

Exploiting the temporal characteristics of tidal stream power for green ammonia production

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ABSTRACT

Green ammonia, a promising zero-carbon energy storage vector, has never been produced using solely tidal stream energy despite its predictable characteristics. Combining tidal stream sites with a phase difference (tidal phasing) facilitates anticorrelation between these sites' power profiles, enabling a more consistent power output. Green ammonia production benefits from a steady and predictable power input. The objective of this paper is to determine if nearby tidal sites have a large enough phase difference (anticorrelation) to reduce the cost of ammonia production. Moreover, producing green ammonia from underutilized or unutilized remote and grid-constrained tidal stream sites may enable viability of these sites. This paper is the first analysis of green ammonia production using solely tidal stream energy and the first analysis of tidal phasing for green fuel production. Two UK case studies are presented in i) the North Channel of the Irish Sea and ii) Orkney. There are tidal sites in each which have a phase difference (e.g. the Mull of Kintyre/Sound of Islay, and Graemsay/North Ronaldsay with correlation coefficients of 0.17 and -0.02 respectively), utilising this phase difference reduces the levelized cost of ammonia by 8% in the Irish Sea and by 12% in Orkney.

1. Introduction

1.1. Tidal phasing for green ammonia production

Some tidal stream power hotspots in the UK are far from the grid (so require new transmission cables to the grid onshore) or are in locations where the grid is constrained (which limits their exploitability). For example, the nearest grid connection to tidal sites in the North Channel of the Irish Sea is via the 132 kV transmission cable in Carradale [1,2] (around 40 km away), on the Kintyre peninsula, Scotland. Moreover, Orkney has significant grid capacity constraints, with only two 20 MW 33 kV cables to mainland Scotland [3]. Producing green ammonia, an energy vector and hydrogen carrier, from tidal stream sites locally has the potential to improve or enable their exploitation. The green ammonia produced can then be combusted for energy in Orkney at peak demand, used as the basis for fertiliser production, as maritime fuel, or transported to where it is needed (e.g. mainland UK or elsewhere).

Aggregate power from different tidal stream sites which each have power production at different times (i.e. have a phase difference), can ensure a more consistent power profile - this effect is known as tidal phasing [4]. Ideally, the power profile for green ammonia production

should not change with time, so as to provide constant power to the Haber-Bosch (HB) reactor and reduce catalyst damage [5,6]. Utilising phased tidal power could be key to enabling cost-competitive tidal-produced green ammonia. Moreover, tidal stream power is predictable, which is ideal for green ammonia production as the green ammonia plant can operate with perfect forecasting of input power. Thus, additional CAPEX costs from equipment oversizing and additional OPEX costs from model predictive control (MPC) can be avoided. Equipment oversizing and MPC are necessary for green ammonia production from unpredictable energy sources such as wind [7].

Previous literature on tidal phasing in the UK utilises between 100 MW [8] to several GW [9] of tidal stream power, from locations all around the UK, for the purpose of grid power consumption (see section 1.3.). Realistically, local ammonia production from tidal stream power requires tidal sites close together. This paper utilises around 200–314 MW of tidal stream power in two case studies i) a relatively small area in the North Channel of the Irish Sea, and ii) around Orkney. Small-scale tidal power phasing is more likely to benefit ammonia production than grid power utilisation, especially if a high baseload power from the combined sites is not achieved as, unlike the grid, ammonia production benefits from consistent power but does not require constant power.

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Moreover, the total power from the combined sites would be a small fraction of the total grid power.

Salmon and Bañares-Alcántara [10] demonstrated that offshore green ammonia production has considerable potential, particularly in the UK, due to land availability restrictions and significant offshore renewable energy potential. This study did not include tidal stream energy as an energy source (only offshore wind and offshore solar). A previous paper by the authors demonstrated that adding unphased tidal stream energy to offshore wind energy for green ammonia production decreased the LCOA by up to 18% in the Pentland Firth [11]. Adding phased tidal stream energy to offshore wind may further reduce the LCOA (compared to unphased tidal stream energy and offshore wind), which could be key to enabling cost-effective offshore green ammonia production.

Beyond academic interest, there is no reported practical utilisation of tidal phasing for tidal stream power production globally. This lack of utilisation of tidal phasing at a local and national level is likely due to the prohibitively high tidal stream levelized cost of energy (LCOE) [12]. Moreover, to the best of the authors' knowledge, there is no academic or commercial work on tidal stream power phasing for the production of green fuels, such as green ammonia or hydrogen. Only one paper has analysed green ammonia production from tidal stream power (and wind power), with a case study on the Pentland Firth, Scotland [11]. Thus, the current study provides novel research in the areas of tidal phasing for green fuel production and feasible tidal stream-produced green ammonia sites.

The objective of this paper is to determine if there are anticorrelated tidal stream regions (i.e. regions with a phase difference) within Orkney and within the North Channel of the Irish Sea that can enable a smoother, more consistent power profile for the purpose of green ammonia production. A smoother power profile should result in a reduction of the levelized cost of ammonia.

1.2. Smooth power profile

In order to achieve a smoother power profile for ammonia production from combined tidal turbine locations compared to single tidal turbine locations, various metrics can be compared (Table 1). It should be noted that a lower proportion of time in a year with zero power for a combined site compared to an individual site is indicative of tidal phasing [4]. Moreover, comparing the percentage of time in a year that 1 to >90% of nameplate power capacity is attained indicates the quality of the tidal resource [4]. The Haber-Bosch reactor installed power requirement accounts for around 5% of the total power required by the green ammonia plant and the minimum power required by the Haber-Bosch reactor is estimated to be around 20% of its installed power capacity [13], which is 1% of the total power required by the ammonia plant. Thus, the combination of aggregate turbines, which gives the highest time periods of >1% and >5% of nameplate capacity is a useful metric for ammonia production. Giorgi and Ringwood [14] used a genetic algorithm to solve a multi-objective optimization problem to find the best combination of turbines to (i) maximise the average power (i.e. the capacity factor) (ii) maximise the minimum, baseload, power and (iii) minimise the variance of the power profile. The variance (i.e. power

Table 1
Ideal smooth power profile characteristics for green ammonia production.

Metric	Ideal value	Main impact on ammonia production
Frequency of >0% to >5% rated power	High	Size of storage capacity
Minimum power	High	Ability to run HB constantly and size of storage capacity
Average power	High	Amount of ammonia produced
Variance (power instability)	Low	Ability to meet HB ramping constraint
Rate of change of power	Low	Ability to meet HB ramping constraint

instability) in this paper will be modelled as the ratio of standard deviation to capacity factor [15]. Unlike the electrolyser, the HB reactor cannot ramp up and down instantaneously [16] – ramping limits of 2–20% per hour have been suggested [17]. These HB ramping constraints inhibit constant ammonia production with an intermittent power profile, so the rate of change of power is also an important metric to compare.

In order to achieve a smoother aggregate power profile, various parameters can be changed in the modelling of turbines, as shown in Table 2. The turbine type determines the turbine diameter which in turn affects the location of the turbine in the water column, the tidal current velocity at the position of the turbine, and the power output of the turbine. The number of regions and the number of turbines in each region will significantly impact the power profile and should be decided based on the ammonia production cost. Almoghayer et al. [3] demonstrated that reducing the rated power of each tidal turbine in a farm by 33% (in Hoy Sound, Orkney) can provide power with less variability to Orkney's grid and improve the capacity factor of the farm by 42.5%. While the aggregate energy produced by the farm is lowered (by 4.29%), decreasing revenue, this is counterbalanced by the lower CAPEX and OPEX costs. However, when tidal energy is used directly for green ammonia production (i.e. not for the grid), limiting the maximum power is unlikely to be justified as there are already internal storage mechanisms in place within the green ammonia production process to provide constant power to the Haber-Bosch process (battery storage, hydrogen storage and fuel cell capacity).

There are restrictions in the placement of turbine locations. The water depth has a major impact on which turbine sites and which types of turbines can be utilised. More powerful turbines have a larger diameter, so shallow water restricts the power production in a given region. Ideally, sites in close proximity should be used to reduce the magnitude of the underwater cable cost between sites. Moreover, shipping routes and fishing areas should be avoided to reduce the impact on the local economy.

1.3. Tidal phasing literature

The waters around the UK abide by a semi-diurnal system due to the prominent tidal constituents: M2, the lunar constituent (360° period of 12 h 25 min) and S2, the solar constituent (360° period of 12 h) [18]. Tidal stream currents are subject to a flood-ebb cycle, a spring-neap cycle and an 18.6-year lunar cycle [12]. There is a significant tidal power phase difference along the UK coastline – near firm power could be achieved if three tidal sites with a phase difference of 120° (~4h) are exploited together [19] or if two tidal sites with a phase difference of 90° (~3h) are exploited together [9]. Determining appropriate sites for firm power is challenging as the bathymetry and the British Isles topology significantly impact the tidal stream power phase difference [9].

The most established and most powerful tidal stream devices, first-generation devices, are restricted to water depths of 25–50 m and mean peak spring velocities of >2.5 m/s [9]. Firm power production from sites with first-generation tidal devices around the UK is not

Table 2
Modelling parameters and their impact on the aggregate power profile.

Parameters impacting smoothness of power profile	Main impact on aggregate power profile
Turbine type (cut-in and rated speeds)	Rate of change of power, power instability, frequency of zero power, average power
Velocity averaged over specific water depths	Average power (velocities are generally larger near the ocean-air boundary than near the seabed)
Number of regions (with a net phase difference)	Frequency of zero power, minimum power
Number of turbines in each region	Average power, power instability
Limiting turbine capacity	Lower power instability

possible, as these sites happen to be mostly in-phase [9]. However, less powerful tidal stream sites around the UK have significant phase diversity [8]. For example, the co-tidal lines vary considerably (6–11 h) in the relatively small body of water between the north of Northern Ireland and Scotland (North Channel of the Irish Sea) [9,18]. Co-tidal lines are lines on a map that display the time of high water, which is indicative of the phasing of tidal velocities.

Academic studies on tidal phasing have modelled tidal sites around the UK [8,9,20–24], around Ireland [14], around West Japan [25] and around the states of Washington and Alaska in the US [26]. For example, Neill et al. [21] used the greedy algorithm to find the optimal phasing of combined tidal stream sites in the Pentland Firth, the English Channel (around the Channel Islands), the North Sea (around Flamborough Head), the North Channel and around the Faroe Islands. The sites that optimise the average power and avoid near-zero power periods are determined as the Pentland Firth, the Channel Islands and Anglesey.

Iyer et al. [9] modelled first-generation tidal sites in the Isle of Wight, the Race of Alderney, Ramsey Island, Anglesey, Islay, Orkney and the Pentland Firth and determined that the combined maximum environmentally acceptable power is around 2 GW. Interestingly, all of these sites are mainly in phase, apart from the Race of Alderney, which has a phase difference of around 1 h.

Lewis et al. [24] reported that utilising peak spring tide velocities >1.5 m/s with no water depth restrictions could enable firm tidal power production in the Irish Sea. The Irish Sea has many areas of substantial tidal potential, including Anglesey, Isle of Man and the Bristol Channel [24]. For example, in the Irish Sea, over seven times less practical power is exploitable for 1st generation turbines, compared to 3rd generation turbines (i.e. utilising mean peak spring velocities >1.5 m/s and water depths >25 m). Lewis et al. [24] also highlight that misalignment of flood and ebb currents can introduce significant uncertainty in tidal power quantification for turbines that are not able to yaw (i.e. are fixed).

Commin et al. [4] analysed leased tidal sites in the Pentland Firth and Orkney Waters at 10-min resolution and determined that exploiting tidal phasing for firm capacity is not feasible in this region. However, Commin et al. also determined that tidal phasing is useful as zero power is produced between 4.2% and 14.5% of the year for individual sites, but is reduced to 1.4% of the year for combined sites.

The first tidal phasing study in the US [26] analyses the Salish Sea around Washington and Inside Passage, Bristol Bay and Kodiak and Cook Inlet around Alaska. Specific turbine characteristics are not considered (such as cut-in/cut-out speed), but theoretical power is evaluated. The region of Kodiak Island and Cook Inlet is determined as the best region for anticorrelation (complementarity) between turbine sites.

Combining ebb-dominant tidal stream sites with flood-dominant tidal stream sites can facilitate a more consistent power output compared to utilising either site individually, as demonstrated in Orkney between Westray Firth and Stronsay Firth [27]. As well as location, the tidal stream turbine's power curve can affect the smoothness of the power profile. Generally, the rate of increase of tidal stream power with time is lower than the corresponding rate of decrease [9]. Secondly, the cut-in velocity value affects how often the power profile is zero. Therefore, the phase difference between tidal sites can be, effectively, altered. A low cut-in velocity value enables power production at low velocities which is ideal.

The exceptional tidal stream resource in the Pentland Firth is far from locations of substantial demand, which will result in electric cable transmission losses [8]. The North Channel of the Irish Sea is a less powerful tidal stream resource [9] but is closer to locations of significant demand and may also benefit from tidal phasing. The time lag between relevant tidal stream sites around the UK is quantified in Table 1 of Neill et al. [8]. Notably, there is a time lag of 0.7 h in the relatively small area between the Isle of Islay and the Mull of Kintyre. The tidal current phase difference in the North Channel of the Irish Sea is also shown visibly in Fig. 4 of [8], in Fig. 2 of [21] and in Fig. 7 of [18].

The literature described in this section demonstrates that tidal phasing can facilitate a smoother power profile, ensuring zero power occurs less frequently than if tidal phasing were not utilised. Most of these studies use tidal sites which are far apart (such as around the UK), and none of the studies illustrate the utilisation of phased tidal power for green fuel production. This study utilises local, small-scale tidal power phasing for green ammonia production, which is a novel concept.

1.4. Paper structure

The methodology (Section 2) describes how the tidal power profiles are obtained, how to determine if tidal regions are correlated and discusses which combinations of tidal locations are suitable to be compared to see if phasing can benefit green ammonia production. The results and discussion (Section 3) graphically compares tidal power profiles from aggregate tidal locations, quantifies the correlation between tidal regions, and quantifies how much green ammonia benefits from tidal phasing (if at all). Then, the limitations of the study and potential future work is discussed (Section 4). Finally, the conclusions of the study are described in Section 5.

2. Methodology

2.1. Tidal stream velocity models

The Pentland Firth and Orkney Waters Climatology 1.02 model [28, 29] (hereafter PFOV model) and the Firth of Clyde Climatology 1.03 model [30] (hereafter FOC model) are used to model tidal stream velocities and minimum water depths. Both the PFOV and the FOC models have a temporal resolution of 1 h, provide a 1-year climatology, representative of 1990–2014 with a 1993 tidal component, and are three-dimensional – they have 10 sigma layers to represent the water column, and are a part of the Scottish Shelf Model [31]. The tidal stream velocity at the top of the water column is utilised (sigma layers 2–4) as floating turbines are modelled. The tidal stream turbine's power coefficient is assumed to be constant over all velocities. A restriction of one tidal device per node (referred to as location from hereon) is applied, which is a conservative modelling decision. More than one device per location could potentially be deployed, without breaching the 10–20 D downstream spacing heuristic rule which allows for wake recovery [3, 32] (where D is the diameter of the turbine).

2.2. Green ammonia production optimization model

To find the minimum levelized cost of ammonia (LCOA) from the tidal stream power profile, a mixed integer linear program (MILP) green ammonia production optimization model was used [33]. Internal storage assets include hydrogen storage, battery storage and a fuel cell. Equipment efficiencies are modelled as constant values [33]. 14 days of maintenance per year are modelled (at the end of each calendar year) whereby no ammonia is produced. As in Ref. [11], the ramp up and ramp down limits of the HB reactor are modelled as 2% per hour and 20% per hour respectively [17]. The minimum load of the HB is modelled as 20% of rated capacity [34]. The CAPEX values are shown in Table S.1. A low and high value of tidal turbine CAPEX is incorporated, given the large uncertainty in its value. The other modelling decisions for the operation of the ammonia plant and the production of power from tidal stream turbines are discussed by the authors in previous work [11], the key differences being ammonia production exclusively onshore and the exclusion of wind power.

2.3. Turbine types

The tidal turbine is modelled as a horizontal axis, twin-rotor, Orbital O2 turbine. This turbine model was chosen firstly due to its low rated velocity of 2.5 m/s [35] at 2 MW rated power which allows a high

quantity of energy to be extracted from the turbine over a spring-neap cycle, and secondly as it is a floating turbine, which utilises the fast currents near the sea surface and suits a large range of water depths [9]. The cut-in velocity is 1 m/s, the rated velocity is 2.5 m/s and the cut-off velocity is 4.5 m/s [36]. Each turbine has a rotor diameter of 20 m and a minimum water depth of 23.2 m [36]. The Orbital O2 turbine is deployed at the EMEC Fall of Warness tidal test site [36], and is a part of the FORWARD2030 (Fast-tracking Offshore Renewable energy With Advanced Research to Deploy 2030 MW of tidal energy before 2030) project [37].

For shallow tidal hotspots in the Orkney Islands, a smaller turbine is used: the 0.28 MW PLAT-I device with 4 SIT250 turbines, each with a rotor diameter of 6.3 m and a minimum water depth of 10 m [3]. The cut-in velocity is 0.5 m/s, the rated velocity is 2.7 m/s and the cut-off velocity is 4 m/s [3,38]. The PLAT-I device has been modelled in Graemsey, Orkney [3].

2.4. Region division and choosing turbine locations

The North Channel of the Irish Sea and the water around the Orkney Islands are divided into regions to split up each tidal hotspot (see Figs. 2 and 7, respectively).

For the North Channel of the Irish Sea, the power profiles from the highest 500 annual energy production locations are determined using the FOC model. The spatial resolution in the area of the FOC model considered is around 1000 m [30], so the minimum water depth at each turbine location is hard to determine accurately. Thus, no turbine locations at specific water depths will be excluded from the analysis. It is recognised that the Sound of Islay is relatively shallow (water depth <50 m [9]), but 23 m diameter turbines have been proposed for this region in other works [39]. Thus, Orbital O2 devices (rotor diameter of 20 m [36]) should be feasible in the Sound of Islay.

For Orkney, the highest 10,000 annual energy production locations are determined using the PFOV model and the Orbital O2 device. Locations with a minimum water depth <10 m are removed. To account for potential phasing between regions of all water depths >10m, the resulting locations (<10,000) are then modelled with a PLAT-I device.

In both the North Channel of the Irish Sea (Table 3) and in Orkney (Table 4), Pearson correlation coefficients between the regions are established and analysed to determine if there is phasing between each region. Correlation coefficients are a standard metric to determine if tidal sites are correlated or anti-correlated [9].

In Orkney, if there is a region which has phasing potential but has a water depth below <23.2m, the PLAT-I device is used. All other regions are modelled with the Orbital O2 device.

To determine the number of aggregate locations that are most suitable for ammonia production, the percentage of time in a year that the aggregate power profile is above 1–5% of nameplate capacity is compared. The aggregate power profile is then compared to the power profile from a single region of equal installed power capacity, and a theoretical single location (with no phasing benefit) of equal annual energy production. These three power profiles are then inputted to the green ammonia production cost optimization model to determine the LCOA and the equipment capacities.

For the purpose of phasing comparisons, ‘theoretical’ in this context

means many turbines are modelled with the same power profile (which is not realistic), not that the turbine location is theoretical. These three power profiles are inputted to the green ammonia production cost optimization model. The cable costs from combining tidal locations are also factored in (Table S.2).

To quantify how much green ammonia production benefits from combining flood and ebb-dominated tidal sites, green ammonia production from Westray Firth and Stronsay Firth is compared to a theoretical single location of equal annual energy production and Stronsay Firth only (section S.2 of the Supplementary Information).

3. Results and discussion

3.1. Firth of Clyde (FOC) model – North Channel of the Irish Sea

The highest 500 annual energy production locations with high capacity factors (up to around 60%) are displayed in Fig. 1.

The 500 locations in Fig. 1 are divided into regions, as shown in Fig. 2. The locations considered in the North Channel of the Irish sea do not appear to be along major shipping or ferry routes. For example, ferry routes between Northern Ireland and Scotland are exclusively to the south of the analysed regions [40].

The Sound of Islay is the most out-of-phase region, reflected in the low correlation coefficient values with respect to other regions in Table 3. Jura, Islay and the Mull of Kintyre have relatively high correlation coefficients, indicating a lack of phasing between these regions. Correlation coefficients less than or equal to 0.5 (in bold), represent out-of-phase behaviour, in line with other tidal phasing literature [9].

The maximum proportion of time that power is above 1%–5% of nameplate capacity is when around 100 locations are utilised (Fig. 3 – corresponding to turbine positioning in Figure S1). Thus, the following analysis will focus on 100 locations. However, at 100 locations, the capacity factor is not the highest, and the power instability is not the lowest. The percentage of time that power is above 20% or 10% of nameplate capacity decreases as the cumulative number of locations increases, which is due to the decreasing capacity factor as the cumulative number of locations increases.

As the cumulative number of locations increases, the percentage of time that the power profile is above 0% of nameplate power increases, which is indicative of the phasing occurring. Above around 63 cumulative locations, the power profile is always above 0% of nameplate capacity, which is clearly preferable for ammonia production.

The theoretical single location of equal total energy to the top 100 locations is included for comparison to quantify the storage requirement and resulting LCOA differences with and without phasing effects. However, the theoretical single location is not a realistic scenario for producing ammonia, as it is not possible to have 100 co-located turbines with the same power profile.

In the neap part of the power cycle (Fig. 4 top), the top 100 locations power profile has a higher minimum power than the 100 locations in the Mull of Kintyre and than the theoretical single location of equal total energy, indicating that phasing is occurring. The power exceedance curves in Fig. 5 also demonstrate this - the aggregate power profile from the top 100 locations is above low power values for a larger percentage of time compared to the other two power profiles. Power exceedance is defined as the percentage of time at or exceeding a given power value. In the spring part of the power cycle (Fig. 4 bottom), the top 100 locations and the 100 locations in the Mull of Kintyre have similar power profiles but the theoretical single location has a larger range of power, regularly varying from 0 MW to rated power (with around 12% of time spent at rated power in Fig. 5), which is not ideal for operating the Haber-Bosch process.

The Mull of Kintyre has the highest number of locations within the top 100 high-energy locations. Thus, since the cost of the offshore cabling depends on the power capacity being transmitted, and in order to reduce the total cost of offshore cables, three offshore cables from Islay,

Table 3

Correlation coefficients between regions and regional yearly capacity factors (top 500 annual energy production locations in the FOC model [30]).

	Jura	Islay	Sound of Islay	Mull of Kintyre
Jura	1.00	0.88	0.24	0.89
Islay	0.88	1.00	0.53	0.82
Sound of Islay	0.24	0.53	1.00	0.17
Mull of Kintyre	0.89	0.82	0.17	1.00
Yearly Capacity Factor	0.32	0.22	0.30	0.22

Table 4
Correlation coefficients between regions, regional yearly capacity factors (using the PLAT-I device), and regional mean minimum depths using the PFOV model [28].

		1	2	3	4	5	6	7	8	9	10	11	12
		Inner Sound	Pentland Firth West	Pentland Firth East	Pentland Firth	Graemsay	Stronsay Firth	Westray Firth	Lashy Sound	North Ronaldsay	South Ronaldsay	Shapinsay Sound	Papa Westray
1	Inner Sound	1.00	0.63	0.91	0.76	−0.11	0.83	0.68	0.79	0.85	0.75	0.74	0.50
2	Pentland Firth West	0.63	1.00	0.72	0.90	0.06	0.76	0.85	0.78	0.82	0.77	0.78	0.69
3	Pentland Firth East	0.91	0.72	1.00	0.83	0.13	0.88	0.83	0.93	0.80	0.84	0.86	0.69
4	Pentland Firth	0.76	0.90	0.83	1.00	−0.08	0.74	0.82	0.81	0.76	0.75	0.76	0.58
5	Graemsay	−0.11	0.06	0.13	−0.08	1.00	0.21	0.34	0.29	−0.02	0.37	0.37	0.62
6	Stronsay Firth	0.83	0.76	0.88	0.74	0.21	1.00	0.86	0.95	0.89	0.92	0.95	0.77
7	Westray Firth	0.68	0.85	0.83	0.82	0.34	0.86	1.00	0.92	0.79	0.94	0.93	0.89
8	Lashy Sound	0.79	0.78	0.93	0.81	0.29	0.95	0.92	1.00	0.83	0.95	0.96	0.83
9	North Ronaldsay	0.85	0.82	0.80	0.76	−0.02	0.89	0.79	0.83	1.00	0.84	0.83	0.64
10	South Ronaldsay	0.75	0.77	0.84	0.75	0.37	0.92	0.94	0.95	0.84	1.00	0.98	0.90
11	Shapinsay Sound	0.74	0.78	0.86	0.76	0.37	0.95	0.93	0.96	0.83	0.98	1.00	0.89
12	Papa Westray	0.50	0.69	0.69	0.58	0.62	0.77	0.89	0.83	0.64	0.90	0.89	1.00
	Yearly Capacity Factor	0.26	0.24	0.32	0.31	0.28	0.18	0.22	0.29	0.19	0.19	0.16	0.15
	Mean minimum depth (m)	57	74	58	67	13	30	32	21	48	15	14	37

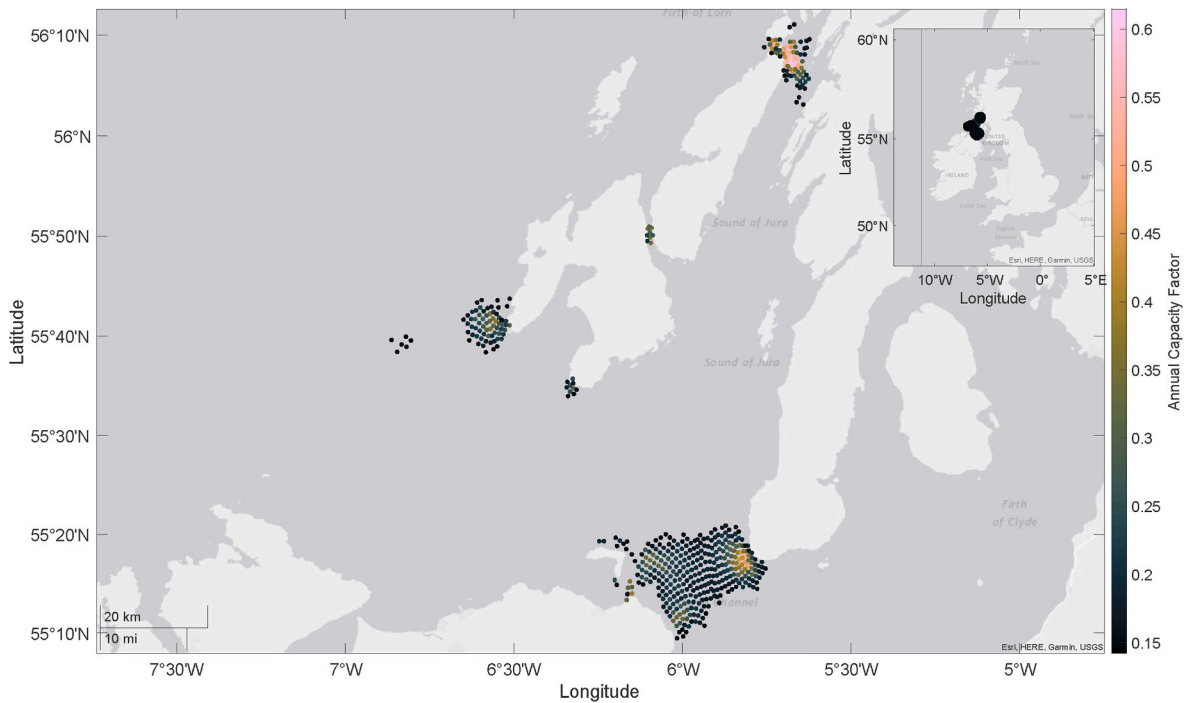


Fig. 1. Highest 500 annual energy production locations (using Orbital O2 devices) in the North Channel of the Irish Sea. The inset shows the North Channel of the Irish Sea relative to the United Kingdom. The velocity values are extracted from the FOC model [30].

the Sound of Islay and North Jura are routed towards the Mull of Kintyre. For the construction of a single green ammonia plant onshore, the land restrictions are taken as avoidance of urban, mountain, heath, and bog land [41] and avoidance of protected land [42]. It is assumed that

grassland can be utilised (as in Ref. [10]). A location such as [55.311338, −5.675104] near Southend on the Kintyre peninsula could be suitable (location shown in Figure S1). The nearest port is Campbeltown, around 20 km away.

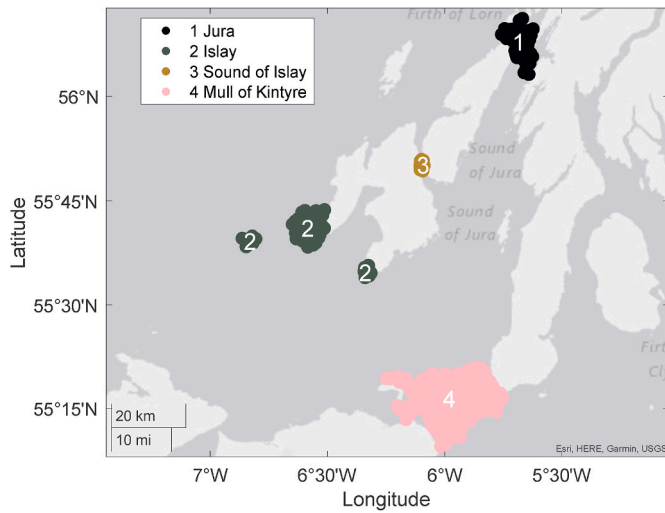


Fig. 2. Four regions of tidal hotspots in the North Channel of the Irish Sea.

The top 100 locations have the lowest LCOA (773 USD/t or 1190 USD/t in the low/high tidal turbine CAPEX scenarios) and the lowest battery and hydrogen storage requirements, as shown in Fig. 6. The theoretical single location has high battery and hydrogen storage requirements and a large LCOA (837 USD/t or 1,264 USD/t in the low/high tidal turbine CAPEX scenarios), due to the lack of phasing. The 100 locations in the Mull of Kintyre have the largest LCOA (978 USD/t or 1517 USD/t in the low/high tidal turbine CAPEX scenarios), partly due to the lack of phasing (increasing storage requirements). Since the top 100 locations and 100 locations in the Mull of Kintyre do not have the same capacity factor, the LCOA cannot be directly compared. Overall, the top 100 locations provide the lowest LCOA so, combining regions for phasing purposes is advantageous, despite the additional cost of the offshore cable between regions (adding 2 M USD – see Table S.2).

3.2. Pentland Firth and Orkney Waters model

The only region in Orkney that is significantly out of phase with other regions is Graemsay, as shown in Table 4 by the low values of the correlation coefficients between Graemsay and other regions (region

placement is shown in Fig. 7). In terms of total area and power magnitude, the best tidal resource is located in the Pentland Firth (2, 3, 4) and the Inner Sound (1). Stronsay Firth (6), Westray Firth (7) and North Ronaldsay (9) have mid-range water depths and capacity factors. Lashy Sound (8) has a high capacity factor, but a low water depth, meaning the larger Orbital O2 device will not be suitable throughout the whole region. South Ronaldsay (10) and Shapinsay Sound (11) have very low water depths and Papa Westray (12) has a low capacity factor. Thus, South Ronaldsay (10), Shapinsay Sound (11) and Papa Westray (12) will be excluded from further analysis. It should be noted that, for low tidal current speed regions (i.e. speed is often below the cut-in velocity), such as Papa Westray, the power profile is often 0 MW, which makes conclusions of phase difference/anticorrelation with other regions difficult to determine accurately.

In Fig. 7, the Pentland Firth is split up into 3 regions (2–4) as they would have a large number of turbines. Each region (2–4) was chosen to have a similar number of turbines. The Inner Sound (1) is taken as the turbine locations south of Stroma. Westray Firth (7) incorporates the turbine locations north of the island of Muckle Green Holm, and Stronsay Firth (6) includes the turbine locations surrounding and to the south of Muckle Green Holm. Regions 6 and 7 were chosen to have a similar number of turbines.

Combining out-of-phase power from Graemsay (5), with Stronsay Firth (6), Westray Firth (7) or North Ronaldsay (9), which each have mid-range capacity factors, could improve the exploitability of each regional tidal resource. It could be argued that, given the exceptional tidal stream resource in the Pentland Firth (2, 3, 4) and the Inner Sound (1) (Fig. 8), this resource will be used regardless, and combining a small quantity of out-of-phase power from Graemsay may not significantly improve the exploitability of the tidal resource in the Pentland Firth and Inner Sound.

As discussed in section 1.3., combining Westray Firth (7), which is a ebb-dominant tidal stream site, with Stronsay Firth (6), which is a flood-dominant tidal stream site, can facilitate a more consistent power output compared to utilising either site individually [27].

Two comparisons will now be carried out: ammonia production from North Ronaldsay (9) and Graemsay (5) versus North Ronaldsay only. Then, ammonia production from Stronsay Firth (6) and Westray Firth (7) versus Westray Firth only.

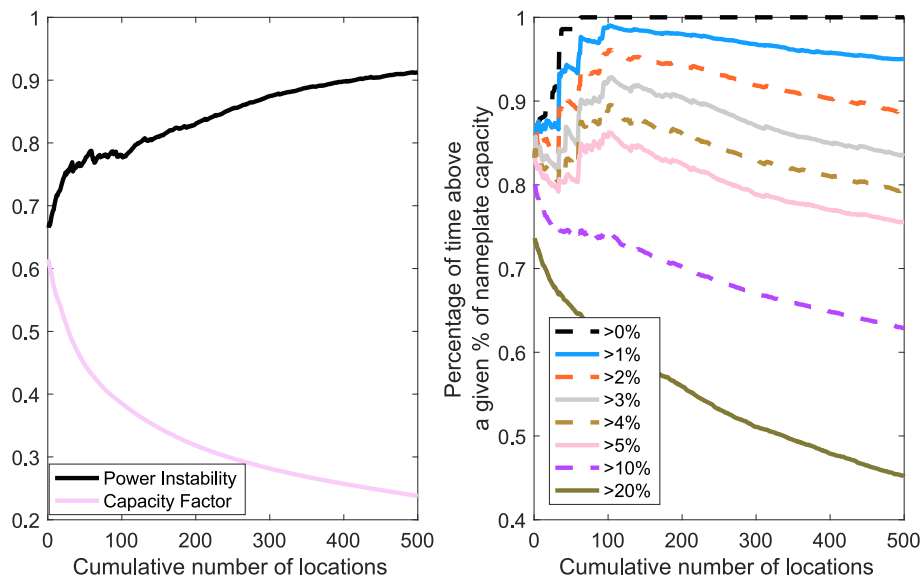


Fig. 3. Aggregate power profile characteristics for cumulative locations in the North Channel of the Irish Sea (in order of highest annual energy production to least). Left – Power instability (standard deviation/capacity factor) and capacity factor. Right – Percentage of time above 0–20% of nameplate capacity.

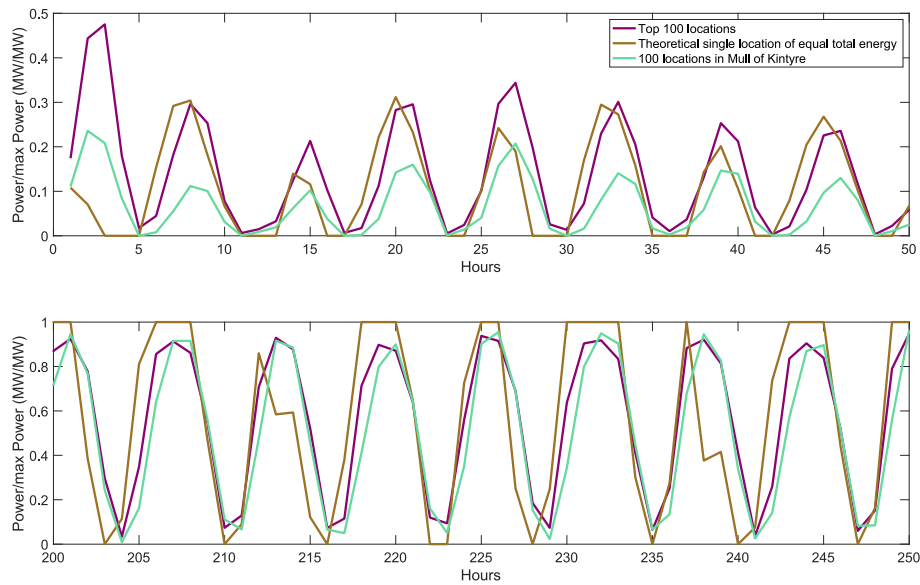


Fig. 4. Power profiles of the top 100 locations, a theoretical single location of equal total energy (to the top 100 locations), and 100 locations in the Mull of Kintyre. Top – 50 representative hours of the neap part of the cycle, Bottom – 50 representative hours of the spring part of the cycle.

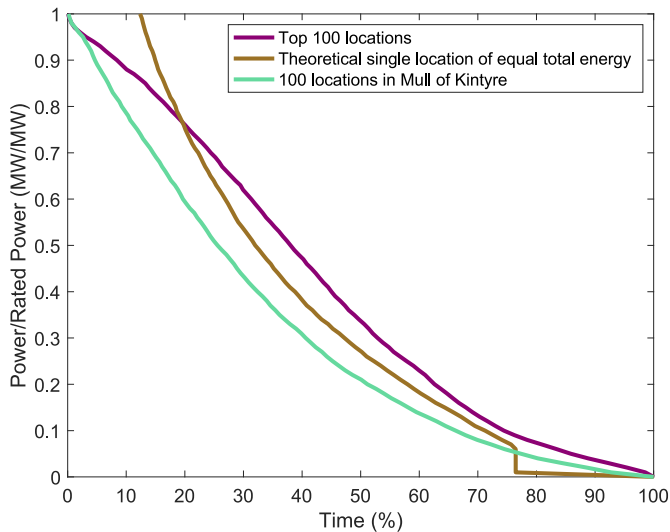


Fig. 5. Power exceedance curve for the top 100 locations, a theoretical single location of equal total energy (to the top 100 locations), and 100 locations in the Mull of Kintyre.

3.2.1. North Ronaldsay (9) and Graemsay (5)

Using fifty 0.28 MW PLAT-I devices in Graemsay (total of 14 MW) and varying the number of Orbital O2 devices in North Ronaldsay, the power instability, capacity factor and percentage of time above a given percentage of nameplate capacity are shown in Fig. 9. The percentage of time above 0–5% of nameplate capacity is >94% with a maximum at around 7 turbine locations from North Ronaldsay. This corresponds to a total power of 28 MW, which is a small power capacity and would produce a low quantity of ammonia. The percentage of time >1% and >5% of nameplate capacity is relatively high and the power instability is quite steady over the range of turbine locations from North Ronaldsay modelled. A combination of 150 turbine locations from North Ronaldsay (and 50 turbine locations from Graemsay) is chosen for ammonia production, which corresponds to a capacity factor of 30%. Fig. 10 demonstrates that 150 turbine locations from North Ronaldsay and 50 turbine locations from Graemsay provide a smooth power profile, which is particularly evident in the spring part of the cycle when the minimum

power is above 14% of rated power. The aggregate power profile from Graemsay and North Ronaldsay is above near-zero power values for a larger percentage of time compared to the other two power profiles (Fig. 11).

For the construction of a single green ammonia plant onshore, as in section 3.1., the land restrictions are taken as avoidance of urban, mountain, heath, and bog land [41] and avoidance of protected land [42]. It is again assumed that grassland can be utilised (as in Ref. [10]). A location such as [59.389466, −2.389769] in North Ronaldsay could be suitable (location shown in Figure S2).

The lowest LCOA (910 USD/t or 1452 USD/t in the low/high tidal turbine CAPEX scenarios) is achieved when phasing between North Ronaldsay and Graemsay is exploited, indicated by the purple bar in Fig. 12 (right). The theoretical single location has large battery and hydrogen storage requirements and the largest electrolyser capacity (Fig. 12 left), resulting in a large LCOA (1027 USD/t or 1563 USD/t in the low/high tidal turbine CAPEX scenarios), due to the lack of phasing. 157 locations in North Ronaldsay produce the lowest quantity of ammonia with the largest LCOA (1040 USD/t or 1617 USD/t in the low/high tidal turbine CAPEX scenarios), partly due to the lack of phasing. In the lower tidal turbine CAPEX scenario, the LCOA is 12% lower when Graemsay is added to North Ronaldsay versus North Ronaldsay alone, and 10% lower in the higher tidal turbine CAPEX scenario. That is, switching only 4.5% of the total tidal power capacity from North Ronaldsay to Graemsay, decreases the LCOA by 10–12%. Thus, adding Graemsay to North Ronaldsay for phasing purposes is beneficial, despite the cost of the offshore cable between the two sites (adding 1 M USD – see Table S.2).

3.3. Case study comparisons

To determine which case study (Irish Sea or Orkney waters) benefits more from phasing, it is useful to compare the power exceedance curves (Figs. 5 and 11), the reduction in storage requirements, and the reduction in LCOA (Figs. 6 and 12).

A useful metric from the power exceedance curves is the time that the aggregate power profile is at or above 5% of nameplate capacity (the HB reactor installed power requirement accounts for around 5% of the total power). For the Irish Sea case study, Fig. 5, the time at or above 5% nameplate capacity is 77% for 100 locations in Mull of Kintyre and 86% for the top 100 locations. For the Orkney waters case study, Fig. 11, the

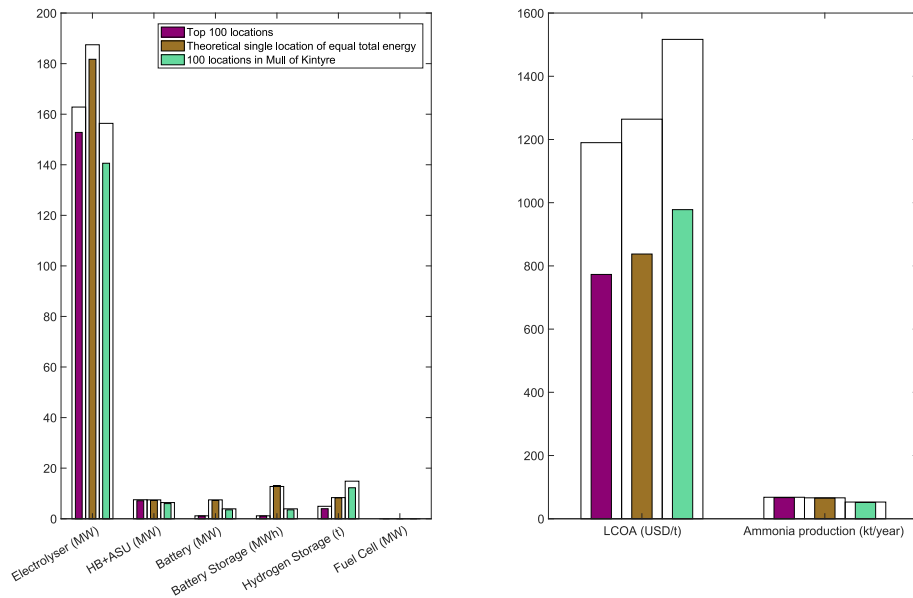


Fig. 6. Results from the ammonia optimization model for the North Channel of the Irish Sea. Left – Equipment sizing. Right – LCOA and ammonia production per year. 200 MW of tidal capacity is fixed for each simulation. Wider bars represent the higher end of the tidal turbine CAPEX, and the narrow bars represent the lower end of the tidal turbine CAPEX.

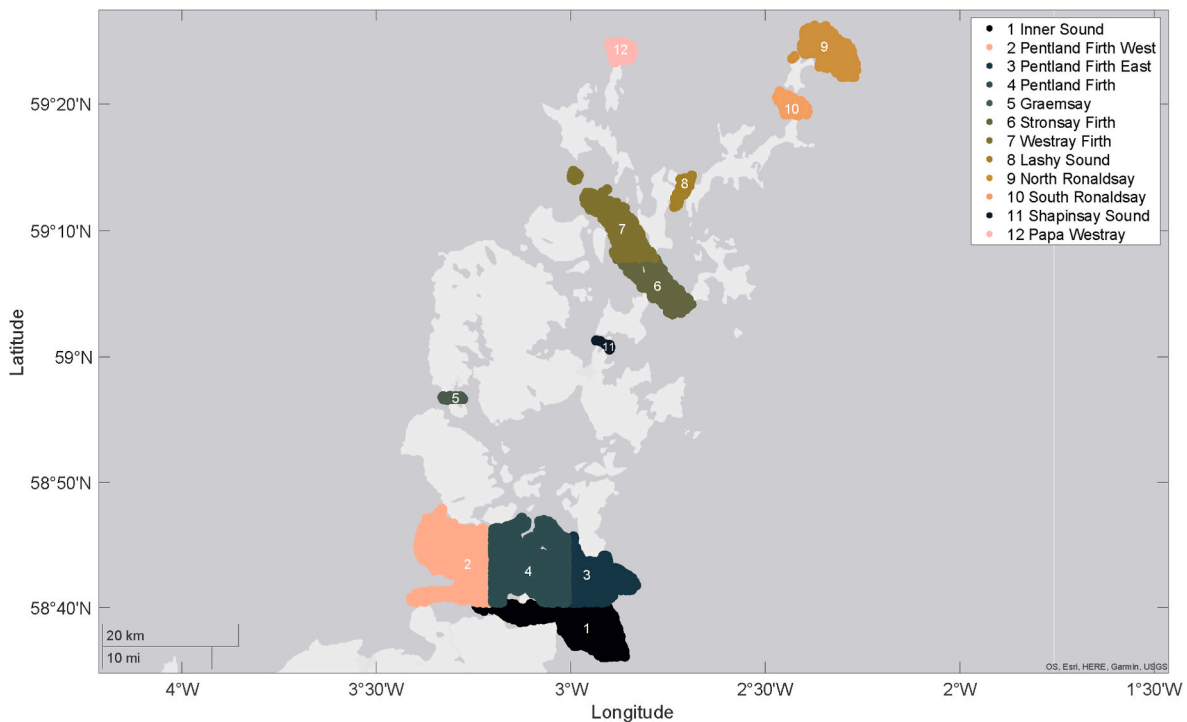


Fig. 7. Regions in the PFOV model [28] with minimum water depths >10 m.

values are 75% for 157 locations in North Ronaldsay and 96% for 50 locations in Graemsay and 150 locations in North Ronaldsay. Thus, compared to the corresponding scenarios of equal installed power capacity, phasing facilitates a 9% rise in time at or above 5% nameplate capacity in the Irish Sea and a 21% rise in the Orkney waters.

Compared to the theoretical single location of equal annual energy production, the phased scenario's hydrogen storage requirements are reduced by 41–52% in the Irish Sea and 89% in the Orkney waters. The phased scenario's battery storage capacity requirements are reduced by 91–92% in the Irish Sea and 67–68% in the Orkney waters. Thus, in both

case studies, the storage requirements are reduced significantly.

A fair measure of how much phasing reduces the LCOA requires comparison of two power profiles of equal capacity factor. For the Irish sea case study, in the lower tidal turbine CAPEX scenario, the LCOA is 8% lower for the top 100 locations versus the theoretical single location of equal annual energy production, and 6% lower in the higher tidal turbine CAPEX scenario.

For the Orkney waters case study, in the lower tidal turbine CAPEX scenario, the LCOA is 12% lower when Graemsay is added to North Ronaldsay versus the theoretical single location of equal annual energy

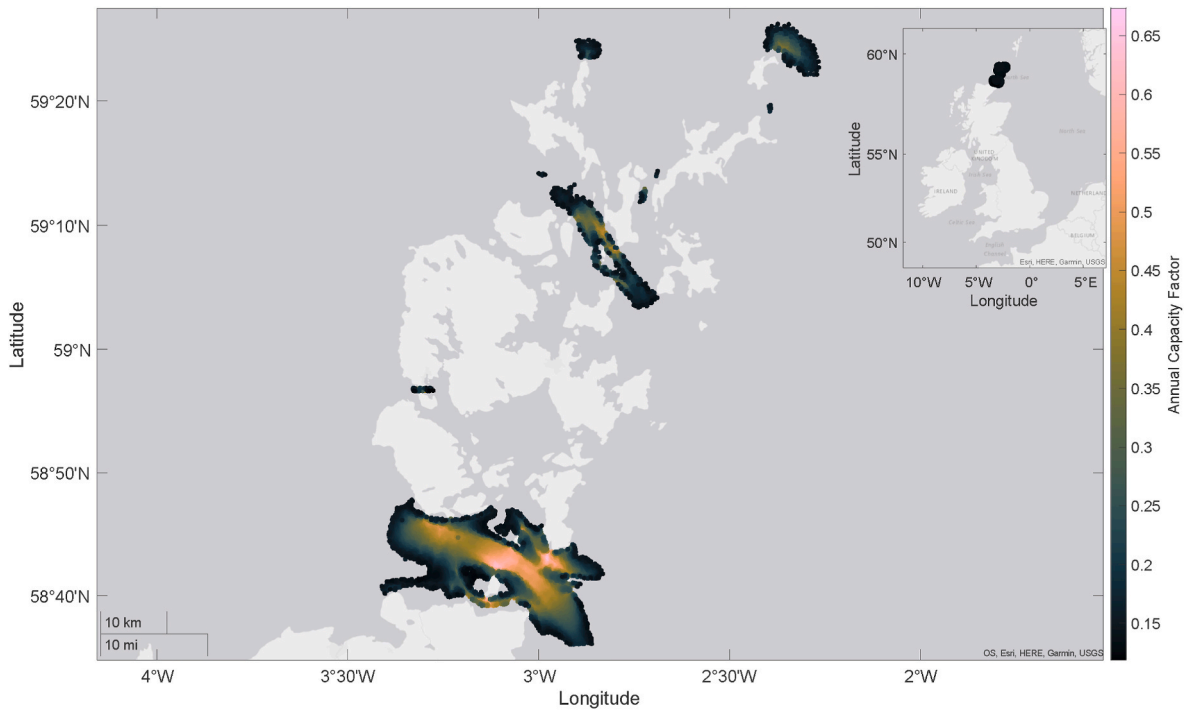


Fig. 8. Annual capacity factor for each turbine location in the Orkney waters using the PFOV model [28]. A PLAT-I device is used for each location in Graemsay and an Orbital O2 device is used for all other regions. The inset shows the Orkney waters relative to the United Kingdom.

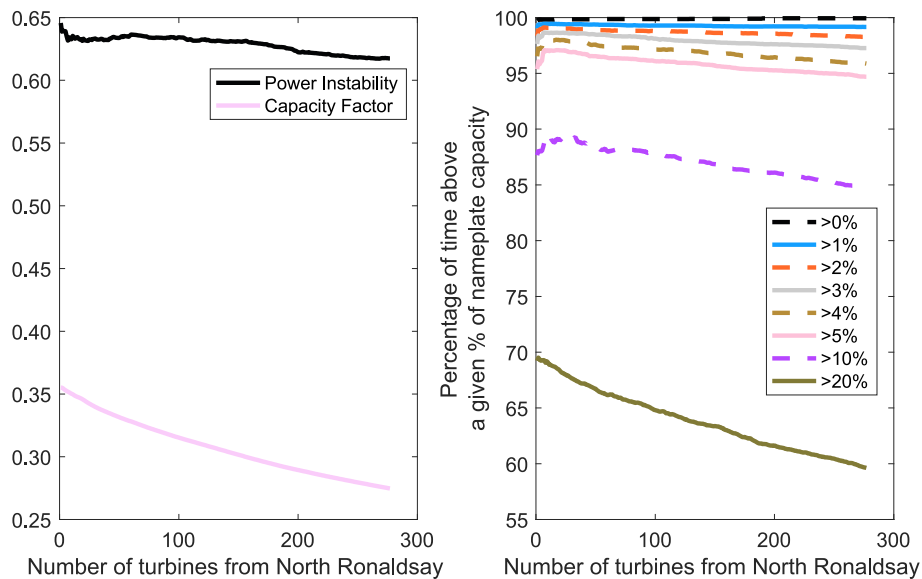


Fig. 9. Aggregate power profile characteristics for cumulative locations in North Ronaldsay (in order of highest annual energy production to least) and 14 MW of power in Graemsay (constant). Left – Power instability (standard deviation/capacity factor) and capacity factor. Right – Percentage of time above 0–20% of nameplate capacity.

production, and 10% lower in the higher tidal turbine CAPEX scenario.

Overall, of the two case studies, due to the larger rise in time at or above 5% of nameplate capacity, phasing is more significant for the Orkney waters case study and thus more beneficial to ammonia production (i.e. the LCOA reduction is greater).

4. Limitations and future work

While attention was given to ensuring the modelling decisions were reasonable, there are potential improvements that could be made.

The FOC and PFOV models have a 1993 tidal component [28,30].

However, it is recognised that, throughout the 18.6-year lunar cycle, the power will fluctuate. For example, Thiébot et al. [43] determined that the annual power variation over 18.6 years is $\pm 10\%$ for tidal sites in north-western Europe (Alderney Race, Ramsey Sound and Fromveur Strait). Moreover, the ammonia plant will be expected to run for 30 years, and the power variation year-on-year will affect the ammonia production and the resulting LCOA.

The PFOV and FOC models have a temporal resolution of 1 h [28, 30]. This may limit the accuracy of the capacity factors and the time difference between power profiles at different tidal sites and thus the degree of correlation. Moreover, tidal stream power phasing literature

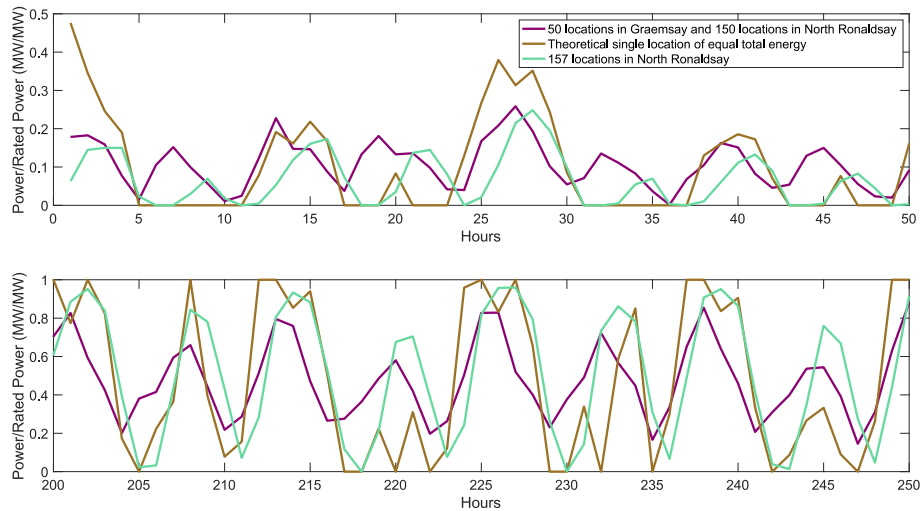


Fig. 10. Power profiles from 50 locations in Graemsay (14 MW) and 150 locations in North Ronaldsay (300 MW), a theoretical single location of equal total energy, and 157 locations in North Ronaldsay (314 MW). Top – 50 representative hours of the neap part of the cycle, Bottom – 50 representative hours of the spring part of the cycle.

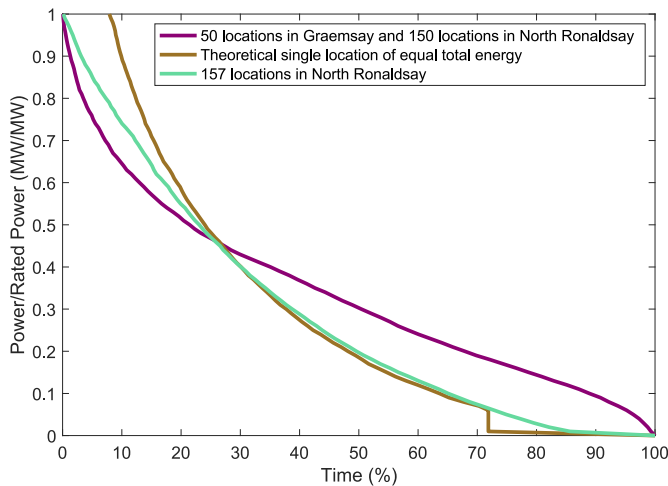


Fig. 11. Power exceedance curve for 50 locations in Graemsay (14 MW) and 150 locations in North Ronaldsay (300 MW), a theoretical single location of equal total energy, and 157 locations in North Ronaldsay (314 MW).

typically uses sub-hourly resolution tidal power data [8,9,20,21]. However, hourly resolution tidal power data is also reported in tidal stream power phasing literature [14,22,24–26]. Therefore, using power data at hourly resolution is sufficient.

The spatial resolution in the area considered in the FOC model is around 1000 m [30], so the minimum water depth at each turbine location is hard to determine accurately. Therefore, sites with a minimum depth of less than 23.2 m are potentially not excluded, which could mean that unrealistically shallow sites are included in the tidal power output.

Shipping routes and fishing areas were not excluded from the analysis as these areas can, in principle, be altered around high-energy tidal turbine sites. However, getting approval for tidal turbine sites (and associated cables) in shipping routes and fishing areas could be prohibitively time-consuming, and there could be significant opposition from local residents.

It is recognised that the optimal combination of turbine sites to minimise the LCOA is not determined in this paper. There are many modelling parameters that can impact the aggregate power profile (Table 2) and there are many restrictions in the placement of turbines.

Future work could incorporate all these parameters and restrictions to determine the optimal placement of turbines for ammonia production. Moreover, more tidal sites could be included in future analyses, such as the Mull of Galloway, Anglesey or the Alderney Race.

The same tidal CAPEX (in USD/kW) was used for the Orbital O2 device and the PLAT-I device (in section 3.2.1). The 0.28 MW PLAT-I device is expected to have a larger CAPEX (in USD/kW) than the 2 MW Orbital O2 device, due to its lower rated power capacity [44]. However, due to the novelty of the tidal turbine industry, the CAPEX values are difficult to determine accurately [44]. Moreover, in section 3.2.1, the PLAT-I device only accounts for 14 MW (5%) of the total 314 MW tidal capacity. Thus, using the same CAPEX for the Orbital O2 device and the PLAT-I device is reasonable for academic modelling in this paper.

Due to the high tidal turbine CAPEX cost, the LCOA values for the phased scenarios (773–1452 USD/t) are relatively high, although they are very close to the range of a standard green ammonia LCOA in 2020 (720–1400 USD/t [45]). Future work will incorporate CAPEX costs in 2050, which may result in a more competitive LCOA compared to wind or solar-powered green ammonia as well as to grey ammonia.

Correlation coefficients are determined for power profiles over a year using tidal velocity data with a 1993 tidal component [28,30]. It is acknowledged that the tidal stream velocity phase may vary slightly over 18.6 years, although any change would likely be on the order of minutes/seconds, not hours [43]. Thus, correlation coefficients may change very slightly over the 30-year plant operation, but this is unlikely to affect the long-term viability of relying on tidal phasing for a consistent power profile. Residual currents [46] and climate change [47] could potentially influence the phase difference. However, the magnitude of phase difference change is difficult to determine and is likely to be highly region dependent. Moreover, using large-scale tidal arrays could alter the phase difference, but this would likely only be significant if tens of thousands of turbines are utilised [29].

Tidal stream power extraction can alter tidal range, marine currents and ocean stratification which could potentially negatively affect ecosystems and marine animals [47]. The specific environmental impact of combining power capacity in different regions or combining flood and ebb-dominated sites would need to be modelled. Since the power capacity analysed is relatively small, it is unlikely that the environmental impacts would be significant. A detailed analysis is out of the scope of this paper.

As well as the uncertainties in the LCOA values already addressed (the 18.6-year lunar cycle and the spatio-temporal resolution of the tidal

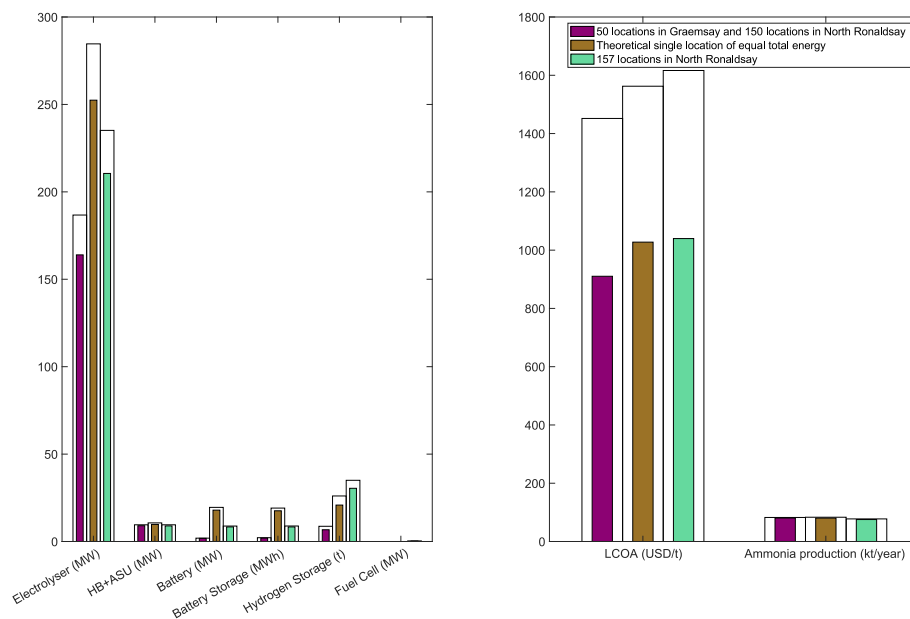


Fig. 12. Results from the ammonia optimization model for North Ronaldsay and Graemsay. Left – Equipment sizing. Right – LCOA and ammonia production per year. A fixed capacity of 314 MW of tidal stream power is fixed for each simulation. Wider bars represent the higher end of the tidal turbine CAPEX, and the narrow bars represent the lower end of the tidal turbine CAPEX.

stream velocity data), other uncertainties include the accuracy of the tidal stream turbine power curve, the accuracy of the turbine positioning in the water column, wake/blockage effects and equipment CAPEX. A sensitivity analysis of these parameters on the LCOA would identify the most important uncertainties. Moreover, quantification of the sensitivity of the phase difference on the magnitude of LCOA reduction would be useful for future work.

5. Conclusions

In the North Channel of the Irish sea, the Sound of Islay is the main region which is out of phase (and anticorrelated) with the other tidal stream regions. For example, the separate power profiles from the Sound of Islay and Jura have a correlation coefficient of 0.24 (and 0.17 for the Sound of Islay and Mull of Kintyre). Utilising tidal stream power from the top 100 tidal locations (which have a difference in phase) reduces the LCOA by 6–8% versus a theoretical single location of equal annual energy production (which has no phasing benefit).

In Orkney, Graemsay is the main region which is out of phase (and anticorrelated) with the other tidal stream regions. For example, the separate power profiles from Graemsay and North Ronaldsay have a correlation coefficient of -0.02 . Switching only 14 MW (5%) of the total tidal power capacity (314 MW) from North Ronaldsay to Graemsay reduces the LCOA by 10–12%. Producing green ammonia, an energy vector, from tidal sites in Orkney, which is significantly grid constrained, would potentially enhance the exploitability of these tidal sites.

As well as tidal phasing, a smoother power profile can be achieved by combining flood and ebb dominated sites. Combining tidal stream power from Westray Firth (ebb-dominated) and Stronsay Firth (flood-dominated) for green ammonia production ensures a 2–4% lower LCOA than from a flood-dominated theoretical single location of equal total energy (see section S.2).

This paper provides novel research on utilising the difference in phase between tidal sites for green fuel production (specifically for green ammonia). The method presented here can be applied to any other tidal region worldwide. However, the phase difference and correlation coefficients will highly depend on the tidal region. Anticorrelated tidal stream regions within Orkney and within the North Channel of the Irish

Sea were identified and the extent of anticorrelation was quantified. Combining these anticorrelated regions enabled cheaper ammonia production due to a smoother, more consistent power profile.

Data availability

The data that support the findings of this study are openly available from Marine Scotland at <https://data.marine.gov.scot/dataset/pentland-firth-and-orkney-waters-climatology-102> [28] and <https://marine.gov.scot/information/firth-clyde-model> [30].

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CRediT authorship contribution statement

Honora Driscoll: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft. **Nicholas Salmon:** Methodology, Software, Writing – review & editing. **Rene Bañares-Alcántara:** Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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The use of MATLAB and its toolboxes was under an academic license. The use of Gurobi was under a free academic license.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.renene.2024.120377>.

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