The Feasibility of Salinity Gradient Technology for Ireland

An Initial Case Study for the River Suir

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Abstract

Under its EU obligations, Ireland has committed to generate 40% of its electricity demand from renewable means by 2020, and the objective of the minor dissertation from which this paper evolved, was to evaluate the feasibility of Salinity Gradient (SG) power technologies to contribute to this target. The country could be said to be currently over reliant on intermittent wind energy for its renewable quotient, and SG power could perhaps provide a local, continuous, base load power that would strengthen the security of national energy supply. At present, SG power, though the concept is long established, is a fledgling technology but one that is gaining international recognition and financially backed industry research and development. Ireland, with its long coastline in relation to its physical size and with many rivers draining into the surrounding seas, would seem to offer significant opportunities for harnessing the inherently extractable energy when fresh river and saline sea waters mix. As a background, a brief summary of the SG concept and the operational cycles of the most promising SG power generation technologiesare outlined. Solid baseline data in terms of sea salinity concentration, temperature and river flow for the main rivers of Ireland was drawn together, and then applied to three,academically sourced, SG potential estimation models. These outcomes were then balanced with the practical, physical aspects of coastal estuaries and tidal movements in order to quantify the country's SG potential. A specific case study, based on field measurements, for the River Suir in the south of the countryshowed the practical, geomorphological difficulties for SG power application in an Irish context. Overall, though there is a case to be made for consideration of SG technology for Ireland, it would appear that process technology efficiencies would have to be improved and natural, physical limitations overcome in order to make the proposition feasible in the long term.

Keywords

Salinity;Gibbs; Flow; Concentration; Osmosis; Electrodialysis; PRO; RED; Tidal; Limit; Bay; Estuary; River; Model;

Introduction

Fundamentally, when solutions of differing salinity concentrations mix, energy is released due to entropy; considered as a measure of the disorder of the mix in terms of change. The 2nd Law of Thermodynamics states that for any closed system, the entropy of the system will either remain constant or increase, and considering this concept for a closed mixing of differing salinity concentrations; the entropy increase can ultimately be used to generate electricity. Recognised for over half a century and termed Salient Gradient (SG) power, this has been defined as "the energy represented by the salinity concentration gradient between fresh water and seawater" [1]. The benefits of SG power can be summarised as:

- It produces no CO_2 emissions or other elements that contribute to climate change.
- It is non-periodic, unlike wind and solar power and so suitable for base load.
- It can be designed for large or small scale plants that are modular in layout.
- It is "clean and green" and costs are acceptable if supported by relevant subsidies.
- It can provide local power supply at population centres with low transmission losses.

SG power application was initially considered for areas where there are extremes of salinity concentration, as in the Dead Sea region of the Middle East[2], or where industrial waste waters have high brine content. There are two predominant types of SG technology in varying stages of current research and development; Pressure Retarded Osmosis (PRO) and Reverse Electrodialysis (RED), which will both be summarised in principle and are the basis of published theoretical models for estimation of electricity generation capacity.

Potential of SG Power

How much power that can be generated by an SG technology, is largely intuitively understood anddepends primarily on the magnitude of salinity concentration difference between feedwaters,the temperature and availability of feed waters.

Worldwide Potential

SG power is now recognised amongst the range of technologies in the ocean energy field and after the energy crisis of the 1970's, its potential was assessed and the possible energy production, from estuaries alone, was estimated at 2.6 TW globally; having the highest inherent energy density of all the marine renewables, as seen in Table 1[3].

TABLE 1 GLOBAL OCEAN ENERGY RESOURCES

Resource	Power	Energy Density
	TW	m
Ocean Currents	0.05	0.05
Ocean Waves	2.7	1.5
Tides	0.03	10
Thermal Gradient	2	210
Salinity Gradient	2.6	240

Stenzel and Wagner (2010) went further and considered the SG potential using the ultimate, practically exploitable or *Ecological Potential*, as in Table 2[4].

TABLE 2 SG GLOBAL ECOLOGICAL POTENTIAL

Continent	Ecological Potential	
	GWel	TWhel/a
Europe	5	39
Africa	6	50
Asia	21	166
North America	10	79
South America	20	159
Australia & Oceania	3	24
World	65	517

Theoretical Power Output

For any two saline solutions, the Gibbs energy of a system describes the potential difference between them and so reflects the energy that is available for work[5]. This amount of "free" energy available upon mixing is simply the chemical potential difference after mixing minus the chemical potential before, as seen from Equation 1; which is the starting point for estimation of SG electricity generation potential.

$$\Delta G_{mix} = G_b - (G_c + G_d)$$

EQUATION 1 GIBBS ENERGY OF MIXING

Where:

ΔG_{mix} = the change in Gibbs energy,J/mol
G_b= Gibbs energy of the brackish solution, J/mol
G_c =Gibbs energy of the concentrated solution,J/mol
G_d = Gibbs energy of the diluted solution, J/mol

Post et al. (2006) demonstrated the theoretical range of SG energy potential under ideal conditions, and as clearly seen in Figure 1[6], the magnitude of difference between solution salinity concentraions is the main driver.

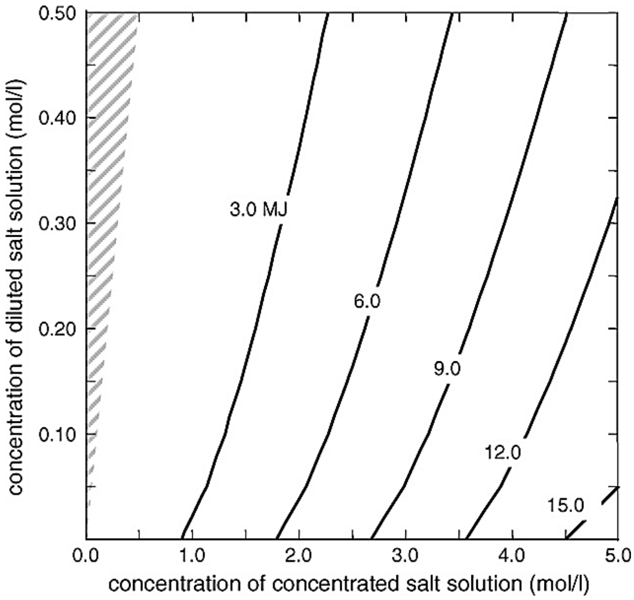

FIGURE 1 THEORETICALLY AVAILABLE SG ENERGY

Predominant Technologies

1) *Pressure Retarded Osmosis (PRO)*

In PRO, a semi permeable membrane, one that allows water (solvent) through but not salt (solute), separates fresh and saline waters as in Figure 2[7].

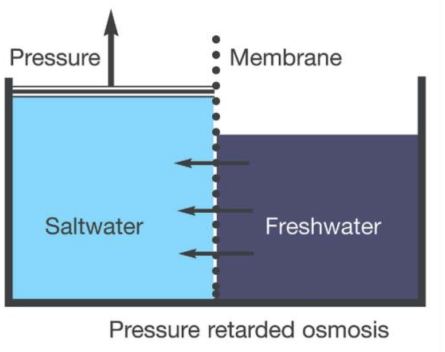

FIGURE 2 FUNDAMENTAL PROCESS OF PRO

- The chemical potential difference between the solutions causes transport of water from the diluted fresh water solution to the more concentrated salt water solution, resulting in a rise in level on the salt water side.

- If downward hydrostatic pressure is then applied to the concentrated salt solution side, the fresh water transport or flux through the semi permeable membrane will be partly retarded by this opposing pressure.

- This results in an increase in overall pressure on the volume of the concentrated salt water side, which can then be used to generate electrical power when released, via a standard turbine arrangement.

Since 2009, Norway's Statkraft, has developed and operated a prototype PRO plant outside Oslo, and the goal is to produce a financially viable 5 W/m^2 of electricity and to be competitive by 2030, with a levelized cost of energy (LCOE) of €50- €100 per MWh[8]. Currently, the main challenge to PRO commercial viability is improving membrane characteristics; such as increasing the water permeability of the membrane skin and optimizing the porous support[9].

2) *Reverse Electrodialysis (RED)*

In RED, salt ions move through ion-selective membranes from saline water to fresh water until the ion concentrations on both sides are equal.

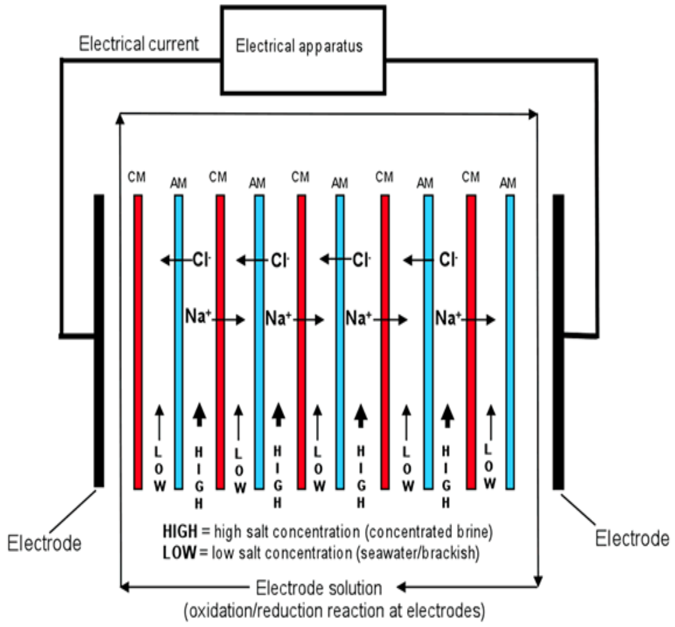

FIGURE 3 FUNDAMENTAL PROCESS OF RED

As shown in Figure 3 [10], the two solutions of different salt concentrations are brought into contact through an alternating series of stacked Anion Exchange Membranes (AM) and Cation Exchange Membranes (CM).The chemical potential difference causes the selective transport of ions and energy is then extracted through electrochemical reactions[11].

- The salinity gradient results in a potential difference over each membrane.

- The chemical potential difference results in the transportation of ions through the membranes from the concentrated to diluted solution.

- The negatively charged anions of Cl^- flow through the positively charged AMs to the anode where to achieve electro-neutrality oxidation reactions take place, releasing electrons.

- The positively charged cations of Na^+ flow through the negatively charged CMs to the cathode where to achieve electro-neutrality reduction reactions take place, thereby gaining electrons.

- The ionic current in the membranes is converted into electrical current by redox (reduction – oxidation) reactions at the electrodes in order to maintain electro-neutrality; a redox couple mitigating the transfer of electrons.

- Electrons released at the anode go through the external circuit to the cathode to produce an electrical current.

- As the chemical potential difference between the two differing solution concentrations generates the voltage over each membrane, the total number of membranes defines the overall potential of the system.

REAPower is an EU based autonomous publicresearch companywith an objective to prove the concept of electricity production through RED using brine and sea water and to develop the necessary components and processes by 2014. Through using normally conductive seawater (35 g/l) and very highly conductive brine water (300 g/l), the aim is to create a low resistance in the battery cell which would allow the use of thinner membranes and thus promote higher power density[12]. The main challenge to the commercial viability of RED is optimizing the system characteristic of internal resistance, mainly determined by spacer width between membranes[9].

Data Gathering

As data is always the foundation for any model, the availability of trustworthy data and physical parameters is vital and although information was gathered from a number of sources there was sometimes gaps in what was worthwhile using and the author had to use his own judgment and interpretation. Data gathered was based on:

- Estuary geomorphological type.
- River flow data.
- Water quality data (salinity, temperature and BOD) for sea and river/ estuary.
- Overall quality standard for both sea and river/ estuary waters.
- Estuary tidal limit and salinity limit estimation.

To note that at present, there are noalternative resources for SGpower generation in Ireland as no industries or facilities produce brine waste waters and salt mining is limited to road salt production.

Estuary Geomorphological Type

Particular to PRO (though applicable also to RED), Stenzel and Wagner (2010) laid down certain criteria that determine the suitability of coastal locations where the feed waters of river and sea meet. Besides the base factors of salinity, temperature and flow, they pointed out that the physical type of river mouth influences the structure of the salinity gradient locally. Prototype PRO plant has been pioneered in Norway and possible full-scale pilot facilities have been targeted for fjords, where the typical "V" like vertical profile of the river bed ensures a considerable depth of water. These are classed as salt-wedge type estuaries and have a distinctive vertical salinity gradient. Common to areas of low tidal impact, there is reduced mixing of river and sea waters as any such activity will generally only occur in the surface layers. Thus there is almost a distinctive boundary between feed waters of different salinity concentrations with both readily available for use within a short distance, [4].

Cooper (2004) conducted a preliminary, though substantial, analysis of the geomorphology of Irish coastal estuaries[13], which broadly points to the fact that there are no river mouth locations around Ireland which would correspond to the preferred "fjord like" characteristics. So at first glance, the physicality of Irish rivers and estuaries is not encouraging for the practical set-up of SG power plants but it was still considered worthwhile to forge ahead and evaluate other factors.

River Flow Data

Combined river flow information was sourced from the Irish state bodies of the Environmental Protection Agency (EPA) and the Office of Public Works (OPW), with the *long average flow* ultimately taken as the most suitable data[14].

TABLE 3 LONG AVERAGE FLOW FOR IRISH RIVERS

Main Irish Rivers – Long Average Flow			
River	**m^3/s**	**River**	**m^3/s**
Boyne	38.67	Feale	37.50
Liffey	17.10	Maigue	17.35
Avoca	22.03	Shannon	208.96
Slaney	38.80	Fergus	19.00
Barrow	46.53	Corrib	105.53
Nore	42.24	Moy	63.01
Suir	76.29	Ballysadare	16.28
Blackwater	87.37	Bonet	13.60
Lee	24.60	Erne	84.87
Bandon	21.57		
Laune	43.10	Total	1024.4

It was reasoned that this flow rate was reliable for sustainable SG power production and that taking the minimum *dry weather flow* would be overly cautious, as well as estimating very little generation capacity.

Water Quality Data and Standard

For quality data of fresh river and saline sea waters, the EPA provided the required details [15][16]:

- Salinity data for river estuary and sea bay.
- Temperature for estuary and bay.
- BOD for estuary and bay.

There is no direct data available for river salinity so the minimum value for the estuary was taken, which was judged to be when the saline sea water had no effect on the upstream fresh river water. For bay/ estuary salinity, the medium all year round value was taken, as this did not vary much throughout the year.The mean seasonal temperature was used for both winter and summer, as this was deemed sufficient for the initial assessment model calculation, to avoid over complication. Understandably, there were slight variations in salinity and temperature parameters around the Irish coastline and so in order to obtain acceptable values for modeling purposes, four locations were taken around the country (two west coast and two east coast) and from this combination of data, as seen in Table 4, averages were taken.

TABLE 4AVERAGE SALINITY AND TEMPERATURE DATA

	Galway	**Sligo**	**Dublin**	**Wexford**
Salinity	**g/l**	**g/l**	**g/l**	**g/l**
Est Min W	0.27	0.59	0.17	0.10
Est. Min S	0.25	0.14	0.16	0.10
Average	0.26	0.37	0.17	0.10
Bay Med W	28.74	31.93	32.92	
Bay Med S	31.44	32.92	33.30	31.80
Average	30.09	32.43	33.11	31.80
Temp	**^{0}C**	**^{0}C**	**^{0}C**	**^{0}C**
Est. Med W	7.88	6.60	6.90	8.20
Bay Med W	8.14	7.36	6.95	
Average W	8.01	6.98	6.92	8.20
Est. Med S	16.50	16.18	14.70	14.20
Bay Med S	16.44	15.75	13.40	15.40
Average S	16.47	15.96	14.05	14.80

The "W" and "S" refer to winter and summer, and averages from the four chosen locations were then combined to provide the following parameters for modeling:

- River/ minimum estuary salinity of 0.22g/l
- Bay/ sea salinity of 31.86g/l
- Winter temperature of 7.53^{0}C
- Summer temperature of 15.32^{0}C

Biochemical Oxygen Demand (BOD) was initially considered as an indication of the amount of Natural Organic Matter (NOM) in feed waters; which would influence pre-treatment facility requirements. Overall Irish estuary and bay water quality is generally very good and the BOD data is well within the standard required (<1mg/l), and so it was deemed unnecessary to factor this in at the SG power modeling stage.

Estuary Tidal and Salinity Limits

The limit of the maximum tide and so sea salinity influence up an estuary is very important from a practical infrastructural aspect [4]because the longer the fresh river or salt waters have to be pumped/ transported, the greater the cost of any SG plant. There are no official records for Irish estuary tidal or salinity limits and any information is largely anecdotal from fishermen, other river users and general local knowledge. From a quick survey of websites that mention such limits, many Irish estuaries experience maximum tides from 20km to even 50km upstream. This information, though hardly "scientific" is considered to be solid and trustworthy,being provided by enthusiasts, and is borne out for the River Sir case study detailed later.

ModelingSG Power Generation

Theoretical Gibbs Energy Calculation

Gibbs free energy can be expanded,as in Equation 2[5],and so seen to depend upon the mol fraction of salt in feed solutions, which is in turn determined by molar volume.

$$\Delta G_{mix} = \sum_i \left[c_{i,c} V_c RT \ln\left(x_{i,c}\right) + c_{i,d} V_d RT \ln\left(x_{i,d}\right) - c_{i,b} V_b RT \ln\left(x_{i,b}\right) \right]$$

EQUATION 2 GIBBS ENERGY OF MIXING EXPANDED

Where:
ΔG_{mix} = change in Gibbs energy,J/mol
$c_{i,c}$= component i, concentrated saline solution, mol/l
V_c= volume of the concentrated solution
R= universal gas constant, 8.314 J/mol K
T= absolute temperature, K
$x_{i,c}$= mol fraction of i, concentrated solution

Subscripts d and b refer to the dilute and brackish solutions respectively.Determination of the mol fraction is shown inEquation 3 below.

$$x_i = c_i V_m$$

EQUATION 3 MOL FRACTION

Where:
V_m = molar volume, m^3/mol

Using the gathered parameters for salinity and temperature under Irish conditions, values for the molar volumes of dilute (river), concentrated (sea) and brackish (mixed) waters were estimated on a "unit" basis. For "unit" volumes of 1.0m^3 for both river and sea feed waters, electricity generation potential was then estimated to be:

- 1.695MJ during winter/ colder months
- 1.742MJ during summer/ warmer months

In comparative justification, a salinity time series data set (average 34.31g/l) provided by the Marine Institute for mid Galway bay from May to December of 2009 is shown in Figure 4, along with the corresponding calculated Gibbs energy (average 1.84MJ).

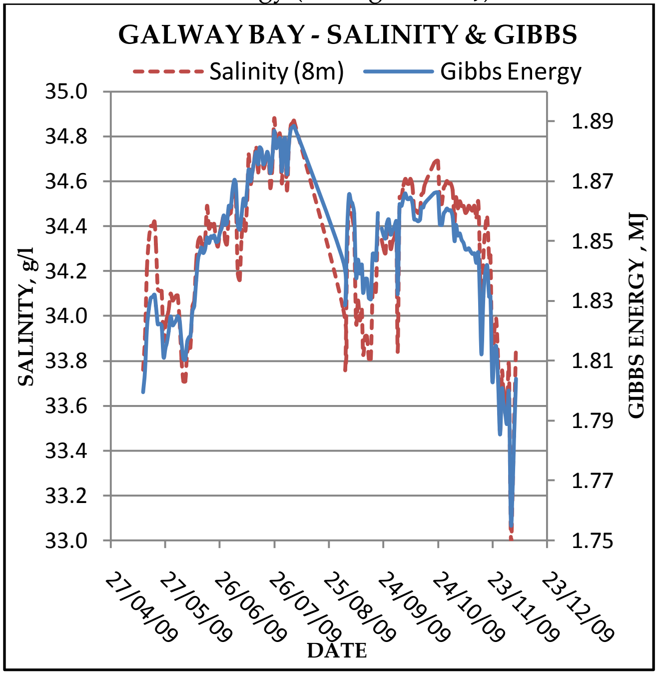

FIGURE 4 GALWAY BAY SALINITY & GIBBS ENERGY

From the variation in salinity over the months itis evident that the average concentrationis high, but overall this comprehensive data supportsthe 31.86g/l salinity parameter adopted (conservative). This gives an average Gibbs energy of 1.72MJ for power production and was the theoretical basis for estimation of Ireland's SG potential - as suggested by the following models.

Model 1 – Stenzel and Wagner (2010)

Starting with the Gibbs energy value of 1.72MJ, the long average flows for the main Irish rivers (as in Table 3) were simply multiplied up and the country's total *Theoretical Potential* estimated. Suitable operating variables and a capacity factor for a typical PRO process were then calculated so that a *Technical Potential* could be estimated. Finally, a reasonable factor was chosen for the maximum amount of river water that could be extracted without adverse consequences on the rivers environmental health or other usages, and termed *Ecological Potential*[4].

Model 2 – Yin Yip and Elimelech (2012)

This model states that although the Gibbs formula provides a theoretical estimation of the maximum free energy or work that can be extracted,dueto the 2ndLaw of Thermodynamics, all this is not useful. First of all presented was a reversible thermodynamic model for PRO verifying that it was equal to Gibbs free energy, then the maximum *Extractable Work* was derived, taking into account system friction losses and unutilised energy, and finally the *Ultimate Actual Work* from the SG process was estimated[17]. Osmotic pressure is calculated throughout the PRO process for both dilute river water (termed feed) and concentrated sea water (termed draw) and then thermodynamic and system efficiencies used in order to estimate the final electricity generation potential on a unit basis. So as to keep results in line with Model 1, the long average river flows were subject to the same practical extractable factor.

Model 3 – Post (2009)

RED was chosen as the preferred SG technology as it was maintained that this had better energy recovery potential than PRO, which looses a lot of potential output through process inefficiencies. This model also used Gibbs energy as a theoretical basis and from setting up a 200kW RED test rig, subsequent practical operation meant estimation of technical conversion losses due to system components of pumps, valves etc. was achieved. It is mentioned as awide proviso that river flows vary substantially and a factor of *Exploitable Potential*(extractable) was suggested (though no figure given), and so was taken as the same as for the previous two models.

Comparison of Model Results

Unfortunately, none of the models could be manipulated to replicate similar results,with the potential outputs dependingprimarily on the technical efficiencies chosen. For all models a capacity factor of 91% and an ecological/ exploitable potential of 10% was used. As seen from Table 5 below, the results for SG potential vary a lot but even the optimistic Post model predicts that only 0.52% of Ireland's Primary Energy Requirement (PER – excluding non-energy) in 2011and just under 10% of renewable energy contribution could be provided[18].

TABLE 5 IRELANDS SG GENERATION POTENTIAL

Model	SG Tech	GWh/a	% PES	% Ren
S & W	PRO	288	0.18%	3.34%
YY & E	PRO	432	0.27%	5.01%
Post	RED	845	0.52%	9.79%

Taking an average ouputof all the models estimates only a small amount of power, in the region of low single digit MW values for the majority of the 20 main rivers modeled. Only the river with the largest flow volume in Ireland, theShannon,is predicted to have a generation potential of over 10MW.

River Suir Case Study

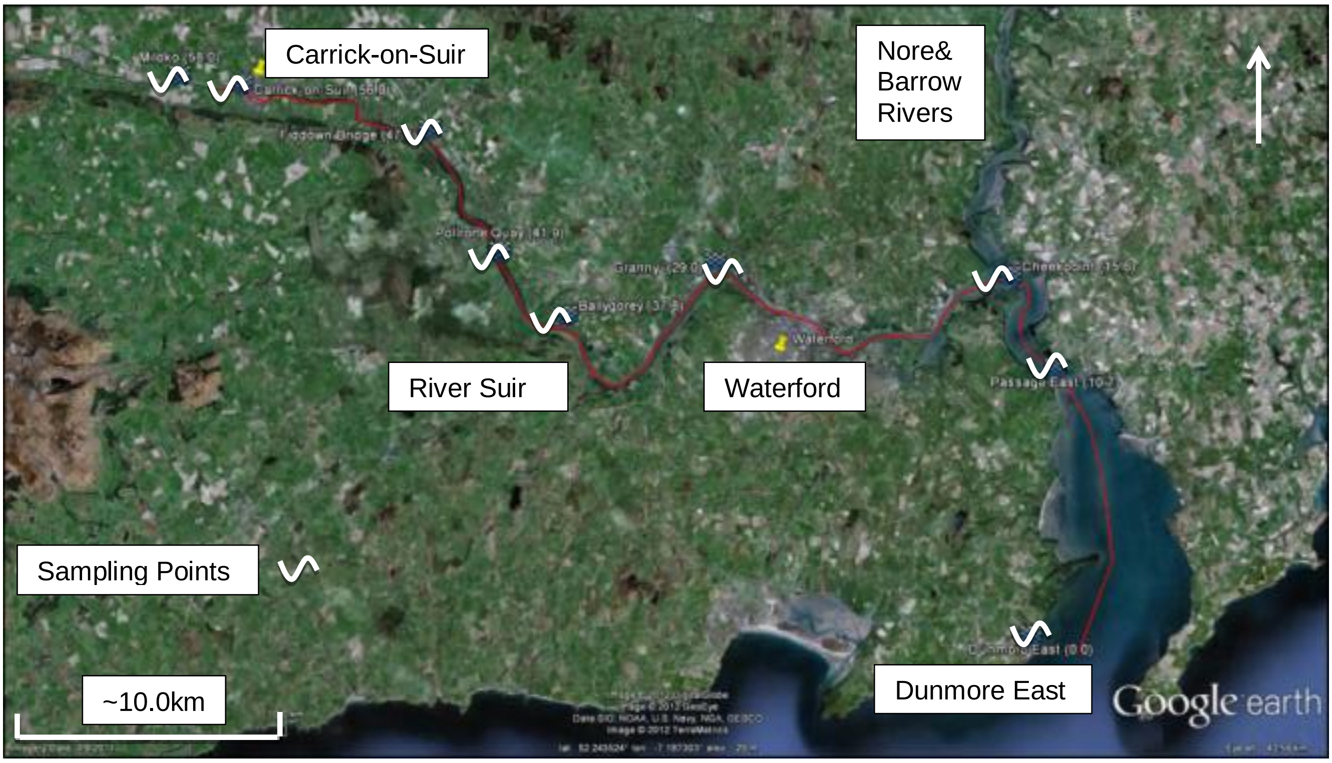

FIGURE 5SAMPLING POINTS ALONG THE RIVER SUIR FOR SURVEY 1 ON 21/08/2012

Background

In order to demonstrate how tidal movements and subsequent mixing in shallow estuaries affectthe viability of SG power for Irish rivers, a case study for the river Suir flowing through Counties Tipperary and Waterford was undertaken. The Suir is one of the more substantial rivers in the country and it joins up, just after Waterford city,as in Figure 4 above, with the Nore and the Barrow rivers (already joined) to flow to the sea at Dunmore East, and together they are known as the “Three Sisters”. The high tide influences the river Suirto just past the town of Carrick-on-Suir where the limit is commonly known as reaching the Miloko factory. Taking approximate distances (from Google Earth) starting downstream from Dunmore East, Carrick-on-Suir is about 56 km upstream.

As the potential for SG power is mainly dependent on the difference in feed water salinity concentrations, the influence of brackish tidal waters is important to understand. To this end it was decided to measure the salinity values along the length of the River Suirfollowing the tidal movements. After reviewing the length of the river from Carrick-on-Suir to the coast, sampling points were chosen at practical locations where access to the water was easy; by public roads and preferably at piers etc., and ensured a more or lesseven spacing of distance. The plan was to follow the tidal movements as predicted by the Irish National Tide Gauge Network[19], using Dungarvan as the nearest applicable station, sampling at the individual locations, thus painting a picture throughout the day.

Survey of 21/08/12

A start was made at Carrick-on-Suir to coincide with high tide in the morning,and salinity, conductivity and temperature readings were taken and then the ebbing tide was followed downstream to Dunmore East, further sampling along the way. Upon reaching the open sea at more or less low tide, the survey was repeated by following the river back upstream to Carrick-on-Suir. This was not an ideal scenario as it did not provide a “snapshot” of an instant in time along the river; which would give the ideal salinity profile. Such a survey would have requiredthe coordinated effort of many measurements at the same time and was beyond the scope of thedissertation project, but as along as measurements were taken as quickly as possible in succession within a reasonable timeframe; then it was judged that the salinity profile produced would be satisfactory. The EPA kindly provided a quality salinity/ conductivity measuring The flow across a river section naturally varies because of turbulence and drag due to surface roughness and any vegetation, and this may affect the salinity concentration and temperature, but for the purposes of this study it was taken that these were uniform across the river, as measured from the side bank (no boat was involved). It was easier to take measurements at high tides rather than low tides as the flow was higher and more accessible. And of course it would have been beneficial if the survey had coincided with an annual high tide in order to know for certain the tidal limit past Carrick-on-Suir, and the associated salinity limit; but this did not coincide with sampling in the month of August 2012. Table 6 shows the salinity measurements taken along the River Suir.

TABLE 6 RIVER SUIR SURVEY - 21/08/12

Location	Dis.	Time	Depth	Salinity
	km		m	g/l
Carrick-on-Suir	56.0	07:48		0.28
Fiddown Bridge	47.5	08:33		0.27
		08:47		0.26
Pollrone Quay	42.0	09:05		0.24
Granny	29.0	09:37		1.70
Cheekpoint	15.5	10:30	0.0	15.55
			1.0	16.03
			2.0	16.06
Passage East	11.0	11:10	0.0	17.85
			1.0	19.01
			2.0	19.25
Dunmore East	0.0	11:40		27.70
Passage East	11.0	12:47		9.53
Cheekpoint	15.5	13:08		7.76
Granny	29.0	14:07		0.23
Pollrone Quay	42.0	14:30		0.22
Fiddown Bridge	47.5	14:52		0.25
Miloko	58.0	15:48		0.27

It is noticeable that where the river was deep enough to enable readings at different depths to be taken; the salinity expectedly increases with depth. Figure 5 illustrates these measurements by using a polynomial (least squares method) trendline for the best-fit option. The salinity of course decreases in the upstream direction and there seems to be no real difference between high tide (HT) and low tide (LT) data. The

device in a *WTW Conduktometer LF 191* model.

first evidence of salt (above standard background concentration) is at Granny for high tide and the highest value of 27.7g/l at Dunmore East is not quite the expected 32.0g/l for pure sea water as perhaps, sampling was done by the shore and not farther out into the sea body.

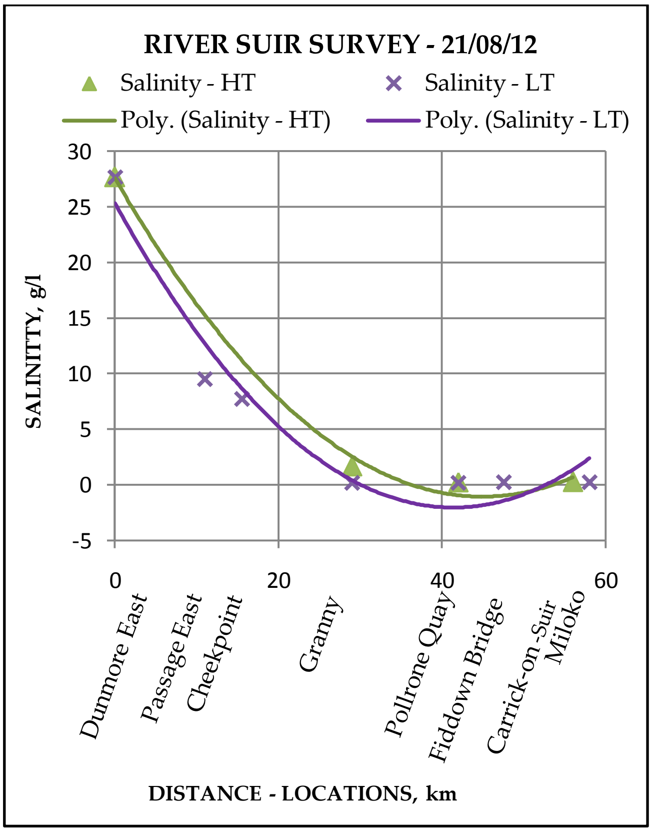

FIGURE 6 RIVER SUIR SALINITY PROFILE - 21/08/12

Note: where there were more than one salinity measurements (with depth) the 1m depth was used.

Survey of 23/08/12

For the first survey,the high tide did not extend up as far as Carrick-on-Suir but this did not matter as the main criteria for SG potential is an accurate location of the salinity limit; so a second survey was conducted to try and find the limit of salt water penetration upstream. As the following day's tides were subsiding slightly, it was decided to meet the high tide at FiddownBridge and start the survey from there.Another sampling point location at Ballygorey was introduced because in talking to a local fisherman, it was learnt that, although anecdotally only with no proof, local knowledge estimated that even at high tides, the saline sea water only penetrated up as far as this location on the river. On the day, with the tide ebbing, no salinity could be found at Ballygorey and again was not encountered until the Granny location.

Figure 6 shows the reduced sampled river length

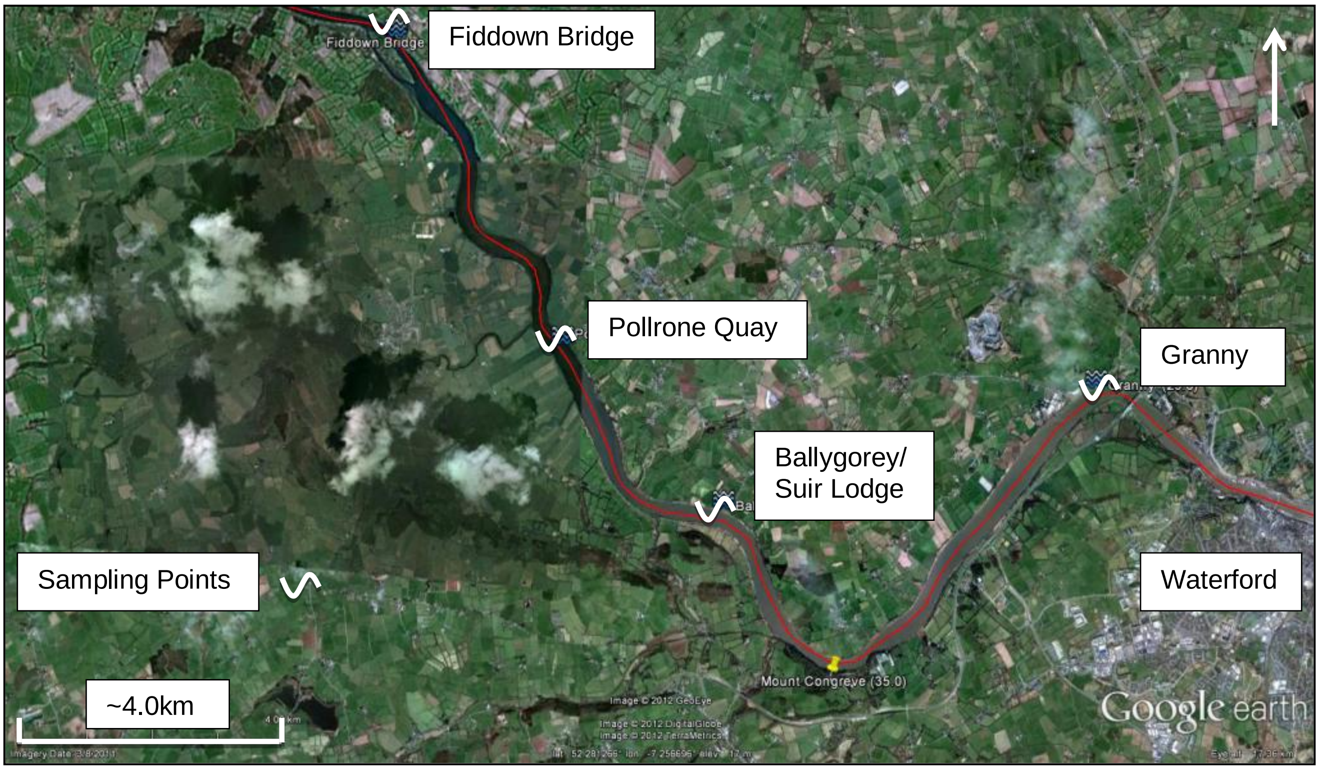

FIGURE 7 SAMPLING POINTS ALONG THE RIVER SUIR FOR SURVEY 2 ON 23/08/2012

And Table 7 shows the results of the second survey.

TABLE 7 RIVER SUIR SURVEY - 21/08/12

Location	Dis.	Temp	Depth	Salinity
	km	^{0}C	m	g/l
Fiddown Bridge	47.5	14.9	0.0	1.03
			1.0	0.28
	47.5	14.9		0.27
	47.5	15.1		0.27
Pollrone Quay	42.0	16.1		0.26
Granny	29.0	16.8	0.0	7.83
			0.5	8.90
	29.0	16.9	0.0	8.55
			0.5	9.45
Ballygorey	37.8	16.8	0.0	0.99
			0.5	0.25

These results plotted in Figure 8 (using the same least squares polynomial trendline); show a similar salinity pattern as in Figure 6. The temperature noticeably increasing towards the sea is something which was merely observed and not investigated further.

Comparison with EPA Survey Data

The EPA regularly conducts comprehensive river surveys that include both salinity and temperature measurements and such data (not published but provided in spreadsheet form) was separated out in order to support both the field surveys.

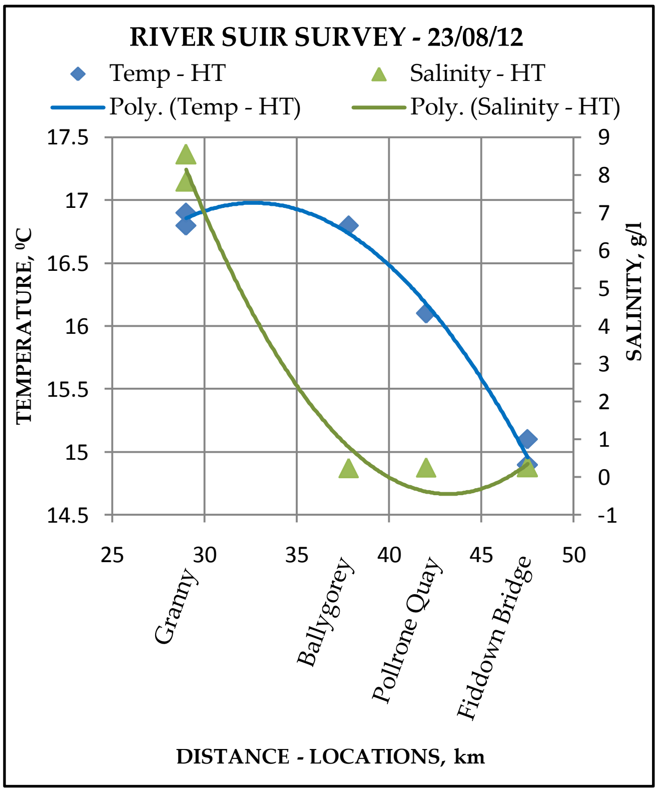

FIGURE 8 RIVER SUIR TEMP & SALINITY PROFILE - 23/08/2012

EPA data supported the survey findings that Granny seemed to be the usual location where saline sea water was first measured, as in Figure 8.

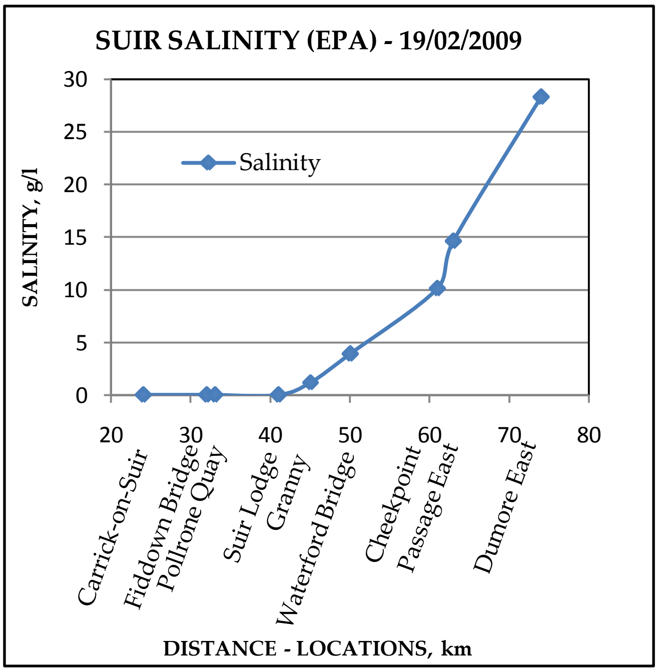

FIGURE 9 EPA MEASURED SUIR SALINITY – 19/02/2009

Small amounts of salt were also found father upstream than Ballygorey at Pollrone Quay (0.77g/l on 19/07/2010) and even at Fiddown Bridge (0.50g/l on 29/09/2003). Overall, this confirms that Ballygorey/ Suir Lodge can be confidently claimed to be the location of the salinity limit up the Suir River under the vast percentile of circumstances for the combination of river flow, sea tidal activity and the prevailing weather.

Conclusions

The worldwide resource for SG power is vast with certain regions considered more advantageous due to substantial river flow volumes and physical geomorphological aspects, but much of the theoretical energy is estimated to be lost through the technical conversion processes and limited by how much water you can actually take out of a living river, in order that it is not negatively affected in the long term. The current status of the most promising PRO and RED technologies suggests that the processes are moving beyond the prototype phase and with gathering international industry and research support, the future is promising but economically commercial operation will probably not materialize for 15 – 20 years at least.

For the case of Ireland, only the main rivers (> 10m3/s) were considered as a starting point to evaluate the broader picture of power generation obtainable. Three models, though they started off with the same principle of Gibbs theoretical energy, provided differing results (Table 5). So perhaps taking an average value is the best approach for SG power estimation. At around 500GWh/a, this is a small amount of power and unless process plant is proved reliable and robust as a base-load option, with the possibility of increase in efficiencies to track the inevitably increasing electricity demand, it is hard to see SG power as a largely contributing to Ireland's PER. Coupled with this, is the natural disadvantage due to the geomorphological aspects of Irish rivers and estuaries, which are all tidal and well mixed to some degree. Meaning that due to the lack of distinct coastal boundaries between fresh river and saline sea waters, tides and salinity extend far upstream in shallow river beds, as largely borne out by the River Suir case study.

As a first assessment, the potential of SG power for Ireland appearslimited and uneconomical, from an infrastructural and capital investment point of view, but is nevertheless worth being kept in mind as a part of the renewable energy supply mix and further work and research is to be considered.

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REFERENCES

[1] A. Jones and W. Finley, "Recent Developments in Salinity Gradient Power," in *OCEANS 2003*, San Francisco, 2003.

[2] S. Loeb, "Production of energy from concentrated brines by pressure-retarded osmosis : I. Preliminary technical and economic correlations," *Journal of Membrane Science*, vol. 1, pp. 49-63, 1976.

[3] G. Wick and W. Schmitt, "Prospects for Renewable Energy from the Sea," *Marine Technology Society Journal*, 1977.

[4] P. Stenzel and H. Wagner, "Osmotic Power Plants: Potentail Analysis and Site Criteria," Bilbao, 2010.

[5] K. Nijmeijer and S. Metz, "Salinity Gradient Energy," in *Sustainability, Science and Engineering*, Twente, Elsevier, 2010, pp. 95-139.

[6] J. Post, J. Veerman, H. Hamelers, G. Euverink, S. Metz, K. Nymeijer and C. Buisman, "Salinity-gradient power: Evaluation of pressure-retarded osmosis and reverse electrodialysis," *Journal of Membrane Science*, no. 288, pp. 218-230, 2006.

[7] S. Skilhagen, "Osmotic Power - "A New, Renewable Energy Source"," Washington, 2008.

[8] S. Skilhagen, J. Dugstad and R. Aaberg, "Osmotic power - power production based on osmotic pressure difference between waters with varying salt gradients," *Desalination*, no. 220, pp. 476-482, 2007.

[9] J. Post, "Blue Energy: electricity production from salinity gradients by reverse electrodialysis," Wageningen University , Wageningen, 2009.

[10] REAPower, "Reverse Electrodialysis Technology," 2010. [Online]. Available: http://www.reapower.eu/index.php?option=com_content&view=article&id=4&Itemid=3. [Accessed 05 08 2012].

[11] P. Dlugolecki, "Mass Transport in Reverse Electrodialysis for Sustainable Energy Generation," Leeuwarden, 2009.

[12] I. Genne and E. Brauns, "Reverse Electrodialysis Alternative Power, Energy Generation and Desalination: The REAPower Project," Brussels, 2011.

[13] J. Cooper, "Geomorphology of Irish Estuaries: Inherited and Dynamic Controls," Santa Catarina, 2004.

[14] M. Mac Carthaigh, "OSPAR Convention - Comprehensive Study of Riverine Inputs, Hydrometric Data for 2009," EPA, Dublin, 2011.

[15] M. McGarrigle, J. Lucey and M. O Cinneide, "Water Quality in Ireland 2007-2009, Chapter Five Estuarine and Coastal," EPA, Dublin, 2010.

[16] M. McGarrigle, J. Lucey and M. O Cinneide, "Water Quality in Ireland 2007-2009, Chapter Three Rivers," EPA, Dublin , 2010.

[17] N. Yin Yip and M. Elimelech, "Thermodynamic and Energy Efficiency Analysis of Power Generation from Natural Salinity Gradients by Pressure Retarded Osmosis," *Environmental Science & Technology*, vol. 46, no. 9, pp. 5230-5239, 2012.

[18] SEAI, "2011 Energy Balance," 2012. [Online]. Available: http://www.seai.ie/Publications/Statistics_Publications/Energy_Balance/. [Accessed 02 01 2013].

[19] Marine Institute, "Irish National Tide Gauge Network," 2012. [Online]. Available: http://www.marine.ie/home/services/operational/oceanography/TidePredictions.htm. [Accessed 25 07 2012].