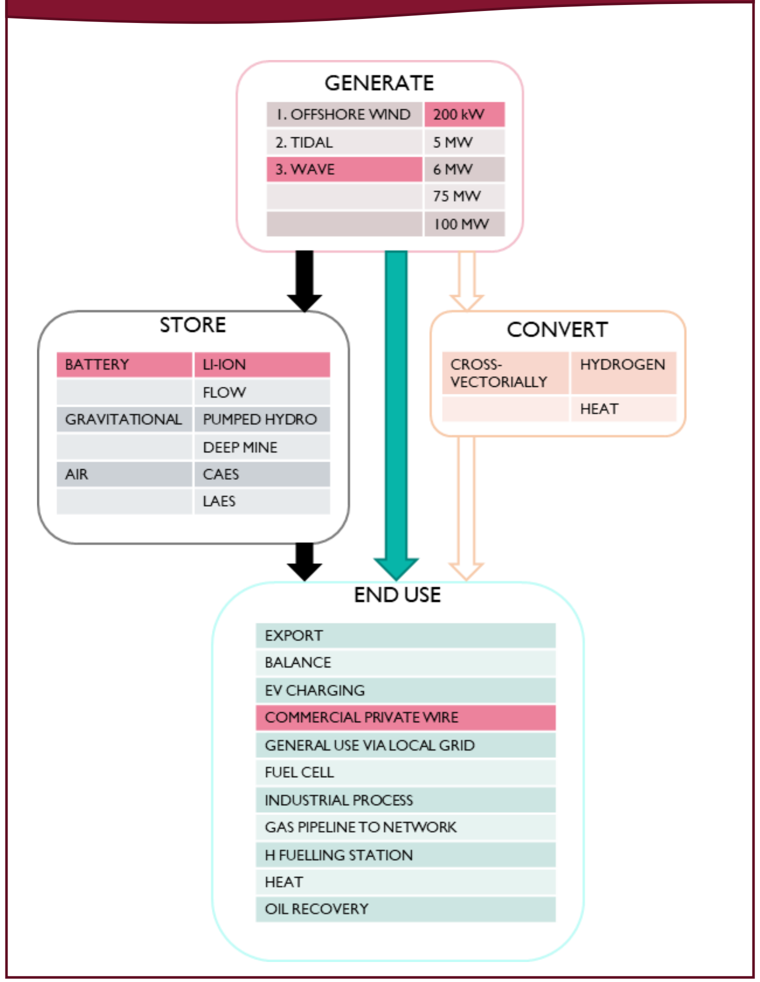
Everoze reviewed potential storage and cross vector options. This concluded that a private wire to the aquaculture farm was the best option, with potential for a battery to provide back up power:

- This is an off-grid purely offshore energy system focused on private wire to the aquaculture farm
- Small battery considered to provide backup power and improve the correlation between electricity supply and demand

SYSTEM ELEMENTS	Deployable in this location	Appropriate storage capacity	Viable use of stored energy
Electric Vehicles	Unlikely to be viable	Unlikely to be viable	Unlikely to be viable
Li-ion battery	Viable	Viable	Viable
Lead-acid battery	Viable	Viable	Viable
Flow battery	Viable	Viable	Viable
Pumped hydro	Unlikely to be viable	Unlikely to be viable	Unlikely to be viable
Deep mine	Unlikely to be viable	Unlikely to be viable	Unlikely to be viable
CAES	Unlikely to be viable	Unlikely to be viable	Unlikely to be viable
LAES	Unlikely to be viable	Unlikely to be viable	Unlikely to be viable
Hydrogen	Unlikely to be viable	Unlikely to be viable	Unlikely to be viable
Heat	Unlikely to be viable	Unlikely to be viable	Unlikely to be viable
Private wire	Viable		

KEY: Unlikely to be viable; Potentially viable; Viable

SUMMARY OF PROPOSED ENERGY SYSTEM



WHAT MIGHT IT LOOK LIKE?

The initial analysis allows the development of an overall proposed energy system for Scenario 1b.

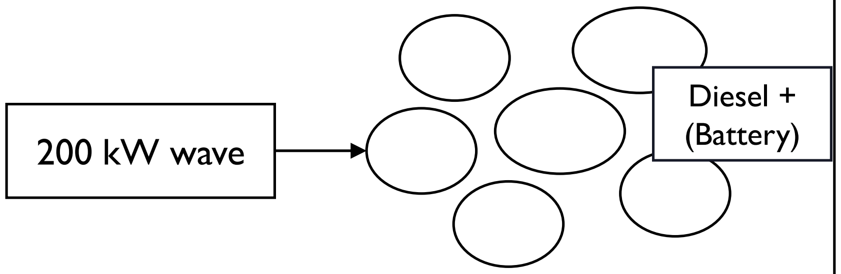
i) Aquaculture farms currently has diesel generators to provide power

ii) Wave developer connects directly to farm through private wire

How would the proposed system work?

Wave device exports to fish farm. Battery may be used to store excess generation although will increase costs. Hybrid power management system required to manage wave, diesel and battery system.

Conceptual model

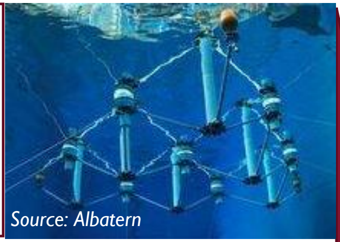
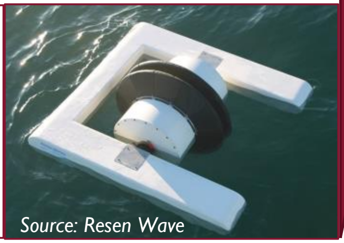


THEORETICAL POTENTIAL BENEFITS OF THIS ENERGY SYSTEM AND WHICH STAKEHOLDERS COULD POTENTIALLY BENEFIT		Wave developer	Aquaculture	Local community
Access to higher prices for power generated	Fish farm currently paying for imported cost of diesel from generators which is typically significantly higher than average energy costs.	x		
Lower cost of energy for fish farm	Potential for fish farm owners to break reliance on diesel imports and use alternative energy source.		x	x
More sustainable aquaculture	Switch from fossil fuel generation to carbon neutral renewable source.		x	x
Use wave device as buffer to fish farm	Reports suggest that the wave energy devices' ability to capture energy from potentially damaging waves may allow reduction in damage and fatigue on the fish farm.		x	x

The viability of realising these benefits are assessed in the following section of this report.

WHAT CAN WE LEARN FROM ELSEWHERE?

This page provides some examples where elements of this system have been or are being deployed. Lessons learnt from these have been taken into account during assessing potential energy systems.

LESSONS LEARNT	EVIDENCE	
WAVE TO OFFSHORE AQUACULTURE PROJECTS HAVE ALREADY BEEN SUCCESSFULLY PILOTED	In 2013 Albatern installed 3 WaveNET SQUID devices at Marine Harvest's salmon farm off the Isle of Muck. A further pilot was deployed near Ardnamurchan, in conjunction with Scottish Salmon Company, which used a hybrid power management system. The pilot aims to validate the use of Albatern's device for powering fish farms.	 *Source: Albatern*
COMMERCIAL INTERGRATED AQUACULTURE-WAVE PROJECTS ARE IN THE PLANNING	Following the success of the pilot project, Albatern and Aquabiotech Group were planning a commercial project in Malta, however it is not clear on current status. Plans stated that the energy needs of the fish farm are roughly 720 kW which will be provided by wave energy as well as storage and back up diesel power. The fish farm will be located approximately 6 km offshore.	 ***Source**: maribe.uu*
THERE IS SIGNFICANT INTEREST IN THE USE OF WAVE DEVICES ON AQUACULTURE FARMS	A range of companies are actively developing this concept. These companies include both wave device developers and aquaculture companies, including InnovaSea, Wave Dragon, Resen Wave, Fusion Marine and Akva Group.	 *Source: Resen Wave*

CONCLUSION

There is significant end-user interest in this concept. This suggests that the concept is worthy of further investigation and could potentially be commercialised in the next 5 years.

Sources:

- Albatern http://albatern.co.uk/
- Meribe.eu http://maribe.eu/wp-content/uploads/2016/11/b-4-albatern-and-abt-final-report-abt.pdf

IS THE SYSTEM VIABLE?

Having established a proposed system, conceptual and economic models were developed to assess the economic and technical viability of the scenario.

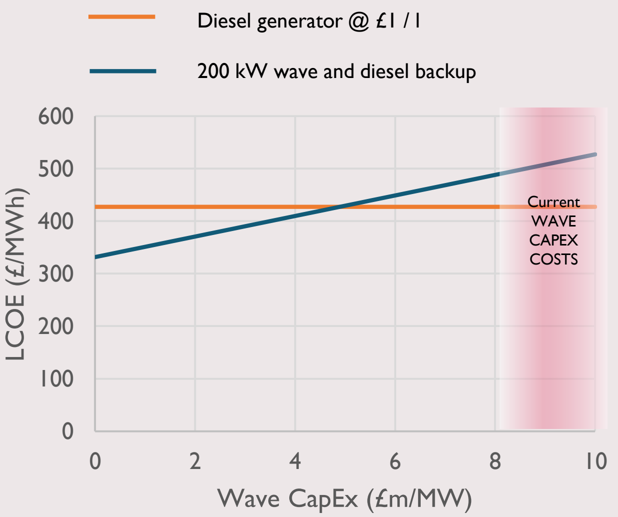
TECHNO-ECONOMIC VIABILITY — Good

HYPOTHESIS: Off-grid aquaculture farms could viably switch from using diesel generator to wave energy devices for their electricity supply.

RESULT:
- Wave can technically provide a potentially viable alternative source of power for off grid aquaculture farms.
- Wave energy cannot fully displace diesel due to the variable generation and large fluctuation between peak and minimum demand. It is economically viable under high diesel cost scenarios to reduce the amount of diesel consumed through wave energy generation.
- Under our central diesel cost scenario, £1/litre, the modelled Wave CapEx would need to be £4.9m/MW before a 0.1 MW wave device is competitive with diesel generation.
- A 0.2 MW wave device was also modelled but was less competitive for this scenario due to high levels of spilt energy.

RATIONALE:
- As wave technology is still immature, getting consistent accurate CAPEX and OPEX costs is not possible. However interpreting costs and load factor data based on IRENA and World Energy Council data, the cost of wave required in the high diesel cost scenario is aligned to large scale wave demonstration costs and may be possible for small scale deployment over time.
- The modelling does not take into account additional commercial risks and complexity that the aquaculture farm would face with two generation sources. Further consideration would be needed to manage the control system of the diesel generator to accommodate the variable power supply from wave.

IMAGE:
The graph below shows the levelised cost of supply for the aquaculture farm assuming a central diesel cost assumption. The orange line shows the base case – that the aquaculture farm just uses an onsite diesel generator. The blue line shows the combined wave and diesel system, assuming a range of wave costs (shown on the x axis). The graph shows that wave costs need to be less than ~£4.9m/MW to be viable.



REGULATORY VIABILITY — Medium

- Relatively long licensing/consenting process for fish farming, which may be increased through addition of novel wave device.
- Insurance and liability for integration of the aquaculture farm and wave generation device may also be a concern. This is routinely managed for diesel generation but wave devices have less of a proven track record. The barrier is likely to be surmountable.
- Installation may require an amendment to existing Town & Country Planning consents and an additional Marine Licence.

OTHER POTENTIAL CHALLENGES — Medium

- Reliability of wave technology is still not fully proven.
- Aquaculture farms are often located in sheltered areas, away from significant wave resource.
- Willingness of aquaculture owners to accept higher risk.
- Control of diesel device and matching supply and demand may prove challenging.
- Solar could potentially offer a more cost effective energy source in some areas.

Sources:
World Energy Council – World Energy Resources: Marine Energy 2016
International Renewable Energy Agency (IRENA) – Wave Energy Technology Brief 2014

CONCLUSIONS & RECOMMENDATIONS

CONCLUSIONS

Use of wave devices on aquaculture farms to reduce diesel use looks potentially economically and technically viable. It is unlikely that they can viably fully replace diesel, even with the use of a storage technology, due to the mis-alignment of the end-demand and energy use profiles. This scenario potentially provides a good opportunity for positive marine stewardship as well as providing commercial benefit. However, barriers to deployment are likely to be the location of aquaculture farms, often in sheltered areas with low wind resource, and reluctance of aqua-culturists to widely adopt new, relatively immature technology.
An option not considered in this study is to have the wave device connecting to the fish farm and grid connections to the local island. This could potentially improve cohesion of demand and generation profiles.

LEVEL OF BARRIERS TO DEVELOPMENT

BARRIER	CURRENT	MEDIUM-TERM
Technical	MEDIUM	
Economic	LOW	
Regulatory	LOW	
Other	MEDIUM	

SCENARIO LIMITATIONS

The results and conclusions of this scenario are heavily reliant on a range of scenario assumptions and fixed technical parameters – for more details see methodology section in the appendix. Scenario limitations which may have a material impact on real life projects are:

- Site specific resources and aquaculture energy consumption.
- Operational parameters of aquaculture site. These can vary based on the site location, species being farmed, and the stage of development of the organisms.
- Performance and cost of system elements.
- Additional costs associated with transporting diesel to site.
- Feasibility of alternative renewable energy generation.

RECOMMENDATIONS

WHAT NEEDS TO BE DONE

- Aquaculture operators will need to be provided with evidence that the technology is viable, the risk of operating is low and any potential benefits can be realised.
- Companies developing devices for small scale wave generation are likely to require investment to bring their product to full commercialisation.
- If this progresses, significant work will be needed to develop appropriate insurance, liability and O&M solutions for these devices.

WHAT SHOULD THE PUBLIC SECTOR DO?

- Provide support for demonstration opportunities and facilitate research into the use of wave devices on aquaculture farms, potentially through demonstrator funding schemes.
- Dissemination of findings of demonstration project and studies to the aquaculture community.
- Continue to provide support for companies developing wave device demonstrators at the relevant scale (sub-500kw).

SCENARIO 2:

TIDAL CONNECTING INTO LARGE ISLAND WITH SIGNIFICANT INDUSTRIAL USERS

WHAT COULD BE DONE IN THIS SITUATION?

SCENARIO 2: TIDAL CONNECTING INTO LARGE ISLAND WITH SIGNIFICANT INDUSTRIAL USERS

SITUATION

This situation was chosen as it is representative of the scale, location and constrained connection typical of small scale tidal arrays

- An Island with a relatively large industrial demand for energy. The local economy includes four large whisky distilleries as well as agriculture and fishing
- Electricity – Island network with constrained mainland connection
- This scenario assumes construction of a small scale tidal site (6 MW)

REQUIREMENTS

Connection to mainland is constrained, limiting export

PROPOSED ENERGY SYSTEM OPTION

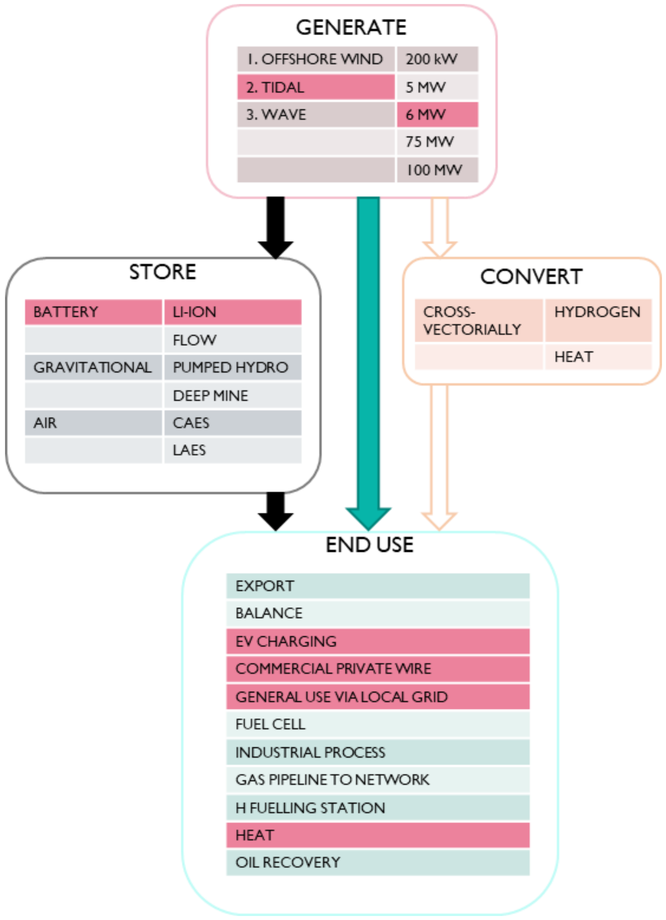
Everoze reviewed potential storage and cross vector options. Plenty of options were available. However, the team concluded that identifying local demand source could a) help alleviate constraint and b) provide access to higher revenue streams:

- Private wire to distilleries could help alleviate export constraint and provide access higher revenue streams
- This could potentially be combined with batteries and/or EV charging to manage excess generations
- Hydrogen, heat and LAES are also potential options (not examined)

SYSTEM ELEMENTS	Deployable in this location	Appropriate storage capacity	Viable use of stored energy
Electric Vehicles	Potentially viable	Potentially viable	Viable
Li-ion battery	Viable	Viable	Viable
Lead-acid battery	Viable	Viable	Viable
Flow battery	Viable	Viable	Viable
Pumped hydro	Potentially viable	Unlikely to be viable	Viable
Deep mine	Unlikely to be viable	Viable	Potentially viable
CAES	Unlikely to be viable	Unlikely to be viable	Viable
LAES	Viable	Potentially viable	Viable
Hydrogen	Viable	Viable	Viable
Heat	Potentially viable	Viable	Viable
Private wire	Viable		

KEY: Unlikely to be viable; Potentially viable; Viable

SUMMARY OF PROPOSED ENERGY SYSTEM



WHAT MIGHT IT LOOK LIKE?

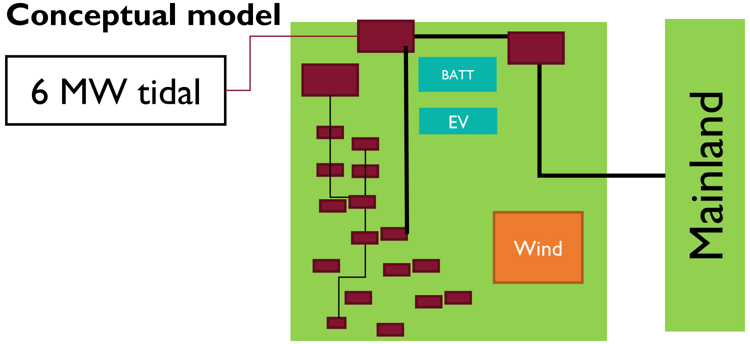
The initial analysis allows the development of an overall proposed energy system for Scenario 2.

i) 6 MW of tidal generation	ii) Private wire connection into distilleries	iii) With potential for batteries or EV Charging as well

How would the proposed system work?

6 MW of tidal generation connects with a private wire to private network of distilleries. This scenario also looks at the consequences of converting distillery stills to using electricity as a heat source, instead of gas. The system is connected to a wider grid network.

Conceptual model



THEORETICAL POTENTIAL BENEFITS OF THIS ENERGY SYSTEM AND WHICH STAKEHOLDERS COULD POTENTIALLY BENEFIT		Tidal developers	Local community	Local industry
Access to higher revenue	Private wire provides access to 'retail' rates as opposed to wholesale prices.	x		x
Reduction in energy costs for distilleries	To go ahead, it must provide potential benefits in form of reduced energy costs to distilleries.			x
Reduction in carbon for distilleries/ island	Low carbon energy for distilleries.			x
Support to electrify transport	Excess generation can be used to help provide charging for electric vehicles.	x	x	

The viability of realising these benefits are assessed in the following section of this report.

CASE STUDIES

CS

WHAT CAN WE LEARN FROM ELSEWHERE?

SCENARIO 2: TIDAL CONNECTING INTO LARGE ISLAND WITH SIGNIFICANT INDUSTRIAL USERS

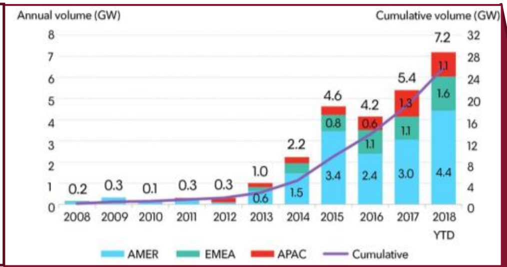
This page provides some examples where elements of this system have been or are being deployed. Lessons learnt from these have been taken into account during assessing potential energy systems.

EVIDENCE

LESSONS LEARNT

THERE IS SIGNIFICANT GROWTH IN CORPORATE PPA MARKET

Driven by RE100 commitments and a desire to manage energy costs, there has been significant growth in corporate PPAs. These can be delivered under three models including private wires.



MAJOR DISTILLERIES ARE SEEKING TO DECARBONISE PRODUCTION. ON-SITE RENEWABLES AND CORPORATE PPA'S (WITH RENEWABLES) ARE PART OF THIS TREND

Diageo installed 30 MW bio-energy facility at Cameronbridge in 2013. This combines biomass combustion, anaerobic digestion and water recovery facility that can meet 95% of the site's energy needs and saving water.


Source: Diageo

PRIVATE NETWORKS HAVE BEEN DEVELOPED AT VARIOUS INDUSTRIAL AND COMMERCIAL SITES

Private networks are common at large industrial and commercial sites, housing developments and business parks. These private networks are often managed and operated by independent DNOs. These are independent providers regulated by Ofgem to ensure adherence on price controls and other regulations placed upon DNOs. For instance, Energetics are the DNO for the large MediaCity development in Salford, Manchester.


Source: Energetics

CONCLUSION

There is increasing interest across many sectors for development of localised generation with private wires. Distilleries are looking to decarbonise and reduce energy costs and in some cases, have installed on-site generation. Use of tidal energy for distilleries has not yet been trialled.

http://www.energetics-uk.com/sectors-we-serve/customer-testimonials/

F&E

FEASIBILITY & ECONOMICS

IS THE SYSTEM VIABLE?

SCENARIO 2: TIDAL CONNECTING INTO LARGE ISLAND WITH SIGNIFICANT INDUSTRIAL USERS

Having established a proposed systems conceptual and economic models were developed to assess the economic and technical viability of the scenario.

TECHNO-ECONOMIC VIABILITY — Medium

HYPOTHESIS: TIDAL GENERATION THROUGH A PRIVATE WIRE CAN PROVIDE A COST EFFECTIVE ALTERNATIVE TO OBTAINING ELECTRICITY FROM MAINS SUPPLY

RESULT:

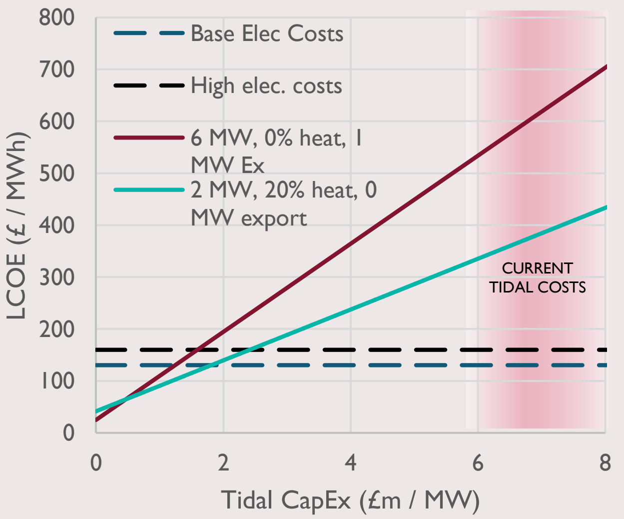
- 6 MW of tidal generation provides more demand than required for the distilleries leading to a significant amount of spilt energy and high system costs (black line on the graph). Actual revenue will be less than wholesale prices in this scenario as a proportion of generation is exported.
- Reducing tidal capacity to 2 MW and electrifying 20% of the distillery heating demand provides a better match and lower system costs. However, tidal CapEx still needs to be ~£2.4m/MW for this system to be viable at high electricity costs.
- This is above the £3.75m/MW assumed for next large scale deployments but in line with expected CapEx following 1 GW of deployment.
- Adding a battery to capture the spilt energy does not improve the economics. Adding EV charging also has limited benefit, even in high charger and utilisation scenarios.

RATIONALE:

- Distilleries have an average electricity demand of 0.7 MW and 4.2 MW of heat.
- Current retail costs for electricity are ~£130/MWh. This is with a dispensation on distilleries such that they only pay 5% of the CCL.
- BEIS forecasts that retail prices for industrial customers will increase by ~20% over the next 3 years. This provides the higher price line.
- Under current ORE-Catapult forecasts* tidal is expected to reduce to £90/MWh once 1 GW is installed. Using Everoze assumptions this equates to £2.25m/MW CapEx.
- The cost at which this system is viable may be reduced by more closely aligning consumption to generation. The green line on the graph represents a case in which 15% of energy generated is spilled.

IMAGE:

- Graph shows the levelized cost of tidal generation (under different installed capacities and assumptions on the amount of electrification of heat at the distilleries) and current and high retail costs paid by the distilleries.
- It shows that 2 MW of capacity with 20% electrification offers lowest cost of energy, yet this is only viable under future retail costs when tidal prices are <£2.4m/MW.



REGULATORY VIABILITY — Medium

- Interaction with local DNO may be challenging – electrical and mechanical interlocks likely to be required to avoid paralleling of the two grid supplies to the distilleries. Project likely to consider use of independent DNO to manage network.

OTHER POTENTIAL CHALLENGES — High

- The majority of energy used by the distilleries is heat based and there is a high capital and operational cost of electrifying heat demand. Potentially biomass is a more attractive all-round solution for decarbonising distilleries.
- Coordination across distilleries particularly on PPAs may be challenging.
- There is currently little incentive for distilleries to chose tidal over wave or solar (except reduced visual impact).

Source: ORE-Catapult – 'Tidal stream and wave energy cost reduction and industrial benefit

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CONCLUSIONS & RECOMMENDATIONS

CONCLUSIONS

This scenario could be viable with tidal energy cost reduction. Cost reductions required are in line with industry estimates yet require 67% reduction in CapEx costs and 1 GW of deployment globally. Delivery also requires overcoming concerns of distillery owners about electrification of heat and committing to long term contracts with a more immature technology.

It should be noted that the LCOE of £300 / MWh from ORE-Catapult may be higher than expected for some mature tidal turbine concepts. In 2017 Atlantis Resources were publicly pushing for a £150 / MWh CfD for Phase 1C (80 MW) of their MeyGen project, following an unsuccessful bid into Action Round 2.

LEVEL OF BARRIERS TO DEVELOPMENT

BARRIER	CURRENT	MEDIUM-TERM
Technical	MEDIUM	
Economic	MEDIUM	
Regulatory	MEDIUM	
Other	HIGH	

SCENARIO LIMITATIONS

The results and conclusions of this scenario are heavily reliant on a range of scenario assumptions and fixed technical parameters. Scenario limitations which may have a material impact on real life projects are:

- Site specific resources, distillery and EV energy consumption.
- Operational parameters of distilleries.
- Performance and cost of system elements.
- Feasibility of alternative renewable energy generation. Specifically, distilleries may choose to decarbonise heating through biomass boilers, combined heat and power units or other technology.

RECOMMENDATIONS

WHAT NEEDS TO BE DONE

- The cost of tidal generation needs to be reduced significantly.
- The business case for the distilleries to switch both the renewable energy and electrifying heat needs to be clearly assessed.
- The distilleries are likely to need incentivising to chose relatively immature tidal generation over more established renewable technologies such as wind.
- Coordination of multiple-party private wires would be needed.

WHAT SHOULD THE PUBLIC SECTOR DO?

- Provide support for tidal energy cost reduction initiatives.
- Engage with distilleries to determine appetite to investigate use of tidal.
- Support with coordination of projects across multiple stakeholders.
- Help incentivise the use of tidal energy (i.e. through financial incentives / grants etc).

SCENARIO 3:

TIDAL CONNECTING TO REMOTE MAINLAND PORT WITH MARITIME HYDROGEN SYSTEM

WHAT COULD BE DONE IN THIS SITUATION?

SCENARIO 3: TIDAL CONNECTING TO REMOTE MAINLAND PORT WITH MARITIME HYDROGEN SYSTEM

SITUATION

This situation was chosen as it is representative of the scale, location and constrained connection typical of the next tranche of commercial tidal arrays

- 5 MW tidal generation being constructed off the coast of a small community
- Network highly constrained with limited ability to export
- The local economy is heavily reliant on the local port facility and maritime activity

REQUIREMENTS

Overcome grid constraint while supporting local economy

PROPOSED ENERGY SYSTEM OPTION

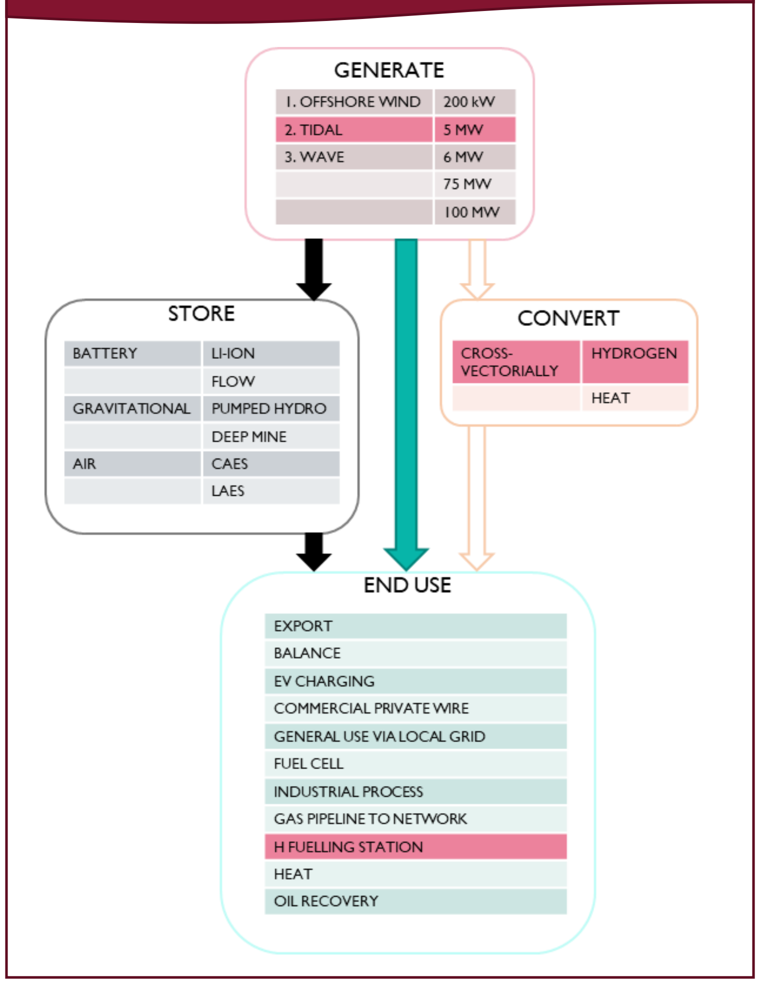
Everoze reviewed potential storage and cross vector options. This concluded that a hydrogen solution was the best option as:

- Local demand is insufficient to provide viable use of energy if stored electrically
- Hydrogen is a viable option at this scale of generating capacity
- Vessel fleets can add significantly to the carbon emissions of remote communities. Hydrogen being actively considered as an alternative fuel sources by some maritime communities

SYSTEM ELEMENTS	Deployable in this location	Appropriate capacity	Viable use of energy
Electric Vehicles	Potentially viable	Potentially viable	Potentially viable
Li-ion battery	Viable	Viable	Potentially viable
Lead-acid battery	Viable	Viable	Potentially viable
Flow battery	Viable	Viable	Potentially viable
Pumped hydro	Potentially viable	Potentially viable	Unlikely to be viable
Deep mine	Unlikely to be viable	Viable	Unlikely to be viable
CAES	Unlikely to be viable	Unlikely to be viable	Unlikely to be viable
LAES	Viable	Potentially viable	Unlikely to be viable
Hydrogen	Viable	Viable	Viable
Heat	Potentially viable	Potentially viable	Viable
Private wire	Potentially viable		

KEY: Unlikely to be viable | Potentially viable | Viable

SUMMARY OF PROPOSED ENERGY SYSTEM



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WHAT MIGHT IT LOOK LIKE?

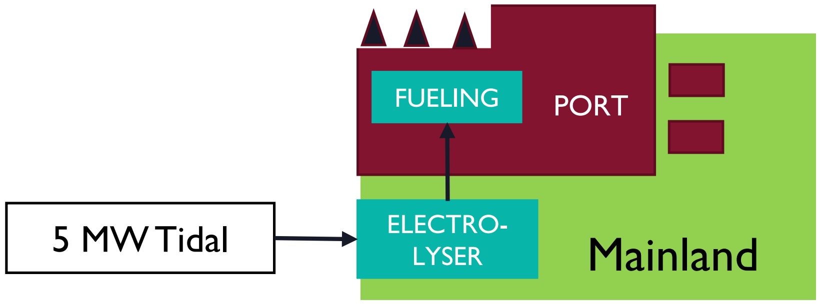
The initial analysis allows the development of an overall proposed energy system for Scenario 3.

i) 5 MW of tidal	ii) Connects into mainland port	iii) Energy converted to hydrogen using electrolyser	iv) Hydrogen stored in bunkers and used to fill local vessels

How would the proposed system work?

Tidal generates power which is exported to shore. Onshore this drives an electrolyser which uses the power to split water into hydrogen and oxygen. The hydrogen is then stored in bunkers before being used to fuel vessels. Hydrogen (and the oxygen) could also be used locally.

Conceptual model



THEORETICAL POTENTIAL BENEFITS OF THIS ENERGY SYSTEM AND WHICH STAKEHOLDERS COULD POTENTIALLY BENEFIT		Tidal developers	Local community	Other*
Integration into local energy systems	Offering potential for larger deployment if viable.	x		
Diversity of revenue streams	Provides tidal generator with range of revenue streams. Could potentially include heat, O_2 and electricity.	x		
Decarbonisation of vessels / port	Vessels are a major contributor to carbon emissions in coastal communities.			x
Air quality benefits	Reduction of pollutants in local area through move to hydrogen vessels.		x	
Marketing for port and vessels	Could help attract companies to port and people to the area.		x	x

The viability of realising these benefits are assessed in the following section of this report.

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* Others include vessel operators and public sector

WHAT CAN WE LEARN FROM ELSEWHERE?

This page provides some examples where elements of this system have been or are being deployed. Lessons learnt from these have been taken into account during assessing potential energy systems.

LESSONS LEARNT

PILOT PROJECTS USING TIDAL ENERGY TO PRODUCE HYDROGEN HAVE BEEN OPERATING FOR SOME TIME

THERE IS ONGOING R&D BEING UNDERTAKEN TO INCREASE THE VIABILITY OF USING HYDROGEN GENERATED ON REMOTE SCOTTISH ISLANDS IN MARINE VESSELS BUT IT HAS NOT YET BEEN DEPLOYED IN SCOTLAND

EVIDENCE

The European Marine Energy Centre (EMEC) has been generating hydrogen from tidal energy since August 2017 through its Surf and Turf project. The initial driver for the project was to provide a storage solution to circumvent local grid constraints but the deployment sparked off other projects looking to use hydrogen locally. Hydrogen produced is transported by road and then shipped to Kirkwall using a purpose-built storage trailer. The hydrogen is used in a fuel cell installed on land (although designed to marine standards) and will provide electricity on demand to ships and activity within Kirkwall Harbour. Heat produced as a by-product will be piped into nearby buildings.

The Project used a Proton Exchange Membrane (PEM) type that are better suited to handling variable energy inputs than other electrolyser techniques.

Source: Surf and Turf

Two ongoing projects are looking at the use of Hydrogen in the Orkney ferry fleet and building on the success of the Surf and Turf project.

HyDIME is a small project which looks at small scale hydrogen storage and use on a passenger ferry using a ULEMCO hydrogen injection system into one of the auxiliary engines. The project allows demonstration that hydrogen can be safely deployed as a fuel, and is helping build the dataset for MCA / IMO approvals.

HYSEAS 3 is a larger hydrogen ferry project, funded by EU and Scottish Government that is currently ongoing. It is looking at the development of ferry engine technology that allows the use of hydrogen produced using renewables to power the Orkney ferry fleet.

Source: Orkneyology

CONCLUSION

Generating hydrogen from tidal energy has been demonstrated in Scotland but has not yet been used in vessels. Work is ongoing to develop the technology and build insurer confidence in hydrogen used for vessels.

IS THE SYSTEM VIABLE?

Having established a proposed systems conceptual and economic models were developed to assess the economic and technical viability of the scenario.

TECHNO-ECONOMIC VIABILITY — Medium

HYPOTHESIS: HYDROGEN PRODUCED FROM TIDAL CAN BE USED AS AN ALTERNATIVE VESSEL FUEL

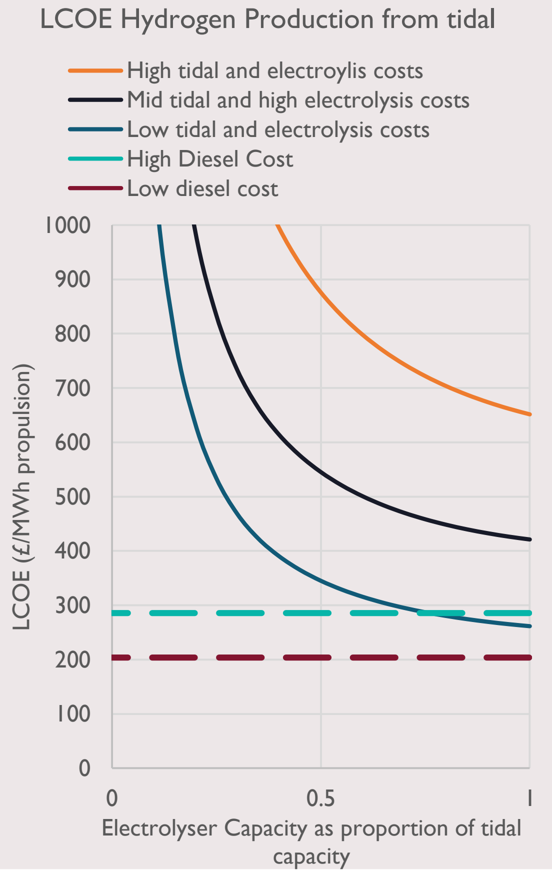
RESULT:

- The results indicate that hydrogen production from tidal for use in vessels is not currently feasible (orange line on graph vs red dashed line).
- However it could be feasible with a significant decrease in tidal LCOE (to £80/MWh) and electrolysis costs (to £0.576m / MW). This is the blue curving line shown on the graph and in line with ORE Catapult and E4Tech future projections.*

RATIONALE:

- Metric used is £/MWh of propulsion. This takes into account the on-board efficiency of the propulsion system and is calculated as below:
  - Diesel has calorific value 0.0109 MWh/ l.
  - Dividing by diesel prices of £0.8/l, £1.0/l, and £1.4 gives diesel fuel prices of £73/MWh, £92/MWh, and £128/MWh for sensitivity cases.
  - Multiplying by the assumed efficiency of diesel engines (40%) gives £183 / MWh, £229 / MWh, £321 / MWh for propulsion.
  - The cost of producing hydrogen per MWh fuel is multiplied by fuel cell efficiency of 60% to provide model costs.
- High value revenue stream - The LCOE of diesel per MWh of propulsion is more valuable than retail price electricity. This helps overcome efficiency losses inherent in the system.
- Vessel costs not included - Model assumes hydrogen vessel is paid for by others (i.e. not included in the model). The difference in capital cost of hydrogen vessels against diesel vessels has therefore not been considered.
- High efficiency scenario - Fuel cells are assumed to produce electricity at high end of efficiency range.

IMAGE:



REGULATORY VIABILITY — Medium

- Hydrogen storage is a challenge with only 5 tonnes currently allowed under regulations.
- Regulation of hydrogen for vessels at early stage. Expensive and time-consuming to carry hydrogen on vessels.
- No renewable transport fuel obligation for marine.

OTHER POTENTIAL CHALLENGES — High

- Low availability and high cost of vessels using hydrogen and technology still under development.
- Infrastructure for ports not yet developed.
- Large amount of on-vessel storage required.
- Stakeholder willingness to adopt technology.
- (For ferries) Timetables may need to be adapted.

*Sources: *ORE-Catapult – Tidal Stream and Wave Energy Cost Reduction and Industrial Benefit (2018)*
E4tech et al. – Scenarios for deployment of hydrogen in contributing to meeting carbon budgets and the 2050 target (2015)

CONCLUSIONS & RECOMMENDATIONS

CONCLUSIONS

Using a per MWh of vessel propulsion metric and with significant reductions in tidal and electrolyser costs, this scenario could potentially be viable. This is because diesel fuel currently represents a relatively high value revenue stream that could be accessed with tidal generated hydrogen. It should be noted that any new build or vessel conversion cost differences between hydrogen and diesel vessels are not included. Hydrogen vessel refuelling and propulsion infrastructure development is still very much at an early stage of development and is likely to represent the limiting factor in the delivery of this scenario.

LEVEL OF BARRIERS TO DEVELOPMENT

BARRIER	CURRENT	MEDIUM-TERM
Technical	MEDIUM	
Economic	HIGH	MEDIUM
Regulatory	MEDIUM	
Other	HIGH	MEDIUM

SCENARIO LIMITATIONS

The results and conclusions of this scenario are heavily reliant on a range of scenario assumptions and fixed technical parameters. Scenario limitations which may have a material impact on real life projects are:

- Per MWh of propulsion metric may not accurately reflect real world conditions.
- No consideration of on-board storage requirements of fuel.
- Performance and system cost assumptions (as shown in Appendix 1), in particular reduction in tidal and electrolyser costs and efficiency.
- Cost and availability of hydrogen vessels versus diesel vessels is not considered.
- Value of electrolysis by-products, heat and oxygen, not considered.

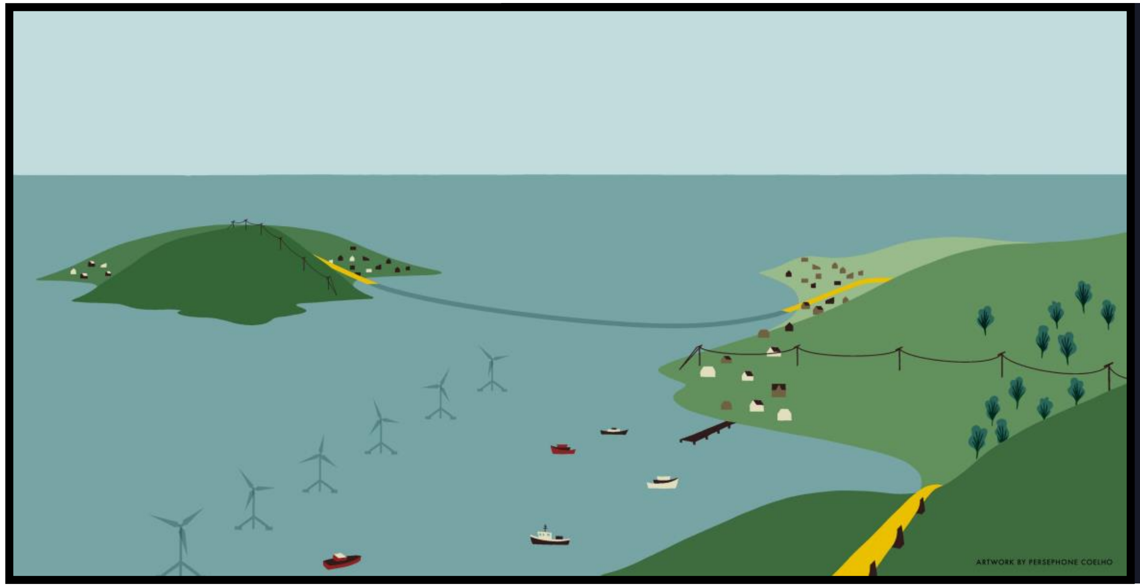
RECOMMENDATIONS

WHAT NEEDS TO BE DONE

- The cost of tidal generation needs to drop significantly.
- A decrease in cost and increase of efficiency electrolysers is required.
- Maritime regulations for hydrogen vessels need further development.
- Hydrogen vessels and refuelling infrastructure needs to be developed further (following on from current case studies).
- Viability of whole system needs to be demonstrated.

WHAT SHOULD THE PUBLIC SECTOR DO?

- Support tidal cost reduction initiatives.
- Support demonstration projects looking at hydrogen, particularly those that are operational and curtailed – thereby providing a potential source of 'free' energy.
- Engage with vessel specialists to determine appetite for investigating hydrogen propulsion.
- Undertake more detailed studies into the feasibility and business case for ports and vessel owners.



SCENARIO 4:

TIDAL ARRAY WITH BATTERY STORAGE PROVIDING AN ALTERNATIVE TO GRID UPGRADE

Sit Opt

SITUATION & OPTIONS

WHAT COULD BE DONE IN THIS SITUATION?

SCENARIO 4: TIDAL ARRAY WITH BATTERY STORAGE PROVIDING AN ALTERNATIVE GRID UPGRADE

SITUATION

This situation was chosen as it is representative of the scale, location and constrained connection typical of the next tranche of commercial tidal arrays

- A 75 MW tidal project is planned between a small island and remote mainland community
- The project is seeking to connect into a local substation with 30 MW of spare capacity
- Grid upgrade requires significant works and is expected to be expensive
- Minimal local demand (population of 300 and light commercial users)

REQUIREMENTS

To build out the full 75 MW, a cost effective solution to network upgrade is required

PROPOSED ENERGY SYSTEM OPTION

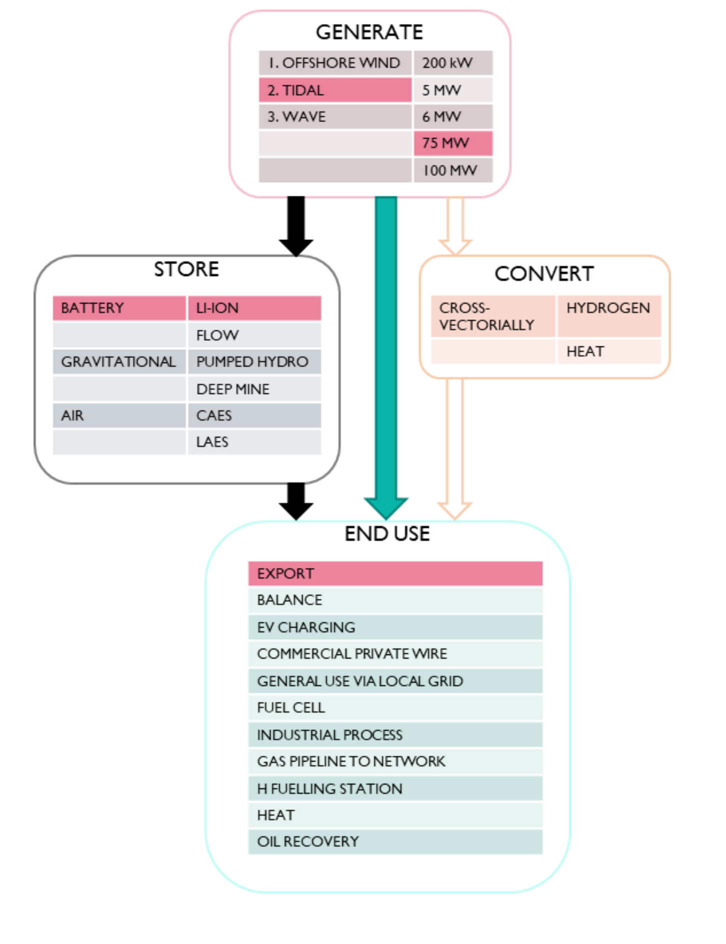
Everoze reviewed potential storage and cross vector options. This concluded that a battery solution was the best option as:

- Local demand insufficient for electrification of transport or heat to provide alternative use of energy in peaks
- Hydrogen conversion possible but limited use potential at this scale
- Limited scope for pumped hydro, deep mine, CAES or LAES
- Batteries can be deployed in this location, at the scale required and can discharge to the network. 3-4 hour peaks are well suited to storage capacity of batteries. Li-ion chosen as technology more commercially mature than flow batteries at present

SYSTEM ELEMENTS	Deployable in this location	Sufficient energy capacity	Viable use of stored energy
Electric Vehicles	Potentially viable	Potentially viable	Potentially viable
Li-ion battery	Viable	Viable	Viable
Lead-acid battery	Viable	Potentially viable	Viable
Flow battery	Viable	Viable	Viable
Pumped hydro	Potentially viable	Viable	Unlikely to be viable
Deep mine	Potentially viable	Viable	Unlikely to be viable
CAES	Unlikely to be viable	Potentially viable	Unlikely to be viable
LAES	Potentially viable	Potentially viable	Viable
Hydrogen	Viable	Potentially viable	Potentially viable
Heat	Viable	Unlikely to be viable	Potentially viable
Private wire	Unlikely to be viable		

KEY: Unlikely to be viable; Potentially viable; Viable

SUMMARY OF PROPOSED ENERGY SYSTEM



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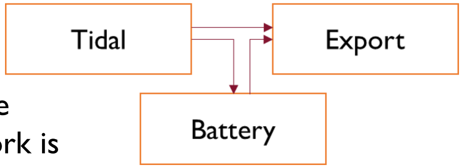
WHAT MIGHT IT LOOK LIKE?

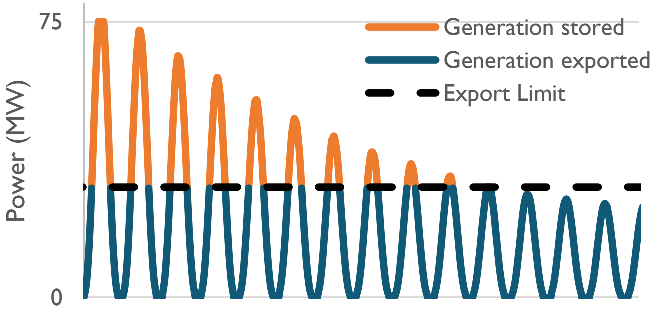
The initial analysis allows the development of an overall proposed energy system for Scenario 4.

i) 75 MW of tidal	ii) Local substation with 30 MW of spare capacity. This is insufficient to export 75 MW of tidal generation & upgrade expensive.	iii) Therefore seek to install 45 MW x MWh li-ion battery plant

How would the proposed system work?

Under this proposed scenario, energy generated above that can be exported to the network is stored in a battery and discharged into the network during periods of slack tide





THEORETICAL POTENTIAL BENEFITS OF THIS ENERGY SYSTEM AND WHICH STAKEHOLDERS COULD POTENTIALLY BENEFIT		Tidal developers	Local community
Avoidance of network upgrade costs	Batteries could provide a more cost-effective solution if there are high network upgrade costs, contestable works or long timescales for connection. Batteries may also be able to help manage local power quality issues.	x	
Potential to attract large energy users to stable significant local energy source	Stabilising energy output (and voltage) with a battery storage system may attract high-energy users to establish facilities in the area. This end-use was not modelled within this study.	x	x

The viability of realising these benefits are assessed in the following section of this report.

WHAT CAN WE LEARN FROM ELSEWHERE?

SCENARIO 4: TIDAL ARRAY WITH BATTERY STORAGE PROVIDING AN ALTERNATIVE GRID UPGRADE

This page provides some examples where elements of this system have been or are being deployed. Lessons learnt from these have been taken into account during assessing potential energy systems.

LESSONS LEARNT	EVIDENCE
TIDAL ENERGY HAS BEEN DEPLOYED IN THE TYPE OF LOCATION AND THE SCALE OUTLINED IN THIS SCENARIO	In 2016, the MeyGen project (Phase 1a) completed installation of 4x1.5 MW turbines. This was the first multi-MW, multi-turbine tidal stream array installed globally. These first turbines were deployed as part of a ‘deploy and monitor’ strategy and act as a precursor to the addition of 73.5 MW (40 turbines) in phase 1C. If successfully deployed, the MeyGen offshore lease permits up to 398 MW of tidal stream capacity to be installed within the site.
A PROJECT INTEGRATING A TIDAL ARRAY AND BATTERY HAS BEEN DEPLOYED ON A SMALLER SCALE, WITH GRANT FUNDING SUPPORT	In Autumn 2018, Nova Innovation recently announced that they had integrated a 300 kW tidal array with a Tesla Powerpack battery to provide baseload tidal power. The key aim of the project is to demonstrate the economic and technical benefit of combining Nova’s tidal array with energy storage to overcome grid constraints, improve grid stability and facilitate the expansion of the array.
LI-ION BATTERIES HAVE BEEN USED TO DEFER NETWORK UPGRADES	In 2017 Fluence delivered a 2 MW 4-hour duration battery energy system to Arizona Public Service for less than its next best alternative – a 20 mile transmission upgrade. The battery had a faster speed of deployment, lower implementation costs and could provide additional benefits. In addition as batteries are modular, they provide network operators with optionality to deal with uncertainty over load growth.
THERE IS SIGNIFICANT INTEREST IN THE UK IN USING BATTERIES (AND OTHER DISTRIBUTED ENERGY RESOURCES) TO HELP DNOs DEFER NETWORK UPGRADES	UK Power Networks, amongst others, will use flexibility tenders as part of optioneering assessments when preparing network investment plans and during network investment delivery to ensure optimal network solutions are selected.


Source: Meygen

Source: *Nova Innovation*


Source: *AES*

CONCLUSION

Both tidal energy and batteries have separately been deployed at the scale required by this scenario. The integration of the two technologies has been carried out but only at pilot scale.

Sources:

- Simec Atlantis Energy – https://simecatlantis.com/projects/meygen/
- Nova Innovation https://www.novainnovation.com/tess
- Fluence - http://blog.fluenceenergy.com/energy-storage-for-transmission-and-distribution-planning
- UKPN - http://futuresmart.ukpowernetworks.co.uk/wp-content/themes/ukpnfuturesmart/assets/pdf/FutureSmart-Consultation-Report.pdf

IS THE SYSTEM VIABLE?

Having established a proposed system, conceptual and economic models were developed to assess the economic and technical viability of the scenario.

TECHNO-ECONOMIC VIABILITY — Poor

HYPOTHESIS: Batteries can provide cost effective alternative to grid upgrade for tidal now and in 2030

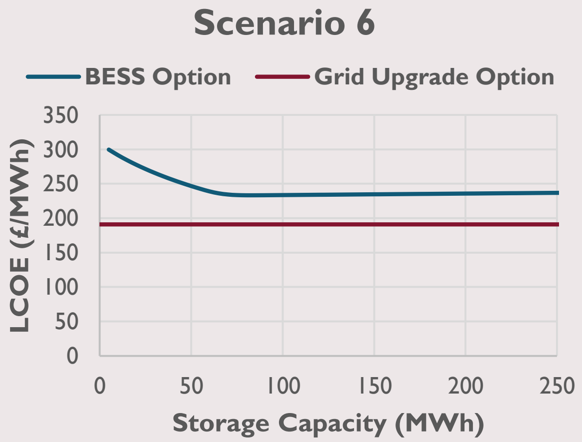
RESULT:
- Even with significant upgrade costs proposed (£500k/MW) and a 50% reduction in Li-Ion costs, the model indicates that there is no economic case for using batteries to defer large scale grid infrastructure upgrade.
- Reducing cost of tidal does not change the results
- Generally not considered viable option.

RATIONALE:
- Model assumes project is connecting into distribution network and is therefore responsible for bulk of network upgrade costs.
- In the base case the capex for a new battery system and grid upgrade are of a similar magnitude, yet the battery system costs more during the lifetime and has higher efficiency losses. These include:
  - Spilt energy - challenging to capture all of the energy generated.
  - Usable capacity – batteries are limited to within 10-90% of their nameplate MWh capacity to avoid damage to the cells.
  - Round trip efficiency – li-ion batteries have RTE of 80%.
  - Degradation – Assumed to be 2% per year degradation due to high energy throughput.
  - Lifetime – the batteries need replacing after 10 years.

- Upfront cost of network upgrade therefore has to be ~7x more expensive than initial battery capex to make viable to install battery.

IMAGE:
The graphic below shows the analysis for scenario 6 with the red line showing the LCOE for the system with network upgrade and the blue line showing the LCOE with battery solution.

The main inputs are £500k / MW and a 50% reduction in battery energy storage CapEx costs per MWh. As can be seen the network upgrade is always a cheaper option, regardless of the capacity of the battery installed.



REGULATORY VIABILITY — Good

- Metering requires careful consideration – we assume that the battery is connected behind the tidal generation meter with a separate sub-meter to allow any subsidies for the tidal to be accounted for.
- As battery is charged from tidal generation (as opposed to energy imported from the network), no issues with double charging of energy charges or lack of definition of storage.
- Overall though li-ion is commercially deployed technology in UK with no major concerns expected.

OTHER POTENTIAL CHALLENGES — Medium

- Limited benefit to local community (beyond more MW installed).
- Low consenting risk so should be limited push back from local community.
- There is a discord between scale of generation and local demand.

NB: Wind and solar generation profile is different to tidal which means not possible to extrapolate this result for these more mature technologies.

CONCLUSIONS & RECOMMENDATIONS

CONCLUSIONS

It is challenging to foresee a scenario where this type of energy system becomes widely economically viable even if battery prices fall faster than predicted. This is because the initial battery costs are similar to the upgrade costs assumed, yet (due to round trip efficiency losses, state of charge management, degradation) the battery can export far fewer MWh to the network and the battery system needs to be repowered after 10-15 years. Study estimates upgrade costs need to be 7x that of battery capex for the proposed system to be viable under the assumptions made in the scenarios. Viability would be significantly increased in areas with higher upgrade costs.

LEVEL OF BARRIERS TO DEVELOPMENT

BARRIER	CURRENT	MEDIUM-TERM
Technical	LOW	
Economic	HIGH	
Regulatory	LOW	
Other	MEDIUM	

SCENARIO LIMITATIONS

The results and conclusions of this scenario are heavily reliant on a range of scenario assumptions and fixed technical parameters. Scenario limitations which may have a material impact on real life projects are:

- This study assumes a fairly significant grid constraint (50% of generating capacity), requiring a very large number of MWh to 'go through' the battery. Batteries may be more viable when the grid constraint is lower.
- Smaller projects may be able to access grant funding that could significantly improve viability.
- This study assumes no additional revenue from ancillary service markets such as frequency response. This is not unrealistic given the high utilisation of the battery that would make it challenging to 'stack' with other services.
- This model has only considered Li-ion batteries. Flow batteries are credible alternative, with particular advantages for longer duration and high energy systems such as this. However the round trip efficiency of this option is currently lower than Li-ion batteries and deployment volume (to date and forecast) significant lower than li-ion. Flow batteries are considered unlikely to change results significant.

RECOMMENDATIONS

WHAT NEEDS TO BE DONE

- Review viability assuming a less significant grid constraint.
- There is a small chance that the development of this type of systems could attract high-energy users to the region. In which case, alternative commercial model may be adopted which may change the economic viability and communities benefits of this scenario.
- This viability of this type of project should be considered by developers on a site by site basis, taking into the opportunities. presented by delivering ancillary services from the site.

WHAT SHOULD THE PUBLIC SECTOR DO?

- Assess opportunities to engage on tidal-battery projects on a case by case basis, ensuring a detailed feasibility stage is carried out if significant investments is required.

SCENARIO 5:

LARGE SCALE FLOATING WIND WITH OFFSHORE ELECTROLYSIS AND USE OF GAS PIPELINES

WHAT COULD BE DONE IN THIS SITUATION?

SCENARIO 5: LARGE SCALE FLOATING WIND WITH OFFSHORE ELECTROLYSIS AND USE OF GAS PIPELINES

SITUATION

This situation was chosen as it is representative of the scale, location and constrained connection typical of sites identified by Marine Scotland as potentially suitable for offshore wind in the next leasing round

- 100 MW floating wind situated off large island
- Island has highly constrained connection to mainland. Upgrade would take over a decade and is not considered feasible
- Limited local demand on island

REQUIREMENTS

Find alternative vector or route to transport energy to mainland

PROPOSED ENERGY SYSTEM OPTION

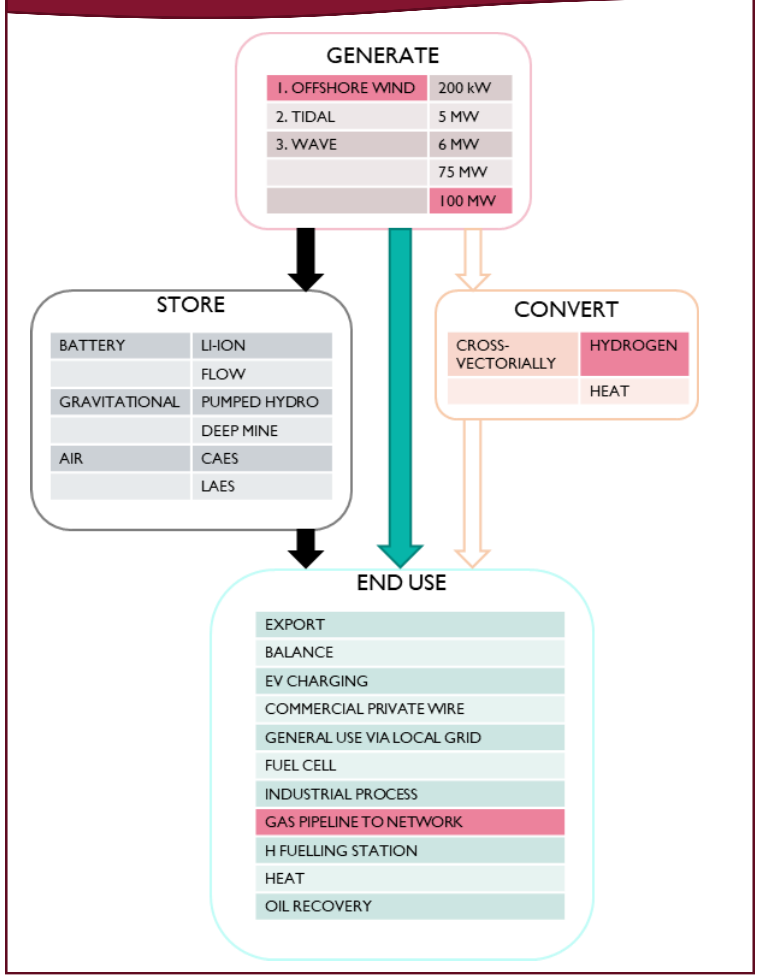
Everoze reviewed potential storage and cross vector options. This concluded that converting power to hydrogen offshore and transporting through existing gas network best options as:

- Limited local demand means cannot use power locally
- Grid constraint means not possible to export power to mainland even if it could be stored
- Potential to utilise existing gas pipeline network
- Hydrogen electrolysers are being built at this scale
- Various studies exploring inputting of hydrogen into gas network

SYSTEM ELEMENTS	Deployable in this location	Appropriate storage capacity	Viable use of stored energy
Electric Vehicles	Potentially viable	Unlikely to be viable	Unlikely to be viable
Li-ion battery	Viable	Potentially viable	Unlikely to be viable
Lead-acid battery	Viable	Potentially viable	Unlikely to be viable
Flow battery	Viable	Potentially viable	Unlikely to be viable
Pumped hydro	Potentially viable	Viable	Unlikely to be viable
Deep mine	Potentially viable	Unlikely to be viable	Unlikely to be viable
CAES	Unlikely to be viable	Viable	Unlikely to be viable
LAES	Viable	Potentially viable	Unlikely to be viable
Hydrogen	Viable	Potentially viable	Potentially viable
Heat	Potentially viable	Unlikely to be viable	Unlikely to be viable
Private wire	Unlikely to be viable		

KEY: Unlikely to be viable | Potentially viable | Viable

SUMMARY OF PROPOSED ENERGY SYSTEM



WHAT MIGHT IT LOOK LIKE?

The initial analysis allows the development of an overall proposed energy system for Scenario 5.

i) 100 MW Floating Wind	ii) Offshore electrolyser to convert power into hydrogen	iii) Inputted into existing gas pipelines in North Sea	iv) Exported to refineries on mainland

How would the proposed system work?

The power generated by the 100 MW floating wind farm drives an electrolyser situated offshore. This produces hydrogen which is exported through ideally existing, reconditioned or potentially new gas pipelines into the main gas grid network.

Conceptual model

100 MW Floating Wind → Offshore Electrolyser → Gas Pipelines → Mainland gas network

THEORETICAL POTENTIAL BENEFITS OF THIS ENERGY SYSTEM AND WHICH STAKEHOLDERS COULD POTENTIALLY BENEFIT		Developers	Local community	Other*
Overcomes grid constraint	Provides export route for the energy. May open up new areas.	x		x
Delivers renewable heat at scale	Large scale hydrogen production.			x
Postpones decommissioning of pipelines	Offers potential to repurpose assets coming to end of life.			x
Reduced electrical connection for wind farm	No connection needed to island.	x		
Employment benefits locally	Through deployment of large scale wind farm.		x	

The viability of realising these benefits are assessed in the following section of this report.

* Others include electrical infrastructure operators, gas pipeline operators, and the public sectors

CASE STUDIES

CS

WHAT CAN WE LEARN FROM ELSEWHERE?

SCENARIO 5: LARGE SCALE FLOATING WIND WITH OFFSHORE ELECTROLYSIS AND USE OF GAS PIPELINES

This page provides some examples where elements of this system have been or are being deployed. Lessons learnt from these have been taken into account during assessing potential energy systems.

LESSONS LEARNT

FLOATING WIND IS EXPECTED TO BE DEPLOYED AT THIS SCALE SOON

SCENARIO IS ATTRACTING INTEREST FROM MAJOR PLAYERS

THE AMOUNT OF HYDROGEN THAT CAN BE INJECTED INTO GAS NETWORK IS LIKELY TO BE INCREASED OVER COMING DECADES. THIS COULD PROVIDE AN INTERESTING ROUTE FOR CONSTRAINED FLOATING WIND

EVIDENCE

Equinor's 30 MW Hywind project was commissioned in Scotland in 2017, featuring spa-buoy technology. Another 237 MW of floating wind is expected to be deployed by 2020 (Equinor). Pilot scale projects are being developed in Japan and France. The upcoming ScotWind leasing round includes areas which are suitable for fixed and floating solutions.

Source: Equinor

World Energy Council with PWC, Shell, Siemens, TenneT and others reviewed viability of repurposing oil and gas platforms and pipelines with offshore electrolysis from offshore wind. This found offshore electrolysis using re-used platform was potentially viable, subject to significant cost reduction and higher hydrogen prices.

Source: AES

HyDeploy project, led by gas network Cadent, in partnership with Northern Gas Network, Keele University, is kicking off a year-long pilot that will blend 20% of hydrogen (by volume) with the normal gas supply in part of Keele University's gas network. Customers will continue to use the gas as they do today.

The H21 Leeds City Gate Feasibility study, published in 2018, showed that the UK entire gas network could theoretically be converted to 100% hydrogen with minimal disruption to customers. See Northern Gas Networks H21 Leeds Citygate project for more details.

Source: ITM Power

CONCLUSION

Floating wind is close to commercial deployment but access to high revenue streams for output would ease short-term deployment. Work is ongoing to look at the viability of large-scale injection into the gas network. This is at pilot stage but significant investment and development would be needed to make this a substantial market for hydrogen. Studies aiming to look at the viability of this scenario have been completed but as things stand viability would require a high value end use for the hydrogen produced.

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F&E

FEASIBILITY & ECONOMICS

IS THE SYSTEM VIABLE?

SCENARIO 5: LARGE SCALE FLOATING WIND WITH OFFSHORE ELECTROLYSIS AND USE OF GAS PIPELINES

Having established a proposed systems conceptual and economic models were developed to assess the economic and technical viability of the scenario.

TECHNO-ECONOMIC VIABILITY — Poor

HYPOTHESIS: WOULD REVENUE FROM HYDROGEN PRODUCTION AND INJECTION INTO THE GAS GRID PROVIDE AN ALTERNATIVE VIABLE REVENUE FOR AN OFF-GRID OFFSHORE WIND PROJECT?

RESULT:

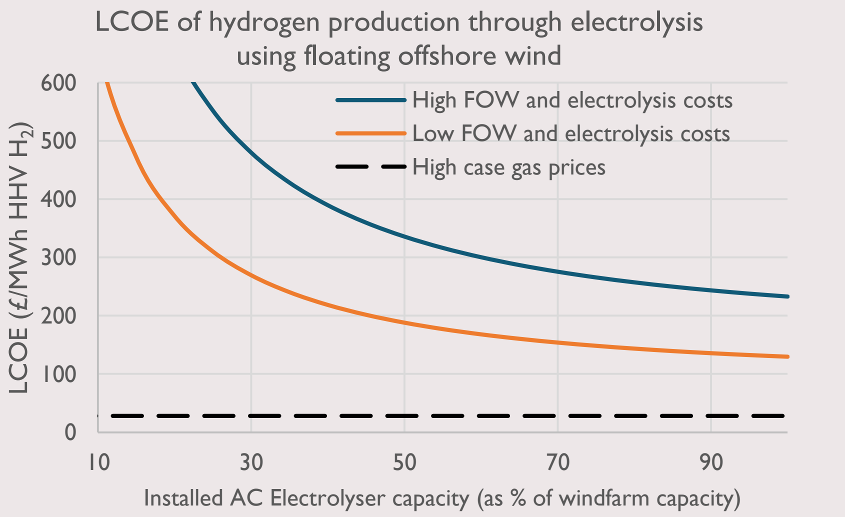
- Modelling suggests that hydrogen from floating wind is highly unlikely to become competitive with natural gas for heating in the mid-term.
- Under best case assumptions* (orange curve on graph) for floating wind and hydrogen production costs this system could deliver hydrogen into the network for ~£130/MWh. This is significantly above the wholesale gas prices expected, even with a doubling of the carbon price.

RATIONALE:

- There are no insurmountable technical challenges that would prevent this scenario being realised and this technology could technically provide a route to partial decarbonisation of heat infrastructure.
- Despite reduced electrical costs for the floating wind farm, the efficiency losses involved in converting to hydrogen combined with the low revenues available in the wholesale gas market make this an unattractive option.

IMAGE:

- The graph shows the levelized cost of energy for a MWh of H_2 produced by a floating wind farm.
- It shows a high gas price (black dotted line) reflecting a doubling of the carbon price.
- The curving blue and orange lines show the revenue needed to deliver 1 MWh of hydrogen into the gas network with varying levels of electrolysers installed. As can be seen even under low FOW and hydrogen production costs, gas grid injection revenue is significantly lower than required for this project.



REGULATORY VIABILITY — Medium

- At present the amount of hydrogen that can be blended into gas transmission and distribution network is to 0.1% by volume in line with GSMR limits.
- 20% stated as safe limit in various studies, including HSE's into the amount of hydrogen tolerated by domestic appliances.
- Gas is currently billed on a calorific value basis. As a low calorific value gas, hydrogen may fall under CV value with 3.5% hydrogen by volume. This can be addressed by either adding hydrogen or through reform in billing regimes.

OTHER POTENTIAL CHALLENGES — Medium

- Hydrogen produced may be more valuable as a fuel than as export into gas network.
- Range of technical challenges associated with injecting hydrogen into pipelines.
- If using pipelines likely to have additional charges / OpEx costs not covered within model.

- Best case floating wind costs assumed align Everoze's technical performance assumptions with ORE-Catapult's LCOE projections within 'Macroeconomic Benefits of Floating Offshore Wind in the UK.
Best case electrolysis assumptions sourced from E4tech 'Scenarios for deployment of hydrogen in contributing to meeting carbon budgets and the 2050 target'
Hydrogen injection into grid costs taken from World Energy Council's report – 'Bringing North Sea energy ashore efficiently'

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CONCLUSIONS & RECOMMENDATIONS

CONCLUSIONS

Producing hydrogen by offshore electrolysis, powered by floating wind, and injecting this into existing gas pipelines for sale in the wholesale gas network is unlikely to viable. This is due to high efficiency losses and the low prices available in the wholesale gas market.

Alternative (higher value) revenue streams such as replacement of diesel on offshore oil and gas rigs or export for fuel or industrial processes, and possible benefits from postponing decommissioning liabilities could help improve viability but these mitigations were not assessed in this study.

LEVEL OF BARRIERS TO DEVELOPMENT

BARRIER	CURRENT	MEDIUM-TERM
Technical	MEDIUM	
Economic	HIGH	
Regulatory	HIGH	MEDIUM
Other	MEDIUM	

SCENARIO LIMITATIONS

The results and conclusions of this scenario are heavily reliant on a range of scenario assumptions and fixed technical parameters. Scenario limitations which may have a material impact on real life projects are:

- Costs assumed for all elements of the system, with high uncertainty over the cost of adapting existing infrastructure to inject hydrogen into gas pipelines.
- Gas prices far into the future, particularly if considering large scale move to a hydrogen economy.
- Potential benefits from postponing decommissioning liabilities was not included - Scenario could provide existing oil and gas infrastructure with alternative end of life opportunities, which could help postpone decommissioning. This was not accounted for in the modelling.
- Alternative, potentially higher value, revenue streams for the hydrogen: There include using the gas as a fuel for shipping or as an alternative to diesel on oil and gas rigs. These alternative revenue streams have not been modelled for this scenario and could help improve viability.
- Other options may exist for direct offshore use of power from floating wind farms, including use on oil and gas infrastructure and oil recovery and vessel refuelling. These were not modelled under this study.

RECOMMENDATIONS

WHAT NEEDS TO BE DONE

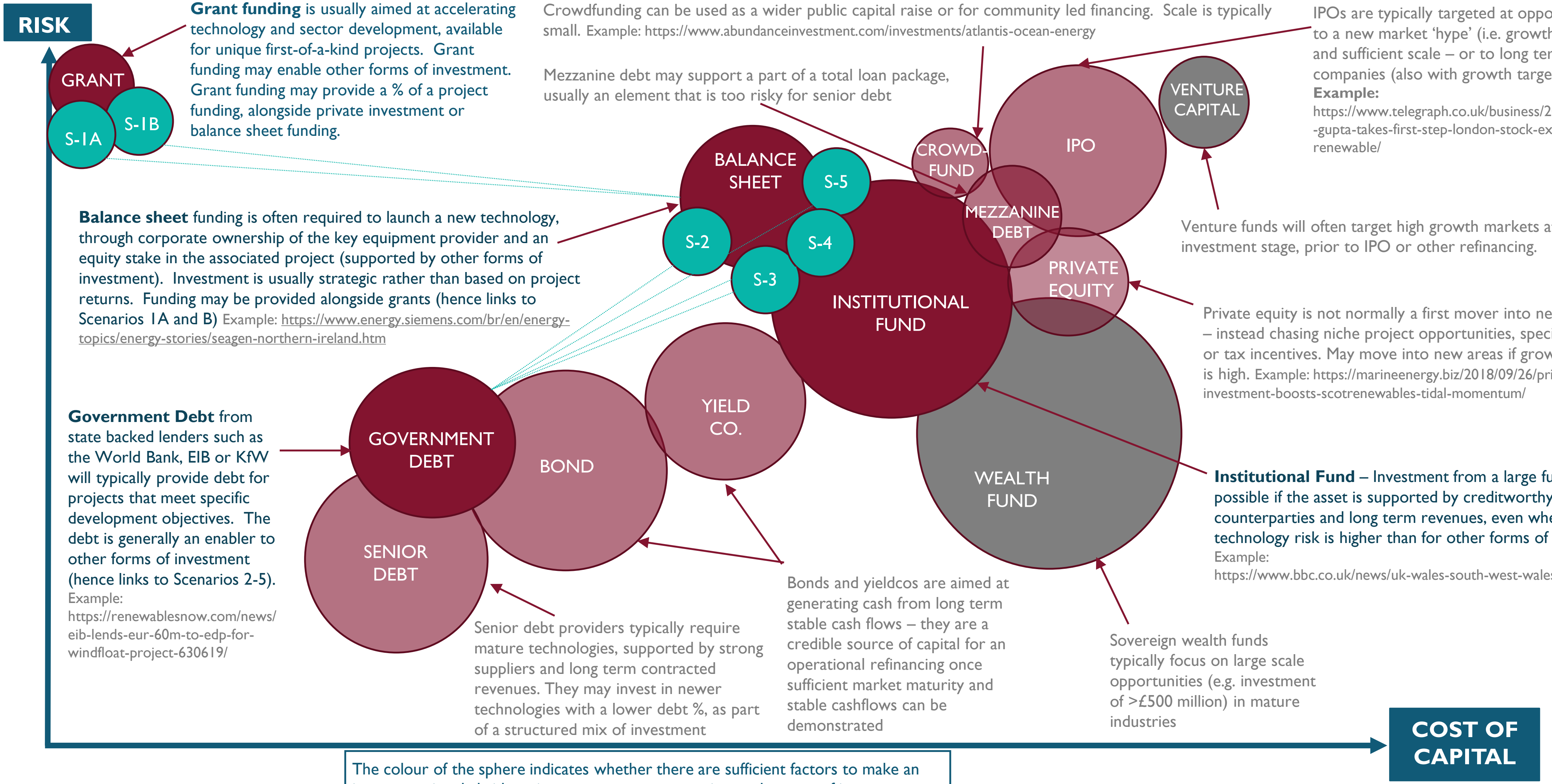
- Consider whether postponing decommissioning liabilities for oil and gas infrastructure could aid economic viability.
- Higher value alternative options could be explored such as refuelling for cruise ships or displacement of diesel generators on oil and gas rigs. However it is not clear whether these would provide the volume of demand required for this scenario.
- Further development needs to be undertaken (and is underway) to review the use of hydrogen in the gas network.

WHAT SHOULD THE PUBLIC SECTOR DO?

- Follow developments in hydrogen-gas grid technology and regulatory changes.
- Track and potentially support, further studies looking at the viability of using offshore generated hydrogen for higher value end-uses.

WHAT INVESTMENT IS AVAILABLE FOR DEVELOPMENT OF THESE SCENARIOS

The image below shows the various investment considerations for different types of investors, within the context of potential investment in future marine energy systems (projects) .



Grant funding is usually aimed at accelerating technology and sector development, available for unique first-of-a-kind projects. Grant funding may enable other forms of investment. Grant funding may provide a % of a project funding, alongside private investment or balance sheet funding.

Crowdfunding can be used as a wider public capital raise or for community led financing. Scale is typically small. Example: https://www.abundanceinvestment.com/investments/atlantis-ocean-energy

Mezzanine debt may support a part of a total loan package, usually an element that is too risky for senior debt

IPOs are typically targeted at opportunities linked to a new market 'hype' (i.e. growth expectation) and sufficient scale – or to long term development companies (also with growth targets). **Example:** https://www.telegraph.co.uk/business/2017/12/14/sanjeev-gupta-takes-first-step-london-stock-exchange-renewable/

Balance sheet funding is often required to launch a new technology, through corporate ownership of the key equipment provider and an equity stake in the associated project (supported by other forms of investment). Investment is usually strategic rather than based on project returns. Funding may be provided alongside grants (hence links to Scenarios 1A and B) Example: https://www.energy.siemens.com/br/en/energy-topics/energy-stories/seagen-northern-ireland.htm

Venture funds will often target high growth markets at seed investment stage, prior to IPO or other refinancing.

Private equity is not normally a first mover into new technology – instead chasing niche project opportunities, specific markets or tax incentives. May move into new areas if growth potential is high. Example: https://marineenergy.biz/2018/09/26/private-investment-boosts-scotrenewables-tidal-momentum/

Government Debt from state backed lenders such as the World Bank, EIB or KfW will typically provide debt for projects that meet specific development objectives. The debt is generally an enabler to other forms of investment (hence links to Scenarios 2-5). Example: https://renewablesnow.com/news/eib-lends-eur-60m-to-edp-for-windfloat-project-630619/

Institutional Fund – Investment from a large fund may be possible if the asset is supported by creditworthy counterparties and long term revenues, even where the technology risk is higher than for other forms of senior debt. Example: https://www.bbc.co.uk/news/uk-wales-south-west-wales-29685642

Senior debt providers typically require mature technologies, supported by strong suppliers and long term contracted revenues. They may invest in newer technologies with a lower debt %, as part of a structured mix of investment

Bonds and yieldcos are aimed at generating cash from long term stable cash flows – they are a credible source of capital for an operational refinancing once sufficient market maturity and stable cashflows can be demonstrated

Sovereign wealth funds typically focus on large scale opportunities (e.g. investment of >£500 million) in mature industries

Size of ● shows the typical investment 'ticket size' (relative basis)

The colour of the sphere indicates whether there are sufficient factors to make an investment in a hybrid marine energy system attractive to that type of investor:
Likely ● Possible ● Unlikely ●

Positioning of the scenarios (relative to most likely funding source) is presented by a blue sphere. ● Blue lines indicate alternative funding sources.

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS AND RECOMMENDATIONS

SUMMARY OF SCENARIOS:

This study has reviewed 6 potential energy system scenarios that might help overcome grid constraints and support the development of offshore renewables. The high level results are as follows:

SCENARIO		WHY OF INTEREST?	LEVEL OF BARRIERS TO DEPLOYMENT	WHAT COULD INCREASE DEPLOYABILITY?	WHAT COULD THE PUBLIC SECTOR DO TO REDUCE BARRIERS?	WHAT SHOULD THE PUBLIC SECTOR DO NEXT?
1a	Small wave connecting to remote island with private network	• Potential to decarbonise island energy generation • Provide low visual impact alternative to wind farms • Allow wave sector to access higher value energy market	MEDIUM: Assuming a diesel only system and cost reduction in wave energy	• More significant reduction in wave costs • Higher diesel costs • Recognition of wider social benefits such as bringing 24hr electricity to communities	• Support broader initiatives to reduce cost of wave • Identify communities which could benefit from this system and have high energy costs • Coordinate feasibility projects for potentially attractive communities • Incentivise use of marine energy within viable local energy systems	• **Support broader initiatives to reduce cost of wave** • **Identify communities which could benefit from this system and have high energy costs**
1b	Wave to aquaculture	• Reduce cost and carbon intensity of farmed fish • Synergies between two offshore industries important to Scotland • Global export potential	LOW: Potentially viable now	• Reduction in wave generation costs • Higher diesel prices • Development of improved hybrid control systems (wave/diesel/storage)	• Assess viability of wave vs solar • Bring aquaculture and wave sectors together • Work with innovation agencies to develop competition on specific technical challenges • De-risk projects (insurance or underwriting) • Reduce lease costs for demonstration projects and support permitting process	• **Review in more detail the findings from existing demo projects** • **Engage with aquaculture and wave device developers to determine barriers for deployment** • **Investigate mechanisms for overcoming barriers**
2	Tidal connecting into large island with significant industrial users	• Opportunity to access higher revenues at MW+ scale • Carbon and costs reduction at distilleries • Good local story	MEDIUM: With tidal cost reduction, potentially viable	• Reduction in tidal costs • Higher retail energy prices • Electrification of heating demand in distilleries	• Support broader initiatives to reduce cost of tidal • Map high energy users in areas of high marine resource to determine viability of wave energy use in other sectors. • Support/incentivise the decarbonisation of distilleries	• **Support broader initiatives to reduce cost of tidal** • **Map high energy users in areas of high marine resource to determine viability of marine energy use in other sectors** • **Engage with distilleries to better understand decarbonisation programmes**

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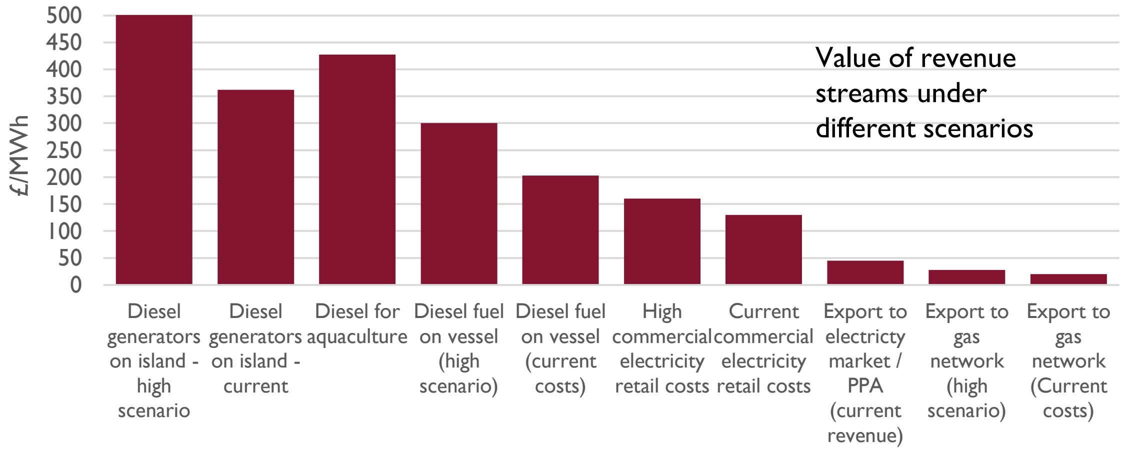
CONCLUSIONS AND RECOMENDATION (2/2)

SCENARIO		WHY OF INTEREST?	LEVEL OF BARRIERS TO DEPLOYMENT	WHAT COULD INCREASE DEPLOYABILITY?	WHAT COULD THE PUBLIC SECTOR DO TO REDUCE BARRIERS?	WHAT SHOULD THE PUBLIC SECTOR DO NEXT?
3	Tidal connecting to remote mainland port with maritime hydrogen system	• Opportunity to access higher revenue at MW+ scale • Supports decarbonisation of marine fleet • Interesting local cross-vector energy system	MEDIUM: With tidal and electrolyser cost reduction, potentially viable	• Reduction in tidal costs • Reduction in electrolyser costs • Higher diesel costs • Identifying potential from other revenue streams (i.e. oxygen, heat) • Improvements in hydrogen vessels • The use of 'free' sources of hydrogen i.e. constrained offshore wind	• Support broader initiatives to reduce cost of tidal • Support projects looking at hydrogen-based port infrastructure • Detailed mapping and feasibly study into the deployment of a commercial hydrogen port at a location in Scotland	• **Ongoing engagement with EMEC/Orkney trials** • **Detailed mapping and feasibly study into a route to the deployment of a commercial hydrogen port around Scotland.** • **Watching brief on development of hydrogen based marine infrastructure**
4	Tidal array with battery storage providing an alternative to grid upgrade	• Aim is to reduce grid upgrade costs and timescales for deployment	HIGH: In scenarios modelled, grid upgrade would be cheaper than batteries but may be viable in other situations	• Disruptive new battery or other storage technology well suited to high energy applications • Reduce significance of constraint • Provision of other services from the battery	• Review alternative models with the battery providing other services	• **Watching brief of demonstration sites**
5	Large scale floating wind with offshore electrolysis and use of gas pipelines	• Potential large scale solution • Innovative use of existing infrastructure	HIGH: Low value of wholesale gas make the economics of gas to grid challenging in this scenario but may be viable with other end-uses	• Cost reductions in electrolysers • Include benefits from extending life of existing infrastructure • Finding alternative higher value revenue stream for the hydrogen produced	• Review other options including use on oil and gas rigs or as shipping fuel • Consider other benefits such as extending end of life	• **Watching brief on demonstration projects particularly those looking at alternative end uses for hydrogen**

OTHER FINDINGS

Key learning from the study include:

- **Some scenarios demonstrate potentially realisable benefits,** with wave to aquaculture the most promising over the short term. In others, the scenarios are potentially viable, if wave and tidal costs fall substantially.
- **Focus should be on scenarios with higher value revenue streams** – higher revenue stream can provide a niche that can support the additional cost of generating using early stage offshore renewables. The value of these revenue streams are highlighted in the chart below. Export to the wholesale gas or electricity market is challenging given low revenue available.



- **At present, there is no real incentive to select offshore over mature onshore renewables** – even when there is potential, there is limited rationale as to why wave and tidal would be chosen over more mature (and cheaper) technologies such as solar and wind. For instance, in the aquaculture scenario solar may be a cheaper and lower risk option to wave. For the island scenarios, wind has been and is likely to continue to be a more economic option (although with potential visual impacts), unless an incentive to use these less mature technologies is put in place.

- **Large scale projects are more challenging –** potential higher value revenue streams generally have only limited scale. For instance, private wire networks and local use (i.e. hydrogen vessels) is only likely to have limited demand potential (~<10 MW of less). This makes offtake arrangements for larger projects more challenging.
- **Hydrogen systems will initially focus on 'excess' sources of 'free' energy** (as opposed to new build assets specifically targeting this revenue stream) as we have seen with the Surf and Turf project in Orkney. In time and with electrolyser cost reductions and changes to regulations, large scale cost effective green hydrogen sources will become more viable.
- **Community acceptance and coordination** – many remote Scottish communities are already heavily engaged in the development of localised energy systems and the infrastructure and capabilities are in place to further extend these activities to include offshore renewables. However, communities will need to be convinced of the benefits of adopting immature technologies.
- **Public sector investment is available for energy systems but challenges remain in finding funding for large scale marine projects** – public sector investment are widely available for localised or innovative energy system development and it is likely that small scale marine devices can be supported within funding for these types of projects. However, a gap still remains in public or private sector funding for large scale marine renewables projects, either due to the technology maturity or the long term outlook for their competitiveness against other renewables technologies. However, some scenarios offer a stable and high-value offtake which should make the technology risk alone is manageable for private sector investors and development banks.

APPENDIX I Elements of an Energy system

ELEMENTS OF AN ENERGY SYSTEM

GENERATION: For the purpose of this study generators are restricted to offshore renewables, namely tidal stream, wave, and floating offshore wind. Notably, fixed bottom offshore wind is not included within the study. Generators have variable energy capture profiles depending on resource exploited and device performance.

FLOATING OFFSHORE WIND

Floating structures moored to the seabed for the deployment of wind turbines in regions of deep water.


Goto Floating Turbine

Why it is being considered?	A significant number of Marine Scotland's Areas of Search have water depths in excess of 60 m. Cost reduction and innovation required to reach cost parity with fixed bottom wind.
Current status of deployment	Scotland is home to the world's only multi-turbine floating offshore wind project, Hywind Scotland. Turbine technology is mature with over 6 GW installed offshore in the UK.

TIDAL STREAM

Turbines installed in regions of fast tidal current flow to convert tidal energy into electricity.


Source: Sustainable Marine Energy

Why it is being considered?	High tidal flow regions in Scottish waters and project scale potentially compatible with local energy systems.
Current status of deployment	Initial multi-megawatt devices deployed in commercial projects. The largest of which is the 6 MW installed in MeyGen Phase 1.

WAVE

Wave Energy Converters convert energy from oscillating waves into electrical energy.

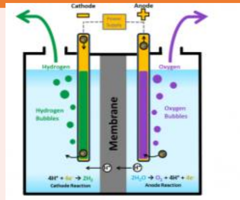
Source: Wello

Why it is being considered?	Good resource in Scotland and scale potentially compatible with local energy systems. Scotland has a strong track record in wave device innovation.
Current status of deployment	Limited commercial deployment to date. EMEC is the hub of testing in Scotland., with single devices of up to 750 kW at their site.

CONVERSION: Conversion is used to convert electrical energy to meet the demands of another energy vector. Methods of conversion considered in this study are electrolysis and the electrification heat

Electrolysis

Electrolysis is the process of using electricity to split water into hydrogen and oxygen. The hydrogen can then be used as a fuel.



Source: US Department of Energy

What is it used for?	Decarbonisation of heat and transport. Can be used permanently or only when a renewable energy source would otherwise be curtailed.
Current status	Emerging technology.

ELECTRIFICATION OF HEAT

The use of electric heating elements to provide heat which often would have been supplied by gas.

What it is used for?	Decarbonisation of heat (when coupled with renewable electricity generation).
Current status	Widely deployed.

ELEMENTS OF AN ENERGY SYSTEM

ENERGY STORAGE: Storage is predominately used to align the time varying generation and demand profiles, provide a stored backup, and allow for grid upgrade deferral. These are all considered in our modelling.

LITHIUM-ION BATTERIES	
A form of rechargeable battery technology used in portable personal electronic devices as well as large-scale stationary storage projects.	
What it is used for?	Ideal for scenarios where a fast response time, small size or low weight are key.
Constraints and status:	Few location constrains and extensively deployed (over 920 MW).

FLOW BATTERIES	
A chemical battery system in which the electrolyte is stored externally and pumped through the battery cells.	
What it is used for?	Wide range of applications due to variable power and energy ratio.
Constraints and status:	Few locational constraints and increasing deployment (84 MW and 304 MWh).

LIQUID AIR ENERGY STORAGE (LAES)	
Cools air until it liquefies. Stored as liquid and returned to gas as required. Gas expanded through a turbine to generate electricity.	
What it is used for?	Suitable for bulk storage where space is limited
Constraints and status:	Few locational constraints and one operational project.

PUMPED HYDRO	
Stores energy by pumping water to a high reservoir and recovers it by releasing water through turbines back to the lower reservoir.	
What it is used for?	Suitable for bulk storage applications that do not require fast response times.
Constraints and status:	High and low reservoir required. Widely deployed in large commercial project (Over 190 GW).

COMPRESSED AIR ENERGY STORAGE (CAES)	
Compresses air to storage energy and expands it through a turbine when electricity is required.	
What it is used for?	Suitable for bulk storage.
Constraints and status:	One long duration facility under operation. More economical with natural cavern.

DEEP MINE	
Stores energy gravitationally by raising a weight and recovers it by lowering the weight.	
What it is used for?	Limited commercial use to date, but would be suitable for high power applications.
Constraints and status:	No known deployment to date. Concepts under development.

END USE: Energy generated and stored can be used in four key ways.

DIRECT USE

Use by customers through direct wires to consumers not using national or local grid networks. Industrial, commercial and domestic facilities are all potential users.

USE OF CONVERTED ENERGY

Consumption of converted energy predominately to decarbonise of heat and transport.

LOCAL USE

Use within localised grid networks by domestic, commercial, and industrial users. It can include includes electrification of heat and vehicles.

EXPORT TO GRID

Export of electricity and hydrogen into national grid system.

Photo source Crown Estate Scotland

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APPENDIX 2 Modelling methodology

Global Assumptions

Parameter	Value	Comment
Weighted Average Cost of Capital (WACC)	8%	Assumed reasonable value for major capital project and immature technologies.
Tidal CapEx	**High** - £7.5m/MW **Mid** - £3.75m/MW **Low** - £2.25m/MW **Very Low** - £2m/MW	Used when assuming tidal costs (Scenario's 3 and 4). These correspond to a tidal generation LCOE of £300 / MWh, £150 / MWh, £90 / MWh, and £80 / MWh using Everoze's assumed tidal device performance and an energy flow. These correspond to the LCOE projections given within ORE-Catapult's 'Tidal Stream and Wave Energy Cost Reduction and Industrial Benefit' report.
Annual Tidal OpEx costs	3.5 % of CapEx	At present highly uncertain but assumed high on early plants; expected to reduce in due course but reduction not modelled (assumed a second order influence).
Floating Offshore Wind CapEx (Exc. Electrical infrastructure)	**High –** £6m/MW **Mid –** £4.8m/MW **Low –** £3.1m/MW	Derived using Everoze's CapEx and DevEx values from ORE-Catapult's 'Macroeconomic benefits of floating offshore wind in the UK', deducting costs associated with electrical infrastructure.
Floating Offshore Wind OpEX	**High and mid-** £0.11m/MW pa **Low -** £0.10m/MW pa	Derived using Everoze's CapEx and DevEx values from ORE-Catapult's 'Macroeconomic benefits of floating offshore wind in the UK', deducting costs associated with electrical infrastructure due to scenario 5's proposed use of gas infrastructure.
Wave OpEx	5%	Everoze experience.
Annual BESS OpEx	£6k-9k/MWh	Inversely related to rated capacity, based on Everoze experience; again sensitivity not modelled as considered a second order influence.
BESS CapEx	£250k/MW BoP £250k/MWh @ 2018 £125k/MWh @ 2030	Fixed cost proportional to rated MW (Everoze experience). Variable energy-related cost α MWh (Everoze experience). Assumed cost reduction (Bloomberg predictions).

Parameter	Value	Comment
Battery degradation	2% per year	Everoze experience.
Max permissible State of Charge Min permissible State of Charge	90% 10%	Current state of art Li-ion BESS. Degradation increase significantly if battery fully charged and/or discharged. Modelled as an additional CapEx to ensure BESS has 20% greater plant capacity than nominal rated at start of life.
Charging / discharging efficiency	92.2%	Current state of art Li-ion BESS – All round-trip electrical losses are included in model. Equates to round-trip efficiency of ~85%.
Battery Life	10 years	Full battery replacement is assumed at 10years. This may be optimistic in some scenarios given the high number of cycle. Battery CapEx is typically 50% of total CapEx; assumed replacement cost is 60% of installed CapEx.
AC to DC efficiency	92.5%	
Diesel Generator Efficiency	Litre per MWh calculated using source database.	Diesel Service and Supply – 'Approximate diesel fuel consumption chart' Assumed efficiency bands operate between: ¼ load - 0-37.4%, ½ load - 37.5-62.4% ¾ load - 62.5-87.4% Full load - 87.5-100%
Diesel costs - High	**High -** £1.4 / litre **Mid -** £1.0 / litre **Low -** £0.8 / litre	**High -** Everoze assumption for sensitivity testing. Represents an approximately for the removal of tax rebate available for marine fuel and diesel for electricity generation. **Mid -** Representative of high diesel costs at the pump in remote locations (£1.40-1.58 / litre) from online sources), minus the tax rebate available for diesel for non-diesel engine road vehicles £0.4681 / litre **Low –** Everoze experience. HM Treasury: Consultation outcome Red diesel: call for evidence Updated 25 July 2018 Confused.com on the road fuel prices PetrolPrices.Com

This table outlines assumptions made within for the modelling of multiple scenarios.

FEASIBILITY & ECONOMICS

F&E

MODELLING METHODOLOGY: 1a

SCENARIO 1a: SMALL WAVE CONNECTING TO REMOTE ISLAND WITH PRIVATE NETWORK

MODELLING AIM: To test the feasibility of displacing diesel generation on a remote island using wave energy.

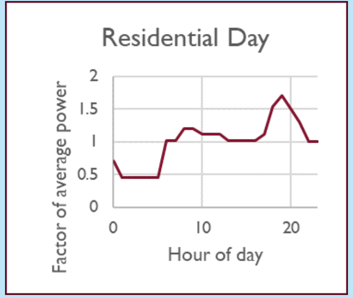
PARAMETER	VALUE	COMMENT / SOURCE
Project life	25 years	
Diesel Generator Capacity	0.2 MW	Sized so that peak demand can be met at all times.
Storage Max. charge / discharge rate	0.3 MW	Sized so that a period of peak demand can be met from a charged battery alone.
Electrical demand per household	2.88 MWh / year	Derived from DUKEs 'Energy Consumption in the UK – 2018 Update' data. Assumes no electrical heating demand.
Number of households	100	Assumption.

MODELLING APPROACH

ENERGY GENERATION AND CONSUMPTION MODELS

WAVE FLOW MODEL: A wave flow model was created using data collected from a real physical location along the UK's Atlantic coast. In reality the energy available is site specific, however a representative site was necessary.
WIND FLOW MODEL: A model representing a standard onshore wind site was created. The energy generation is calculated on a 10-minute basis given the wind speed conditions
CONSUMPTION MODEL: Daily and seasonal electricity demand profiles were generated to take into account for when energy is used in our communities. This included separated daily profiles for residential and commercial electricity demand.

EXAMPLE OUTPUT



ENERGY FLOW MODEL

ENERGY FLOW MODEL: A time-series energy flow for the community was modelled, determining in ten-minute intervals the surplus or excess generation, the change in battery state of charge, diesel backup required and the amount of spilled energy.

COST OF ENERGY MODEL

COST OF ENERGY MODEL
The metric used to compare cases was the standard Levelised Cost of Energy (LCOE), calculated using a simple discounted cash flow (DCF) model. The key assumptions are outlined on the next page. A number of sensitivity cases were modelled as follows, to establish the sensitivity to various key assumptions. These were framed around pushing assumptions to the limits to ensure that cliff-edge and boundary effects were adequately captured: Theses are outlined on the next page.

	Wind Capacity (MW)	Wave Capacity (MW)	Diesel Costs (£/l)	Battery Capacity (MWh)	Battery CapEx (£m / MWh)	Tidal CapEx (£m / MW)
Group 1	0	0	1.4, 1, and 0.8	0	0	0-10
Group 2	0.2	0	1.4, 1, and 0.8	0	0	0-10
Group 3	0.2	0	1.4, 1, and 0.8	0	0	0-10
Group 4	0.2	0	1.4, 1, and 0.8	0	0	0-10
Group 5	0.2	0.2	1.4, 1, and 0.8	0	0	0-10
Group 6	0.2	0.2	1.4, 1, and 0.8	0-0.5	0.25	0-10
Group 7	0.2	0.2	1.4, 1, and 0.8	0-0.5	0.125	0-10
Group 8	0.2	0.15	1.4, 1, and 0.8	0-0.5	0.25	0-10
Group 9	0.2	0.15	1.4, 1, and 0.8	0.05	0.125	0-10

Cost of energy cases modelled to test sensitivity to assumptions and therefore potential future or alternative scenarios.

The case of 0.0 MWh storage represents the case where no storage plant is provided.

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MODELLING METHODOLOGY: 1b

MODELLING AIM: To assess the technical and commercial feasibility of using wave energy to displace diesel generation on a aquaculture site

KEY ASSUMPTIONS WITHIN THE COST OF ENERGY MODELLING FOR SCENARIO

PARAMETER	VALUE	COMMENT / SOURCE
Project life	25 years	
Number of aquaculture feeding barges	3	Assumption
Peak demand per feeding barge	0.62 MW	Source : Scottish Aquaculture Research Forum – 'Renewable Power Generation on Aquaculture Sites'
Feeding system demand	0.44 MW	Source : Scottish Aquaculture Research Forum – 'Renewable Power Generation on Aquaculture Sites'
Daily power variation	Derived from source above. Key assumptions derived from table 2.4 and Figure 6.1 of this report. Key contributed to daily fluctuation are the Feeding used during daylight hours and additional lighting during the night.	
Seasonal variations	Derived from source above. Operating periods derived from table 2.4. Two additional daylight hours assumed in summer.	

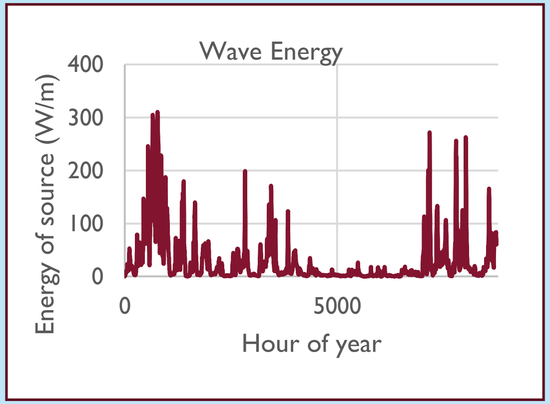
MODELLING APPROACH

ENERGY GENERATION & CONSUMPTION MODELS

WAVE FLOW MODEL: A wave flow model was created using data collected from a real physical location along the UK's Atlantic coast. In reality the energy available is site specific, however a representative site was necessary.

CONSUMPTION MODEL: Daily and seasonal electricity demand profiles were generated to take into account how energy is used in aquaculture sites. The largest power demand is considered to be the compressors used in the feeding system. As feeding typically occurs during sunlight hours, there is a large fluctuation in demand between daylight and non-daylight hours.

EXAMPLE OUTPUT



ENERGY FLOW MODEL

ENERGY FLOW MODEL: A time-series energy flow for the community was modelled, determining in ten-minute intervals the surplus or excess generation, the change in battery state of charge, diesel backup required and the amount of spilled energy.

COST OF ENERGY MODEL

COST OF ENERGY MODEL: The metric used to compare cases was the standard Levelised Cost of Energy (LCOE), calculated using a simple discounted cash flow (DCF) model. The key assumptions are outlined on the next page. A number of sensitivity cases were modelled as follows, to establish the sensitivity to various key assumptions.

	Wave Capacity (MW)	Cost of Diesel Aquaculture (£/l)	Battery Size (MWh)	Battery CapEx (£m/MWh)
Base	0	0.8, 1.0, 1.4, and 2.0	0	0
Group 1	0.1	0.8, 1.0, 1.4, and 2.0	0-1	0.125
Group 2	0.1	0.8, 1.0, 1.4, and 2.0	0-1	0.250
Group 3	0.2	0.8, 1.0, 1.4, and 2.0	0-1	0.125
Group 4	0.2	0.8, 1.0, 1.4, and 2.0	0-1	0.250

Cost of energy cases modelled to test sensitivity to assumptions and therefore potential future or alternative scenarios

The case of 0.0 MWh storage represents the case where no storage plant is provided.

MODELLING METHODOLOGY 2:

SCENARIO 2: TIDAL CONNECTING INTO LARGE ISLAND WITH SIGNIFICANT INDUSTRIAL USERS

MODELLING AIM: a tidal site and group of distilleries was postulated. The model aims to find test the technical and economic case for connecting a tidal site to distilleries through a private wire network. Electrification of heat and transport were considered, as was lithium-ion battery storage. The outcomes show a range of scenarios and the levelised cost of electricity supplied to the distilleries.

KEY ASSUMPTIONS WITHIN THE COST OF ENERGY MODELLING FOR SCENARIO

PARAMETER	VALUE	COMMENT
Project life	25 years	Standard for early wind farms.
Total distillery capacity	16 million litres / year	Representative of four large distilleries in close proximity. Understood to be an extreme case but tidal capacity required can be adjusted accordingly.
Distillery electrical demand	0.99 kWh / lpa	Source: Scotch Whisky Industry Environmental Strategy Report 2015
Distillery heating demand	5.61 kWh / lpa	Source: Scotch Whisky Industry Environmental Strategy Report 2015

MODELLING APPROACH

TIDAL FLOW MODEL

TIDAL FLOW MODEL: A typical tidal flow cycle was synthesised using a double-sinusoid to represent the semi-diurnal and spring-neap periods. In practice, the actual generation from tidal plants is not purely sinusoidal, but is distorted by tidal harmonics, waves and local hydrological flow features. For the purposed of modelling, however, a deterministic function was necessary. This simplification is not considered to affect the validity of the conclusions.

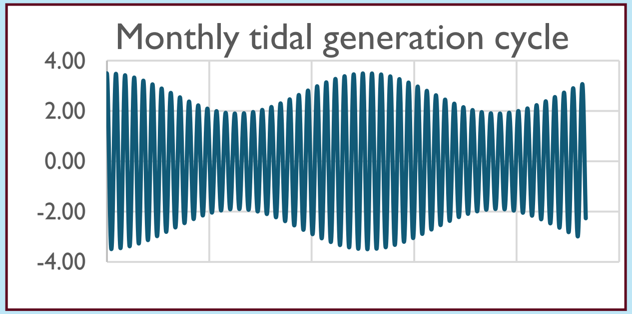
ENERGY FLOW MODEL

ENERGY FLOW MODEL: A time-series energy flow model and an annual tidal cycle was modelled, determining in ten-minute intervals the surplus or excess tidal energy, the exported power, the change in battery state of charge, and the amount of spilled energy.

COST OF ENERGY MODEL

COST OF ENERGY MODEL: The metric used to compare cases was the standard Levelised Cost of Energy (LCOE), calculated using a simple discounted cash flow (DCF) model. The key assumptions are outlined on the next page. A number of sensitivity cases were modelled as follows, to establish the sensitivity to various key assumptions. These were framed around pushing assumptions to the limits to ensure that cliff-edge and boundary effects were adequately captured: Theses are outlined on the next page.

EXAMPLE OUTPUT



Tidal Capacity (MW)	Export Capacity (MW)	Electrification of heat (%)	Installed EV Charging Capacity (kW)	Lithium-ion capacity (MWh)
6, 3, 2, and 1	0, 1, and 2	0, 0.1, and 0.2	0, 58, and 116	Range 0-12

As the capital costs associated with the electrification of heat and transport is not considered in our modelling. The main influence on results is how closely aligned energy generation and consumption are. To model this accurately a range of scenarios were conducted which both influence the generation and consumption within this scenario, along with energy storage to minimise excess.

MODELLING METHODOLOGY: 3

MODELLING AIM: A tidal site and group of distilleries was postulated. The model aims to test the technical and economic case for connecting a tidal site to distilleries through a private wire network. Electrification of heat and transport were considered, as was lithium-ion battery storage. The outcomes show a range of scenarios and the levelised cost of electricity supplied to the distilleries.

KEY ASSUMPTIONS WITHIN THE COST OF ENERGY MODELLING FOR SCENARIO

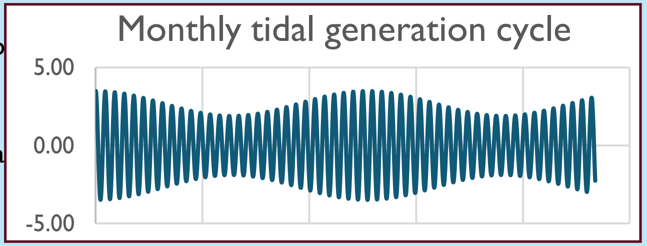
PARAMETER	VALUE	COMMENT
Project life	25 yrs	Assumption – Matches expected lifetime of major components.
Efficiency of hydrogen fuel cell	60%	Source: H2FCSuperGen 'The role of hydrogen and fuel cells in future energy systems'
Efficiency of diesel engine	40%	

MODELLING APPROACH

EXAMPLE OUTPUT

TIDAL FLOW MODEL

TIDAL FLOW MODEL: A typical tidal flow cycle was synthesised using a double-sinusoid to represent the semi-diurnal and spring-neap periods. In practice, the actual generation from tidal plants is not purely sinusoidal, but is distorted by tidal harmonics, waves and local hydrological flow features, For the purposed of modelling, however, a deterministic function was necessary. This simplification is not considered to affect the validity of the conclusions.

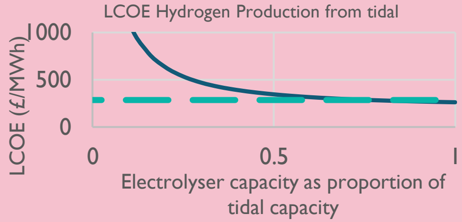


ENERGY FLOW MODEL

ENERGY FLOW MODEL
A time-series energy flow model and an annual tidal cycle was modelled, determining in ten-minute intervals the tidal energy generated, the amount of hydrogen produced, and the amount of spilled energy.

COST OF ENERGY MODEL

COST OF ENERGY MODEL: The metric used to compare cases was the standard Levelised Cost of Energy (LCOE), calculated using a simple discounted cash flow (DCF) model. The key assumptions are outlined on the next page. A number of sensitivity cases were modelled as follows, to establish the sensitivity to various key assumptions. These were framed around pushing assumptions to the limits to ensure that cliff-edge and boundary effects were adequately captured



	Tidal CapEx (£m / MW)	Decom Tidal (£m / MW)	Electrolyser CapEx (£m / MW H_2 out HHV)	Electrolyser OpEx (£m / kW AC Capacity / year)	Electrolyser DC Power Consumption (MWh / Nm³ H_2)	Electrolyser AC Capacity (as % of tidal capacity)
S1	5	0.184	1.215	0.033	0.004	Range 0-100
S2	2.5	0.124	1.215	0.033	0.004	Range 0-100
S3	2.5	0.124	1.215	0.033	0.0038	Range 0-100
S4	2.5	0.124	0.576	0.022	0.0038	Range 0-100
S5	1.25	0.101	0.576	0.022	0.0038	Range 0-100

Cost of energy cases modelled to test sensitivity to assumptions and therefore potential future or alternative scenarios

FEASIBILITY & ECONOMICS

F&E

MODELLING METHODOLOGY

SCENARIO 4: REMOTE TIDAL ARRAY WITH BATTERY STORAGE

MODELLING AIM: A 75 MW tidal array (25 x 3 MW turbines) was postulated, connected to a grid having a constrained capacity, and provided with a battery energy storage system (BESS). The aim was to investigate whether, and if so under what assumptions and range of circumstances, the integration of a BESS with a tidal plant can potentially compete in LCOE terms compared with upgrading the local grid.

KEY ASSUMPTIONS WITHIN THE COST OF ENERGY MODELLING FOR SCENARIO

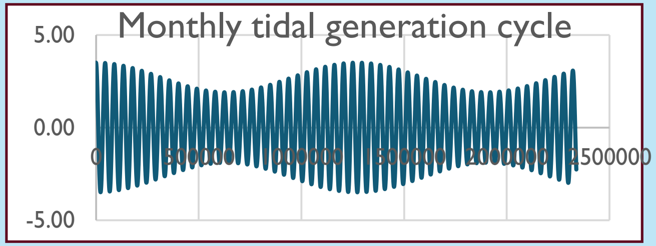
PARAMETER	VALUE	COMMENT
Project life	20yrs	Standard for early wind farms; difficult to consider longer at present owing to uncertainties in battery life.
Tidal Array Capacity	75 MW	Assumed
Tidal CapEx	£3.75 m/MW	Derived from Everoze performance assumptions to match £150/MWh LCOE.
BESS CAPEX	£0.125/MWh	
TNUoS Charges	£24.733/kW pa £5.647/MWh	Current high costs within UK transmission network

MODELLING APPROACH

EXAMPLE OUTPUT

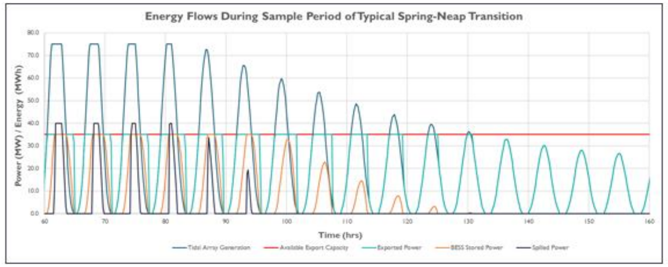
TIDAL FLOW MODEL

TIDAL FLOW MODEL: A typical tidal flow cycle was synthesised using a double-sinusoid to represent the semi-diurnal and spring-neap periods. In practice, the actual generation from tidal plants is not purely sinusoidal, but is distorted by tidal harmonics, waves and local hydrological flow features, For the purposed of modelling, however, a deterministic function was necessary. This simplification is not considered to affect the validity of the conclusions.



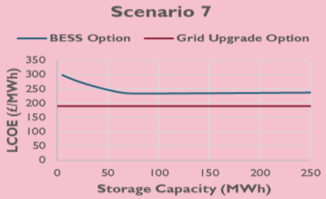
ENERGY FLOW MODEL

ENERGY FLOW MODEL: A time-series energy flow model and an annual tidal cycle was modelled, determining in ten-minute intervals the surplus or excess tidal energy, the exported power, the change in battery state of charge, and the amount of spilled energy.



COST OF ENERGY MODEL

COST OF ENERGY MODEL: The metric used to compare cases was the standard Levelised Cost of Energy (LCOE), calculated using a simple discounted cash flow (DCF) model. The key assumptions are outlined on the next page. A number of sensitivity cases were modelled as follows, to establish the sensitivity to various key assumptions. These were framed around pushing assumptions to the limits to ensure that cliff-edge and boundary effects were adequately captured:.



Case Ref.	Grid Export Constraint (MW)	Cost of Grid Upgrade (£k/MW)	BES Storage Capacity (MWh) (Range)
Base	30	0.125	0* - 250
Scenarios 1-5	35, 45, 55, 65, and 70	0.125	0 - 250
Scenarios 6-11	30, 35, 45, 55, 65, and 70	0.5	0 - 250

Cost of energy cases modelled to test sensitivity to assumptions and therefore potential future or alternative scenarios.

Scenarios with assumed current BESS CapEx costs were run but were not competitive and therefore no detailed analysis of these has been carried out.

The case of 0.0 MWh storage represents the case where no storage plant is provided, but the grid is upgrade to the full rated power of the tidal array.

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MODELLING METHODOLOGY

MODELLING AIM: The model shows the flow of energy between electrical generation at a floating wind site, the conversion to hydrogen offshore, and the injection into existing oil and gas infrastructure.

KEY ASSUMPTIONS WITHIN THE COST OF ENERGY MODELLING FOR SCENARIO

PARAMETER	VALUE	COMMENT
Project life	25 yrs	Standard for offshore wind projects.
Levelised Cost impact of hydrogen compression and injection	High – £5.22 Low - £4.35	Source: World Energy Council – 'Bringing North Sea Energy Ashore Efficiently'
Reduction is floating wind LCOE due to reduced electrical infrastructure costs	8%	Source: ORE-Catapult – 'Macroeconomic benefits of floating offshore wind in the UK' Source states 8% of undiscounted lifetime costs are associated with electrical infrastructure. Everoze has reduced CapEx and OpEx by 8% compared with floating wind with electricity transported to shore.

MODELLING APPROACH

WIND FLOW MODEL

WIND FLOW MODEL: An annual offshore wind flow model was generated, along with a power curve for a representative 10 MW offshore wind turbine. The wind regime and power curve created are used to determine the amount of electrical energy produced at the site in 10 minute intervals.

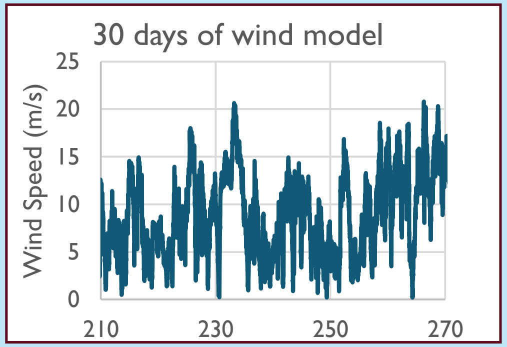
ENERGY FLOW MODEL

ENERGY FLOW MODEL: A time-series energy flow model the generation of electricity at site, the conversion into hydrogen, and the injection into the grid network. This was determined in 10 minute intervals and the amount of spilled energy was recorded.

COST OF ENERGY MODEL

COST OF ENERGY MODEL: The metric used to compare cases was the standard Levelised Cost of Energy (LCOE), calculated using a simple discounted cash flow (DCF) model. The energy of the hydrogen is given as the Higher Heating Value (HHV). The key assumptions are outlined on the next page. A number of sensitivity cases were modelled as follows, to establish the sensitivity to various key assumptions. These were framed around pushing assumptions to the limits to ensure that cliff-edge and boundary effects were adequately captured:

EXAMPLE OUTPUT



	Floating Wind CapEx (£m / MW)	Floating Wind OpEx	Decom Floating Wind (£m / MW)	Electrolyser CapEx (£m / MW H_2 out HHV)	Electrolyser OpEx (£m / kW AC Capacity / year)	Electrolyser DC Power Consumption (MWh / Nm^3 H_2)	Electrolyser AC Capacity (as % of FW capacity)
S1	6.026	0.11	0.184	1.215	0.033	0.004	Range 0-100
S2	4.825	0.106	0.124	1.215	0.033	0.004	Range 0-100
S3	4.825	0.106	0.124	0.576	0.022	0.0038	Range 0-100
S4	3.146	0.101	0.078	0.576	0.022	0.0038	Range 0-100

Cost of energy cases modelled to test sensitivity to assumptions and therefore potential future or alternative scenarios

Stress test conducted include changing the costs associated with injecting hydrogen into the grid.

Floating Wind CapEx, OpEx, and Decommissioning costs are derived using the performance of our assumed turbines and ORE-Catapult's LCOE forecasts for offshore floating wind (minus electrical infrastructure component).

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DISCLAIMER

This report has been prepared and is issued in accordance with contract document CES001-P-01 dated 16 November 2018, which governs how and by whom this report should be read and used.

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