Architecturally Integrated Reverse Electrodialysis [RED]

Through the combination human (e.g., urban outflows of wastewater and storm water runoff) and natural (e.g., coastal ecologies) system we can extract a source of previously untapped chemical potential to generate electricity and restore biodiversity and ecosystem services to urban areas.

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COASTAL DEVELOPMENT AND THE DISAPPEARING INTERTIDAL ZONE

Global trends in high-density development indicate that populations in coastal cities, as centers for cultural and economic activity, have grown and will continue to grow at alarming rates. Currently, over half of the world population lives on or within proximity to a coastline (Barbier 2008). The pressure of growing populations has led to development along the coastlines that has radically altered, and continues to destruct coastal environments. Building out of infrastructure into marine environments that occurs along many coastlines has virtually eliminating the topographical and ecological transition in the intertidal zone.

These developments have numerous benefits for human populations living along the coastline, but they have a strong negative impact of the health of the ecological communities of the intertidal zone. Large-scale land reclamation and build-out of coastal cities can bury entire ecosystems by filling in or increasing naturally occurring water depths that accommodate particular habitat requirements for vegetation or other species. The relative ease of building urban areas out into shallow coastal waters means ecosystems in these zones are likely at high risk for impacted through urban coastal development (Van de Riet 2012).

CURRENT APPROACH : OFFSHORE ENERGY PRODUCTION

Along with the increasing development of urban coastal centers has come an increasing effort to produce renewable energy “offshore”. There are numerous benefits to this approach, as offshore renewable energy can be extremely important during large storm events that wipe-out on-shore energy production and transport infrastructure. Additionally, placing these systems on and in the open sea allows exposure to unobstructed bioclimatic flows without infringing on valuable on-shore land area.

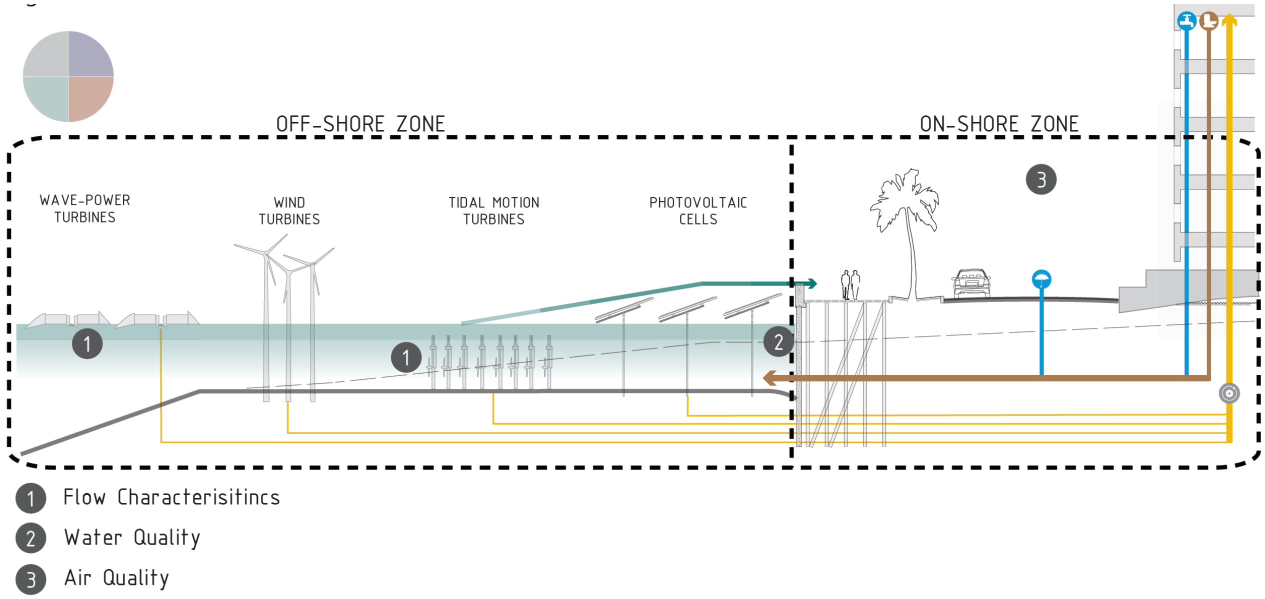

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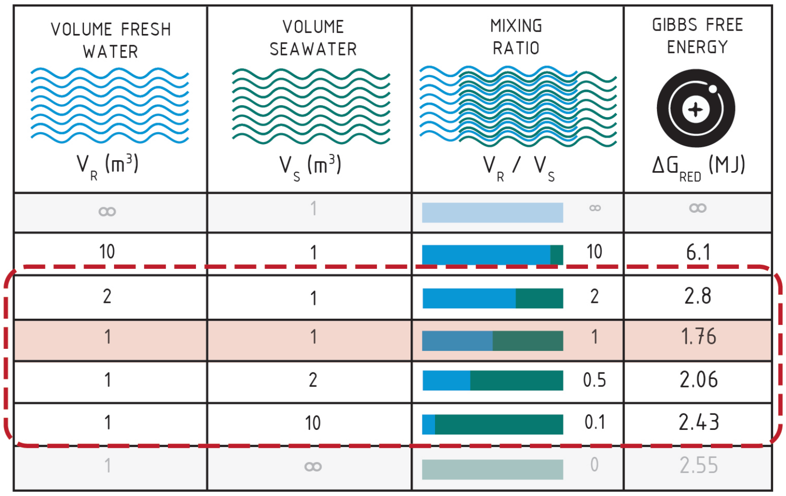
Figure 1: Existing Conditions - Coastal Energy Flows (1), Sewage outflow point resulting in high pollutant levels (2), and Urban heat island effect and air pollution contributing to poor air quality (3).

The current methods and technologies can be very effective in harnessing these bioclimatic flows. For example, Figure 1 shows the key technologies existing in what is marked as the offshore zone. Urban coastal environments today are highly altered and generally in poor ecological health due to the aforementioned development patterns. Because coastal ecosystems are often excluded from coastal areas, the technologies that have been developed to harness "offshore" renewable energy do not consider, and in some cases exacerbate the exclusion of native species. For instance, maximal performance of wind turbines requires high velocity winds. As this technology is applied closer to the coastlines, the type of turbine that might work well in an truly "offshore" environment, unobstructed and unobstructing, would interfered with the mangrove trees and other species existing in a healthy coastal ecology. The support structures and construction/installation would greatly disturb any coastal and marine ecosystems in proximity, and the wind flows might be dampened and altered by coastal vegetation such as mangrove trees. The issues are similar when considering offshore photovoltaic installations. For maximal performance these arrays must have maximum exposure to solar rays. This maximal absorption would essentially exclude any photosynthetic life forms from growing beneath it, inhibiting the growth and development of coastal ecosystems. Thus, while these technologies are valuable and effective in many circumstances, they are not well suited for installation in close proximity to the coastline.

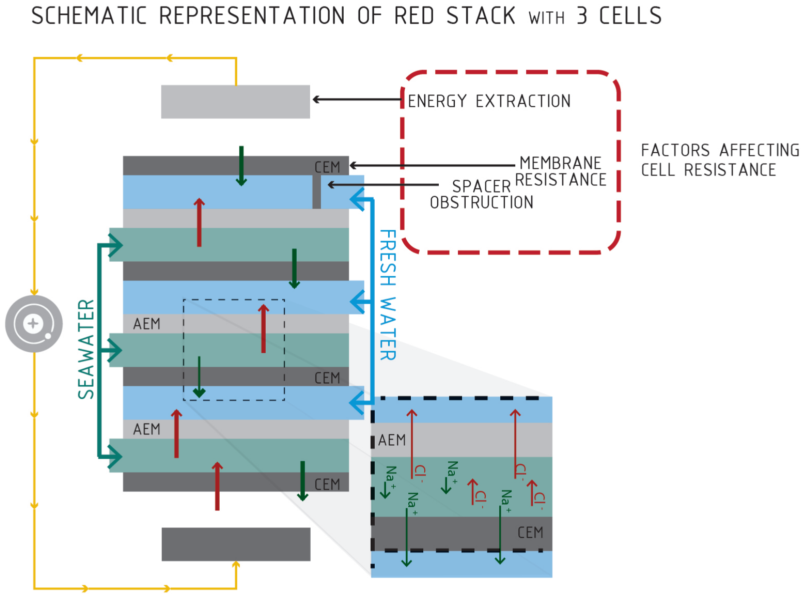
MARINE-SOURCED ENERGY AND BENEFITS OF CHEMICAL POTENTIAL ENERGY

Figure 1 also shows the main technologies harnessing the power of the ocean that are in development and use today: wave power and tidal power. These technologies are highly dependent on certain flow conditions that may not be synergistic with the conditions required for ecological health, and human health and safety when applied close to the shoreline. Tidal turbines work at maximal efficiency with consistent, high-velocity currents. Placing a technology that requires these conditions for optimal functioning near the shoreline is an investment relying on a flow condition that contradicts the desire to decrease and dampen water velocity to reduce risk and



VOLUME FRESH WATER V_R (m^3)	VOLUME SEAWATER V_S (m^3)	MIXING RATIO V_R / V_S	GIBBS FREE ENERGY ΔG_{RED} (MJ)
∞	1	∞	∞
10	1	10	6.1
2	1	2	2.8
1	1	1	1.76
1	2	0.5	2.06
1	10	0.1	2.43
1	∞	0	2.55

2a



2b

Figure 2a: GIbbs Free Energy Comparison based on volume ratios of sea water and freshwater.

Figure 2b: Representation of a RED stack schematic highlighting the factors that affect cell resistance.

impact of flooding. This same contradiction applies for wave energy applied near the coastline. Wave attenuation to reduce flooding is a requirement of most coastal infrastructure, so installing systems that require maximum wave energy is seemingly a contradiction of goals. Due to the flow requirement along the coastline, harnessing the existing chemical potential rather than kinetic potential would be ideal, and this would mean moving away from the typical marine renewable resource technologies.

Where freshwater mixes with seawater, as occurs in areas where rivers meet the ocean, there exists a potential for energy extraction for the salinity differential. The salinity gradient energy is available from the difference in ionic concentrations between seawater and freshwater, and is represented by the osmotic pressure difference between freshwater and seawater (Wick GL. Power from salinity Gradients. Energy 1978;3:95-100).

The equivalent pressure head between 0.5 M seawater and freshwater is about 24 atm. This has potential to generate power by extracting the Gibbs free energy during the mixing. The mixing of 1m3 of freshwater per second with a large volume of seawater can generate 2.25 MW of power (Spiegler KS. Salt-Water purification. New York. Wiley; 1962). Figure 2a shows a table with mixing ratios and the Gibbs Free energy, highlighting the mixing ratios that might be feasible in an architectural integration of salinity gradient harvesting in urban areas (Veerman et al. 2009)

VIABILITY OF REVERSE ELECTRODIALYSIS

Wick and Schmidt (1977) estimated the total global salinity power (limited to the interface between river and ocean) to be 2.6 TW, which is sufficient to supply the global electricity demand (2 TW) or 16% of the total present global energy consumption (Energy Information Administration; official energy statistics from the US government. (GL Wick, WR Schmidt, Prospects for renewable energy from sea, Mar Technol. Sco. J 11 (1977) 16-21) www.eia.doe.gov.) This calculation is based solely on fresh-seawater interfaces that occur where rivers meet oceans does not include the interfaces where channeled freshwater outputs meet seawater in coastal urban environments.

The potential difference between seawater and freshwater solutions can be calculated using the Nernst Equation. If seawater is considered as a solution of 30 kg NaCl/m3 and river water as a solution of 1 kg NaCl/m3, this potential difference is 140-160 mV per cell. The ionic current is extracted then converted to an external electron current via redox reactions at the electrodes (Veerman et al. 2009).

One technology that has been employed and researched in recent years is Reverse Electrodialysis [RED]. This technology extracts the energy from the mixing of salt and freshwater. The mixing leads to a change in the Gibbs free energy and RED converts this to electricity via direct ion transport through selective membranes (Hong 2013). Figure 2b shows a schematic representation of a typical RED cell. A typical RED system consists of alternating cation and anion exchange membranes. These are shown as dark (cation) and light (anion) gray bars in the schematic representation. The amount of membranes is variable in any given system. Figure 3 b shows one cell of a typical reverse electrodialysis stack. This cell consists of a cation exchange membrane (CEM), adjacent to a saltwater compartment, adjacent to an anion exchange membrane (AEM), then a freshwater compartment. The setup allows the positive ions from the sea water to diffuse through the CEMs into the freshwater compartment and build up on one side of the stack, while the negative ions from the seawater diffuse through the AEMs to the other freshwater compartment, causing a negative potential in this location. The RED system extracts electrical power an external circuit connected through end electrodes. In many systems, the ionic current in the cells is then converted to an external electron current through redox reactions at the electrodes (Veerman et al. 2009).

The key parameters to the power density and delivered power of an RED system are the electromotive force within the system, and the internal resistance. Figure 3a shows a chart of the relevant values and equations to determining the potential for delivered power of an RED system. Gibbs free energy (ΔG_{RED}), as described above is the chemical potential between 2 solutions of different concentrations. It is established that there is enough potential energy when volumes of freshwater and seawater are mixed at 1:1 ratio to make the pursuit of energy-extracting systems feasible at

REVERSE ELECTRODIALYSIS KEY PARAMETERS AND POWER PRODUCTION

EFFICIENCY AND POTENTIAL ENERGY FRESHWATER-SEAWATER INTERFACE

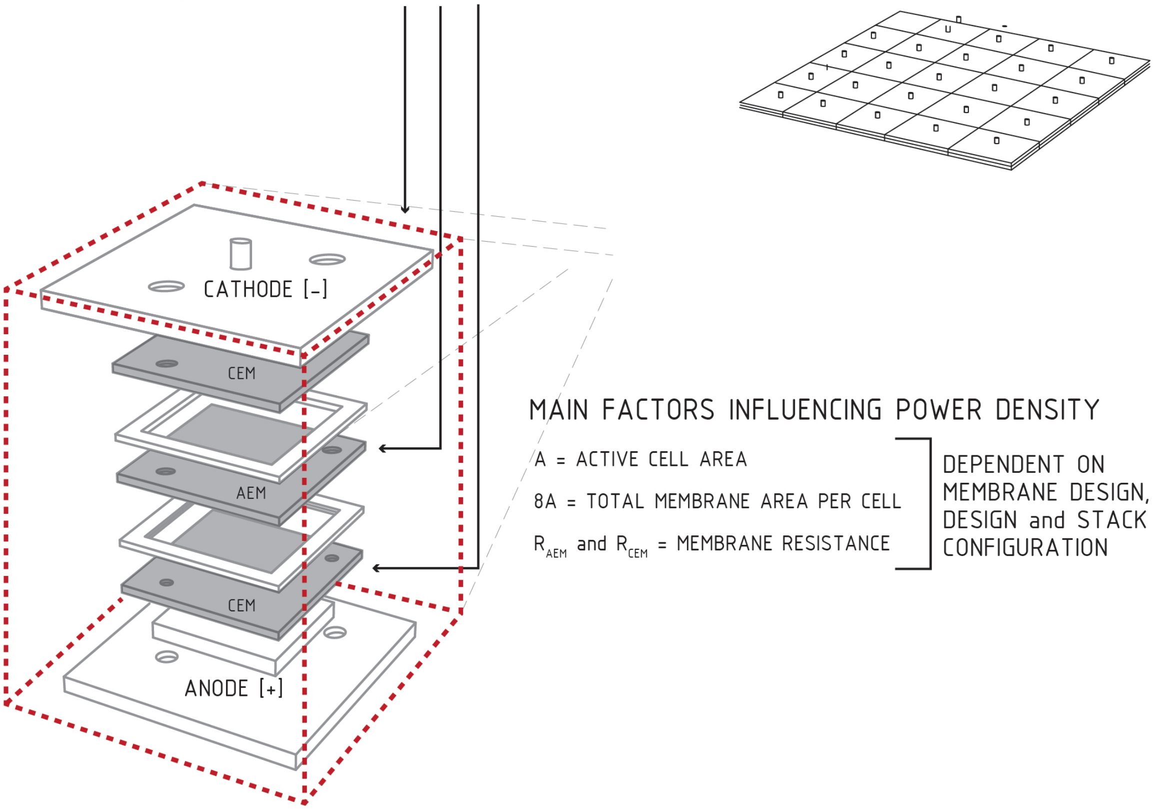
GIBBS FREE ENERGY: ΔG_{RED} $= 2RT\,[\,V_S C_S \ln \frac{V_S+V_R}{V_R}\,] =$ 1.76 MJ
CHEMICAL POTENTIAL BETWEEN FRESH AND SEAWATER SOLUTIONS

ELECTROMOTIVE FORCE: E_{cell} $=$ 0.080 V CEM + 0.078 V AEM $=$ 0.158 V per cell
SUM OF THE VOLTAGE ACROSS CELL WITH 100% PERMEABLE MEMBRANES

POWER EFFICIENCY: η_P $= \frac{R_u}{R_u+R_i} \leq$ 50% with for maximal power output
THE FRACTION OF THE TOTAL POWER THAT IS DELIVERED TO AN EXTERNAL POWER CONSUMER WITH RESISTANCE R_u

POWER DENSITY: P_D $= \frac{E^2_{cell}}{8A(R_{AEM}+R_{CEM}+R_{fresh}+R_{sea})} =$ 0.93 W/m^2
THE EXTERNAL POWER PER MEMBRANE AREA. MAXIMAL when $R_u = R_i$

50 CELL STACK MEMBRANE SURFACE AREA = 1 m^2



MAIN FACTORS INFLUENCING POWER DENSITY

A = ACTIVE CELL AREA
8A = TOTAL MEMBRANE AREA PER CELL
R_{AEM} and R_{CEM} = MEMBRANE RESISTANCE

DEPENDENT ON MEMBRANE DESIGN, CELL DESIGN and STACK CONFIGURATION

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Figure 3: Key Equations and Parameters in Reverse Electrodialysis Energy Efficiency. Image of typical RED cell showing main factors influencing power density.

architecturally viable scales. Veerman (2008) calculates that the electromotive force, or the potential difference between the two solutions can be calculated through the Nernst equation using concentrations of 30 kg NaCl/m3 for seawater and 1 kg NaCl/m freshwater. Over 100% selective membranes the voltages are 0.080 V for CEM and 0.78 V for AEM. The resulting potential difference is 0.158 V per cell.

The potential power output can be calculated from the electromotive force, and the power efficiency (n_P). Power efficiency is the fraction of the total power that is delivered to an external power consumer with resistance Ru. Figure 3a shows the equation for power efficiency which implies that at maximal output (when internal resistance [Ri] is equal to external resistance [Ru].

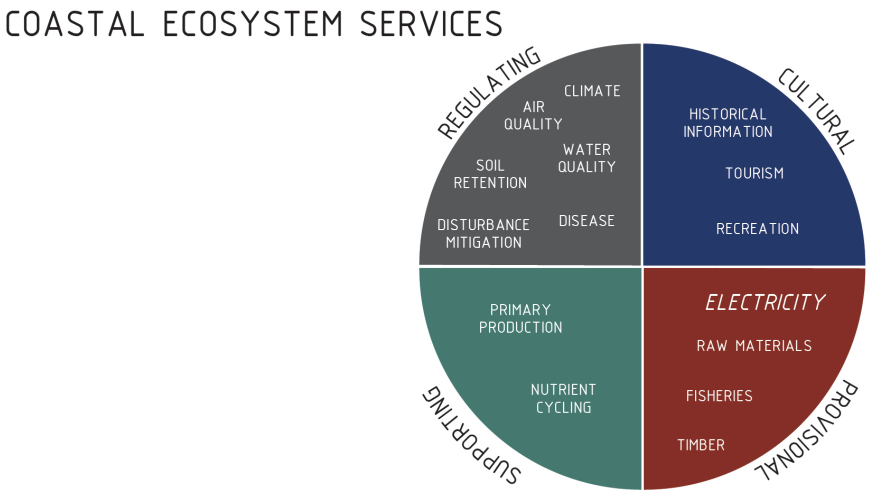
The power density (Pd , Figure 3b) of a RED system is defined as the external power per membrane area (W/m2) and is maximal under the conditions of Ru=Ri. Power density is influenced by the total active membrane area, and the resistances of the AEMs, CEMs, seawater and freshwater.

In RED there are some main parameters that that affect power density and energy efficiency; 1 current density, 2 membrane and spacer resistance 3 feed flow rate. These factors are influenced by cell and stack design, which can be adjusted, improved, and fit into different architectural scenarios fairly freely. What must remain constant is the salinity differential. This could mean that it may be feasible to install site-scale RED systems along the coastline, provided there is a reliable source of freshwater. The power potential could even expand beyond site scale with improvements in technology. On a stack with 1 m2 surface area Veerman et al. (2009) was able to generate a power output of 0.93 W for a 50 cell stack. Figure 2b shows the dimensions of a functioning RED cell with standard membrane technologies. This power output implies that in a volume 33 m3 there is potential to create close to one megawatt of electricity with taking into account the inefficiencies of aggregation and series functioning, which are a serious consideration in large-scale, multistack RED systems. Currently the only full-scale applications of these prototypes have been installed at the interface between river and sea. This proposal calls for the consideration of the application of RED systems at the coastline, at the interface between channeled freshwater outputs and seawater.

CHEMICAL POTENTIAL AND ECOSYSTEM RESTORATION

The incorporation of ecology and ecosystem services into coastal infrastructure is an essential step in future development of coastal protection solutions. Ecological systems have the capability to perform as sustainable and cost-effective protection solutions that can mediate threats related to climate change such as rising sea level in the increase in intensity and frequency of coastal storms and flooding. Figure 4a shows costal ecosystem services categorized into regulating services, supporting services, cultural services and provisional services. This proposal aims to incorporate potential energy-harvest systems that provide electricity as a provisional service while enhancing the potential for the other ecological services to be provided as well. Harnessing the chemical potential present at the coastline is an attractive alternative to harnessing the kinetic energy currently available at the coastline. The former energy production option would work synergistically with an increase in biodiversity and vegetation at the coastline as well as decreased tidal and wave energy at the coastline, all of which are desired conditions at urban coastlines.

One applicable case study of coupled costal ecologies and urban ecosystems is the research on reinforced mangrove trees as protective coastal infrastructure. Mangroves provide a number of ecosystem services valuable to human habitat, specifically the wave attenuation characteristics of the mangrove tree root architecture. Van de Riet (2012) explores the potential for a hybrid landscape that integrates mangroves as protective wave attenuators as an alternative to ecologically-inhibiting vertical costal barriers. The research proposes a conceptual proposal that reinforces mangroves with structural substrates that anchors the trees and amplifies wave dissipation. Ecological restoration through this type of hybrid landscape could capitalize on self-repairing and self-building aspects of tree growth while providing long term



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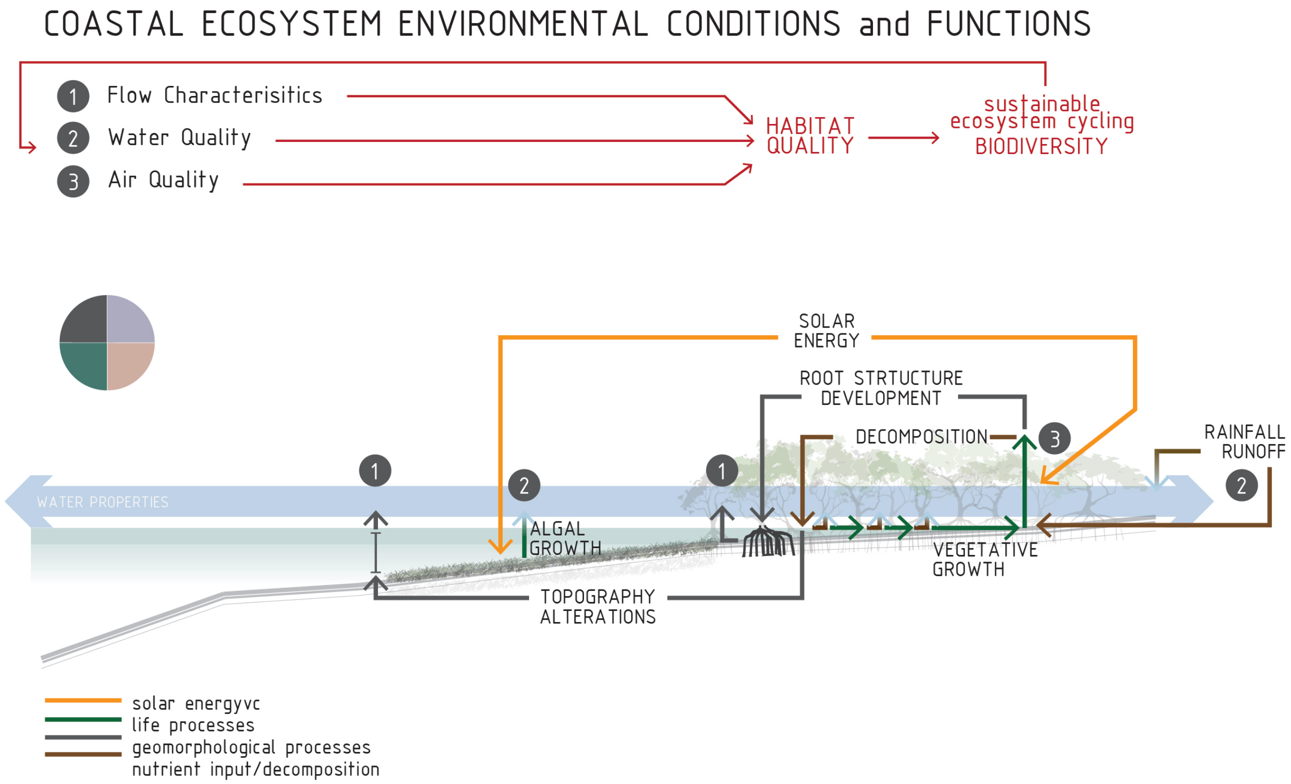

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Figure 4a: Coastal Ecosystem services broken into regulating, cultural, provisional, supporting categories.

Figure 4b: Coastal Ecosystem flows and cycling.

security to coastal communities. These ecologically engineered systems also have the potential to integrate with RED and other energy production systems harnessing chemical potential because RED and other chemical-potential-based systems have few limitations in the way that they occupy space, and could be optimized to fit the architectural requirements of the biological-hybrid system. density is influenced by the total active membrane area, and the resistances of the AEMs, CEMs, seawater and freshwater.

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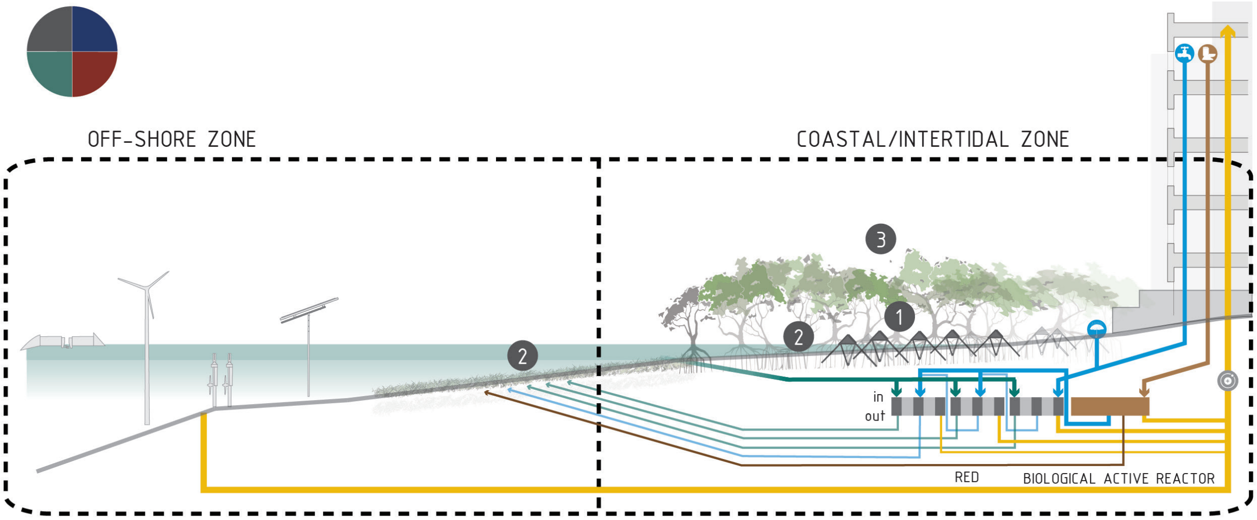

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Figure 5: Proposed energy capture and system integration.

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RED AND BAR SYSTEM INTEGRATION

In undisturbed coastal ecosystems, there is generally in influx of fresh water and nutrients that entered the seawater from runoff during rain storms. This input is a crucial source of nutrients for the health of coastal ecosystem. A schematic representation of nutrient cycling of a typical tropical coastline is shown in Figure 3 with brown and green arrows. In this natural input and cycling, the freshwater mixes with the seawater only when it rains, and highly dispersed along the area of the coastline. Through coastal development and urbanization, humans have engineered storm water systems that essentially funnel freshwater into the ocean through a drains and pipes; however these systems do not necessarily result in freshwater inputs into coastal environments.

However, in most urban areas, sewage from buildings in the form of both black water and grey water are combined with storm water drain systems. When it rains, the high volume input of storm water into the sewer system and when treatment plants have reached capacity, which can occur with small amounts of rainfall, the combination of storm water and raw sewage is output directly into the marine environment from what are called Combined Sewer Overflows or CSO's. These outflows are represented in Figure 1. In many cases, what has potential to be a concentrated and semi-controlled flow of freshwater mimicking the inputs at a small river or stream inflow, is contaminated with pollutants that reduce water quality and exacerbate the exclusive environment to coastal native species and ecologies.

Since RED systems are not dependent on architectural-scale morphology, there is an opportunity to integrate with other similar energy production systems at the coastline that can simultaneously intercept the contamination of raw sewage, and enhance the energy production of the RED system. Manfredi (2012) proposes the integration of anaerobic bio-digester and microbial fuel cell technologies at the New York City coastline. The BAR system takes the inputs of organic matter fed from urban waste water systems and through the process of anaerobic digestion releases methane, carbon dioxide, freshwater and organic sludge. The methane output can be harnessed to fuel gas systems, and the sludge can be fed into the microbial fuel cell for electricity production. integration of RED and BAR systems considers the separation of black water and gray water within buildings and infrastructure, and the combination of grey water and storm water systems to provide an influx of freshwater to create the salinity differential that would allow for site-scale energy generation through Reverse Electrodialysis in the intertidal zone (shown in Figure 5). The systems would utilize urban infrastructure to concentrate freshwater to certain locations of RED cell stacks.

Integrated RED and BAR systems have the potential to provide outputs that enhance the ecological health of coastal systems, as well as fuel the differential for energy production through RED. The integration of these systems along with the ecological restoration by reinforced mangrove ecologies has potential to reducing the impacts of wave and tidal energy, transform pollution of the water while at the same time restoring vegetation and biodiversity and producing energy for coastal development.

CONCLUSION

Through the combination human (e.g., urban outflows of wastewater and storm water runoff) and natural (e.g., coastal ecologies) system we can extract a source of previously untapped chemical potential to generate electricity and restore biodiversity and ecosystem services to urban areas.

In conventional urban coastal infrastructure we either segregate or ignore the interface between human outflows (fresh and black water) and coastal ecological health. In the case of this proposal, based on preliminary calculations, we see significant potential in the integration of these flows and just cause for further research pursuits. Further exploration of this topic requires research into the ideal membrane technologies for this type of architectural application. Additionally, the influx of freshwater from the combined systems must be quantified, and validated as a viable source for RED system functioning. Although we have addressed the implications and benefits of applying chemical-potential-based energy production systems in terms of the physical conditions at the urban coastline, we have very little understanding of the degree of chemical impact this technology would have on coastal ecological health. Intensive comparisons between pollutant and nutrient levels tolerated/required by coastal ecological systems and the levels provided by site-scale application of integrated RED and BAR systems are required to validate the coastal application of integrated RED and BAR technologies.