Potential Array Sites for Tidal Stream Electricity Generation off the Pembrokeshire Coast

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***Abstract*— This paper details a resource and constraint assessment for tidal stream deployment sites around Pembrokeshire, Wales. Based on a minimum peak spring current of 2ms^{-1}, seabed depth and gradient constraints, four sites, providing a total area of 48.3km^2 were identified. Using the significant impact factor method, it is estimated that these sites could provide 1.3TWhrs per year. Constraints such as port proximity, fishing activity and SAC habitats were considered. It is suggested that the most promising area for first stage turbine array deployment is the Bishops and Clerks area.**

***Keywords*— tidal stream, Pembrokeshire, sites, GIS, constraints**

I. Introduction

Tidal stream turbines are well recognised as a method of deriving electricity from the tides without the need for larger structures such as barrages or lagoons. Tidal stream energy deployments are only economically viable in discrete geographic areas where sufficient flow velocities are combined with suitable bathymetry.

Wales has a significant percentage of the total UK's tidal resource, located in three areas: Bristol Channel; Pembrokeshire; and Anglesey [1]. Given the potential for a Severn Barrage to affect tidal streams [2], long term deployments will naturally favour locations around Anglesey and Pembrokeshire. Both areas not only have excellent tidal stream resource, but are close to good port facilities and large energy demand areas. The first consent in Wales for a tidal stream device was granted in March 2011 for the deployment of a demonstration device (Tidal Energy Ltd.'s Deltastream) in Ramsey Sound, Pembrokeshire [3].

Welsh Assembly Government (WAG) has a large commitment to producing renewable energy and ambitious targets to match that commitment, WAG aim to extract 9TWh per year from tidal stream and wave by 2025 [4]. To achieve this target WAG commissioned RPS to conduct a Marine Renewable Energy Strategic Framework [5]. WAG is also supporting the work of the LCRI-marine consortium [6] that aims to deliver research expertise to the growing marine energy industry in Wales. One initiative that WAG is considering is a tidal stream test site in West Wales [4].

This work presents Pembrokeshire (Figure 1) as a case study. The work identifies potential tidal stream deployment sites based on tidal current and depth constraints, calculates likely power output and considers constraints to propose the most likely regions for turbine deployment in Pembrokeshire. Typically, mean peak spring flow speeds must exceed 2ms^{-1}[7] but this is device dependant. Individual devices have specific depth constraints depending on both blade and foundation design: in this study a hypothetical 10m diameter turbine with a gravity foundation was used to generate depth and gradient constraints.

Much resource assessment has been conducted using the renewables energy atlas [1]. However, it is recognised that in coastal regions and channels, the resolution of this atlas means

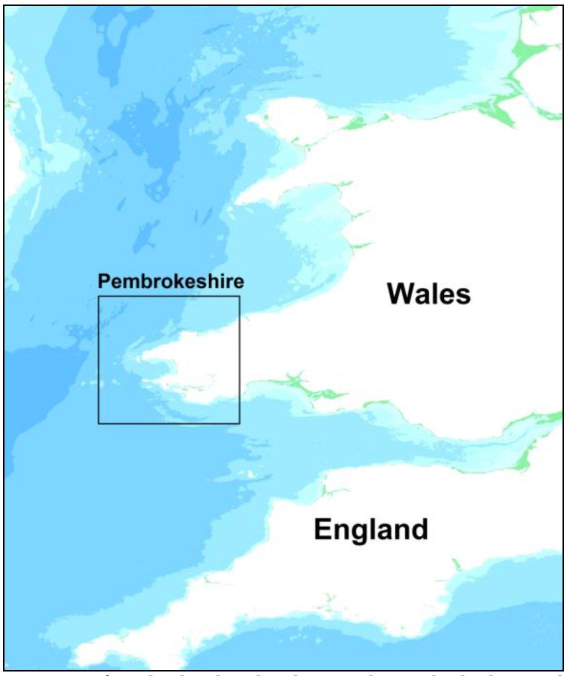

Figure 1 A map of England and Wales showing the Pembrokeshire study area

resource may be underestimated [8] and therefore it must be supplemented by more detailed models [9] or measurements [10]. Once total resource is calculated, estimation of power output for a given area can be achieved in a variety of ways. Most accurately, a numerical model of a region can be set up, validated against site data, and different arrays tested. The grid spacing must be fine enough to resolve complexities in the site bathymetry and hence localised hydrodynamics. Often arrays are implemented by increasing the bottom drag co-efficient to achieve energy loss [8]. However, such an approach is only useful when a final site has been selected, turbine specifications are known and hydrodynamic measurements are available for model calibration. During earlier stages of development, a simpler assessment of extractable resource is favoured. Two methods are predominately used: the 'farm method' [11] or 'flux method' [12]. One version of the flux approach is to use a significant impact factor (SIF) [12]. This approach considers the total flux through the vertical cross-section of the deployment region and applies a percentage factor to suggest the maximum extractable energy without significant environmental impact. Shortfalls of the SIF method include the difficulty of determining an impact factor. In this study an impact factor of 20%is used: the value suggested by Black and Veitch in their phase two tidal resource assessment [12].

The Marine Renewable Energy Strategic Framework by RPS [5] includes a GIS tool and has looked at a wide range of constraints to deployment ranging from military interests in Welsh waters to marine ecology. Combined with basic resource information they have suggested extractions scenarios ranging from 1.5GW to 6.4GW installed capacity, depending on the level of constraint considered acceptable for deployment. However only regions rather than specific areas are suggested and potential resource extraction is based on a percentage of the renewable energy atlas [1] data.

The study differs from the RPS study in that it focuses on resource estimation by calculating extractable power using the SIF method and finer resolution numerical models. The RPS study conversely focuses on a wide range of constraints and uses the renewables energy atlas for resource. Only a few engineering focussed constraints are utilised in this study to estimate site prioritisation.

II. METHODOLOGY

This paper takes a three stage approach to describing the available areas and resource in Pembrokeshire. Firstly, suitable areas are defined; secondly, estimates of power output for each area is determined; and thirdly, additional constraints are considered to rank the relative merits of the identified sites.

A. Site area definition

The areas available for turbine deployment were determined based on mean spring peak current exceeding $2ms^{-1}$, a standard threshold for tidal stream sites [7]. The mean spring peak current is the peak current based on a mean spring tidal cycle and is often used in resource assessments. These areas were defined in ArcGIS using three sources of current data. Firstly, the spring peak current layer of the renewable energy atlas [1] was used; secondly, outputs of a finer resolution model were used for coastal areas not covered by the atlas; thirdly, areas not covered by either model were determined based on Admiralty chart current information (Jack Sound only). The numerical model used the 3D POLCOMS model [13], covering the domain shown in Figure 3. The model grid contained 6 sigma levels in the vertical and had a horizontal grid resolution of 300m. Boundary conditions for this model consisted of 15 tidal constituents (Q1, O1, P1, S1, K1, 2N2, MU2, N2, NU2, M2, L2, T2, S2, K2, M4), including the dominant semi-diurnal constituents M2 and S2, extracted from an outer POLCOMS model of the Irish Sea [14]. The POLCOMS model solves the incompressible, hydrostatic Bousinesq equations of motion on a spherical co-ordinate system. Turbulence closure is handled using the using the Mellor-Yamada-Galperin level 2.5 scheme [24,25].

The areas with sufficient current were then refined based on a sufficient depth requirement and a suitable gradient requirement. The minimum depth constraint ensures that there is unlikely to be collisions between shipping and the turbine. A hypothetical turbine with a diameter of 10m was and a nacelle height of 12m above the seabed was considered; hence absolute minimum water depth for deployment is 17m. Turbine diameters vary between developers and are often scaled up and down due to site specific constraints, however liaison with developers suggests 10m is a reasonable figure.

Automatic Identification System (AIS) vessel data from Milford Haven [15] (Figure 2) was used to establish a threshold clearance. The 75^{th} percentile (6.6m) is believed to be a sufficient threshold because AIS data shows that large ships avoid the areas of interest for tidal stream turbine deployment (apart from the area off Stockholm where depths exceed 37m). Hence the minimum depth required is 23.6m.

Shallow sea-bed gradient is a requirement for gravity based devices which is necessary to avoid instability when undergoing the stresses of a high energy tidal regime. This constraint is included by utilising ArcGIS to mask out regions where the gradient is greater than 10%, a value suggested by a tidal stream turbine developer.

Finally, hard constraints which are likely to prohibit turbine deployment are used to exclude some sites. Areas of military use around Pembrokeshire are excluded since developments will be only considered on a case by case basis [5]

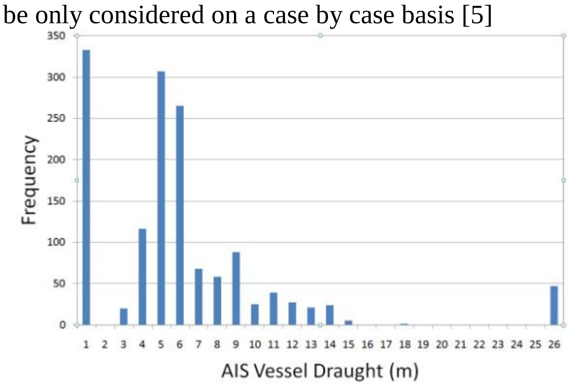

Figure 2 A histogram of AIS vessel draught

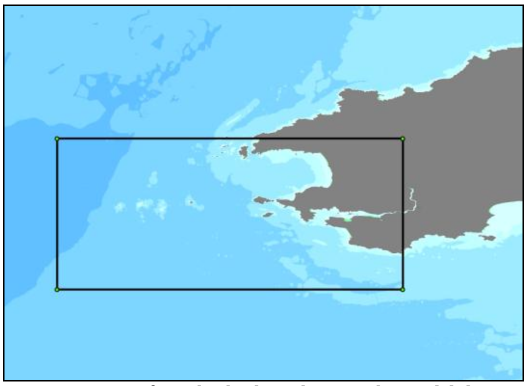

Figure 3 A map of Pembrokeshire showing the model domain.

B. *Estimate of Power Output*

Power estimates were based on the significant impact factor approach [12]. This approach takes the total power through a representative cross-sectional area and multiplies that by the significant impact factor (SIF). The SIF estimates the amount of flux extractable without significant environmental or power extraction effects. This value is given as 20% by Black and Veatch [12]. Therefore power extractable form flux through a given cross-section is calculated as:

$$P_{Cross\text{-}section} = SIF \frac{1}{2} \rho A u^3 \qquad (1)$$

Where: SIF=0.2, ρ is density of seawater; A is the area; u is the tidal velocity.

The cross sectional area for each site was calculated from a slice of the bathymetry data across each site (Figure 4). In order to avoid double counting of flux in the three adjacent sites, bathymetric slices were all taken in an E-W direction.

Depth averaged current speeds, from the previously described POLCOMS model, were taken at the bathymetric slice locations for a 15 day period between 10-25 Jan 1997. This covered one spring - neap cycle and hence multiplication by 24 gives an estimate of yearly power output.

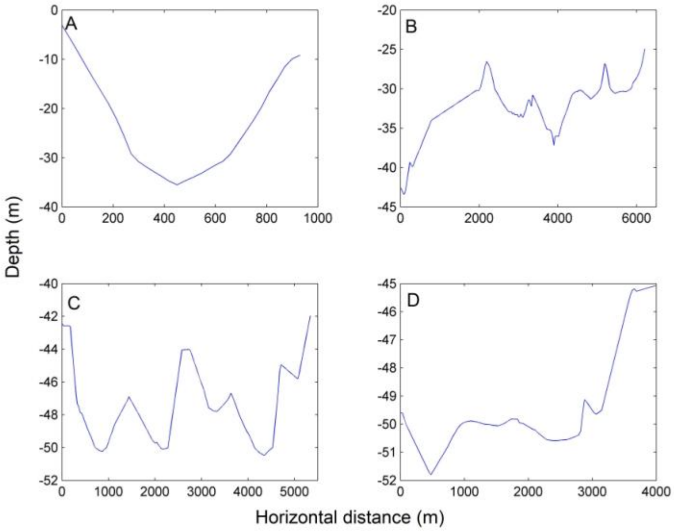

Figure 4 The area slices used in the flux calculations for A) Ramsey Sound, B)Bishops and Clerks, C) West of Bishops and D) Stockholm

C. *Additional Constraints*

A GIS approach was used to consider several other constraints and suggest the optimum area for deployment. The constraints were: fishing activity, port proximity, distance from electricity sub stations, special area of conservation habitat classifications and shipping use.

Fishing activity was considered based on both physical surveillance records and satellite tracking records downloaded from the maritime data website [15]. Physical surveillance covered a three year period 2006-2008, satellite surveillance the year 2007. The physical surveillance captures the smaller vessels not captured by the satellite tracking. Both datasets were given a rank from 1-5 to represent density of fishing activity [15]. Here, the two datasets were summed for each grid cell to give a single rank of fishing density, and the proposed tidal turbine sites overlaid.

Port proximity was based on distance from Milford Haven. The ArcGIS cost based distance tool was used to determine sea distances between the port and the potential tidal turbine sites. Milford Haven Port Authority has a commitment to renewable energy and is planning to build new facilities in anticipation of both wet marine renewables and offshore wind requirements [16].

Locations for Western Power Distribution's 11kV/33kV substations around Pembrokeshire were imported into ArcGIS and the multiple ring buffer tool used to provide distance from the different sites.

SAC habitat data was acquired from the Countryside Council for Wales. The only relevant habitats for the turbine sites were sea caves, reefs and offshore sandbanks. These were combined on a GIS map with the turbine sites.

No specific weighting was given to these different constraints, but rather a qualitative approach is taken to elucidate the salient concerns for tidal stream turbine deployment. To compare the four sites, they were simply ordered 1-4 from best to worst for each constraint.

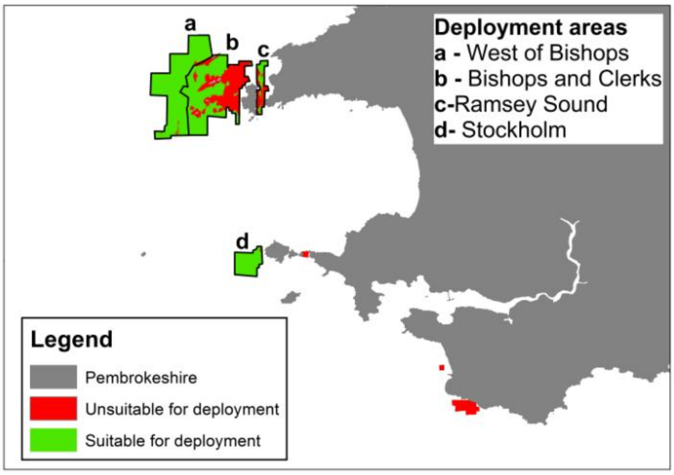

Figure 5 A map showing the areas available for tidal stream deployment

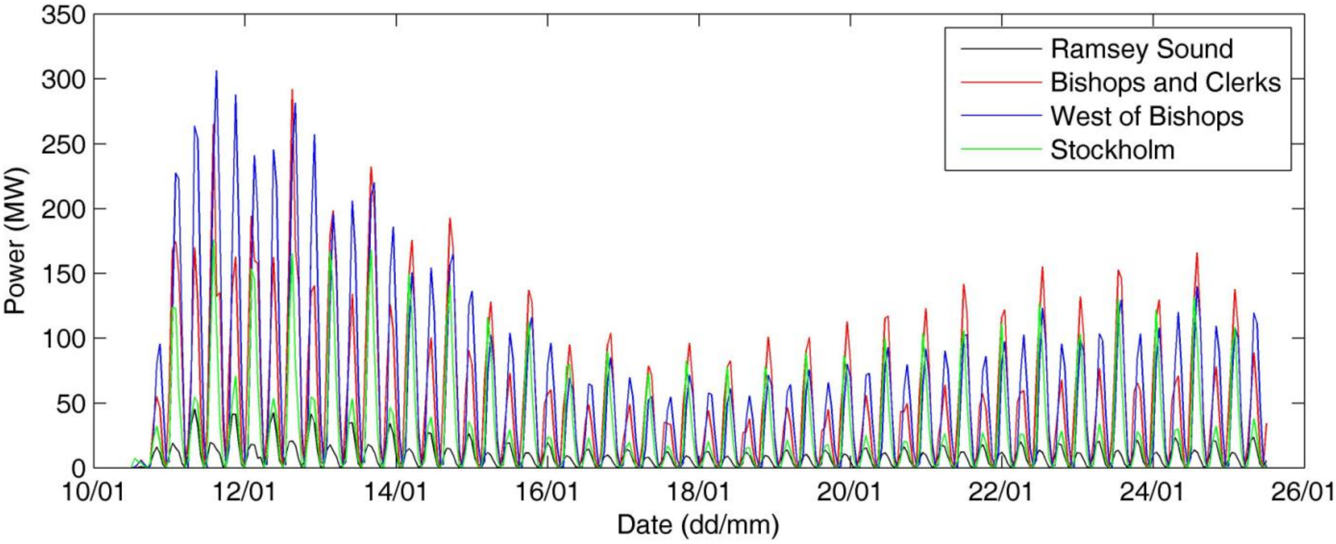

Figure 6 A plot of instantaneous power output from the four sites over the modelled spring-neap cycle

III. RESULTS

TABLE I
AREAS AVAILABLE FOR TIDAL TURBINE DEPLOYMENT

Site name	**Area (km^2)**	**Percentage area suitable**	**Area (km^2) for turbine deployment**
Stockholm	5.5	93	5.1
Ramsey Sound	3.6	47	1.7
Bishops and Clerks	30.7	58	17.8
West of Bishops	24.1	98	23.7

TABLE II
POTENTIAL POWER ESTIMATES FOR THE FOUR SITES BASED ON THE SIF METHOD

Site name	**Two week test period (GWh)**	**Yearly estimate**
Ramsey Sound	3.12	74.89
Bishops and Clerks	19.40	465.62
West of Bishops	19.99	479.81
Stockholm	10.21	245.12
Total	52.72	1265.28

TABLE III
RANKING OF CONSTRAINTS FOR THE FOUR SITES

Constraint type	**Ramsey Sound**	**Bishops and Clerks**	**West of Bishops**	**Stockholm**
Fishing	4	2	2	1
SAC habitat	1	1	1	1
Substation proximity	1	2	3	4
Port Proximity	2	2	2	1
Shipping	1	2	3	4
Total	9	9	11	11

A. Site area definition

In the initial site selection, four sites were determined: Stockholm; Ramsey Sound; Bishops and Clerks; and West of Bishops. These are shown in Figure 5, which shows the areas where current speeds exceed 2ms^{-1}. These areas are colour coded such that green indicates depth, gradient and hard constraints are suitable and red indicates areas where current speed is suitable but depth and gradient constraints currently prohibit turbine deployment. The Bishops and Clerks and West of Bishops have been separated due to the depth in the region West of Bishops meaning that deployment there is likely to come at a later stage. Table 1 shows the areas available for each site.

B. Power Estimate

Figure 6 shows the estimate of instantaneous power generated over the tested spring neap cycle based on the SIF method. The power generation estimate is given in Table 2, along with a yearly estimate of power generation. The area West of Bishops shows the greatest potential power output and Ramsey sound the least. The total for all sites suggests that tidal stream energy in Pembrokeshire could supply over 1TWh per year towards WAG's renewable energy targets. It is interesting to note that the asymmetry between power on the flood and ebb is much greater for Stockholm than for the other sites. Ramsey Sound displays a flood dominance whereas the other 3 sites all display ebb dominance. It is thought that this could be due in part to the constriction in the sound.

C. Additional Constraints

Maps of the additional constraints are shown in Figure 7. Each site's rank (1-4) for each constraint is displayed in Table 3. Ranking was assigned as 1 showing most constraint and 4 showing least constraint.

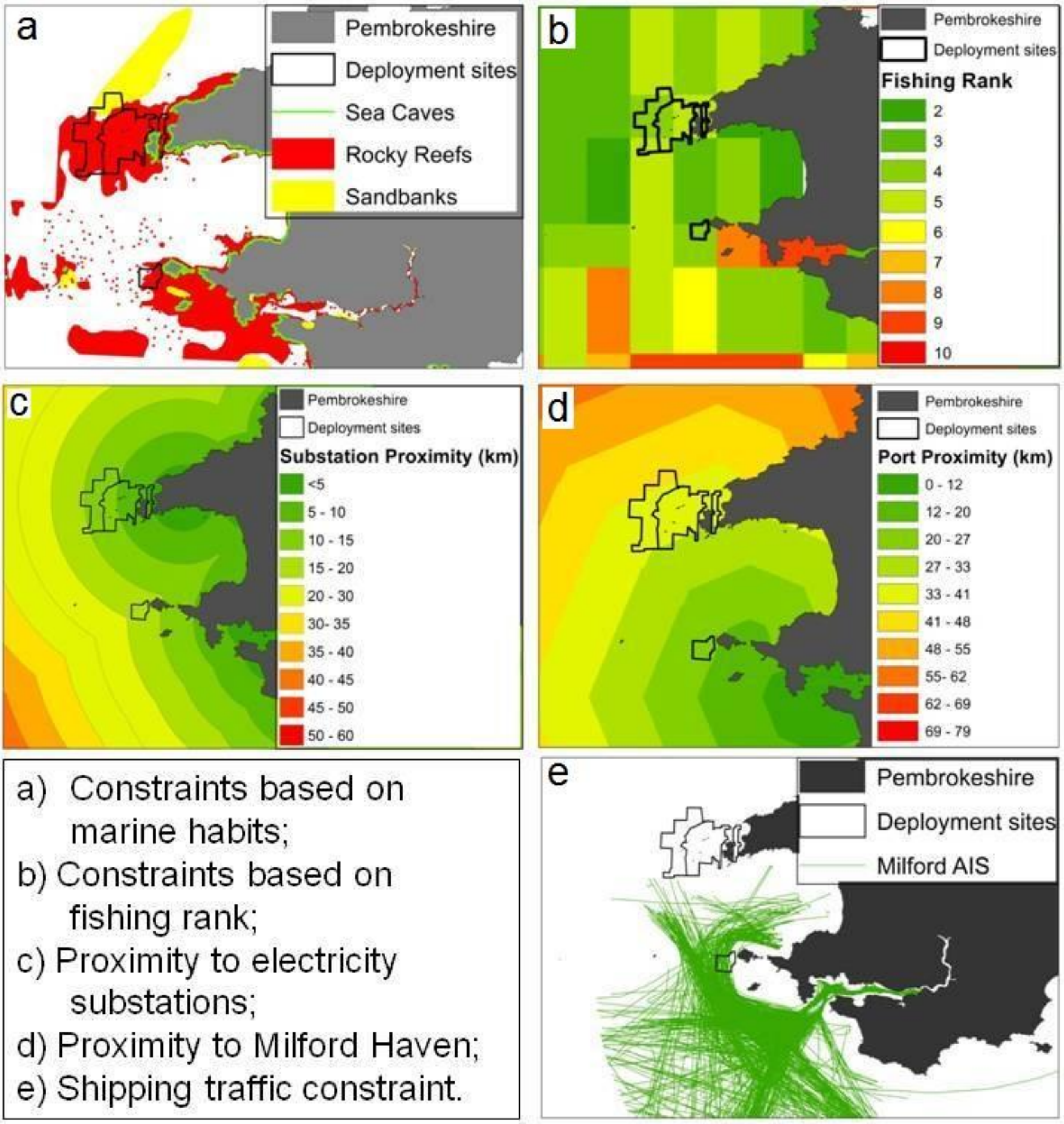

Figure 7 Pembrokeshire and the four potential turbine sites with different constraints mapped.

None of the proposed sites show high fishing activity, with density being ranked between 4 and 5 out of 10. Lowest fishing density occurs for Stockholm and highest in Ramsey Sound.

All sites are situated in the Pembrokeshire Marine Special Area of Conversation (mSAC). All sites have components of rocky reef; the area West of Bishops also has a section of sub tidal sandbank. Sea caves are in present at the coastline adjacent to all the turbine site areas, however it is unlikely that turbines would have any effect on sea caves.

Ramsey Sound, Bishops and Clerks and West of Bishops are all closest to the St Davids substation whereas Stockholm would utilise a different station South Hook SW. Ramsey Sound is the closest at 5km from a substation and Stockholm the furthest at ~17km from a substation

The closest site to Milford Haven port is Stockholm, which is 20km away; the other sites are all ~40km from Milford Haven. Ramsey Sound, Bishops and Clerks and West of Bishops are all also a similar distance away from Fishguard (not shown).

Ranking of the sites shipping constraint is based on the Milford Haven AIS data and visual extrapolation of the ship trajectories outside of the AIS area. Given its proximity to Milford Haven, it is unsurprising that the Stockholm area is the most constrained by shipping. Ramsey sound is the least constrained, only being used by small boats which don't carry AIS.

IV. DISCUSSION

A. Site area definition

The initial sites were selected based on current speed and depth constraints. A $2ms^{-1}$ threshold was used in this study, in line with other resource assessments [7]. It is hoped that as technology advances, current thresholds will reduce, allowing greater areas to be utilized. However, at present most devices require currents greater than $2ms^{-1}$ [17]. Depth constraints were based on a hypothetical gravity based turbine and AIS shipping data from Milford Haven giving a minimum depth of 23.6m. No maximum depth was specified, given the easier installation of a gravity base foundation in deeper waters, however very deep areas will clearly be more expensive to exploit. Clearly different devices will have different requirements. The depth constraint used here is within the range (18 – 55m) of values given in the 2011 Renewables UK state of the industry report [17]

The areas suggested in this study are similar to previous studies [5, 18]. The four sites provide a total $48.3km^2$ of potential sea area for turbine deployment. Whilst the entire area is unlikely to be monopolized, the area represents a substantial opportunity for development. Moreover, more detailed numerical modelling of the wider Pembrokeshire area may highlight additional resource in specific areas such as around headlands. Three sites, Ramsey Sound, Bishops and Clerks, and the West of Bishops are in close proximity, giving the potential for a 'tidal hub' in that region and a possible location for the hypothesized WAG test facility [4].

B. Power Estimate

The SIF methodology was used to provide an estimate of extractable power for the four sites. The other main method of simple power estimation is the farm method, whereby the number of devices in an area is calculated, however this method depends on rated capacity and hence resource can be over-estimated [19]. Therefore the SIF method is likely to be more realistic, provided that flux is not double counted and a realistic impact factor is used. Double counting of flux occurs where the same flux streamline is counted in two cross-sections in close proximity. In this case, three of the sites lie in a line perpendicular to the direction of flux, removing the possibility of double counting. The fourth site is in the same flux line as the other three, it is believed that the sites are sufficiently apart that they can be treated as independent but a 2DH numerical model including the farms would be needed to determine this with certainty. In this study the impact factor was set as 20%, in line with the Black and Veatch study [12], however it is suggested that this value can range from 10% to 50% depending on the farm setting [12].

Both this study and the renewables energy atlas [1] used the 3-D POLCOMS model [13], the primary difference is that in this study the grid resolution was approximately 300m and in the renewables energy atlas the grid resolution was approximately 1800m [1]. This means that the bathymetry around the headlands, sounds and islands of Pembrokeshire better resolved in this study. Since flow compression in channels enhances the flow speed, there are areas, such as the Bishops and Clerks, where the model used here gives higher current speeds than the renewable energy atlas. Additionally the higher resolution models allows for modelling of currents in areas that are missed in the renewables energy atlas, most notably Ramsey Sound. The power estimate was calculated from a modelled spring neap cycle in January 1997. This was then multiplied by 24 to provide an estimate of yearly output. Such an approach was motivated by data availability. Spring-neap cycles will vary throughout the year altering power output; however the multiplication approximation is reasonable for an initial resource assessment.

The greatest potential power extraction is achievable in the West of Bishops region with a very similar power level achievable in the Bishops and Clerks region, Stockholm has half that potential and Ramsey Sound is significantly lower. The lower power potential in Ramsey Sound is due to the narrow channel constraining deployment. If all sites were developed there is the potential to extract over 1TWhr from tidal stream in Pembrokeshire which equates to $1/9^{th}$ of the WAG wave and tidal renewable energy target [4]. Maximum power ranges from 45MW (Ramsey Sound) to 307MW (West of Bishops), however the rated power of devices is likely to be lower than possible on a peak spring to increase the utilisation factor and improve cost efficiency during the rest of the spring-neap cycle.

All sites show an asymmetry between power output on the flood and the ebb. Given the grid requirement for a steady electricity supply, parity between flood and ebb is preferable. Greatest parity is observable in the West of Bishops region with greatest asymmetry in the Stockholm area. This means that, especially as the West of Bishops region has the greatest extractable power potential, from a generation perspective the West of Bishops region is most preferable. The Bishops and Clerks region, while showing similar potential power, shows greater asymmetry and so is likely to be less preferable based on power considerations alone. It is hypothesized, based on bathymetry, that the flow is likely to be less turbulent to the West of Bishops, which also favours that location since turbulence both reduces turbine efficiency and increases loading on turbine parts.

C. Additional Constraints

Five constraints were considered, while this is not an exhaustive list, several key constraints are considered. A more thorough constraint assessment was conducted by RPS and this will be used by WAG for marine spatial planning of renewable energy. Data availability and project scope prevented a comprehensive constraint assessment in this paper. However such an assessment would have simply duplicated the RPS work and it is believed that the 5 constraints tested allow for definition of the relative constraint levels for the four proposed areas.

Implementation of marine renewable energy devices has the potential to alter the substrate via foundations and cabling [20]. It has been suggested that this could increase and alter biodiversity [21] and act as stepping stones for invasive species [22]. This is especially a consideration in a marine special area of conservation (mSAC) such as Pembrokeshire. Figure 6a shows that most of the tidal turbine sites are in areas of rocky reef, a hard substrate and, in effect, very similar to concrete foundations or cabling. Some foundations have been specifically designed to better mimic natural reef [23]. Hence it is not expected that the implementation of turbines would alter biodiversity. Moreover, the large areas of reef in the mSAC and the small footprint of devices and cables mean that large areas of the natural habit will not be affected. For this constraint all sites are rated equally given the similarity in habitats present.

Array implementation could affect the fishing economy since turbines and trawling are mutually exclusive. A fairly simplistic representation of fishing activity is presented here, however it does show that none of the turbine sites are in prime fishing areas. The density of shipping in the Stockholm site precludes intensive fishing and hence this site is least constrained by fishing. Ramsey sound has the highest fishing rank, although, anecdotally, this is largely via static gear. The other two sites are equally ranked.

Substation proximity is a crucial constraint to development given the financial cost of offshore electricity cables and the potential for electricity losses over long distance transmission. The cost of cable makes distance from substations particularly important; it has been suggested [7] that tidal stream deployments have a maximum distance offshore of 20-35km. All four sites in Pembrokeshire are within this buffer and hence distance from substation is not a prohibitive constraint. Nonetheless, cost means sites closer to shore will be preferable. Therefore Stockholm is the least likely to be developed based on this constraint.

Proximity to good port facilities is important to reduce cost in both the initial installation and in routine maintenance. Distance from ports increase both time and fuel cost.

The AIS data which shows shipping activity does not extend to cover 3 of the 4 areas and therefore shipping traffic was estimated by visually extending ship paths following a linear trajectory. Whilst this method does not allow for definitive ranking of the shipping activity over the different sites, no other data was available to this study. Other data on shipping density can be examined online [15] and this corroborates the ranking produced here. Shipping activity affects the ability to access a site for deployment and maintenance. Additionally, the presence of ships affects the depth requirements of a device, with larger draft ships leading to greater depth requirements. The Stockholm site is the only site inside the AIS region and shows a significant amount of traffic. Despite this, the depth of the site (~50m) means that turbines could still be deployed, although deployment and maintenance would be more difficult than the other sites.

The four sites were ranked on their relative level of constraint for the five categories and the total constraint estimated. Ramsey Sound and the Bishops and Clerks have same level of constraint and West of Bishops and Stockholm have slightly higher levels of constraint. Given the small size of Ramsey Sound, this makes Bishops and Clerks the most likely region for the first phase of turbine array deployment. Given the higher constraint level of the Stockholm area, and the lesser extractable power potential, this area is least likely to be exploited. While the area West of Bishops has higher constraints than Ramsey Sound, its larger size will make it attractive to array developers in the future. It is believed that Ramsey Sound will primarily be used as a prototype testing area, which is the fashion in which TEL are using the area.

The constraint matrix put the four sites onto 2 levels, where in reality it is likely that they all have different levels of constraint. This is in part due to the limited number of constraints tested and simple ranking system and in part due to the similarity of the sites. Until exact array locations have been determined it is difficult to identify fine differences in constraints in such similar environments. Greater number of constraints in the matrix would likely provide better definition of the difference between sites; however data availability becomes an issue. The constraint maps created in the MRESF, which include many other constraints, are not currently available online because of data ownership restrictions, although RPS welcomes enquiries from interested parties via the MRESF contact [5]. Future work could aim to place a financial cost on the different constraints which would not only make the ranking more accurate but facilitate a cost-benefit analysis of the different sites when combined with expected power output and electricity price forecasts.

In order to further WAG renewable energy goals and facilitate understanding about sustainable exploitation of the Pembrokeshire tidal stream resource, the LCRI Marine consortium [6] are conducting a multidisciplinary measurement campaign focussing on Ramsey Sound and the Bishops and Clerks. This will investigate constraints such as fish behaviour, underwater noise and marine mammals and conduct acoustic doppler current profiler (ADCP) transects to determine more accurately the available resource. The current data will be used to validate numerical models of the region which can then be used to more accurately predict the feasible level of extraction and the impacts of these extraction levels. The LCRI-Marine consortium is happy to discuss access to this data with potential collaborators from both industry and academia.

V. CONCLUSIONS

Pembrokeshire has an excellent tidal stream resource. Four areas were identified as suitable for tidal turbine deployment, which gives 48.3km^2 of sea space suitable for deployment. The significant impact factor method was used with a factor of 0.2 to estimate potential power extraction levels. If the four areas are developed there is the potential to extract 1.3TWhrs per annum. This equates to 1/9th of the WAG target of 9TWhrs of wave and tidal energy by 2025. The most likely area for development is the Bishops and Clerks region, followed by the area West of Bishops.

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