GENERATING POWER WITH ENERGY UPGRADING OF OCEAN FLOWS

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Abstract

Kinetic energy of water currents is generally very low. Without upgrading on this hydro-kinetic energy, none of marine/river current turbines has proved commercially viable anywhere. This paper discusses a new possible system – namely Hydro-kinetic Power Plant (HKPP), which upgrades the hydrokinetic energy directly in the water body/area employs very old Bernoulli principle using twin laterally reversed funnel instead of expensive inland dam. The upgraded waterpower which automatically occurs in the funnel throat drives hydrokinetic turbine and generator so that generates electric power cost effectively. With this way, on the sea of least available depth 60m (with sufficient area) and minimum current velocity of 0.25m/s (very low) for example, there is possible for HKPP to generate electric power 500 MW/unit which requires water area of maximum 44 hectares. So, if 1% of Japanese water area includes EEZ owns the said depth and velocity, there is possible for development of more than 110,000 units HKPP with a combined capacity more than 55,150,000 MW. This figure equivalent to an endless oil/fuel consumption/production more than 2.25 billion barrels/day. By assuming the funnel and other buildings are made of high grade concrete, power supply with 2 units x 500 MW/unit = 1000 MW is possible to be realized at levelized cost of electricity about $4.5cent/kWh – indicatively competitive against the cost of other power plants. Further intensive and detail R&D with involving competent experts hopefully can prove the system viability.

Keywords: hydro-kinetic energy, Bernoulli, twin funnel, turbine, levelized cost of electricity

INTRODUCTION

Ocean is the greatest natural water dam of the universe, covers an area about 350 million km^2 or about 70% the earth surface with an average depth (h) of 3,827 m, so it holds water volume (Q) of about 1,338 million km^3[i,ii]. Base on the water mass density (ρ) ±1027 kg/m^3 and force/acceleration due to gravity (g) ±9.81 m/s^2, ocean provides static or hydrostatic pressure (ρ*g*h) of average 38.56 MPa and thus stores potential energy (ρ*g*h*Q) of globally about 51,589,000 trillion megawatts (±51.59 x 10^{18} MW). However, this huge static energy can only generate useful waterpower if change into dynamic or kinetic energy, but how?

On the other hand, global water mass (ρ*Q) generally moves, mostly in form of water currents with normally very low speed (V) hence provides very low dynamic pressure (½*ρ*V^2) and thus generates very low kinetic energy (½*ρ*V^2*Q) – the real love of Allah, not giving storm and tsunami all of the times. In the scope of conservation of mass and energy, where pressure is defined as energy per volume (ρ*g*h = ½*ρ*V^2 = conserved), marine current speed (V) of even 3.5 m/s which is uncommon found over the global ocean provides only dynamic pressure (½*ρ*V^2) of ±6.29 kPa – stills lower compare to static pressure (ρ*g*h) ±9.81 kPa is available in inland waterfall of 1m height (h). Moreover, none of conventional hydropower plants is commercially developable too at the waterfall as low as 1m height. That's the reason why kinetic energy of water streams (hydro-kinetic energy) needs to be upgraded.

In fluid mechanics, water is known as an in-viscid (un-viscous) and incompressible fluid, so it always easily flows while keeping its mass density (ρ) remains constant even under pressure, e.g. ±1027 kg/m3 for seawater, ±1000 kg/m3 for freshwater, depending on the environment.

Anywhere on the earth surface includes ocean floor, force/acceleration due to gravity (g) stills constant ±9.81 m/s^2. None of matters includes waters in the earth orbit can avoid the force or acceleration due to gravity (g). Thereby here would be noted that accelerating water flow speed in order to increase the kinetic energy by only decreasing the flow cross section area in accord with continuity principle – without involving the gravity (g) should be misleading.

For laterally moving fluid as of common water currents, the flow depth or fluid column height is also commonly used as head/hydraulic head (h) instead of only surface elevation difference is usually used in vertically moving fluid as of common waterfalls/falling water in conventional hydroelectric dam. Thus here would be noted too, "zero/low head hydropower" in many literatures so far is named for marine/river current turbines could be also misleading because water currents can have significant head (h) in form of water depth/column height.

The above logics existed in very old Bernoulli principle [iii,iv] which basically states that in an inviscid and incompressible flow, sum of the flow energy in form of dynamic pressure plus static pressure (½*ρ*V^2 + ρ*g*h) remains constant/conserved satisfies conservation of energy, (i.e. energy can't be created nor destroyed, it can only change in form, but can't change in the magnitude). Accordingly, an increase in one of those energy requires a decrease in another proportionally. Therefore, as/when volume of the flow (Q) is engineered remains constant to satisfy conservation of mass (ρ*Q = constant), the increase in the flow speed (V), dynamic pressure (½*ρ*V^2) and kinetic energy (½*ρ*V^2*Q) respectively balances with the decrease in the flow depth/head (h), static pressure (ρ*g*h) and potential energy (ρ*g*h*Q) or so forth.

This universal principle is employed in developing an idea about Hydro-Kinetic Power Plant (HKPP) which is an invention of the first author Cicip Hadisucipto, Patent: ID.P000035093.

SUMMARY OF THE INVENTION

In HKPP (see sketch), kinetic energy of laterally moving water mass is upgraded directly in the water body/area by decreasing its potential energy using twin laterally reversed funnel instead of expensive inland dam. In either two ways flows as of common tidal currents or one way flows as of common rivers, the maximum upgraded hydrokinetic power automatically occurs in the funnel smallest section (throat). At one of the funnel largest ends (inlets), the flow automatically backs to the natural condition, so HKPP friendlier to the water environment. Vertical axis (cross flow) hydrokinetic turbine of any appropriate types which is protected in special housing and placed at the throat converts the maximum hydrokinetic power into rotating mechanical power. High dynamic pressure concentration and turbine protection in the relatively small throat area makes the turbine more efficient – not subject to what so called Betz Limit. The power of turbine is the transmitted through vertical shaft with/without gearbox to electric generator is mounted in pontoon deck (Float Type HKPP), or platform floor (Fixed Type HKPP) or directly underwater just outside above the turbine house (Immersed Type HKPP as depicted below) and thus the rotating mechanical power is converted into low cost (cost effective) electrical power. The HKPP turbine can also be directly used as prime mover to water pump for irrigation, industries, water energy storage and other purposes.

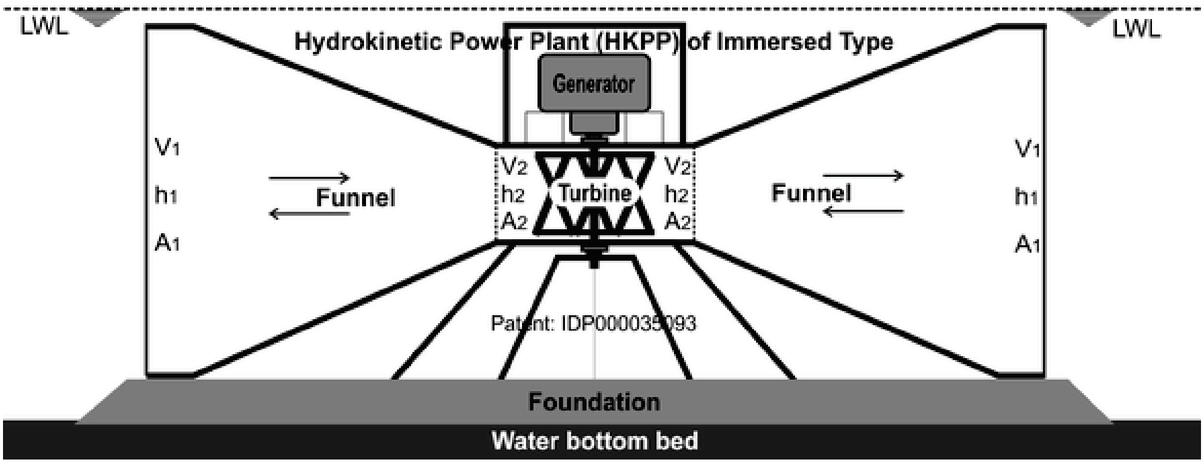

Figure 1. Scheme of HKPP

CONCEPTUAL FEASIBILITY STUDY

Table below summarizes a model of hydrokinetic energy upgrading process, formulation and the results and its conversion into electric power. The scenario, immersed type HKPP (sketched above) is developed in Japanese water area on the least available depth of 60m and distanced 15 km offshore to the southeast from the coastline of Hitachi City (see map). The maximum flow rate coefficient (Cq = 100%) is set upon the minimum current velocity (V_0) of 0.25 m/s – which is very low but looks more common found in the area and could be presents in an optimum duration (hours/year) compare to the faster one as indicated by Chu[v].

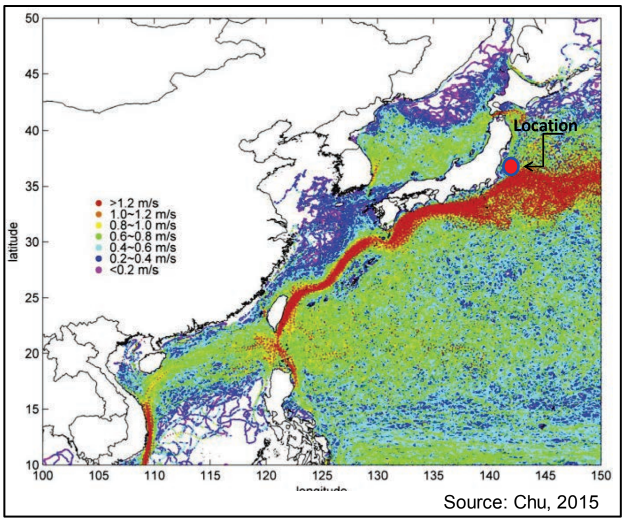

Table 1. Model of hydrokinetic energy upgrading process.

HYDROKINETIC ENERGY UPGRADING & CONVERSION PROCESS				
Parameter	**Formulation**	**Min. Value**	**Max. Value**	**Unit**
Local water mass density	ρ = constant	1,027.00	1,027.00	Kg/m^3
Gravitational acceleration	g = constant	9.81	9.81	m/s^2
Free Stream velocity	***V_0***	***0.25***	***2.00***	***m/s***
Least available depth	***Z***	***60.00***	***60.00***	***m***
Distance from LWL	y = 5%*Z	3.00	3.00	m
Foundation height	t = 5%*Z	3.00	3.00	m
Funnel inlet height	**$h_1 = Z - y - t$**	**54.00**	**54.00**	**m**
Funnel inlet width	$w_1 = 2.5*h_1 + h2$ (= roundup)	143.00	143.00	m
Inlet cross section area	$A_1 = h_1*w_1$	7,722.00	7,722.00	m^2
Inlet pressure coefficient	$c_{pi} = h_1/Z$	0.90	0.90	
Screen/trash rack efficiency	η_s = calculated	0.93	0.93	
Inlet velocity	$V_1 = V_0*c_{pi}*\eta_s$	0.21	1.67	m/s
Inlet volume flow rate	**$Q_1 = V_1*A_1$**	**1,614.08**	**12,912.66**	**m^3/s**
Funnel throat height (= width)	**h_2 (= w_2) = optimized**	**7.42**	**7.42**	**m**
Throat cross section area	$A_2 = h_2*w_2$	55.06	55.06	m^2
Ideal throat velocity	$V_{2id} = \sqrt{2*(g*(h_1 - h_2) + ½*V_1^2)}$	30.23	30.28	m/s
Funnel throat coefficient	c_{th} = calculated	0.9821	0.9821	
Turbine obstruction coeff.	$C_{tob} = 1 - c*n*h_T/A_2$	0.9534	0.9534	
Operating pressure drop	$\Delta P = ½*\rho*(V_{2id}^2 - V_1^2)*c_{th}*C_{tob}$	439.39	439.39	kPa
Operating thoat velocity	**$V_2 = \sqrt{2*\Delta P/\rho}$**	**29.25**	**29.25**	**m/s**
Operating volume flow rate	$Q_2 = V_2*A_2$	*1,610.51*	*1,610.51*	*m^3/s*
Flow rate coefficient (CHECK)	$C_Q = (Q_2/Q_1)$>99%<100%	**99.78%**	12.47%	**TRUE**
UPGRADED WATERPOWER	**$Pw_2 = ½*\rho*A_2*V_2^3$**	**707.64**	**707.64**	**MW**
Turbine height	$h_T = ±95\%*h_2$	7.05	7.05	m
Turbine diameter	$d_T = ±95\%*w_2$	7.05	7.05	m
Turbine radius	$R = d_T/2$	3.53	3.53	m
Turbine cross section area	$A_T = d_T*h_T$	49.70	49.70	m^2
Blockage ratio	$b_R = A_T/A_2$	0.9028	0.9028	
Bearing & blade efficiency	η_{bb} = assumption	0.8900	0.8900	
Max. turbine power coef.	**$Cp_{max} = b_R*\eta_{bb}$**	***80.35%***	***80.35%***	
Number of blade	**n**	**4.00**	**4.00**	**blades**
Blade azimuth angle	$\theta = 360^o/n$	90.00	90.00	degrees
Est. Optimal tip Speed Ratio	**λ = (>4<5.2)*π/n**	**3.49**	**3.49**	
Angle of attack	$\alpha = \arctan((\sin\theta)/(\cos\theta+\lambda)$	16.00	16.00	degrees
Angular velocity	$\omega = \lambda*V_2/R$	28.94	28.94	Rad/s
Rotation speed	$Nt = \omega*60/2*\pi$	276.34	276.34	RPM
Relative velocity	$V_R = \sqrt{(V_2+\omega*R*\cos\theta)^2 + (\omega*R*\sin\theta)^2}$	106.12	106.12	m/s
Designed blade chord length	**c**	**91.00**	**91.00**	**mm**
Designed solidity ratio	$\sigma = n*c/\pi*d_T$	0.0164	0.0164	
Blade Reynold number	$Re = V_R*c/ú$	9.62	9.62	x 10^6
Lift coefficient	c_L = Sandia NL, naca 0015	1.4233	1.4233	
Drag coefficient	c_D = Sandia NL, naca 0015	0.0176	0.0356	
Lift force	$L = c_L*½*\rho*c*h_T*V_R^2$	5.28	5.28	MN
Drag force	$D = c_D*½*\rho*c*h_T*V_R^2$	0.07	0.07	MN
Dynamic Torque	$T = n*R*(L*\sin\alpha - D*\cos\alpha)$	19.64	19.64	MNm
Coefficient of torque	$C_T = T/(½*\rho*A_T*V_2^2*R)$	0.26	0.26	
MECHANICAL POWER	**$P_T = T*\omega$**	**568.27**	**568.27**	**MW**
Turbine power coef. - CHECK	**$Cp = P_T/P_W = b_R*\lambda*C_T$ >80%<Cp_{max}**	**80.30%**	**80.30%**	***TRUE***
Generator rated speed	Ng	1,000.00	1,000.00	RPM
Gear ratio	gR = Ng/Nt	3.62	3.62	to 1
Gearbox efficiency	η_{gb}	95%	95%	%
Generator efficiency	η_g	95%	95%	%
ELECTRICAL POWER	**$Pe = P_T*\eta_{gb}*\eta_g$**	**512.86**	**512.86**	**MW**
INSTALLED CAPACITY	**Pe (round-down)**	**500.00**	**500.00**	**MW**

In short, subject to further research and development with involving competent experts, **anywhere** in a water stream of the least available depth of 60m (with sufficient width and area) and minimum natural steam velocity of 0.25 m/s (even very low) there is possible for development of HKPP of an installed capacity **500 MW/unit**, using 1000 RPM fixed speed (fixed frequency) electric generator as of common conventional hydroelectric power plant.
The above table also shows, power coefficient of turbine → $Cp = P_T/Pw > 80\% < Cp_{max}$ TRUE is achieved as a result of the following optimization process:

1) The numbers turbine blade (n) = 4 brings into the blade azimuth position ($\theta = 360^o/n$) = 90^o and meet optimal tip speed ratio: → $\lambda = (>4<5.2)*\pi/n = \pm 3.49$ in accord with Ragheb[vi], resulting into angle of attack (α) = 16^o, angular velocity ($\omega = \lambda * V_2/R$) = 28.94 rad/s and blade relative velocity: → $V_R = \sqrt{}(V_2+\omega*R*\text{Cos }\theta)^2 + (\omega*R*\text{Sin }\theta)^2 = 106.12$ m/s.
2) With refer to kinematic viscosity of water ($\tilde{v}$) about 1 per million m^2/s at the approx. 20^oC, the blade's air/hydrofoil chord length (c) = 91 mm and/or turbine solidity ratio ($\sigma = n*c/\pi*d_T$) = ±0.0164 is designed to complies maximum Reynold number ($Re = V_R*c/\tilde{v}$) $<1 \times 10^7$ that matched with air/hydrofoil section of NACA0015 in accord with Sheldahl[vii].

However here's would be noted that NACA0015 foil with maximum thickness of only 15% x chord length (c) = 15% x 91mm = 13.65 mm – could be too thin as compared to the turbine height (h_T) = 7.05m or 7,050 mm. Thus, blade hydrofoil selection and/or overall turbine design needs to be further detail analysed through laboratorial computational fluid dynamic (CFD).
Based on the funnel wall inclination of average $>20^o<21^o$ and length of turbine house that's sized by 150% the height of funnel throat (h_2), here's found that total length of twin funnel plus turbine house is maximum 256m, whilst the maximum funnel width of 143m occurs at the inlet. If let say a unit HKPP needs water length = 4 x 256m and water width = 3 x 143m, the HKPP of 500 MW/unit only requires maximum water area about 44 hectares. Procurement of 44 hectares water area should be theoretically simpler and cheaper compare to land acquisition for conventional hydroelectric dam and the supporting facilities of the same capacity.
Therefore, if only 1% (one percent) of approx. 448 million hectares Japanese jurisdiction water area includes exclusive economic zone/ZEE [viii] has the least available depth of 60m and minimum current velocity of 0.25m/s – there is possible for development of more than 110,300 units HKPP x 500 MW/unit with a combined capacity more than 55,150,000 MW. If this compare to oil fuel consumption 1.70 barrels/MWh (= 0.27 litres/kWh), the combined capacity equivalent to an endless (sustainable) oil fuel consumption/production of more than 2.25 billion barrels per day, or more than 500 times the volume of recent daily Japanese oil import. Therefore with ocean flows energy upgrading, Japan can be more independent in energy. Furthermore, Japan and Indonesia as the archipelago country can to be the pioneers toward reduction of greenhouse gas emission from fossils fuelled power plants for a better civilization.
In this conceptual study, the twin funnel and other buildings are assumed to be made of layered wire mesh reinforced concrete with tensile strength about 35 kgf/cm^2. Based upon common formula in penstock wall thickness calculation for conventional hydropower, maximum hydrostatic pressure 5.55 kgf/cm^2 correspond to funnel wall thickness requirement of max. 60 cm, but here 10 cm abrasion factor is added. Four layered sandwich concreting cost here is estimated up to max. USD270/m^3 – excluding installation. Generator cost is estimated base on regression analyses made by Podio from ENEL – Italy [ix], resulting into maximum USD46/kW – includes 50% contingency for some uncertainties. Capacity and cost

of subsea cable and power electronics are estimated from Intech [x] and Sally [xi] in relation with offshore wind farms. Other costs are estimated upon common practices.

CONCLUSION

Despite of very low, kinetic energy of naturally moving water mass in ocean and river is an abundant and eventually widespread source of clean, renewable and upgradable energy.

It can be concluded from Bernoulli principle that a portion of kinetic energy is contained in water streams can be increased directly in the water body/area by decreasing a portion of its potential energy proportionally. In HKPP, a portion of high potential energy in the funnel inlet is decreased in the funnel throat, so that upgrades the kinetic energy proportionally. The upgraded energy then used to drive vertical axis hydrokinetic turbine of well-known type which is connected via vertical shaft with/without gearbox to electric generator is positioned above the turbine, so that possible to generate low cost (cost effective) electric power.

Subject to further intensive and detail R&D, on the sea of least available depth 60m and minimum sea current velocity 0.25m/s is possible for development of HKPP with an installed capacity 500 MW/unit which requires water area of maximum 44 hectares. Thus, in 0.1% of approx.36.2 billion hectares global ocean of the same characteristic as above, there is possible for development of more than 822,000 unit HKPP x 500 MW/unit with a combined capacity more than 411 million MW which is equivalent to sustainable oil fuel energy consumption/production rate more than 16.77 billion barrels per day.

Again, subject to further R&D with involving competent experts, conceptual feasibility study so far indicates, power supply with two units HKPP x 500 MW/unit = 1000 MW is possible to be implemented by total capex about $485/kW, total opex about $2.2cent/kWh and LCOE about $4.5cent/kWh – indicates that HKPP competitive as against the other power plants.

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