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An overview on green house gas emission characteristics and energy evaluation of ocean energy systems from life cycle assessment and energy accounting studies

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Abstract: An analysis has been made as regards emission characteristics of ocean energy systems from life cycle assessment and scope of energy availability from energy accounting studies. Assessment tools developed and standardized were the indices like scope of Green house gases (GHG) emission per kWh power generation, percentage of CO2 saved compared to coal fired power station and the energy payback period. Emission characteristics of ocean energy systems were also compared with that from solar power, bio-fuels and wind energy systems. Four case studies were made comprising of wave energy converters, Ocean Thermal Energy Conversion (OTEC) system and tidal energy. It could be observed that CO2 emission percentage saved from ocean energy schemes were more than 95 per cent; and energy payback period varied between one year and a little higher than two years, depending on the type of the device.

Keywords: Barrage, Energy accounting, Global warming, Ocean thermal energy, Pelamis, Wave dragon

INTRODUCTION

Like all other renewable energy schemes, application of life cycle analysis (LCA) are useful for the ocean energy (OE) schemes as well, to assess the degree of benefits accrued from the saving of GHG emission. Energy payback period (EPBP) estimations from energy accounting (EA) studies are also considered important criterion for evaluating the scope of acceptability of the concerned OE device for power generation. The OE types considered in the present study include all three OE systems comprising of the wave schemes, ocean thermal energy conversion (OTEC) systems, as well as of the tidal energy (Thresher and Musial, 2010)

It may be relevant to add that though large scale commercial application of OE systems, other than barrage, are yet to come up; but pilot plant studies have proved successful in number of OE devices for all three OE systems. Case studies of some of the OE devices that have the potential of commercial application have been taken up in the present study. The scope of GHG emission saving capability as also of energy payback periods have been estimated from LCA and EA studies, respectively (Helius and Reinout, 2007). In the present study, the case studies taken up included- two wave energy converters (Pelamis and Wave Dragon), one type of OTEC scheme (CC-OTEC) and a proposed barrage project (Severn barrage). A brief account of LCA and EA studies of above 4 cases are appended below.

Methodology adopted in LCA and EA estimations: Life time emission of GHGs expressed in g/kWh power generation of an energy device, as per LCA estimations, would be = $\sum Gi \times Mi / P_i$ + operational stage emission in g/kWh. (1)

In the above equation, Gi represents the gas emission in kg/kg of the inventory items; Mi is mass of the inventory items of the device; and P_l is the life time power generation of the device, expressed in kWh. Like all other renewable energy systems, in case of OE systems also the operational stage emission would be rather marginal, excepting OTEC schemes which do contribute some emission in its operational stage as well.

Likewise, energy payback period (EPBP) would be = $\sum Ei\ Mi / Pa$; (2)

Where, Ei is the embodied energy of the inventory items of the device expressed in MJ/kg; Mi is their respective mass in kg, Pa is the annual power generated by respective OE devices, also expressed in MJ (Mega Joule).

The data as regards Gi of inventory items was adopted from Danish model of LCA estimations as used for wind energy systems (Schleisner, 2000), estimating the emission characteristics of construction materials of OE devices as per ISO 14040 with LCA boundary conditions of 'cradle to gate' (ISO 14040, 2006). The results obtained as regards CO_2 emission in particular, were corroborated

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Table 1. Emissions in kg/kg of the construction materials as per the Danish model of LCA (Schleisner, 2000).

Materials concerned	CO_2 (kg)	NO_x(kg)	N_2O(kg)	CH_4(Kg)	SO_2 (kg)
Steel*	2.3065	0.0095	0.00007	0.00004	0.0145
Aluminum*	3.4335	0.013	0.000105	0.000065	0.021
Copper	6.536	0.02319	0.00019	0.00016	0.03561
Plastics	3.113	0.01049	0.00009	0.00008	0.01475
Iron*	3.114	0.00889	0.00009	0.00006	0.01458
Concrete /Cement *	0.835	0.0025	0	0	0.00001

*Only mean values are considered.

Table 2. Bath data source giving CO_2 emission in kg/kg of inventory materials (Hammond and Jones, 2008).

Inventory materials	Steel	Copper	Iron	Concrete	Plastics	Aluminium
*CO_2emission in kg/kg	2.83	3.0	1.91	0.95	2.53	8.26

* Only mean values are considered.

from Bath University data source as well (Hammond and Jones, 2008), for checking up the degree of discrepancy of results (if any), since LCA has been known to be process specific and country specific (Blengini, 2008).
Ei, the embodied energy data of the inventory items were also adopted from both the Danish model ((Schleisner, 2000), and corroborated from Bath University data sources as well (Hammond and Jones, 2008).
Respective Gi values of GHGs of different inventory items, as are commonly used in OE devices, are shown below in table 1, giving the data base from Danish model. The Gi values of respective inventory items as per Bath data source are shown in table 2, giving the emission characteristics of CO_2 only. Likewise in table 3 is shown the data base as regards embodied energy of respective inventory items of OE devices, for both Danish model as well as of Bath University data source. These three tables, giving the respective data base for estimating LCA and EA of OE systems are shown in Tables 1, 2 and 3.

CASE STUDIES OF OE DEVICES

In order to make LCA and EA studies, both lifetime and annual power generation data of different OE devices are required to be availed, in addition to the mass of all the inventory items of the device concerned. Thus knowing the life of a device, its annual power production and inventory data- both emission characteristics and energy pay back periods can be estimated from computation of Tables 1 and 2, and equation 1; as also of Table 3 and equation 2, respectively.
Four case studies as made from the above premise are appended below in Fig. 1.

LCA AND EA STUDIES OF 750kW PELAMIS TYPE WAVE ENERGY CONVERTER

Pelamis is a cylindrical type wave energy converter consisting of semi-submerged structure with cylindrical sections linked by hinged joints, as shown below in Fig.1. Its life period is reported to be around 20 years (Parker *et al.*, 2007) with annual power generation of 2.5GWh, if placed in Ireland coast (Dalton *et al.*, 2010). Thus its lifetime power production would be 50GWh. The distribution of mass of inventory materials of 750 kW Pelamis unit was learnt to be broadly constituting of steel: 380,000 kg and copper: 15000kg (Taylor, 2006).
The life time emission characteristics of Pelamis in g/kWh, could then be estimated employing the equation 1 and making computation of the above data with table 1, that gives mass of emitted gases in kg/kg of the inventory materials, as per the Danish model. The GHG equivalent of respective gases could also be determined multiplying the emission in g/kWh with their respective global warming potential (GWP) value; which for CO_2, N_2O and CH_4 are '1', '310' and '21', respectively. The results thus obtained, are shown below in Table 4.
It would be evident from the above table that emission of CO_2 is only of relevance in assessment of GHG, despite its low GWP of only '1'; mainly because of its much

Table 3. Energy requirement in MJ / kg of the inventory materials of OE devices.

Materials	Steel	Iron /Cast iron	Copper	Aluminium	Glass	Concrete /Cement	Plastics
Embodied Energy MJ/kg *	25.65	36.3	78.2	39.15	8.1	3.68	45.7
Embodied Energy –MJ/kg **	25.4	25	70	34.1	18.50	3.01	45.7

*Danish model (Schleisner, 2000), ** Bath data (Hammond and Jones, 2008).

Table 4. Emission of gases in g/kWh of 750 kW Pelamis.

Gases	CO_2	NO_x	N_2O	CH_4	SO_2	Total GHG equivalent of gases
Amount in g/kWh	19.49	0.079	0.0006	0.0003	0.12	19.68

higher degree of emission compared to other gases. Because of the importance of CO_2, its emission was checked up from Bath University data base also as per table 2, which on computation yielded the value of 22.41g/kWh. Both these two values fairly tallied with that of Parker *et al.* (2007) giving CO_2 emission to be 22.8g/kWh. EPBP values as estimated from computation of Table 3 and Equation 2, based from annual energy production of Pelamis, showed the value of 1.21 year and 1.18 years, for Danish model and Bath data respectively.

CASE STUDY OF 7MW WAVE DRAGON

Wave Dragon (WD) is an overtopping type of wave energy converter. It focuses the incoming waves towards a huge reservoir (a floating ramp) with two wave reflectors and overtopping the reservoir water to run a number of turbines by converting the pressure head of water to power generation, as shown below in Fig.2.

It has been claimed that its annual power generation when placed in Wales Coast would be 20 GWH (Millar *et al.*, 2007). Also its life is claimed to be 50 years (Tedd, 2007) thereby with life time power production of 1000GWh.

Its inventory data has been shown below in Table 5 (Russell, 2007).

Based from above data and table 1, giving emission characteristics of inventory items as per the Danish model, computation made on life time emission of gases of 7MW Wave Dragon is shown below in Table 6.

Bath University data of CO_2 emission estimated from table 2, yielded results as 31.79 g/kWh, which is a little higher value than that, availed from Danish model.

Computation of EPBP values, on the basis of 20GWh annual power generation of Wave Dragon, showed values of 1.75 years and 1.57 years, for Danish model and Bath data, respectively.

CASE STUDY OF 100MW CLOSED CYCLE OTEC

Electricity from OTEC is generated utilising the small temperature difference between warm surface seawater and deep cold seawater, usually following a Rankin cycle heat engine (Green and Guenther, 1990). OTEC however, requires power for its operations to generate the power. Hence, the terms gross energy output and the net energy availability comes up for OTEC schemes; the latter being usually 65 percent from its gross energy output, the value of which increases with larger sized OTEC plants (Vega, 1999).

In case of 100MW OTEC plant, net energy may obviously be presumed to be 75% of the gross power generated. Presuming the capacity factor to be at least 30% (as observed for most of OE schemes), annual power production from 100MW CC-OTEC would be = 100*0.75*0.3*365*24= 191.7 GWh; with life time power production of 5913GWh, considered for its 30 years life period. The mass of construction materials of the above OTEC plant is shown below in Table 7.

Life time emission of CO_2 estimated from the above data with computation as per equation 1, and table- 1 giving data of Danish model =27.18g/kWh, with GHG equivalent

Fig. 1. *Diagram of Pelamis at sea. Source: <http://www.pelamiswave.com/media/pelamisbrochure.pdf> [29.7.2009].*

Table 5. Inventory data of 7MW Wave Dragon (Russell, 2007).

Inventory materials	Steel	Aluminium	Copper	Plastic	Iron	Concrete
Mass(in kg)	553000	24100	69300	31540	120920	31068000

Table 6. Emission of gases from 7 MW Wave Dragon.

Gases	CO_2	NO_x	N_2O	CH_4	SO_2	Total GHG equivalent of gases
Amount in g/kWh	28.23	0.086	0.00006	0.00004	0.013	28.25

Table 7. Inventory data of 100 MW CC-OTEC (Tahara *et al.*, 2000).

Inventory materials	Steel*	Iron	Copper	Plastics	Concrete
Mass in tons	4157	16187	270	14216	75000

*Different types of steel clubbed together

of gases =27.37g/kWh. Bath data results yields CO_2 emission to be =26.38g/kWh.

In addition to the above emission data, in case of OTEC the operational stage emission has also to be taken into account, as per equation 1; unlike the wave schemes. This needs adding up CO_2 emission from the working fluid NH_3 plus other sources of operational stage emission. The former was estimated to be 0.49g/kWh from the inventory data of Japanese researchers (Tahara *et al.*, 2000); whereas the latter is reported to be a little less than 1g/kWh (Green and Guenther, 1990), presumed as 0.8 g/kWh- thus totalling 1.29g/kWh.

Adding up the above value during operational stage of CC-OTEC, its life time emission would be = 28.47g/kWh, as per Danish model and 27.67 g/kWh, as per Bath data source. It may be relevant to add that employing data source of NIRE-LCA software, which the Japanese researchers used (Tahara *et al.*, 2000), the value arrived at was only 24.08 g/kWh for 100 MW CC-OTEC.

EPBP of 100 MW CC-OTEC, based from its net annual power production of 197.1GWh and computation with equation 2 and table 3 data, was estimated to be = 2.35 years from Danish model and 3.07 years from Bath data source.

CASE STUDY OF SEVERN BARRAGE PROPOSAL, UK

This project proposes to construct a 15-18 km long barrage from Cardiff to Weston Super-mare, UK, creating a basin area of 480km^2, for holding high tide water of Severn river having mean tidal range 7m (Sir Robert Mc Alpine & sons Ltd 1986). Annual power output from this barrage is expected to be 17 TWh, with the life period of 100 years (Woollcombe Adams *et al.*, 2009).

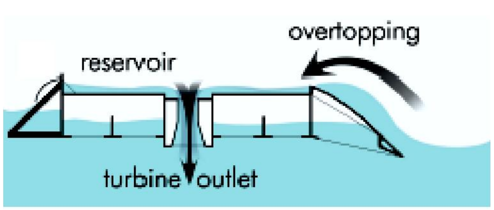

Fig. 2. *Mode of operation of power capture in Wave Dragon (Kofoed et al., 2006).*

The inventory materials required for constructing the barrage were reported to be mainly consisting of steel, copper and concrete (including cement), with their mass requirement of 588.8 kilo ton (kt), 43.2 kt and 3800 kt, respectively (Woollcombe Adams *et al.*, 2009).

The emission of CO_2 may be determined from the above data base making computation of equation 1 and table 1. But in order to determine its life time emission, the results are to be added with 2% extra emission required for transportation as also of emission for operational & maintenance, which is around 2days/year in its life of 100 years (Elliott, 2004).

Computation of all these emission data divided by its life time power generation extending 100 years, the value of CO_2 emission showed 3.01 g/kWh for Danish model and 3.26g/kWh from Bath data source.

Computation of EPBP values, on the basis of annual power generation of the Severn barrage showed values of 0.53 years and 0.48 years, for Danish model and Bath data, respectively.

CRITICAL APPRAISAL OF RESULTS

It could be observed from the above results that Severn barrage project with 100 years life and high power generation capability showed minimum values of both CO_2 emission and energy payback period. In fact, these values are mainly influenced from the capability of annual power generation of the device concerned, its life period as well as of the mass and type of inventory materials of the device concerned.

It is to be noted that the above stated 750 kW Pelamis if placed in Portugal coast would have produced half the power than that availed (2.5 GWh annually) from its placement in Ireland coast (Dalton *et al.*, 2010). Obviously, both CO_2 emission and energy payback period would have shown just double the value than that estimated from its application in Ireland coast. Likewise, if the life period of Wave Dragon were considered to be of 30 years duration (like OTEC), its values on CO_2 emission and energy payback period would have shown

Table 8. Data from LCA studies of OE systems compared with other energy types.

Device concerned	Pelamis*	Wave* Dragon	CC-OTEC*	Severn* Barrage	Solar **	Bio - fuels **	Wind energy **
CO_2 g/kWh	19.49	28.23	28.47	3.01	35	25	6
% CO_2 saved							
EPBP in years	1.21	1.75	2.35	0.53	-	-	-

*Only danish model considered; **Minimum values are considered

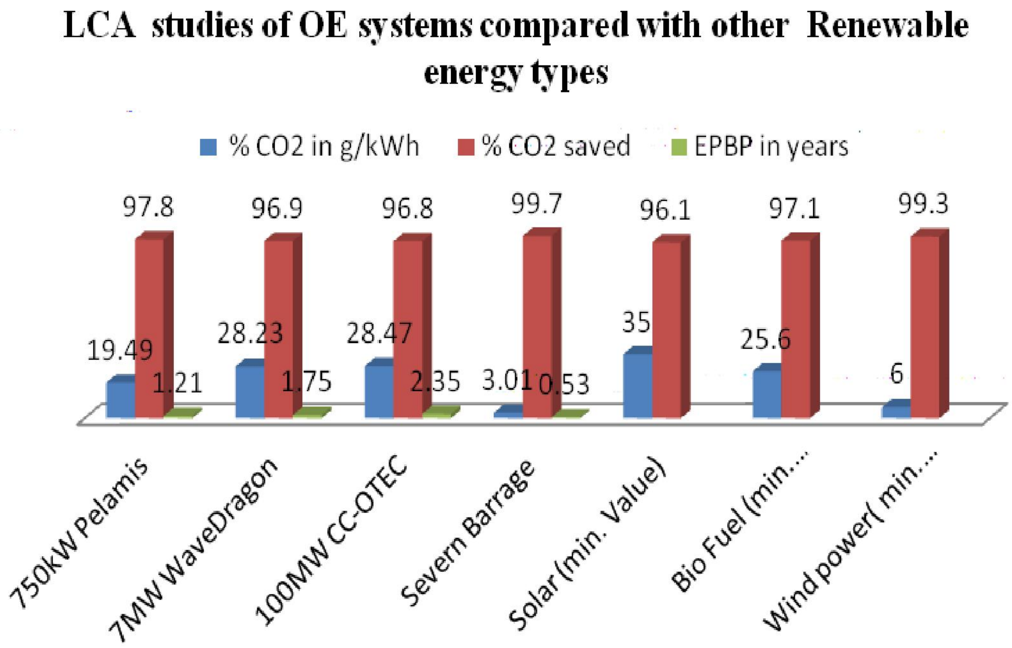

Fig.3. *CO_2 emission of OE systems compared with other renewable energy types.*

40% higher values than that estimated in the present study considered for 50 years life.

Also, the discrepancy (though minor) of the results between Danish model and Bath data source, for the same device, are caused because of the varied data base of respective inventory items concerned.

It may be relevant to add that the values obtained from LCA and EA studies pertained only for the respective OE device concerned, without considering the input as would accrue for power transmission from cable lines etc. However, the results prove to be important as one of the assessment tools, making comparative study of the competing OE devices for their acceptability.

It has hence been considered important to compare the above results of OE systems with other renewable energy types, like solar, bio-Fuels and wind energy, as well as determining the GHG saving compared to coal fired generator. These studies have been made in the subsequent section.

COMPARATIVE STUDY ON CO_2 SAVING PERCENTAGE

CO_2 emission from coal fired generator, as obtained from LCA studies was found to be 900 g/kWh (Odeh and Cockerill, 2008). Considering this to be the 100 % emission, the percentage of CO_2 saved from the application of an energy device would be

= 100 - Emission of device concerned in g/kWh* 100/ 900 (3)

It has also been noted that emission of CO_2 from solar power may vary between 58g/kWh and 35 g/kWh, depending on the technology adopted (Parliamentary office post note, 2006). In case of bio-fuels it varies between 25g/kWh and 93 g/kWh, depending on the type of bio-mass used (Parliamentary office post note, 2006). Wind energy shows the least value of 6 g/kWh (Crawford, 2009).

Based from the above data, GHG saving percent of different types of OE device, as determined from equation 3 are shown in Table 8 and Fig. 3, given below.

Conclusion

It could be inferred that CO_2 is the main contributor in GHG emission. Emission of CO_2 as determined from LCA studies and EPBP values estimated from EA studies, depend on annual energy production, device life, as also of mass and type of the inventory materials required. Amongst the OE systems, it is the barrage that showed maximum efficiency as regards CO_2 saving as also of achieving minimum energy pay back period. All the OE devices showed more than 95% CO_2 saving than the coal power plant. Amongst the other renewablle energy types, it is only the wind energy that showed minimum emission, whence solar power showed maximum values, with bio-fuels comparable to the OE systems.Values of EPBP varied between less than one year to two years, with only OTEC showing a little higher than two years. Though LCA studies are known to be counry specific and process specific, but results obtained from the present study, carried out using both Danish model and Bath data source, broadly conformed with each other.

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