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Assessment of Reduction in Carbon Dioxide Emission with Wave Solar Hybrid Generation Along Coastal Karnataka

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ABSTRACT

This article assesses reduction in carbon dioxide emission by wave solar hybrid generation of electricity, replacing the thermal generation of electricity along coastal Karnataka. Electricity generation utilizing wave energy of one kilometer of combined width of wave-fronts and 1000 m × 100 m of area exposed to solar radiations has been considered for calculations. Irradiance is highest in April i.e., 7.1 KWH/m^2/day, but reduces to 4.6 to 4.8 KWH/m^2/day in the monsoon months. It reduces electricity generation potential of solar panels by around 20 to 30 W per m^2 area. The wave data collected from the wave rider buoy at Karwar (Karnataka) installed by INCOIS (Indian National Centre for ocean information studies) suggest that wave energy potential for electricity generation increases during monsoon period. It is around 3000 to 4000 Watts per meter width of wave-front which is ten times more than the non monsoon average potential of around 300 Watts per meter width of wave front. Wave energy can very well supplement deficit in solar generation during monsoon months. A wave solar hybrid generation system instead of thermal generation exploiting only 1 km coastal length can reduce carbon footprints by around 71500 metric tonnes of carbon dioxide per annum.

INTRODUCTION

India is blessed with large amounts of solar radiation, but during southwest monsoon months, i.e. from June to September, western coast of India receives heavy rainfall and sky is mostly covered with clouds. During these months, the amount of solar irradiation reduces considerably. It affects the output of solar installations. India has a long coastline and a study conducted by CRISIL, IIT Madras, a French agency (AFD) and IREDA estimated wave energy potential for India to be around 40 GW (CRISIL, IIT Madras, AFD & IREDA Report 2014). Wave energy contained in sea waves is directly proportional to the product of square of significant wave height H_s^2 and mean wave period (T). Data collected from INCOIS wave rider buoys installed along western coast of India at Ratnagiri in Maharashtra, Karwar in Karnataka, Kozhikode and Kollam in Kerala suggest that significant wave height and wave period increase during monsoon months (Goswami et al. 2016, Hammar et al. 2012, Kumar et al. 2013). A hybrid arrangement of generation of electricity using wave and solar resources can give a stable output.

Wave power calculations

Wave power (Anderson et al. 2011, Herald et al. 2000) per unit width of wave front considering a sinusoidal wave and water depth more than 0.5 λ is given by:

$$P = \rho g^2 H^2 T / 32\pi = \alpha H^2 T \text{ KW/m} \qquad ...(1)$$

Where,
ρ = density of sea water = 1024 kg/m^2 (approximately with slight variation with location)
g = Acceleration due to gravity = 9.8m/s^2
H = wave height (vertical distance between trough to crest)
T = wave period

The equation indicates that the wave power is directly proportional to product of square of the wave height H and wave period T.

To represent irregular waves, two quantities, i.e. significant wave height H_s and mean wave period T_Z are defined.

- Significant wave height H_s is defined as the mean height of the largest 33% waves of the wave spectrum.
- T_J is taken as 1.2 times T_Z, where T_Z is the time-period between two successive crossings of mean water level. T_J is said to be the period of energy transport.

For irregular waves $\alpha_J = \alpha/2$,

Where, constant $\alpha = \rho g^2/32\pi = 978.25$ W/m^2

$$P = 0.489 H_s^2 T_J \text{ KW/m} \qquad ...(2)$$

Oscillating water column

Oscillating water column (Heath 2012, Alberdi et al. 2011,

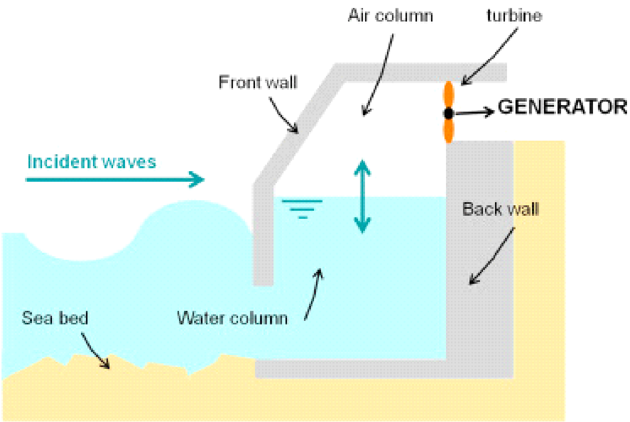

Fig. 1: Oscillating water column.

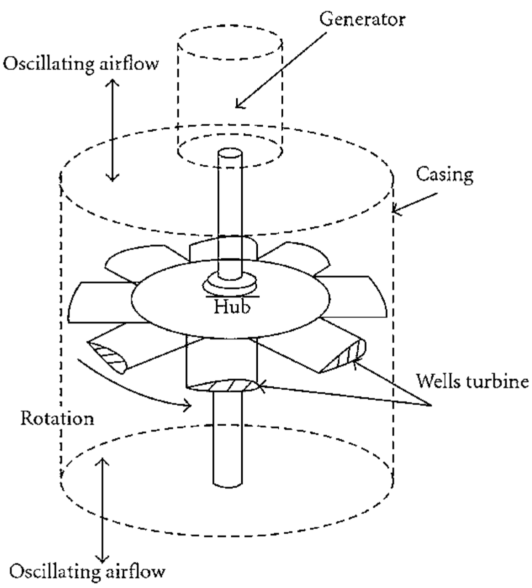

Fig. 2: Wells turbine.

Amundarain et al. 2011) is a concrete hollow vertical column as shown in Fig.1 installed near shore with an opening in the direction of incoming wave. As the wave strikes or recedes the water level in the oscillating water column rises and falls with rising and receding wave. The water columns oscillate like a piston and causes the air trapped inside to rotate the pneumatic turbine, which is coupled with a generator for electricity generation.

The turbine used is normally Wells turbine as shown in Fig. 2 which rotate in the same direction irrespective of the direction of air, whether it is incoming or outgoing depending upon the water column moving up or down.

Wells turbine is a simple turbine having linear characteristics. Wells turbines have a tendency to stall and experience a sudden fall in efficiency at higher flow constant values. Impulse turbines for higher efficiency are also used. There have been many improvements suggested in the turbines (Setoguchi et al. 2001, 2007, 2011, Takao et al. 2012, Okuhara et al. 2012, 2013, Ceballos et al. 2013, Dorrel & Heish 2010, Jayshankar 2010, Kelly et al. 2015, Shehata et al. 2017) to increase their efficiency. Fig. 3 shows characteristics of Wells and impulse turbines. Examples of commercial oscillating water columns are Wave-gen or Ocenlinx.

MATERIALS AND METHODS

Wave power assessment: Month-wise estimate of wave energy potential has been obtained based on the significant wave height and mean wave period obtained from INCOIS wave rider buoy located at Karwar (Karnataka). Monthly average of significant wave height and mean wave period is calculated based on data of four years. Month-wise wave power estimate in kW/m for Karwar is obtained in Table 1. Considering hydrodynamic efficiency of oscillating water column as 60%, turbine efficiency around 40% and electrical generator efficiency close to 90% the overall efficiency comes out to be around

$$\eta_{OVERALL} = \eta_{owc} \times \eta_{TURBINE} \times \eta_{GENERATOR}$$

$$= 0.6 \times 0.4 \times 0.9 = 0.216 = 21.6\%$$

For simplicity, considering wave to wire efficiency around 20%, an estimate of output electrical power (Alberdi et al. 2011, Delmonte et al. 2015, Dorrel et al. 2010, Jayshankar et al. 2011, Okuhara et al. 2013) has been obtained in Table 2 according to the wave profile from January to December.

Solar power assessment: Month-wise solar irradiance obtained from global horizontal irradiation data from Ministry of Non-conventional and Renewable Energy (MNRE), solar resources for grid code 75151485 (Karwar) have been used. Conversion efficiency of PV module is given by:

$$\eta_{PV} = P_{OUTPUT}/P_{INPUT}$$

Input power at standard conditions is 1000 kW/m^2 GHI at 25°C. Assuming average 7 hours of daily sunshine, P_{INPUT} can be calculated as:

$$P_{INPUT} = GHI \times 1000/7$$

For a typical value of 5.6 GHI it will be 800 kW/m^2. Coastal area does not experience large variations in temperature and average temperature varies between 29°C and 33°C. Effect of temperature on output is presently ignored.

Polycrystalline silicon PV modules are mostly used in India and their efficiency is assumed to be 15% for estimate purposes. Assuming PV efficiency as 15% and the actual output as 68% (Ramchandra et al. 2011) of maximum, an assessment of electricity output has been obtained.

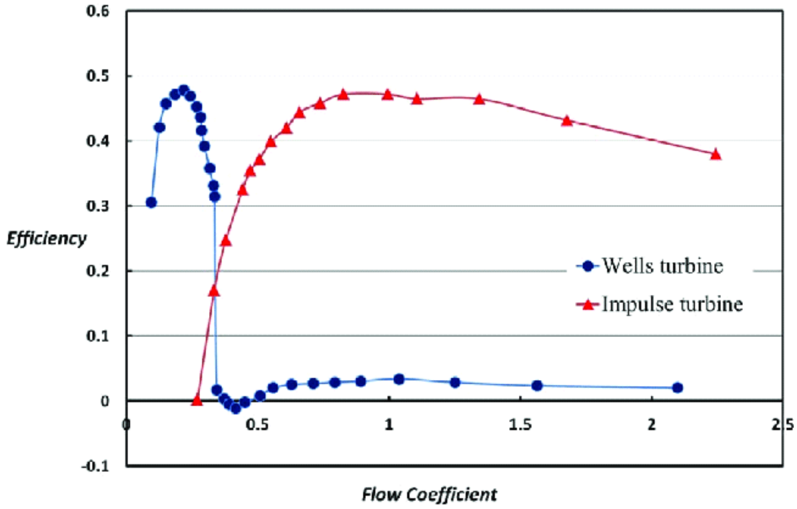

Fig. 3: Characteristics of wells and impulse turbines.

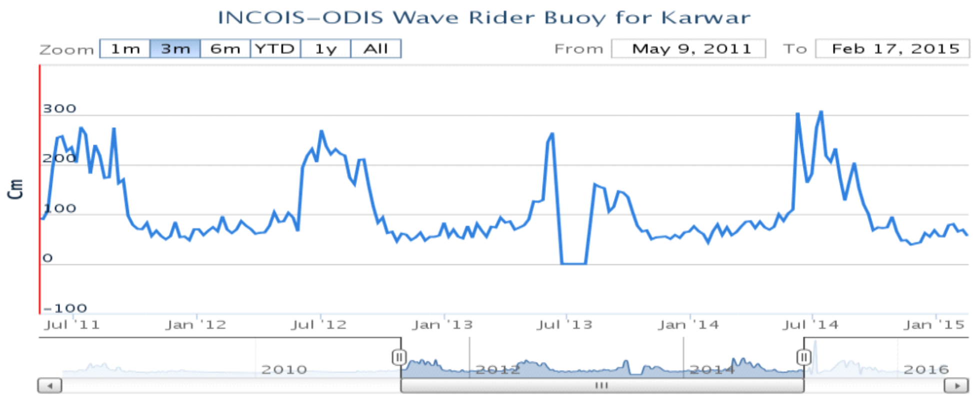

Fig. 4: Variation of significant height data collected from wave rider buoys (courtesy INCOIS) installed at Karwar in Karnataka.

Assessment of carbon footprint reduction: The assessment has been done based on a solar PV plant using around 1000m × 100m space for solar PV installations and exploiting wave energy of the total 1000m width of wave front for electricity generation with oscillating water column technology. Table 2 shows the estimate of electricity generated with wave and solar resources.

A solar power plant has estimated carbon footprints of 50 to 60 kg/MWh generation and wave energy generation has carbon footprints around 25 to 50 kg/MWh generation (Fineko et al. 2014, POSTNote 268, 2006, POSTNote 383 June 2011). As the focus is mainly on generation utilizing solar resource, an estimate of reduction in emissions of CO_2 has been done considering an average of 50 kg CO_2 equivalent for wave solar hybrid generation. Thermal generation average of CO_2 emission is considered as 900 kg CO_2 equivalent/MWh (Mittal et al. 2012, Chakraborty et al. 2008, Chowdhuri et al. 2004). Month-wise as well as annual assessment of reduction in emissions of CO_2 has been obtained in Table 2.

RESULTS AND DISCUSSION

Wave energy potential along Karnataka coast: Wave energy is directly proportional to the product of square of the significant wave height and the mean period as shown in Eq. 1.

Variation of significant height data and mean wave period data (INCOIS data) collected from wave rider buoys installed at Karwar in Karnataka are shown in Figs. 4 and 5. Table 1 also shows month-wise assessment of hybrid wave solar generation.

Assessment of wave and solar energy along coastal Karnataka: Wave to wire conversion has three stages wave power to pneumatic power in OWC, pneumatic to mechani-

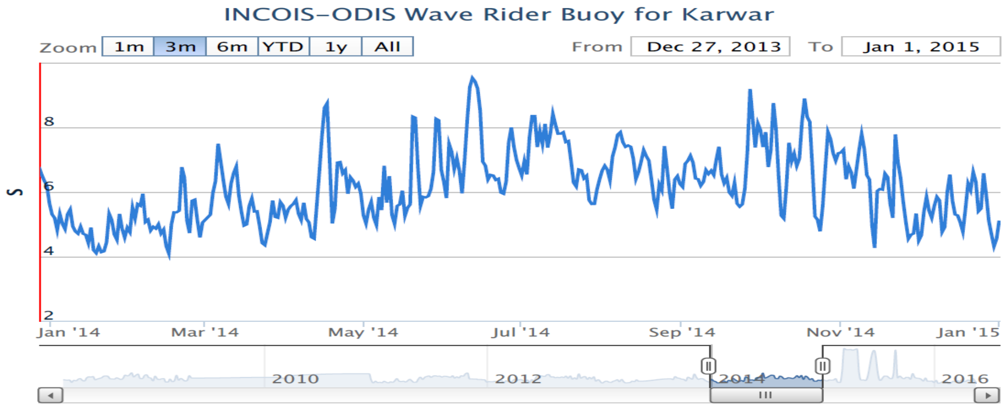

Fig. 5: Variation of mean wave period data collected from wave rider buoys (courtesy INCOIS) installed at Karwar in Karnataka.

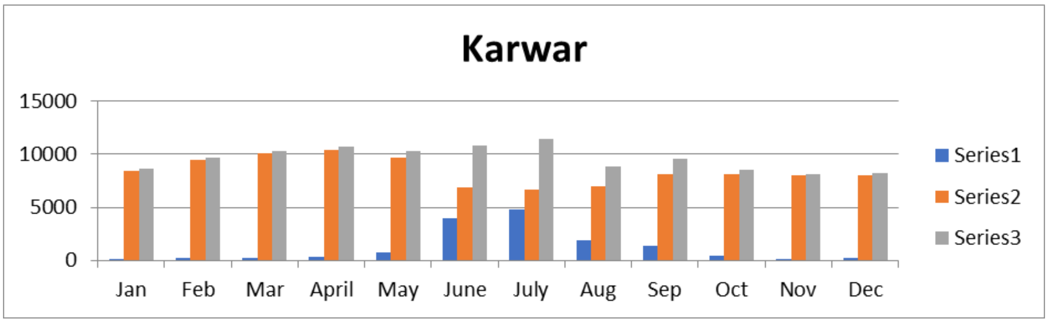

Fig. 6: Wave, solar and total wave-solar hybrid potential for electricity generation for Karwar.

cal power in turbine and mechanical to electrical power conversion in electrical generator. PMSG (O'Sullivan et al. 2011, Ramirez et al. 2015, Penalba et al. 2016, Samrat et al. 2014) is considered to generate electricity to supply remote coastal areas which are either not connected to the grid or receive electricity for a very little time. In areas having grid connectivity, squirrel cage induction (SG) generator or doubly fed induction generator (DFIG) may be considered

Fig. 6 shows wave, solar, and total wave-solar hybrid potential for electricity generation for Karwar. Series 1, 2 and 3 represent wave, solar and combined wave solar potential for electricity generation.

Carbon foot print reduction: Installed capacity of thermal generation plants in Karnataka as per Government of India data as on 31 July 2017 is 9560.82 MW. Out of which coal based generation is 26905.43 MW and gas based generation is 3753 MW. Government of India has decided to phase out old thermal power units to reduce carbon footprints.

Replacing existing thermal units with super critical ones will not make considerable difference in carbon footprint reduction. To achieve targets according to Paris Agreement, India needs to increase its non-fossil fuel generation to 40% of total capacity. To achieve this, a considerable shift to renewable generation is required. Comparing a conventional subcritical thermal power plant with supercritical ones or ultra-super critical ones, the only difference is increased efficiency of the plants. Presently sub critical thermal power plants have efficiency around 34%, whereas, the efficiency of super critical ones is around 38% and that of ultra-super critical ones is 43%. For same amount of power generation, it may be assumed that the amount of coal consumed in these plants is inversely proportional to the efficiency of the plants. If a subcritical plant generates approximately 900 kg CO_2 per MWh generation of electricity (Mittal et al. 2012, Chakraborty et al. 2008, Chowdhuri et al. 2004), a super critical and ultra-super critical one will generate approximately 800 and 700 kg CO_2 per MWh generation.

Carbon footprints of solar and wave energy installations will not heat the environment directly and will be due to their installation and commissioning.

Per MW saving due to solar power generation will be 850 kg/MWh in comparison to subcritical plants and 750

Table 1: Estimate of electricity generated with wave and solar resources.

Karwar										
Month	Hs(cm)	T(s)	Wave power (kW/m)	Output electrical power (kW/m)	Output electrical power (kW/1000m)	GHI (KWH/sq m/day)	Solar power input (Watts/sq.m)	PV output watts/ (sq.m)	PV output (kW/ 1000×100 sq.m)	Total hybrid wave + solar
Jan	53.74	4.81	0.679	0.136	136	5.8	828.6	84.5	8450	8586
Feb	62.86	4.82	0.931	0.186	186	6.5	928.6	94.7	9470	9656
Mar	72.66	5.25	1.354	0.271	271	6.9	985.7	100.5	10050	10321
Apr	75.15	5.73	1.582	0.316	316	7.1	1014.3	103.5	10350	10666
May	106.4	6.3	3.488	0.698	698	6.6	942.9	96.2	9620	10318
Jun	228.7	7.75	19.827	3.965	3965	4.7	671.4	68.5	6850	10815
Jul	257.8	7.3	23.711	4.742	4742	4.6	657.1	67	6700	11442
Aug	169.6	6.76	9.509	1.902	1902	4.8	685.7	69.9	6990	8892
Sep	148.1	6.47	6.945	1.389	1389	5.6	800	81.6	8160	9549
Oct	76.22	7.14	2.028	0.406	406	5.6	800	81.6	8160	8566
Nov	49.63	6.23	0.751	0.15	150	5.5	785.7	80.1	8010	8160
Dec	63.51	5.73	1.131	0.226	226	5.5	785.7	80.1	8010	8236

Table 2: Carbon footprints reduction using wave solar hybrid generation in comparison with thermal generation.

	Wave power (kW/m) (kW/m)	Output electrical power (kW/ 1000m)	Output electrical power m/day)	GHI (KWH/ sq. sq.m)	PV output (watts per 1000× 100 sq.m)	PV output (kW/	Total hybrid wave + solar	Carbon footprints ($kgCO_2$/ MWh)	Carbon footprints of thermal generation of equal amount	Carbon footprints reduction $kgCO_2$ per hour	Carbon footprints reduction $kgCO_2$ per month
Jan	0.679	0.136	136	5.8	84.5	8450	8586	429.3	7727.4	7298.1	5429786
Feb	0.931	0.186	186	6.5	94.7	9470	9656	482.8	8690.4	8207.6	5515507
Mar	1.354	0.271	271	6.9	100.5	10050	10321	516.1	9288.9	8772.85	6527000
April	1.582	0.316	316	7.1	103.5	10350	10666	533.3	9599.4	9066.1	6527592
May	3.488	0.698	698	6.6	96.2	9620	10318	515.9	9286.2	8770.3	6525103
June	19.827	3.965	3965	4.7	68.5	6850	10815	540.8	9733.5	9192.75	6618780
July	23.711	4.742	4742	4.6	67	6700	11442	572.1	10297.8	9725.7	7235921
Aug	9.509	1.902	1902	4.8	69.9	6990	8892	444.6	8002.8	7558.2	5623301
Sep	6.945	1.389	1389	5.6	81.6	8160	9549	477.5	8594.1	8116.65	5843988
Oct	2.028	0.406	406	5.6	81.6	8160	8566	428.3	7709.4	7281.1	5417138
Nov	0.751	0.15	150	5.5	80.1	8010	8160	408	7344	6936	4993920
Dec	1.131	0.226	226	5.5	80.1	8010	8236	411.8	7412.4	7000.6	5208446
Carbon footprints reduction per annum total ($kgCO_2$ per annum)											71466484

(Considering wave energy exploitation of 1km width of wave fronts using multiple installations and using solar generation potential of 1000m×100m area exposed to solar radiations).

kg CO_2 per MWh in comparison to supercritical power plants. This is in addition to the advantage of solar and wave power generation plants having low operating cost as they do not need fossil fuels.

A comparison of carbon footprints is given in Table 2 for electricity generation using 1 km shoreline of Karnataka coast. The assessment has been made on assumption of wave energy exploitation of 1 km width of wave fronts using multiple installations and using solar generation potential of 1000m × 100m. Total coastline of Karnataka is around 320 km. Exploiting wave and solar power of only 1 km gives rise to substantial reduction in carbon footprints. A longer stretch of the coast is suitable for wave energy generation and can be exploited.

CONCLUSION

Karnataka State is already generating a good percentage of non-fossil fuel electricity. Adding wave solar hybrid along coastal areas can further reduce carbon footprints. Harnessing wave solar hybrid energy is a better option over increasing thermal power generation capacity as far as CO_2 emission is concerned. Overall operating cost of wave solar hybrid is less as there is no fuel consumption involved.

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