Recent Developments in Salinity Gradient Power

A.T. Jones
oceanUS consulting
22 Battery St., Ste. 401
San Francisco, CA 94111, USA
jxocean@yahoo.com

W. Finley
Wader, LLC
1076 Skyline Drive
Laguna Beach, CA 92651, USA
wfinley@suremail.com

***Abstract*- An often-overlooked source of marine renewable energy is the energy available from salinity gradients. The potential resource for the osmotic pairing of fresh water and seawater is estimated at 2.6 TW. Several concepts have been proposed. Obviously, any scheme to desalinate seawater can be operated in reverse. Recent developments in pressure-retarded osmosis, vapor compression, reverse dialysis and hydrocratic generation are highlighted. Commercial barriers prevent necessary investment. The power available in salinity gradients will be exploited, but not without substantial investment.**

"We must and we can start the world development process that leads to an environmentally sustainable world habitat for humanity there is no alternative… there is none."

Dr. John P. Craven
Common Heritage Corporation
Doherty Lecture, 2001

I. INTRODUCTION

Energy drives the global economy. Global consumption of energy is growing at an astonishing rate. The US Department of Energy projects an increase of 60% in worldwide total energy consumption from 1999 to 2020 [1]. Accompanying this forecast is a 20-year increase in carbon dioxide emissions (60% increase above 1999 levels) as the world's population increases from 6.0 to 7.5 billion people.

While the United States with 5% of the world's population generates 30% of the world GDP, consumes 25% of the world's energy and emits 25% of the world's CO_2, it is believed the developing countries with their thirst for energy will drive the energy demand over the next two decades. Developing countries are projected to increase energy consumption by 3.8% per annum [1]. Adjustment of this projection to a more realistic level of 2% per annum is the consensus among energy industry analysts [2].

The major source for low-cost, convenient energy globally is fossil fuels and fossil fuels will continue to be the major source of energy for the foreseeable future. Renewable energy use while expected to rise 53% during the period 1999 to 2020, still represents less than 10% of the total energy consumption. Major hydroelectric dam projects such as Three Rivers Gorges in China are considered 'renewable' and account for most of this renewable contribution. Ocean-based renewable energy systems do not yet register in these global projections, yet they have the potential to solve the energy challenge facing rapidly developing countries [3].

Sustainable future economies will require renewable energy sources. Long-term decisions on energy futures need to consider long-term climatic impacts, economic issues and supply factors in addition to geopolitical realities.

II. OCEAN SOURCES OF RENEWABLE ENERGY

Sources of marine renewable energy include ocean currents, ocean waves, tides, thermal gradients, and salinity gradients. Tidal energy relies on the gravitation attraction of the Earth- Moon-Sun system whereas the others all rely on solar energy. Prospects for the various energy sources including their power potential and energy density were assessed after the 1973 energy crisis (see Table 1). Most have been discussed at length in other publications (e.g., [4] or more recently in [5]).

TABLE 1.
MARINE RENEWABLE RESOURCES

Resource	Power (TW)	Energy Density (m)
Ocean Currents	0.05	0.05
Ocean Waves	2.7	1.5
Tides	0.03	10
Thermal Gradient	2.0	210
Salinity Gradient	2.6	240

Source: [6]

III. WHY SALINITY GRADIENT POWER?

Salinity Gradient Power is completely renewable and sustainable. Salinity Gradient Power is the highest energy concentration (i.e., energy density) of all marine renewable energy sources, an ultra-dense energy resource. It was recognized in the 1970s, that salinity power or "the energy represented by the salinity concentration gradient between fresh water and seawater" [7] could be an attractive, large and untapped resource to explore (see [7 - 10]).

In principal, there is no fuel cost. Salinity Gradient Power produces no CO_2 emissions or other significant effluents that may interfere with global climate. Inefficient extraction would be acceptable as long as there is an adequate return on investment.

Basically, it is clean and green. Salts are not consumed in the process.

Depending on the technology chosen, systems could be non-periodic, unlike wind or wave power. Systems can be designed for large or small-scale plants and could be modular in layout.

A. The Resource

The osmotic pressure difference between fresh water and seawater is equivalent to 240 m of hydraulic head. In theory, a stream flowing at 1 m^3/s could produce 1 MW of electricity. The worldwide fresh to seawater salinity resource is estimated at 2.6 TW [6] – comparable to the ocean thermal gradient (estimated at 2.7 TW [6]).

Inland highly saline lakes (hypersaline) have an even greater potential. For example, the Dead Sea osmotic pressure differential corresponds to a head of 5,000 m (almost twenty times greater than seawater [10]). Underground salt solutions or deposits have also been recognized [11].

Almost all of the proposed schemes rely on the fundamental natural process of evaporation to separate the fresh water from the salt.

IV. TECHNOLOGIES

A thorough review up to 1987 is included in Seymour and Lowrey [12]. As Seymour and Lowrey [12] state "Limited attention has been directed to salinity power because it is so easy to overlook; there is no dramatic change in temperature at a river mouth, and an estuary seems far more tranquil than a 240 m waterfall."

Various concepts were proposed more than twenty years ago. As others have noted, at least in theory, any strategy to desalinate seawater could be reversed to produce power.

A. Pressure-Retarded Osmosis

Sidney Loeb was the first to recognize Pressure-Retarded Osmosis (PRO) as a source of energy. In PRO, seawater is pumped into a pressure chamber where the pressure is less than the osmotic pressure difference between fresh water (or low salinity water) and seawater (or higher salinity water). Freshwater flows through a semi-permeable membrane and increases the volume (or pressure) within the chamber; a turbine is spun as the pressure is compensated.

In 1975, after concluding that the cost per kW were prohibitive for a fresh water – seawater system, Loeb [10] considered much saltier water bodies, such as the Dead Sea, promising. Details later [13 – 15] revealed issues with the Dead Sea brines oxidizing conventionally available semi-permeable membranes.

In commenting on PRO, Wick [16] pointed out advances in membrane science that would benefit PRO such as

- Significantly greater flow rates (on the order of 10x).
- Use of glass membranes, and
- Mass produced membranes at much reduced costs.

Additional theoretical work has been done on improvements in mechanical efficiencies of subsystems [16] and optimization of PRO power generation [17].

PRO has been suggested as an energy production scheme for the Dead Sea [18]. With a drop of 400 m and evaporation rates of 3 million m^3/d, seawater delivery could produce potable water by RO prior to descending through a PRO plant near the Dead Sea. Energy costs are estimated at $0.058/kWh.

Analysis of a hydroelectric power plant with PRO at the Great Salt Lake suggests it would be feasible using spiral module membranes. One scenario tapping the Jordan River would envision a 66 MW plant with capital costs of $9,000/kW and energy costs would be $0.09/kWh [19].

Loeb [20] examined power production for the osmotic pairing, river water/ seawater. The economics are a function of the plant capital costs and produced energy costs. He argued that large economies of scale are available for a large-scale PRO plant. With river flow rates on the order of 1,500 million m^3/d, acceptable energy costs of $0.13/kWh are attainable.

A major Norwegian company, Statkraft, opened the first laboratory dedicated to salt-power in 2003. They have been focusing since 1997 on pressure retarded osmosis and reverse electrodialysis. They have calculated that in Norway up to 25 TWh/yr would be available. They have begun field-testing of a simple membrane system. Development of a high performance membranes are the focus of a co-operative research project with Norwegian University of Science and Technology. The theoretical potential was verified by the Foundation for Scientific and Industrial Research (SINTEF).

B. Vapor Compression

First proposed by Olsson et al. [21], the technique exploits differences in vapor pressure of water and seawater to obtain power from the gradient in salinity. Freshwater is evaporated under a vacuum and condensed in seawater. The resulting vapor flow drives a turbine. The turbine conditions are analogous to the open cycle OTEC. According to Cavanagh et al. [5], the technology has been hampered by strategic and operational issues related to consumption of fresh water, an exceedingly valuable resource in parts of the world.

Several promising developments in vapor compression distillation for use in desalination are suitable for technology transfer to address challenges in vapor compression approach to salinity gradient energy conversion. The attractiveness of utilizing vapor pressure differences is that it eliminates the need for membranes and all the associated problems with membranes including degradation of the membrane, fouling, etc. Vapor Compression Distillation systems require no pretreatment of water and are highly reliable, especially if mechanical compression components are not used. New technology in the way of hydrophilic plastic evaporation condensers, compact compressors, highly efficient ejector, non-metallic vacuum chamber, and low construction costs offer advantages for vapor compression.

C. Reversed Electrodialysis (Reverse dialysis)

Weinstein and Leitz [22] proposed creation of a salt battery as follow:

> "An array of alternating anion and cation exchange membranes can be used to generate electric power from the free energy of river and sea water."

An installation in Vladivostok has operated for at least three years producing up to 4 V (0.15 kWh/m^3 of freshwater). Theoretically, the system can approach 0.7 kWh/ m^3 [23].

D. Hydrocratic Generator

A patented technology, known as the Hydrocratic Generator [24] captures the free energy of mixing between two bodies of water having different salinity concentrations. The technology does not require the use of any type of membrane and can be used to recover energy from a wide variety of environments.

During tests of an upwelling device, it was discovered that the amount of upwelling flow was in excess of the energy put into the system in terms of hydraulic head and buoyancy. By reducing the salinity at depth in the aphotic zone, nutrient-rich water could be delivered to the surface ocean, thus fertilizing the immediate area. Experiments using a modified upwelling device where fresh water was introduced into a vertical tube in the water column confirmed that the total hydraulic energy output of the system significantly exceed the input from buoyancy and hydraulic head.

The excess energy is attributable to the release of osmotic potential energy upon remixing of the fresh water and the salt water in the upwelling tube. The term hydrocratic generator is applied to the apparatus.

The system consists of three components: 1) a fresh water injection system, 2) an open vertical tube immersed in the water column, and 3) a means to extract the energy (such as an underwater turbine) and deliver the power to shore.

Fresh water is introduced into the bottom of the vertical tube. Fresh or low salinity water is conducted through a tube from a reservoir on shore. The low salinity water then in direct contact with the high salinity water enters an enclosed second tube to form a mixture. The second tube, known as the "vertical tube", is a cylinder in which fluid is in communication with the source of relatively high salinity water through one or more openings. Contacting the higher salinity water causes entrainment into and upwelling of the mixture within the vertical tube.

The system generates power using a process, which efficiently exploits the osmotic energy potential between two bodies of water having different salinities. The process overcomes past limitations, such as expensive semi-permeable membranes or specially formulated bio-elastomers.

A set of tests on small-scale systems in 50,000-liter pool and in natural seawater conditions in a harbor has validated the concept. Test to date include injecting fresh water (up to 5.5 x 10^{-3} m^3/s) into tubes with varying diameters (15 - 60 cm) and lengths (< 6 m) undertaken in a harbor setting. Results indicate a strong correlation between the rate of fresh water injected and the rate of flow exiting the device. Seawater entrainment, on the order of 10 to 30 times the fresh water volume, has been observed.

IV. DEVELOPMENT TRENDS

A spurt of research activities in the late 1970's, as a reaction to the energy crisis of 1973, resulted in a handful of papers and reports. For the past thirty years, there has generally been a lack of systematic research and development activity. Early technical advances were not considered promising, mainly because they relied on expensive membranes. Membrane technologies have advanced, but to date, they remain the technical barrier to economical energy production [12]. Additional shortcomings at the moment include the following:

- High capital costs for plant installation,
- Equipment not yet developed to level of efficiency desirable,
- Energy costs for most technologies is quite sensitive to membrane efficiency and membrane costs, and
- In membrane systems, membranes are vulnerable to fouling [12].

Efforts are underway to address those issues and alternatively develop designs that eliminate membrane. Other commercial barriers included entrenched competition from hydroelectric utilities, distortion of the governmental policies favoring fossil-fuel technologies through tax incentives or spending policies, and market prices not reflecting public benefit of renewable energy (i.e. reduced air pollution).

The resource does exist and will be exploited in the course of developing alternative energy systems that are sustainable.

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