TABLE 2: OUTPUT RESULTS (example using input data from Table 1)

A. Performance Indicators

Indicator	Value	Units
Rotor mechanical output power	938	kW
Rotor torque	860	kN.m
Electrical output power	1675	kW
Thrust on rotor	663	kN
Rated electrical output per unit area of rotor	2.20	kW/m^2
Load factor	42%	
Operational Availability	97%	
Capacity Factor	41%	
Energy captured per turbine	6,014	MWh/yr
Specific energy capture	15.82	MWh/m2 yr

B. Cost and Mass Values per system

Per Turbine (marginal)	Cost	Mass (t)	Unit cost/kW
Rotor & hub	£166,357	42.40	£99
Gearboxes & generators	£431,732	55.49	£258
Electrical control & misc.	£139,516	11.21	£83
Structure	£301,444	191.88	£180
Assembly & transportation	£29,030	-	£17
Cost c.I.f quayside (sub total)	£1,068,078	-	£638
Installation & interconnect	£143,404	-	£86
MCT margin	£41,884	-	£25
Total installed cost	£1,253,366	300.98	£748
Specific output			5.57kW/tonne

C. Overhead and O&M costs

Overhead costs per farm	£3,365,110
Recurring annual O&M costs per system	£57,851

D. Total capital costs

No. of Turbines in Farm	total cost	cost/unit	cost/kW
1	£4,618,476	£4,618,476	£2,757
6	£10,885,306	£1,814,218	£1,083
10	£15,898,770	£1,589,877	£949
15	£22,165,600	£1,477,707	£882
20	£28,432,430	£1,421,621	£849

E. Annualised costs

No. of Turbines in Farm	Cost/kW	p/kWh
1	£315	8.78
6	£145	4.03
10	£131	3.65
15	£124	3.46
20	£121	3.37

TABLE 3: Analysis of turbine performance and cost-effectiveness at various specified locations

Location	Mean max Spring	Mean max Neap	Ratio Neap to Spring	Ratio Ebb to Flood	Water depth at LAT (m)	Distance to connect to grid (Marine equivalent km) *	Turbine rotor dia. (m)	Optimum turbine rated velocity (m/s)	Optimum turbine rated power (kW)	Energy capture per year per unit (MWh)	Energy capture per year per m2 (MWh)	unit cost of elect-ricity (p/kWh)	unit cost of elect-ricity (p/kWh)	unit cost of elect-ricity (p/kWh)	unit cost of elect-ricity (p/kWh)	unit cost of elect-ricity (p/kWh)
	m/s	m/s										1 unit	5 units	10 units	15 units	20 units
Strangford																
1	3.23	2.57	0.80	0.86	30	**1**	20	2.45	1912	8369	26.64	4.73	3.21	3.02	n/a	n/a
2a	2.95	2.28	0.77	0.91	30	**1**	20	2.3	1582	6865	21.85	5.38	3.52	3.29	n/a	n/a
2b	3.25	2.50	0.77	0.91	30	**1**	20	2.5	2032	9093	28.94	4.45	3.04	2.87	n/a	n/a
3	3.03	2.34	0.77	0.87	25	**1**	16	2.5	1300	4983	24.78	6.58	3.92	3.60	n/a	n/a
Copeland																
4a	2.5	1.72	0.69	0.97	30	**8**	20	2.1	1204	4527	14.40	n/a	6.46	5.21	4.71	4.58
4b	2.5	1.72	0.69	0.97	35	**8.5**	24	2.0	1498	6113	13.51	n/a	5.64	4.66	4.34	4.17
5	2.2	1.50	0.69	0.79	35	**9**	24	1.7	920	3202	7.07	n/a	n/a	7.40	6.74	6.42
6	2.0	1.38	0.69	0.79	35	**9**	24	1.6	767	2075	4.59	n/a	n/a	n/a	9.70	9.19
NE Coast																
7a	3.08	2.10	0.69	0.83	40	**7**	28	2.2	2714	12450	20.22	7.04	3.76	3.35	3.21	3.15
7b	3.08	2.10	0.69	0.83	35	**6**	24	2.15	1861	8767	19.34	8.11	3.99	3.47	3.30	3.21
8	3.00	2.11	0.69	0.70	35	**8**	24	2.2	1994	8081	17.86	n/a	4.72	4.01	3.78	3.66
9	3.00	2.11	0.69	0.70	40	**8**	28	2.1	2360	10200	16.56	n/a	4.38	3.82	3.64	3.54
Offshore	3.08	2.11	0.69	0.92	50	**15**	36	2.1	3902	18488	18.16	n/a	4.00	3.57	3.42	3.35
Offshore	3.08	2.11	0.69	0.92	70	**15**	50	2	6502	32329	16.46	n/a	4.14	3.89	3.81	3.77

* Assumptions on grid connect costs are as follows:-
marine cable cost = £100k/km
marine cable installation cost = £400k/km
33kV spur cost to landfall from sub-station = £25k/km
Hence on-shore connection costs are such that 1km on land costs the same as 0.05km offshore so we have taken the marine cable connection distance and added 0.05km for each on-shore km to arrive at a similar connection cost measured in terms of "equivalent marine cable". Therefore the figures in the table above are "marine cable equivalent distance"

4.2.2 Results of running MCT model in relation to locations identified by KMM model

The KMM model indicated locations as described in section 4.1, the Review of Tidal flows, A,B and C in the Strangford Narrows, E, D and F in the Ram Race just off the Copeland Islands and X, Y and Z off the NE coast, together with a much larger area of fast flowing deeper water further off shore on the NE coast, (see ***Figures 12, 10 and 7*** respectively).

When turbines of suitable sizes for these locations were sized and optimised using the MCT Techno-Economic model, the results summarised in ***Table 3*** were generated. The relevant locations are given as 1, 2 and 3 in ***Figure 17***, as 4, 5 and 6 in ***Figure 18*** and as 7, 8 and 9 in ***Figure19*** respectively.

Because any such project carries a large fixed overhead due to planning, site survey work, mobilisation, the cost of providing the umbilical cable to shore and the grid connection costs, it clearly incurs much higher unit costs and generating costs to install one or a small number of turbines than to install a larger field of turbines, where the overheads can be spread across a larger number of units; ***Table 3*** gives unit costs for 1, 5, 10, 15 and 20 units.

Generally speaking it can be seen that it is not cost-effective to install a single turbine with its own umbilical for grid connected operation, although if extra turbines are added to an existing single turbine installation the average costs for such a system will eventually reflect the sharing of overheads.

4.2.3 Deployment plan in the locations assessed taking relevant issues into account

Having assessed the potential characteristics of a turbine system if installed at various locations, the next step was to evaluate how many such turbines might be usefully employed (to gain an indication of the likely overall potential of the tidal stream resource) and hence to suggest a possible programme to develop the resource.

a) Strangford Narrows

Strangford Narrows is the most attractive location due to the high level of energy available there, but clearly this is the least attractive in terms of available space and the likelihood of conflicts arising with other users and interested parties. However theoretically it should be possible to install up to a maximum of around 20 turbine installations in 3 groups in the narrows, the first group ought to be in area “2” (***Figure 17***) near the centre of the narrows, probably on the west side of the navigable channel, the next group would preferably be in the north in area “1” and finally a group might be installed in area “3” to the south (which is slightly shallower so the turbines there would need to be smaller and hence less powerful). The Narrows have important amenity value for leisure boating, tourism, etc and have been designated as an area of Special Scientific Interest. Hence a key requirement if any tidal stream turbines are to be installed in this area is to balance the benefits with potential impacts and gain adequate assurances that commercial deployment will not significantly damage any natural processes or cause unacceptable impact. The technology proposed is considered to have a low environmental impact (confirmed by the EIS completed for the Lynmouth Project by Casella Stanger). It is also considered that the impact of a small deployment of turbines in Strangford could be managed to remain acceptable. A modest research and a demonstration site could be considered under strict conditions to confirm this view.

The initial R&D site would be the subject of a detailed environmental impact analysis by Queens University Belfast which has a field research centre almost ideally positioned at Portaferry beside the narrows.

Initially one unit of 1600 to 2000kW could be installed (depending on which set of velocity figures prove most accurate). This would not be cost-effective on its own although it has the potential to deliver some 6800 to 9000MWh per year into the grid which would partially pay for the cost of the system. The notional electricity generating costs from this single system, based on its lifecycle costs and an 8% interest rate for the capital, would be in the order of 4.5 to 5.5p/kWh. The purpose of sponsoring such a project would be as a sub-economic demonstration system for the purposes of engineering, environmental and scientific assessment. It could also be used perhaps in conjunction with the aquarium in Portaferry to inform the public by having an appropriate exhibit – perhaps using underwater real-time TV. If such a project goes ahead it could well be one of the pioneering efforts to develop this new form of energy technology and as such it ought to be of considerable public interest.

Part of this study could also be to determine whether and, more precisely, to what extent the initial single turbine project could sensibly be extended in the Strangford Narrows. Locations referenced 2a and 2b in ***Table 3*** relate to such a project, where 2a is based on current velocities derived from the mathematical model while 2b is based on actual measurements made during the site visit.

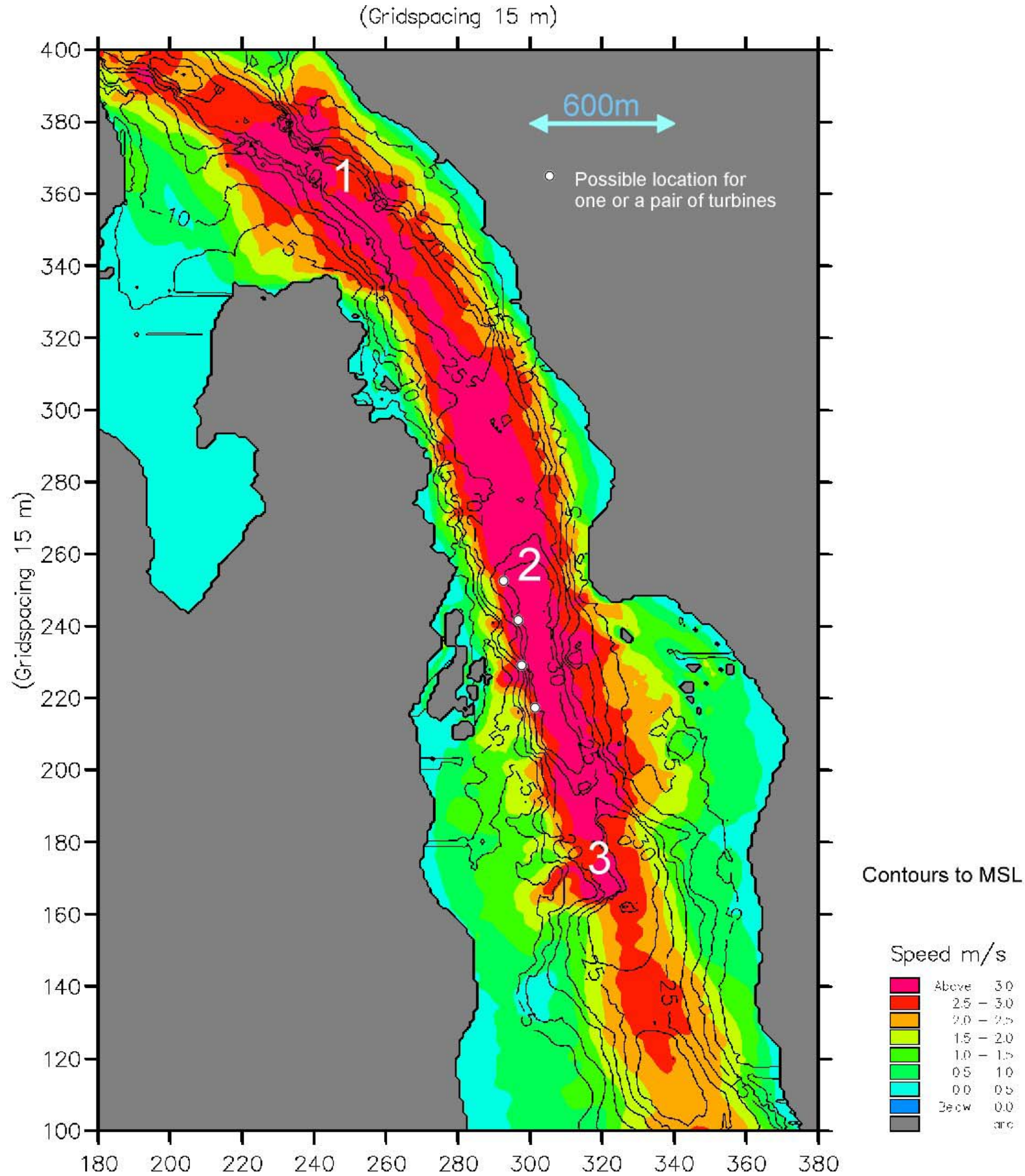


Figure 17: Potential for deployment of turbines in Strangford Narrows (note it may not be feasible to utilise all the possible places as marked)

b) Off the Copeland Islands

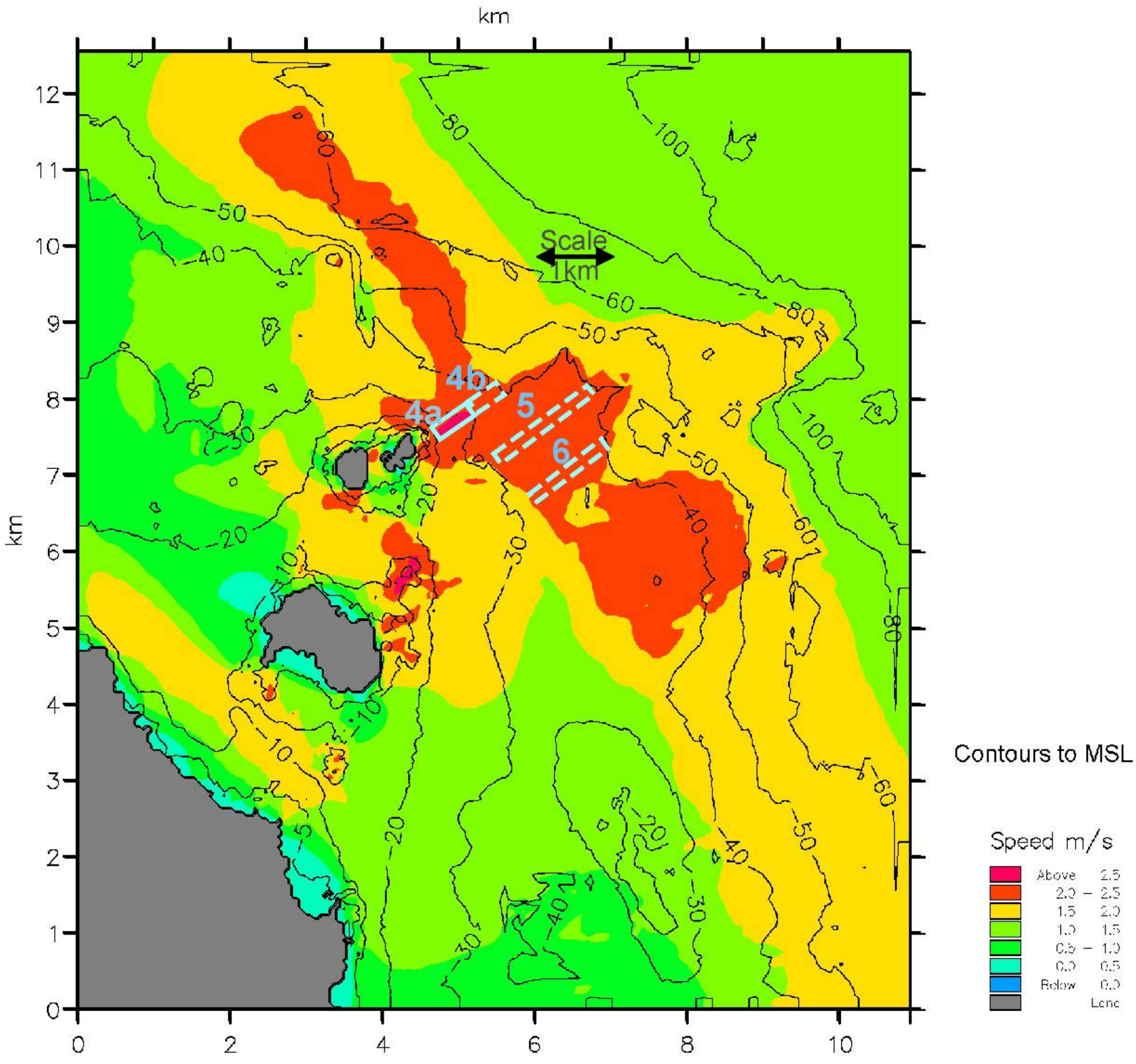


Figure 18: possible deployment of turbines in vicinity of the Copeland Islands (note it is not necessarily proposed to utilise all the possible places as marked – see discussion in text)

The proposed deployment for the Copeland Islands area is indicated in ***Figure 18***. Here the initial project would clearly be area 4a which is both nearest to shore (minimising cable connection costs) and has the fastest flows.

The next step looks to be two or possibly 3 rows of turbines deployed across the area as shown labelled from 4a and 4b through 6. The starting point would be row 4a where slightly higher velocities are to be found but in shallower water – this could accommodate a 500m row of about 10 machines with

20m diameter rotors rated at 12MW in total. This could be further extended along 4b with 10 more turbine units with 24m rotors adding a further 15MW; i.e. row 4 in total might be rated at around 27MW. (see ***Table 4***)

Row 5 could follow if investigations indicated adequate energy recovery in the distance indicated (about 800m in the direction of flow); it should be noted that the deployment pattern indicated might not be achievable if insufficient energy recovery occurs or if adding too many turbines causes modification of the flow pattern. However at least the outer end of row 5 should be feasible as it will not be affected by, or affect row 4b. If row 5 proves feasible then it would consist of some 20 turbines probably rated at around 920kW each, giving a total installed capacity of 15MW. This is shown as "1st extension" in ***Table 4***. The table also shows that if a "2nd Extension" shown in ***Figure 18*** as row 6 is added, the performance of this row will be rather poor and electricity costs would be sub-economic. This is due to the relatively slower current velocities in that area. However such an extension could add some 18 further megawatts and given future improvement in the technology it is possible that it could eventually become a cost-effective project (for example wind turbine technology today costs 25% of what it cost 20 years ago in real terms – so there may be scope for significant improvements in cost-effectiveness compared with the "First Generation" technology used in this exercise.

Hence this field if developed using "first generation" technology looks like it could have a gross installed capacity of around 27MW with possible potential for later development to 45MW given more cost effective tidal turbines.

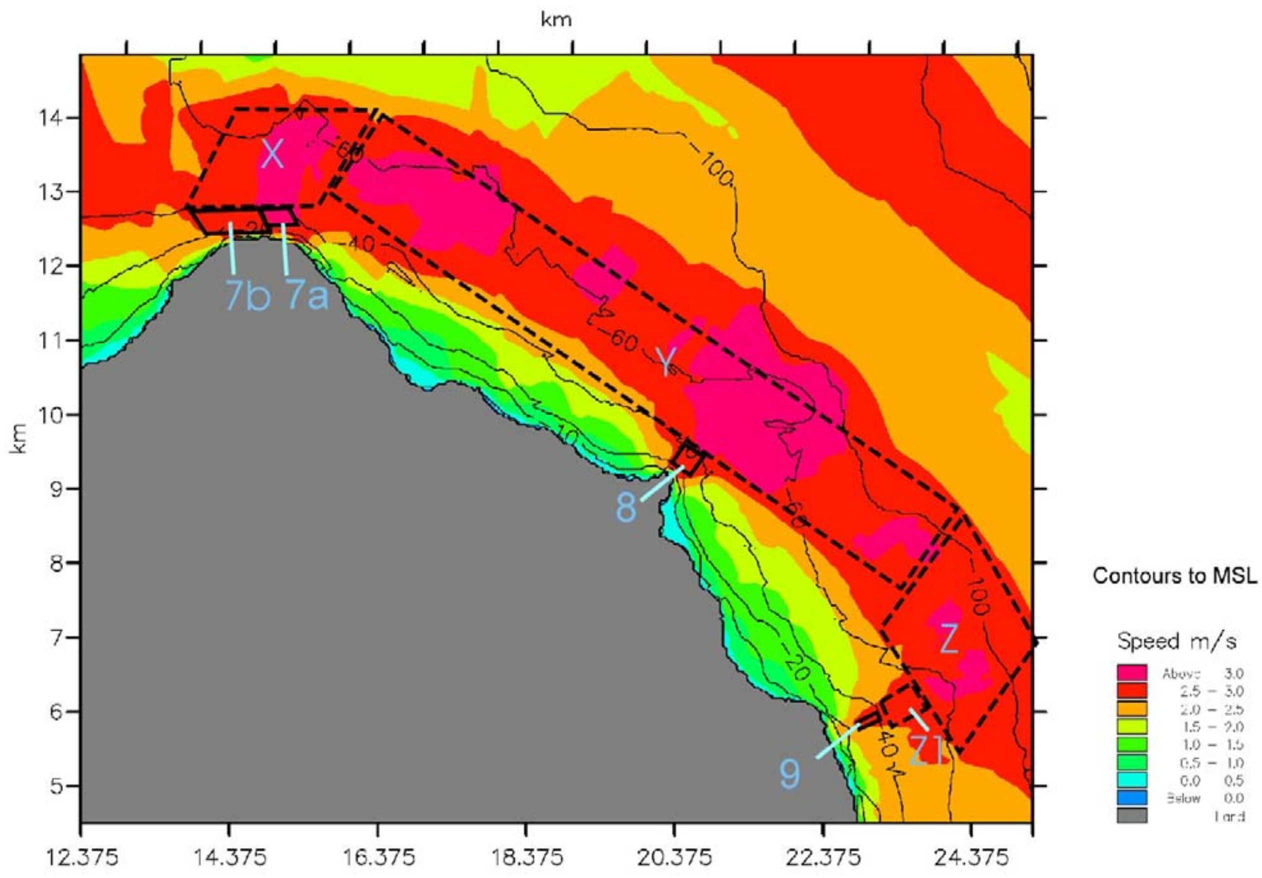
<u>c) NE Coast</u>

Of the areas with high tidal stream energy, this coast is the least attractive to carry out installation work due to its exposure and the extreme currents in the area. Moreover ***Figure 19*** shows there are only 4 locations, each quite small, where the water is shallow enough to permit the pile-mounted first generation technology to be installed; these are marked 7a, 7b, 8 and 9 and are in all cases in highly turbulent flow locations. Location 7a is the only one with over 3m/s mean spring peak in water of less than 40m depth.
Table 4 indicates that "First Generation" technology with 28m rotors could be deployed along the 40m depth contour at locations 7a and 9 while 24m rotor systems deployed along the 35m contour may be necessary at 7b and 8. More detailed bathymetric survey work will be needed to develop a more certain knowledge of these areas as it is known that the seabed in these locations is relatively uneven, so these aforementioned assumptions as presented in Tables 3 and 4 represent what we believe to be a reasonable assessment of the situation.

The preferred location for initial development appears to be area 7a and then 7b (off Fair Head) as these have both the best flow pattern with regular flows at 3m/s, they are larger and they also are relatively close to the 33kV grid which is about 6 to 7km away at Ballycastle. The next most favourable locations will be 8 and 9.

However, when Second Generation systems are developed, capable of being deployed in water depths from 40 to 100m, then a much larger potential can be seen to open up in areas marked X, Y, Z and Z1. Z1 might in fact be the place for a pilot project for 2nd generation systems as the adjacent location 9 could be developed by then using 1st generation technology first and could then provide a grid connection. This would allow the first 2nd generation project to be developed at marginal cost if it had been planned for when location 9 is developed.

Figure 19: Possible deployment of turbines along NE coast



The results in Tables 3 and 4 were developed on the basis of using scaled up first generation systems, each with 2 x 36m or in deeper water 2 x 50m diameter rotors, giving each unit a rated power of 4MW and 6.57MW respectively.

Table 3 indicates possible generating costs for these on the basis of extrapolating "First Generation" systems beyond the level where the model is completely reliable and such that diminishing returns set in; in effect it gives costs for "scaled up 1st Generation" rather than any viable "2nd generation" technology – which ought to be more cost-effective. However even if 2nd generation technology is no more cost-effective than first generation technology the unit costs for generation with projects of the size envisaged will be in the range 3 to 4p/kWh (probably around 3.5p).

Table 4 shows the results of populating areas X, Y and Z with a fairly sparse packing density (it is not yet known how closely packed tidal turbines can be without interfering unduly with each other, particularly in the flow direction, so a conservative and cautious approach has been used of at least 20 rotor diameters separation in the flow direction – the rule of thumb with windfarms is 10 rotor diameters). It was also assumed that no more than 60% of the available area as marked can be used due to seabed conditions or other constraints such as the need to leave clear passages for shipping. On this basis it seems some 120 systems could be installed having an aggregate installed rated capacity of 640MW and with the capability of delivering in the order of 3TWh per annum.

It has to be said that both the flow model and the technology model were being used in such a way that the accuracy of prediction for the NE coast area is only approximate (the Strangford and Copeland results should be much more certain). However there is no doubt that the energy resource in the tidal streams off the NE coast are real and large and likely to have a potential for several hundred MW as and when suitable technology for exploiting this resource in water from 40 to 100m deep becomes available. Knowledge that such resources exist will no doubt help to encourage the development of the required technology, which no doubt will benefit from the lessons to be learnt from deployment and operation of "first generation" technology.

TABLE 4: Theoretical energy yield for all sites reviewed

Project	Likely time for implementation	Location (Figs 17, 18 & 19)	Mean max. Spring velocity (m/s)	Turbine size (rotor dia. m)	rated power (kW)	No. of systems	Gross rated power (MW)	Gross energy capture (MWh/yr)	Average cost of energy (p/kWh)
Strangford									
Demo Project	2004-5	2a	2.9	20	1582	1	1.6	6865	5.38
1st extension	2006	2b	3.2	20	2032	5	10.1	45465	3.04
2nd Extension	2008	1	3.2	20	1912	5	9.5	41845	3.21
3rd extension	2010	3	3.0	16	1308	10	10.3	49830	3.60
sub-total						***21***	***31.5***	***144005***	***3.46 ****
Copeland									
Initial Project	2006	4a	2.5	20	1204	10	12.0	45270	5.21
1st Extension	2008	4b	2.5	24	1498	10	15.0	61130	4.66
Sub-sub-total						*20*	*27.0*	*106400*	*4.93 **
2nd Extension	2010	5	2.2	24	920	20	18.4	32020	6.42
sub-total						***40***	***45.4***	***138420***	***5.67 ****
NE Coast									
1st Generation	2008	7a	3.08	28	2714	10	27.1	124500	3.35
1st Generation	2010	7b	3.1	24	1861	10	18.6	87670	3.47
1st Generation	2010	8	3.0	24	1994	5	10.0	40405	4.72
1st Generation	2010	9	3.0	28	2360	5	11.8	51000	4.38
sub-total						***30***	***67.5***	***303575***	***3.79 ****
2nd Generation	after 2010	Z1	3.1	36	3900	4	16	73952	4.00 **
2nd Generation	after 2010	Z	3.1	36	3900	10	39	184880	3.42 **
2nd Generation	after 2010	Z	3.1	50	6500	10	65	323290	3.82 **
2nd Generation	after 2010	Y	3.1	36	3900	40	156	739520	3.42 **
2nd Generation	after 2010	Y	3.1	50	6500	40	260	1293160	3.82 **
2nd Generation	after 2010	X	3.1	36	3900	10	39	184880	3.42 **
2nd Generation	after 2010	X	3.1	50	6500	10	65	323290	3.82 **
sub-total						***123***	***640***	***3122972***	~ 3.50
GRAND TOTAL						***214***	***784***	***3709 GWh***	

Note: 1st generation consists of twin rotor monopile-mounted systems whereas 2nd generation will probably be moored floating systems with multiple rotors or large jacketed piles with multiple rotors which have yet to be developed in sufficient detail to obtain a realistic cost. It is assumed here that for 2nd generation systems to be successful they will at least have to equal or improve on the costs for first generation systems if extrapolated to the size to suit the depth of water.

* weighted average unit cost

** based on extrapolation from first generation model – note the larger systems seem less cost-effective since the first generation shows diminishing returns with such large rotors – it can be expected that a successful 2nd generation concept will have components more appropriately sized to keep unit costs competitive or (it is to be hoped) better than for 1st generation systems.

5. *Proposal for future development*

5.1 The rest of this report addresses future developments which are recommended in order to take the development of the Northern Ireland tidal energy resource forward. This is based largely on a programme to install a research and demonstration project using Marine Current Turbines Ltd technology at one of the suggested locations in Strangford Lough, within two to three years.

The demonstration project will serve largely to gain experience of the performance of tidal turbines under the local tidal flow patterns and assess the environmental impact of using such turbines in a sensitive location.

5.2 ***Table 4*** indicates that a demonstration project could be substantially completed by mid 2005 (i.e. design and applications for permissions). Further progression of a Strangford narrows project would depend upon the outcome of the QUB study but in theory up to 140GWh per year could be extracted from Strangford at economic prices.

A project could also be developed off the Copeland Islands. The first phase would be an initial project of 10 units (12MW) which could be followed by at least one extension project bringing the gross installed capacity to 27MW. The average generating cost for the first phase of a project off the Copeland Islands could be around 4.9p/kWh. A possible further extension is hypothesised in ***Table 4***, but lower velocities in the area concerned would increase the kWh price. However the Copeland Islands projects could yield between 106 to 138GWh per year respectively. These projects could be completed during the period 2006 to 2010.

The north east coast in particular off Fair Head (areas 7a and 7b) could host up to 45MW using first generation technology.

However a huge resource is present whenever "Second Generation" systems (capable of deployment cost-effectively in 40 to 80m of water depth) become available. Experience of first generation systems suitable for 20 to 40m water depth will yield the necessary know-how to develop suitable second generation systems.

Table 4 indicates that – on a <u>conservative</u> basis – the yield from second generation systems in the order of 3TWh per annum. The technical challenge to access this energy should not in any way be underestimated, but there are no fundamental reasons why it could not be exploited at some stage after 2010.

5. Conclusions and Recommendations

6.1 In conclusion, it would be feasible to install around 100MW of "first generation" tidal turbine power capacity in NI waters by about 2010, (up to 30MW in Strangford Lough, 27MW off Copeland and 45MW off Fair Head). However, understandable environmental concerns relating to those of innovative technology will have to be addressed if this level of capacity is to be realised. Developing suitable technology for exploiting the much larger resource in deeper water can only become available, if "first generation" systems are installed, studied and ultimately perfected. This will undoubtedly take to beyond 2010 to achieve but the significant tidal stream active around the Northern Ireland coastline could yield around 3TWh of clean predictable energy from such technologies

6.2 The results of this study confirm that tidal stream technology deployed in Northern Ireland is sufficiently attractive (compared with the other clean energy generation options) to justify the development of a small research and demonstration project as follows:-

6.2.1 Prepare a detailed study and costed plan/proposal for a research and demonstration site in Strangford Narrows to be used as a means to work up a second stage prototype and check the environmental impact of tidal turbines in a sensitive location and on a small enough scale to avoid conflict. This could also be a ground breaking project to demonstrate the technology and to gain "hands on" experience in relatively sheltered operating conditions. The study does however need to be in sufficient detail to include detailed site investigation (including flow measurements, engineering designs and geo-technical surveys) as well as the necessary environmental impact studies. Such a project could readily be monitored by Queens University Belfast which has a marine research facility at Portaferry, within line of sight of several possible locations for such a project.

Figure 20: An artist's impression photo-montage indicating the approximate appearance of a single turbine in the Strangford Narrows viewed from the old mill site above Portaferry. The most noticeable feature will be the wake which will be no more prominent than that from rock outcrops, buoys or small boats using the Narrows, however without the arrow to point it out it would be barely visible.

6.2.2. Subject to satisfactory results of the survey work, a project should be sponsored to develop a research and demonstration site in the Strangford Narrows (see ***Figure 20***) – this could readily provide a focal point for the development of tidal turbine technology and could provide NI industry with the opportunity to develop world leader status in the application of tidal stream technology. Queens University Belfast (at Portaferry) would be used as the land-base for monitoring the project.