Feasibility Study of Energy Storage using Renewable and Off Peak Utility for Hydrolysis Cogeneration and Stored Gravitational Energy at Depth

Developed by Ralph Bencriscutto of Tower Energy International LLC for the efficient storage of unused renewable or generated power as a by-product of hydrolysis and the goal of carbon neutral elimination of fossil fuel dependence.

This document details the analysis of the Gravitron Ballast System proposed by Ralph Bencriscutto and Tower Energy Partners. The analysis covers the energy production possibilities using the movement of the tanks as well as the use of a Rankine cycle to capture waste energy from hydrolysis to store energy. The resulting production cost of hydrogen is greatly reduced by the use of cogeneration and waste heat to subsidize the production, storage and distribution.

Table of Contents

Introduction

The Gravitron Ballast System was an idea generated by Ralph Bencriscutto of Tower Energy International LLC in Racine, Wisconsin. The concept involved breaking down distilled water into its components, hydrogen and oxygen, using hydrolysis units that are submerged in a water filled quarry. Two hydrolysis units and hydrogen/ oxygen expandable capture tanks (inflatable ballast bladders) would be attached to a cable that allowed them to sink to the bottom and rise to the top. As the tanks move, one up and one down, the pulley is turned. The pulley is attached to a gearbox and then to a generator to generate electricity. This electricity can in turn be used to supply some of the power needed by the hydrolysis unit for facilities operation or additional compression. The Rankin cycle option recognized the significant heat generated during the process and offers a method for additional energy recovery from that aspect which would otherwise be absorbed in the water. Rankin is the use of ammonia is a refrigeration cycle (change of state) with which the heat is expelled at the surface and energy is recovered during de-compression of the ammonia gas. This cycle is a closed loop that is repeated during the process.

This report details the analysis, calculation spreadsheet setup, power generation feasibility of the Gravitron Ballast System, analysis of using low speed generators, analysis of the addition of a Rankine cycle, and provides conclusions drawn from the analysis and theoretical data.

Main Assumptions

Assumptions were made during the initial analysis to enable the calculations to be made. The assumptions that affect the entire analysis are detailed below along with their justifications. Further assumptions that were made for a specific aspect, such as power generation assumptions, will be noted and justified in the section to which they pertain.

The tank and hydrolysis unit together are represented as a sphere. This assumption allows for the application of a drag coefficient specific to its shape to be used. It also takes into account the likelihood that the end product would be of a hydrodynamic shape.

The velocities of the falling or rising units are always considered to be at a constant value equal to or below the terminal velocity. This excludes the transient response as the units gather speed from a resting position. Since this is the greatest speed that will be achieved, and the speed directly impacts the amount of power that can be generated, the terminal velocity is the velocity most likely to impact the feasibility. If a development is pursued, the transient velocity responses of the tanks starting and stopping would need to be taken into account.

The coefficient of drag used for the spherical unit is 1.5 [1]. In the NASA webpage depicting flow types and drag coefficients around a sphere, case number 2 which includes low flows through a viscous fluid. The speed of the spheres is expected to be slow, thereby inducing slow flow rates around the spheres. Seawater is a viscous fluid, so the second case fit the situation best.

After the tank discharges its gas at the surface, it is assumed to be completely full of water. This assumption makes the force of the falling sphere easier to calculate. It is valid because it is conceivable that once the hydrogen and oxygen are pumped out, the entire sphere is allowed to fill with water to create a negatively buoyant object.

The tank is assumed to be a perfect sphere made of completely incompressible material. According to the first assumption, the tank and hydrolysis unit are housed in a perfect sphere. It is assumed that the tank will be made of metal that is rigid enough to remain incompressible at the depth to which it was designed to descend. This assumption eliminates the need to take into account any reduction of internal volume or increase in interior pressure as a result of the container being compressed.

The interior of the sphere is to have 3 expandable bladders with which to hold the segregated gasses of hydrogen, oxygen and ammonia under pressure. The placement of the gas will be originally designed to have the superheated ammonia in the center to aid achieving buoyancy and balancing the waste heat off the hydrolysis reaction while cooling the unit.

Seawater is assumed to be an incompressible fluid. The compressibility of water is so small as to be negligible. For instance, the water at the bottom of a mile deep column of water will compress less than 1% [2]. This assumption simplifies calculations because compressibility factors do not need to come into play.

The spheres, though linked, were assumed to not act upon each other. This was assumed because the goal was to make the upward buoyancy force the same as the gravitational downward force so that they would rise and sink at the same rate. This is possible by varying the ratios of water, oxygen, and hydrogen in the rising sphere so that the rising force is twice the falling force. Thus the upward force less the falling force (weight) would be approximately the same.

Force Balance Setup

The first step in analysis was to construct a free body diagram to determine the forces acting on each sphere as it sank or rose. The goal of the free body diagrams was to enable the calculation of the amount of torque generated at the pulley. The falling sphere was evaluated first, Figure 1.

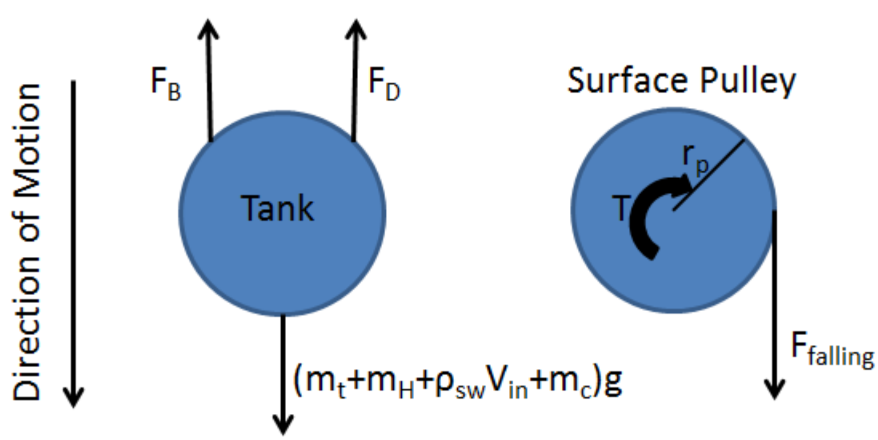

Figure 1 - Free body diagram of the falling tank and surface pulley

As the tank falls towards the sea floor, the forces that are exerted upon it are the buoyancy force, F_B, the drag force, F_D, and the gravitational force, the equivalent mass multiplied by gravity. The sum of these forces, assuming that the positive y-axis is towards the surface of the water, is then used to determine the torque exerted at the axis of the pulley. The sum of the forces is:

$$\Sigma F_y = F_B + F_D - (m_t + m_H + \rho_{sw} V_{in} + m_c)g$$

Where m_t is the mass of the tank full of water, m_H is the mass of the hydrolysis unit, ρ_{sw} is the density of sea water, V_{in} is the inner volume of the tank, and m_c is the mass of the cable. When the terms for F_B, F_D, and m_t are substituted, the force equation is:

$$\Sigma F_y = \rho_{sw} g V_{out} + \frac{1}{2} C_D \rho_{sw} v^2 A - ((V_{out} - V_{in})\rho_{ss} + m_H + \rho_{sw} V_{in} + m_c)g$$

Where ρ_{ss} is the density of stainless steel, V_{out} is the volume of the tank using the outer diameter, C_D is the drag coefficient, v is the velocity of the tank, and A is the surface area of the tank. The sum of the forces can be used to determine torque that is exerted upon the axis of the pulley. The torque is calculated using:

$$T = F_{falling} * r_p$$

Where $F_{falling}$ is the sum of the forces acting on the falling sphere, and r_p is the radius of the pulley. This equation is used to determine the power generation feasibility of the system under different conditions.

The same forces are in action on the rising tank, Figure 2. However, the direction that these forces act, and the composition of the mass term are different, and create different results. One important factor that is taken into account in the spreadsheet is that the density of oxygen and hydrogen are dependent on temperature. Since the hydrolysis unit produces hot gas, it is conceivable that as the gas cools the density increases, and therefore the mass of the tank, will change. As a result, varying temperatures were acquired and used in the spreadsheet to get a sense of the what difference it will make [3].

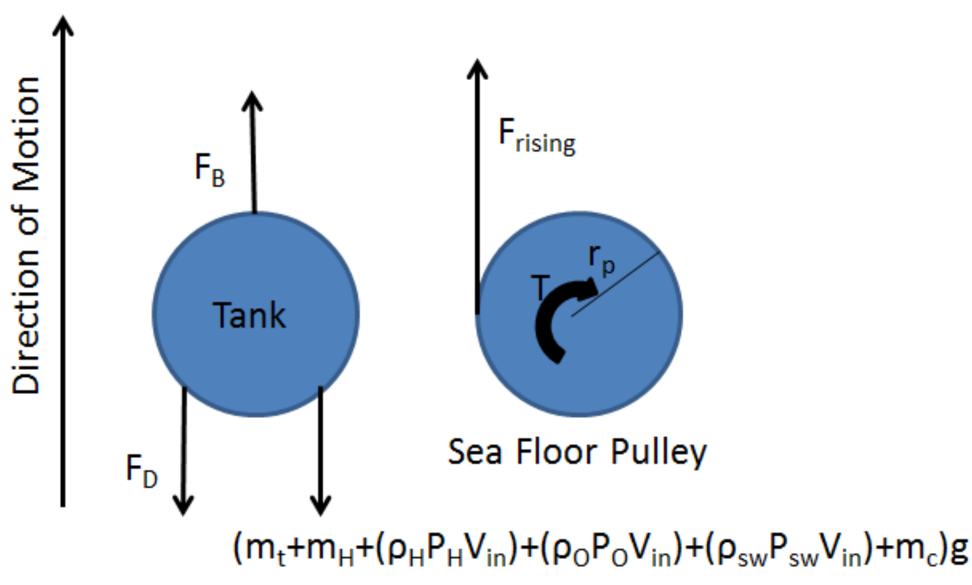

Figure 2 - Free body diagram of the rising sphere and the pulley moored to the sea floor

The force balance for the rising tank is very similar to the falling tank:

$$\Sigma F_y = F_B + F_D - (m_t + m_H + (\rho_H P_H V_{in}) + (\rho_O P_O V_{in}) + (\rho_{sw} P_w V_{in}) + m_c)g$$

Where ρ_H is the density of hydrogen gas, P_H is the percentage of the inner volume occupied by hydrogen gas, ρ_O is the density of gaseous oxygen, P_O is the percentage of the inner volume occupied by oxygen gas, and P_{sw} is the percentage of the inner volume occupied by water. These percentages can be varied to get the amount of buoyancy desired, or the amount of gases desired in the tank. When the terms for F_B, F_D, and m_t are substituted, the force equation is:

$$\Sigma F_y = \rho_{sw} g V_{out} + \frac{1}{2} C_D \rho_{sw} v^2 A - ((V_{out} - V_{in})\rho_{ss} + m_H + (\rho_H P_H V_{in}) + (\rho_O P_O V_{in}) + (\rho_{sw} P_w V_{in}) + m_c)g$$

The torque exerted on the bottom pulley is then equal to:

$$T = F_{rising} * r_p$$

F_{rising} is equal to the sum of forces acting in the y direction upon the rising sphere. Since the most efficient place to mount an electric generator is on the surface of the ocean, the torque exerted on the surface pulley is used in the power generation feasibility study. The sea floor pulley can be assumed to be free spinning and acts to define and constrain the path of motion of the spheres.

Spreadsheet Setup

The Feasibility spreadsheet which accompanies this report is set up with six tabs. The first tab has all of the calculations and data contained in it. The second tab lists the assumptions that were used. The third tab contains the density versus temperature data for hydrogen and oxygen. The fourth and final tab contains all of the equations that were used in the first tab. The fifth tab has a spreadsheet that lists generator angular velocities versus tank sizes. The interior of the table is populated with the required gear ratio and torque available. The sixth tab offers insight into the feasibility and cost comparisons for the project, Figure 3.

Figure 3 – Spreadsheet Tabs

The Calculations tab has all of the variables that can be set highlighted in light orange, Figure 4. These variables allow the user to determine what changes variations to tank size, cycle time, depth, pulley diameter, among others, have upon the torque and gear ratio results.

Variables			
Variable	Description	Units	Value
ρ_{sw}	Density of seawater	kg/m^3	1027.00
ρ_{ss}	Density of 316 stainless steel	kg/m^3	7861.1
m_h	Mass of hydrolosis unit	kg	14514.96
m_t	Mass of tank (empty)	kg	24290.80
m_c	Mass of cable	kg	7292.60
od_t	Outer diameter of tank	m	5.00
id_t	Inner diameter of tank	m	4.92
t	Thickness of tank	m	0.04
A	Surface area perpendicular to flow	m^2	78.54
C_D	Coefficient of drag	-	1.50
g	Acceleration due to gravity	m/s^2	9.81
Vo	Outer volume of tank	m^3	65.45
Vi	Inner volume of tank	m^3	62.36
F_B	Buoyancy force for tank	N	659400.24
d_p	Diameter of pulley	m	8.00
h_w	Depth of water	m	700.00
T	Cycle time of tanks (time to cover h_w)	hr	1
V_n	Necessary velocity to cover h_w	m/s	0.19444444
μ	Viscosity of seawater	$N\text{-}s/m^2$	0.001830
ρ_t	Density of tank with water	kg/m^3	1619.91
V_f	Terminal falling velocity	m/s	2.51
m_w	Mass of water in tank	kg	64,043.72
P_h	Percentage of hydrogen in rising tank	%	0.6
P_o	Percentage of oxygen in rising tank	%	0.3
P_w	Percentage of seawater in rising tank	%	0.1
ω	Angular speed of the pulley	rpm	0.23210096
$\omega_{generator}$	Angular speed input to the generator	rpm	84
R	Gear ratio needed to achieve $\omega_{generator}$ (1::	-	361.911474

Figure 4 - Variables Column

The torque results for the falling sphere is contained in the first row or results and the rising sphere results, as they vary with the temperature and density of hydrogen and oxygen, are below the falling sphere results, Figure 5. The results detailed in the power generation feasibility were obtained by varying the designated factors in the spreadsheet, and the results were calculated within the spreadsheet.

Falling Cylinder			
Shape Drag Force (N)	Mass of Tank of Water (kg)	Total Force of Falling Tank (N)	Torque Generated* (Nm)
2,287.25	102,849.48	-418,806	-1,675,224

*Torque generated at terminal velocity

Rising Cylinder					
Temperature (°C)	Oxygen Density (kg/m^3)	Hydrogen Density (kg/m^3)	Shape Drag Force (N)	Total Force of Rising Tank (N)	Torque Generated (Nm)
-0.15	48.57	3.04	2,287.25	132,031.52	528,126.08
6.85	47.36	2.96	2,287.25	132,282.95	529,131.80
16.85	45.72	2.86	2,287.25	132,620.64	530,482.56
26.85	44.2	2.76	2,287.25	132,936.30	531,745.20

Figure 5 - Calculations in the calculations tab

The table contained in the fifth tab helps illustrate what gear ratios are necessary, and what torque is available to move them for various tank diameters. The torque available stays constant for each of the different generator angular velocities, and varies with the tank diameter. The necessary gear ratio varies with the angular velocity of the generator and remains constant with the tank diameters. Tank sizes range from 2 m to 40 m by increments of 2 m, Figure 1. Generator speed specifications were found from various sources [4], [5], [6], [7], [8], [9], [10], and [11]. The water depth, cycle time, and pulley diameter can be varied to observe the difference in results.

		Tank Diameter (m)							
		2		4		6		8	
Generator Power	$\omega_{required}$ (rpm)	$T_{available}$ (Nm)	R_{needed} (1:x)	$T_{available}$ (Nm)	R_{needed} (1:x)	$T_{available}$ (Nm)	R_{needed} (1:x)	$T_{available}$ (Nm)	R_{needed} (1:x)
1.5MW DD	20.5	-144994.2915	132.48545	-96856.5619	132.48545	165729.381	132.48545	769368.088	132.48545
1MW	2000	-144994.2915	12925.4098	-96856.5619	12925.41	165729.381	12925.41	769368.088	12925.41
750kW DD	28.6	-144994.2915	184.83336	-96856.5619	184.83336	165729.381	184.83336	769368.088	184.83336
500kW	1517	-144994.2915	9803.92331	-96856.5619	9803.9233	165729.381	9803.9233	769368.088	9803.9233
400kW	1560	-144994.2915	10081.8196	-96856.5619	10081.82	165729.381	10081.82	769368.088	10081.82
100kW	1800	-144994.2915	11632.8688	-96856.5619	11632.869	165729.381	11632.869	769368.088	11632.869
6kW	400	-144994.2915	2585.08195	-96856.5619	2585.082	165729.381	2585.082	769368.088	2585.082
3.5kW	350	-144994.2915	2261.94671	-96856.5619	2261.9467	165729.381	2261.9467	769368.088	2261.9467
1kW	84	-144994.2915	542.867211	-96856.5619	542.86721	165729.381	542.86721	769368.088	542.86721

Variables			
Symbol	Description	Unit	Value
h_w	Water Depth	m	700
T	Cycle time	hr	12
d_p	Pulley Diameter	m	1

Figure 6 – Gearbox manufacturer table

The final tab, Feasibility and Cost Comparisons, contains a spreadsheet that allows different variables to be changed in order to determine how that will affect the design. Variables that can change are: depth of the water, cycle time, the number of tanks on each side of the cable, speed needed by the generator, rated generator output, generator rotor diameter, stack length, and air gap diameter, pulley diameter, hydrolysis unit specifications, market values of hydrogen, oxygen, and electricity. By changing these variables, the consequences of the change can be seen in the green highlighted section. Important values in this section include the number of hydrolysis units needed, the necessary size of the tank, and the torque needed to turn the generator. The potential revenue is also included. An important note about the revenue calculation, this number does not take into account transportation of the gases, licensing, maintenance, inspection, equipment, labor, or any other costs associated with running the project. As a result, this number should be used as a reference, and when those other costs are better understood, this number should be revised. The table can be seen in Figure 7.

Variables														
Depth (m)	Cycle Time (hr)	# Tanks per Side	Generator speed (rpm)	Generator rated output (kW)	Rotor Diameter (m)	Stack Length (m)	Radius of Air Gap (m)	Diameter of Pulley (m)	Nominal Hydrogen Flow Rate (m^3/hr)	Min. Power for Hydrolysis (kWh/m^3)	Market Value of Hydrogen ($/$m^3$)	Market Value of Oxygen ($/$m^3$)	Value of Unused Electricity ($/kWh)	Cooling Fluid Volume Flow Rate (m^3/hr)
700	0.166	1	20.5	1500	4	0.91	1.85	1	60	5.4	7	3	0.1259	7

Results		
Description	Units	Value
Min. pressure required to evacuate tank at depth	kPa	7,194.08
Torque needed, approximate	Nm	1,312,756.93
Outer Diameter of tank(s), needed	m	5.71
Inner volume of tank(s), needed	m^3	92.45
# Hydrolysis units needed	#/tank	4.64
Min. electrical power to run hydrolysis	kWh/day	2,214.09
Ammonia expansion	m^3/day	23.92
kWh generated	kWh/day	10,250.43
Volume of H_2 generated	m^3/day	205.01
Volume of O_2 generated	m^3/day	68.34
Profit from H_2	USD/year	$ 523,800.55
Profit from O_2	USD/year	$ 74,832.30
Profit from selling excess power	USD/year	$ 369,297.95
Revenue*	USD/year	$ 967,930.80

Figure 7 - Feasibility and cost comparison tab table

Power Generation Feasibility

The power generation ability of the apparatus is dependent upon the speed at which the pulley rotates and the amount of torque that is generated and the distance of time of movement when released or dropped. In order to generate optimal power, electrical generator shafts need to spin quickly, more quickly than the pulley spins during cycling. As a result of this, a gear reduction needs to be installed in between the pulley and the generator. The amount of torque it takes to turn the gear reduction and the generator is dependent upon the backdrive torque of the generator and the backdrive torque after the gear reduction. The higher the gear ratio, the more backdrive torque is necessary to rotate it. Starting torque is the highest, though the torque to keep it moving is also a factor. Because of various mechanical and electrical losses inherent in generating electricity, the electrical power generated will always be considerably less than the amount of mechanical power that is available at the source.

The power generation analysis detailed here examines the feasibility of generating 1.5MW using existing specifications from existing technology. The factors that are changed to determine the feasibility are the pulley diameter, cycle time, and size of the tank.

Determination of Necessary Torque

The concept of coupling a low speed turning device to a high speed electric generator with a gearbox is also used in wind turbines. As a result of this close parallel, specifications from wind turbine gearbox-generator pairs were used as a basis for the necessary generator speeds and gearbox backdrive torques for a 1.5MW device.

Varying Pulley Diameter and Cycle Time

The pulley diameter and cycle time have the greatest impact on the necessary gear ratio and torque generated. As a result, these factors were varied to determine if there was a feasible combination. The procedure followed was that the cycle time was used to find the speed tanks would be moving. This speed was put into the force balance equations in the spreadsheet, which impacted the torque generated. The gear ratio was calculated using the angular velocity of the pulley and the necessary output velocity for the specific generator. Three different pulley diameters were used for each different cycle time, 16.76m, 8m, and 1m.

When the pulley diameter is varied, it impacts the necessary gear ratio (R). When the cycle time is varied, it impacts the torque generated, tank speed, and the pulley speed. The torque generated by the falling sphere is taken to be the important torque, and is represented in the results.

Low Speed Generator Options

Some wind turbines make use of a technology that allows the slow turning blades to directly drive the generator. These generators require slow shaft speeds and large rotor diameters. They employ permanent magnets on the rotor to increase efficiency. The machines are synchronous and the power electronics invert the generated power to produce 60 Hertz. The power electronics also allow it to run at variable speed while maintaining the necessary 60 Hz [15]. This type of generator opens a promising door for this project. It would require a significantly smaller gearbox than conventional generators, while also generating 1.5 MW of power.

This section will cover torque calculations for a standard sized direct drive generator. Additionally, it will cover cost estimates for components, assembly, and testing. These analyses used data from a National Renewable Energy Laboratory (NREL) report comparing and contrasting different drive train configurations for wind turbines [4].

Torque Calculation

In the conversation with Ed Hellbock Sr. he provided a rule of thumb for calculating the amount of torque that is required to turn the generator, it is 9 pounds of force per square inch of rotor, this force is then multiplied by the radius of the air gap of the generator to get the torque [15]. The necessary dimensions and characteristics were obtained from the NREL report for a 1.5 MW [4].

1.5MW Direct Drive Generator

Using the torque method recommended by Mr. Hellbock Sr., the torque required to turn the generator was calculated. The dimensions used can be seen in Table 1 [15].

Table 1 - 1.5MW required dimensions and characteristics

Symbol	Description	Units	Value
ω_{gen}	Required speed of generator	RPM	20.5
n_p	Number of poles	-	96
d_{rotor}	Rotor diameter	m	4
L_{stack}	Rotor stack length	m	0.91
d_{ag}	Air gap diameter	m	3.7

$$Force = 9\frac{lbf}{in^2 rotor} * 2\pi rh$$

$$Force = 9\frac{lbf}{in^2 rotor} * 2\pi(78.74in)(35.98in) = 160{,}206.06\ lbf$$

$$T = Force * d_{ag}$$

$$T = (160{,}206.06\ lbf)(72.83\ in) = 11{,}667{,}807.55\ in - lbf = 1{,}318{,}284.76Nm$$

For a 10 minute cycle, the gear ratio would be 1:2.2 for a 1.5 MW generator. This would require 2,900,226.47 Nm of torque to turn, which would require an 18 m tank. The required dimensions, surface area, and volume can be seen in Table 2.

Table 2 - Tank dimensions for 1.5MW generator, 10 minute cycle

Symbol	Description	Units	Value
T_{in}	Minimum torque requirement	Nm	2,900,226.47
d_{sphere}	Necessary diameter of the sphere	m	18
SA	Surface area of the tank	m^2	1,017.88
V_{outer}	Outer volume of the tank	m^3	3,353.63
V_{inner}	Inner volume of the tank	m^3	2,952.97

Cost Approximation

The NREL report also provided cost approximations for the components, assembly, testing, and maintenance [4]. The majority of the data is for the 1.5MW generator. Since the report was published in 2002, the results were adjusted for inflation [16]. The cost of assembly and testing was calculated using the rate described in C.2-1, $65/kg. The total weight was found in the table on page C-18 to be 27,251 kg [4]. This is how the total cost of assembly and testing was calculated. They can be seen in Table 3.

Table 3 – Approximate costs for 1.5MW system

Cost Description	Reference	1.5MW Cost	After Inflation
Total Component Cost	Table 8-3, pg. 127	$540,000	$711,446.25
Assembly and Testing Cost	Pg. C-18	$1,771,315	$2,333,695.20
Approx. Maintenance Cost/year	Table 8-4, pg. 129	$29,732	$39,171.70
Total	-	**$2,341,047**	**$3,084,313.15**

This cost is just for the generation component of the system. The hydrolysis component and associated gas separation, cooling and additional compression would be a separate component.

Rankine Engine Addition

The addition of a Rankine cycle was also proposed in order to bolster the amount of electricity that could be generated and utilize the heat generated by the hydrolysis unit. A Rankine cycle utilizes temperature differentials to generate a superheated fluid that then turns a turbine, Figure 8. The Rankine cycle operates by a pump pressurizing a fluid in its liquid form and cycling it through a boiler (in this case the hydrolysis unit), state 2 in the diagram. The heat source would superheat the fluid causing it to change phase to a vapor, state 3. The high pressure, superheated vapor then expands into a turbine, causing it to turn, and thereby run a generator. The fluid exits the turbine as a saturated mixture of vapor and liquid, it is at low pressure and a cooler temperature, state 4. Next, the saturated mixture goes through a condenser where it becomes a cooled, low pressure liquid and is ready to re-enter the pump, state 1.

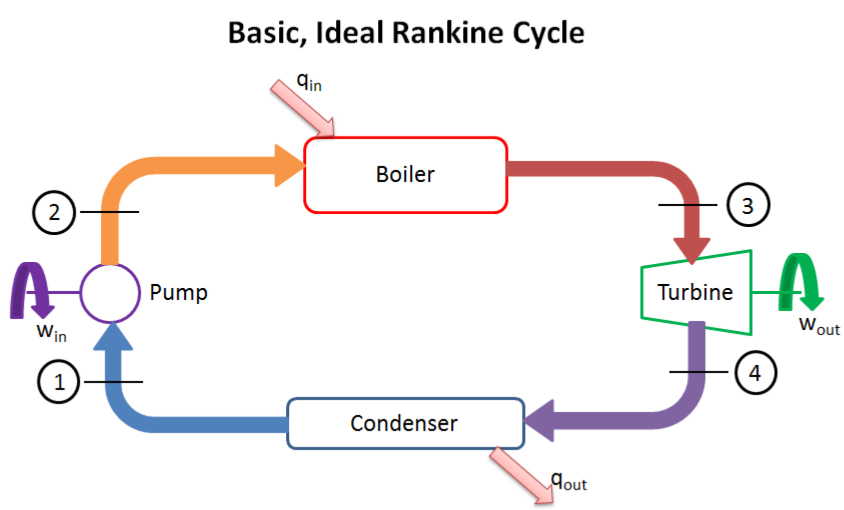

Figure 8 - Basic, ideal Rankine cycle

Ideally, this cycle would provide cooling to the hydrolysis unit as well as generate more electricity that can then be used to power the hydrolysis unit. The working fluid would be ammonia, since it has a low temperature for vaporization. The ammonia would be used as the cooling fluid in the hydrolysis unit, so the hydrolysis unit would act as the boiler. The turbine would need to be located at the surface, so the superheated ammonia would then need to be stored, at high pressure during the cycle of the tank. When the tank surfaced, the superheated, high pressure ammonia vapor would be evacuated through a turbine. The saturated mixture that exited the turbine would then be returned to the unit to be cooled and condensed by the surrounding ocean water so that it could then be used again as coolant.

Observations

The evaluation of the addition of a Rankine of Kalina cycle to the Gravitron Ballast system began with some qualitative observations. Power generation would be able to be continuous with multiple units set in series. With the turbine located at the surface the gas it would then need to be stored, and insulated to remain superheated, until the tank reached the surface. This would be done by having the superheated gas stored in the center bladder that is surrounded by the 2 compressed gasses of hydrogen and oxygen which will also be heated by compression. The superheated vapor could then be used to generate electricity. Once the stored vapor compression was used, electricity generation would cease. While this energy could theoretically be stored, the hydrolysis unit requires continuous power while in operation. It is assumed that the excess power would be used to subsidize the hydrogen production at the surface to create additional compression of the hydrogen and oxygen gasses for distribution.

Analysis

The analysis of the Rankine cycle was done under four assumptions unique from the main assumptions stated earlier in the report.

First, the cycle is assumed to be ideal. Meaning that there are no inefficiencies present, no leakage, the heating cycle is isentropic and adiabatic, and no energy is lost to the environment.

Second, it is operating in a continuously running cycle. This means that there is no starting or stopping of the turbine as would be present under actual operating conditions.

Third, the cycle is operating under steady conditions. This assumes that the turbine and pump are running at a steady rate and that there is no warm up time for the boiler.

Fourth, kinetic and potential energy changes are negligible, which means that height differences, or energy associated with moving pieces do not come into play in the analysis.

With these assumptions in mind, the conditions were chosen for the four important states of the cycle, Figure 9. The fluid leaves the condenser and enters the pump in state 1 at 50 kPa, a 40 percent decrease from turbine inlet pressure. After being compressed by the pump, the fluid moves to the boiler at 2 MPa, state 2. After going through the isentropic boiler, the superheated enters the turbine at 2 MPa and 60^{o}C, state 3. This pressure and temperature combination was chosen because the pressure at which the hydrolysis unit generates hydrogen is 145psi (14.6 MPa), so the ammonia should be compressed no more than that, however, available tables for superheated ammonia only went as high as 2 MPa [17] [18]. The temperature of 60^{o}C was chosen because it would be required to create superheated ammonia and because this represented a reasonably achievable amount of heat addition. After exiting the turbine, the saturated mixture went to the isentropic condenser at 50 kPa, state 4.

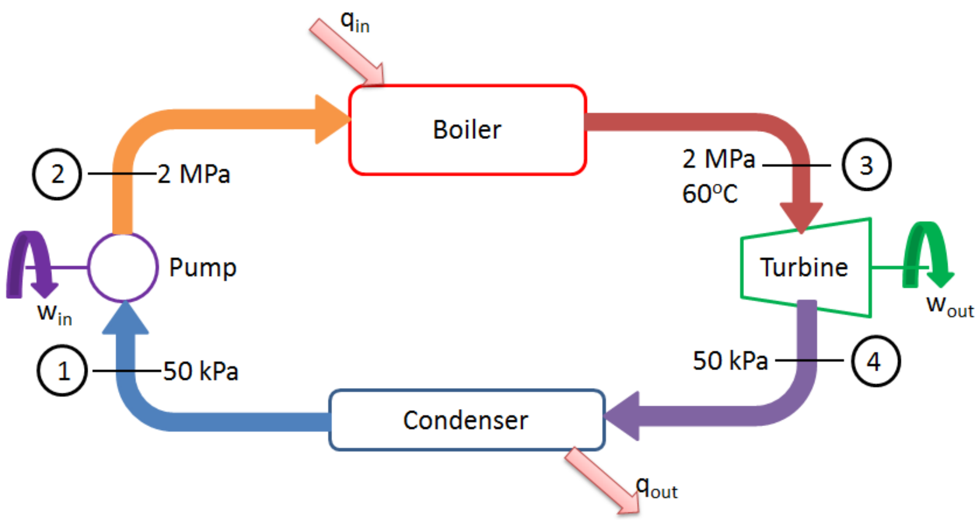

Figure 9 - Rankine cycle with state conditions listed

The first step in the analysis was to determine the key parameters at each state. Parameters symbols are: v = specific volume (m^3/kg), h = enthalpy (kJ/kg), s = entropy (kJ/kg·K), w = work, x = quality. All equations in this section were obtained from [19]. All parameter values in this section were obtained from [18], unless otherwise stated.

State 1: P_1 = 50 kPa, saturated liquid

$h_1 = h_{f@50kPa} = -15.8$ kJ/kg

$v_1 = v_{f@50kPa} = 0.001433\ m^3/kg$

State 2: P_2 = 2 MPa, saturated liquid, $s_2 = s_1$

$$w_{in} = v_1(P_2 - P_1) = \left(0.001433\frac{m^3}{kg}\right)[(2000-50)kPa]\left(\frac{1\ kJ}{1\ kPa{\cdot}m^3}\right)$$

$w_{in} = 2.79435$ kJ/kg

$$h_2 = h_1 + w_{in} = -15.8\frac{kJ}{kg} + 2.79435\frac{kJ}{kg}$$

$h_2 = -13.00565$ kJ/kg

State 3: P_3 = 2 MPa, T_3 = 60°C, superheated gas

$h_3 = h_{g@2MPa,\ 60C} = 1{,}529.6$ kJ/kg

$s_3 = s_{g@2MPa,\ 60C} = 5.1742$ kJ/kg·K

State 4: P_4 = 50 kPa, saturated mixture, $s_4 = s_3$

$$x_4 = \frac{s_4 - s_f}{s_{fg}} = \frac{5.1742\frac{kJ}{kg{\cdot}K} - 0.1356\frac{kJ}{kg{\cdot}K}}{6.2376\frac{kJ}{kg{\cdot}K}}$$

$x_4 = 0.8078$

$$h_4 = h_f + x_4 h_{fg} = -15.8\frac{kJ}{kg} + (0.8078)\left(1413.9\frac{kJ}{kg}\right)$$

$h_4 = 1126.35$ kJ/kg

The heat (q) added by the boiler and rejected by the condenser were found next.

$$q_{in} = h_3 - h_2 = 1529.6\frac{kJ}{kg} - \left(-13.00565\frac{kJ}{kg}\right)$$

$\underline{q_{in} = 1{,}542.6 \text{ kJ/kg}}$

$$q_{out} = h_4 - h_1 = 1126.35\frac{kJ}{kg} - \left(-15.8\frac{kJ}{kg}\right)$$

$\underline{q_{out} = 1{,}142.15 \text{ kJ/kg}}$

Using these values, the thermal efficiency for the Rankine cycle was calculated.

$$\eta_{th} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{1142.15\frac{kJ}{kg}}{1542.6\frac{kJ}{kg}} = 0.2596$$

$\underline{\eta_{th} = 25.96\%}$

Next, the net power done by the Rankine cycle was found. A mass flow rate of 2 m^3/hr was used [17]. Density of ammonia is 602 kg/m^3 [19].

$$\dot{m} = 2\frac{m^3}{hr} \cdot 602\frac{kg}{m^3} \cdot \frac{1\ hr}{3600\ sec} = 0.00344\frac{kg}{sec}$$

$$w_{out} = h_3 - h_4 = 1529.6\frac{kJ}{kg} - 1126.35\frac{kJ}{kg}$$

$\underline{w_{out} = 403.25 \text{ kJ/kg}}$

$$w_{net} = q_{in} - q_{out} = 1542.6\frac{kJ}{kg} - 1142.15\frac{kJ}{kg}$$

$\underline{w_{net} = 400.45 \text{ kJ/kg}}$

$$\dot{W}_{net} = \dot{m} \cdot w_{net} = \left(0.00344\frac{kg}{sec}\right)\left(400.45\frac{kJ}{kg}\right)$$

$$\boldsymbol{\dot{W}_{net} = 1.38\ kW}$$

Results

The power generated by the Rankine cycle is 1.38 kW per cu meter of ammonia. This is assuming an ideal, continuous process. In this setup, the ammonia would need to cool and condense on the way down, and then there would be a variable time on the way up to generate hydrogen based on the size and amount of hydrolysis units utilized. Taking into account inefficiencies such as bearing friction, startup losses, turbine and pump inefficiencies, leakage of ammonia, air or water that leak into the system, pressure drop in the boiler, condenser, and piping, among others, the power that would be generated would be significantly less than 1 kW. The amount of ammonia that can be used will be determined by the heat available from the hydrolysis reaction and the volume of pressurized gas that is desired to charge the ballast. The larger the tank, the larger the volume needed and the deeper the vessel the higher the pressure. The heat by-product off the reaction is substantial as it generates approx. 12,857 BTU per cubic meter of hydrogen produced. This cooling is needed regardless so the Rankine cycle addition accomplishes a mechanism for cooling while generating both compression and electricity from the heat. Feasibility and Cost Comparison Calculations

The methodology for calculating each of the required values in the Feasibility and Cost Comparison tab. Presenting the equations used and methodology in obtaining those equations allows for the end user of this spreadsheet to understand what is happening behind the scenes. The equations are presented below in order of their appearance in the table.

Minimum Pressure Required to Evacuate Tank at Depth

The minimum pressure that is required to evacuate the tank is a function of the maximum depth to which the tank will descend. For every 10 meters below the surface of the water the pressure increases by 1 atmosphere, which is 101.325 kPa. This can be represented by the fraction

$\frac{101.325\ kPa}{10\ m}$. When this is multiplied by the depth it gives the amount of pressure supplied by the water, adding the atmospheric pressure present at the surface gives the equation:

$$P = \left(h_w \frac{101.325\ kPa}{10\ m}\right) + 101.325\ kPa$$

Torque Needed

The torque needed to turn the generator is a function of the rotor and airgap size of the generator. The rough amount of force needed is 9 lb/in^2 of rotor. After converting this number to N/m^2, the final equation used was:

$$T_{needed} = 62{,}052.793\frac{N}{m^2} \cdot 2\pi r_{rotor} h_{stack} \cdot r_{airgap}$$

Outer Diameter of Tank(s)

Finding the necessary outer diameter of the tank, or tanks is dependent on the necessary torque. So the torque as a function of the diameter of the tank is found from the force balances. The torque equation is:

$$T_{needed} = \Bigg\{\rho_{sw} g \tfrac{4}{3}\pi \left(\frac{d_{ot}}{2}\right)^3 + \tfrac{1}{2} C_D \rho_{sw} \left(\frac{h_w}{T \cdot 3600}\right)^2 4\pi \left(\frac{d_{ot}}{2}\right)^2 - \left[\left(\tfrac{4}{3}\pi \left(\frac{d_{ot}}{2}\right)^3 - \tfrac{4}{3}\pi \left(\frac{d_{ot}-t}{2}\right)^3\right)\rho_{ss} + m_h + \tfrac{4}{3}\pi \left(\frac{d_{ot}-t}{2}\right)^3 \rho_{sw} + m_c\right] g\Bigg\} \tfrac{1}{2} d_p$$

This equation is then rearranged into an equation in the form $0 = ax^3 + bx^2 + cx + d$ so that the cubic formula can be used to solve it for d_{ot}.

$$0 = \left(\frac{\rho_{sw} g \pi}{3}\right) d_{ot}^3 + \left(\frac{C_D \rho_{sw} h_w^2 \pi}{2T^2 3600^2} + \frac{\pi \rho_{ss} t g}{2} - \frac{\rho_{sw} \pi t g}{2}\right) d_{ot}^2 + \left(\frac{\pi t^2 g}{2}(\rho_{sw} - \rho_{ss})\right) d_{ot} + \left(\frac{\pi \rho_{ss} t^3 g}{6} - \frac{\pi \rho_{sw} g t^3}{6} + m_h g + m_c g - \frac{2T_{needed}}{d_p}\right)$$

Assigning the coefficients a, b, c, and d to the coefficients in the rearranged equation allows the cubic formula to be used. The coefficients are as follows:

$$a = \left(\frac{\rho_{sw} g \pi}{3}\right)$$

$$b = \left(\frac{C_D \rho_{sw} h_w^2 \pi}{2T^2 3600^2} + \frac{\pi \rho_{ss} t g}{2} - \frac{\rho_{sw} \pi t g}{2}\right)$$

$$c = \left(\frac{\pi t^2 g}{2}(\rho_{sw} - \rho_{ss})\right)$$

$$d = \left(\frac{\pi \rho_{ss} t^3 g}{6} - \frac{\pi \rho_{sw} g t^3}{6} + m_h g + m_c g - \frac{2T_{needed}}{d_p}\right)$$

Using these coefficients for simplicity's sake, the cubic formula is:

$$d_{ot} = \sqrt[3]{\left(\frac{-b^3}{27a^3} + \frac{bc}{6a^2} - \frac{d}{2a}\right) + \sqrt{\left(\frac{-b^3}{27a^3} + \frac{bc}{6a^2} - \frac{d}{2a}\right)^2 + \left(\frac{c}{3a} - \frac{b^2}{9a^2}\right)^3}}$$

$$+ \sqrt[3]{\left(\frac{-b^3}{27a^3} + \frac{bc}{6a^2} - \frac{d}{2a}\right) - \sqrt{\left(\frac{-b^3}{27a^3} + \frac{bc}{6a^2} - \frac{d}{2a}\right)^2 + \left(\frac{c}{3a} - \frac{b^2}{9a^2}\right)^3}} - \frac{b}{3a}$$

Once this equation is solved for d_{ot}, the resulting answer is then divided by the number of tanks on each side to give the necessary diameter of each of the individual tanks.

Inner Volume of Tank(s)

The inner volume of the tanks is simply based upon the thickness of the tank, set in the constants section of the spreadsheet, and the diameter of the tanks found above.

$$V_{in} = \frac{4}{3}\pi\left(\frac{d_{ot} - t}{2}\right)^3$$

Number of Hydrolysis Units Needed

The number of hydrolysis units that are needed is dependent upon the interior volume of the tank and the flow rate of hydrogen from the specified hydrolysis unit. The SCFM of hydrogen required for displacement in the tank is relative to the pressure at the depth of the system and will increase proportionally to the multiples of atmospheres. It was assumed that only 15% of the aggregate tanks must be filled with hydrogen and the rest will be filled with vaporized ammonia and oxygen. The amount of hydrogen that can be generated in one cycle time is first calculated, and then is divided into the necessary volume. This gives the number of hydrolysis units required for a specific amount of production per hour/ shift.

$$\# = \frac{V_{in}/2}{T \cdot \dot{V}}$$

The above result is multiplied by the ratio of P2/ P1.

Where # denotes the number of hydrolysis units needed, V_{in} is the interior volume of the tank, T is the cycle time, and $\dot{V}$ is the volume flow rate of the hydrolysis unit.

Minimum Electrical Power to Run Hydrolysis

The power required by the hydrolysis unit is 5.4 kWh/m^3 [17]. Knowing this, the units that are needed to obtain kWh/day are m^3/day. Considering that the tanks will need to stop at the surface to discharge the hydrogen, ammonia, and oxygen and fill up with water, each cycle will need to have two discharge periods. Assuming that this discharge period is about 30 minutes, then an extra hour needs to be added to the cycle time. The number of cycles in a day can be found by:

$$\frac{\#\,cycles}{day} = \frac{24}{T + 1}$$

Then, the volume gotten per cycle is found by:

$$\frac{m^3}{cycle} = T \cdot \dot{V}$$

Putting these together, and multiplying by two for the two sides of the cable:

$$\frac{m^3}{day} = \left[\left(\frac{24}{T+1}\right) T\dot{V}\right] 2$$

Multiplying this by the power to run the hydrolysis unit, the power required to run the hydrolysis unit per day is found:

$$Power = \left[\left(\frac{24}{T+1}\right) T\dot{V}\right] 2 \left(5.4\ \frac{kWh}{m^3}\right)$$

Ammonia Expansion

This metric denotes what volume of ammonia can be vaporized in a day given the heat that is generated by the hydrolysis unit. Per the data sheet, the HyStat 60-10 requires a cooling fluid flow rate of 7 m^3/hr, represented as $\dot{V}$ in this equation [17]. To find out how much of this will pass through in a day, the same idea as the minimum electrical power needed was used, assuming that the cooling would not need to be running when the hydrolysis unit is not running.

$$\frac{m^3_{ammonia}}{day} = \left(\frac{24}{T+1}\right) \cdot T \cdot \dot{V}$$

Parameters Needed for Ammonia Expansion

In order to determine how much heat would need to be input into the cooling system from the hydrolysis unit, the following analysis was completed. The assumptions that are made in this section are that the pressure in the system remains the same between the liquid ammonia and the superheated ammonia. It is also assumed that the ambient ocean temperature ammonia is pressurized prior to being stored. West coast ocean temperatures generally range between 50^{o}F and 58^{o}F (10^{o}C - 14.4^{o}C), in order for the ammonia to be liquid at this temperature, the pressure would need to be between 650 kPa and 750 kPa. This analysis will use 700 kPa and 13.8^{o}C as the starting parameters.

State 1:
Saturated liquid ammonia at ambient ocean temperature
P_1 = 700 kPa
T_1 = 13.8^{o}C
$h_{f,1}$ = 264.7 kJ/kg

State 2:
Post cooling loop, ammonia is now superheated
P_2 = 700 kPa
T_2 = 20^{o}C
h_2 = 1,492.8 kJ/kg

To determine the amount of heat needed to accomplish this, the following equation is used:

$$q_{in} = h_2 - h_1 = 1{,}492.8\frac{kJ}{kg} - 264.7\frac{kJ}{kg} = 1{,}228.1\frac{kJ}{kg}$$

If the hydrolysis unit can consistently generate 1,228.1 kJ/kg of heat, then the ammonia cooling loop will be able to produce superheated ammonia.

kWh Generated

The number of kWh that are generated in a day is a function of the amount of time the tanks move per cycle, the number of cycles per day, and the rated power of the generator.

$$\frac{kWh}{day} = (gen\_out)(2T)\left(\frac{24}{T+1}\right)$$

Volume of Hydrogen Generated

The volume of hydrogen that is generated in a day is based upon the volume flow rate of the hydrolysis unit, the cycle time, ratio of hydrogen to the ancillary gasses and number of cycles per day.

$$\frac{m^3}{day} = \left(\frac{24}{T+1}\right)T\dot{V}$$

Volume of Oxygen Generated

The volume of oxygen generated in a day is based upon the volume flow rate of the hydrolysis unit, the cycle time, and number of cycles per day. Assuming that one third the amount of oxygen is generated as hydrogen, the equation is:

$$\frac{m^3}{day} = \left(\frac{24}{T+1}\right)T\frac{1}{3}\dot{V}$$

Profit from Hydrogen

The profit that can be made from hydrogen is the volume of hydrogen generated per day multiplied by the market value of hydrogen, then multiplied by 365 days to get the profit per year.

$$\frac{\$}{year} = \frac{m^3}{day} \cdot (value\ of\ H_2) \cdot 365$$

Profit from Oxygen

The profit that can be made from oxygen is the volume of oxygen generated per day multiplied by the market value of oxygen, then multiplied by 365 days to get the profit per year.

$$\frac{\$}{year} = \frac{m^3}{day} \cdot (value\ of\ O_2) \cdot 365$$

Profit from Selling or Using Power during Peak vs Off-Peak

The profit from utilizing any excess power from power company can be found by taking the peak power generated cost minus the power used by the hydrolysis unit and multiplying this value by the market value of electricity [20]. This power would be used to compress, pump and run the facility thus subsidizing the cost of producing and distributing the hydrogen. Energy that is stored as potential gravitational energy is designed to shift off peak unutilized power from the existing system to on peak usage or used to further reduce the cost of the production of the hydrogen. The value of this shift would be based on your current cost of energy and the amount of unutilized energy potential to run the system.

$$\frac{\$}{year} = \left(power_{gen} - power_{hydrolysis}\right) \cdot (value\ of\ electricity) \cdot 365$$

Revenue

The revenue is calculated by adding the profit from oxygen, the profit from hydrogen, and the profit from selling excess power together. If more power is used than is generated, then that negative value will be subtracted from the profits of the gases. This is an optimistic revenue considering that costs from labor, maintenance, transportation, licensing, equipment, etc.

$$\frac{\$}{year} = profit_{oxy} + profit_{hyd} + profit_{elect}$$

Conclusions

The use of low speed generators would allow a large amount of power to be generated with significantly slower speeds and thus over longer time periods. 1.5MW of power per side or 3 MW can be generated using larger slow speed generators to convert stored gravitational energy to power over approx. nine hours. For this solution, the tanks would be split into multiple slower modules to enable manufacturing and transportation. It is estimated that 4.8 MW of unutilized off-peak wind or off peak power plant energy to accumulate the required stored gravitational energy to power the system for on peak usage. Since the tank would be filled with valuable hydrogen and medical grade oxygen and the compression required for displacement would be subtracted from the amount of energy required at the surface for further compression and distribution, the resulting stored gravitational energy becomes a by-product. This buoyant force raises the tanks and allows for equal energy from the fall to the bottom when designed to balance. It is this co-generation that accounts for a cyclical potential for the utilization of stored gravitational energy as a source to subsidize the production.

The addition of a Rankine cycle could potentially generate more electricity using the heat generated by the hydrolysis unit to fuel the cycle. This was discovered to be 26% efficient and able to generate 1.38 kW per cu meter of ammonia in an ideal and continuous scenario. Because the cycle would not be ideal the power likely to be generated through the use of this cycle would be less than 1 kW per cu meter. The cycle has several advantages to charge the ballast and not require the hydrolysis of hydrogen and oxygen to displace the ballast. Using pressurized ammonia under pressure as the center of the expansion would allow for 50% or more of the expansion needed to run the ballast. This compressed superheated ammonia would also be kept hot by surrounding the ballast compartments with the pressurized hydrogen and oxygen. At the surface the pressurized superheated gas can run a turbine and be re-collected to repeat the cooling cycle for the hydrolysis units. During the fall to the bottom the ammonia will condensate with the water temperature and convective ports in the ballast. This system would need to be balanced with the number of hydrolysis units to match the waste heat available. The excess heat could also be used to deionize the water for the reaction or other water purification procedures.

The Following Advantages Are Evident.

1. Compression required for buoyancy displacement is re-captured at the surface. This would only be relevant if further compression was useful and valuable as in the production of hydrogen and oxygen. The compressed oxygen could also be used in the generation of power of not sold for other purposes.
2. Use of unutilized energy from wind or off peak power generation is solved by both hydrogen production which is in itself energy storage and stored gravitational energy as a by-product.
3. Production under water reduces the infrastructure costs of current storage options using stored gravitational energy. It also eliminates substantial costs associated with mechanical cooling of above ground hydrogen production. By utilizing the Rankine Cycle the superheated ammonia under pressure becomes not only stored heat but stored gravitational energy again as a double byproduct. This energy is also re-captured at the surface by running a generator while de-compressing and cooling itself for re-use. Since a system is required for hydrogen production, this cogeneration becomes a valuable efficiency improvement for the production of hydrogen by minimizing energy losses.
4. Desalination would be a logical addition to the system to utilize the waste heat stored in the ammonia that is de-compressed at the surface. Energy required to desalinate water would be subsidizes with this substantial heat source. Since most power plants also desalinate water, eliminated fossil fuels would have to take into account this missing component.
5. Water purification and storm water catchment if installed in a quarry could solve multiple problems of the surrounding areas during times of heavy rain and sewer overflow that ends up in the lake. Local storm sewers could be diverted into the quarry for collection and then used for the process. The same water could be filtered and re-used in the local area to mitigate local water shortages during times of drought and ease the burden of the local treatment plant. Pressures accumulated during the production process could also be used to fund filtration again lowering cost of that process.
6. Scaling the operation would be a function of how much hydrogen could be sold profitably into the market. It is assumed that compression would be done on site for efficient distribution to other locations. A series of standardized twin modules are envisioned that could be combined for any size operation. One production facility could service a large nearby area with hydrogen at a low cost to service the auto and fuel cell industry. Backup power generation could also be converted to hydrogen or a combination of hydrogen and natural gas.

Summary

The net result would be a very efficient hydrogen/oxygen manufacturing method with a combined off peak energy storage method and co-generation of power by use of a gravity/ buoyancy cycle that is using the waste energy. The added benefits of water conservation and management and the stored energy of the cold water itself to run the process makes the existing quarry an ideal application. Utilizing an existing quarry would lower installation costs exponentially over an ocean installation. Preparing the manufacturing area for storms would be much easier than the alternate ocean installation that could encounter hurricanes or extreme waves and stress. There would also be no limit to the consumption of the resulting hydrogen in the local automobile market in an urban area and distribution costs would be very low.

For information on this system contact:

Ralph Bencriscutto

President

Tower Energy International LLC

ralphb@towerenergypartners.com

262-664-3166 direct cell

Bibliography

[1] T. Benson, "Shape Effects on Drag." NASA Glenn Research Center, 12-Jun-2014.

[2] "Water Compressibility, USGS Water Science School," *U.S. Geological Survey*, 17-Mar-2014. [Online]. Available: http://water.usgs.gov/edu/compressibility.html. [Accessed: 10-Nov-2015].

[3] "Physical Properties Online Calculator ..." [Online]. Available: https://www.engineering-4e.com/calc1.htm. [Accessed: 10-Nov-2015].

[4] R. Poore and T. Lettenmaier, "Alternative Design Study Report: WindPACT Advanced Wind Turbine Drive Train Designs Study," National Renewable Energy Laboratory, Kirkland, WA, Subcontractor Report NREL/SR-500-33196, Aug. 2003.

[5] K. Remington, "Nordic Windpower's N1000 1-MW turbine," *Windpower Engineering and Development*, 08-Jun-2010. [Online]. Available: http://www.windpowerengineering.com/design/nordic-windpower%E2%80%99s-n1000-1-mw-turbine/. [Accessed: 10-Dec-2015].

[6] "Nordic Windpower Nordic 500," *The Windpower: Wind Energy Market Intelligence*, Dec-2015. [Online]. Available: http://www.thewindpower.net/turbine_en_1267_nordic-windpower_500.php. [Accessed: 14-Jan-2016].

[7] "Nordic Windpower Nordic 400," *The Windpower: Wind Energy Market Intelligence*, Dec-2015. [Online]. Available: http://www.thewindpower.net/turbine_en_1266_nordic-windpower_400.php. [Accessed: 14-Jan-2016].

[8] "PowerWorks wind turbines, American made 100 kW wind turbine sales, new used rebuilt wind turbines." [Online]. Available: http://www.powerworks.com/100kw_wind_turbine.aspx. [Accessed: 19-Jan-2016].

[9] "6 kW Bergey Excel 6 - Bergey Wind PowerBergey Wind Power," *Bergey Windpower*, 2012-2011. [Online]. Available: http://bergey.com/products/wind-turbines/6kw-bergey-excel. [Accessed: 14-Jan-2016].

[10] "3.5 kW Wind Turbine System Specification Sheet." Raum Energy.

[11] "1 kW Bergey Excel 1 - Bergey Wind PowerBergey Wind Power," *Bergey Windpower*. [Online]. Available: http://bergey.com/products/wind-turbines/bergey-excel-1. [Accessed: 10-Dec-2015].

[12] "West Coast Wire Rope." [Online]. Available: http://www.wcwr.com/catalog/webcat.pdf. [Accessed: 10-Dec-2015].

[13] "Minimun cable bend radii - Mechanical engineering other topics - Eng-Tips," 21-Jan-2007. [Online]. Available: http://www.eng-tips.com/viewthread.cfm?qid=175678. [Accessed: 04-Jan-2016].

[14] M. Stieber, "Design of a Small Scale Power Generation Device for Undersea Moored Sensor Arrays," Master's, Oregon State University, Corvallis, OR, 2015.

[15] E. Hellbock Sr., "Power Train Engineers Gearbox Consultation," 21-Jan-2016.

[16] "Inflation Calculator | Find US Dollar's Value from 1913-2015," *US Inflation Calculator*. [Online]. Available: http://www.usinflationcalculator.com/. [Accessed: 22-Jan-2016].

[17] "Outdoor Generators - Water Electrolyser - HySTAT 10 Outdoor," *Hydrogenics*, 2013. [Online]. Available: http://www.hydrogenics.com/hydrogen-products-solutions/industrial-hydrogen-generators-by-electrolysis/outdoor-installation/hystat-trade-10. [Accessed: 06-Jan-2016].

[18] The Department of Mechanical Engineering at The University of Texas at Austin and The Department of Environmental Resources Engineering at Humboldt State University, "List of Tables," *ThermoNet*. [Online]. Available: http://www.wiley.com/college/moran/CL_0471465704_S/user/tables/index.html#ammonia. [Accessed: 05-Jan-2016].
[19] Y. A. Cengel and M. A. Boles, *Thermodynamics: An Engineering Approach*, 7th ed. McGraw Hill, 2011.
[20] "Electric Power Montly," *U.S. Energy Information Administration*, Oct-2015. [Online]. Available: https://www.eia.gov/electricity/monthly/epm_table_grapher.cfm?t=epmt_5_6_a. [Accessed: 07-Jan-2016].

For more information on Hydrogenics hydrolysis units, their capabilities and limitations, contact Rob Delcore with Hydrogenics at 858-386-8930 or rdelcore@hydrogenics.com.