PATHWAY TO ENERGY GENERATION FROM MARINE TIDAL CURRENTS IN NEW ZEALAND'S KAIPARA HARBOUR

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SUMMARY

Crest Energy Limited plans to generate, subject to acquisition of Resource Consents, ~200 MW of electricity from flood and ebb tidal currents in the Kaipara Harbour, Auckland, New Zealand, by submerging some 200 marine turbines into an 18-km^2 area of the harbour's entrance channel.

Tides generated by the sun, earth and the moon's gravity are predictable for centuries and therefore effectively ensure an infinite supply of sustainable energy. The Kaipara Harbour's tidal currents flow four times daily, exchanging at each spring flood or ebb movement a tidal prism of ~1,990 million cubic meters at velocities of <2.4 meters per second. It is anticipated, given the available currents, that each turbine will generate ~1.2 MW [peak]. Energy produced is to provide substantial generation north of Auckland's isthmus, and thereby improve diversity and security of supply to the Auckland and Northland regions.

Turbines mounted on gravity-based foundations are to be located strategically throughout the harbour's channel. The size and position of individual turbines will be optimized for power output, based on the harbour's bathymetry and currents. The turbines, linked in arrays of around 30 units, will generate direct current (DC) for transmission via two buried, sub sea cables to a substation located adjacent to the Hoteo River in the harbour's eastern catchments. The high voltage DC power is to be converted at the substation to high voltage alternating current (HVAC). The latter is to be transformed commensurately to match the existing 33-, 110- or 220-kV transmission systems for distribution through the networks.

The design of the marine turbine arrays and the transmission cables engage ecological principles, to mitigate effects on environmentally-sensitive areas of the harbour's channels and estuaries. The "Assessment of Environmental Effects and Resource Consent Applications" were lodged in July, and supplemental information in November, 2006, with the Northland Regional Council, Auckland Regional Council and Rodney District Council, for purposes of the Resource Management Act and consultation with Tangata Whenua and other interested parties.

Introduction

Sustaining and securing electricity supplies to meet Auckland and Northland's ever increasing consumer demand are constrained by the region's dependence on transmission from the far south, up through South Auckland's narrow isthmus. Transpower has assessed the transmission constraints on lines bypassing Auckland at 986 MVA[5]. Transmission demands could exceed this level during periods of peak loads by the year 2013. Such limitations could be offset by developing more substantial generation capacity north of Auckland to supplement energy produced by the Wairau hydroelectric dam (3.5 MW) and Ngawha geothermal field (9.5 MW). Substantial generation capacity north of Auckland would have three benefits: 1) help meet peak demand in regional networks; 2) reduce transmission demand on electricity networks passing north of Auckland; and 3) provide Northland with secure supply while incurring lower transmission losses and therefore supplying consumers at greater efficiency. The regional goal of long-term sustainable electrical power, given recent government mandates, needs to be derived from renewable resources – hydroelectricity, geothermal, solar, wind, biomass, wave and/or tidal energy.

Generating power in New Zealand from predictable tidal streams and ocean currents is feasible given the recent development of efficient marine turbines. Turbines submerged below the harbour's surface would have negligible impact on the environment while offsetting detrimental greenhouse gases accumulating from thermal power generation[10]. Two commercial turbines have reached advanced stages of development; the twin-bladed, monopole-based turbine by Marine Current Turbines, Ltd, Bristol, and the Venturi-ducted, marine turbine of Lunar Energy/Rotech, Hessle, England. The latter turbine with its gravity base is designed to rest on the harbour floor, submerged entirely below the surface. In this way, Lunar Energy's turbine mitigates auditory and visual effects on the environment.

Crest Energy, having evaluated world-wide, marine turbine development, then undertook an initial review of tidal resources available throughout New Zealand[7,8]. Based on this review, focus was placed on assessing tidal resources in the Kaipara Harbour, by quantifying its bathymetry, tidal currents and marine biota. Prerequisites were set regarding turbine design most suitable for the Kaipara environment. This information led to the lodging of resource consent applications for installing 200 marine turbines in a designated area of the Kaipara harbour's main channel.

Rationale

Crest Energy applied the following criteria for selecting renewable resources north of Auckland's isthmus:

Firstly, electricity generation is required north of Auckland to meet local demand and to mitigate constraints imposed by the narrow isthmus immediately south of the city[5]. Secondly, generation is needed closer to Northland for diversity and security of supply and capping local electricity costs. Demand growth for the Vector Rodney, Northpower and Top Energy's electricity networks is estimated to be 3-5% per annum. Thirdly, renewable energy needs to be harnessed to offset thermal power generators producing harmful green house gasses. Meeting these requirements has been constrained in the past by the region's 'limited' energy resources. However, with the development of tidal turbine technology, it now is possible to exploit the substantial tidal resources of Auckland and Northland.

Tidal volumes and current velocities have been determined for most harbours throughout New Zealand (Table 1)[7,8]. The largest – Kaipara, Manukau, Hokianga, Whangarei and Waitemata Harbours - are located at or north of Auckland City. Of these five, the spring tidal flows of Kaipara Harbour are the greatest at 1,990 million cubic meters per tidal movement or ~7,960 million cubic meters daily. The Kaipara Harbour's tidal prism volume, by comparison, is ~2-fold greater than that of Manukau Harbour, the second largest in New Zealand.

General Features of the Kaipara Harbour

Kaipara Harbour is one of the southern hemisphere's largest (~947 km^2) with extensive catchments feeding five rivers and over a hundred streams[6]. The largest tributaries, the northern Wairoa, Otamatea, Oruawharo, Tauhoa (Channel) and southern Kaipara converge into the harbour's very large entrance channel. The latter extends westward ~18 kilometers to curve into the Northern Channel and thereafter the Tasman Sea (Fig. 1). The main channel has depths ranging down to 50 meters, and is 5.6 km across at the widest point. Its outer reaches are bounded by the extensive Southern Shoals and associated sand banks. These shoals are penetrated by a narrow and relatively shallow South Channel.

The southern shoals continually accumulate sand transported northward along the coast primarily from the Waikato River. Sand movement across the delta is aided by the prevailing coastal currents and southwest winds. Most sand carried into the harbour cycles out again through the main channel and thereafter northwards along the west coast. Some sands sediment onto the extensive sand flats within the inner harbour as current velocities drop to 0.3 m/sec.

Harbour Bathymetry and Current Surveys

Surveys of the Kaipara Harbour's bathymetry and currents during successive spring tides were undertaken during January/February 2006, under the direction of Dr. Kerry Black, Dr. Shaw Mead and associates (ASR), on the 55' Seatow tug, Herenui, and a 10-meter, rigid-hulled, inflatable cabin vessel, equipped with 200-hp outboard motors.

Current directions and velocities were quantified in two-meter bins during flood and ebb tides, by using a vertically-directed, Sontec Acoustic, Doppler Profiler (ADP6) deployed on the harbour floor at selected locations (Fig. 1). The ADP6 meter was mounted on a stand (>350kg) for stability in the high-velocity currents. Measurements were recorded at nine locations; four during complete and five during partial tidal cycles. The current meter was transferred to a new site during slack tide.

Bathymetry measurements are consistent with a main channel ranging in depth from 30 to 50 meters at MLWS. The channel's width varies throughout its length (Fig. 2). Generally, the channel floor is smoothly contoured throughout its length, with only a few marked elevations evident. By contrast, contours of the sand banks forming the southern shoals vary considerably.

Currents passing through the main channel are consistent with an ebb-dominated harbour where the ebbing current velocities exceed those occurring during a flood tide. Peak ebb current velocities range up to 2.4 meters per second at the western extremities of the channel. Generally, though, the current velocities range from 1-2 meters per second. Moreover, velocities are comparable at different depths throughout the water column until frictional forces along the harbour floor slow the currents measurably. The direction of flood tidal currents is not always 180° from those of ebbing currents. This is particularly the case for currents occurring in the area of confluence of the Wairoa and Kaipara Rivers at the inner region of the harbour's main channel.

Turbine Deployment in the Main Channel

Depths and currents within the Kaipara Harbour are suitable for the deployment of marine turbines, particularly those based on the Lunar Energy/Rotech Energy turbine design (Fig. 3). This turbine, with its symmetrical Venturi shrouds and central rotor, captures and accelerates flood and ebb currents. Efficacy of the Lunar Energy/Rotech turbine is enhanced by currents entering the turbine at an oblique (yaw) angle through 25°-30° from perpendicular (*See*: *www.lunarenergy.co.uk*).

The power output of marine turbines, for their size, is considerably greater than wind turbines, because water is non-compressible and 832-times denser than air.

The turbines are to be deployed throughout the main channel in sectors of greatest current velocities and depths to maximize power output (Fig. 4). Both conclusions are drawn from the Power equation, $P = \frac{1}{2} d A V^3 \epsilon$, where: d = density of seawater (1.025 kg/m^3); A = swept area of blades (m^2); V = velocity of currents; and ϵ = power coefficient. Thus, current velocity and blade radius are the two major parameters determining turbine power output. While current velocity *per se* is determined by tidal forces, current flow through each turbine would be enhanced substantially by the Venturi shrouds, yaw angle (see above), and the relative position of turbines to each other. Given the number of parameters determining marine turbine power output, computer-based analyses are being applied to size and locate turbines to ensure optimal efficacy.

Crest Energy, by lodging resource consent applications with the Northland Regional Council – the lead agency, Auckland Regional Council and Rodney District Council in July 2006, and related appendices in November 2006, has gained the first-right to install marine turbines into the Kaipara Harbour (*See* www.crest-energy.com *for Resource Consent applications*). The designated area of 18 km^2 comprises the greatest currents and depths of the harbour's main channel.

If the resource consents are granted by the Commissioners following the Council Hearings, now scheduled for February/March 2007 (and by the subsequent Environmental Court rulings), the area shall be designated a no-anchoring and no-fishing zone. The area is likely to be marked by 'special cardinal' markers to signify the location of the turbine arrays. In effect, the zone would become a marine reserve thereby enabling replenishment of the harbour's currently depleted fish stocks. The sub sea transmission cables typically would be indicated by shore-based markers.

Notably, the turbine arrays would have a relatively long life-span. The turbine's cassettes along with the generator (Figs. 3 and 4) would require servicing every 4-5 years, whereas the Venturi shrouds and base, and the sub sea cables would have considerably longer life spans.

HVDC Cable Transmission

The DC-generated electrical power shall be transmitted eastward under the harbour floor via two, shielded, polymer-insulated, transmission cables(1,3,4). This route is preferred to transmission overland for the relatively long distances through the North Head and/or South Head, neither of which currently have suitable transmission networks. Moreover, the sub-sea cables shall be shielded to mitigate EMF emissions, and also be invisible, in keeping with the completely submerged profile of the turbines. The cables would be laid in close proximity to each other, within the same sub-sea trench, so as to balance out small magnetic fields caused by the passage of steady-state currents.

The choice of HVDC transmission over an equivalent HVAC circuit is justified for several reasons(1,3,4). For DC these include: 1) electrically safer, 2) lower capital costs due to the simpler, bipole, cable structure; 3) lower charging currents and greater power transmission capabilities during the moment of circuit connection; 4) greater transmission efficiency over long distances; 5) distribution of high converter costs when transmitting over increasingly longer distances; and 6) complete mitigation of low EMF emissions by cable shielding and burial. EMF mitigation is important to avoid effects on elasmobranches (sharks, skates, stingrays) known to populate the harbour.

The ability of HVDC transmission to use the full cross-sectional area of the conductor (*cf.* AC concentrates at the conductor's periphery), allows the use of relatively small conductors in HVDC systems. For example, <500MW can be transferred by using ±150kV-rated, bipole cables, with 2,000 mm^2 copper conductors as two, single-cored cables each of ~112-mm diameter, weighing ~42 tonnes per km(2). Transpower's Cook Strait DC Link consists of 80 km, 1,400 mm^2, copper, bi-pole cables rated for 500 MW at 350 kV.

The two HVDC cables can be laid in separate trenches, or in a common trench, separately or co-wrapped. Conductor core sizes of 1,000 mm^2 and 2,000 mm^2 are used for circuit power ratings of 245MW and 295MW, respectively, at ±75 kVDC per pole. The proposed operating voltage for the HVDC bi-pole, submarine transmission circuit will be +/- 75kV DC with a continuous maximum rated current of 1,550A per pole. The cable's overall diameter is expected to be around 160 mm and weigh ~26 tonnes per km. The submarine cables will be laid directly by a submersible, drag-line, mole-plough [or high-pressure water jet] into the soft mud/sand seabed from the turbine arrays to the shore-based, indoor, converter station.

The HVDC, bi-pole, submarine cable design [yet to be finalised] would consist of one or more, stranded wire cores covered with several impervious concentric layers (Fig. 5). Each cable will be insulated with an XLPE layer and swelling tapes, shielded with copper foil, armoured with steel wire, and sheathed(3). The outer covering can be HDPE or polypropylene and will serve to protect the steel wire armour during installation. Each cable will incorporate a thick wall, copper tube conveying pressurised dry-air, primarily for hermetic sealing of the submersible HVDC switchgear junction box and individual generator module cassettes, as well as heat dissipation. The copper air tube will house a small MDPE tube carrying 12 single-mode, optic fibres, to be used for relay protection signalling, SCADA & Video data communications, and thermal [OTDR] trace wire would be embedded within the cable's central vortex.

Interconnection among Turbines

Turbines (<30) within an array will be interconnected in a series network, rather than by individual connections, to form a ring main circuit on the seabed (Fig. 6). Each array will be connected via the ring main cables to a centralised air tight, gas-pressurized, bus-coupler switchboard or 'junction box'. This will enable a turbine array to be isolated either singularly or in groups as required for automatic fault clearance operations and safety reasons for routine maintenance and extraordinary generator module repairs.

Arrays of marine turbines will be clustered into six, 10-km long, ring-main cables with an operating voltage of 150kV [+/-75 kV DC] and a maximum rated current of 350A per ring. Each cable's overall diameter will be ~80 mm and weigh ~5 tonnes per km. Cables connecting the turbines will be laid directly on the sea bed and held down by concrete block ballasts at a spacing of 30m to 50 m. The ring main cables will carry pressurized dry air for hermetic sealing, and optic fibres for relay protection, instrument data, video and communication signaling between the individual generator modules.

Land-based Sub Station

The HVDC array-to-shore transmission schemes for the CREST Project will incorporate a shore-based DC to AC Converter station. Key engineering details for array-to-shore transmission will be:

- Point-of-supply with the transmission and distribution networks (33 kV or 110 kV), which has adequate capacity to accept Crest's oscillatory power curve. Electrical export cables will run underground from the substation to connect with nearby 33-kV or 110-kV overhead lines or, in the future, with the adjacent 220-kV transmission lines;
- Indoor and outdoor switchgear and step-up, power transformers at an onshore substation;
- Land DC cables via a shoreline jointing chamber into the HVDC converter station;
- Cabling within an array will connect each turbine-gearbox-generator cassette unit;
- Turbines, each having its own generator, and control and protection systems, will have links to a supervisory control and data acquisition (SCADA) system via single-mode, optic fibres.
- The main 160-kV DC switchgear will combine primary and back-up electrical protection, with an ability to automatically reconfigure the marine turbine arrays remotely by utilizing pneumatic-operated, spring-charged, circuit breakers incorporating vacuum technology and SF6 gas-pressured, welded tank enclosures with duplicate 110-kV DC duty and standby inter-trip protection, controls, video surveillance alarms and DC-tripping banks.

Construction and maintenance will require suitable vehicular access via the property's driveway. Provision will be made for utility services; telecommunications, power, water, fire alarms and drainage within the leased area. During construction, the substation will be sound-proofed and sheathed to reduce noise and electromagnetic fields (EMF), respectively. The converter station and transmission substation surroundings will be contoured and landscaped.

The land-based, DC-to-AC converter station will be enclosed and rated at 204 MW, by utilizing Voltage Source Converter [VSC] self-commutating IGBT [Inverted Gate Bipolar Transistor] valve technology. This would include water-air-cooled heat exchangers, pumps and HVAC output waveform, along with the necessary mechanical fan cooling.

The substation facility will house HVDC-HVAC power controls, primary and back-up relay protection, revenue and check metering, SCADA and HMI systems, VHF-RT and DMR communications, alarms, fire protection and suppression equipment cabinets, low-voltage, AC mains and DC essential power and control panels, process air-filtration, and drying and compressor plants.

Grid Exit Point [GXP] Inter-Connection

Options for connecting to the national grid include linking to: 1) Transpower's 110-kV or 220-kV, overhead lines adjacent to the Kaipara Coast Highway (Route 16); 2) Vector's 11-kV line and upgrading it to either 33 kV or 110 kV; and 3) North Power's 33-kV line through Maungatoroto.

Connection from the HVDC Converter station can be interfaced directly with Transpower's system at the proposed Glorit 110/220-kV substation. An outdoor switchyard is planned to intercept and bus-couple to Transpower's existing dual-circuit, 110/220-kV transmission lines located immediately westward of the proposed substation site.

Construction of the new GXP substation will comply with Transpower's standards for outdoor, high voltage, switching stations and substations. The connection, operational and maintenance safety and performance requirements will comply with the Electricity Governance Rules 2003 technical codes and associated EEA standards and guides, including current Electricity Industry Safety Rules Manuals.

Relative Generation Capacity

The proposed installation of 200 marine turbines in the Kaipara Harbour is expected to generate around 1.750 GWh per annum or about 6.3 Terra joules. Realistically, the actual level of generation will be determined by the total number of turbines and their collective efficiencies and associated transmission losses. Power output will vary depending on flood and ebb flows during spring to neap tides, on the size and position of each turbine, local current velocities, and the configuration of each array.

This level of generation (200 MW peak) should exceed the projected peak electricity needs of Northland (<150 MW) or provide ≥10% of Auckland's peak power requirements. In addition, it would have major environmental benefits in offsetting carbon emissions from a thermal-based, gas turbine generator of 14.3 grams carbon per MJ or 575,000 tonnes of carbon as a natural gas each year(2).

Conclusions

Renewable energy is to be harnessed from sustainable tidal currents in New Zealand's Kaipara Harbour, subsequent to acquisition of resource consents. The proposed HVDC submarine turbines will produce ~200 MW and, when operating on the harbour floor, the units will be silent and invisible. The turbines will generate power daily during four periods, comprising each flood and ebb current flow. Moreover, transmission lines interconnecting the submerged turbines will connect with the two buried, 30-km, bipole cables for transmitting HVDC to the proposed shore-based, converter station, where the tidal power-generated HVDC will be converted to HVAC. From the substation

HVAC will be uploaded to the national 110-kV or 220-kV transmission grid for distribution to consumers in Auckland and Northland.

Power generated by the turbines will be derived from renewable currents, since oceanic tides are driven by the gravitational forces of the sun, earth and moon. Tidal times and volumes are predictable for centuries. Moreover, marine turbines are very effective in generating power as water is non-compressible and ~832 times denser than air. Tidal currents only attain <2.4 meters per second and therefore marine turbines can produce power over a range of current flows without needing to 'feather' the blades. The Kaipara Harbour augments these features by having a massive prism volume (1,990 million cubic meters)[7,8], enhanced period of tidal flow (flood and ebb), and comparable flow velocities at different depths, at least until nearing the harbour floor. The relative uniformity of flow at different depths ensures the rotating blade tips are subjected to comparable current velocities.

The marine turbine arrays and associated DC transmission cables will be deployed with consideration of environmental issues. The turbines will be positioned on gravity-based, concrete plinths, rather than on a monopoles penetrating the harbour floor, be fully submerged and therefore invisible and silent, and abstract only <4% of the total tidal energy. The blades will rotate once every 5-6 seconds at maximal currents, and therefore will not endanger intelligent and mobile marine mammals. The generators will produce DC power as opposed to AC, to substantially reduce EMF emissions, enhance transmission efficiency, and minimize capacity loading during oscillatory fluctuations of tidal cycles. HVDC will be transmitted eastward via bipole cables buried in the Tauhoa Channel and Hoteo River to avoid Zostera (Karepõ), a flowering sea grass resident on the nearby mud flats. The DC cables will be brought ashore directly to an HVDC/HVAC converter station and substation to link with the national transmission grid. Finally, annual marine turbine power generation will offset 575,000 tonnes of carbon (as a natural gas) produced by a thermal power station.

Development of a large marine turbine-based generation capacity in the Kaipara Harbour will provide a significant renewable resource ensuring diversity and security of supply for Auckland and Northland consumers. In the future, tidal power generation could be coupled to an economical series of large scale, super-capacitor, energy-storage arrays or alternatively to hydrogen gas storage for modern fuel-cell electricity generation. Then, Auckland's and Northland's security-of-supply could achieve significant levels of instantaneous energy reserve, in keeping with concepts advocated by, and imminent concerns of the Electricity Commission.

Acknowledgements

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References

1. ABB (2002) HVDC light submarine cable link. Cross Sound cable project, Connecticut – Long Island. ABB Cables Catalogue, Number 7, pp. 1-2

2. Barker, A. (2003). Greenhouse energy use and carbon dioxide emissions. MAF Technical paper No. 2003/03. AgriLINK, New Zealand

3. Cowdroy, S., Hill J. and Halliday, M. (2005) Study on the development of offshore grid for connection of the round two wind farms. Econnect Project No. 1312, pp 1-75

4. Delby, B., Bergman, G., Ericsson, A. and Karlstrand, J.P. (2004) High-voltage XLPErformance cable technology. A Special Report. ABB Cables. pp. 1-6.

5. Goodwin, D. (2006) Operating a constrained grid – future directions. Electrical Engineers Association Conference (EEA) "Empowering New Zealand", Transpower Ltd, June 2006

6. Heath, R. A. (1976) Broad classification of New Zealand inlets with emphasis on residence times. New Zealand J. Marine & Freshwater Research. 10 (3):429-44.

7. Hicks, D.M, and Hume, T.M. (1996). Morphology and size of ebb tidal deltas at natural inlets on open-sea and pocket-bay coasts, North Island, New Zealand. J. Coastal Res. 12: 47-63

8. Hume, T.M. and Herdendorf, C.E. (1992). Factors controlling tidal inlet characteristics on low drift coasts. J. Coastal Res. 8: 355-375

9. Hume, T.M. and Herdendorf, C.E. (1993). On the use of empirical stability relationships for characterising estuaries. J. Coastal Res. 413-422

10. Ministry for Economic Development (2006) Draft - Pyuowering our future: Towards a sustainable low emissions energy system. (Foreword: David Parker, Minister for Energy). ISBN 978-0-478-30458-9 – print version, pp 1-84

Table 1: Tidal prism volumes and mean currents of major harbours in Auckland and Northland regions*

Harbour	Tidal Prism Volume (cubic meters x 10^3)	Average Current (meters/sec)
Kaipara	1,990	1.12
Manukau	918	0.92
Hokianga	228	0.81
Whangarei	164	0.54
Raglan	46	0.59

* Data are drawn from Hume and Herdendorf(8,9) and Hicks and Hume(7).

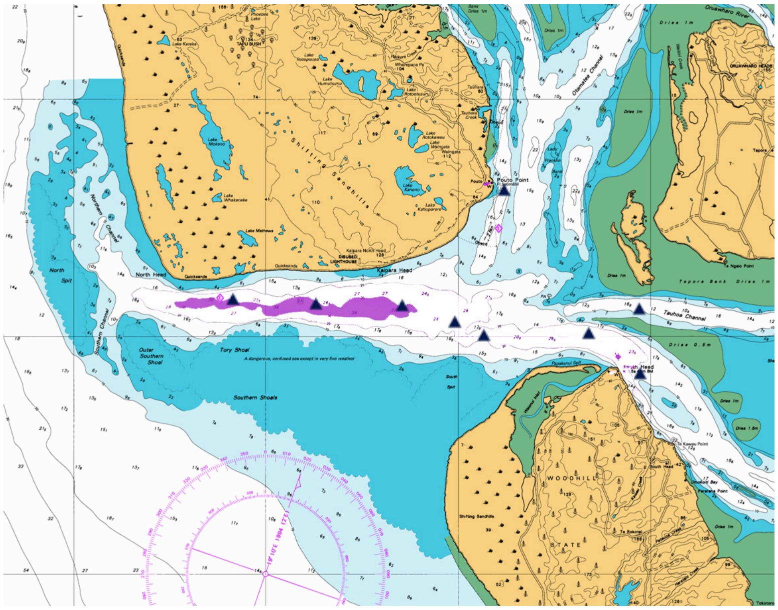
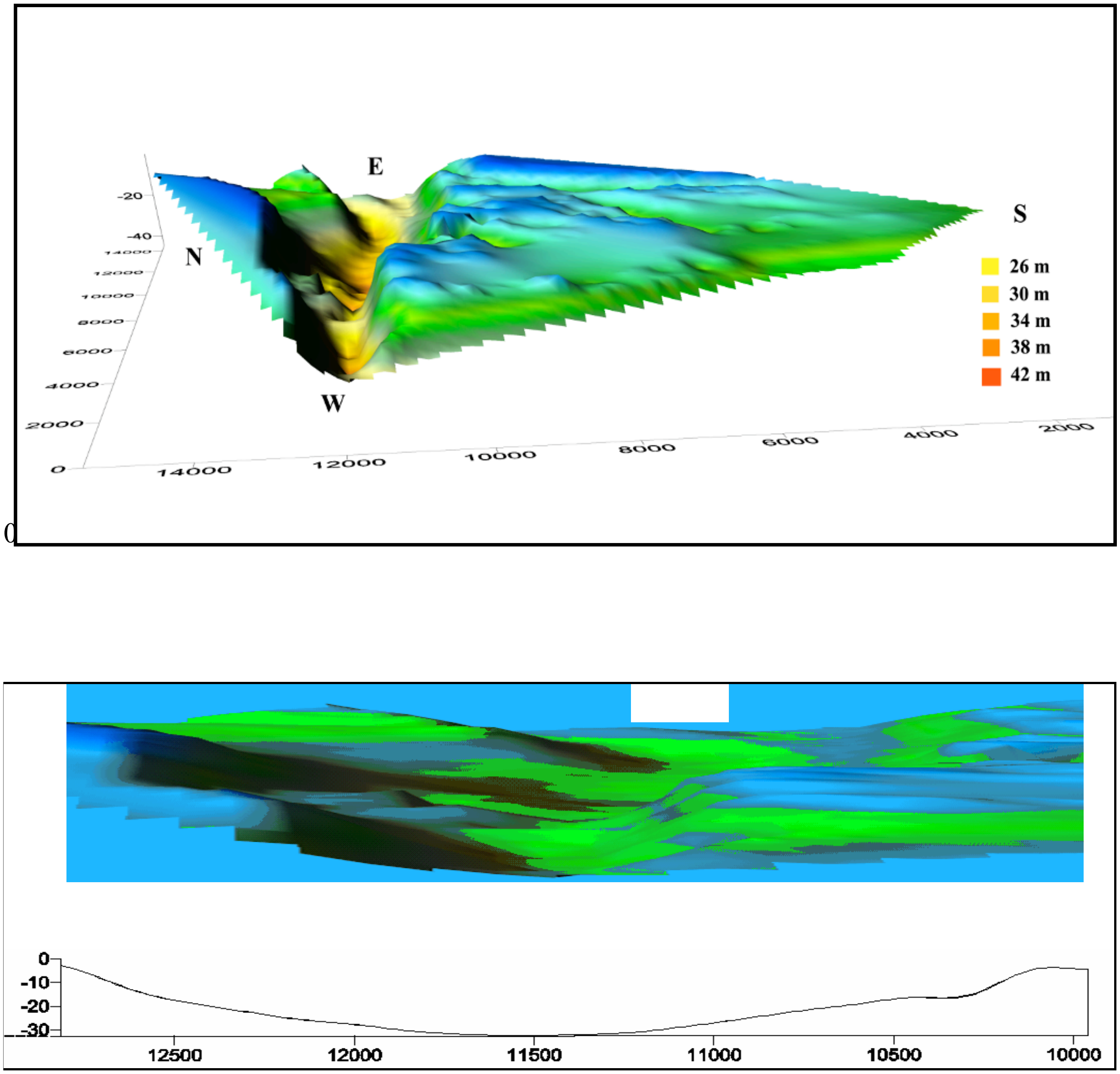


Fig. 1. Kaipara Harbour's main channel and the confluence of the Northern Wairoa River and Southern Kaipara River. Also shown are: North Head with Pouto in the southeast corner; South Head with the Waionui Inlet and Papakanui Spit at the northern tip; and the Southern Shoals (blue shading) (from marine chart NZ 4265).

Purple: Designated turbine area (~9 x 2 km) with 30-50 meter depths and high current velocities. *Black triangles*: Sites of vertically-directed, ADP6 current meters recordings. The ensuing current and bathymetry data are facilitating dynamic modeling of flows during different tides and depths throughout the harbour's channel.



Figs. 2A & 2B. Bathymetry data were processed with the Surfer8 computer program to reconstruct the harbour channel in 3-dimensions for assessing contours of the harbour floor. Depths of the main channel at MLWS are shown (26-42 meters); Southern Shoals in blue/green. Note: The scales of horizontal and vertical axes differ substantially.

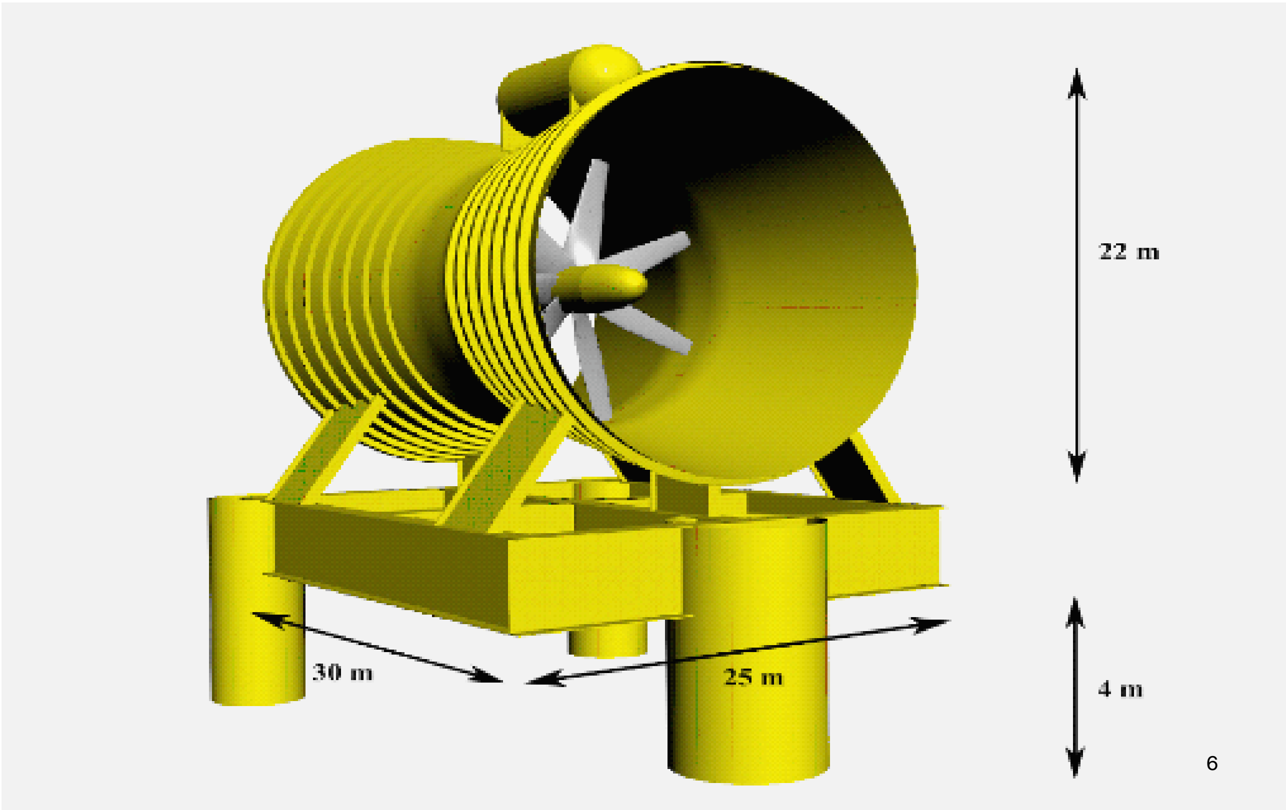


Fig. 3. Marine turbine developed by Lunar Energy/Rotech Ltd for harnessing power from tidal currents. The turbines will be constructed in sizes optimal for installation at depths of 30-50 meters, with outputs ranging from 1.0 – 1.2 MW. The Venturi structure is designed to enhance flood and ebb current flows. The cassette containing the symmetrical turbines blades (grey) and generator (apical cylinder) will be removed every four years for servicing. The rectangular base will be filled with ballast to ensure stability in the rapid currents (Artist rendition reproduced by permission of Lunar Energy, Hessle, England).

Fig. 4. Array of gravity-based, Lunar Energy/Rotech turbines placed on a harbour/ocean floor. The turbines will be positioned to maximize tidal currents passing though their throat. DC generated by the turbines will be collected by linking sub sea cables and then transmitted via larger, sub sea, bipole cables to the shore-based substation located on the bank of the Hoteo River. A maintenance ship in the background retrieves a cassette for servicing (Artist rendition reproduced by permission of Lunar Energy, Hessle, England).

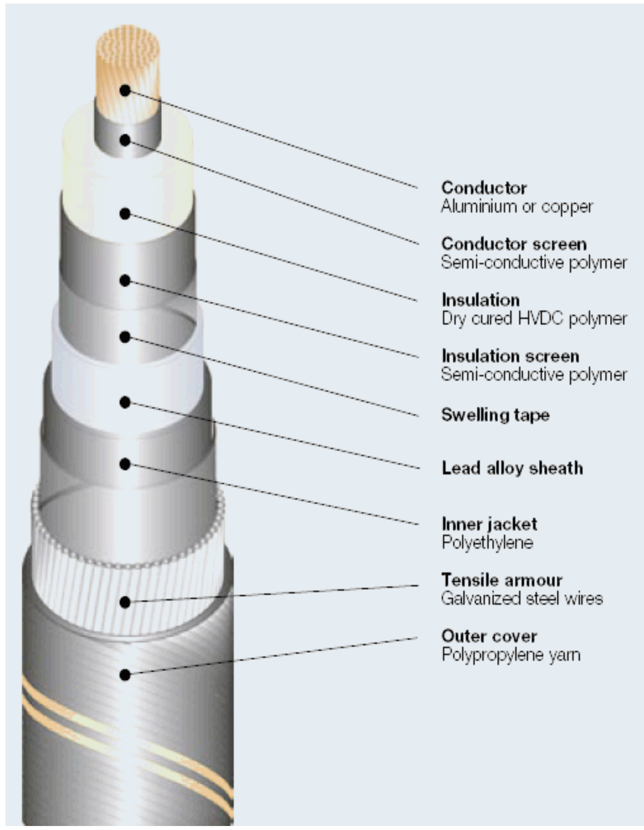


Fig. 5: Submarine DC cable depicting layers in a general cutaway drawing.

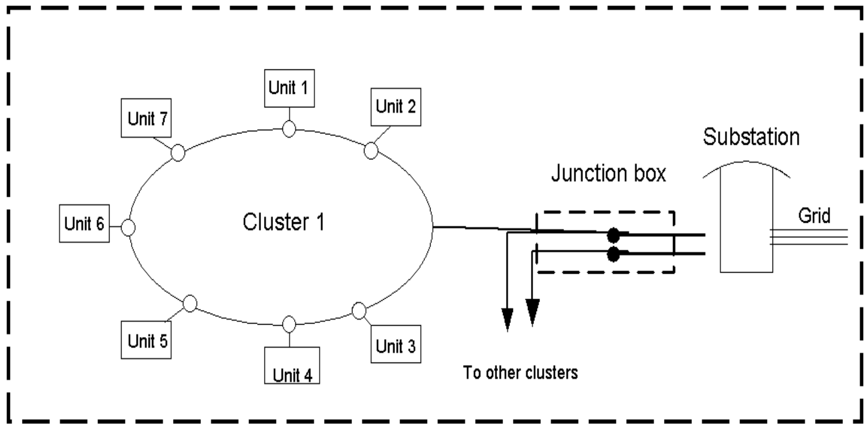


Fig. 6. HVDC electrical power collection and grid interconnection