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Ocean energy assessment: an integrated methodology

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AN INTEGRATED METHODOLOGY

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OCEAN ENERGY ASSESSMENT; AN INTEGRATED METHODOLOGY

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Abstract

The huge natural energy resources available in the world's oceans are attracting increasing commercial and political interest. In order to evaluate the status and the degree of acceptability of future Ocean Energy (OE) schemes, it was considered important to develop an Integrated Assessment Methodology (IAM) for ascertaining the relative merits of the competing OE devices being proposed.

Initial studies included the gathering of information on the present status of development of the ocean energy systems on wave, OTEC and tidal schemes with the challenges faced for their commercial application.

In order to develop the IAM, studies were undertaken for the development and standardization of the assessment tools focussing on:

- Life Cycle Assessment (LCA) on emission characteristics.
- Energy Accounting (EA) studies.
- Environmental Impact Assessment (EIA) over different environmental issues.
- Resource captures aspects.
- Defining economy evaluation indices.

The IAM developed from such studies comprised of four interrelated well defined tasks and six assessment tools. The tasks included the identification of the *modus operandi* on data collection to be followed (from industry) for assessing respective OE devices, and also advancing relevant guidelines as to the safety standards to be followed, for their deployment at suitable sites.

The IAM as developed and validated from case studies in ascertaining relative merits of competing OE devices included: suitable site selection aspects with scope for resource utilisation capability, safety factors for survivability, scope for addressing global warming & energy accounting, the environmental impact assessment both qualitatively and quantitatively on different environmental issues, and the economic benefits achievable.

Some of the new ideas and concepts which were also discovered during the development of the IAM, and considered useful to both industry and researchers are given below:

- Relative Product Cost (RPC) ratio concept- introduced in making an economic evaluation. This is considered helpful in sensitivity analysis and making design improvements (hybridising etc) for the cost reduction of OE devices. This index thus helps in making feasibility studies on R&D efforts, where the capital cost requirement data and life span of the device is not well defined in the primary stages of development.

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- Determination of the threshold limit value of the barrage constant - considered useful in determining the efficacy of the planning process. The concept ascertained the relative efficiency achieved for various barrage proposals globally. It could also be applied to suggest the revisions required for certain barrage proposals and also found useful in predicting the basin area of undefined barrage proposal for achieving economic viability.

- Estimations made on the future possibility of revenue earnings from the by-products of various OTEC types, including the scope of chemical hubs from grazing type OTEC plants.

- Determination of breakeven point- on cost versus life span of wave and OTEC devices studied, which is useful in designing optimum life of the concerned devices.

The above stated multi-criterion assessment methodology, IAM, was extended leading to the development of a single criterion model for ascertaining sustainability percent achievable from an OE device and termed IAMs.

The IAMs was developed identifying 7 Sustainability Development Indices (SDI) using some the tools of the IAM. A sustainability scale of 0-100 was also developed, attributing a Sustainability Development Load Score (SDLS) percentage distribution pattern over each SDIs, depending on their relative importance in achieving sustainability. The total sum of sustainability development (SD) gained from each SDI gave the IAM**s** (for the concerned device), indicating the total sustainable percentage achieved.

The above IAMs developed, could be applied in ranking OE devices alongside the unsustainable coal power station. A mathematical model of estimating the IAM**s** was formulated, in order to ascertain the viability to the sustainable development of any energy device.

The instruments of IAM and IAM**s** which have been developed would be helpful to the OE industry in ascertaining the degree of acceptability of their product. In addition it would also provide guidelines for their safe deployment by assessing the relative merits of competing devices.

Furthermore, IAM and IAM**s** would be helpful to researchers undertaking feasibility studies on R&D efforts for material development research, 'hybridization studies' (as also new innovations), cost reduction, the performance improvement of respective devices, and any economic gains.

With future advancements in OE systems and the availability of field data from large scale commercial applications, the specific values/data of the IAM & IAM**s** may be refined, but the logic of the models developed in this research would remain the same.

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List of Abbreviations

CPBP	Carbon pay Back Period
CWP	Cold Water Pipe
EPBP	Energy Pay Back Period
EA	Energy Accounting
EIA	Environmental Impact Assessment
IAM	Integrated Assessment Methodology
IAM**s**	Integrated Assessment `Model on sustainability
kWh	kilo Watt hour
MWh	Mega Watt hour
GHG	Green house gas
GWh	Giga Watt hour
HMTSTA	Heat and Mass Transfer Scooping Test Apparatus
g/kWh	Gram per kilo Watt hour
LCA	Life Cycle Assessment
LCIA	Life Cycle Inventory Analysis
MITC	Ministry of Environmental Trade and Commerce
NELH	National Energy Laboratory Hawaii
OE	Ocean Energy
OTEC	Ocean Thermal Energy Conversion
CC-OTEC	Closed Cycle Ocean Thermal Energy Conversion
OC-OTEC	Open Cycle Ocean Thermal Energy Conversion
OECD	Organization of Economic Cooperation & Development
OWC	Oscillating Water Column
p/kWh	Pence per kilo Watt hour
PPM	Part per million
PPB	Parts per billion
PV	Photo Voltaic
RE	Renewable Energy
RPC ratio	Relative Product Cost ratio
R/P	Resource/Production
SD	Sustainable Development
SDI	Sustainability development index
SDIgw	Sustainability Development Index from global warming abatement
SDIen	Sustainability Development Index from gain in preventing energy loss
SDIsp	Sustainability Development Index from arresting species loss (if any)
SDIgf	Sustainability Development Index from growth of food materials
SDIv	Sustainability Development Index from scope of hazard mitigation
SDIec	Sustainability Development Index from scope of economic gains
SDIqi	Sustainability Development Index in improving upon quality of life
SERI	Solar Energy Research Institute
SI	Sustainability Index
SDLS	Sustainable Development Load Score
TWh	Terra Watt hour
TW	Terra Watt
TISEC	Tidal In-stream Energy Conversion
UN	United Nations
WEC	Wave Energy Converter
WD	Wave Dragon
WWP	Warm Water Pipe

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CHAPTER 1

INTRODUCTION

1.0 Preamble

The use of energy has been identified with the quality of life, since the dawn of human civilization. The hall mark of economic advancements has now been identified with the generation of electricity, first used in 1883 (Shier 1990). As a result the demand and consumption of fossil fuels has increased tremendously over the last hundred years (International Energy Outlook, 2011).

Given the high levels of consumption and reliance on fossil fuel it is unsurprising that any increase in the cost of fossil fuels has a great impact on the economy of the affected areas, through an increase in inflation (Morimoto & Hope 2006:526). In developing countries its consumption is likely to increase sharply in order to catch up their economic progress. It has been projected in the World Energy Outlook report that by 2035, coal fired power production in India, China and other non-OECD countries would increase sharply, though   may rather decline for OECD countries (Baroni 2011).

This ever increasing use of fossil fuels confronts the global community with two big problems. They are: the emissions of harmful gases in large quantities from fossil fuel, vitiating the environment threatening global warming, as well as the resource depletion of fossil fuels that might stall the very progress of economy altogether.

In recognition of these issues energy planners and policy makers have now started thinking in terms of using sustainable development in order to safeguard the interests of future generations through using innovative alternate sources of energy.

Taking this into account it is therefore necessary to provide an overview of current concerns which impact this thesis topic. These include:

- Global warming and the ozone hole, from the anthropogenic emissions of fossil fuels beyond a limit, threatening the very existence of civilization.
- Depletion of fossil fuel resources and the impact this will have on nations economies
- Sustainable development with suggested use of alternative energy/renewable energy.
- Present status of use of alternative/renewable energy resources.
- The scope for tapping the Ocean Energy systems, this having the advantage of no pressure on land use.
- Justification for the undertaking of this thesis topic, on Ocean Energy that could be of assistance to energy planners.
- Defining the aims and objectives of the thesis topic.
- Outlining the methodology of work which was followed in meeting the above objectives, including the scheme of thesis writing.

Each of these points will be addressed in subsequent sections.

1.1 Green House Gases (GHG) and Global warming

The gases responsible for global warming, termed Green House Gases [GHG] are: water vapour, carbon dioxide, argon, neon, helium, methane, hydrogen, nitrous oxide and ozone. Besides these natural atmospheric GHGs, there are other man-made GHGs as well, these include the three groups of fluorinated compounds – sulphur hexafluoride, HFCs and PFCs. But oxygen and nitrogen, which are the major atmospheric constituents, have no green house effect as they neither absorb nor emit infra-red radiation. This is because of the fact that they are homo nuclear diatomic molecules with no net charge in dipole moment when they vibrate.

In fact, the three factors that influence the degree of warming from GHGs are – the global warming potential (GWP) of the particular gas, its concentration in the atmosphere and the mean life. CO_2, that is generated from the burning of carbon based fuels (fossil fuels) has GWP of 1 with a lifetime of several hundred years. Man made CFCs and fluorinated compounds, made for refrigerants, have GWP of several thousand, but their life is around 14 years (Kato & Widiyanto 2005).

It is evident from table-1 given below, that the contribution towards warming in case of other GHGs is negligible compared to that of CO_2, despite their higher GWP values, because their atmospheric concentration is negligible.

Table-1.1 Percentage composition of dry air (water vapour varying from 0.1%-6%) (Sakhasiri 2007).

Gases	N$_2$	O2	Ar	CO$_2$	Ne	He	CH$_4$	Kr	N$_2$O	H$_2$	Xe	O$_3$
% (v/v)	78.08	20.95	0.93	0.033	18×10^{-4}	52×10^{-5}	2×10^{-4}	11×10^{-5}	5×10^{-5}	5×10^{-5}	87×10^{-7}	1×10^{-6}

In fact, it has been said in a report, that if the CO_2 concentration exceeds 450 PPM from the present 350 PPM level, then there may be irreversible temperature rise continuing for centuries. Scientists forecast that with the present trend of CO_2 increment, average global surface temperature would rise between 0.6-2.5°C in the next fifty years and between 1.4-5.8°C in the next century. This may lead to significant regional variations leading to major environmental disasters (Glickson 2009).

Such is the threat of a potential catastrophic situation the scientific community forewarns planners and policy makers, to reconsider the present trend of unabated fossil fuel consumption. Thus, we are compelled to think of alternative non-carbon sources of energy, to stop further enhancement of the GHGs level (CO_2 mainly).

In addition to the global warming from GHGs (CO_2 mainly) we are confronted with another problem, termed ozone hole which has already done some damage towards maintaining environmental equilibrium (Varotsos 2004).

Besides the above stated environmental problems faced from the over use of fossil fuels, the imminent danger of resource depletion is of great concern, a brief account of which is given below.

1.2 Fossil fuel depletion

In addition to the disastrous environmental consequences of global warming and ozone hole problems, the increasing trend of the use of fossil fuels (oil, gas, coal) is resulting in the rapid depletion and exhaustion of these fuels.

The particular fossil fuel energy that has already started to show signs of depletion is oil. The world's transportation system is based on its assured steady supply. But there is a decline in its production by 3 % per year, whereas the world's oil demand rises by 2% per year (Dov and Roy 2004). It is also to be noted that the production cost will always increase, with the depletion of the resources. This hard reality is true for all types of fossil fuel energy resources including coal and this is applicable not just for oil.

A study on the life of fossil fuels suggests that the planet may become depleted of oil and gas within the next half a century at the current rate of consumption whilst coal will last a little longer. In fact the production of fixed resources would follow the law of diminishing return, a sharp decline following peak production, termed Hubbert peak, named after Hubbert (Hemmingsen 2010).

The ratio of reserve/production, i.e the R/P ratio of fossil fuels in the global perspective with the present rated use has been predicted to be: oil – 40 years; natural gas - 60 years; whereas coal will last another 200 years, as estimated by World Energy Council in 2006 (Smith 2007: 107-113).

In light of these stark realities, the global community is thinking in terms of sustainable development in energy planning, as highlighted below.

1.3 Sustainable Development with Application of Renewable Energy

The finite nature of the world's fossil fuel resources places a further stress on the need to develop sustainable energy systems. That is why scientists and planners started forward planning, in terms of sustainable development. It means a developmental strategy that would be able to meet the needs of the present without compromising the ability of future generations to meet their own needs, both in respect of energy and raw materials (UN General Assembly 96th Plenary meeting 1987).

It must be stressed that sustainable development, is not just confined to energy issues. It also seeks to; eliminate the risk of species extinction (plants and animals), address the environmental issues affecting soil/land/water, and the extinction of minerals and other resources including energy (Sneddon *et al*. 2006). The guiding principle underlying sustainable development spells out categorically that:

- "Each generation should require the diversity of resource base so that it does not unduly restrict the options available to future generations.
- Each generation should maintain the planet's overall qualities so that it does not get into worse condition than received and

- Members of every generation should have comparable rights of access to the legacy of past generation and should conserve this access to the future generation'' (Dincer 2000).

With energy being an important issue in all developmental work, including addressing issues of poverty prevention and alleviation, it is imperative to ensure that any solutions are sustainable both in terms of energy production and the economic impact. Clearly for those countries where fossil fuels are a main source of income there cannot be a complete move away from the use of fossil fuels, without first identifying a viable alternative income source, due to the negative economic impact. Current rates of consumption will lead to an eventual depletion of these resources anyway and therefore it is imperative that development plans recognise these issues and consider moving to non carbon producing renewable energy sources. Such sources should not only be of non-carbon origin, but they should also be replenishable with no scope of future depletion. Switching over to such sources has been advocated in UN resolutions No- A/58/484/Add.1, 58th session of agenda 94(a), for achieving sustainable development.

1.4 Renewable Energy systems

The very definition of renewable energy implies an energy source that:

- Automatically replenishes, or one that has infinite resource potential.
- They are clean energy, almost free from generating GHGs.
- Their large scale use would not only decrease the presently increasing trend of GHGs and thereby avert global warming, but also ensure a steady and virtually unlimited supply of energy from diverse sources.

Some of the major sources of such renewable energy systems could be from the following sources:

- Utilising the energy of solar insolation over the earth's surface called solar energy.
- Generating oils or gases from decomposition/degeneration of bio sources, including bio-wastes called bio-fuels.
- Wind energy of blowing wind.
- Utilising the hydro-power, either natural or creating artificial level difference of natural water bodies and/or the energy of the flow of water bodies.
- The huge untapped reservoir of energy in oceans, termed ocean energy.

To date, only a small fraction of these energy forms are being tapped compared to the conventional fossil fuels, as shown below in fig-1.1 (Thresher and Musial 2010).

Fig. 1.1 Different types of energy use in USA including renewable sources (Thresher and Musial 2010).1 Btu (British Thermal Unit) = 1018 Joule.

It is evident from the above figure 1.1, that only 7% of energy is currently used from renewable energy sources, despite the UN resolution (No-A/C.2/58/L.26 and A/C.2/58/L.59) suggesting a switch over to RE sources, in order to achieve sustainability.

With the current lack of development, energy forms such as Solar, Bio-fuels, Wind or Hydro are not in a position to solely support the current high demand for energy. R&D studies are therefore required in order to achieve large scale energy production, with increased techno-economic viability.

It may be relevant to add here that all energy systems (including fossil fuels) are directly or indirectly linked to solar radiation reaching the earth's surface. The surface of the oceans surrounding the earth is three times greater than the earth's land mass. It is therefore rich with its energy resource potential. But this vast renewable energy resource has not yet been advanced to the stage of large scale commercial application, even though a small percentage of this energy could have met the growing global energy demand many times over (DTI report 2003).

1.5 Scope of tapping ocean energy (OE) systems

The global power consumption, as per the estimations made in 2008 have been reported to be around $1.6*10^7$MW (Zabihian and Fung 2011), which is around an energy consumption of 0.14016 TWh/yr. This is compared to the estimated resource potential of different types of OE which are detailed below (Khan and Bhuyan 2009).

- The mechanical energy of wave schemes having resource availability for electricity production of 8000-80,000 TWh/year.
- The thermal energy resource of ocean surface water that can advantageously be utilised to produce 10,000 TWh/yr, by utilizing the thermal gradient of the bottom layer of cold water; the system being termed Ocean Thermal Energy Conversion (OTEC).

- The potential energy that can be stored making tidal barrages at suitable sites with the prospect of producing 800TWh/ year.
- The kinetic energy of tidal current at suitable sites that can be utilised for producing 800 TWh/year.
- The salinity gradient between fresh water and ocean's saline water that may be tapped using reverse osmosis process with suitable semi-permeable membrane, for power generation- the potential power resource may reach around 2000 TWh /year (Khan and Bhuyan 2009).

Amongst the above five types of OE systems, salinity gradient between ocean water and fresh water (in estuaries) utilizing semi-permeable membrane, remains in the conceptual stage only; whereas the most researched one being carried out is the wave system option. In fact, the resource potential per sq. m of wave energy is considered to be more than 15-20 times than that of solar or exploitable land based wind energy, originating from equivalent solar insulation/sq.m. (Vining 2005). In addition to the availability of higher resource potential, the utilization factor of wave energy is also nearly double that of wind energy. Therefore wind energy can produce power for a maximum period of 2190hrs only of the 8760 hours available per year, for wave schemes it could be 4380 hours per year (Vining 2005).

The other advantage of OE is its predictability thus enabling future planning. Tidal energy can accurately be predicted 100 years ahead (Englander & Bradford 2008). However, waves originating at a site can propagate thousands of miles, and its size and energy can be predictable 3-5 days in advance (Englander and Bradford 2008).

Wave schemes being the most researched area amongst the OE systems. There are a number of Wave Energy Converters (WECs) floated by different companies that have proved to be successful in sea trials. But it is yet to be trialled for large scale commercial exploitation (Nadeau 2007). The same is true for OTEC schemes; though small scale OTEC plants have already been tried with success (Nadeau 2007). Amongst all the OE schemes, it is only the tidal barrage scheme that has emerged as a mature technology with long term unhindered commercial scale power supply. For example, La Rance Barrage in France successfully installed in 1968, is providing unhindered power supply of 480 GWh/year since then (Andre 1978).

It is a fact, that most OE systems that have been developed have mainly been confined to prototype trial runs, and have yet to overcome many technical challenges including; the cost component, and energy security for unhindered commercial scale energy supply (Mueller and Wallace 2008). However, there has been renewed interest in the last few decades (Pelc and Fujita 2002). A number of OE scheme projects are under development in different countries as shown in the following fig.1.2 (Khan and Bhuyan 2009).

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Fig.1.2 Country-wise distribution pattern of projects of most active countries on different OE systems (Khan and Bhuyan 2009).

It is clear from the above figure that the leading countries working on OE energy projects are UK, USA & Canada, who are mostly working on wave schemes. In fact the global distribution of Ocean Power companies is also quite high in countries like the UK and USA, as also shown in the following figure 1.3.

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Fig.1.3 Ocean industries in countries with greatest future market potential (Englander and Bradford 2008).

The countries shown in fig. 1.3 are considered to be important players in power generation from OE schemes. It has been claimed that the future power generation capacity from OE systems, could be; 20% of the total energy demand for the UK, 25% for Canada and 9% for USA (Englander and Bradford 2008). With R&D investment for different types of OE systems, there could be huge potential, particularly for the rich resource potential with no additional pressure on land use (Mueller and Wallace 2008).

It may be relevant to add the observation of US researchers in the context of the scope of future commercial applications of OE systems. They made some projections on the scope of the imminent applications of different forms of OE resources, though they stressed the huge resource availability of off-shore wind. The estimated results of the US resource potential, with scope for the immediate exploitation made by the Electric Power Research Institute & National Renewable energy Laboratory, shown below in figure 1.4, gives the immediately (estimated in 2010) exploitable resource status of US (Thresher and Musial 2010).

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Fig.1.4 Proposed exploitable sources on various ocean energy systems of USA (Thresher and Musial 2010).

US researchers however, considered that because of the 'nascent state of development' of the commercial scale application of OE systems, the scope of determining their immediate exploitable resources are in a 'preliminary stage' with scope for improvement from R&D studies (Thresher and Musial 2010).

It may be added that the UK Govt. has also formed an action plan, Marine Energy Action Plan (MEAP), for the advancement of OE technology, with a view to cut carbon emission in the UK to 80% by 2050 (Bahaj 2011). The impediment discouraging the investment in OE systems for large scale commercial application is the potential economic constraints of not achieving an acceptable level of energy cost (Bahaj 2011).

It is however to be appreciated that the economic consideration should not be the only criterion for assessing the relative merits of an energy system, nor of a device. It is recorded, that in the initial years of development, electricity cost from fossil fuel was much costlier than the-then energy source of burning wood, animal/vegetable oils/fats, etc (Shier 1990). Therefore it is necessary to consider different assessment criterion/tools, including; the environmental consequences, the sustainability of development activities, examining the prospect of the application of different types of OE systems, and adjudging the relative merits of competing OE devices. It was by taking all of these factors into consideration that determined the topic and relevance of this thesis.

1.6 Importance of the thesis topic

To date there has been neither internationally recognized guidelines nor standards for assessing the performance efficiency of OE systems, nor of assessing competing OE devices (Ocean Energy Technology Overview 2009), from the perspective of environmental consequences, sustainable development, or their economic considerations (AEA Energy & Environment on the behalf of Sustainable Energy 2009). It is in light of this that this thesis topic of developing the Integrated Assessment Methodology (IAM) for OE systems was undertaken.

It is considered that such study would not only be helpful in assessing the relative merits of a number of competing OE devices that have been devised by a number of companies; but be also useful in R&D studies for the technological improvement of OE systems. In order to identify the areas of R&D required to meet the challenges faced for the large scale application of the OE systems, a closer examination on the knowledge base of current OE systems and those in development is required. This is the first part of this thesis.

It is not yet known to what extent the huge off-shore wind energy resource as advocated by US researchers (shown in figure 1.4) could be effectively utilised, may be with the hybridization of wave energy schemes. Also, there is a need to examine the possible environmental and economic effects caused from the churning of the ocean and from the application of different types of OTEC technology. It might be helpful if it could be determined, if the number of proposed tidal barrage projects, have the scope of improved planning and also of their effect on the local ecology and economy.

The proposed thesis topic is therefore focused not only on ascertaining the scope of judging the relative merits of different OE systems and categorizing the sustainability of OE devices, but also serves as an aid for further R&D studies for improving the performance of devices.

The aims and objectives for the study are detailed in subsequent sections.

1.7.1 Aim

The overall aim of the project was to develop an **Integrated Assessment Methodology**, which could be used as a model to investigate the scope of Ocean Energy for its market viability and long term acceptability with sustainable development. Besides looking at the economy and the scope of resource tapping, this also takes into account the environmental and economic consequence both locally and globally.

1.7.2 Objectives

The focus of the present project was on Ocean Energy technologies. Therefore the immediate objectives, with time targeted work schedules were:

1. Development of an Integrated Assessment Methodology (IAM) for Ocean Energy (OE) systems, covering Wave Energy, Ocean Thermal Energy Conversion systems (OTEC) as well as Tidal energy schemes.
2. IAM included development of a model enabling; Environmental Impact Assessment (EIA), estimations both qualitatively as well as quantitative, Life Cycle Assessment & Energy Accounting studies suitable for all three OE systems
3. Examination of the scope of resource utilisation, and comparative analysis of the economic advantages.
4. The proposed IAM was developed to serve as a composite model encompassing all three types of OE systems; Wave, OTEC and Tidal schemes
5. The above IAM should not only enable ascertaining relative merits of different types of OE devices with scope of their application, but be also useful in ranking the competing OE devices from sustainable development aspects.
6. It will also examine the scope of performance improvement of OE devices, and identify areas for R&D in respect of cost reduction and acceptability.

1.8 Outlining the research methodology for developing the IAM

Before the research methodology could meet the predefined objectives it needed to define an initial baseline for the work programme and potential constraints.

1.8.1 Initial Premise

It might be considered to be quite logical to put forward the following premise, before planning the work programmes and tasks required to be fulfilled to meet the above objective. They were as below:

- Since there has been very little commercial application of OE systems, there is no universally accepted, standardized assessment methodology, for

evaluating the relative merits of different power generation devices of OE schemes.

- The IAM as was considered for development should have the scope for further improvement, after availing of feedback data as and when the wide scale commercial application of the OE systems come into force.

- The developed model was intended to be helpful to stakeholders/researchers, by identifying the areas with scope for further improvement of their device(s), for making large scale commercial application.

1.8.2 The constraints faced and the methodology adopted in overcoming them

The cost of Wave and OTEC devises increases depending on the location due to the ocean conditions. Whereas the cost of barrage schemes escalates because of the length of planning required.

These factors associated with non-uniform wave resource availability with occasional storm waves and related constraints resulted in not achieving large scale commercial application of OE systems to date. Due to this lack of large scale application, there remain constraints as regards availability of field data on the use of commercial scale OE systems. This was a challenge in meeting the objectives of the study.

There are few documented journal references on such data on commercial application of OE schemes are available, but there remain quite a number of reports from Govt. bodies, concerned organizational literatures/brochures, and website references of manufacturing concerns etc, giving pilot plant-scale data as also theoretical conceptual evaluations on different aspects of OE schemes. These data, and personal interaction with manufacturing concerns and experts on the topic was utilized in developing the logic to meet the objectives of the study.

Examples may be cited from the effect of barrage construction that suggests to even out the lower and higher limits of tidal range (Elliott 2004). It is logical to presume that this phenomenon would cause less churning with less turbidity and thereby increasing in euphotic zone which is likely to help overall growth of flora and fauna, though this may be marginal. Likewise, though there is no data available on the environmental consequences of flora and fauna on the commercial application of OTEC; but the Humboldt Current upwelling the bottom ocean water, resulting in higher fish growth in west coast of South America (Anderson 1998), may be presumed to cause similar growth for OTEC schemes as well.

Likewise, though there is no literature available on the raw material requirements of wave energy converters, required for LCA & EA studies; it could be resolved from personal communication with concerned officials of manufacturing concerns. The reliability of LCA & EA results obtained thereby could be cross checked from subsequently published literatures as also of data sources from different concerns.

In order to compare the relative economy of OE products, a new concept 'relative product cost ratio' based on respective raw material inputs was introduced, from which the cost of power production could be derived. In the case of the economic

evaluation of barrages it was the concerned contractor's/engineering firms reports that proved helpful in providing the required data.

Thus, despite a lack of available commercial scale data, the constraints faced could be deduced from available data from all sources, along with the logical development of the topic, to meet the objectives of the study.

1.8.3 Methodology followed to meet the objective with scheme of thesis writing

The time targeted tasks comprised of the following stages of knowledge based development and data generation to meet the above objectives. They were:
.
Stage-1. A comprehensive analysis from literature review as regards the updated status of development of the three OE systems; Wave, OTEC and Tidal schemes, with limitations and challenges for their large scale deployment (Chapter-2). This was imperative to assess various aspects of the OE devices, as required for developing the IAM as well as for identifying scope of R&D areas yet to be resolved for their large scale commercial application.

Stage-2. Development and updating of the knowledge base and database from a review of literature, as regards the assessment tools like, scope of resource utilisation aspects for different OE schemes, the environmental consequences that may be encountered (Chapter 3), Life Cycle Assessment (LCA) & Energy Accounting (EA), as well as the economic indices for rating the economic viability of the energy systems (appendix 1&2). The sources utilised for developing and standardising the same were: relevant text books, journal studies, internet search using key words, reports, project reports, personal communications and dialogues with experts, including research guides, as well as consultation of websites of the concerned organisations.

Stage-3. Development of a model for qualitative and quantitative assessment of EIA, from examinations of various aspects, as may be applicable for wave energy converters. The developed EIA model for wave schemes could be extended to accommodate OTEC and tidal systems as well (Chapter 3). Case studies thereafter pursued with logical development of the topic and literature search could enable the developing of the EIA model, accommodating the specialties of all three OE schemes on Wave, OTEC & Tidal systems.

Stage-4. Assessment of all the three OE systems independently and separately, from application of the indices that have been developed and standardized like; scope of resource utilisation aspects, LCA & EA studies inclusive of comparison with fossil fuels, examinations from the economic instruments identified. Case studies were thereafter undertaken for Wave, OTEC and Tidal schemes respectively, employing all the above assessment tools (Chapters 4, 5 & 6).
.
Stage-5. Development of the IAM, encompassing all three OE systems under one canvas, based on the case studies as made up of different types of OE devices. The composite model development included; defining the tasks with deployment guidelines, giving precautionary stipulations, as also on scope of application of all

the assessment criterion/tools for ascertaining relative merits and applicability of the competing OE devices (Chapter 7).

Stage-6. Application of the IAM with identification of sustainability indices (and extending it to the formulation of IAM**s)**, for ascertaining sustainable development of competing OE devices and their ranking thereof. Development of the generalized mathematical model of IAM**s** applicable for ranking sustainable development of a RE system including OE schemes (Chapter 7).

Stage-7. Discussions on R&D areas for making performance improvements on concerned OE devices, based on the application of IAM & IAM**s** that would be of advantage and relevance to industry/researchers (chapter 8).

Stage- 8. Overall conclusions reached from the study made (chapter 9).

Stage-9. Writing the thesis incorporating all the above results and data generated, as well as with citations of source references, at appropriate places of the studies made.

<div align="center">

CHAPTER -2

PRESENT STATUS OF DEVELOPMENT OF OE SYSTEMS

</div>

2.0 Introduction

The OE systems included in the present studies are: the Wave schemes, Ocean Thermal Energy conversion (OTEC) systems, and Tidal Energy covering Barrage as well as Tidal in-Stream Energy Conversion (TISEC) schemes. A literature review was undertaken on the above three OE schemes, mainly to ascertain the present state of development as regards the suitability for commercial deployment. Also reviewed was:

- Information retrieval on the guiding principles of different types of OE systems,
- An overview of the different types of OE devices developed and the stage of development,
- Identification of the challenges yet to be resolved
- The scope for further developing OE devices to ensure they are fit for purpose on commercial scale

It may be relevant to add that the guiding principles with *modus operandi* of operation of the three OE systems Wave, OTEC and Tidal schemes, are entirely different. Information pertaining to the status of each device in terms of development is covered later in this thesis. However during the literature review of the three OE systems emphasis were placed on specific areas, which are broadly as below.

- Resource aspects giving its origin as also of the basic principles followed for utilising the resources of the individual OE systems.
- Stages of development of the devices concerned.
- *Modus operandi* of operation and functioning of the individual devices developed.
- Present status of development of the devices concerned with identification of the challenges to be resolved.
- A critical appraisal of the present status of development of the devices, with scope of further studies in meeting the challenges.

An overview of the above topics for the three OE systems is appended below.

2.1 WAVE SCHEMES

2.1.1 Origin of Resources & the guiding principles in utilising them.

Ocean waves are formed from the effect of blowing wind over the vast stretch of background water surface called the "fetch". The larger the fetch and the stronger the wind the more powerful is the wave (Duckers 2004). It has been reported that with average solar insolation (at a latitude 15^oN) of $0.17kW/m^2$, causing wind speed of around 10m/sec and thereby with power intensity of $0.58kW/m^2$, may generate waves (in the pacific) with power intensity as high as $8.42kW/m^2$ (Mc Cormick 1981:1-2). It has been estimated by the World Energy Council (1993) that the

exploitable reserve of the ocean wave energies mechanical energy transformation to equivalent electrical energy amounts to > 2TW (Thorpe 1999). Even if a small fraction of it could be fruitfully utilized, it could meet the global energy demand many times over. Though there have been studies carried out in tapping this energy for centuries, but serious attempts to tap this huge energy resource has only been considered for last few decades, after the oil crisis struck globally in the 1970s (Duckers 2004). In the context of power generation from wave energy, ocean wave characteristics can be studied from the following two aspects:

- Relationship between wave length, period and velocity of waves and also the shore line characteristics of waves.
- Power production relationship with wave characteristics, and the global distribution pattern of such wave power density.

A brief outline of the relevant points on above is given below.

2.1.2.1 Relationship between wave length, velocity and period of waves

The kinematic properties of ocean waves in deep water may be considered to be dependent only on the wave length λ & the time period T independent of wave height H or, depth d (Duckers 2004). Their relationship is expressed as:
$$\lambda = gT^2 / 2\pi \quad \& \quad V = gT/2\pi \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \text{[2.1]};$$
where, V is the phase velocity or, speed of the wave also termed celerity, and g is the gravitational constant. But this relationship holds well in deep water only, where water depth is $> 1/2 \ \lambda$.

In shallow water having depth $d < 1/4\lambda$, only depth decides the phase velocity or celerity of the ocean wave, independent of all other wave characteristics. Making suitable approximations, the relationship would assume:
$$V = \sqrt{(g \cdot d)} \ \& \ \lambda = VT \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots[2.2];$$
where, d denotes the depth .

But with intermediate depth between $\lambda/ 2\pi$ & $\lambda/ 4\pi$, both the parameters like, depth (d) and time period (T), would dictate the properties of wave.

It would be obvious from equation (2.1) that phase velocity of deep ocean water is around 1.5 times its wave period; making long waves faster than short waves. In shallow depths however, the velocity is 3 times the square root of the depth irrespective of the time period, as evident from equation (2.2) given above (Duckers 2004).

As waves approach the shore they change shape with lowered wave length and period but with proportionate height increase. This increment of the height of shoreline approaching wave depends on the wave length and period of the impounding wave, as well as of the beach slope (Floor 2000). These breaking waves creating breakers loose energy producing heat. Moderate slope is experienced then, termed spilling breakers. With medium slope are noticed plunging breakers but with slopes steeper than wave's slope is experienced in surging breakers producing foam and large surges of water. With very steep slopes in rocky shores the wave is reflected back to the ocean and helps growth of marine life there (Floor 2000).

It may be relevant to add that a 1m high wave breaking in the 5 m shoreline beach, say with 10kW energy, may be compared with that of the crashing of a speeding small car (Floor 2000).

2.1.2.2 Wave power estimation and its global distribution

In waves it is not the individual water particles that move, it is their collective energy that advances forward. Rather, the waves may be considered to be composed of orbiting water particles. These orbits are of the same size as the wave height of the surface wave that gradually lowers down in exponential order with depth. In fact, 95% of this energy is confined to a depth of quarter of the wave length from the surface. In estimating wave power is considered this surface wave power only (Duckers 2004).

The wave power (*P*) per crest length of a monochromatic wave for all depths, can be expressed from the following equation (Thorpe 1999).

$P = \rho g^2 H^2 T / 32\pi$ kWm^{-1} ……… …………………………..[2.3]

where, *P*=wave power, expressed in kWm^{-1};
ρ= the density of sea water (1.025 kg/m3);
g= the acceleration due to gravity (9.81m/s^2);
H =the wave height (in meters);
T =the time period of the wave (sec)= $\sqrt{(2\pi\lambda/g)}$; where, λ= wave length.

However, the real wave patterns in oceans are rather complex with varied wave heights and wave periods. Thus for all practical purposes, replacing H with H$_s$ the significant wave height, T with Te the average energy period-- the wave power density *P,* can be expressed as:

P= 0.49 H$_s^2$ T$_e$ kW per meter of crest length...……………………… [2.4]

It may be relevant to point out that sea wave heights being constantly varying, maximum wave height at a particular place may be many times more than the average value of *Hs*. Hence, average of significant wave height *Hs* and periods *Te* with their maximum frequency as noted from the scatter diagram of a round the year observations, are considered for estimating wave power at a place using equation [2.4] as above (Duckers 2004).

Global distribution patterns of wave power density, giving an annual average on scope of power generation expressed in kW/m crest length of the concerned zone of the ocean, as could be estimated from determinations of Hs & Te values following above equation [2.4], has been shown below in figure 2.1) .

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Figure 2.1 –Global distribution of wave energy density in kW/m crest length (Duckers. 2004).

It would be obvious from the above figure that wave power density is minimal in the equatorial zone for obvious reasons of having minimum wind speed, as well as with fetch getting restricted from the presence of islands. On the other side, it is the equatorial zone itself which is the epicentre of typhoons and hurricanes from maximum warming of the seas. They send large waves all around, away from the place of their origin (Floor 2000). Obviously, with availability of larger fetch and higher wind speed the wave power density is maximum in latitude 30° —60°. Since availing higher wind speed and longer fetch makes taller waves (Hs) and longer periods (Te), and thus increases the scope of availability of rather higher wave power density.

Hence, the western coast of UK with a long fetch of the stormy Atlantic has a wave power density which can reach as high as 70kW/m crest length; whereas in the Arabian sea in the western coast of India with smaller fetch and less wind speed (equatorial zone), the average wave power density is just 10kW/m crest length.

It may be added that despite the fact that exploitable wave energy from the global perspective, as estimated from above global distribution of ocean energy as above, might be many times more than the global energy demand; but this huge energy resource yet remains mostly unutilised. In fact, the main hurdle for availing power from this huge resource of wave energy lies in the cost-effectiveness of building huge and robust wave energy converters, in order to negotiate and withstand the

rough seas with varied and severe weather conditions. Hence it is considered important to analyze the factors and guiding principles for deployment and development of Wave Energy Converters (WECs) and the advancements made on the same. These topics have been examined in subsequent sections.

2.1.3 Factors & guiding principles for development and deployment of WECs

Different innovative types of WECs can be grouped either from the perspective of deployment site, or on aspects of technology used. The broad principles of these two categories are detailed below.

2.1.3.1 Deployment sites characteristics

1. The *deployment* of WECs should be preferred at sites that have maximum wave power density, but at the same time it has to ensure the survivability of the WECs, in the rough ocean weather, including coping up storm waves. Too rugged a device, which uses a large amount of construction materials, would on the other side become a financial burden. Hence, a compromise is made in the construction and in the choosing of deployment sites, this is broadly be described as: Land-based/Shore: based (to a maximum depth of 10 m) types:
   They are easy to construct but have less wave- power density; e.g. 0.01kW/m in UK coast (Duckers 2004). Typical examples of such shore-based WECs are; Tapchan, OWCs, Pendular types, etc.
2. Near-shore: types (deployment site depth, 10--25 m):
   They have wave density a little above land based ones; e.g. between 0.3—0.7kW/m in UK coast (Duckers 2004). Typical converters could be OWCs, etc.
3. Off-shore converter: types (usually depth > 50 m):
   They have wave density of 10—70 kW/m (Duckers 2004). In these types, WECs are required to be floated with mooring systems suiting the type of converter employed. They could be slack moored, fixed moored or even be fixed to the sea-bed in cases of not too deep a sea bed.

It may be relevant to add here that the main limitation of shore based WEC's are not only the lack of availability of high wave power density, making it less effective, but also the limited availability of suitable sites for deployment. It has therefore been considered that the feasibility of future proposition of near shore WECs will hardly reach 10% of future market (Westwood 2004).

Hence, most of the WECs designed are the off-shore types enabling higher power output and thereby assuring better economic prospect in their commercialization (Westwood 2004).

2.1.3.2 Technology wise categorization of WECs

It is important to note that the guiding principle of WECs is that there must be some central stable structure with active parts, which would move relative to the main structure under the force of the wave. For floating structures, a stable frame of

reference must be established for allowing the active parts to move relative to it. Of course, the physical size and shape of WECs are to be decided from the technique of operation.

All WEC types may be classified as either point absorber or line absorber types based on the nature of the device in respect of the devices confrontation with the wave to capture its power. In the former type, the size of the wave capture zone of the device is rather small compared to the wave length e.g. wave buoy or, Archimedes swing types. Whereas the wave power capture length of the latter type is comparable to the wave length of ocean waves e.g. Pelamis, Wave Dragon (Brooke 2003:27-35).

The power capture technique of WECs for converting the mechanical energy of the wave to electrical energy may also be viewed from another perspective, when deciding on their classification. They could be:

- *Overtopping type* that function like a hydro power plant, collecting water from incident waves in a tank and then run the water head thus formed to run a low head turbine e.g. the Wave Dragon.
- *Heaving type* device, converting heave motion of the wave, which is the vertical movement of the wave, that is used to run a turbine e.g. in Archimedes Swing, Water Buoy or
- *Surging devices* that exploits the horizontal velocity of the wave to generate a pumping effect facing the wave e.g. Coventry Clam;
- *Pitching type* device which exploits the angular motion about an axis parallel to the wave's crest;
- Finally it could be a combination of all of the above where movement from waves is used to pump high pressure oil through hydraulic motors to drive the generator (Brooke 2003:27-35).

However, the European Marine Centre, suggested 6 broad types of WECs based on their technique of operation (Zabihian & Fung 2011). They are:

- Over topping device, like Wave Dragon, Tapchan.
- Oscillating wave surge converters like Pendular.
- Attenuators like Pelamis.
- Oscillating water column type, like OWC.
- Point absorber like, linear type generators.
- Submerged pressure differential converters, like Archimedes wave swing.

There may be other types of innovative designs of WECs, which cannot be accommodated in any of above 6 categories (Zabihian & Fung 2011). A typical example of this may be cited, of a yet to be perfected, WEC type, like Coventry Clam. A brief overview and working principles of some of the above stated WECs that have potential e for commercial application is given below. They are however, grouped under two broad headings: *Shore based* and *Off-shore* WECs.

2.1.4 Shore based converters

The three major types of shore-based WEC devices are::
1. Tapered channel type (Tapchan).

2. Oscillating water column (OWC).
3. Pendular type.

2.1.4.1 Tapchan

In Tapchan (tapered channel), ocean water is allowed to rise 3-5m above the sea level through a long horn-shaped narrow channel which rotates the turbine as in hydroelectric power while the elevated water is allowed to flow down the sea level, as shown below in fig 2.2 (Twidell and Weir 2006).

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Fig. 2.2 Schematic diagram of Tapchan type WEC. (Twidell and Weir 2006).

The 350 kW prototype built in Norway in 1985, had a mouth that was 40m wide with the channel wall 170m long and wave power was captured using a Kaplan type turbine (Duckers 2004).

2.1.4.2 OWC

In the case of Oscillating Water Column type (OWC), ocean water is allowed to enter a partly submerged steel/concrete structure with a chamber of air column. With the adequate provision of valves, the advancing and receding ocean water alternately compresses and expands the trapped air column. This to and fro movement of the trapped air column with the advancement of the crest of the wave and receding with the trough, makes the turbine rotate generating electricity. A typical diagram is shown below infig.2.3 (Bedi *et al*. n.d.)

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Fig.2.3 Schematic diagram showing functioning of OWC type WEC (Bedi et.al. n.d.)

A prototype on OWC type WEC was made in 1991 in Islay of Scotland, making the concrete chamber of 4m by 9m using a Well's turbine, having a capacity of 75kW. A 2nd OWC was put in to commission in 2000 (termed Limpet) with rated power of 0.5MW (Westwood 2004).

2.1.4.3 Pendular

In this device a Pendular flap, hinged to the open end of a box, is allowed to swing back and forth with the action of waves and thereby run the turbine to generate power, as shown below in fig.2.4 (Thorpe 1999a). Such types of generators extensively tried in Japan, are being proposed to be built on the southern coast of Sri Lanka, having 4 chambers with expected power generation of 250kW [Crest 2004/2005].

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Fig.2.4. Schematic diagram of a typical Pendular type WEC
(Thorpe 1999a)

2.1.5 Off-shore WEC's

Offshore wave energy converters that are of interest for power generation, should have a wave length of 40m to over 300m (Tedd.*et al* 2006). The preliminary

investigations of them are carried out from prototype studies, which are finally tested from on-sea scaled down trials before commercialization.

A brief overview of some of the important off-shore devices that have the potential for commercialization in near future or are being tried in commercial applications, have been discussed below. They include:

- Wave Dragon.
- Pelamis.
- OWC.
- Orecon's OWC.
- Linear Generator.
- Archimedes wave swing.
- Coventry Clam.

In addition to these, a large number of different innovative types of WEC's that have already completed their prototype scale studies, (as gathered from questionnaire replies made by EPRI) –have also been compared, highlighting their relative power production capacity and other design data (Mirco, Bedard and Hagerman 2004).

2.1.5.1 Wave Dragon

Wave Dragon is virtually an off-shore Tapchan type WEC with certain modification in its design. The principle lies in focusing 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 given in the figure below.

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Fig.2.5 Mode of operation of power capture in Wave Dragon
(Kofoed et al. 2006).

The preliminary prototype trial with device dimensions of length 170m and height 3-6m above sea level with draught 11-14m --proved its sea-worthiness, except for a few failures of connecting parts in the rough sea-waves. This lapse was thoroughly investigated and the problem successfully resolved (Tedd et al. 2006). The plant being proposed to be commissioned in Wales coast, would weigh 33,000 tons with overall geometric layout identical to the prototype tested. The plant is designed for

each unit to produce 4-11 MW power depending on the wave climate. The efficiency obviously grows with the size of the converter. Even in the preliminary prototype demonstration, the dimensions of the device are quite high, as shown below (Titel et al. 2006):

- Arm length =145m
- Distance between tips of its arms =300m
- Maximum height above sea level = 6-3m
- Draught =11-14m

It has slacked catenary system of moorings and hence is considered to give better safety from storm waves. A typical   diagram of Wave Dragon –for both high wave and low wave situations, has been shown below in fig.2.6. (Titel *et al.* 2006).

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Fig.2.6 Wave Dragon in good waves (left) and in smaller waves (right)
(Titel *et al*. 2006)

The WD platforms being quite stable even in storm waves, it would have an added advantage of accommodating off-shore high capacity wind turbines in its robust platform with buoyant moored device—and thereby adding power generation efficiency with cost-reduction.

It is claimed the Wave Dragon on Welsh coast, UK would be the world's largest WEC with a total width of 300m [Kofoed *et al.* 2006).

2.1.5.2 Pelamis

The slacked moored type WEC, based on the Salter Duck device, was later on improved upon and termed Pelamis, meaning sea-snake in Greek (since it resembles a snake like elongated structure).   It consists of a semi-submerged articulated structure composed of cylindrical sections linked by hinged joints. The wave-induced motions of the cylinders are rested at the joints by hydraulic rams that pump high-pressure oil through hydraulic motors via smoothing accumulators. Hydraulic motors drive electrical generators to produce electricity. A novel joint configuration is used to induce adjustable cross couple resonant response, which greatly increases power capture and also control system for tuning to the particular sea state. In fact, the principal advantage of the design of Pelamis is its high degree of survivability. The fundamental mechanism are the use of length as the source of reaction to allow the system to de-reference in long storm waves, in conjunction with a finite diameter to

induce full submergence and emergence, even on confronting with large steep waves.

Each hinge of the device contains its own hydraulic power take off, and each power take off contains three hydraulic rams which convert the motions into hydraulic pressure. The hydraulic power generates electricity using accumulators and two 125 kW generators. The hydraulic system uses a bio-degradable fluid, which is in conformity with the environmental standard. Over 80% of the primary power absorbed is converted into electrical power. Its moorings are slacked mooring type ensuring its survivability.

A few relevant structural data of 750 KW Pelamis, are given below in table 2.1
Table -2.1 Dimensions of Pelamis (pelamiswave.com)

Overall Length	150m
Diameter	3.5m
Displacement	700tonnes (including ballast)
Nose	5m long dropped conical
Power take off	3 independent power conversion units

A typical diagram of Pelamis is shown below in fig.2.7.

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Fig.2.7 – Diagram of Pelamis at sea (pelamiswave.com)

Installation of Pelamis involves minimum onsite work. The moorings, seabed power cable and flexible umbilical are pre-placed in advance of the arrival of the device itself. Installation only involves connection of mooring lines and power of the umbilical. The system is 100% removable at the end of its service life.

By and large, the structure of Pelamis is made of steel with a robust structure. It is likely that significant cost savings may be possible in future if steel is replaced with other materials such as concrete (even partly) –as practicable, without compromising

the efficacy. Scope of future improvement also lies in reducing the losses in operation of the hydraulic motor set up.

Pelamis was deployed in Scotland in August 2004 by Ocean Power Delivery Ltd. It was a prototype structure having capacity of 750 kW. Its operational life is said to be more than 20years (Parker *et al*. 2007).

2.1.5.3 OWC (off-shore type)

An OWC device has been tested by Energy- Tech to a depth up to 50m off-shore -- though it had originally been planned for near shore to 10m depth only. The device employs a variable pitch blade air turbine, which raises conversion efficiency from 30% to 60% than that of fixed pitch blade design. Its structural weight is 450 tons with rated power capacity ranging from 500kW—2MW. The proposed cost involvement for a single device is £1.2—1.5 million (Mirco, Bedard and Hagerman. 2004).

A diagram of the device is shown below in fig. 2.8 (Mirco, Bedard & Hagerman 2004).

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Fig. 2.8 – Diagram showing the off-shore OWC
(Mirco, Bedard and Hagerman 2004).

2.1.5.4 Ore-Cons off-shore WEC [MRC 1000]

This is also an OWC type converter, but has a multiple resonant chamber and can operate at water depths greater than 50m. The structural weight is 1250tons with the device diameter 32m and having rated power of 1000kW. The unit is slack moored in the sea-bed using six anchors. The manufacturers claim the cost for a single unit including mooring, for rated power of 1MW to be around £1.7m. (Mirco, Bedard and Hagerman 2004).

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Fig. 2.9- Off-shore OWC, Ore Cons MRC 1000
(Mirco, Bedard and Hagerman 2004)

2.1.5.5 Linear Generator

Linear generator type of WECs, using multisided permanent magnet linear generators is still in the developmental stage only. But they have an edge over the conventional WECs from two counts. In the first place, it ensures power generation from low density waves as well, even from a wave density as low as a few kW/m (Szabo *et al*. 2007). Secondly, linear wave generators are deployed on the sea bed, hence need not withstand storm waves avoiding the costly option of making them rugged unlike the costly conventional WECs. The WECs of such generator deployed at sea bed with concrete foundation are tethered with point absorber type floating buoys, as shown below in fig.2.10 (Leijon *et al*. 2006).

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Fig. 2.10 Interconnected linear generators with floating buoys (Leijon *et al.* 2006).

To and fro movement of the buoy from surface wave gets transmitted through the tethered spring to the generator producing power. The generator consists of iron core rings fixed on a shaft with alternated permanent magnet rings, producing strong

magnetic flux outside the moving armature. The power transmission scheme is shown below in fig. 2.11.

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Fig.2.11 Power generation system of linear generator (Szabo *et al*. 2007)
Different design options for making electromagnetic field simulations of linear generator type WECs that may be applicable for low, medium or, for high wave density zones--are in progress.

2.1.5.6 Archimedes Swing

Archimedes swing is a fully submerged type WEC, which has two main parts, an air filled cylindrical chamber fixed at the bottom; and a movable upper cylinder, termed the floater. The upper cylinder or the floater heaves due to change in wave pressure and compresses or releases the air filled chamber, depending on the floater's position in crest or trough of the wave. The floater's heaving motion is converted to electricity, through electrical linear generator fitted between the air chamber and the floater. A typical diagram of Archimedes swing, showing the floater and air filled chamber separately, is shown below in fig. 2.12 (Valerio *et al.* 2007).

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Fig. 2.12 A typical diagram of Archimedes Swing (Valerio *et al*. 2007).

Successful trial of power generation could be made in Portugal coast by this submerged device, termed Archimedes swing (Valerio *et al*. 2007).

2.1.5.7 Coventry Clam

This is an 80 m dia toroid-shaped clam with interconnected 12 air-cells, each containing a turbine. When floated in off-shore ocean (50m depth or above), the waves compressing air chamber in some of these cells would push the air to the next one that remains coupled together. The cells are sealed against the water with flexible rubber membrane. Thus the air-compression caused from wave energy may be transformed to electrical energy by running the turbine connected with the cells. Thereby, at least one cell must be an active power generator unit. It has been claimed that the rated output could be 3MW, at a cost of 8p/kWh; which with necessary R&D studies on optimization can lower the power generation cost to 4p/kWh (Duckers et al. 1994). A schematic diagram of the clam, also termed Coventry clam is shown below in fig. 2.13(ETSU report 1993).

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Fig.2.13 Schematic Diagram of a typical Coventry Clam shown
(Duckers 1999)
More studies are needed for testing its sea-worthiness–which has immense possibility from economy and efficiency.

2.1.6 Critical Appraisal with comments on challenges of wave schemes

It could be noted from literature review that large scale commercial application of WECs is yet to be achieved and further research and design improvements need to be made to achieve their economic viability. In order to maintain survivability in rough ocean waves, WECs are built robust enough which escalates their cost from requirement of huge inventory materials. It may thus be not an exaggeration of the quote that "low wave gives the profit but high waves contributes to the cost'' (Floor

2000); since to accommodate the latter, huge construction materials are required, particularly for withstanding the storm waves.

It is hence considered that point absorber type WECs like, linear generators etc. that can ensure power generation from a wave density as low as a few kW/m only, with a much lower inventory material requirement (having no problem on survivability, being embedded in sea-bed), might with further R&D studies emerge with good prospect for commercial acceptance. Coventry clam also has immense scope of improvement with further research (Duckers *et al*. 1994). In fact EPRI, USA, made a detailed report of off-shore WEC's that passed the sea trial tests with prospect of commercial application (Mirco, Bedard and Hagerman 2004). A comparative study of them is tabulated below in table 2.2.

Table 2.2 Developmental status & technical data of off-shore Wave Energy Converters

WEC type	Dimensions*	Structural Mass*	Rated Power per unit*	Rated Power per ton of the Converter's Structural Mass	Remarks
OWC Offshore up to 50 m depth	35m / 60-90m	450 tons	500kw-2MW	1.11kWh (4.44 for 2 MW)	Mooring & survivability tests not completed.
PELAMIS >50m depth	150m/ 4.63m	380 tons	750kW	1.97kWh**	Shortly to go for commercialization
OreCons MRC1000-Offshore OWC[depth>50m]	32m/100m	1250 tons	1000kW	1.25kWh	Sub-scale testing and sea trials incomplete
Wave Bob [point absorber] depth->50m	Buoy dia-15m[draught Water-30--40m	440 tons	1000kW [250-350KW; resized cases]	2.27kWh**	Further work needed for commercialization
Wave Dragon-large overtopping device- terminator type [depth >25m]	Width-260-300m, water Reservoir size -5000-8000cu.m.	22000-33000 tons	4000kW [4-7MW For high wave climate]	0.18kWh to 0.32 kW	Prototype being too big –deployed for 2 years sea testing [awaits commercialization]
Aqua Buoy -point absorber, heaving type. [depth>50m]	Buoy diameter 6m water draught 30m	not available	Upto250kW Depending on sea state.	not available	Further trials with 3 m dia buoy, needed for commercialization.
Wave Swing -completely submerged point absorber[depth 43m]	Diameter - 9.5m, Centre line spacing - 80m	Not available	Upto 4000kW depending on wave climate	not available	Being a bottom mounted device, suitable for shallow depth also. .Further studies await for commercialization

* Data Source (Mirco, Bedard and Hagerman. 2004)..**Wave Bob is the only WEC showing higher efficiency than PELAMIS, the latter being the 2nd best with minimum weight vs. power generation ratio.

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It may be noted that a host of ideas for different types and designs of WECs with new innovations are being floated by different firms for improving upon their commercial acceptance. It thus becomes rather imperative to develop assessment tools to examine their relative merits and demerits including the feasibility for accepting their commercial possibility, not necessarily with economic considerations alone, but considering all other factors that ensures sustainable development. This could then be useful in R&D studies enabling the identification of the relative merits of innovative WECs from the point of their sustainable development. It thus emphasizes the need for the development of assessment tools for judging the relative merits of wave schemes, from the point of view of their sustainable development.

It is also important to provide an overview on the present state of development of OTEC systems as well, which has been elucidated in subsequent sections.

2.2 OCEAN THERMAL ENERGY CONVERSION SYSTEMS (OTEC)

2.2.1 Origin of resources of OTEC

The Ocean serves as a huge reservoir of heat energy. It has been estimated that 60 million sq. km. of tropical seas absorb solar radiant heat energy equivalent to 250 billion barrels of oil (Zolfagharifard 2011).

The surface temperature profile of the ocean gradually decreases with increasing depth. This is because of lesser transmission of radiant energy of the sun at a greater depth as per Lambert's law that states exponential decrease of light penetration intensity (from the sun) with increasing depth. Besides the above, the colder and heavier polar water at 4^oC flows down in deeper cores of the ocean, making the bottom layer much cooler. The average density of saline ocean water varies from 1020kg/ m^3 to 1029 kg/m^3, with an average 1025kg/m^3. But the cooler bottom layer of ocean water at 4^oC is much heavier, with density reaching up to 1050 kg/m^3. (Chapter 8, Fundamentals of Physical Geography n.d.)

Almost all the radiant energy of the sun is absorbed immediately below the ocean surface with very little light penetration in deeper cores, due to Lambert's law of exponential penetration of light with depth increase. However, because of wave movement, there remains a surface temperature core of around 100m depth having temperature differential 10-25°C from its cooler bottom layer below 600-1000m (Vega 1999). The temperature gradient changes in the interface though normally gradual, abrupt temperature changes are also noticed in places, depending on the local topography (Vega 1999). The surface temperature profile being high in lower latitude regions of the equatorial seas, it would experience higher temperature differential than those of higher latitude regions.

The notion that this small ocean temperature difference 1000m apart can be fruitfully exploited to generate electricity, based from the thermodynamic principle of running heat engine on availability of a heat source and heat sink, was first envisioned by the famous science fiction writer Jules Vernes in his book 'Twenty Thousand leagues under the sea.' A decade later in 1888, D'Arsonval developed its practical applicability from a theoretical approach, which opened up a new field of

technology for power generation-- termed, Ocean Thermal Energy Conversion abbreviated as, OTEC(Heydt 1993).

Such power generation system operates by utilizing the small temperature difference between the surface and deep ocean water, OTEC, has gained renewed interest in recent years. This is because of its availability as a form of vast Renewable Energy resource, with scope of availability of various by products, opening up its immense possibility for achieving sustainable development.

2.2.2 Principles followed for power generation from OTEC

Various researchers tried different techniques for power generation applying this OTEC technology. The broad principles utilized by using a fluid with low boiling point to get evaporated from heat exchange in contact with warm sea water and run a low pressure turbine for power generation. Thereafter the fluid is allowed to condense coming in contact with cold sea water and thus complete the thermodynamic cycle. In other case the warm sea water itself is vapourised in low pressure chamber and run the low pressure steam turbine for power generation. The former process is termed 'closed cycle' or, CC-OTEC, and the latter called 'open cycle' or OC-OTEC. The additional benefit derived from OC-OTEC is the availability of pure desalinated water as a by product, besides the power. There can also be a third method of power generation; which is a combination of both CC-OTEC and OC-OTEC, and termed Hybrid Cycle OTEC.

In fact, OTEC is the only Renewable Energy (RE) type that requires power for its operations, to generate the power. Hence, the terms gross energy output and net energy available comes up. The latter is the output energy availed after subtracting from the gross power output, the input power of running the plant. They are important considerations in OTEC schemes. The energy expended to run OTEC plants are for pumping water from the warm sea water from the surface and upwelling cold water from 1000m depth. In addition to this, power is expended in running the evaporator and the condenser.

.Keeping in view the above perspective, it is considered useful to examine the following aspects on OTEC technology as are elucidated in subsequent sections. They are:

- The methodology of power generation from different types of OTEC plants, including suitable sites for their deployment.
- The practical in- sea trial runs made so far, using different types of OTEC schemes, with future projections of commercial OTEC plants.
- The suggestions as could be made along with simulation studies to meet the engineering challenges on OTEC technology, and also increasing its efficiency.

2.2.3 Different types of OTEC schemes with their working principles

It is broadly the difference in choice of working fluid (whose expansion is used to run the turbine), that differentiates working principle of one type of OTEC from another- whether closed cycle, open cycle or of Hybrid OTEC types.

2.2.3.1 Closed Cycle OTEC [CC-OTEC]

In this type, a fluid with low boiling point such as, liquid ammonia, which has a boiling point of $33.5^{o}C$ at 1.013 bar, and having a vapour pressure of 8.88 bar at $2^{o}C$, is allowed to vapourise when exposed to warm surface- sea-water passed through a heat exchanger (Anderson 1998). The expanded vapour runs the turbine which in turn produces power through the generator. The outgoing vapour from the turbo-generator is cooled to a liquid form for recycling again, allowing it to pass through a 2nd heat exchanger containing the cold sea water which is pumped to the OTEC rig through a pipe reaching 1000m depth below the ocean.

Since anhydrous ammonia is toxic and inflammable, the ideal working fluid could have been the non-inflammable low boiling fluids, like CFCs and HCFCs, had these been not responsible for ozone holes (Heydt 1993). Suggestions have therefore been made for the use of low boiling non-azeotropic mixtures of ammonia and water (Ikegami et al. 2008). However, more common working fluids used are, ammonia and low boiling hydrocarbons e.g. propane, propylene, which are more common (Huang et al 2003). The flow sheet diagram of CC-OTEC operation is shown below in fig. 2.14 (Vega 1999).

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Fig.2.14 The flow-sheet diagram of CC-OTEC
(Vega 1999)

2.2.3.2 Open Cycle OTEC [OC-OTEC]

In this system the warm sea-water acts as the working fluid. The hot tropical seawater is vaporized by flushing it through a spout in a low-pressure container. It may be noted that the boiling point of water is 26.4 ^{0}C, when its super incumbent pressure is reduced to 0.03bar (Engineering toolbox, Pressure and boiling points of water, n.d.)

The steam thus made at reduced pressure, runs a low pressure turbine--which is thereafter cooled, passing it through the heat exchanger with the cooler deeper layer ocean water, for recycling again.

The use of water as a working fluid has the advantage of being non-toxic and environmentally benign. An additional advantage derived, is the scope of availability of pure water as a by–product from the condensation of the steam generated. But only a small fraction of the bulk of water sprayed in the evacuated chamber at around 0.03 bar pressure, would ultimately get evaporated to steam; around 1% to 0.5% (Vega 1993). This low yield is because of the fact that the latent heat of evaporation for steam generation, is drawn from the bulk of the warm sea water, making it cool off with cessation of further boiling.

The condensation of steam (leaving the turbine), required to complete the cycle, occurs in direct contact with cold water using a direct contact heat exchanger [DCC] which have better heat transfer characteristics due to the absence of any solid metal boundary [unlike CC-OTEC]. OC-OTEC however needs a larger sized evaporator, turbine and condenser--compared to CC—OTEC. Because the specific volume of low pressure steam would be much more than that of working fluids like, ammonia vapour etc. This increases the cost for OC-OTEC device (Vega1999).

The incondensable gases like, O_2, N_2 and CO_2, which remained in dissolution with ocean water, comes out of solution on creating a vacuum. They are to be exhausted from the system to lessen the load on the condenser, which otherwise would affect its efficiency.

The flow sheet diagram of different operational phases of OC-OTEC is shown below in fig.2.15 (Vega 1999).

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Fig.2.15 Flow –sheet diagram of OC-OTEC
(Vega 1999)

2.2.3.3 Hybrid type OTEC plant

This type combines both CC-OTEC and OC-OTEC in its operations, using both ammonia and warm sea water as the working fluid. It makes OC-OTEC type steam.

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But for running the turbine to produce electricity, a low boiling fluid like, ammonia etc is used instead of steam (Rai 1997:509). It allows production of desalinated pure water as a by product besides the power generated.   It may be added that the hybrid type OTEC, unlike CC-OTEC or OC-OTEC, has not yet been tested from practical application. It is a theoretical concept maximizing thermal efficiency.

2.2.4 Deployment sites of OTEC plants

In the operation of OTEC schemes, deployment sites are also to be taken into consideration from the point of view of their survivability, accessibility for operations and maintenance of the plant, and of course on the overall economy.

Keeping in view the above perspectives, examination has been made for location-wise deployment of the following OTEC sites, like:

1. Shore based plants;
2. Off-shore floating plants; and
3. Theoretically conceptualized submersible plants.

A brief account of their merits and demerits, are highlighted below.

2.2.4.1 Shore based OTEC plants

Land based plants have the advantages of eliminating expensive mooring cost, as well as long cable line cost for making grid connection ashore. But it has the disadvantage of using much longer cold water pipes, as well as the pipes for mixed discharge of warm and cold sea water, which is required to be sunk at depth in the ocean, quite away ashore. For a normal ocean bed slope of 15^0 such a length of cold water pipe at 1000m depth would come to 1000m/Sine 15^0 =3864m;   involving virtually 3 times more cost burden for land based cold water pipes, than that of off-shore ones (Bechtel and Netz, n.d.). Besides, the pipes are required to be kept well secured with foundations, for damage from storms/breakers in the shallow surfing zone of the ocean.

2.2.4.2 Off-shore OTEC plants

There can be two types of off-shore OTEC plants. They are either fixed moored plants or grazing plants.

Fixed moored plants
Such plants though requiring less cold water pipe length than shore based sites, require much longer sub marine cable lines, 1—15 km in length (Heydt 1993).. They also pose a problem in terms of maintenance and repair, when needed. The vertical long cold water pipe may damage requiring repair, so that continuous power supply is not interrupted. Besides, such plants are difficult to stabilize involving high mooring cost, which is difficult to make where depth is above 2000 m (Anderson 1998).

Grazing plants

It is with the above constraints in view of the fixed moored plants, that drifting off-shore plants-in-ship have been suggested. Instead of laying long undersea cable lines, power transport in such plants have been suggested via H_2 transport, utilizing the generated power in manufacturing H_2. Besides, grazing gives the plant-ship more flexibility with added options to navigate in optimum temperature difference regions. Such grazing plant-ship though reduces initial capital expenditure required for mooring etc., produces less net power, part of the gross power being utilized to move the plant-ship (Ryzin et al. 2005). But this ambitious scheme is still in the R&D stage.

2.2.4.3 Submersible OTEC plants

This is a theoretically conceptualized plant suggesting the build up of OTEC plants with most of the structure below the ocean water level, with some area at the sea water interface. Such plants are considered more stable as experienced from the oil industry. (Anderson 1998).

The water can be taken vertically from the plant with the requirement of much less warm water pipe, suggesting a cheaper option. Scope of availability of net power is also more, because of less warming of cold water in pipes during the upwelling.

But during storms or turbulence with heaving of the sea surface, the plant that normally remains almost submerged in sea level, stops functioning and would work only when the sea is relatively calm (Takahashi 2000). Of course, it needs further study to prove the efficacy of the theoretical concept of submersible OTEC plant for practical applications.

Having discussed the operational aspects with relative merits and demerits of different types OTEC types as also of the placement sites, it is considered relevant to provide an overview of the stages of development of OTEC technology; including history of earlier trial runs and future schemes that are in the pipeline. They are discussed below in subsequent sections.

2.2.5 History of Demonstration trials of OTEC plants

Quite a number of studies on OTEC technology, including that of the pioneering researcher D'Arsonoval's early study, remained in proposition stage only. However, there were also a number of actual on-sea trial runs of OTEC made by different researchers. All these studies listed in chronological order are as below.

1. 1928-1935 -In sea trials of OC-OTEC by George Claude.
2. 1956- Thematic suggestion of 3 MWe OC-OTEC by French researchers.
3. 1979- In-sea trial of CC-OTEC; a Mini-OTEC demonstration plant by National Energy Laboratory at Hawaii Islands [NELHA].
4. 1981- In-Sea trials of CC-OTEC by Japanese researchers (MITI), a 100KWe plant at Nauru.
5. 1993-1998- In-sea trial of OC-OTEC, 210KW by L. A. Vega and his team at Hawaii.

A brief account of them has been illustrated in subsequent sections.

2.2.5.1 George Claude's Study (1928-35)

Claude could generate 22kW gross power, installing a small land-based OC-OTEC plant using warm ocean water as the working fluid, with flash evaporator and direct contact condenser [DCC]. He gave his demonstration on the Cuban coast and could run the plant for a few weeks--till his equipment got damaged by a storm. He could however, never achieve net power gain (Takahashi 2003).

Later Claude designed a 2.2 MW OC-OTEC plant to produce 2000 tons of ice as a by-product for Rio-de-Janeiro city, placing his plant over a 2000 ton cargo vessel off the coast of Brazil (Achievements in OTEC Technology, National Renewable Energy Laboratory, n.d.).
But he had to abandon the project being unable to install the long vertical cold water pipes, with the then undeveloped marine technology (Vega 1999).

2.2.5.2 Thematic Scheme of 3MW OC –OTEC plant in 1956

A 3MW OC--OTEC plant designed by French scientists was proposed to be commissioned for power generation, at Africa's west coast in its equatorial region. But the cost component being prohibitive, compared to other conventional power generation systems, the project had to be abandoned with no in-sea trial. (Achievements in OTEC Technology, National Renewable Energy Laboratory, n.d.).

2.2.5.3 Mini OTEC in –sea demonstration by NELHA in 1979

It was a barge mounted CC-OTEC plant which was the first successful in-sea testing of OTEC technology, generating the predicted net power of 10-15kWe, from gross power production of 50kW (Cohen 1982). The power generated was enough to illuminate the ships lighting system as well as other electrical equipment. It used titanium plate heat exchanger with its cold water pipes extending to a depth of 650m. Its bio-fouling problem in evaporators and condensers were tackled with continued chlorination.

The demonstration plant operating at keyhole point off Hawaii islands continued its operation from August to December, 1979 (Cohen 1982). This in-sea trial in fact, proved the feasibility of OTEC plants, with renewed interest in it.

2.2.5.4 100KWe In -sea trial of CC--OTEC plant at Nauru in 1981

The Ministry of International Trade and Commerce [MITI] of Japan sponsored this 100kW CC-OTEC plant which was commissioned in the Nauru Island of the mid pacific region. This land based plant was run drawing the cold water from a depth of 520m, laying a 900m long pipe through the ocean floor. The cell and tube side heat exchangers used were made of copper coated stainless steel tubes in the evaporator and of titanium in the condenser. Freon was used as the working fluid with the trade name R-22 (Cohen 1982).   .

The 34kW net power successfully produced from this plant since October 1981, could be fed to Nauru Electrical grid for around a year; till the entire plant got wiped out by a hurricane, like Claude's failed attempts (Takahashi 1999).

2.2.5.5 In –sea trial run of 210 kW OC-OTEC–operable from 1993—1998.

It was a land based experimental OC-OTEC plant at Hawaii, with its turbine generator designed for power production of 210kW, utilizing the surface warm sea water temperature of 26°C and bottom cold water at 6°C (Vega 1999).

A small fraction of 10% steam produced in the evacuator was diverted for production of desalinated pure water in the condenser, as a by-product. The experimental plant of gross power production capacity 210kW, could run successfully for 5 years from 1993-1998, with net power production of 103kW and desalinated water 0.4l/sec., as the by-product. The maximum power [gross] produced reached 255kWe, despite the plant not being optimised (Vega 1999). A commercial optimised plant is expected to maintain the ratio of gross to net power to be 0.7, whereas this non-optimized plant showed the ratio to be of 0.5 only (Vega 1999).

2.2.6 Deployment of commercial scale OTEC proposals in near future

Some of the proposals for large scale power generation schemes using OTEC technology are as below:

1. An OC-OTEC plant of capacity 1.1 MW, suggested by Japanese researchers of Hawaii.
2. Conceptual design of Hybrid OTEC of capacity 5MWe suggested by Vega L.
3. British proposal of setting up 10MW floating and 0.5MW land-based OTEC. Plant.
4. A CC-OTEC plant of capacity 1MW by NIOT, India.
5. Conceptual design of 1MW & 10 MW OC-OTEC in Caspian Sea.

A brief resume of their status of development has been made in subsequent sections.

2.2.6.1 OC-OTEC Scheme of 1.1 MW, by Japanese researchers

Takahashi & Trenka worked out a scheme of OC-OTEC plant, for deployment in small island countries of the Pacific Ocean, which can produce net power of 1.1MW and 1.26 million gallons of potable water per day, as its by-product (Takahashi & Trenka 1996).

It was set to operate between heat source and sink of 6156 kg/sec flow of warm sea water at 26^{0}C, and cold water flow of 3085kg/sec at 4°C. It could be estimated that steam produced is only 0.45% of the total mass of warm water input. Thus 6156 kg/sec flow warm water, discharged through spouts of a flash evaporator maintained at a pressure 2740kPa, would first elevate warm water temperature to an additional 3.4^{0}C, and thereafter produce steam at the rate 27.4kg/sec. There would obviously be a temperature drop of 2.7^{o}C to the warm water, from withdrawing latent heat of evaporation for steam formation from it.

The steam thus produced would be passed through a single stage and single flow axial turbine, with a rotor blade diameter of 5.65 m, which is to be coupled to a generator --producing 1800kWe gross power. Subtracting the power required to operate the device, its net power yield would be 1050kW. Potable water produced at the condenser from the heat transfer of steam to the circulating cold water is estimated to be 26.6 kg/sec (Takahashi & Trenka 1996).

2.2.6.2 Hybrid OTEC of capacity 5MWe designed by Vega L.

Vega (1999) designed a hypothetical 5MWe floating hybrid cycle OTEC device, considering warm water feed rate of 27,000 kg/sec at temperature 26 ^{0}C, against a cold water feed of 14,240 kg/sec at 4°C. It has to work in its 1st stage as CC-OTEC with pressurized ammonia as the working fluid for power generation. But in the 2nd stage would use warm water evaporation like OC-OTEC cycle, not for power generation, but for production of desalinated potable water. Thus, the desalinated water cycle unit was to be put in without the turbine.

The cold water was proposed to be drawn through a 2.74m internal diameter glass fibre reinforced plastic pipe from a 1000 m depth, warm water through a 4.6m diameter FRP pipe from a 20m depth, and the mixed discharge made at 60m depth through a 5.5m FRP pipe. The discharge depth was selected such as to minimize the environmental impact.

A chlorination unit was also proposed to be installed to minimize bio-fouling in the evaporator with 50-100ppb [parts per billion] chlorination for 1 hour every day.

The flow sheet diagram of the different stages of operation as also giving heat and mass balance of a 5MWe hypothetical OTEC plant is shown below in fig.2.16 (Vega 1999).

Fig.2.16 Flow sheet diagram of a hypothetical 5MW Hybrid OTEC plant
(Vega 1999)

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The gross power generation possibility, of this Hybrid plant was estimated to be 7920kW, with a net power availability to be 5100kWh. Power for water production was estimated to be 160 kW which was the power requirement for the water cycle. Requirement of operational power for warm water input was estimated to be of 1190kW; with cold water input power requirement of 1280kW and for ammonia to be of 190kW. Desalinated water production was estimated to be 2281 m^3/day.

2.2.6.3 British proposals of OTEC plants

UK researchers undertook developing a 10MW floating CC-OTEC plant and a 0.5 MW land based plant. In fact GEC, England, proposed developing the land based plant with gross power output of 500kW as the first step, with a view to go for future deployment of 10MW OTEC plant (Lenard & Johnson 1988).

Important contributions from British researchers were made by ALCAN, as regards development of a cheaper option of heat exchangers using Aluminum alloy in place of costly Titanium (Achievements in OTEC Technology, National Renewable Energy Laboratory, n.d.).

It had been deduced by British researchers (Lenard & Johnson 1988) from their assessment that deep ocean water itself is a rich resource for producing a variety of by-products. It facilitates aquaculture with its nutrient rich water. Even a small OTEC plant with modest power generation can thus be considered to improve the economy of the concerned area from other benefits accrued from it, besides the power (Lenard & Johnson 1988).

2.2.6.4. Indian Efforts on OTEC power generation

National Institute of Ocean Technology, India, proposed deployment of a CC-OTEC plant of gross power availability of 1 MW, based from necessary demonstration trials and feasibility studies (Jayshankar et al. 1998). It is to be installed 40km off the south east of Tutikorin, in South India. Cold water resource can be made available here, at 1200m depth. The warm sea water in this equatorial zone would maintain 20^0C temperature differential, round the year.

Ammonia would be used as the working fluid operating in Rankine cycle. The evaporators would have a special steel coating to facilitate boiling of ammonia and a four stage axial flow ammonia turbine would be used. It was found to be successful from demonstration trials (Jayshankar *et al*. 1998).

It would be placed on a floating barge with single point mooring. HDPE pipe of 1m diameter would be used for the cold water pipe, which would also act as part of the mooring system.

2.2.6.5 Conceptual designs of OC-OTEC in Caspian Seas

It would be of interest to note the OTEC deployment could be a feasible proposition in Caspian sea despite its shallow depth of < 200m with bottom layer of cold layer temperature as high as 7-8°C (Zabihian and Fung 2011). This is because of the fact

that its surface temperature also remains as high as 30°C, nearly 7-8 months of the year, making it possible to avail of the temperature differential >20°C. A conceptual design of OC-OTEC could hence make for 1MW & 10MW OC-OTEC plant deployment there, so that potable water could also be availed besides power in a water scarcity country like Iran. It was estimated that potable water to an amount of 19.7kg/s & 154kg/s could be availed from OC-OTEC plants of 1MW & 10MW, respectively. (Zabihian and Fung 2011).

However, many of the technological challenges are faced in order to make commercial application of OTEC schemes. Some of the important ones giving the possible solution to meet these challenges are discussed below.

2.2.7 Challenges faced in commercialization of OTEC technology

The most important challenge in commercialization of OTEC technology comes from the cost component of the various parts, required for the plant's operation with maximisation of net power availability. It has also to ensure stability and survivability of the plant.

It is in this context, the following aspects invited particular attention for improvement and/or optimization:

- Heat exchangers with a search for cheaper options and also for better performance.
- Material development studies on cold water pipe as to their cost and stability.
- Addressing sub-sea cable laying and proper mooring at depths.
- R&D with innovative ideas for increasing the power generation efficiency with minimization of power loss for plant operation.

Advancements and suggestions on above, as addressed by some of the global players on OTEC like, Solar Energy Research Institute [SERI],US; Natural Energy Laboratory Hawaii [NELH]; Pacific International Centre for High Technology Research [PICHTER]; GEC, UK –are briefed below.

2.2.7.1. Heat Exchangers

The high cost involvement from heat exchanger (in evaporator and condenser) is mainly due to the costly titanium metal used for construction of the large sized heat exchangers to minimize corrosion problems. This is more in cases of CC--.OTEC type devices, which require cell side and tube side or, of plate type metallic surface heat exchangers (Achievements in OTEC Technology, National Renewable Energy Laboratory, n.d.).

It might be noted from distribution of cost components of various parts of OTEC, that heat exchangers contribute to nearly 40% of the cost of the total device as shown from fig.2.17 given below.

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Fig.2.17.Construction cost distribution of OTEC plant in Japan (Takahashi 2000)£
(162yen = £1; www.http://x rates.com, Aug. 2008 rate; 50 billion yen = £310 million)

In case of OC –OTEC, though the costly surface contact heat exchangers are replaced with direct contact condensers (DCC), but it requires large sized evaporators to accommodate the low pressure steam generated in the evaporator and leak-proofing them as well.

The challenges faced are three-fold- the cost involvement, bio-fouling coating formed over metal surfaces thus lowering the efficiency of heat exchangers, and of course the corrosion from sea-water. Use of stainless steel or titanium may be helpful to address the corrosion problem, but they are costly solutions. A rather cheaper option of using copper-nickel alloy would address the bio-fouling problem (besides corrosion) and is incompatible with ammonia, which is the most commonly used working fluid for CC-OTEC. British researchers are presently working to develop Aluminium alloy heat exchangers, which have promise in reducing the cost] (Achievements in OTEC Technology, National Renewable Energy Laboratory, n.d.).

In order to carry out OTEC experimentations for data generation on heat and mass transfer relationships, in cases of large scale use of sea water, a specialised apparatus, HMTSTA (heat and mass transfer scooping test apparatus) was set up by NELH. Necessary experimentations and operational experiences from this apparatus proved particularly helpful in OC-OTEC's system, addressing the corrosion problems and leakages in evaporators (Link 1989).

Bio fouling problems could be tackled by periodic Chlorine injection as well as mechanical brushing over the heat exchangers, during their maintenance (Vega 1999).

2.2.7.2 Cold water pipe line

The problems required to be addressed particularly in the long [1000m] and large diameter [>1m] cold water pipe adds up to the cost component of OTEC scheme. It gets further aggravated for land-based plants requiring much larger pipe length. In cases of off-shore plants an additional threat is posed on its stability and survivability, mainly during storms.

US researchers suggested use of fibre glass reinforced plastic pipes (FRP) for use in floating off-shore plants (Vega 2002/2003a). Steel or concrete pipes have also been suggested, besides FRP as used in off-shore technology. Scope of the use of soft pipes, made of reinforced elastomeric fibres are also being suggested considering its efficacy for better survivability in rough seas, besides being rather the cheaper option (Vega 1999).

A novel idea is floated to address the problem of stability and survivability of the long overhanging rigid pipes in floating plants. It has been suggested attaching the platform holding the pipe to be flexible enough like those fitted for the oil drilling industry. In the oil drilling industry, the platform swings under sea-state conditions, keeping the drilling pipes stationary. Like-wise for OTEC, the platform might be allowed to heave during storms, without much affecting the joints of the cold water pipes (Anderson 1998). Being supported with cables, these pipes may also be detached from main structure or the platform, and are thus saved. This approach has much scope of further improvement from R&D studies.

2.2.7.3 Mooring at depths and sub-sea cable laying for power transportation

The technology of mooring system for off-shore OTEC plants to 1000m depth, poses engineering challenges, but is available to a large extent from the oil industry's drilling rigs. The problems required to be addressed   are the survivability load as well as fatigue induced load for the mooring set up as well as, for the long cable line and the cold water pipe (Vega 1999).

Experiences of the oil industry's dynamic positioning using thrusters such as powered thrusters or discharged thrusters--to maintain stability, are useful for off-shore OTEC plants as well, like the ones used in the oil industry (Vega 2002/2003a). However, they add cost input which makes small sized plants rather uneconomic. Mooring cost per unit power output for a 20MW plant can be lowered 10 times, if the plant size is increased to 100MW capacity (Vega 1999).

Cable laying at a depth of below 600m adds cost input besides power loss from transmission to long distance (Cohen 1982). In fact, the very production of cable may be required to be increased many fold to transmit off-shore OTEC power, if OTEC starts functioning on a large scale commercially (Cohen 1982).

It is with this in view that instead of transmitting power through long distance sub marine cables, grazing type OTEC plant-ship can better be used to make in-situ conversion of electricity to the production of Hydrogen fuels etc.(also many other types of petrochemicals), and be transported to ports instead of transmitting power

through cables (Ryzin *et al.* 2005). But such ambitious projects are still in the R & D stage.

2.2.7.4 Innovative ideas for increasing efficiency /cost reduction of OTEC

The biggest hurdle in OTEC technology is its low power conversion efficiency for small difference between heat source and sink and of course the cost involvement for drawing cold water from a depth of nearly 1km. Innovative ideas that deserve particular mention to address these problems are:

- A hybrid OTEC plant in combination with off-shore solar pond construction, termed OTEC –OSP.
- Enhancement of ocean thermal energy with solar heating techniques, termed SOTEC [combination of Solar and OTEC].
- Application of polar ice as cold water source obviating drawing cold water from 1km depth in ocean; termed Ice-Tech

A brief resume of the above innovative suggestions are described below.

2.2.7.4.1 OTEC –OSP

Paul *et al.* (2008) suggested a low cost design for building off-shore solar pond making embankment of around 12 km, using shoreline brackish water of the ocean to constitute the upper layer of the solar pond. The deeper core containing the saline water in the solar pond thus made, would serve as heat trap elevating the temperature of the bottom layer of the solar pond –which would supply the input warm water to the conventional type OTEC plant. This would enable the use of a higher temperature gradient between warm solar pond water and cold sea water at 1km depth, and thereby increase efficiency of power conversion.

In this scheme a conceptualised study was undertaken considering a 50MW OTEC plant making hybrid functioning with solar pond built up (Paul *et al.* 2008). It could be estimated that the temperature difference attained in hybrid set up could reach 76^0C, against a conventional OTEC plant's thermal energy availability of around 20^0C temperature differential only. Thereby the OSP-OTEC's efficiency could reach as high as 12% against the conventional OTEC's power conversion efficiency attaining the maximum value of 3%.

However such ideas are in conceptualised stage only.

2.2.7.4.2 SOTEC

Yamada *et al.* (2006) suggested installation of solar collector along with a closed cycle OTEC plant. They undertook simulation studies with a 100kWe capacity OTEC plant, in which the input warm water or the working fluid can be preheated by the installed solar collector, before they enter the generator for power production. The extra thermal energy input, as could be made by the solar collector, would thereby increase power conversion efficiency of the working fluid. They termed this modified OTEC plant to be SOTEC, as this OTEC plant functions in conjunction

with an additional Solar Energy Collector. Flow sheet diagrams of functioning of such SOTEC plants.--SOTEC -1 and SOTEC-2, are shown below in fig.2.18.

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Fig.2.18 .Flow sheet diagram with components & functioning of 2 types SOTEC plants (Yamada *et al*. 2006).

In SOTEC -1, the warm water is heated by the solar collector; whereas in SOTEC -2, the evaporated working fluid is heated by the solar collector. Yamada et al. (2006) also compared their relative advantages gained from simulation studies. They noted that solar collector area of SOTEC -1 should be around 1.6 times larger than SOTEC -2. Also, cost from heat exchanger, which is decisive in cost component of OTEC plants, is less for SOTEC-2. But the corrosion problem is more in SOTEC-2.

It is to be noted that SOTEC can be run selectively only, depending on weather conditions. However, it was concluded that by and large, SOTEC gives 1.5 times more power conversion efficiency than conventional OTEC plants. (Yamada *et al*. 2006).

This ambitious proposal is also still in the R&D stage which has immense possibility in increasing OTEC's power conversion efficiency and thereby cost reduction.

2.2.7.4.3 Ice –Tech

A novel idea had been suggested by Wadhams of Scott Polar Research Institute, Cambridge University, UK in the discussion forum of the Royal Society paper presentation by Cohen in London (Cohen 1982). He proposed a method of OTEC power production by completely eliminating the costly arduous task of drawing cold water from 1km depth in the ocean. His suggestion was to tow icebergs from Antarctica, whose fragments can be stored at suitable sites of lagoons serving as cold water reserve. A land based OTEC power station built in suited spots of nearby ocean can then function, taking warm water from sea surface and cold water from the lagoon concerned –cooled by ice bergs.

This technology, if at all feasible has been termed–Ice-Tech (Cohen 1982). However, it has many technical problems to resolve but also has to ensure the feasibility of meeting the demand of a huge quantity of constant cold water supply, required to run an OTEC plan. Its practical feasibility thus seems to be intriguing.

2.2.8 Critical Appraisal of OTEC

The main problem in OTEC technology is its low temperature differential between heat source and sink, making its efficiency very low; around 1—3% only (Vega 2002/2003a). Besides, it is to be kept in view for choosing the type of OTEC technology, that energy expended to run the OTEC plant be kept in the minimum for availing maximum net power. In addition to these there are many other challenges faced in OTEC technology- like survivability and stability, high cost involvement, technical challenges in cable laying to 1000m depth, and also environmental uncertainty as may be experienced from churning of the ocean on a large scale.

It is also a fact that despite all these challenges, OTEC technology has already come a long way since Claude's time 7 decades back (Takahashi 2000). Many of its technological advancements, particularly on stability & survivability could be ensured from experiences of the oil industry (Anderson 1998). There had already been a successful trial run of a 210kW OC-OTEC that gave not only a continuous net power production of 103kW, but also potable water as a by-product supply, at the rate of 0.4l/sec for 5 continuous years (Vega 1999).

There is of course much scope of reducing the cost component of OTEC, from further R&D studies to improve upon its performance efficiency. This can be achieved using the suggested hybrid OTEC OSP (Paul *et al*. 2008), and/or adding solar collector, as suggested in SOTEC technology (Yamada 2006). Replacement of cheaper construction materials like, trying Aluminium alloy heat exchangers in place of costlier Titanium alloy (still in R&D Stage) also show promise in terms of cost reduction of OTEC plants.

In addition, the prospect of availing of huge by-products from OTEC, like growth of mariculture, potable water, hydrogen and other chemicals (Ryzin *et al*. 2005) - as can be availed from grazing OTEC plants (still in R&D stage), could lead to the emergence of 2nd or 3rd generation OTEC plants to emerge as a lucrative economic proposition.

Therefore there is a clear need to examine OTEC technology from different assessment criterion, such as environmental fall outs, scope of availing economic benefits etc. which could be of assistance in efforts in further R& D studies for improving upon the OTEC technology.

In addition to OTEC technology, which is yet to take off for commercial application like wave schemes, it may be relevant to make an overview of the present status of development of Tidal energy systems as well. This topic has been discussed below – both in terms of barrage schemes as also of TISEC devices.

2.3 TIDAL ENERGY SCHEMES

2.3.1 Origin of resources of Tidal energy

The rise and fall of ocean levels and the affected river flow upstream with tide and ebb, is known since time immemorial. There is evidence that as early as 787 AD, this ocean power termed Tidal Power was utilized to grind corn. This used to be done by

storing water, building dams during high tides and slowly releasing it from behind the dam to run water wheels as the water level receded, and thereby run the grinding mill (Peter et al. 2003). In fact, the Eling Tide mill in the UK is still producing flour utilizing this tidal power, for the last 900 years (Hardisty 2009:57). Previously, the energy stored was used only to turn water wheels for milling grains etc, which has been advanced to produce electricity. It is produced utilizing the potential energy as well as the kinetic energy of tides, at suitable sites that are rich with Tidal Energy resource.

An advantage of tidal energy is that its magnitude and timings are predictable with precision over a long range of time, unlike other RE systems like wave energy, wind energy or of solar energy. Another unique feature of tidal energy is its origin to be mainly from the Moon, unlike all other energy sources including the fossil fuels which owe their origin directly or indirectly from the Sun. In fact, the maximum rise in water level in deep oceans caused from the gravitational pull of the sun has been estimated to be 0.16m, whereas it is around 0.35m from the moon's gravitational pull, more than double than from the sun (Crest notes 2004/05a).

This combined gravitational pull of the earth's -moon and sun system, combined with the centrifugal forces of the earth's water bodies, produce around 0.5 m rise of water level in deep oceans (Pontes & Falcao 2001). But this tidal bulge on reaching shallow coastal waters and estuaries may rise considerably with typical values of 3m or more (Elliott 2004). But with favourable local topographical variations and at suitable periods, it may go up to even 10-15m, as observed in the Severn estuary in the UK (Elliott 2004). In fact, this tidal height termed tidal range is very decisive in deciding the economy of tapping power from tidal energy.

It thus becomes important to examine:

- The factors and causes influencing this tidal range.
- Forecasting their periodicity
- Examining the methodologies of power generation

They are discussed in the following sections.

2.3.2 Factors influencing magnitude of Ocean's Tidal Energy.

It has been pointed out in previous sections that the small water level rise of 0.5m in off-shore Ocean (from tidal pull) can give rise to many fold increase in water levels in estuaries and rivers, under suitable conditions. The influencing factors determining the elevation of tidal range in estuaries and rivers are as below:

1. Funneling of water at entry points of estuaries.
2. Resonance of tidal wave.
3. Coriolis effect from spinning of the earth.
4. Atmospheric changes and natural disasters like storms / earthquakes.

A brief account of them is elucidated in subsequent sections.

2.3.2.1 Funneling Effect

Tidal waves from the seas increase in height on reaching the shallower coastal estuary mouths getting compressed laterally from the sides. This is termed as funneling effect, increasing both the height of tidal range and tidal current (Pelc & Fujita 2002). Such increments in height, allowing the river water from high tides to move upstream, under suitable topography of the estuary and at particular timing of tidal surge, may reach Froude number to unity or even exceed it. This produces a surge of water mass moving upstream, termed Tidal Bore. Such tidal bore (that reaches or exceeds Froude number) moves against gravity, like a wall of water flowing upstream at a rapid pace which ultimately breaks down like the wind generated ocean waves breaking at the shore (Elder and Williams 1996:290). Instances of such Tidal Bores are observed in the Severn and at the Humber in the UK, as well as in the river Hooghly, in Calcutta, India (Elliott 2004).

2.3.2.2 Tidal Resonance

The length and breadth of estuary are very important for the occurrence of Tidal Resonance. It only occurs if the time taken for the tidal wave to reach the mouth of the bay and thereafter getting reflected back on the opposite side, matches the timing of the next approaching high tide, or in other words if the tidal wave length is 4 times the estuary length (Christopher 1972). Example of such resonance causing high tidal range is the bay of Fundy in Canada, reaching tidal range of 11m (Pelc and Fujita 2002). In fact one of the world's highest tides found in the Bay of Fundy, are caused from this fortuitous coincidence of resonance of the tidal wave (Kumpel 1971).

If however, the length of the estuary and tidal wave length does not match and opposes each other, there may be destructive interference, causing rather poorer tidal heights, as observed in certain pacific regions (Elliott 2004).

2.3.2.3 Coriolis effect

The spinning of the earth causing a change of ocean currents, including the tidal wave is termed the Coriolis effect. In fact, the speed of the earth's rotation, from this Coriolis effect is fastest at the equator, which gradually slows down at higher latitudes. The moving water mass over the earth's surface that follows a curved path due to earth's eastward rotation, would follow a path towards right of its intended course in the northern hemisphere and towards the left in the southern hemisphere (Christopher 1972).

As a result of this Coriolis effect, tidal currents deflect from their intended path that they otherwise would have taken (Elliott 2004). Its effect helps the growth of tidal height in northern French coasts, but annuls in southern England (Crest notes 2004/05a).

2.3.2.4 Atmospheric changes & Natural Disasters

Atmospheric changes and natural disasters like storms, tsunamis, or earthquakes in oceans beds may suddenly alter the tidal range scenario. This may affect their predictability and thereby disturb the power generation schedule.

These phenomena like, atmospheric changes or natural disasters being absolutely unpredictable, their excess energy of tidal range increase, but cannot be utilised. They are only important for prior planning on the safety margin required to be maintained over necessary installation /constructions, for harnessing power from tidal energy.

2.3.3 Periodicity of Tidal Energy

Tides being mainly moon oriented than the sun, its peak availability are dependent on the moon's orbital period of 24 hours 50 minutes. Thus the peak tidal power availability is 50 minutes later from one day to the next. This results in 2 high tides per day across the earth's surface, with an interval of around 12hours and 25 minutes (Hagerman et al. 2006). It consists of flood tides or high tides with greatest bulge of the water bodies; as well as of ebb tides or low tides that follows, around 6hrs. 12 minutes later.

There are however changes in the periodicity of tidal forces at different latitudes on the earth's surface –varying from poles to the equator, due to declination of the moon's orbital plane relative to the earth's axis of rotation. This declination produces semi-diurnal tides near the equatorial latitudes, mixed tides in mid-latitude regions and diurnal tides in high latitudes (polar zones), as shown below in fig.2.19 (Hagerman *et al.* 2006).

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Fig.2.19 –The tidal ranges with periodicity at different latitudes (Hagerman *et al.* 2006)

In fact, due to the moon's revolution around the earth being 29 days, we experience maximum bulge termed 'spring tide', twice a month --when the earth, the moon and the sun would lie in the same line causing enhanced gravitational pull (fool-moon and new moon periods). On the other side, minimum bulge of water bodies called the 'neap tide' is experienced when the moon is at 90° with respect to the earth and the sun as shown below in fig.2.20 (Garcia n.d.).

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Fig.2.20 –Spring & Neap tides shown in moon's different phases
(Garcia n.d.)

It could also be observed from fig.2.20 that the magnitude of the tidal bulge of water bodies of the earth facing the moon is nearly similar to the opposite side farthest from it. This is because of balancing caused from lower gravitational pull on the opposite side being neutralized with the higher centrifugal force experienced there, and vice versa.

2.3.4 Power generation from tidal energy.

The technology of power generation from tidal energy may be complete in two ways. It may be either by trapping the tidal water in a basin and utilizing the potential energy of the heightened water, termed Tidal Barrage. Or, the kinetic energy of the tidal current may be utilized for power generation termed Tidal-In-Stream-Energy-Conversion or TISEC. The former, power generation through tidal barrage is a commercially viable renewable energy system with a matured technology enabling commercial production for decades. La Rance Barrage in France with capacity of 240MW is successfully functioning with an annual production of 600 GWh since 1968 (Andre 1978). However, suited sites for Barrage construction are quite restricted globally (Pelc & Fujita 2002).

The other method of using tidal energy is TISEC that utilizes the kinetic energy of the water flow. But it is yet to take off commercially, though quite a number of innovative designs are being floated, as in the case of WECs.

It may be useful to provide an overview as regards construction of barrage with different modes of power generation with examination of the merits and demerits of barrages, as a commercially viable RE. They are covered in the subsequent sections.

2.3.5 Barrage construction

The technology of deriving power through tidal barrages is similar to a that of hydro-electric plant, which runs by utilising the potential energy of the water head (typically 5-10m) to run a turbine. But compared to Hydel plants, its turbine

rotational speed is much less (50-100 revolutions /minute). Hence they require a big assembly of turbines with much higher mass of water flow, for running the generator (Elliott 2004).

In fact, there are four-fold job-scheduling for construction and power generation from tidal barrage. They are:

1. Construction of the dams with embankments across the estuary of the river mouth choosing the most suited site, for storing water in the basin in high tide period. The best site would be such that can yield maximum power with minimum barrage dimension and thus incurring less construction cost.
2. Optimisation of the number and dimension of sluice gate openings to be made, with construction using caissons to make entry and release of water suiting the tidal periodicity. Provision to be kept for the navigational access to the ocean, as per requirement.
3. Selection and placement of the right type and number of turbine assembly, at water entry/exit mouths of the sluice gates be made. Adequate provision also to be kept for their periodic maintenance.
4. Power Generation is made from operation of the turbines, tuning the opening and closing of sluice gates with the periodicity of the high and low tide cycles for entry/release of water from the tidal basin, which is shown below in fig.2.21 (Rosmin & Zakaria 2006).

Fig. 2.21 The operation of turbine for power generation of a barrage.
(Rosmin & Zakaria 2006)

A brief resume of the above stated four-fold job scheduling of barrage construction is stated below.

2.3.5.1 Construction parameters

The site selection and identification of related jobs for the construction of dams with the embankments, sluice gates and caissons, demand a thorough examination of various factors involved for building up the barrage. They include- geological

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characteristics and strength of the river bed/bed rock with their depths at various points, dredging requirements and foundations, the economy and scope of availability of the tidal range. An example may be cited of the Severn barrage feasibility study that suggested the 15--18 km long barrage site from Cardiff to Weston Super-mare. The expert group proposed 3 alternative barrage routes /alignments on above [from Bail rock Lavernock Point to Brean Down]; spelling out their individual merits and demerits based from energy output, dredging requirement, flow characteristics and economy. (Sir Robert Mc Alpine & Sons Ltd. 1986).

The magnitude and the problems required to be addressed for barrage construction', (meticulous planning including job descriptions etc.) may be gauged from the fact that the proposed Severn barrage, assuring 4.5% of the total electricity demand in the UK, still remains in the planning stage. Various committees made different studies preparing their feasibility reports over the last 3 decades with the latest NGO steering group report submitted in 2008 (Frontier economics Ltd. 2008).

2.3.5.2 Sluice Gates

There is a direct correlation between the optimized numbers of turbines accommodated in the sluice gates and the energy output requiring sensitivity analysis of these factors (Frontier economics Ltd. 2008). Hence the number and dimension of the openings of sluices and lock gates are required to be optimized, so that the maximum number of turbines can be accommodated in each of them for achieving the best economy.

The sluices are kept fully open during flood tides for water entry to the basin and raising the water level in it. When the basin is filled, it is closed till the onset of ebb tides for releasing the elevated water to run the turbine assembly and vice versa.

The sluice gates are to be made water tight and robust enough to withstand the full water head pressure of the basin. Provisions have also to be kept for ship movements with alternate route[s], during the construction phase of the barrage that takes several years for its completion (Sir Robert Mc Alpine & Sons Ltd. 1986a).

2.3.5.3 Turbines

The power generation technology in vogue for utilizing tidal energy from barrages, are more or less similar to that of the conventional low head hydro-electric plants. The turbines that are normally used for the purpose may be of the following three types:

1. Bulb type turbines,
2. Rim turbines,
3. Tubular turbines.

In La Rance Barrage, bulb turbine is used but for the Annapolis project in Canada Rim turbines are used, whereas tubular turbines are more popular in the US (Elliott 2004).

2.3.5.4 Power generation modes

The modality of power generation of barrage has 4 alternative routes and areas followed depending on local conditions and energy demand. They could be; ebb generation, flood generation, two way operations or flood pumping types. Their working principles are briefed in subsequent sections (Elliott 2004).

2.3.5.4.1 Ebb Generation

The water level of the tidal basin is raised allowing the upcoming high tide water to pass through the sluice gates with non-operation of the turbines. The water is stored in the basin and is kept trapped by closing the sluice gates. At the onset of ebb tide period later, when the water level on the other side of the basin lowers, the sluices are opened up to run the turbine from the on rush of water to the lower level on the other side of the basin, and thereby generate power in the generator.

Thus, two bursts of power during the ebb-tide periods (covering 3 hours to maximum 6 hours in each time) can be obtained, within 24.hrs 50 mins period.

2.3.5.4.2 Flood Generation

In this case the turbine is run only during upcoming of the tidal water that fills up the basin, but is kept closed when the water recedes back to lower level, on the other side of the basin during ebb tide period.

In fact, this is just the opposite of the ebb-tide generation and would obviously have two bursts of power (of 3-hours to maximum 6 hours) in 24 hours 50 minutes period, similar to the ebb-tide generation types; but available during the high tide period only.

2.3.5.4.3 Two way operation

This method takes advantage of both the upcoming and downstreaming of water flow, running a double pitched turbine for power generation. It therefore gets 4 number of rather lower bursts of power generation in a 24 hours 50 minutes period, covering both during the high tide and ebb tide periods.

This method assures a more uniform power availability for longer periods –since both high tide and ebb tide generations are covered. But not only are such two way turbines rather costlier, but this two-way operation gives much less efficiency. Because, the turbine blades cannot be properly synchronised for two way operations. Also, the tidal phases cannot be completed –to fill the basins, nor fully emptying it, and making them ready for power generation to the next phase.

2.3.5.4.4 Flood pumping type

The other option is to increase the basin height still further than that achieved by the tidal range, by pumping additional water behind the barrage. This is done with imported power from a grid connection, during the periods of low electricity demand

and takes advantage of the higher water level achieved. Thus extra power can be generated during the period of higher demand of electricity, if the operation's timings could be suitably synchronised.

In fig. 2.22 given below, is shown the nature of water level change with power production phases, for different power generation modes, covered in previous sections 2.3.4.4.1 to 2.3.4.4.3. (Elliott 2004).

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Fig.2.22.Water levels & Power generation modes for the 3 types- ebb/flood/two way types. (Elliott 2004).

It is also to be noted that the flood pumping mode of power generation has an added advantage, besides the logic of choosing right timings as to tune the power demand with the tidal power generation. In fact, the extra amount of power spent in water pumping in the case of 'flood pumping method ' is more than compensated from the power gained by elevating the basin height, making flood pumping method the most efficient mode of power generation. This has also been   shown from power generation computation in the following section.

2.3.5.5 Computation on magnitude of power generation from tidal barrage

Mean Tidal power **P watt** that can be derived from tidal range, for water flow in a tidal   basin
.=Mass of water released *per unit time* *mean   water height of basin *acceleration due to gravity(Elliott 2004). Thus,
 $\mathbf{P} = (\text{`}\rho Ar / T\,)*(r/2)^{*}g = \rho Ar^{2}\,g/2T$ [2.5]
where ' ρ ' =density of water, A=Basin area in m^2, r= tidal range in m, which is the water level height of the basin above the sea level, r/2 =the C.G of water mass of the basin, considering it be of regular rectangular shape,   g =acceleration due to gravity, T=the time period.

If an extra energy input is used for pumping water to elevate the water level in the basin to an additional height of 'h', then the value of this extra input energy needed would be :=Additional mass of water*mean CG of extra height reached*acceleration due to gravity = $\rho Ah*h/2*g = \rho Ah^{2}\,g/2$ [2.6]

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By combining the equation [2.5] with equation [2.6], the total energy input required for elevating the basin a height to 'r+h'meter.

$$= \rho A r^2 g/2 + \rho A h^2 g/2 = (\rho A g/2)(\mathbf{r^2} + \mathbf{h^2}) \qquad [2.7]$$

The energy output from this increased height

$$= \rho A(r+h)*(r+h)/2*g = \rho A(\mathbf{r+h})^2 g/2 \qquad [2.8]$$

It would be obvious from equation [2.7] & [2.8], that therre is a net gain of energy by flood pumping method of power generation, by an amount $=\mathbf{\rho A r h g}$

A finding of interst observed from equation [2.5], is the fact that power generation from tidal basins is directly proportional to the square of the tidal range, which makes it of overriding importance in deciding the economy. Also, the availability of power from barrage, may be directly evaluated from the area of the basin and tidal range, the other values of the above equations like ρ, g (and aso T the tidal period), being considered to be constant.

It may be relevant to add that though commercial application of the barrage has already been made at favourable sites of high tidal range of 5m or more, but it is a time consuming project requiring huge capital outlay. On the other side, the technology of TISEC is yet to be perfected for large scale commercial application, though it is a much cheaper option than Barrage. Hence an overview of the present state of development of TISEC technology from different perspectives demand closer examination, and is dealt with in subsequent sections.

2.3.6 Tidal –In stream Energy Conversion systems (TISEC)

Tapping the kinetic energy of the flow of water from rivers and estuaries with water wheels is an old practice which has been used for centuries (Hardisty 2009). But harnessing electricity from the tidal streams is a new concept being developed as the alternative to barrages, for its many advantages. But this technology is yet to take off for large scale commercial application (Elliott 2004).

In fact, unlike the large scale tidal barrages, it would involve much less capital investment with its scope for use of smaller power generation units. Also, with proper site selection this technology is considered rather environmentally benign (Hardisty 2009). Power generation resource from the kinetic energy of tidal streams, is also quite appreciable because of the high density of water.

The status of development of this emerging field has been outlined, including its scope for maximum power capture. Some of the important concepts of TISEC devices and suited tidal current sites are also reviewed along with their limitations and scope for further development.

2.3.6.1 Scope of power capture.

Strictly speaking, tidal current owes its origin not just from the tidal range caused from moon's (also sun's) gravitational field and the centrifugal force of earth-moon-sun system. Other factors like, wind stress acting for extended periods and its

directions, the ocean currents caused from variation of salinity and complex interaction between the warm and cold layers of ocean water, also influence the surge of water in bays and estuaries. They also have some role in influencing the peak water current speed (Elliott 2004).

If a turbine is placed under a flowing stream of water, the power **'P'**, generated by capturing the kinetic energy of the flowing water can be expressed with the following equation:

Power density in watts per sq. meter $=$**P/A=1/2 (ρu^3)**   [2.9]

where, A=cross sectional area in m^2, i.e. the area of flowing water swept by the turbine rotor, ρ= water density in kg/m^3, whose value is 1000 kg/m^3 for water, 1025 kg/m^3 for sea water; and u = current speed of flowing stream expressed in m/sec.

It is obvious from the above equation of tidal power density that it would increase quite sharply with the increment of current speed, being directly proportional to its cubic power. The relationship of tidal power density versus current velocity for a typical US site is shown below in the fig.2.23. (Hagerman *et al*. 2006)

Fig 2.23 Rise of power density with increase in current speed
(Hagerman *et al*. 2006)

It can be observed from the above fig. that tidal current can achieve 500-1000 W/m^2 at flow speeds of only 1 to 1.3 m/s, which is nearly 10 times higher than that achievable from wind turbines of the same speed, because of higher density of water.

Like the wind turbines, the tidal current also must attain a minimum cut-in-speed for enabling power generation through the turbines. But the current speed must synchronize with the rated speed of the turbine concerned. If the water current velocity exceeds the optimum speed level for the turbine concerned, no extra gain of power can be achieved. Such phases of power generation capability from the tidal current are shown in a typical plot of turbine output of power density versus water current velocity, as given below in fig 2.24. (Hagerman *et al*. 2006).

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Fig. 2.24 Typical plot of Turbine power output versus water flow speed (Hagerman *et al*. 2006).

2.3.6.2 Scope of availability of Tidal current density

The speed of tidal currents and its direction--both change with time. The turbine blade movements are hence required to be suitably designed, so as to negotiate this change particularly the flow of direction which is at least once in a day for diurnal, and twice for semi-diurnal tides.

In order to estimate the annual power output, it is required to know the frequency of available current speed round the year. In fig.2.24 below, has been shown a typical histogram giving the frequency of availability of depth averaged velocity of tidal current round the year, as per the survey records from Cape Blomindon transect, East Coast, USA (Hagerman *et al*. 2006).

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Fig.2.25 Frequency of depth- averaged- velocity of tidal current of a US tidal site (Hagerman *et al*. 2006).

It has been estimated   from the above histogram that power take off current-velocity between the range, 1.0—2.5m/sec at the concerned site, would be between 6000 to 7000 hours in a complete year covering 8760 hours. It thus becomes important to select the right site for installation of TISEC devices for gaining maximum power output.

2.3.6.3 Site Selection of TISEC projects

There are two constraints that limit the size of TISEC farm projects. Firstly, it is the physical constraints to install an array of turbine units covering the length and width of the channel for extracting its current velocity to the maximum extent Secondly, the   constraints of not to affect the   water flow characteristics and other major environmental concerns, from indiscriminate installation of TISEC devices. Factors determining *suitable sites* of the TISEC device installation and optimisation study thereof are hence considered important.

It is to be noted that tidal current resource is a function of both tidal current and width (cross sectional area) of the channel, where large mass of water would flow. The constriction effect due to width reduction and bed elevation from estuary mouths, cause appreciable increment of current velocity. This can be predicted at a site from the two equations of continuity of mass flow of water along with Bernoulli's theorem of conservation of energy.

In addition to the requirement of high current speed of water streams, TISEC project sites should also have suitable sea-bed/river bed geology for proper anchoring of the TISEC devices. Besides, they should be reasonably close to the local power grid connection. There should also be support centre for maintenance /repair work, as needed (Westwood 2004).

As regards the water depth clearance required for placement of TISEC devices, it has been suggested to maintain a 5m clearance from the top for free movement of shallow draft vessels, but 15—20m clearance, if it lies within the route of ocean going vessels (Hagerman et al. 2006). Adequate clearance from the bottom/bed is also to be maintained for TISEC placements, so that the benthic population is not affected.

In fact, ideal tidal current sites to satisfy above points are normally found around 1km or, more from the estuary mouth with minimum water depths of 20-30m (Bedard *et al.* 2006).

Unlike wind energy that can replenish its energy within a short distance downwind the turbine site, excessive tapping of tidal stream energy may reduce natural water flow affecting the environment. Bryden *et al*. (2004) suggested that the permissible safe limit of extracting tidal stream power need not be less than 10%. EPRI studies however set a higher limit from model studies and noted that 15% extraction would not affect the estuary circulation appreciably (Hagerman *et al*. 2006).

As regards the spacing for placement of successive units in the turbine array, it has been suggested by Myers and Bahaj (2005) to keep up 3-diameter (turbine blade) gap

between adjacent turbine rotors in a row. Along channel spacing is suggested to be of 15 rotor diameters, so that maximum output of energy can be extracted.

EPRI studies however suggest spacing of a 0.5 diameter gap between adjacent turbines in a row, and 10 diameter separations between adjacent rows of turbines (Hagerman *et al*. 2006)

A brief account of some of the TISEC devices holding promise, are appended below.

2.3.6.4 TISEC Devices

All TISEC devices are fully submersible. They are either horizontal axis turbines or, vertical axis turbines with subsystems consisting of the rotor blades for converting kinetic energy of water flow to rotational motion energy. They are associated with accessories of a gear box and a generator that convert rotational energy to electrical energy. The support structure may be gravity based attached to a foundation or, anchored and moored allowing it to fly in the tidal stream (Westwood 2004). A large number of such units may be placed building up the TISEC farm, depending on the type of device and resource geometry of the concerned site.

A typical such tidal farm with wind like turbines, are shown in fig.2.26 (Myers and Bahaj 2005) given below.

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Fig.2.26. Submerged array of TISEC units in a typical Tidal current site
(Myers and Bahaj 2005).

Besides the above type of Marine Turbines, which functions similarly to the wind turbines, a host of new concepts are tried with varied TISEC designs for achieving better performance and economy. Working principles of some of them like, Stingray, Gorlov helical turbine, Tidal Fence and Sea-Gen turbines, are outlined below.

2.3.6.4.1 Stingray (Rourke *et al*. 2010)

The key components of Stingray consist of wing-like hydroplane attached to a supporting frame with a pivoted arm. Lift and drag forces caused from flow of tidal current causes the stingray arm *to oscillate* actuating the hydraulic cylinders which in turn retracts pumping high pressure oil to run a motor and subsequently the generator. As the hydro plane arm reaches its upper limit, the hydroplane angle gets reversed such that the cycle of power generation gets repeated. A sketch of Stingray machine with its foundation is shown below in fig. 2.27. (Rourke 2010).

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Fig.2.27 A line sketch of Stingray machine (Rourke 2010).

This device is proposed to be installed for power generation from high tidal current in the Severn River, UK. Further studies are in progress to identify the optimum spacing for placement of Stingray, from resource assessment and optimum power capture as can be availed from Stingray machines.

2.3.6.4.2 Gorlov Helical Turbine (Rourke 2010)

The turbine blades are similar to an aeroplane wing twisted into a helix. Water flow into the blades gives a thrust force resulting in lift and drag. It is claimed that the turbine blade of this device would rotate even faster than the water speed. It has been

planned to install an array of 6-twin-turbines in a vertical side by side arrangement and thereby generate 100MW power in South Korea. A sketch of the above TISEC device is given below in fig. 2.28 (Rourke 2010).

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Fig.2.28 .Gorlov Helical Turbine (Rourke 2010)

Dr Gorlov, the inventor of the TISEC device, aims at placing a farm of 100 units of this helical module in some large resource site (gulf stream) and the power be utilised to generate hydrogen gas by electrolysis (Elliott 2004).

2.3.6.4.3 Tidal Fence

The basic design of tidal fence has four fixed hydrofoil blades connected to a rotor that drives an integrated gear box and electric generator via hydrodynamic lift of the blades. Atypical sketch of tidal fence is shown below in fig. 2.29

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Fig 2.29. A typical sketch of tidal fence (fujitaresearch.com, updated 07/00)

Subhashish Banerjee

2.3.6.4.4 Sea Gen Turbine

The design of Sea Gen turbine has much in common with a wind turbine. It has twin 16m diameter axial flow underwater rotors mounted on a cross beam, on either side of a steel tower. There are lift legs on either side of the tower, so that the cross beams and rotors can be lifted above the water surface over the tower-top platform, for repair and other maintenance jobs. A line sketch of such turbine is shown in fig.2.30 (Douglas *et al.* 2008) given below.

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Fig.2.30. Typical Sea-Gen Turbine Unit shown
(Douglas *et al.* 2008)

It is proposed to be deployed at Strangfold Lough in Northern Ireland, and would be the first full type commercial proto turbine. The proposed annual power output has been claimed to be 4736MWh, presuming 94% availability of power (Douglas et al 2008).

2.3.7 Critical appraisal of tidal schemes giving relative merits & demerits

Power generation from tidal barrages have the advantage that once constructed, its life period is more than 100 years, requiring very little cost towards its periodic maintenance/repair and operation which is less than 1% of the construction cost (Alderson 1992). Of course, the turbine life is around 30 years.

Besides, the tidal cycles being fully predictable, prior planning 20-30 years ahead, can be made setting the production target.

Its limitation are however manifold. In the first place, .the high tidal range sites suited for tapping tidal power (from barrage construction) profitably are rather limited globally (Pelc & Fujita 2002). Besides, the barrage construction cost is prohibitive with very high capital cost involvement, even much larger than the Hydro plants. The gestation period to reach the production stage is also very high, discouraging the investors on it (Elliott 2004).

The other limitation is the uncertain environmental consequences from construction of tidal barrages. It affects sedimentation characteristics of the rivers, its carrying capacity, course characteristics, and causing navigational hindrances. These problems may aggravate during the construction phase, which period itself may be more than 5-6 years, with possibility of irreversible environmental changes (Frau 1993).

Keeping the above problems in view, the other alternative such as utilising the kinetic energy from tidal streams are considered (TISEC), which has much less cost involvement and also has less impact on the environment.

TISEC technology involves much less capital outlay and gestation time than Tidal Barrages. In fact, with TISEC placement over a good tidal site and making suitable planning, TISEC technology has the potential to be economically viable. This technology may be considered to be environmentally benign as well, if proper guidelines are maintained on packing density for installing TISEC array, giving adequate space allowances (Bedard *et al.* 2006).

Adequate precautions with periodic maintenance are however needed, to address the problems encountered in TISEC units like, under water bio-fouling, corrosion of TISEC devices and repair work etc. (Douglas et al. 2008). Besides, TISEC technology is yet to take off for commercial deployment, though a number of prototype TISEC devices with innovative designs are available, like the WECs.

In fact, as pointed out both TISEC & Barrages are required to be examined from an environmental impacts and economic perspective. Whereas in TISEC projects, assessment tools are needed to adjudge the relative merits of competing devices in the case of barrage planning such tools are needed to ensure causing minimum eco-imbalance achieving maximum economic gains.

2.4 Comments.

It could be noted from a literature review of OE systems that other than Barrage scheme, which is a commercially matured technology, all other systems including WECs, OTEC & TISEC devices, have immense scope for further improvement with the promise of techno-economic commercial viability in 2nd or 3rd generation devices. Development of suitable assessment criterion, like environmental impact assessment (EIA) and examining scope of economic viability with suitable indices may go a long way in advancing these technologies. In barrage scheme also it would help in making optimized barrage planning, both from ecology and economy; each barrage being of different characteristics.

It is with this in view studies were carried out to develop EIA model, so that it can be applied for the individual OE systems, along with usual economy indices as are available from net present value concept. The EIA model study for OE schemes has hence been taken up in the next chapter.

CHAPTER 3
EIA ESTIMATION MODEL DEVELOPMENT
FOR OCEAN ENERGY SYSTEMS

3.0 Introduction

The Environmental Impact Assessment (EIA) of a project provides identification of its environmental consequences and helps in advance planning to mitigate the negative factors, if any. Legislation for implementation and assessment of EIA have therefore become mandatory for any big project, which has been introduced in UK as well, in 1988 (Glasson, *et al.* 2005). But the standardized methodology for assessing environmental impact, as may be caused from large scale deployment of ocean energy systems, is yet to be evolved for lack of experience of environmental consequences, as might be met from their commercial scale application (Musial 2008). It has therefore been attempted to develop a theoretical model of EIA for ocean energy systems, from collation of information and necessary analysis. This would be helpful in providing guidelines to mitigate negative impacts if any, from deployment of OE devices and also assess their scope for achieving sustainable development.

The European Union directive on the EIA of a project stresses upon examining the environmental consequences on parameters such as- "human health, fauna & flora, soil, water, air, climate and the landscape, material goods, cultural heritage and interaction between them''(Margheritini *et. al.* 2011). Considering the above directive in the context of environmental consequences resulting from deployment of ocean energy systems, the above parameters could be defined as:

- Emission characteristics of the technology specific OE device, impact on global warming from emission of green house gases, as emission of acid gases causing acid rains, etc.
- Landscape/seascape changes, soil erosion, or sedimentation pattern changes affecting the seabed, as may be caused from large scale deployment of OE devices.
- Affecting the water body of the ocean, both from its quality as well as energy density, and from the operational effects of different types of OE systems, which may influence growth of oceans flora and fauna.
- Influence of applied technology of the deployed OE device, affecting the ocean's flora and fauna as may broadly be classed as: birds, fish population, sea mammals, benthic community and plankton.
- Inherent risk involvement from functioning of the OE device concerned, affecting the ecology & scope of adopting mitigating measures on the same.
- Societal acceptance as regards aesthetics or visual impact etc, as also on scope of improvement in quality of life from economic development caused from deployment of the OE schemes.

The EIA model development for the OE systems, with scope for assessing the environmental impacts both qualitatively and quantitatively, has been attempted based on information retrieval of the above stated issues. They are covered below in subsequent sections.

3.1 Emission characteristics of green house gases & acid gases

Unlike fossil fuels, scope of air pollution from GHGs or acid gases would be negligible during operational stages of the OE systems. Hence, in order to assess the environmental burden of OE systems, it is important to determine the life cycle assessment (LCA) of emission characteristics of the system (like all RE systems), covering all its phases of development and operations (Gunilla 1996). This includes the transportation of the product, from extraction to reaching the site of construction added with future O&M operations required during its life time, following the standard of ISO 14040 (British Standards Institute 2006).

The methodology adopted in such a LCA study for estimating emission characteristics of specific OE devices, is based mainly from input emission data of inventory raw materials and life time energy generation of the device concerned. Thus, life time emission is expressed in g/kWh = $\sum$ Gi × Mi / P_L + operational stage emission in g/kWh; where Gi =gas emission in kg/kg of inventory items; Mi =mass of the inventory items of the device; and P_L is the life time power generation of the device in kWh. The operational stage emission is required to be considered for OTEC schemes only, which is negligible for wave or, tidal schemes.

Since such a LCA study of a product is process specific and country specific (Helius *et al.* 2007), the results were required to be ratified from different data sources, like Danish model (Schleisner 2000) as well as from Bath University data sources (Hammond and Jones 2008).

In addition to estimating emission characteristics (most importantly CO_2, being mainly responsible for global warming) of specific OE devices following the above method of LCA study, it is also considered essential to make energy accounting study as well. This denotes the energy expended to construct the specific energy device compared to its annual energy production; expressed as energy payback period (EPBP) in years. Thus EPBP expressed in years = $\sum$ Ei Mi / Pa; where Ei is the embodied energy of the inventory items of the device expressed in MJ/ kg; Pa is the annual power generation of the concerned OE device, also expressed in MJ.

Review of studies giving different relevant aspects on LCA has been incorporated in Appendix 1.

3.2 Landscape /Seascape changes and/or Soil erosion, etc

It is mainly in tidal schemes where there is scope for affecting the landscape with increased sedimentation and/or soil erosion posing a threat, being experienced immediately (Elliott 2004), than that for wave or OTEC schemes, for obvious reasons. There may not be any effect on landscape changes or soil erosion etc. for small scale wave schemes. But in case of large wave farms there remains some scope of reduction (even if marginal) of the shoreline erosion, due to reduction of wave density reaching the shore, from power capture of the incident waves by large number of the devices (Pelc and Fujita 2002). Whether such a reduction of soil erosion in coastline is welcome or not, would depend on the nature of the site concerned (Shaw 1982).

Power capture of the incident waves by large sized wave farms causes a dampening effect of wave density and this might also reduce the tidal ranges in estuaries thereby causing increased sedimentation (Sorensen *et al.* 2003). In fact, such hydrological changes may also affect ocean's water quality and thereby its flora and fauna, as explained in the subsequent section.

3.3 Affecting water bodies from deployment of OE devices

Scope of dissolution of anti corrosion paints and /or anti bio-fouling agents used in OE devices or, accidental hydraulic oil spillage from concerned OE devices, are a potential risk that may adversely affect oceans flora and fauna (Almeida 2007). Their adverse effect might be minimized by choosing the right chemical followed by adequate maintenance (Nendza 2007). However, there remain some other sources of affecting the quality of water bodies in oceans, which are specific to the type of OE system used. They are therefore required to be dealt with separately for wave, OTEC and tidal schemes, as discussed below.

3.3.1 Wave schemes

It could be observed from a WEC like Pelamis, that energy extraction of its wave farms installed near shore, could extract energy between 9% and 23% of the incident wave (Palha *et al.* 2010). Similarly in off-shore installations of other WEC types usual energy extraction from the waves confronting them could be around 22% of the incident wave causing reduced water flow behind these devices, and as a result permanent change in the sediment structure may occur (Duckers 2006). Such a reduction of energy behind large wave energy farms may be harmful to the fish population affecting transport of larva from their feeding ground (Pelc & Fujita 2002). The effect however, may be considered to be rather marginal, being localized around the area surrounding the wave farm.

On the other hand, the stable structure of wave energy converters may be helpful to some extent, for the growth of macro-benthic community and also of certain types of fish population; suggesting the WECs to be acting like an artificial reef that favours their growth (Mergheritini *et al*. 2011).

It may be quite logical to presume that both the above stated negative and positive effects may be considered to be rather marginal. The degree of effect would depend on the size of the wave farm as well as of the technology and dimension of the device concerned.

3.3.2 OTEC schemes

The mixed discharge released in the ocean along with nutrient rich up welled cold water (required for running all types of OTEC plants) is likely to favour growth of marine organism, which include; fish population, sea mammals and plankton. This is similar to that observed in the west coast of South America, because of the upwelling of nutrient rich bottom cold water coming up to surface from the Humboldt current of the ocean (Anderson 1998).

On the other side it has also been noted that nutrient rich up welled water may act as killer to certain organisms such as; small fish, jelly fish, etc. (Pelc & Fujita 2002). It has also been suggested that the very technology of running the OTEC plant over a long period of time invites the risk of slight warming at depth but a little cooling at the surface. This change in eco-system may lead to a reduction in the growth of organisms (Kennish 1998: 80-83).

Thus, though OTEC could have huge potential in favouring growth of oceans flora and fauna, simultaneous annulling forces might ultimately lead to the overall growth of organisms to a moderate level causing the loss of certain species.

3.3.3 Tidal Schemes

The barrage construction in particular has a tendency to even out the tidal ranges. It lowers down the highest water level for high tides, but elevates the lowest water level during ebb tides, with ultimate elevation of the mean water level (Elliott 2004). This would cause less churning of the upstream water with less turbidity and obviously causing an increased euphotic zone with deeper penetration of sunlight (Wolf et al. 2009:165-177). Obviously, this is likely to favour higher growth of Phytoplankton and thereby of many marine species.

But elevation of mean water level with less lowering of ebb tide would reduce the exposure of mud flat regions of the basin. This might affect certain fish types whose preferred zone is the mud flat regions, also affecting birds that feed on them (Colombe & Kydd 2010). In addition, because of less flow of high tide water, upstream salinity of the basin is likely to be lowered. This is likely to reduce growth of saline water fish upstream (Pelc & Fujita 2002); but would not affect fresh water fish. Phytoplanktons and such species would have enhanced growth, benefiting from deeper penetration of euphotic zone and higher mean water level.

It is however, to be noted that there is a possibility of causing a habitat imbalance of estuarine organism of barrages because of the closing of the estuary for a prolonged period during its construction phase; as had been done for La Rance Barrage in France covering a few years (Elliott 2004). It took quite some time for it to re-establish with the new eco-system (Frau, J.P.1993). It is hence being recommended, not to close off the estuary from the ocean, during the construction phase of barrages, which also needs simultaneous monitoring on changes in marine organisms, if any (Pelc & Fujita 2002).

It can be inferred from all the above analysis that there may be adverse effects on certain organisms from barrage construction, but there would be favoured growth of other types with increased growth of Phytoplankton. The overall effect of Barrage construction would thus be rather favourable for overall growth of flora and fauna, and certain types of birds and fishes, if adequate provision for fish movement, avoiding the lethal turbine tunnels, is maintained (Gray 1992).

In addition to affecting flora and fauna both positively and negatively depending on the site and species concerned, barrage construction with heightened mean water level may aggravate flood risk and soil erosion (Colombe & Kydd 2010). With

proper planning of heightening of the embankment etc. during the construction phase this risk may, to a large extent be minimized.

It is however to be noted that in case of TISEC schemes, there is little risk to species loss and they are considered environmentally benign (Pelc & Fujita 2002).

3.4 Influence of technology of OE devices affecting flora and fauna

There are number of technologies which may be developed to harness OE, and each of these technologies may have unique environmental impacts. These influencing factors are:

- Noise pollution accrued mainly in the construction phase, and also to some extent in O&M and dismantling stages of OE devices.
- Physical disturbance (sedimentation etc) as may be caused during the installation of OE devices, including construction of mooring systems etc. in ocean's bed.
- Electromagnetic radiation, as may be experienced from the electrical cable laying in oceans, for transmission of power to the grid line ashore from the concerned OE device.
- Accidental collision of species with moving parts of devices, like turbine blades, etc**.**

In fact the above stated effects are dependent on the technology of OE devices concerned, as well as the location of installation sites (Margharitini *et al.* 2011). Their effect over oceans flora and fauna, broadly classed as: birds, fish population, sea-mammals, benthos community and planktons, are detailed below.

3.4.1 Birds

There is no field data available, on the affect to sea birds, in respect of the application of OE devices and therefore experiences gained from wind energy could be considered helpful (Sorensen 2003). The main problems affecting the bird population, as noted from wind farms are; the risk of mortality from collision and their habitat changes.

The fact that ducks avoid even stationary wind farms, avoiding such structures on their migratory route, suggests that birds are likely to avoid surface protruding OE structures as well, even if the construction site falls in their migratory route or on foraging site with their prey availability. On the other side, certain bird species, are rather attracted to any artificial structures like wind turbines or oil rigs; and have been noticed to die from collision with the moving parts of wind turbines etc (Langton R. et al. 2011). Thus, mortality from collision with submerged moving parts of WECs or TISEC devices (turbine blades etc) could be the potential risk of sea birds diving below for their prey/foraging (Langton *et al*. 2011).

In addition, the impact of noise during the construction phase of shoreline devices may have some impact on birds affecting their roosting and preening, and thus oust

them from their habitat. The sensitive periods of their roosting and preening etc should therefore be avoided while constructing the OE devices (Kaur 2004-5).

European Birds Directory have ear marked special protection zones of birds for conservation of certain bird species, which are extended in off-shore zones as well (European commission 2007:112). Such sites for OE devices should therefore be avoided in choosing OE installation sites.

The risks involved for the bird population, from shrinkage of mud-flat regions because of barrage constructions, have already been explained in previous sections.

In case of large capacity (100MW) OTEC plant, it is considered that the huge flow of cold and hot water at 20°C temperature difference, round the year 24×7, is likely to reach dew point of air around the cold water and warm water pipes (despite insulating coating around the pipes), making a canopy of mist around the plant. This may drive away the routes of migratory birds, if it falls within their route.

Thus both for OTEC and Barrages there is scope for affecting certain types of bird population to some extent, though this may not be wide spread. In the case of wave schemes/TISECs, even the risk from collision from under-water-moving parts for diving birds might be minimized by maintaining wire meshing around turbines.

Avoiding the OE construction sites of bird habitats, earmarked by European commission, would also minimize the effect on the bird population.

3.4.2 Fish population

The impact of noise caused mainly during the construction phase of OE devices, may affect those types of fishes which use sound for communication and detecting their prey (Margharitini *et al*. 2011). In extreme cases, like pile driving during construction of mooring systems etc, the intensity of noise may reach as high as causing physiological damage, affecting their survival (US EERI report, 2009). In fact, it is the rise and decay time of noise which is more decisive in affecting the lethal limit.

In addition to noise level affecting the fish population, the other impeding factor is the impact of electromagnetic fields (EMF) from cable lines laid for power transmission through the sea-bed. Though it is not known to what extent it would affect the fish population (or other marine animals etc); but even if it has some effect this can be averted by burying the cables in sediment (US report to congress 2009). In addition to this, the drilling operation (for mooring / cable laying) resulting in the accumulation of sediment and turbidity may also limit the growth of fish population; but within a distance of 5m around the drilling sites (Duckers 2006).

Contrary to these negative impacts on the growth of the fish population, certain OE devices have positive effects in terms of encouraging an increase in certain fish populations, these devices include; OTEC and Barrage, facilitating water quality change as discussed in previous sections. Also, wave farms and TISECs, because of their ban on fishing trawlers approaching them, could favour some growth in their

vicinity. It could also depend on the design of the WEC; like Wave Dragon is likely to favour some growth of fish larvae in its huge overhead tank.

3.4.3 Sea-mammals

It is required to identify the extent to which the application of OE systems might affect sea-mammals, such as seals, dolphins, whales, sea lions etc, which are important for maintaining the eco-balance of the oceans flora and fauna. A Danish project, who undertook surveillance with radio-tagged seals, concluded that seals are highly mobile over a large distance (Sorensen et al. 2003). Presuming other sea mammals behaving similarly, the impact on sea mammals from the noise or EMF effect during the construction phase would be temporary, since they can easily come back to their original habitat, even if they leave their habitat due to noise effects during OE systems construction phase.

Whether noise and electromagnetic field during the operational phase might cause a loss of habitat of sea mammals, is yet to be ascertained for lack of field data. (Margharitini *et al*. 2011). The vibration of equipment used at infra sound zones can also be a potential pollutant affecting the sea animals' sonar system, used to locate their prey. The impact of different noise levels over sea-mammals is shown below in fig 3.1 (Kaur 2004-5).

Fig. 3.1 Response of sea -mammals for different noise levels
(Kaur 2004-5).

In fact, noise is an important issue for sea-mammals since sound can travel large distances over open water surfaces. Noise created from the movement of mechanical parts added with the background noise of breakers in the sea, intensifies for shoreline devices towards the sea and may affect marine animals. A caisson-based OWC project of 150kW in Trivandrum, India, recorded a sound intensity of 70-90 dB at the sea-ward end but less than 60 dB on reaching near the shore (Duckers 2006).

Under water noise intensifies during the construction period with associated blasting operations etc. which may affect the breeding and nursing of the marine animals

(including fish). Thus, it is always advisable to avoid these sensitive periods for construction and decommissioning of wave farms (Duckers 2006).

However, the effect of electromagnetic fields around cables to sea mammals etc. may be minimised, if these cable lines are buried one metre below the seabed.

The possibility of physical injury to sea-mammals by hitting sub-merged moving parts of OE devices can also be considered to have negative impact on them. On the other side, pinnipeds (sea lions etc) use the offshore OE device platform, for resting above sea level. This fact should be kept in view in building wave schemes, for maintaining their survivability which is a very important criterion while designing wave energy converters.

It may thus be quite logical to presume that OE devices (wave & OTEC), if installed away from the protection area of the sea mammals, and if due precautions are adopted to keep the sound during construction phase to the minimum level as far as practicable, in that case negative effects to sea mammals, even from large scale wave or OTEC farms would be marginal. However, in the case of OTEC, the quality changes of water (as discussed in previous section) would have an appreciable overall positive effect on the growth of marine species.

3.4.4 Benthos

The Benthic community in the sea-bed are vulnerable and are affected during the construction phase of WEC's/OTECs from; drilling, mooring, foundation laying and creating sediments due to trenching on either side during cable laying. Such effects on the benthic community are however localized and small; cables being kept buried in sea bed (Sorensen 2003). In fact, after completion of the construction period, the benthic community would be re-colonized, ensuring any negative effects from construction are only temporary. (Margheritini *et al.* 2011).

3.4.5 Plankton

Plankton consisting of slow moving zooplankton and phytoplanktons etc, forming a part of the web of food chain of sea mammals and fishes. They are rather more influenced by the ocean currents and availability of their mineral nutrients. They thrive in the photic zone of the ocean (Chisholum 1992).

The effect of noise or EMF is uncertain and inconspicuous for their growth (Sieber *et al.* 2007). Rather, temperature, salinity, advection effects and of course nutrients and sunlight availability etc. are more important for their larval growth (Chichao and Chicharo 2001).

Thus, plankton would be affected more by the quality of water facilitating their growth, which in turn influences the growth of fish and sea mammals. However, the dampening of wave and reduction of the ocean current of the sea from the energy capture of large wave farms, as may occur from shore line/near shore deployment of Pelamis etc (Palha *et al.* 2010) or from other types of off-shore wave schemes (Duckers 2006), are likely to affect planktons negatively, but this will be marginal. On the other side, barrage schemes providing deeper penetration of Photic zones, and

OTEC devices with higher availability of   nutrients, as elucidated in previous section, would favour the growth of planktons.

3.4.6 Comments

Based from all the above collation of data, it could be noted that effects on Flora and Fauna depends on the type of the OE system deployed. By and large, OTEC & Barrage schemes are likely to rather help in the overall growth of ocean's flora and fauna excepting some types of birds. TISEC devices are likely to be rather benign (Pelc and Fujita 2002).

It could also be noted from analysis of wave schemes, that deployment of WECs is not likely to cause major negative impact on oceans flora and fauna, being confined to a small area of its application site (Zabihian & Fung 2011).

3.5 Vulnerabilty OE device deployment & suggested mitigating measures

In addition to the above effects on flora and fauna, experienced from the application of OE devices, various types of hazards involved from OE deployment, also need to be examined along with the mitigating measures that are to be adopted. The major ones that could be identified are shown below:

- Malfunctioning of equipment from accumulation of seaweeds and other bio-fouling agents.
- Accidental oil spillage/leakages of chemicals from the device which may be toxic to oceans flora and fauna.
- Accidental collision with oil tankers etc. / navigational access blocking.
- Problems as regards survivability.
- Causing hazards to landscape.

A brief description of the above stated vulnerability of OE devices, as well as the mitigating measures required to be adopted, for different OE systems are stated below.

3.5.1 Malfunctioning from seaweeds & deposits

Seaweeds and deposits may be viewed from two perspectives, the species being affected, and the debris that is collected from them in the active parts of the OE devices. They contribute to the mal-functioning of devices and also cause obstructions in operation and maintenance jobs.

Such deposits include jellyfish / floating seaweeds / soil/ debris etc, hinder proper functioning of the turbine or other moving parts of OE devices, causing malfunctioning of equipment (Sorensen *et al*. 2003). However, this is site and design specific. The Wave Dragon type WEC is likely to collect debris (including organism) in their big reservoir, requiring grid/net trap to annul this problem.

Besides the above type of debris, there may be fouling with marine growths, both inside the turbine as well as in the converter body, requiring   periodic maintenance and inspection. Experiences from the shipping industry and offshore oil installations

suggest such growths to be mainly from certain invertebrates and algae / fouling organisms. This demands the use of suitable paints against colonization by such fouling agents as well as taking care of the corrosion problems (Duckers 2006).

Direct injection of biocides (like chlorine) are thought to retard the growth of such fouling agents (besides use of suitable paints) - which are required to be kept under control for maintenance /inspection of the generators (Vega 1999). But proper foolproof anti-fouling agents/paints for wave converters (as also for other OE devices) are yet to be developed and remain a grey area of research. Although the corrosion-proof paints are virtually technological successes with additional cost involvement (Sorensen *et al.* 2003).

3.5.2 Risk from collision etc / navigational access

The possibility of collision from sea-going vessels with the near-shore /off-shore WEC's or OTEC devices might cause appreciable damage to property and also potential human casualty. In the case of a collision with oil tankers, the oil spillage might affect marine species, though this may only be localized. Hence, it is recommended to ensure proper markings in order for them to be visible from a distance (ensuring suitable colouring as well as audio/visual signal system) in order to avoid such accidents. In fact, such markings would not only reduce the risk from accidental collisions of WEC's & OTEC devices, with other navigating vessels, but also have a positive result in reducing collision with, potent colliding sites of un-noticed sub-merged reefs, which are usually the chosen sites for near-shore WEC's (Sorensen *et al.* 2003).

In addition to maintaining signals etc, WECs or OTEC device installation sites should avoid navigational routes as a preventive measure to avert accidents from collisions.

On the other side, barrages or TISEC devices should ensure clearance for navigational access, like maintaining ship locks for barrages and keeping an adequate clearance (15-20m from top) for installing TISEC devices (Elliott 2004). In fact, adequate dredging of silt in sluice gates is required to be maintained for clearing navigational access in barrage schemes.

3.5.3 Risk from oil spillage / Hydraulic fluids etc.

The risk of accidental oil-spillage from the hydraulic fluids used in WEC turbines, or working fluids like NH_3 etc, for OTEC schemes would only be temporary and have a marginal effect on water pollution in high seas. But the risk in OTEC schemes is much more pronounced as this would have health implication for the operational personnel involved. However adequate maintenance work can minimize such risks.

3.5.4 Risks affecting survivability

Besides the above precautions, the bodies of WECs / OTEC units are required to be designed so as to be robust enough to withstand the roughest of sea-waves. In addition, the moorings of offshore and near-shore WECs/OTECs should not become

dislodged, allowing the converters to drift in the sea creating a danger of collision to sea going vessels.

The vulnerability from survivability is more important for OTEC units with a history of its plants getting wiped away in tropical storms (Cohen 1982), mainly because of its unstable C.G. of overhanging long cold water pipes. However, based on the technology of oil rig platforms, adequate design improvements for stabilizing OTEC devices could be suggested (Vega 1999).

3.5.5 Risks affecting Landscape

Such types of risks, like soil erosion or increasing danger from floods, are more relevant for Tidal schemes. In the case of Barrage it is increased due to the elevation of mean water level, as discussed in section 3.2 and section 3.3.3. However, the mandatory precaution needed in Barrage construction consisting of elevating the embankments, lowers this risk than that involved in the parent river (Elliott 2004). In TISEC devices the guidelines as regards TISEC farm deployment, limiting its size with due spacing etc. of the deployed units as discussed in Chapter 2, would help in reducing soil erosion / floods without affecting much the circulation in the estuary (Bedard *et al*. 2006).

In the case of wave schemes, changes caused in landscape from the dampening of waves, would result in less erosion of the coastline, though only marginally (Palha *et al.* 2010), as discussed in section 3.2 & section 3.3.1.

3.6 Aesthetics and Societal Impact

In the case of shoreline OE schemes (except Tidal schemes), visual impact may pose an important issue for social acceptance, affecting the tourism industry as well (Margheritini *et al*. 2011). This problem can be easily avoided by choosing installation sites away from tourist spots or by improving its outer look and taking in to consideration the views of local bodies prior to the installation of shoreline devices. The important point in this context to be noted is that in the UK, a sizeable population lives within a distance of 10 km from the seashore (Sorensen et al. 2003). Hence, not only the visual impact of shoreline devices, but the acceptance of noise ashore is also a considering factor when looking at social acceptance (Sorensen et al. 2003). Thus, shoreline designs should aim to minimize operational noise.

However, noise would have virtually no effect on social acceptance for the offshore devices. In fact, in the UK / Ireland guidelines for wind energy, a limit of 15 km from the shoreline is considered to have no visual or noise significance (Sorensen *et al.* 2003).

In addition to the above, naval exercise sites and places of marine archaeology (historical shipwreck points) are also to be avoided in choosing sites for near-shore or offshore devices (Sorensen *et al.* 2003), and of course it should also avoid navigational routes.

The positive aspect of all types of OE schemes in terms of social acceptability, is the potential for an abundant supply of pollution free energy, with virtually no emission

during its operational phase, like all other RE types. In fact, the scope of generation of energy itself advances the economy of the place concerned. It thereby holds promise to improve upon the quality of life of the people living ashore /islanders /developing countries.

In this context, it may be relevant to add that countries have their rights to construct offshore converters within 320 km (200 miles) from its shore, as per international law on agreed rights of its own territory, but of course excluding the recognized sea-lanes (Duckers 2006).

As regards tidal schemes, barrages have the additional advantage of improving upon the communication routes and also of developing the tourism industry (Elliott 2004), besides improving upon the overall economy of the place from power generation. It also ensures higher employment as a result of barrage construction and this will remain so over a prolonged period.

Based on the information retrieval made on the above topics, attempts were made to develop an EIA model for OE schemes, for both qualitative and quantitative purpose, focusing on the assessment of the environmental consequences, and highlighting the areas where preventative measure will mitigate any hazards that are posed. The methodology followed for the development of the EIA model, is detailed below.

3.7 Development of EIA model for OE systems

The methods normally followed for determining EIA   are:

- Checklist method--by subjective identification of different influencing parameters.
- Matrices--that incorporates impacting parameters with the Environmental areas.
- Network method --developing an integrated model.
- Quantitative method-- giving score values over the individual factors.

In this study a checklist method has been followed for wave schemes only, as the initial step. This was done by taking recourses to the background knowledge base generated from elucidations made in previous sections, as regards the environmental fallout resulting from the deployment of wave schemes.

This checklist model shown below in table 3.1 could thereafter be extended developing the quantitative EIA model, which could be further advanced from case studies of all three OE systems of Wave, OTEC & Tidal schemes (shown in subsequent chapters 4, 5 & 6).

3.7.1Check list method for Wave Schemes

It follows from the above elucidations, that the environmental impact of wave schemes are not only design specific but also site specific. An attempt has been made in the present study, to qualitatively compare the impacts of various parameters during their construction, operation and decommissioning phases, as per their installed sites, whether shore based(S), near shore(N) or off-shore(O) ones. This has

been shown in the following table 3.1, by tick marking whether the impacts can be perceived or, not.

Table 3.1Environmental Impact Assessment as per sites, at various phases of wave schemes (Nomenclature: SHORE BASED =S; NEAR-SHORE =N; OFF-SHORE=O)

Impact	Construction			Operation & Maintenance			Decommissioning		
	S	N	O	S	N	O	S	N	O
Wave dampening				√	√				
Coast line change				√	√				
Fish & Sea Mammals		√		√	√		√	√	
Benthos		√	√					√	√
Planktons				√	√				
Birds	√	√		√	√				
Malfunction				√	√	√			
Noise	√	√		√	√		√	√	

The above checklist method of qualitative assessment (highlighting negative effects) for wave schemes only, has been extended to develop an Integrated EIA model for making quantitative impact assessments as well, for OE systems as shown below.

3.7.2 Development of an Integrated EIA model

In order to develop the Integrated EIA model for quantitative assessment, the entire environmental aspects that may become relevant for OE systems, have been divided into two groups, labelled as Set A & Set B. Of course both these sets would have different subsets with each having a number of subset elements as well. Set A, signifies all the environmental issues which are of concern as may be effected from the deployment of the OE device. Set B denotes all the relevant impacting parameters (covering different types of subset element in them as well), which influence upon the subset elements of set A, i.e. the environmental issues. In other words it is because of the degree and nature of influence from all the subset elements of set B, that the subset elements of set A i.e. environmental issues, are influenced.

It is evident that the nature of the influence of subset elements B over subset elements A, would decide the qualitative aspect of the influence over each subset element of set A; whether a positive impact supportive of sustainable development or, a negative impact on sustainable development.

On the other side, the degree of influence with number of subset elements of set B, influencing upon the subset elements of set A, would decide the quantitative assessment over which the subset elements of set A, i.e. different environmental issues, would be influenced. In addition to the above, it has also been suggested in a recent study on wave schemes, that the time period persisting the change caused on environmental issues, might be considered an important guideline, in making quantitative assessment of the environmental consequences; categorizing the effects as high, moderate, minor, or negligible. (Mergheritini *et al*. 2011).

In the present study however, the following categories in the categorization of the nature and degree of impact over environmental issues have been applied, as shown below in table 3.2.

Table 3.2 Categorisation of degree and nature of influence over environment

Degree of Influence	Positive influence	Negative influence
High	H(+)	H(-)
Moderate	M(+)	M(-)
Low	L(+)	L(-)
Very low/Negligible	Ll(+)	Ll(-)

In order to work out the above scheme, for developing the integrated EIA model, set A has been divided into the following 4 subsets:

1. Emission aspects.
2. Flora and Fauna.
3. Hazards posed.
4. Societal issues.

The above 4 subsets of set A, could also be subdivided with various subset elements as shown below, in table-3.3.

Table- 3.3 Subset elements of the different subsets of set A for OE schemes

Subsets	Subset elements of different subsets of set A				
Emission	Global warming from emission of GHG gases, like CO_2, etc /kWh			Acid rains from emission of acid gases like, SO_2, Oxides of N_2, etc. / kWh.	
Flora & Fauna	Birds	Fish population	Sea Mammals	Benthos community	Plankton
Hazards Posed	Malfunction equipment	Navigation problems	Oil spillage etc.	Collisions / Survivability/ Stability, etc.	Affecting landscape/ soil erosion/ floods etc.
Societal Issues	Aesthetics /Visual impact	Economic growth	Progress of life quality	Employment generation	Societal acceptance / Tourist econ.

It may be relevant to add that all OE schemes, covering Wave, OTEC and Tidal schemes, maintain more or less similar types of subset elements, as shown above in table-3.3. Of course, there may be further subdivisions for some systems, for example, fish population, may be subdivided into fresh water fish and saline water fish, birds may also be subdivided to migratory birds, mud-flat grown species feeding birds, diving birds.

It may be also be added that, hazards for different schemes may not be exactly alike for all the OE schemes, as shown in table-3.3. For example, survivability is a big problem for wave or OTEC schemes but not for barrage. It is silt formation chocking sluice gates thus affecting navigation which is the biggest hazard. Also collision with

ships is a hazard for wave or for OTEC; whereas giving passage/clearance for ship movement is of importance for tidal schemes.

The broad subdivision of subset elements of set A, remain by and large similar for all types OE schemes; but it is only the subdivision of the subset elements of set B (impact parameter) which may be different for different types of OE schemes. For example an impacting parameter like noise is an important impacting subset element affecting flora and fauna of wave schemes. But for OTEC schemes it would be the quality change in ocean water, from upwelling of cold water, which is rather more important than the noise effect. In tidal schemes it would be the elevation of mean water levels from even out character of tidal range, which have more impact on its flora and fauna. Thus it needs a separate treatment, specific for OE systems concerned, in the identification of the impacting parameters (subset elements of set B), making their impact over different environmental issues (subset elements of set A).

Accordingly, the different impacting parameters (subset elements of set B), as relevant to making their impact over different environmental issues (subset element of set A) could be identified, and is shown below in subsequent sections. The degree and nature of their impact, as appropriate for environmental issues (subsets elements of set A), could also be made. Such assessments on the degree and nature of their impact for each environmental issue was made, based on the elucidations of information retrieval discussed in previous sections of 3.1-3.6 & table 3.2, giving the classification of qualitative and quantitative norm.

3.7.3 Subsets elements of set B influencing upon environmental issues

The degree and number of the impacting parameters affecting different environmental issues, decides the quantitative assessment of each environmental issue. Assessments of environmental impacts over the environmental issues, as per the classification norm made in table 3.2, have been shown below in tables 3.3-3.6 for each of the environmental issues, for the different OE systems.

3.7.3.1 Emission Characteristics

Table-3.4 Impact parameters influencing emission characteristics of OE device

Environmental issue	Impacting parameters	EIA Score
Input to Global warming from GHGs etc/kWh	a) GHGs of device from LCA study. b) GWP of GHGs. c) Life of device d) Annual power produced.	Ll(-)*
Input to acid rains, etc/kWh	a) SO_2 etc. emission from LCA study, b) life, c) annual power production.	Ll(-)*

*Being RE device the values are very low.

3.7.3.2 Flora and fauna

Table-3.5 Impact parameters influencing upon flora and fauna from OE devices

Sl. No	Impacting parameter (subset elements of set B)	Species affected	OE type	EIA rating	Remarks/ Rating rationality
1.	**Noise effect** depending on site of installation (**S**), and Period (**P**) installed (includes O&M stage noise effect, in addition to the installation phase of OE device).				
a.	**S**= species habitat; and P= sensitive period of the concerned species.	Birds, Fish, Sea mammals	Wave & OTEC	M(-)	1(d) best choice for installation; Rating logic discussed in section 3.4.1, 3.4.2 &3.4.3.
b.	S= non-habitat, P= sensitive period.	-do-	-do-	L(-)	
c.	S=habitat, P= non-sensitive period	-do-	-do-	L(-)	
d.	S=non habitat, P=non-sensitive period.	-do-	-do-	Ll (-)	
2.	**EM radiation** from electrical cable laying for power transmission				
a.	Cables exposed in sea bed	Benthos, Sea Mammals, fish	All OE device	L(-)	2b- practised; vide Sections 3.4.3&3.4.4
b.	Cables buried under trenching	-do-	-do-	Ll(-)	
3	**OE Devices operational influence**				
a.	Moving parts exposed	Birds, Fish, Sea mammals	All OE	L(-)	3b preferred; Vide sections 3.4.1, 3.4.2 & 3.4.3.
b.	Moving parts wire meshed etc.	-do-	-do-	Ll(-)	
4	**Sedimentations etc** from mooring foundation/cable laying in sea bed	Benthos/ Fish/sea mammals.	-do-	Ll(-)	Since effect temporary & localised only.
5.	**Change in water quality** from operation of OE schemes				
a.	Enriching with nutrient feed	Plankton, Fish, sea mammals	OTEC Schemes only	H(+)	Helps growth of most of the species, but toxic to some other types. vide section 3.3.2
b.	-do- but, toxic to certain fish/species types.	Certain fish types/species	-do-	L(-)	
c.	Dampening of wave /ocean current from power capture	Plankton, Fish etc	Wave schemes	Ll(-)	Vide section 3.3.1.
d.	Lessening of turbidity/ increment of photic zone/elevation of mean water level	Plankton, Saline Fish, Fish (fresh water ones)	Tidal schemes	M(+) L(-) M(+)	Vide section 3.3.3; saline water species growth is L(-)
e.	Leakages of toxic chemicals/ from paints / biocides, Cl_2 etc.	All species	All OE types	L(-)	Vide section 3.3
f.	Accidental oil leakages/ hydraulic fluids/working fluids.	All species	All OE types	L(-)	Effect local & temporary.

It could be observed that EIA ratings on an oceans flora and fauna, as effected by the above 4 broad impacting parameters, are mostly (L-) for wave schemes, provided the correct choice (installation etc)/ measures are adopted, as shown in the above table.

In OTEC schemes, though (H+) could be noted in some species, but with simultaneous rating of (L-) from the same impacting parameter over some other species. Thus the overall EIA rating on OTEC's flora and fauna could be considered to be of the mean value of (M+). In tidal schemes, EIA scores could be noted to have values (M+), as well as of (L+) and (L-), for a number of impact parameters. Thus the overall EIA rating for Tidal schemes could be considered to be around (L+). However, case studies with specific device would yield more exact results.

3.7.3.3 Hazards posed

The impacting parameters (subset element of set B) that influence the different aspects on hazards posed are mostly the mitigating measures of minimizing it. For example, the impact parameter on collision hazard of OE device (wave/OTEC schemes), would be the inadequacy of setting up audio-visual signal system, to minimize it. The scores of impact parameters, tabulated below are based on accidental failures, despite adopting the measures to mitigate the hazards of OE schemes.

Table- 3.6 Impacting parameters influencing upon hazards posed on OE schemes

Sl No	Hazard posed (subset elements of set A)	Impacting Parameters/Mitigating measures (subset elements of set B)	OE system	EIA Score	Remarks / Rationale of EIA score
1.	Collision with oil tankers etc.	Audio-visual signal & avoid navigation route for installation	Wave/ OTEC Schemes	Ll(-)	Vide section3.5.2
2.	Blocking navigational access	Keeping ship locks for Barrage; &15-20m top clearance for TISECs.	TIDAL Schemes only	(L-)	-do-
3.	Spillage of Oil / Hydraulic fluids/ working fluid	Adequate maintenance work to minimize risk.	Wave & OTEC schemes	(L-)	Vide section 3.5.3
4.	Changes in landscape				
a.	Reduction of coastline erosion	Dampening of wave from power capture	Wave Systems	Ll(-) / or Ll(+)	Vide section 3.5.5; effect +ve or -ve
b.	Flood/ Soil erosion	Proper heightening of basin embankment	Barrage schemes	L(+)	Vide section 3.5.5;
c.	Flow reduction-estuary	Proper installation norm maintained	TISEC schemes	L(+)	Measures helpful
5.	Malfunctioning of device from debris/ seaweeds/fouling agents/ equipment failure				
a.	Seaweeds/debris etc. accumulation	Adequate maintenance periodically	All OE Schemes	L(-)	Vide section 3.5.1
b.	Fouling agents affect	Cl_2 injection	Mainly OTEC	L(-)	-do-
c.	Chocking sluice gate	Dredging periodically	Barrage	M(-)	Vide section 3.5.2
6.	Device failure	To keep proper provision	All OE	L(-)	Section 3.5.4

3.7.3.4 Societal issues

Energy production itself helps in improving upon the quality of life and the degree is decided on the scope of improvement in the economy as well as on social acceptability. Thus in societal issues the impacting parameters are mainly based on various aspects of social acceptability as well as the economic benefits derived. Broad impact parameters drawn from the above premise are shown below in table 3.7, giving assessment of EIA rating also over each of the societal issues.

Table -3.7 Impacting parameters influencing upon societal issues concerned

Sl. No	Environmental issues affected (subset elements of set A)	Impacting parameters (subset elements of set B)	OE scheme affected	EIA Rating	Remarks / Rationale of EIA rating
1.	Tourist economy	a. Visual impact / Operational noise b. Communication improvement	Shoreline-Wave/OTEC Barrage	M(-) M(+)	Vide section 3.6; Para1 Para last but one, section 3.6.
2.	Societal acceptance on installation site	Installation at- a. heritage sites, b. fishing trawler movement sites. c. Naval sites	Wave / OTEC	L(-)	Vide section 3.6 Para3
3.	Societal acceptance from sustainability	a. GHG emission free electricity. b. employment generation etc.	All OE schemes	M(+)	Vide section 3.6 Para. 4,5 & 6.
4.	Quality of life Improvement/ Economy improvement	Power generation itself	All OE schemes	L(+) to (M+)	EIA rating improves depending upon cheaper power availability.

It would be obvious from the above table 3.7, that installation of wave and OTEC schemes should avoid sites as highlighted in Sl. No2, for availing social acceptance. Fishing communities are to be taken in confidence, lest their trawler movement be restricted. Of course, minimum GHG emission is a positive point of OE devices; but cheaper is the power availability, better would be graded in improving quality of life.

3.8 Comments on EIA scoring

Some sort of subjective scoring of EIA was attempted by researchers making EIA scoring on solid waste treatment plants (ELARD 2004:88). It may be important to note that environmental assessment, particularly from the perspective of quantitative fallouts, have always been considered to be rather subjective, mainly for the 'inadequacy of base line data' (Pastakia and Jensen 1998). This is more applicable for OE systems with lack of feedback data for not having its large scale commercial application. However, Pastakia and Jensen (1998) developed a methodology of scoring of environmental issues based from Rapid Impact Assessment Matrix

(RIAM), depending on increasing degree of impact from slight impact to significantly high over which they made five categories. They were with score points: 0-9, 10-18 (low impact); 19-35 (moderate impact) ; and 36- 71 (high impact), or 71-108 -for very high impact (Pastakia and Jensen 1998).

Keeping in tune of their EIA scorings, it may be logical to presume that low impact of OE systems may be considered to make a change of 10-20% in the vicinity of OE application site; 20-40 for moderate impact and above 40%, for high impact. Of course, it would be experienced only in the vicinity of the application site. Also the score values would be positive if the impact favours sustainable development; but negative on declining it.

3.9 Observations

1. The Integrated EIA model for OE systems was developed identifying 4 broad environmental issues; emission characteristics, flora and fauna, hazards posed and societal issues; as well as with identification of various impact parameters influencing upon each of the different aspects of environmental issues.
2. Based on the nature and degree of influence of the impacting parameters as well as from information retrieval undertaking an extensive literature review on the topic, the impact over all on environmental issues could be assessed, qualitatively as well as quantitatively.
3. The integrated EIA model developed for the OE systems also included mitigating measures required on the inherent hazards posed from the deployment of different OE systems, like wave, OTEC or Tidal schemes.
4. This EIA model could thereafter be applied from case studies of different types of OE schemes and devices, examining its scope of practical application and also improving upon it from more detailed examinations of individual systems. They are   discussed in subsequent chapters 4, 5 and 6.
5. The present EIA model developed is a pioneering model to start with, for the qualitative and quantitative assessment of OE systems; with ample scope for perfecting it from practical data feed, on large scale commercial application of OE schemes and devices.

CHAPTER - 4

ASSESSMENT OF WAVE ENERGY SYSTEMS

4.1 Introduction

In order to compare the relative merits of different types of WECs, the most important assessment criteria is their economic prospect and the environmental aspect including emission characteristics. The economic prospect of WECs would obviously be related to the power capture of the concerned WEC from the wave climate at its deployment site, as well as on the cost involvement of power generation.

The assessment tools that could thus be identified and applied for comparing the relative merits and demerits of competing WECs, undertaking case studies for them, are as below:

- Resource assessment of the respective WECs concerned.
- LCA & EA estimations of respective WECs examining the emission characteristics & energy payback period estimations.
- EIA estimations qualitatively as well as quantity wise based from the model developed.
- Economy evaluation of respective WECs, determining their relative merits.

A detailed account of case studies of a few WECs (having prospect for future commercial exploitations) have been analysed in the subsequent sections for evolving an assessment methodology for wave systems.

4.2 Resource assessment of WECs

Availability of resources is the foremost point for deployment of wave energy converters. It would not be profitable to deploy a wave energy converter if it does not have good wave energy density, expressed as kW/m crest length of the wave. The off-shore sites having higher wave power density than near shore ones are therefore preferred, though earlier attempts were the shoreline sites, being less vulnerable to storm waves (Zabihian and Fung 2001). Suited sites of wave farms are also more in off-shore regions, with "less than 10% of future market from shoreline'' sites (Westwood 2004). This brings forth consideration of the aspects of large scale application of wave farms, at off shore sites.

It is a fact that depending on the design parameters, WECs are likely to work best within a certain range of wave density. If it is less than the range, it may not function properly, whereas with too high a range the device design may fail to cope (as in storm waves etc), and it may trip (Folly and Whittaker 2009). Besides the above, capacity factor of the device giving the annual energy output percentage also varies as per the design of the specific WECs (Mirco, Bedard & Hagerman 2004). Hence even for the same wave climate, annual electricity production for different types of WECs could be different. Table 4.1, 4.2, 4.3 & 4.4 depicts such varied annual electricity production for four different WEC's, as observed in their pilot plant scale sea-test trials at similar wave density sites (Mirco, Bedard & Hagarman 2004).

Table -4.1 Annual power production of Wave Dragon (34% capacity factor)
(Mirco, Bedard & Hagarman. 2004).

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Table-4.2 Annual power production of PELAMIS (40% capacity factor)
(Mirco, Bedard & Hagarman. 2004).

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Table-4.3 Annual power production of Wave Bob (40% capacity factor)
(Mirco, Bedard & Hagarman. 2004).

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Table-4.4 Annual power production of Ore Con's OWC (50%capacity factor)
(Mirco, Bedard & Hagarman. 2004).

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In order to undertake an analysis of the nature of change between the wave density and energy output from respective WECs, scatter diagrams have been plotted from the above tables shown in figures 4.1-4.4. But the availability of data being inadequate, no definite relationship could be established. However, it could be noted that annual power production from the same wave density varied depending on the design type. It was also observed that the nature of the increments of power production with rise in wave density was not uniform.
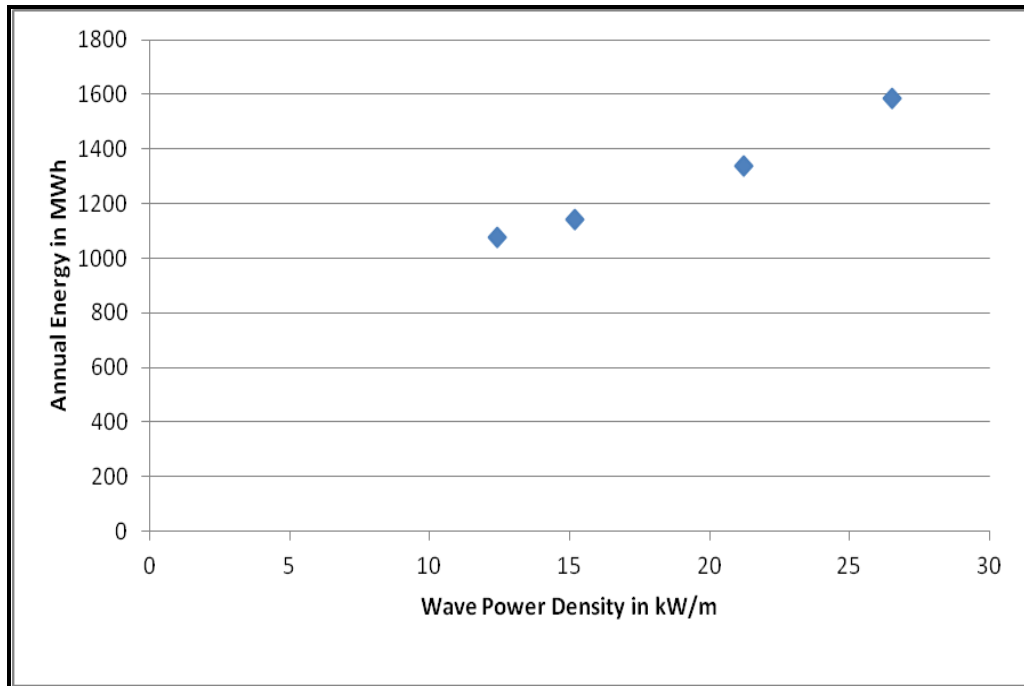
Fig.4.1. Wave Power density vs. annual power production of PELAMIS
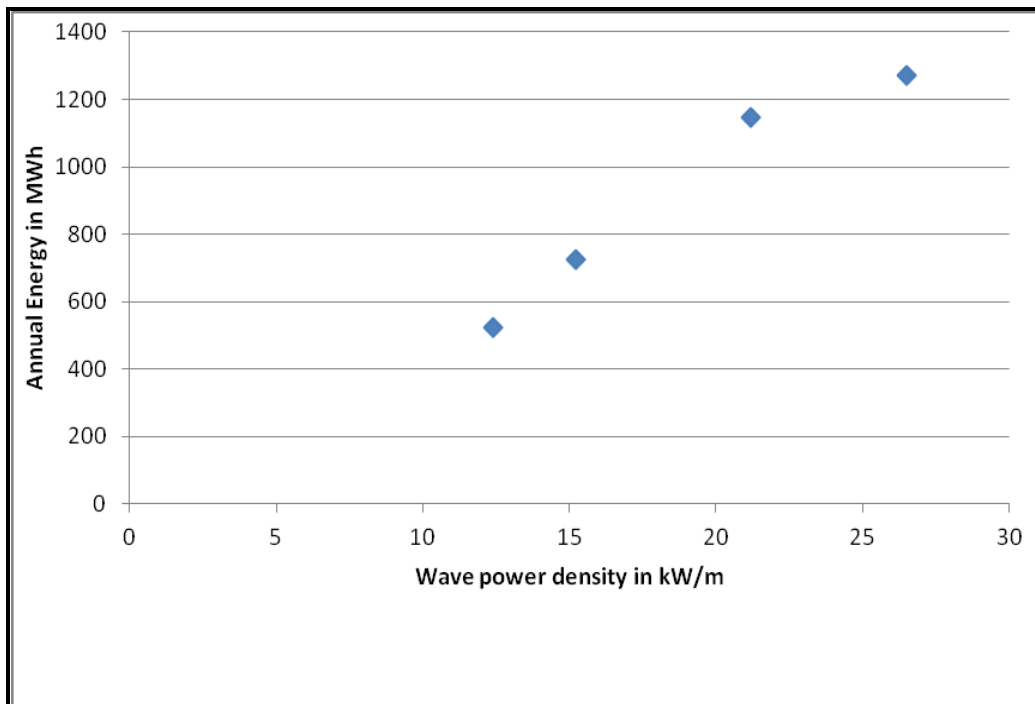
Fig.4. 2 Wave power density vs. annual power production of Wave Bob
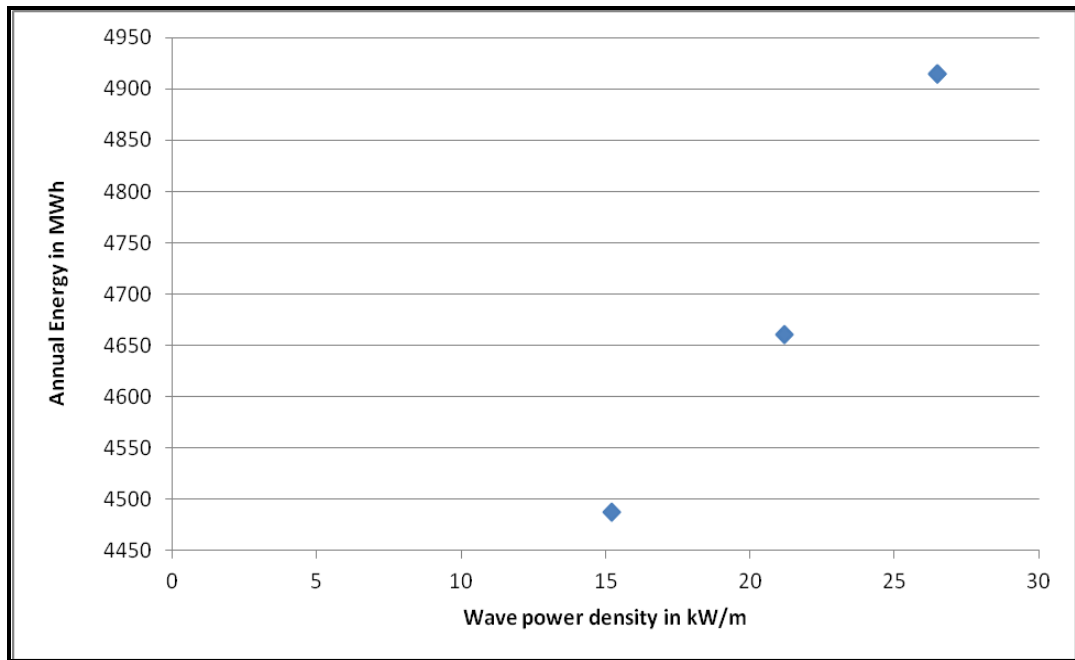
Fig. 4.3 Orecon's Wave power density vs. annual power production.
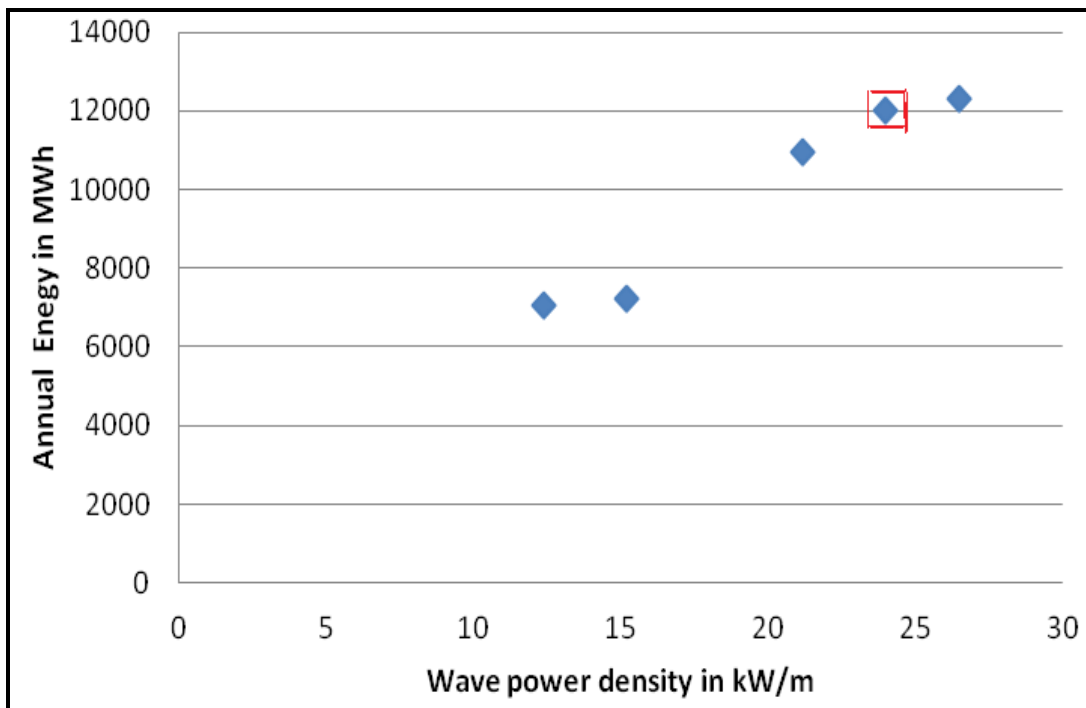
Fig. 4.4 Wave power density vs. Annual power production of Wave Dragon

4.2.1 Critical Appraisal

It is evident from tables 4.1-4.4 that the Wave Dragon shows maximum annual energy output, compared to all other WECs, in all the above stated wave climates. Next in order comes Ore Con type OWC, Pelamis and Wave Bob, respectively.

It has been claimed by the manufacturers that a 4MW Wave Dragon for commercial use, would make an annual production of 12GWh power when deployed in a wave density region of 24kW/m (Kofoed *et al.* 2006). It would seem to be a coincidence that this value of 12GWh annual power production at 24 kW/m wave densities, perfectly fits in Wave Dragons plot of scatter diagram, as shown in red marked point of fig.4.4. This value of 12GWh of annual energy production is also derived, from the usual method of estimating the maximum annual power production, from the knowledge of its capacity factor, which for the Wave Dragon is 34% (4MW*0.34*365*24= 11.91GWh). However, it is also a fact that the same Wave Dragon used to produce much less power when deployed in less wave density regimes, shown in table 4.1 and figs 4.4; its rated power not being achieved in lower wave density ranges.

But similar corroboration of annual power production with a capacity factor is not achieved for Pelamis with its rated power of 750 kW and assumed capacity factor of 40%, as per table 4.2 and fig. 4.1. In this context, it would be of interest to note the findings observed from practical field trials of 750 kW Pelamis device at various sites, covering a year round, with varied configuration (order maintained in the alignment / array of Pelamis units) of Pelamis farms.

In trial runs on the Portuguese coast, it was noted that energy capture from wave density resource varied depending on, the seasonal variations and also of the configuration characteristics maintained in Pelamis wave farms (Pallha *et al.* 2010). Even at the same sites, the scope of power absorbed in January showed the value of 193.04kW; whereas for July it showed a much lower value of 66.8kW only, having their corresponding higher values of Hs & Te as well as in January than in July (Pallha *et al.* 2010). It was however noted that the higher resource availability in the winter months did not contribute to the annual power availability from Pelamis. It was rather availed from its contributions in the summer months, as a result of which the capacity factor for power generation on the Portuguese coast was reduced to less than 20% with a reduced annual power generation (Dalton et al. 2010). The optimum wave density resource availability of generating 2.5 GWh, was achieved from the Ireland coast deployment with attainment of a capacity factor at 38% (Dalton et al. 2010).

Thus, it is not only the scope of availability of wave density resource, but also the availability of optimum wave density range (for the device concerned) throughout the year which is considered decisive in estimating the annual power generation of a WEC with its designed capacity factor and rated power. Too high a wave density is not necessarily helpful and optimum wave density range is more important which depends on the device design characteristic.

It is therefore supposed that future global warming (if any) causing a rise in wave density during the long life of WECs, may offset their optimum wave density range

in their respective operational regions. In addition it may also pose a threat in the survivability of wave schemes. It was therefore considered useful to examine the nature of change in wave density that may occur, in the eventuality of global warming. This aspect has been covered in the subsequent section.

4.2.2 Scope of wave density change in the eventuality of global warming

Increment of temperature in the atmosphere is directly related to wind speed change, which in turn influences wave density. In a fully developed sea, the most commonly used equation giving the relationship between the steady wind speed and the wave spectrum is expressed, as below (McCormick 1981b:23-26).

$Hs = 0.0213V^2$ and $Te = 0.641V$…………………….. [4.1]
Where, V =steady wind speed expressed in m/sec; Hs is the significant wave height in meter and Te is the average time period.

Since, the wave density in m/sec, $P = 0.49Hs^2Te$; hence expressing in terms of V,
$P = 0.49 (0.0213V^2)^2 * 0.641V = 0.000142499V^5$ .... [4.2]

Based on the above equation, and considering an ad hoc steady wind speed to be of 10m/sec, the changes that can occur in wave density values in the eventuality of change in the wind speed can be determined, after the attainment of steady state of the changed wind speed. The results, as determined from the above premise, are shown below in table 4.5.

Table 4.5 Wave density change pattern with wind speed change-after attaining steady state.

Wind Velocity m/sec	% change in Wind speed	Hs in metre	Te in sec. (Average)	P in kW/m	Change in P in kW/m	% change in Wave power density
10	0	2.13	6.41	14.24	0	0
11	10	2.57	7.05	22.94	8.69	37.91
12	20	3.06	7.69	35.45	21.21	59.81
13	30	3.59	8.33	52.91	38.65	73.06
14	40	4.17	8.97	76.63	62.38	81.41
15	50	4.79	9.61	108.21	93.96	86.83

Obviously with an increase in wind speed, wave density in kW/m crest length would increase. Based on the results of the above table, the nature of a change in wave power density as might occur with a change in wind speed (on attaining steady state), is shown below in fig. 4.5.
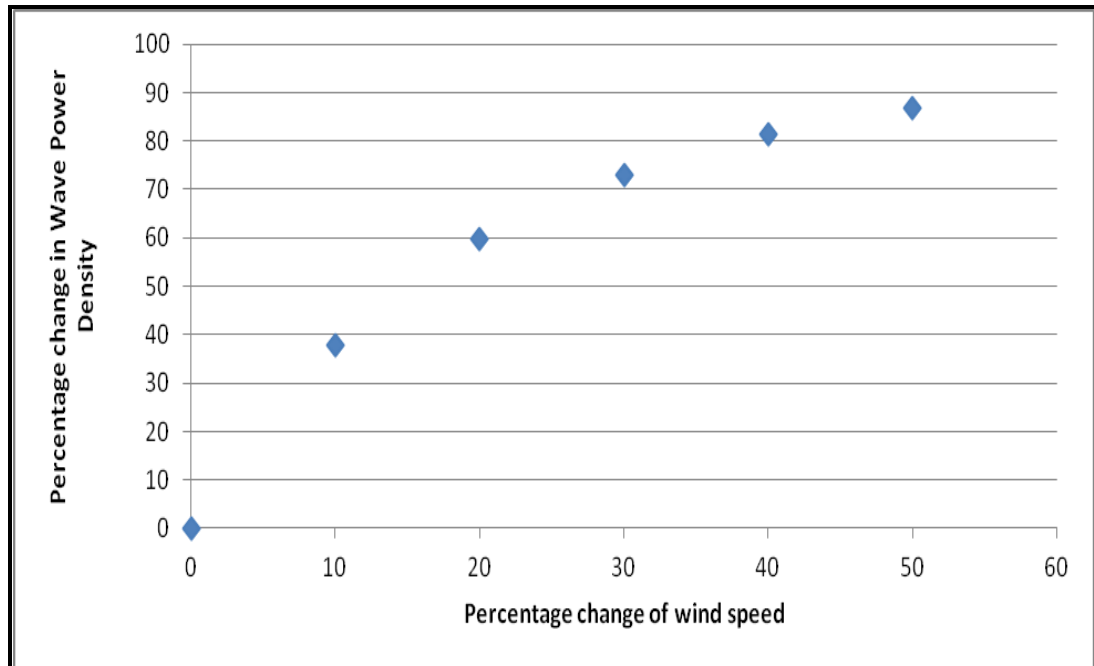
Fig. 4.5   Change of wave power density with change in wind speed percentage

It seems from the nature of the above scatter diagram, that a rate rise in the change of wave power density rather declines above 30% wind speed change, showing a rather logarithmic relationship.

However, in order to develop case studies on LCA & EA estimations as well as economy assessments, the above aspect of the eventuality of global warming was not considered for estimating the annual energy production of the WECs studied. Such estimations on power generation were made based on their rated power as well as their capacity factor, along with sensitivity analysis for variations, as relevant on the same. The results in terms of power generation for the WECs studied are shown below in subsequent sections.

4.2.3 Scope of power generation for selected WEC devices studied

Power production as may be available from the WECs studied would be as below:

1. 7MW Wave Dragon (WD) farm with its 7 units, is supposed to produce 140 GWh/year or, each unit generating 20 GWh/year (Millar *et al*. 2007), obviously having its capacity factor of 34%. The said wave farm is proposed to be tried on the coast of Wales. The life of the Wave Dragon units have been claimed by the manufacturer to be of 50 years (Tedd 2007). Thus the life time power production of a 7MW WD would be = 1000GWh. If however its life is considered to be 20 years, its life time power generation would have been as low as 400GWh.

2. In the case of 750 kW Pelamis it would be 2.5GWh/year as observed in year long trials on Irish coast (Dalton *et al*. 2010). If however, it is deployed on the coast of Portugal, power generation would be half the value giving annual

production of around 1.25GWh, as explained in section 4.2.1 (Dalton *et al.* 2010). Thus life time power production of Pelamis, with its claimed 20 years life would be = 50GWh and 25GWh, for deployment on the coast of Ireland and the cost of respectively.

3. In the case of the Wave Bob, the rated power is 1000kW and capacity factor considered is 40% with life of 20 years (Previsic 2004). Thus, based from the above data its annual power production can be considered to be 3.5GWh, and life time power production =70GWh

4. In the case of Orecon's OWC, the rated power is 1000kW and the capacity factor considered is 50% with life of 20 years. (Mirco, Bedard and Hagerman 2004). Thus, based on the above data its annual power production would be 4.38GWh and life time power production =87.6GWh.

LCA & EA studies of the above WECs are thereby estimated, from the above premise of their life time power generation data, and covered in the subsequent section.

4.3 Life Cycle Analysis (LCA) of wave energy converter (WEC) schemes

The Danish model of LCA estimation used for wind energy systems (Schleisner 2000), was adopted for determining the emission characteristics of the construction of the WECs, as per ISO 14040 with LCA boundary conditions of 'cradle to site'. The results obtained as regards the CO_2 emission in particular, were corroborated by Bath University data (Hammond and Jones 2008), for checking the degree of discrepancy of results (if any), since LCA has been known to be process specific and country specific (Blengini 2008).

The Danish model of the emission of different gases as well as of the Bath University data of CO_2 emission, in kg/kg of inventory materials concerned, are shown below in table 4.6 & 4.7, respectively.

Table 4.6 Emissions in kg/kg of the construction materials as per the Danish model of LCA (Schleisner 2000),

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Table 4.7 Bath data source giving CO2 emission in kg/kg of inventory materials (Hammond and Jones 2008)

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As regards the availability of inventory data of respective WECs, a complete inventory of materials could be available for a 7 MW Wave Dragon, from personal communication with the organization concerned (Russell 2007). In the case of Pelamis, inventory data of construction materials, like steel and copper, were also availed from personal communication with the concerned manufacturing organization (Taylor 2007). Studies in the cases of Wave Bob and Orecon's OWC, were carried out with approximated presumptions considering steel to be the main component and thus provide only a part picture of LCA for the latter two WECs.

Based on the above premise of data generation etc, detailed studies of LCA & EA could be made for the above stated 4 WECs and have been covered in subsequent sections.

4.3.1 Emission from manufacture of 7MW Wave Dragon (WD)

The Wave Dragon studied was a 7MW unit producing an annual power generation of 20 GWh and a life time power generation of 1000 GWh, as detailed in section 4.2.3, Sl. No 1. The inventory materials with their mass, provided by personal communication with concerned manufacturer, is given below in table 4.8

Table 4.8 Inventory data of 7MW Wave Dragon (Russell 2007).

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The Danish model of the emission of different gases in kg/kg from the inventory materials concerned, as determined from computation of tables 4.6 and 4.8, are shown below in table 4.9.

CO_2 emission of inventory materials, as per the Bath data, determined from computation of tables 4.7 and 4.8, are also shown below in table 4.10

Table 4.9 Life time emission of pollutant gases from 7MW WD, as per Danish model

Materials Concerned *	CO_2 (kg)	NO_x (kg)	N_2O(kg)	CH4(kg)	SO_2 (kg)
Steel / Stainless Steel	1275494.50	5253.50	38.71	22.12	8018.50
Aluminum	82747.35	313.30	2.53	1.56	506.10
Copper	452944.80	1607.07	13.17	11.09	2467.77
Plastics	98184.02	330.85	2.84	2.52	465.21
Iron	376544.88	1074.988	10.88	7.25	1763.01
Concrete &Cement	25941780.00	77670	0	0	310.68
Grand Total	28227695.55	86249.70	68.13	44.55	13531.28

It would be obvious from the emission values of gases, as estimated in table 4.9, that it is the CO_2 emission which plays a dominant role, with very little contribution from other gases. It also follows from table 4.9, that life time emission of gases expressed in g/kWh from the WD unit would be as below.

- CO_2 emission = total emission of CO_2/ life time power generation
    = 28.23 g/kWh, Accordingly,
- NOx= 0.086 g/kWh
- N_2 O= 0.00006 g/kWh
- CH_4 = 0.00004 g/kWh
- SO_2 = 0.013 g/kWh

Total GHG potential from the combined effect of the emission from all these gases, could then be estimated taking into account their individual global warming potential values (GWP), and making necessary computation thereof. Since, GWP values for CO_2, N_2O & CH_4, are 1, 310 & 21 respectively, the GWP contribution for each of the GHG, would be as below:

- CO_2=28.23 g/kWh [GWP =1]
- N_2O = 0.019 g/kWh [GWP=310]
- CH_4 = 0.0009g/kWh [GWP=21]
- Total GWP or CO_2 equivalent of GHG (combined effect of all these gases) =28.25 g/kWh

Thus, it could be observed that it is mainly CO_2 emission, which plays a dominant role in determining the global warming potential accrued from the concerned WEC. Since LCA is process specific and country specific (Blengini 2008), and also CO_2 being considered mainly responsible for global warming from GHG emissions;   it was considered useful to recheck the emissions of CO_2 from other data sources, such as the Bath university data. This could be determined from computation of table 4.7 and table 4.8, the results of which are shown below in table 4.10.

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Table 4.10 CO_2 Emission of 7MW WD estimated from Bath University data source

Inventory materials	Steel	Copper	Iron	Concrete	Plastics	Aluminium	Grand Total
CO_2 in kg	1564990	207900	230957.2	29514600	79796.2	199066	31797309.4

Thus, based from Bath University data source of LCA, emission of CO_2
= Total CO_2 emission from table 4.10 / life time power generation of WD
= 31.79 g/kWh; by and large conforming to the Danish model's result
= 28.23 g/kWh.

If the life expectancy period of the Wave Dragon is considered to be 20 years, like the other WECs, then the WD's life time power production would be=400 GWh, as shown in section 4.2.3, Sl. No 1. In that case CO_2 emission values would increase by nearly 2.5 times, as given below:
As per Danish model: CO_2 emission = 70.57 g/kWh (20 years life considered)
As per Bath data: CO_2 emission = 79.47 g/kWh (20 years life considered)

4.3.2 Emission from 750kW Pelamis

The distribution of the mass of inventory materials of 750 kW Pelamis unit, was learnt to be broadly constituting of steel: 380,000 kg & Copper: 15000kg (Taylor 2006).

As regards its life time power generation values are different depending on deployment sites, as already discussed in section 4.2.1 and section 4.2.3, Sl No 2. Its life time (20 years life), power production was noted to be of 50 GWh and 25 GWh, from deployment on the coasts of Ireland and Portugal respectively.

Based on the above power production and inventory data of Pelamis, its life time emission characteristics for different gases, as estimated following the Danish model of LCA as per table 4.6, as well as of CO_2 emission from the Bath data, estimated from table 4.7, are shown below in table 4.11.

Table 4.11 Emission characteristics of 750kW Pelamis

Emission of gases, Danish model	Grand Total (kg)	g/kWh for deployment Ireland coast	g/kWh for deployment Portugal coast
CO_2	974510	**19.49**	**38.98**
NOx	3957.85	0.079	0.158
N_2O	29.35	0.0006	0.0012
CH4	17.6	0.0003	0.0006
SO_2	6044.15	0.12	0.24
GHG gas eqv.		**19.68**	**39.37**

It would be obvious from table 4.11, that only the CO_2 emission plays a dominant role in determining the global warming potential accrued from the concerned WEC.

Similar observations were noted for the Wave Dragon as well. Also, the annual power generation is an important criterion in deciding the life time emission.

The results obtained from the Danish model and the Bath data, fairly tallied with each other. However, studies from Parker et al showed values of CO_2 emission to be 22.8g/kWh (Parker *et al.* 2007), which conformed to the results pertaining to the deployment site in Ireland, and does not tally with the results for coast of Portugal deployment site. The latter does not seem to have an optimum wave density range for the functioning of Pelamis (Dalton *et al.* 2010).

4.**3.3 Emission from 1000kW Wave Bob**

The structural weight of this 1000 kW point absorber type WEC is said to be 440 tonnes, mainly made of steel (Mirco, Bedard and Hagerman 2004). Based on the above premise of inventory data (though incomplete), the emission of gases as estimated for the Danish Model from computation of table 4.6, and of CO_2 for the Bath data from computation of table 4.7, could be estimated. The results are shown below in table 4.12. Emission in g/kWh for both the Danish model and the Bath data could also be determined considering its life time power generation to be 70 GWh, as per discussions shown in 4.2.3 Sl No 3. The results including GWP equivalent of GHGs could also be determined as shown in table 4.12 given below.

Table 4.12 Emission characteristics of 1000kW Wave Bob

Emission of gases Danish model	CO_2	NOx	N_2O	CH_4	SO_2	CO_2 equivalent GHGs	CO_2 as per Bath data
Total amount in kg	1014860	4180	30.8	17.6	6380		1245200
Emission in g/kWh	**14.49**	0.06	0.0004	0.0002	0.091	14.61	**17.79**

Very low value of CO_2, like 14.49 g/kWh from the Danish model and 17.79 g/kWh from the Bath University data source, can be attributed not just to the non-availability of complete inventory data of the device but also to its production of appreciable power in proportion to its structural weight.

4.3.4 Emission from 1000 KW Orecon's OWC

The structural weight of the 1000 kW OWC, is said to be of 1250 tonnes (Mirco, Bedard and Hagerman 2004), and mainly made of steel. Based on the above premise of inventory data (though incomplete), the emission of gases as estimated for the Danish Model from computation of table 4.6, and of the CO_2 for the Bath data from computation of table 4.7, could be estimated. The results are shown below in table 4.13. Emission in g/kWh for both the Danish model and the Bath data could also be determined considering its life time power generation to be 87.6 GWh, as per discussions shown in 4.2.3 Sl No 4. The results including GWP equivalent of GHGs could also be determined, as shown in the above table given below.

Table 4.13 Emission characteristics of 1000kW Orecon OWC

Emission of gases Danish model	CO_2	NOx	N_2O	CH_4	SO_2	CO_2 equivalent GHGs	CO_2 as per Bath data
Total amount in kg	2883125	11875	87.5	50	18125		3537500
Emission in g/kWh	32.91	0.135	0.0009	0.0006	0.207	33.20	40.38

It may be added that a little variation between the Bath University data and the Danish data, as regards CO_2 emission, is because of the non-availability of a complete inventory data for the WEC unit, which for Pelamis and Wave Dragon shows better conformity for better availability of their inventory data.

4.3.5 Comparative studies of emission of WEC's

It is evident that emission of CO_2 is dominant in the entire life cycle of the entire above stated wave energy converters. Their respective emissions of CO_2 and other gases are compared in the following figures 4.6- 4.9, shown below.
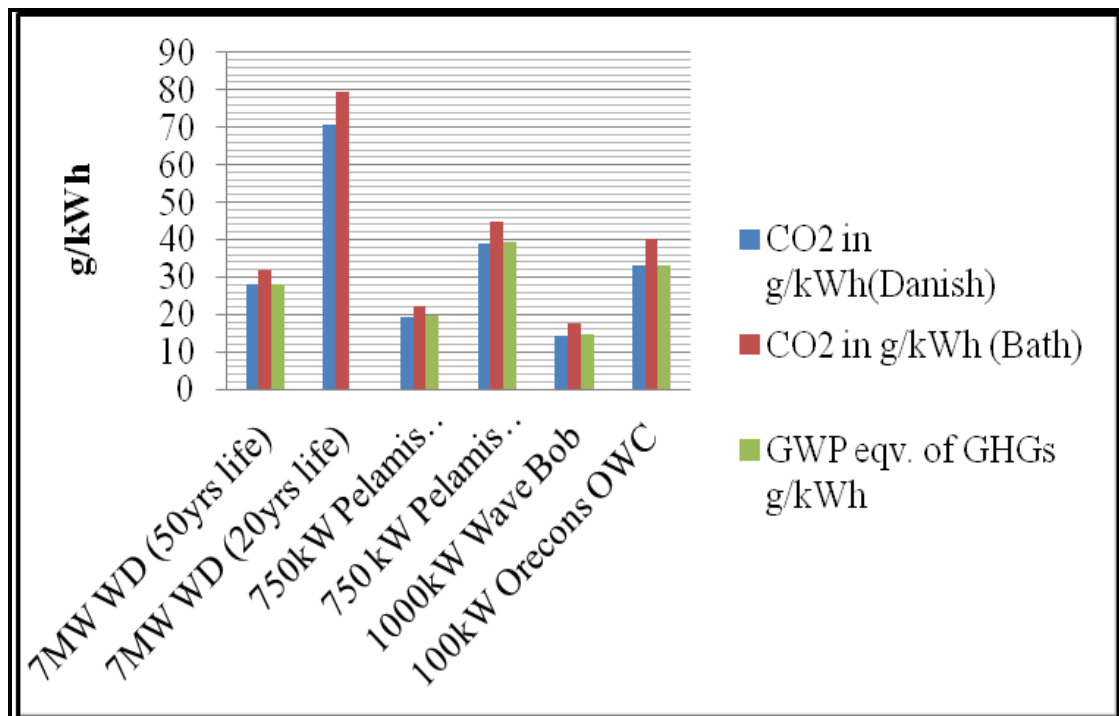
Fig. 4.6 CO_2 emission characteristics of WECs compared at varied conditions
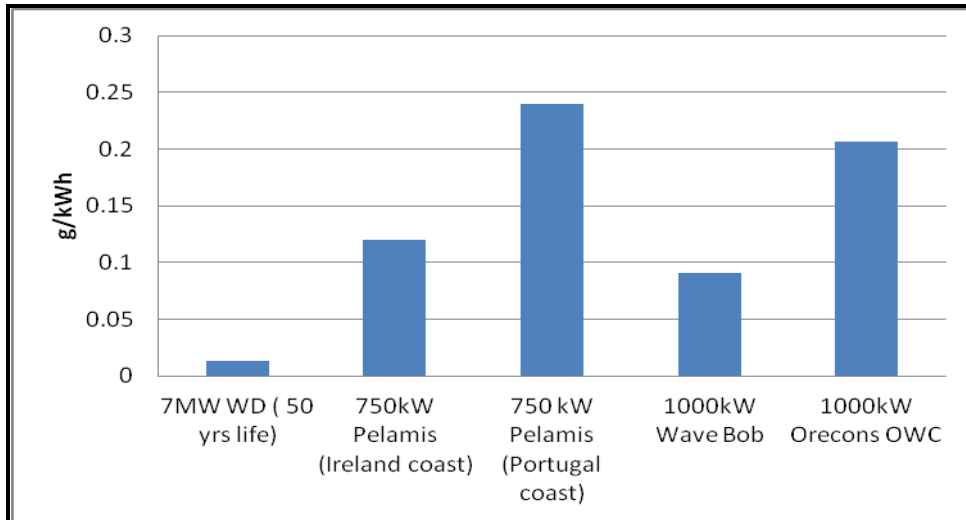
Fig. 4.7 Compared SO$_2$ emission of WECs under varied conditions
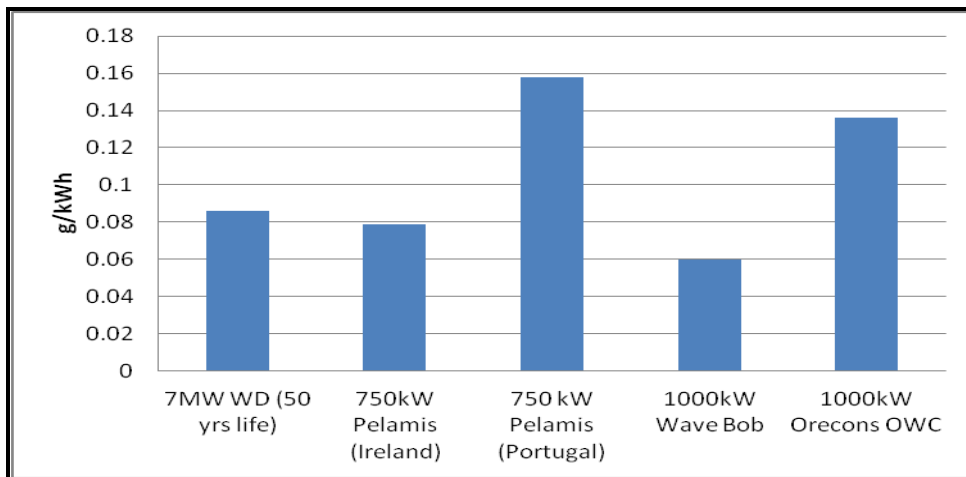
Fig. 4.8 Compared Oxides of N$_2$ in g/kWh of WECs at varied conditions
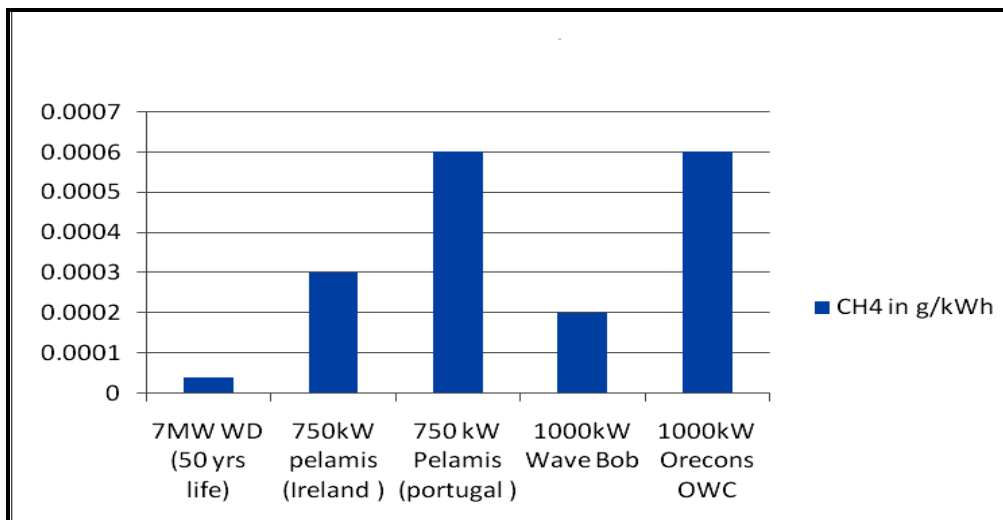
Fig.4.9 Compared CH$_4$ emission of WECs at varied conditions

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4.3.6 Comparative studies with coal fired power station

4.3.6.1 Indices on CO_2 emission saving

In order to assess the advantage gained in CO_2 emission from the use of the respective WECs, it would be of interest to determine the percentage of CO_2 saved, considering its emission from a coal fired power station producing equivalent power to be of 100 percent. The relationship on saving of CO_2 compared to coal power is:

CO_2 % saved = 100- $(W_e/C_e)*100$; ………………………………… [4.3]
where; C_e denotes emission of CO_2 in g/kWh from a typical coal power plant, whereas W_e gives the CO_2 emission in g/kWh, from LCA of the concerned WEC.

The other assessment index of the CO_2 saving could be the CO_2 payback period of the WECs concerned, expressed in years. This is measured in years required for the WEC unit concerned to pay back its entire life time emission of CO_2, as compared to the coal fired power stations emission for production of annual power of the WEC concerned. Thus the **CO_2 payback period [CPBP]= $(L*W_e*P_a)/(P_a*C_e)$**.......... [4.4]

where Pa is annual power production of the WEC concerned with its life period L; and C_e & W_e have their usual values, like emission of CO_2 in g/kWh, for Coal power and WEC concerned, respectively.

Amongst the above two indices shown in equations [4.3] & [4.4], for studies on the gain in CO_2 emission achievable from WECs, only the Ce value is required to be determined. The other values, like W_e, P_a, L, could be availed for different WECs as detailed in previous sections of LCA studies. C_e estimation giving average emissions from coal power has been discussed in the following section.

4.3.6.2 Emission characteristics from coal power station.

Based from LCA studies of coal power plants emission characteristics, undertaken as part of study of UK carbon capture and storage consortium's (UKCCSC), it could be inferred that emission of CO_2 from a typical coal power station amounts to 900g/kWh (Odeh and Cockerill 2008). It has also been commented that the value tallies well with previous studies on the same.

It could also be noted that the Drax coal power station, uses bio fuel with coal to lower CO_2 emissions by 10% (British Bio Energy news 2010). Despite such measures, the Drax power plant is known to emit 20.5 Mt CO_2 while generating 24.5 TWh power (Adams *et al*. 2008). This value amounts to CO_2 emission value of 836.7g/kWh power generation from Drax coal power plant.

On the other side, a CO_2 emission value of 500MW from a coal plant with a capacity factor of 85%, in its performance on super critical and ultra super critical operations are: 830 g/kWe-h and 738 g/kWeh, respectively (Booras and Holt 2004; Beer 2009).

Considering the average of all the above values (like 900, 836.7, 830 and 738) of CO_2 emission expressed in g/kWh, the value **826.17 g/kWh is obtained**. This average CO_2 emission value is therefore considered to be the representative value of

coal power plants, for estimating the advantage gained as regards emission of CO_2 from WECs and other OE devices.

4.3.6.3 Percentage of CO_2 saving and carbon payback period of WECs

The above average and representative value of CO_2 emissions of 826.17g/kWh, may be considered to be 100% emission from a typical coal plant giving the value of C_e of equations [1] &[2], given in section 4.3.6.1. The percentage of CO_2 saved, as well as carbon payback period (CPBP) from respective WECs, as per the Danish model and also from the Bath data source could be compared, from the above value of C_e as well as of values W_e, L and P_a, (estimated for WECs in previous sections), from equations [1] & [2] given in section 4.3.6.1. Thus, the percentage of CO_2 emissions saved and also the carbon payback period could be determined for respective WECs. The results are shown in table 4.14 & figures 4.10 and 4.11, shown below.

Table 4.14 Percentage CO2 saved compared to coal plant & CPBP of WECs

WEC	7MW WD (50 yrs life)	7MW WD (20 yrs life)	750 kW Pelamis (Ireland)	750kW Pelamis (Portugal)	1000 kW Wave Bob	1000kW Orecons OWC
We g/kWh (Danish)	28.23	70.57	19.49	38.98	14.49	32.91
We g/kWh (Bath)	32.79	79.47	22.41	44.82	17.79	40.38
Pa in kWh	$20*10^6$	$20*10^6$	$25*10^6$	$1.25*10^6$	$3.5*10^6$	$4.38*10^6$
L (life yrs)	50	20	20	20	20	20
%CO_2 saved (Danish)	96.58	91.45	97.64	95.28	98.24	96.01
% CO_2 saved (Bath)	96.15	90.38	97.28	94.57	97.84	95.11
CPBP yrs (Danish)	1.71	1.71	0.47	0.94	0.35	0.79
CPBP yrs (Bath)	1.92	1.92	0.54	1.08	0.43	0.97
Ce= 826.17 g/kWh	826.17	826.17	826.17	826.17	826.17	826.17
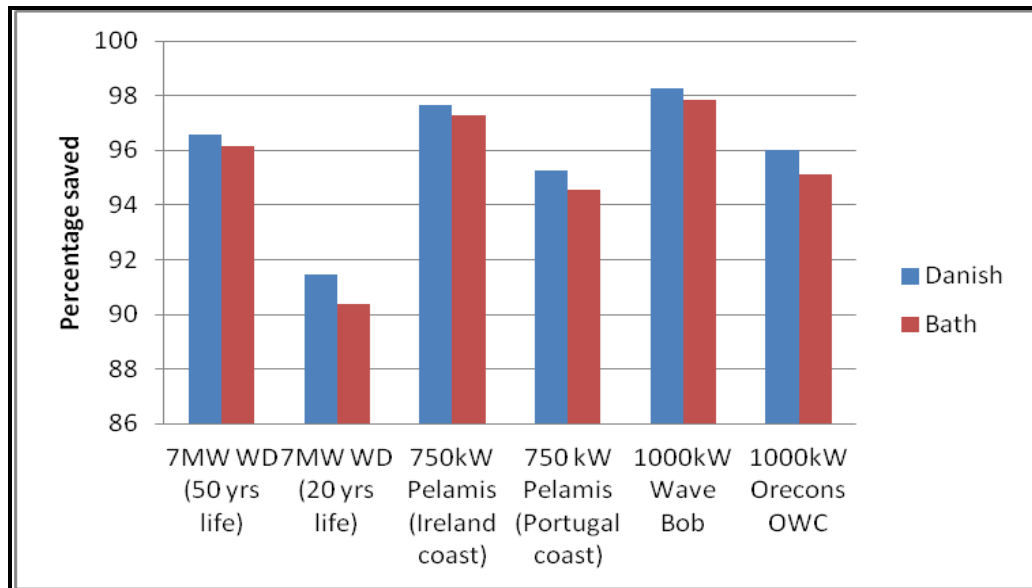
Fig. 4.10 Percent CO_2 saved from WECs compared to coal plant
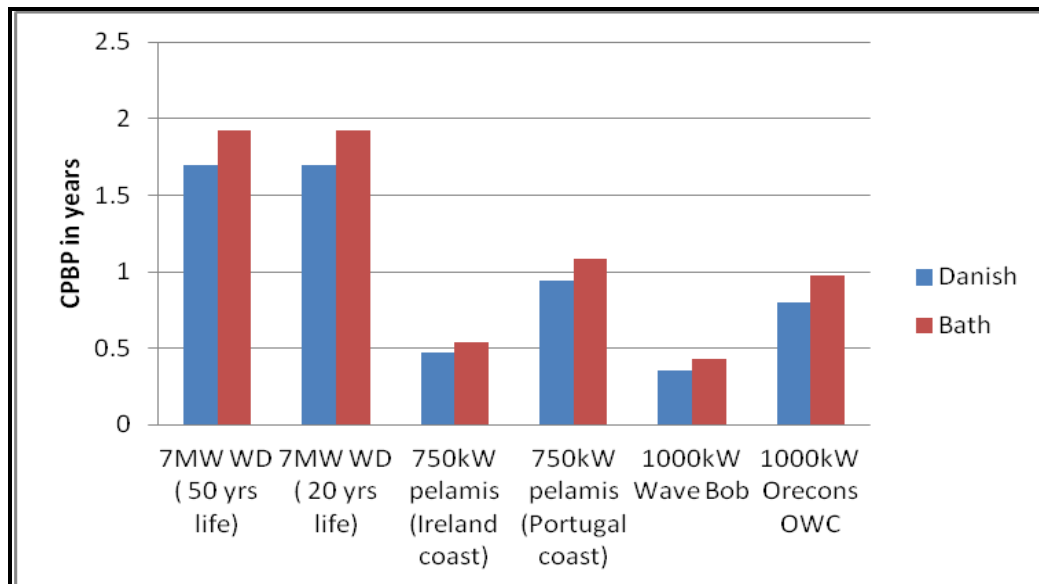
Fig. 4.11 Carbon payback period from both Danish model & Bath data of WECs.

4.3.6.4 Emission of acid gas like SO_2 saved for WECs

The above stated figures compare CO_2 saving aspects of WECs, in comparison to that from the coal fired power station. Likewise the percentage saving as regards emission of acid gas such as SO_2 can also be determined. In fact, coal fired power stations are said to produce 7.8g/kWh SO_2 (Sorensen *et al*. 2003). Considering this emission from coal fired power stations to be of 100%, SO_2 emission saving percentage from WECs would be $= 100 - (W_s/7.8)*100$. The result determined from this equation comparing SO_2 emission savings from WECs, as compared to coal power, is shown below in table 4.15 & Fig.4.12.

Percentage of SO$_2$ saved.

Table 4.15 Percentage of SO$_2$ emission saved compared to coal power station.

WEC type	7MW WD (50 yrs life)	750kW Pelamis (Ireland Coast)	750kW Pelamis (Portugal Coast)	1000kW Wave BOB	1000kW Orecon OWC
SO$_2$ in g/kWh	0.013	0.12	0.24	0.091	0.207
Percent SO$_2$saved	99.83	98.46	96.92	98.83	97.38
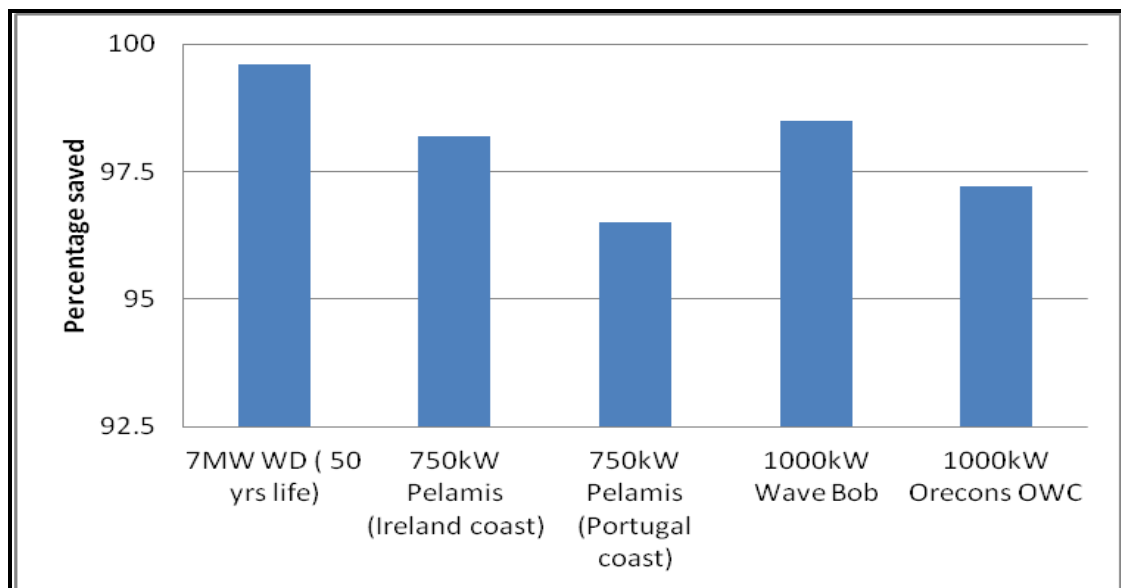
Fig.4.12 SO$_2$ percent saved for WECs in comparison to coal power

4.3.7 Critical appraisal of data giving limitations

It is evident from the above tables and figures, that CO$_2$ emission is predominant compared to other gases in the entire life cycle of the wave energy converters, case studies of which have been undertaken with 7MW Wave Dragon of 50 year life, 7MW WD with 20 year life, 750kW Pelamis for deployment on the coast of Ireland, 750kW Pelamis for deployment on the coast of Portugal, 1000kW Wave Bob and 1000kW Orecon's off-shore OWC. The life time emission of GHGs, as well as of acid gas emissions, like SO$_2$ had also been determined availing inventory data and power production data for respective WECs.

The limitation of LCA is that it is country specific and process specific. Hence to address this limitation, data sources for estimating inventory materials emission were studied from two sources, the Danish model and Bath data source. The results of both, by and large conform to each other, though the Bath results showed a rather higher value than that of the Danish model.

In order to estimate the advantage gained in emission characteristics, made from LCA studies of WECs, comparisons were made with emission from an average coal power station, including those with operations of ultra critical and super critical boilers. The two indices used for the above comparison were carbon payback period (CPBP) and percentage of emission saved compared to coal power, considering coal power's emission to be of hundred percent. The results showed more than 90% emission saving with a payback period of less than 2 years, though the values depended on power generation and inventory data of respective WECs.

It would be of interest to note that the value of CPBP for WD with a 50 year life was found to be the same as that of 20 years, though emissions of the latter was 2.5 times more than the former, for obvious reasons. However, the index on emission percentage saving did not have such anomalous result and conformed exactly to the emission results as expressed in g/kWh. Thus, the latter index giving a percentage saving is considered a better guide than the former CPBP.

The other important point to note is that the impact on global warming from the emission of CO_2 is global and permanent (though small for WECs with almost none during operation and maintenance stage compared to fossil fuels). But the emission from acid gas like, SO_2, responsible for acid rains etc, is just local and temporary not effecting permanent changes, unlike CO_2. However, WECs showed more than 95% saving on SO_2 emission as well, compared to coal power plant.

In addition to the estimations on the emission of gases from LCA, it is also considered relevant to compare their energy accounting scenarios for assessing their relative advantages.

4.4 Energy Accounting

Energy accounting aims to determine the amount of energy that would be required to manufacture the product, calculated from the energy it can produce in a year. It would enable us to know in how many years the total energy required to manufacture the product can be recovered. Thus energy payback period (EPBP) is estimated from the relationship: EPBP $=\sum$ Ei*Mi/Pa; 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.

Since EPBP is dependent on annual energy production only (not life time production); hence the following WECs were only considered (not considered life period variations of WD) for undertaking case studies, as shown below:

- 7MW WD,
- 750kW, Pelamis for deployment in Ireland coast,
- 750kW Pelamis for deployment in Portugal coast,
- 1000kW Wave Bob
- 1000kW Orecon's OWC.

Obviously the lower the value of EPBP the better. The data used as regards embodied energy of the inventory materials for respective converters were based on the Danish model as well as from the Bath University data source, as had been

carried out for LCA studies on emission characteristic determinations, with boundary conditions of 'cradle to site' as per ISO 14040. These values of the embodied energy for construction materials of different WECs' are shown below in table 4.16.

Table 4.16 The energy requirement in MJ / kg of the inventory materials of the WECs

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 Univ. data (Hammond and Jones 2008).

4.4.1 Energy payback period of 7MW Wave Dragon

It has already been shown in section 4.2.3 Sl No.1 that the annual power production of 7MW Wave Dragon would be = 20 GWh .

The total energy requirement for constructing the above Wave Dragon, as determined from the above two models, from computation of table 4.8 & table 4.16, are shown below in table 4.17

Table 4.17 Energy requirement for constructing 7MW wave Dragon [as per ISO 14040]

Constituent materials	Steel	Aluminium	Copper	Plastic	Iron	Concrete	Grand Total
Total Embodied Energy MJ (Danish Model)	14184450	943515	5419260	1441378	4389396	114330240	126523789
Total Embodied Energy MJ (Bath University)	14046200	.821810	4851000	1441378	3023000	93514680	113332168

Thus EPBP, as per Danish model = 126523789MJ / 20 GWh = 1.75 years
EPBP as per Bath data source   = 113332168MJ/ 20 GWh = 1.57 years

4.4.2 Energy payback period of 750 kW Pelamis

It has already been shown in section 4.2.3, Sl No.2 that the annual power production of Pelamis for deployment in Ireland is 2.5 GWh, and for Portugal it is 1.25 GWh.

Based from the computation on mass of inventory materials of Pelamis (section 4.3.2), and embodied energy values of these materials as per table 4.16, the total energy requirement for construction of Pelamis as determined for the Danish model as well as of the Bath University data source, are shown below in table-4.18.

Table 4.18 Energy requirement for constructing 750kW Pelamis [as per ISO 14040]

Construction materials	Steel	Copper	Grand Total
Total embodied energy –MJ – as per Danish model	9747000	1173000	10920000
Total embodied energy –MJ- as per Bath University data	9652000	1050000	10702000

EPBP for Pelamis, for deployment sites on the coast of Ireland and the coast of Portugal st, could thereafter be determined from table 4.18 and their respective annual power production data. The results determined on the above for both the Danish Model and Bath data are shown below.

EPBP for deployment at Ireland site

EPBP as per Danish model = 10920000MJ/2.5GWh = 1.21 year
EPBP as per Bath data   = 10702000MJ/2.5GWh = 1.18 year

EPBP for deployment at Portugal site

EPBP as per Danish model = 10920000MJ/1.25GWh = 2.42 year
EPBP as per Bath   data   = 10702000MJ/1.25GWh = 2.36 year

4.4**.3 Energy pay Back Period of 1000 kW Wave Bob**

It has been shown from section 4.2.3 Sl No 3, that annual power production of the Wave Bob is 3.5 GWH. Its energy payback period determined for both the Danish model and the Bath University data source, following the above methodology are shown below in table 4.19.

Table-4.19. Energy Payback Period of Wave Bob

Data Source	Mass of construction material -Steel in kg	Energy for construction of Wave Bob in MJ, as per table 4.16(a)	Energy payback period = (a) / 3.5GWh
Danish model	440000	11286000	0.89 years
Bath Data	440000	11176000	0.88years

4.4 Energy Payback period of Orecon's off-shore OWC

The annual power production of the unit is shown in section 4.2 Sl No.4, to be 4.38 GWh. Thus following the above methodology, the energy payback period of the 1250000 kg WEC could be determined, and is shown below in table 4.20.

Table 4.20 Energy payback period of Orecon's OWC

Data Source	Mass of construction Material –steel in kg	Energy for construction of Orecon OWC in MJ, as per table 4.16 [a]	Energy Pay Back Period =[a]/ 4.38GWh
Danish model	1250000	32062500	2.03 years
Bath. Data	1250000	31750000	2.01 years

4.4.5 Comparative studies on Energy payback period

EPBP of the WECs studied both from the Danish model as well as from the Bath University data source, with their respective data as regards embodied energy values of construction materials for respective WECs, is compared in fig.4.13 shown below.
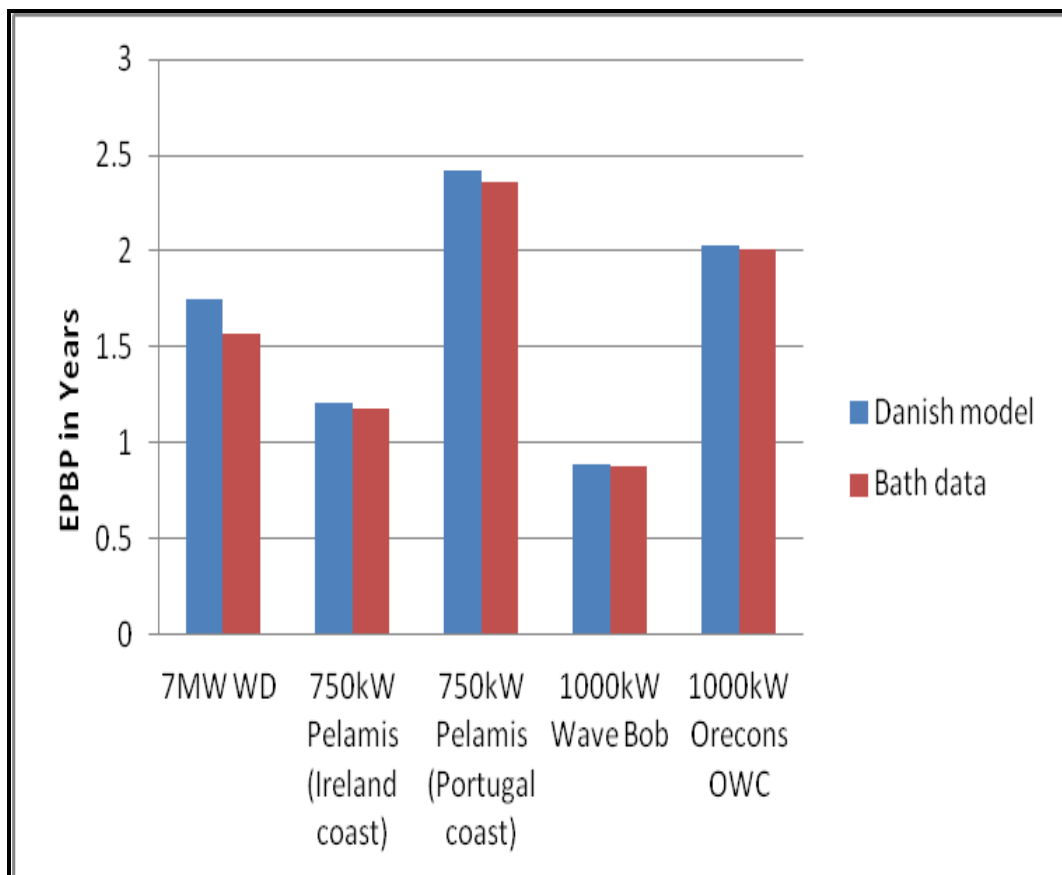
Fig. 4.13 Compared energy payback period (yrs) for WECs with Danish model & Bath data

It could be observed from the above figures that both the Danish model as well as the Bath data results conform well to each other, but the Danish model shows slightly higher values which is because of the fact that embodied energy in kg/kg of steel (main constituent of inventory materials) for the Danish model is higher than the Bath University data, as shown in table 4.16. The results indicate that the EPBP value for all the WECs is small compared to their generating life expectancy.

4.5 Environmental Impact Assessment for wave schemes

In addition to the above stated assessment as regards emission characteristics of WECs from LCA studies, it is equally important to examine the other environmental issues as well such as the effects on flora and fauna, inherent hazards posed with mitigating measures, and also the overall societal impact that may be accrued from the large scale deployment of wave farms. In fact, the integrated EIA model as developed and shown in chapter 3, identifying the four broad environmental issues as well as the impacting parameters influencing them for OE systems, could be successfully applied for the assessment of WECs. It included development of the methodology for the qualitative and quantitative rating of each environmental issue, including guidelines on hazards mitigation measures.

It has already been stated in the above Integrated EIA model, that the nature of the influence of impacting parameters would decide the qualitative aspect with assignment of positive values if it favours sustainable development, whereas negative on annulling it. Accordingly, if the emission characteristics of WECs is expressed as a percentage of saving (>90% observed) compared to coal, it should be assigned positive values. If however, it is expressed as the emission in g/kWh only, then it should be assigned negative values, though very small for WECs compared to coal power. In the case of environmental issues like emission characteristics (both for CO_2 and SO_2), accurate values giving a quantitative rating, both as regards percentage saved or amount emitted, can be assigned as per data derived from LCA studies.

But in the case of the other three environmental issues (Flora & Fauna, hazards posed and societal issues), the exact rating cannot be made due to a lack of OE systems being used for large scale application with non-availability of quantitative data for the same reason.

However, knowing the degree of impact (caused over the environmental issues) would enable us to decide to a reasonable degree the quantitative character of the environmental issues being affected. This could be arrived at from the logical development of the topic. Thus, a rather subjective rating like, high, moderate or low values, could be assigned to the environmental issues that is affected, as highlighted in chapter 3 (section 3.8).

Thus, in case of; flora and fauna of wave schemes, noise during construction period, electromagnetic radiation from cables laid for power transmission, sedimentation caused from mooring etc, as well as choice of construction period avoiding sensitive periods and site selection away from the habitat of species could be the impact

parameters influencing flora and fauna of the oceans. Taking adequate efforts of minimizing their impact for constructing WECs might minimize the negative impact on flora and fauna, reducing its negative effect from moderate to near zero level or to very low/. It is to be noted that all the above parameters have some negative effect, though it may be minimized to quite a low level. It may be relevant to point out that similar observations were made by Zabihian & Fung ((2011), opining WECs to cause 'minimal negative effects' over marine species.

The risks to marine species from operational stage of WECS could originate from:

- Collision of moving parts if any, affecting fish and/or sea mammals;
- Scope of reduction of wave density and ocean current from power capture by the wave farm (though small), and thus affecting species including planktons (Chichao & Chicharo 2001),
- Pollution of water from dissolution of corrosion proof paints of WECs (though not appreciable), as also from accidental leakages of hydraulic fluids which could be detrimental to marine species growth, though their degree is minor.

Apart from the negative input from all these impact parameters, there are some positive impacts as well for species growth, though to a small extent. The blanket ban of fishing trawlers approaching wave farms is likely to facilitate the growth of fish populations and other species. In addition, certain devices like WD in its huge reservoir may facilitate species growth. In addition certain WECs may also facilitate species growth acting as an artificial reef (Margheritini *et al.* 2011).

Qualitative and quantitative assessment on scope of species growth from the deployment WEC farms was undertaken, keeping the above considerations in view. A range of values are assigned as regards the qualitative and quantitative character of flora & fauna, since they are dependent on the type of WECs, site of deployment (land based or off-shore), mode of construction and also on operational aspects. The overall results as per above considerations, have been shown below in table 4.21.

Table-4.21 Impact on Flora and Fauna of Wave schemes*

Construction stage	Birds	Fishes	Sea Mammals	Benthos	Planktons
Sensitive period & habitat	M(-) To L(-)	M(-) To L(-)	M(-) To L(-)	L(-)	L(-)
Sensitive period & non-habitat	M(-) To L(-)	M(-) to L(-)	L(-)	L(-)	L(-)
Non-sensitive period & habitat	M(-) To L(-)	M(-) To L(-)	L(-)	L(-)	L(-)
Non-sensitive period & non-habitat	L(-) to 0	L(-) to 0	L(-) to 0	L(-) to 0	L(-) to 0
EMR effect-- exposed cables	L(-)	L(-)	L(-)	M(-) To L(-)	L(-)
EMR effect-- buried cables	0	0	0	0	0
Sedimentation	L- to 0	L(-) to 0	L(-) to 0	M(-) to L(-)	L-
Exposed moving parts	L(-) to 0	0	L(-)	0	0
Netted moving parts	0	0	0	0	0
Operational stage	L (-)	L(-) to L(+)	0	0	0
Decommissioning stage	L(-)	L(-) to L(+)	L(-)	M(-) to 0	L(-) to 0

* L(-) low negative score, M(-) =moderately negative score; L(+) =low positive score;
0= no effect; as per the nomenclature discussed in chapter 3.

It would be clear from the above table that oceans flora and fauna would have negligible negative effect from deployment of wave farms; if its construction is made avoiding the usual habitat and sensitive periods of marine species, the cable lines are kept buried below the sea-bed and moving parts of WECS are netted/sheathed (to avoid collision). Rather, there may be some possibility of a positive effect on fish population (fishing trawlers being non-approachable in the vicinity) which also depends on the design type of WEC (favoured for WD); though such positive effects, if any at all are marginal and localized.

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It is also needed that adequate maintenance, minimizing leakages of hydraulic fluid and other necessary precautionary measures against probable hazards, are adhered to. The mitigating measures against probable hazards, as may be experienced from deployment of WEC farms, are given in table 4.22. The assigned score values of the table indicates only the probability on accidental failures, despite taking action to the preventive measures (set elements of set B, as per Integrated EIA model).

Table 4.22 Hazards posed from WEC deployment with mitigating measures *

Environmental Issues (subset elements of Set A)	Impact parameters / mitigating measures (subset elements of set B)	Scores	Remarks
Risks from collision with oil liners etc	a) adequate audio visual signaling system installation b) avoidance of navigation routes at deployment site	L(-)	Accidental Risks despite the measures
Malfunctioning of WECs deployed	a) accumulation of sea weeds and deposits b) accidental failure of parts of WECs c) maintenance work to take care of causes of malfunctioning including above hazards.	M(-) to L(-)	Score depends on the deployment site and also of the degree of vigil with maintenance work to annul the hazards.
Accidental oil spillages (hydraulic fluids) and polluting water	Keeping vigil with adequate maintenance	L(-)	Accidental failure despite Maintenance.
Affecting the coast line	Resource capture from WECs, with reduction in wave density reaching the shore.	L(-) to 0	Negligible effect for off-shore devices, a little higher for shoreline ones.
Survivability of WECs	a) making WECs robust enough b)Prior on sea trial runs before commissioning c) maintaining adequate safety factor	L(-)	Affected only from Tsunamis/ Future global warming with Increased wave density.
collision of floating parts from incomplete decommissioning	Adequate vigil against such eventuality	L (-)	Almost negligible if adequate vigil is maintained.

*M(-) = moderately negative; L(-)= low negative- as per nomenclature of Chapter 3.

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It may be reiterated that the score values, mostly low to very low, are only from accidental failures, despite adoption of the suggested mitigating measures.

In table 4.23, giving societal issues, a range of score values are assigned. Obviously the degree of influence would be dependent on the deployment of the concerned site (whether avoided heritage etc sites for deployment or not), local needs, as well as the amount of power generated, besides the degree of influence over the local economy. The table gives a guideline as regards quantitative assessment over societal impacts that also indicate the scope of improvement in quality of life in the concerned zone.

Based on the above premise, EIA scoring for wave schemes on societal issues, deciding the scope of improvement in quality of life, is given below in table 4.23

Table 4.23 Societal Impact signifying influence over the quality of life*

Environmental Issues(subset elements of Set A)	Impact Parameters (subset elements of set B)	Scores*	Remarks
Tourist economy	a)Visual impact b) Operational noise>65dB	M(-) To L(-)	Scores depend on degree of impact from (a) or(b) for on shore/shore line device; but marginal for off-shore ones
Social acceptance	a) Opposition, if any from fishing community b) Sites in naval exercise, heritage sites	L(-) to L(+)	Scores depends on the dialogues between local authorities and power production companies; which may be both positive or negative; but would have low values for both
Local economy	Scope of power production	M(+) To L(+)	It would always have positive inputs; values vary depending on the amount of power availability & cost involvement

*M(-)=moderate negative; M(+)=moderate positive; L(-) =low negative; L(+)=low positive-as per EIA score nomenclature discussed in Chapter 3.

4.5.1 Critical appraisal

The above studies on the environmental impact assessment (EIA) indicates that by and large wave energy converters do not have an appreciable adversary effect on the environment in its operation, provided adequate precautionary measures as suggested above are undertaken. But, the impact on the flora and fauna during the construction and disposal phase of wave energy converters cannot be ignored, which invites special attention as regards the choice of site for their deployment and period of commissioning [as well as for decommissioning].

The hazards can be minimized if adequate precautions like marking the off-shore WECs with lighting and. signal provisions are maintained with fool-proof round the clock functioning and also avoiding vulnerable sites for their deployment (navigational route avoidance; etc). Adequate maintenance against malfunctioning of equipment is also required to be followed. It may be relevant to add that power production always opens up the scope for improving upon the quality of life, however for social acceptance local community/Govt. is required to be taken into confidence while choosing deployment sites in order to derive maximum benefit.

A better quantitative evaluation on EIA would however emerge from data availability from large scale commercial application of wave schemes.

4.6 Evaluation of Economy of Wave Energy systems

In the last two to three decades considerable progress has been made in the technological field of wave energy systems. The UK government funded extensive research from the year 1974 to 1983 in Wave Energy Programmes. Department of Trade and Industry (DTI) continued to support many small programmes which led to the development of many designs of wave energy converters, like PS Frog, SEA Clam, Solo Duck, and shoreline OWCs etc. They showed a decreasing trend in the cost of electricity generation with passage of time, by improvements in designs and the technology adopted (Thorpe 1999). It was also noticed that by and large, off-shore designs are not only rich in resource potential but cost competitive as well (Thorpe 1999).

It is because of such benefits of the resource potential as well as cost aspects, off-shore WECs are the preferred choice for commercial application. But such off-shore WECs have to be robust enough to withstand the rough weather of the ocean, keeping this in view the rise in wave density climate with the passage of time, as discussed in section 4.2.2. This of course involves an additional cost input to the WECs. Thus, economic evaluation of WECs are imperative for developing designs with optimum cost input for attaining survivability in the lifetime period, as well as taking care of the economy.

The economic tools employed for such assessment are based on the net present value method of economy evaluation, and determined the following indices (detailed methodologies elucidated in appendix 2).

- Net present value of cost involved covering the operational costs in the entire life period.

- Net present value of energy generated in its life time.
- Cost of electricity generated per kWh power generation.
- Net cash generated annually.
- Simple payback period of capital invested.
- Percentage of the internal rate of return (IRR).
- Comparative studies of WECs from RPC (Relative Product Cost) ratios.

Case studies for the economic evaluations were undertaken in respect of the prospective WECs from the above indices include: WECs like 7MW Wave Dragon and 750 kW Pelamis. These case studies were performed at different discount rates from 5-20%, as well as considering different life time periods in order to assess their respective influence over the economies of scale of the concerned WECs.

Comparative studies on the economic benefits derived for the concerned WECs were also undertaken, from their respective of RPC ratios. The results are detailed in subsequent sections.

4.6.1 Case study with 7MW Wave Dragon

Capital cost (Cc) of the Wave Dragon has been reported to be £1740/kW (Friis-Madsen et al. 2006), leading to a capital cost involvement for 7MW WD to be of £1740*7000= £12,180,000. The annual energy production of this 7MW WD with its scheme of use on the coast of Wales is considered to be of 20GWh (Millar et al. 2007); and life of 50years (Tedd 2007). The operational & maintenance cost (Co) is considered to be 3% of the capital cost (Parkar et al. 2007)
 = £0.03 * 12,180,000=£365400.

Keeping in view this base data, the economic tools determined for economy evaluation of the 7MW WD could be computed as below, considering the discount rate of 8% , and with life period 50 years.

Capital cost 'Cc' = £ 12,180,000
O&M cost 'Co' = £0.03*12180000 =£365,400
Annual Energy Production =20,000,000 kWh
Discount factor (DF) at discount rate 8% with life of 50 years = 12.23348
(Vide appendix 2, for calculation aspects on discount factor (DF).

Net present value of total cost =£12180000+365400*12.23348 =£16650115.29
Net present value of energy   =20,000,000kWh*12.23348 =244669692.9kWh
Cost of electricity production =Present value of cost/Present value of energy
=**6.8p/kWh**
Net cash generated annually (Nc) =Annual electricity production*cost/kWh--Co
=£995,628.01
Simple Payback period of money invested
= (Cc+ Co)/(Annual Energy production*cost/kWh).
=9.22 years

Accordingly, the different economic evaluation tools on the above could be determined for different discount rates between 5 and 20%, with its claimed life period of 50 years. The results are tabulated below in table 4.24.

Table 4.24 Economic evaluation indices of WD with 50 years life period

Discount Rate %	NPV of cost involved [£]	NPV energy in kWh	Cost of in p/kWh	Simple pay back period (years)
5	18850715	365118509	5.1	12.1
8	16650115	244669692	6.8	9.21
10	15802873	198296289	7.9	7.8
12	15214463	166089969	9.1	6.8
15	14613752	133210293	10.9	5.7
20	14006799	99989011	14	4.5

It could be observed from the above table 4.24, that the cost of electricity/kWh for the Wave Dragon varies between 5 and 14 p/kWh with variation in discount rate from 5-20%, and 'simple payback period' varies between 5 and 12 years, considering its life period to be of 50 years. It was evident that cost/kWh increased, with increase in discount rate. Also SPBP decreased with an increase in cost/kWh.

In order to evaluate the effect of the life of a WEC over its economy, affecting the cost of electricity production, all the above stated economic indices were determined considering situations under different life periods and at different discount rates. The life of WD considered for such data generation was for 30 years, 20 years and 10 years. Discount rates were varied from 5-20%. The results are shown in tables 4.25-4.27. The data thus generated from the above tables, have also been depicted in figures 4.14- 4.15, for examining the nature of changes of cost/kWh caused from changes in discount rates and life periods.

All the above tables and figures are shown below.

Table 4.25- Economic evaluation indices of WD with 30 years life period

Discount percentage	NPV cost [£]	NPV Energy in kWh	Cost in p/kWh	SPBP years
5	17797093	307449020	5.8	10.83
8	16293594	225155666	7.2	8.66
10	15624594	188538289	8.3	7.56
12	15123364	161103679	9.4	6.68
15	14579208	131319592	11.1	5.65
20	13999303	99578727	14.1	4.46

Table 4.26 Economic evaluation indices of 7MW WD considering 20 years life period

Discount percentage	NPV cost in [£]	NPV Energy in kWh	Cost in p/kWh	SPBP Years
5	16733691	249244206	6.7	9.34
8	15767551	196362948	8.0	7.81
10	15290856	170271274	8.9	6.98
12	14909334	149388872	9.9	6.28
15	14467159	125186629	11.5	5.42
20	13959344	97391594	14.3	4.37

Table 4.27 Economic evaluation indices of 7MW WD considering 10 years life period

Discount [%]	NPV cost in [£]	NPV energy in kWh	Cos in p/kWh	SPBP Years
5	15001521	154434698	9.7	6.45
8	14631863	134201628	10.9	5.75
10	14425224	122891342	11.7	5.34
12	14244591	113004460	12.6	4.98
15	14013858	100375372	13.9	4.49
20	13711929	83849441	16.48	3.83
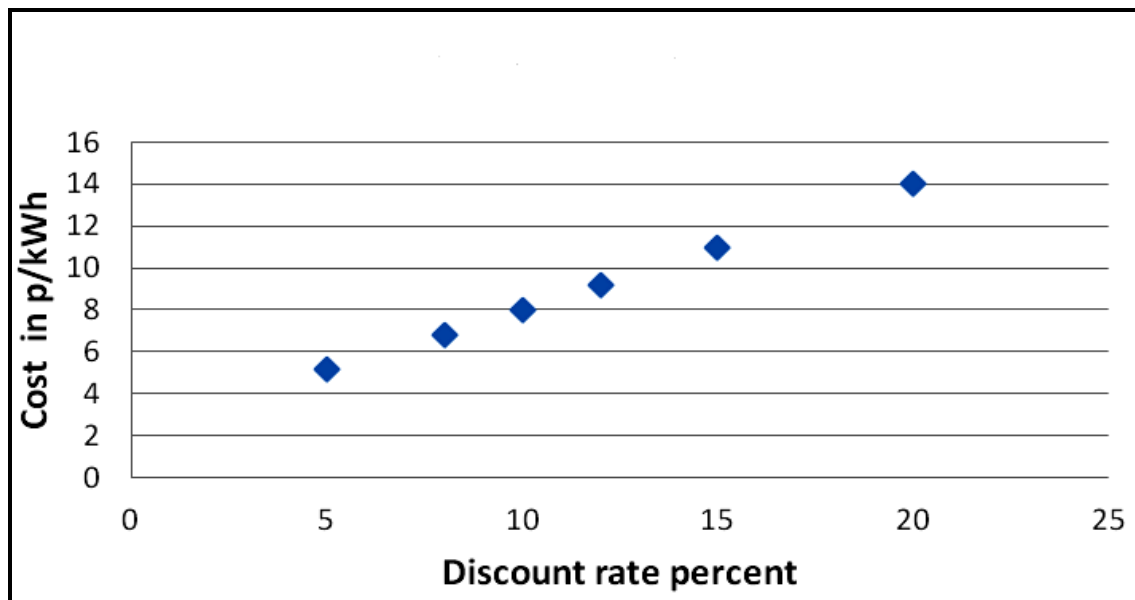
Fig.4.14 Discount rate percent vs. cost in p/kWh for 50 years life of 7MW WD

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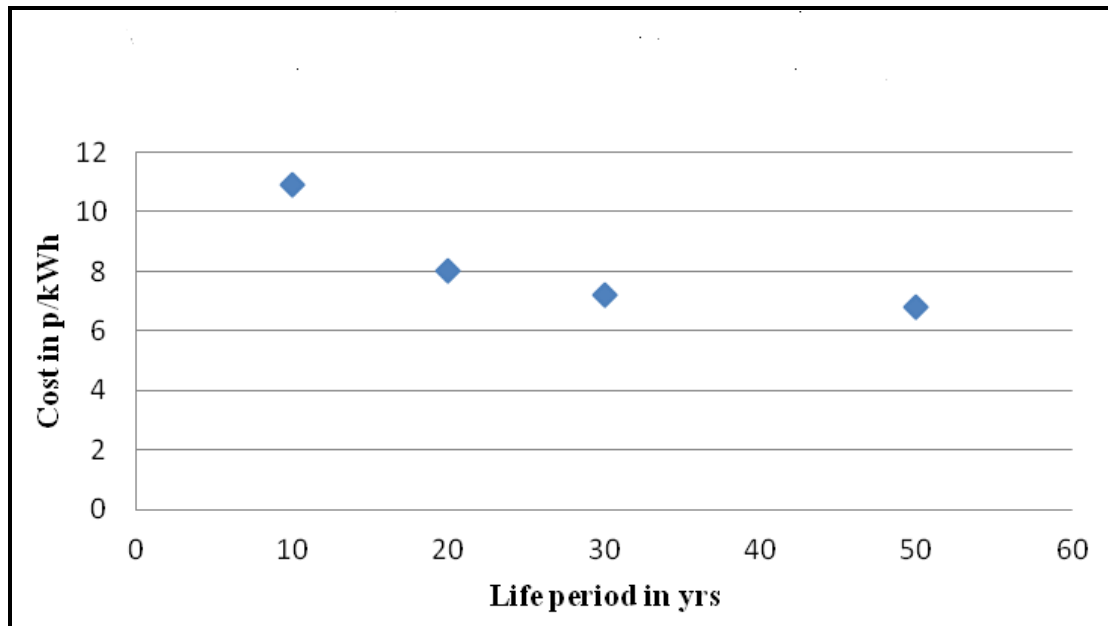
Fig. 4.15 Cost in p/kWh vs. life period of 7MW WD at 8% discount rate

It could be observed from fig. 4.14 that the cost of electricity escalates rather linearly with a rise in discount rates. But cost vs. life periods (at 8% discount rate), shown in 4.15, does not show a linear trend. It would be obvious from tables 4.24-4.27, and figures 4.15, that though the cost of electricity systematically decreases with a rise in life period, but this decline of electricity cost is rather less sharp above 30 years. In other words if it is below 30 years the cost of electricity rises sharply with declining years of life time (fig.4.15). This suggests that in designing the Wave Dragon, its life period should not be kept below 30 years, which otherwise would escalate the cost of electricity at a faster rate. Above 30 years life, declining cost is much less sharp. Thus 30 years life may be considered to be its break-even point.

Similar inferences could be drawn from estimations of the Internal Rate of Return (IRR) percentage as well, which is also an important economy evaluation index, in deciding the rate, above which the system starts becoming profitable (discussed in Appendix 2). The methodology of estimating IRR has been shown below for 7MW WD considering an 8% discount rate and a 50 years life. Internal Rate of Return (IRR) may be estimated as below (explained in appendix 2).

In fact, by definition the discount rate at which NPV is zero is the IRR.
-Cc + Nc*DF = 0; where Cc is the Capital cost, DF is the Discounting factor and Nc is the Net cash generated.

Nc =£995628, as estimated before considering a 50 years life and at an 8% discount rate.

IRR is therefore determined by trial and error methods of choosing discount rates, when one value would be positive and the other negative. Since the value of IRR must lie in between these two values it can easily be determined by computation from the above equation,transposing it as: DF-Cc/Nc = V.

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V would show a positive value at a discount rate, say R_p; but may show a negative value at some other discount rate, say R_n; and 'zero' when the discount rate is the same as the Internal Rate of Return.

Thus, for the above case of 7 MW WD with a life of 50 years and a discount rate of 8%, in which the annual net cash generation (Nc) is £995628, the IRR can be determined from a trial error method of different discount rates in determining the 'V' values.
For 7% and 10% value of r, the value of V+ =1.5672 and V- = -2.3187 respectively.

Hence the value of V would be zero in between the value of discount rate lying between the value 7% and 10%.
Thus that discount rate coinciding with IRR can be computed as below:.
7 +(0.1-.07)*1.5672)*100/(1.5672-(-2.3187))
=7+1.2002
=8.2%

Thus Internal Rate of Return for above 7 MW WD with 50 years life period would be = 8.2%
Based on the above premise, various values of IRR for different life periods, considered at 8% discount rate for the Wave Dragon could be estimated, the results of which is shown below in table 4.28 and also shown in fig.4.16, given below..

Table 4.28 IRR % of WD with changes in life period, considered at 8% discount rate

Life in years	IRR percent
50	8.2
40	7.7
30	7.2
20	5.25
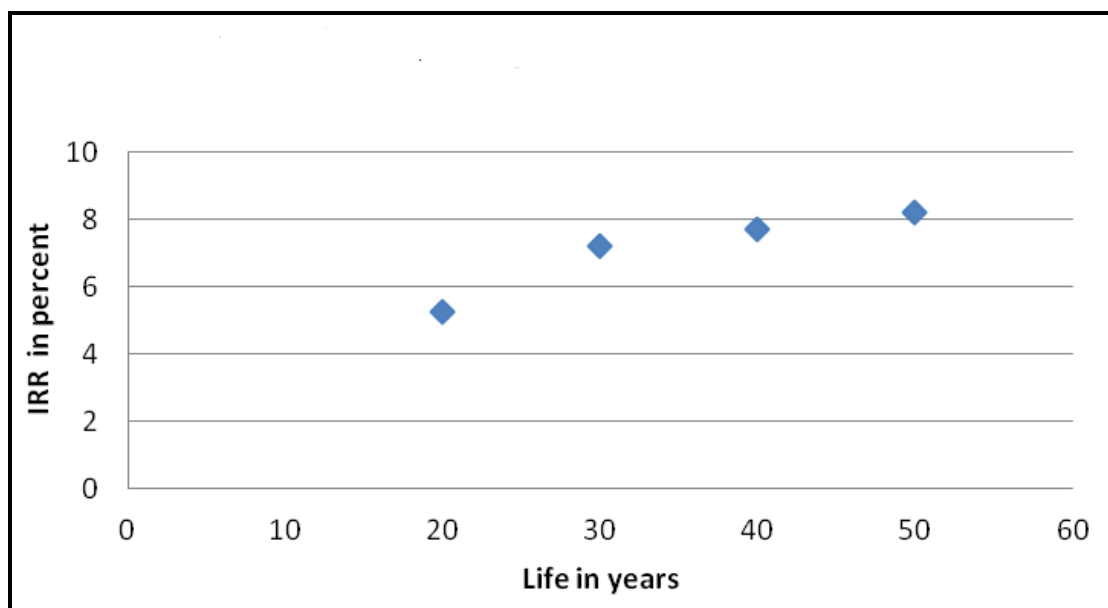
Fig. 4.16 IRR percent vs life in years for 7MW WD considered at 8% discount rate

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IRR signifies the discount rate above which only the business concern starts becoming profitable. Obviously with a higher life giving a lower cost of electricity, IRR values would increase. It would be apparent from fig. 2.28, that above a 30 year life this increment of IRR is rather less sharp, corroborating the inferences drawn from fig.4.15, that a 30 year life of the device may be considered to be the break-even point, below which the cost escalates at a sharper rate for the device concerned.

Keeping the above perspective in view it was considered worthwhile to undertake a case study with Pelamis, to cross check the above premise whose design life unlike WD is considered to be around 20 years (Parker *et al*. 2007).

4.6.2 Case Study with 750 kW Pelamis (application on the coast of Ireland)

It has been reported that the initial capital cost of 750kW Pelamis would be= €1533000 (Dalton et al. 2010). Hence £ 1,533,000 /1.26 = **£ 1, 216, 667;** since £1= €1.26, as per the exchange rate in Aug 2008 (x-rates.com, 2008)

The economic indices of Pelamis has been estimated, considering its O&M cost to be around 3% of the initial capital cost involvement with a 20 years life (Parker et al. 2007); and for its annual energy production on application on the coast of Ireland , as noted to be = 2.5 GWh (Dalton *et al*. 2010).

Based on the above premise the economy indices were determined as below, following the methodology as detailed in the computation of WD, in the previous section (vide also Appendix 2).

Capital cost = Cc = £1,216,667
Annual O&M cost = Co = £1216667*0.03=£36,500
Annual Energy production (at Ireland coast) of 750kW Pelamis) = 2,500, 000kWh
Discount factor for 20 years life time with 8% discount rate =DF=9.818147
(Vide also appendix 2)
Net present value of cost =Cc+ Co*discount factor =£1,575,029
Net present value of energy =2,500,000*discount factor=24,545,368
Cost /kWh=Net present value of cost/ Net present value of energy
=**6.4p/kWh**

Net cash generated annually = Nc= £0.064*25,00000-£36,500
=£123,500
Simple payback period (SPBP)=(Cc+ Co) /[(Cost/kWh)*(Annual energy production)]=7.81 years.

Economy indices of Pelamis could thereafter be determined following the above method of estimating them, for different life time periods and at different discount rates, as per computations made for 7MW WD. Thus the life period variations were made considering 10, 30, 50 years (in addition to the above determined 20 years). Discount rate variations were between 5 and 20%. The results are shown in tables 4.29-4.35 and figs. 4.21-4.35, as shown below.

Table 4.29 Economy indices of 750 kW Pelamis considering 20 years life period

Discount percent	NPV cost £	NPV energy kWh	Cost in p/kWh	SPBP years
5	1671537	31155525	5.3	9.34
8	1575029	24545368	6.4	7.81
10	1527412	21283909	7.1	6.98
12	1489301	18673609	7.9	6.28
15	1445132	15648328	9.2	5.47
20	1394406	12173949	11.4	4.38

Table- 4.30 Economy indices of 750 kW Pelamis considering 30 years life period

Discount percent	NPV cost £	NPV energy in kWh	Cost p/kWh	SPBP in years
5	1777761	38431127	4.6	10.83
8	1627576	28144458	5.8	8.66
10	1560749	23567286	6.6	7.57
12	1510681	20137959	7.5	6.68
15	1456325	16414949	8.9	5.65
20	1398398	12447341	11.2	4.46

Table- 4.31 Economy indices of 750 kW Pelamis considering 50 years life period

Discount percent	NPV cost in £	NPV energy in kWh	Cost in p/kWh	SPBP in years
5	1883008	45639813	4.1	12.14
8	1663189	30583711	5.4	9.21
10	1578557	24787036	6.3	7.87
12	1519781	20761246	7.3	6.84
15	1459775	16651286	8.8	5.71
20	1399146	12498626	11.1	4.47

Table 4.32 Economic indices of 750kW Pelamis considering 10 years life period

Discount percent	NPV cost in £	NPV energy in kWh	Cost in p/kWh	SPBP years
5	1498510	19304337	7.8	6.45
8	1461584	16775203	8.7	5.75
10	1440943	15361417	9.4	5.34
12	1422900	14125557	10	4.97
15	1399852	12546921	11.1	4.49
20	1369692	10481180	13	3.83

It could be observed from the above tables that the cost of electricity/kWh for 750kW Pelamis, varied between 4-13 p/kWh with variations in discount rates and life periods considered. In fact a cost/kWh power generation shows an increasing trend with a rise in discount rates.

It could also be noted from the tables, that the cost/kWh decreases if the life period of Pelamis is extended from its design life of 20 years, and increases with lowering of the life period.

The above tables 4.29-4.32 also showed that simple payback period (SPBP), as expected, decreased with a rise in cost/kWh of electricity generated.

In order to determine the trend of such changes; the results were plotted against the variable parameters like, discount rates and life periods, as shown below in figs 4.17 and 4.18, respectively.
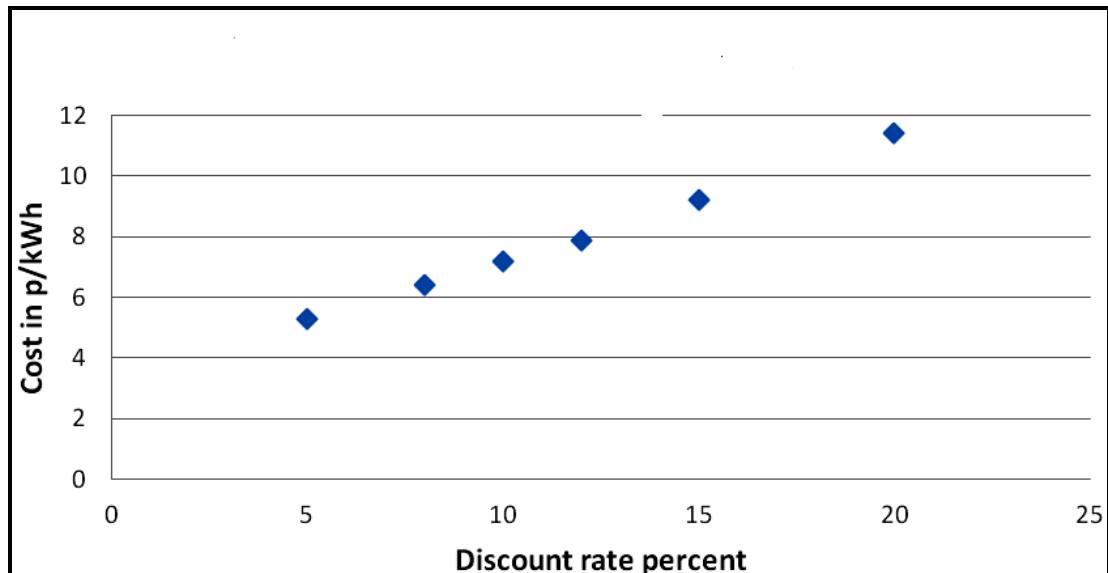
Fig.4.17 Cost/kWh of 750kW Pelamis for 20 years life vs. discount rates

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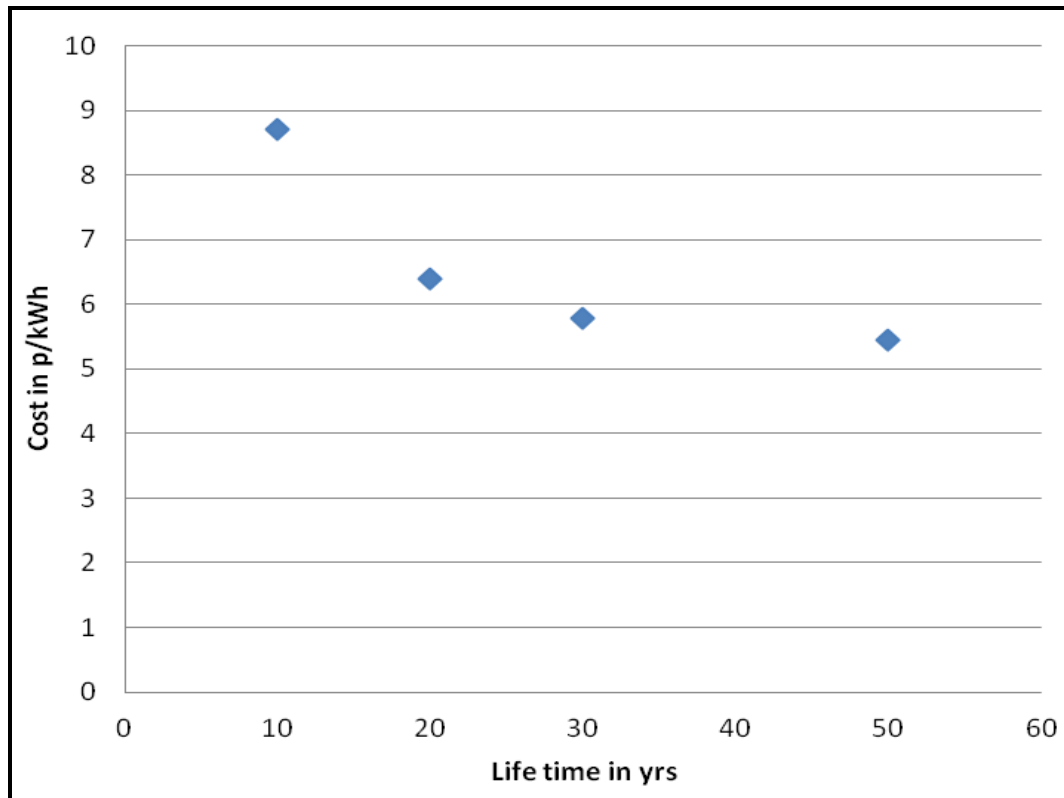
Fig. 4.18 Cost/kWh at 8% discount rate vs. of life period of 750 kW Pelamis

It would be clear from fig. 4.16 that cost/kWh increases with a rise in discount rates (considered from 5-20%), the relationship of which is by and large linear like WD. On the other side, cost/kWh declines with an increase in life, as evident from fig.4.17. But cost/kWh for Pelamis, like WD increases sharply below a 30 years life period, above which the decline of cost is not that pronounced, and also noted for WD. This suggests a 30 year life period may be considered as the break-even point, below which cost escalation is quite sharp causing economic disadvantage to the device considered. This data would be helpful in the device design to make it cost-effective.

It may be reiterated that IRR against a particular cost/kWh, is decisive in determining the economic viability of a project. Hence it was considered useful to identify changes in IRR values also with changes in life period, as determined in the case of the Wave Dragon.

The methodology of estimating IRR for 750kW Pelamis   is the same as that of WD.

IRR for 20 years life time, can be determined based on the premise that NPV =0, at IRR; or, - Cc + Nc *Df = 0, at IRR.
By transposing, the above equation would assume the form:
DF – Cc/Nc = 0, at IRR.
Nc for Pelamis as was estimated for 8% discount rate with 20 years life =£123,500.

Through a trial and error method of estimating at different discount rates, if we get a positive value for one discount rate and negative for the other then by computation

an in between value of discount rate, at which NPV would be zero i.e. IRR can be determined.

In the case of Pelamis the value of V will be positive when r = 6% and negative when r = 8% where V=DF - Cc/Nc.
Thus V+ = 1.6183 and V- = - 0.0334
Hence, the value of r will lie between 6% and 8%.
Obviously, the value of IRR must lie between the above two values.
Thus would be
=6 +1.6183*(0.08-0.06)*100/(1.6183-(-0.0334))
=6+1.96
=7.96%

Based on the above premise IRR values were estimated for 20 years, 30 years, 40 years and 50 years life, and are tabulated below in table 4.33 and also compared in fig. 4.18.

Table 4.33 IRR with changes in life period for Pelamis, computed at 8% discount rate

Life in years	IRR percent
50	10.08
40	9.93
30	9.54
20	7.96
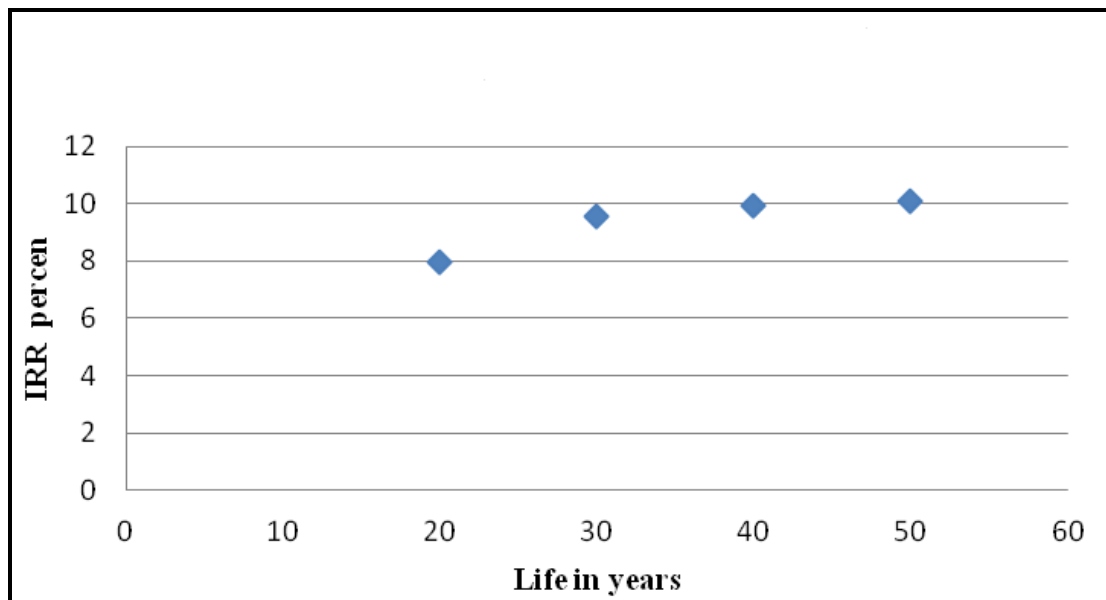
Fig. 4.19 IRR vs. life period of 750kW Pelamis, computed at 8% discount rate

A trend of increment of IRR with a life period as noted from the above fig. 4.18, as well as cost/kWh vs. life in years of Pelamis also show the same trend as that of the

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Wave Dragon giving a 30 year life to be the breakeven point below which the cost escalates and above which the increment is not that sharp.

It may be relevant to point out that the above stated results are applicable for application of the 750kW Pelamis on the coast of Ireland only. But for its application on the coast of Portugal, yielding half the annual energy production than that of the Irish coast (Dalton et al. 2010), the results as regards cost/kWh power generation, would obviously be double that of the Irish coast application values, as shown in tables 4.29-4.32.

4.6.3 Comparative studies of WECs' Economy

Comparative studies on the economic evaluations of WECs may be made from two perspectives. They could be either from the determination of different economic indices based on discounted cost methods, or it could be made from the comparison of Relative Product Cost ratios (RPC ratio) of the raw materials required for constructing the product WECs. The data generation of the former has already been deduced from case studies of 2 WECs, detailed in previous sections of 4.6.1 & 4.6.2.

The comparative values of economic indices of the above two approaches are discussed in subsequent sections.

4.6.3.1 Comparison on economy indices from NPV cost methods

The economy indices compared are: the cost of electricity generation in p/kWh and the simple back period values of WD & Pelamis. The IRR percent values of WD and Pelamis are widely different, with much smaller values in the case of WD than that of Pelamis.

Since discount rates and life periods play an important role in the values of the economic indices, hence a similar discount rate at 8% is maintained for making comparative studies. As regards the life period is concerned, considerations have been made on the design life of respective WECs, and also of the life at their respective breakeven points, which is found to be 30 years for both. The former i.e. the design life periods of respective WECs, are indicated with the suffix 'o' and the latter with the suffix 'c'. Thus WD_o indicates WD with its designed life period of 50 years; whereas $Pelamis_o$ indicates its design life of 20 years. Likewise WD_c & $Pelamis_c$ indicated these devices and their respective life periods of 30 years, which is the breakeven point in life period of both these WECs.

The results comparing the economy evaluation indices of these WECs are shown below in fig.4.20.
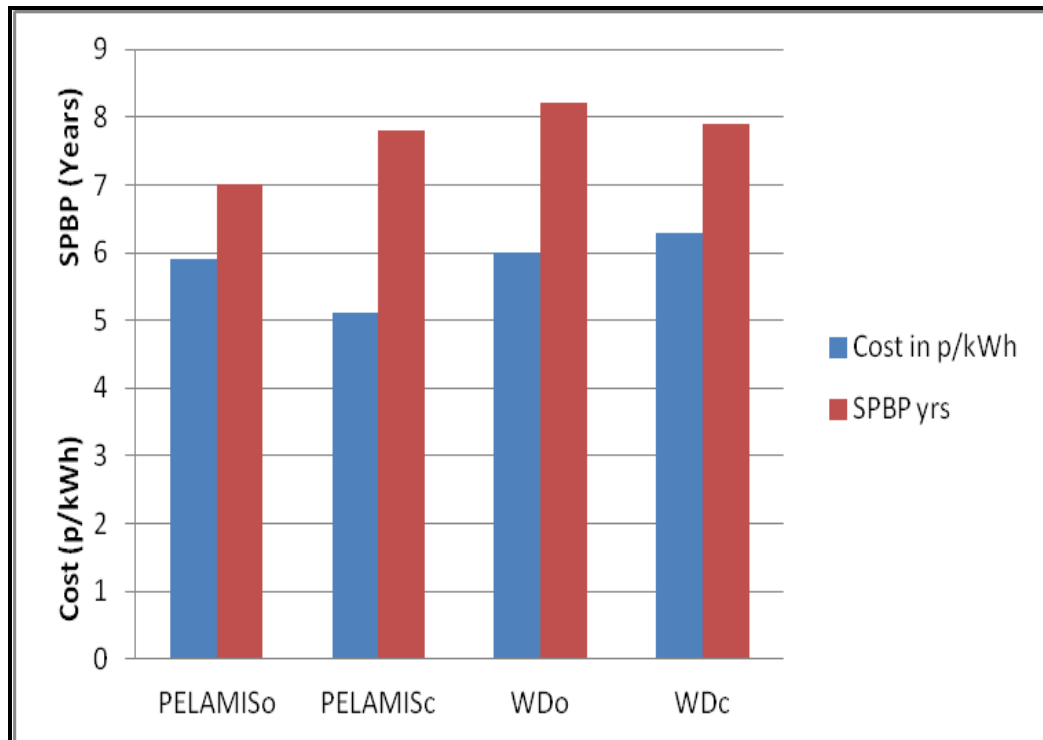
 Fig.4.20 Comparative studies of economy indices of WECs

It could be observed from the above table, that by and large the Pelamis shows a rather cheaper power generation than that of WD, as evident from cost/kWh and SPBP values. Even the cost/kWh power generation of Pelamis at only 20 years life period shows a little less value than that of WD of 50 years life. However, at their breakeven point of 30 years life, such advantage of Pelamis could be seen to be more pronounced.

It is however to be reiterated that such values of Pelamis are achievable for its application on the coast of Ireland only; whereas on the coast of Portugal , it might not be that advantageous, as per the trial run results recorded by Dalton et al (2010).

Since all these results are based on capital costs quoted by concerned manufacturers, a RPC ratio determination approach has been proposed as another index of comparing respective economy, which with reasonable approximations can be used for a comparative study. The methodology developed on the same has been elaborated in the following section.

4.6.3.2 Comparative studies on economy from Relative Product Cost ratios

An attempt has been made to introduce an index **Relative Product Cost (RPC)** ratios, to compare relative economy for different types of WECs. It may be considered to be particularly suited for OE energy devices, which involve huge raw materials, unlike many others RE systems.
The following logical presumptions are made for developing the above tool, RPC ratio, for comparing the relative economy of different devices. They are:

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- The average cost of the different inventory materials /constituents, required for constructing the devices, may be considered to maintain a definite ratio, which could be determined from market survey, as shown in table 4.32 given below. This enables the production of comparative studies of RPC ratios of raw material cost though not of the actual product cost involved.
- The cost involvement of the components (and their assembly) made from respective raw materials, may be approximated to be directly proportional to the cost of the raw materials concerned.
- By and large, the transportation & installation cost is likely to be dependent on the respective weights of products, on transportation/ installation (not the actual cost involvement, but relative ratios only).

It is also to be stressed upon these RPC ratios give only a broad guidance providing a comparative study, not the actual cost involvement of any product.

In table 4.34 shown below, provides the relative product cost ratios (RPC ratios) of the usual raw materials that are normally used for constructing WECs. The values of RPC ratios are based on the market survey undertaken

Table-4.34 RPC ratios of various inventory items, as observed from market survey (metalprices.com)

Inventory items	Stainless Steel/ Special steel	Aluminium	Cu	Plastic/ HDPE	Glass	Iron / Steel	Concrete
RPC ratios	2.5	1.9	3.0	1.6	1.2	1.3	1.0

The cost ratio of the respective converter units may be made by multiplying the mass requirement of each item with the RPC ratios of the respective inventory items and thereafter adding them up to give a grand total cost ratio for each converter type. This grand total cost ratio divided by the annual power generation for respective generators, would give the **cost ratio/kWh** which could be an important index to compare the relative advantages gained from the different types of converters.

Expressed mathematically, RPC ratio of a WEC = $\sum I_m * I_{rpc}$ ………… [4.5]; where, I_m is the mass of respective inventory items of the product, with cost ratios I_{rpc} for each of the individual inventory items.

For comparative study, the index used is: RPC/kWh = $\sum I_m * I_{rpc} / Ea$…………. [4.6]; where, Ea is the annual energy production of respective converters.

In the case of 750 kW Pelamis, Ea, the annual power production is 2.5GWh, for its deployment on the coast of Ireland (Dalton *et al*. 2010); whereas the annual power production of 7MW WD has been reported to be 20 GWh (Millar *et al*. 2007).

Comparative studies on the economic evaluation from the above premise of **RPC ratio** concept is shown below in table 4.35.

Table 4.35 Comparative studies of WECs based from RPC ratios of constituent materials

Materials	RPC values [Irpc] (*)	7 MW Wave Dragon		750 KW Pelamis	
		Mass kg (**)	Cost of inventory items	Mass(kg) (***)	Cost of inventory items
Steel (Special	2.5	553000	1382500	380000	950000
Aluminium	1.9	24100	45790		
Copper	3	69300	207900	15000	45000
Plastic	1.6	31540	50464		
Iron	1.3	120920	157196		
Concrete	1	31068000	31068000		
Grand Total		31866860	32911850	395000	995000
Mass ratios/kWh		1.59		0.158	
Cost ratios /kWh			1.64		0.398

(metalprices.com) (**) (Russell 2007); (***) (Taylor 2006).

It could be observed from the table that, Pelamis shows a very much lower mass ratio/kWh as well as a cost ratio/kWh, than that of WD. It may be relevant to add here that the cost/kWh power generation of Pelamis, as determined from NPV concept, was found to be only marginally better than WD.

It may be added that the RPC ratio index can only be used for comparison purposes and does not give an absolute value of any economic index. But the advantage of the method is that it does not require the product cost/capital investment data, nor is data required for life of the product. Also, it would give better result for similar design types of WECs, than those of different design types, for.

Thus this index of RPC ratio would be more suited in R&D efforts for making sensitivity analysis, to examine the scope of performance improvements of products. They have been discussed at appropriate sections in subsequent chapter-8, discussing the scope of the use of the RPC ratio concept, in making R&D efforts for advancing OE devices.

4.6.4 Critical appraisal of economy evaluation results

It may be relevant to point out that the economic evaluation developed from the present   day data analysis, is likely to show declining values with advancement of the technology and also from an increased production volume from future commercialization (with advanced technology) of wave energy converters. On the other side, future WECs might be required to be made more robust, to ascertain stability in higher wave density as may be accrued from a rise in global temperature /wind velocity. This paradox, unless resolved by some innovative better technology, might demand a higher requirement of construction materials with an additional cost burden.
It is also important to note that the resource capture of wave converters in choosing the right site for application, is an important criterion that decides the annual power generation of the device and thus of the economy. It may be worth mentioning about

the application of Pelamis in Ireland vs. Portugal, with the latter giving half the power production values than the former (Dalton et al. 2010) therefore affecting the overall economy.

Another important criterion that is decisive is the designed life of the converters. It could be suggested that for both the WD and Pelamis, cost/kWh power generation shoots up sharply below 30 years life, suggesting this to be the breakeven point in making the design criterion.

It is needless to point out that in undertaking an economic evaluation, the; insurance costs, local taxes (as levied) etc, (that varies from country to country) have not been taken into account in making the economic evaluation. They are required to be considered, once the WECs start power production on commercial scale. The present economy evaluations are thus more relevant in comparing the relative economy of competing WECs.

In R&D efforts for undertaking the sensitive analysis of the WECs in efforts of designing performance improvements/cost reduction; RPC ratio index would be useful in comparing relative advantage gained, without requiring capital cost involvement data, nor of the data on design life; in its initial stage of development.

It is to be reiterated that if the RPC cost ratio of constituent materials change in international markets as well as in local markets, it may off-set the entire values determined. However, the methodology of determining them remains unaltered, if not the actual values of cost/kWh ratios (RPC ratios).

Thus, both discounted cost methods of determining economic indices or the RPC approach of cost comparison could be considered to be the right and appropriate economic evaluation tools, depending on the purpose of evaluation and/or comparing relative economy of devices.

4.7 Observations

- It could be noted that resource capture capability, producing an annual power generation of a WEC is both design specific as well as site specific which can only be ascertained from sea-trial runs.
- Emission characteristics including GHG gases and SO_2, estimated from LCA studies of a few WECs, showed more than a 95% saving of CO_2 emission compared to a typical coal fired power generator. Such results could be observed for all types of WECs, with some of them having a slightly better efficiency. The results thus arrived at on CO_2 emission, carbon payback period or CO_2 saving percentages, made by the Danish model fairly corroborated with that estimated by the Bath University data source as well.
- The energy payback period of WECs showed the results to vary between 1 to 2 years, depending on the design type of WECs.
- EIA models developed for OE systems could be applied for wave energy schemes in the assessment on flora and fauna, as may be accrued from the application of WECs. It could be noted that the effect on flora and fauna, though mostly negative, is marginal for wave schemes.

- The guidelines as regards keeping hazards to a minimum level, in the cases of application of WECs, could also be spelt out. It included identification of hazard types with suggested mitigating measures.
- The impact assessment on various aspects of social issues could also be spelt out, and highlighted the possible positive and also of the negative inputs. It showed to have mostly a positive social impact, helping improve quality of life.
- The economic tools including cost in p/kWh at various discount rates, percent IRR, cost payback period as well as influence of life period of WECs over cost/kWh could also be determined from case studies of two different types of WECs (Wave Dragon & Pelamis).
- It was observed from the economy evaluation indices thus studied that below a 30 year life, cost/kWh sharply increases, suggesting a 30 year life to be the breakeven point of these WECs.
- For undertaking a comparative study, a novel concept of RPC ratios, based on cost ratios of inventory items of a product (WEC), could be introduced. This enables comparing economic evaluation, even if the data on capital cost involvement or of the life of the device concerned are not made available. Thus this index of comparative study would be helpful in R&D studies for advancing the WECs.
- The four assessment tools thus developed, such as resource examination, LCA & EA studies, EIA model application and evaluating the economy from the usual tools (cost/kWh etc) including comparison from RPC ratios – proved helpful in ranking the WECs and in making an assessment of the relative merits of competing WECs.

Chapter -5

ASSESSMENT OF OCEAN THERMAL ENERGY CONVERSION (OTEC) SYSTEMS

5.0 Introduction

In order to examine the efficacy of OTEC systems, it is considered useful to undertake a critical analysis of its different types, employing assessment tools such as resource analysis, LCA & EA studies, EIA studies and economic issues involved. In the case of OTEC systems however, the scope of availability of by-products deserves special attention, in addition to studies on the above assessment tools.

Assessment of OTEC systems has hence been undertaken by employing the following assessment tools:

- Resource Analysis.
- LCA & EA studies.
- EIA studies to assess environmental fall outs.
- Economic Issues involved.
- Scope of by product availability for various OTEC types.

An analysis of them has been detailed in subsequent sections.

5.1 Resource analysis

The energy resource of OTEC is the temperature differential between the surface of ocean water and the cooler water layer at the bottom (may be 800-1500m below). From 10^0 North to 10^0 South of the equator, covering 60 million sq. km and to a depth of 35—100m, temperature between 25^0C to 28^0C is maintained throughout the year and round the clock (Anderson 1998).

This huge reservoir of energy can be made available from OTEC systems, by utilizing the temperature differential of the ocean surface water, from the heavier and cooler bottom layer of ocean water, around 4^0C, below >800 m depth from the ocean surface. Its low temperature at the bottom layer is due to the exponential lower rate of penetration of solar energy with increasing depth (Lambert's Law), added with the ice-cold heavier water current fed from the northern and southern polar regions, through the bottom layer of the oceans.

The global surface temperature profile has been shown below in fig. 5.1

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Fig. 5.1 Annual average of global ocean surface temperature profile shown. (Aquarius.Nasa n.d.)

In the tropical zone, the annual average surface temperature ranges between 22 and 27 ^{0}C. In the temperate zone, it varies between 14 and 20 ^{0}C. In the North Sea or, in Atlantic around the coastal regions of UK (between latitude 52—58^0 N) the annual average of ocean surface water temperature is around 14^{0}C, as noted from fig.5.1.

The limiting efficiency of power generation i.e. the Carnot efficiency can reach a maximum 10% only, where the surface temperature is 30 ^{0}C above the cooler bottom layer water temperature, as shown below in figure 5.2. For all practical purposes however its efficiency hardly reaches more than 2.5%, operating in Rankin cycle (Vega 1999).

carnot cycle efficiency
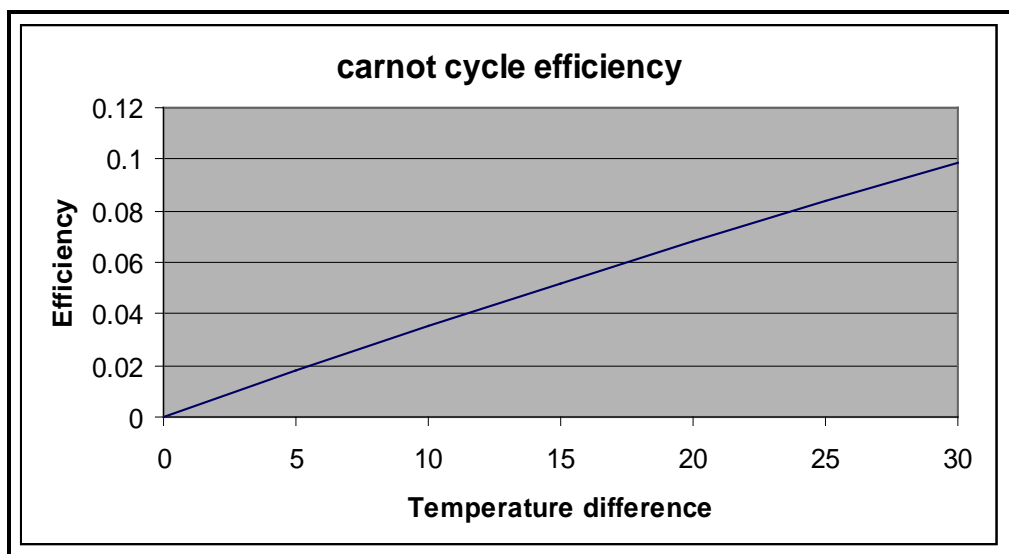
Fig. 5.2 Carnot efficiency vs. ocean's temperature differential for running OTEC.

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An ideal site of OTEC resource would however be availing not only the higher temperature differential between surface layer and bottom layer of the ocean, but rather a combination of high surface temperature profile all year round with sharp thermal gradient profile near the shore. This is shown below in fig.5.3 [Binger n.d.] (greenocean.org)

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Fig. 5.3 Thermal gradients with depth for an ideal OTEC site (Binger n.d.)

Such sites are available in; Cuba, Haiti, Latin American coast, and Seychelles islands coast in Indian ocean within 1 km of the shore. In the Indian & Pacific ocean it is availed normally between 1 & 10 km from the shore (Binger n.d.).

A limitation of OTEC resources however, is its very low efficiency in power generation, requiring huge volume of water to be pumped for tapping the power from warm surface water of the ocean. The maximum power output from warm surface water would obviously depend on:

- The mass flow times the heat capacity of the water feed.
- The temperature differential between the warm and cold water.

5.2.0 Life Cycle Assessment and Energy Accounting studies of OTEC.

It is important to note that, unlike other RE systems OTEC systems would require energy input for its operations. Thus the GHG emission and energy requirement, for its operational stages are also to be taken into account for undertaking LCA studies of OTEC.

The ratio between gross energy generated and net energy availed from OTEC, is usually around 1:0.65 (Vega 1999). Thus around 65 % of net energy can be available (depending on methodology and capacity of OTEC unit), from its gross energy output. LCA & EA estimations are to be made accordingly.

5.2.1 Scope of CO$_2$ Emission during operational phases of OTEC

As regards CO$_2$ emissions from operational phases in OTEC, there can be two possible sources. The first one is from its evolution from warm sea water during steam formation, along with the permanent gases like O$_2$, N$_2$, etc where warm water is used as the working fluid, as in OC-OTEC. In Hybrid cycles where warm water is used for providing potable water, CO$_2$ (g) emission occurs during steam formation of warm sea water. The second source of CO$_2$(g) emission in OTEC operation is from the possibility of its liberation from cold water, when its temperature gets elevated in the condenser and is discharged in ocean mixed with warm water.

In fact, the solubility of CO$_2$ in water is inversely proportional to the temperature and directly proportional to the depth of the ocean (Teng et al. 1996). It may be relevant to add here, that despite the fact that the solubility of CO$_2$ (g) decreases with salinity of the water, the role of the ocean is considered quite important in maintaining the atmospheric CO$_2$ (g) concentration balance (Enick and Scott 1990). In fact, CO$_2$ (g) from air after dissolution in ocean water, remains in the form of soluble carbonates, bicarbonates as well as in gaseous form, depending on the temperature and pressure following Henry's law. Upwelling of cold water is likely to release this dissolved gaseous CO$_2$, on temperature rise and also for lowering of the super incumbent pressure of the water.

The role of organisms, such as planktons is also to be considered while deciding maintenance of equilibrated concentration of CO$_2$ in the ocean water. They consume CO$_2$ during photosynthesis and also in the formation of shells. The dead cells of these and the marine species feeding on them thereafter sink below the ocean with enriched carbonate content. This phenomenon of CO$_2$ burying by dead species, at ocean floor and thereby maintaining CO$_2$ balance in global environment, by the ocean's natural process is termed sequestering of CO$_2$ (Christopher and Barry 2008).

The churning of the ocean caused by OTEC deployment, with the upwelling of cold water as well as their discharge in the euphotic zone of the ocean as the mixed discharge (with warm & cold water), may affect the CO$_2$ balance of the ocean. This may be caused by fluctuations of the following three factors.

- Temperature elevation / lowering.
- Pressure release.
- Plankton concentration

It would be expected that a rise in plankton concentration from the upwelling of cold bottom layer water, would help lowering GHG gas level in the atmosphere, consuming more CO$_2$ over ocean surface water. On the other hand, a huge quantity of dissolved CO$_2$ (g) is likely to be released from temperature rise and the pressure release of the upwelled water.

In fact, Green and Guenther (1990) noted from their experimentations in Heat and Mass Transfer Scooping Test Apparatus (HMTSTA), that evolution of CO$_2$ from operations in case of OC-OTEC is expected to be 11.7g/kWh from warm water, and 26.8 g/kWh from cold water; totalling 38.5g/kWh. In the case of Hybrid OTEC it is

expected to be lower, 11.7g/kWh, and still lower value of <1g/kWh for operations with CC-OTEC (Green & Guenther 1990).

They however, opined that if this cold water instead of getting discharged into the ocean is used for mariculture, it would emit more CO_2 (g) for its longer exposure. But the cultured marine plants etc. are likely to absorb extra CO_2 (g) released and thus neutralize it (Green & Guenther 1990).

In the present study, CO_2 emission during the working phase, for CC-OTEC, OC-OTEC and Hybrid OTEC types were estimated, based on the above stated studies of Green and Guenther (1990) as per their experimentations on HMTSTA apparatus (38.5g/kWh for OC-OTEC, 11.7g/kWh for Hybrid type & <1g/kWh for CC-OTEC, say 0.8g/kWh).

The total GHG emission could thereafter be estimated from LCA studies, added with the above stated operational phase CO_2 emission values, as determined by Green & Guenther (1990).

5.2.2 Case study of GHG emission from 100MW OTEC.

LCA studies of GHG emission were made from a case study of a 100 MW OTEC plant. The inventory data of the OTEC plant was taken from the hypothetical Japanese model of a 100MW CC--OTEC unit, proposed by Tahara *et al* (2000).

Since LCA results are not only process specific, but may also vary on source of available data (country-wise), it was considered to examine LCA & EA based data sources of both the Danish model, as well as from the Bath University data, in addition to that used by Japanese researchers. This was considered useful in cross checking the results and to assess the degree of repeatability of LCA & EA results.

The data sources used satisfied the boundary conditions of 'cradle to gate' of LCA studies, as per ISO 14040, giving CO_2 emission in kg/kg of the inventory materials concerned. GHG emission of OTEC could thereafter be examined from the perspective of carbon saving compared to the average representative CO_2 emission values of coal fired power plants, producing equivalent power (vide section 4.3.6.2).

It may be added that Japanese researchers (Tahara *et al*. 2000) used the software NIRE-LCA (developed by National Institute for Resources and Environment), in making their LCA estimations on CO_2 emission for the 100 MW CC-OTEC.

But before undertaking case studies on LCA & EA for a 100 MW OTEC plant, its annual power generation as well as life time power generation also needs to be determined. Net power availed from OTEC is considered to be around 65% of the gross power, the value of which increases with higher capacity OTEC plants (Vega 1999). Hence, the net power from 100MW OTEC is considered 75% of the gross power generation. Also, for estimating annual power generation the capacity factor of OTEC is presumed to be 30%, as normally obtained for wave schemes. An adhoc presumption of 30 years life is considered for OTEC plants, considering 30 years life to be the breakeven point, as obtained for the wave schemes studied.

Keeping in mind   the above facts and logical presumptions are; the net annual and life time power generation from 100MW OTEC could be considered to be as below:

Net annual power production of 100MW OTEC = 100*24*365*0.3*0.75

= **197.1GWh**

Net life time power production of 100MW OTEC = 197.1*30

=**5913 GWh**

The results from the above three sources- the Danish model, the Bath data as well as of the Japanese model have been elaborated in subsequent sections.

5.2.2.1 Danish model of LCA estimation

The Danish model of emission data used for off-shore wind energy has been utilized in the present study (Schleisner 2000). The LCI data as regards the emission characteristics of different gases, for Danish model is given below in table 5.1

Table 5.1 Emissions in kg/kg of the materials as observed from Danish model of LCI (Schleisner 2000).

Emission of pollutant gases of 100MW OTEC determined   from the above table5.1 of the Danish model, (excluding the operational phase emissions)   are shown below in table -5.2.

Table 5.2 Emission of Pollutant gases of the 100MW CC- OTEC device.

Constituent materials	Mass (kg) of the materials **	CO_2 (kg)	N_2O (kg)	CH_4 (kg)	NO_x (kg)	SO_2 (kg)
Steel*	4157000	9588120.5	291	166	394915	60276
Iron	16817000	52 36 138	1513	1009	149503	245192
Copper	270000	1764720	51	43	6261	9615
Plastics	14216000	44254408	1706	1137	209117	325688
Concrete	75000000	52725000	0	0	187500	750
Grand Total		160700386	3561	2356	591873	641521

.*Different types of steel for OTEC manufacture are clubbed together for simplifying the estimations.
** source ref.: Tahara *et al*. 2000, as regards the inventory materials of 100MW CC –OTEC.

It follows from the above table 5.2 that:

- The total CO_2 emission from the above OTEC upto its construction phase = 160 700 386.5 kg
- Its CO_2 emission if expressed in g/kWh =160700386kg/5913GWh **=27.18 g/kWh**
- Since GWP value of CH_4 is 21, its GHG potential =0.0004g/kWh
- Since GWP of N_2O is 310, its GHG potential =0.1867g/kWh
- Total GHG potential computing the contributions of GHG potential from N_2O & CH_4 in addition to that from CO_2 =27.37 g/kWh

It would be evident from the above results that it is only the CO_2 emission, which plays a dominant role in determining the global warming potential accrued from the concerned device.

But the above estimation gives emission results from LCA studies, excluding the emissions in operational stages. In order to include CO_2 emission for operational phases, it is required to add up CO_2 emission from warm & cold sea water inputs, as well as that from the working fluid – Ammonia used in running the CC-OTEC plant. The value of CO_2 emission for CC-OTEC, as per studies of Green and Guenther (1990) would be less than 1g/kWh, say 0.8 g/kWh.

CO_2 emission from Ammonia used as working fluid in CC-OTEC would however be = 2 220 000 kg, as per the Japanese model (Tahara *et al*.2000), who used NIRE-LCA software for their CO_2 emission estimations. Since the total power production would be 5913 GWH in its lifetime, the contribution from Ammonia (used as working fluid in CC-OTEC) in CO_2 emission for CC-OTEC would be =2220000kg/5913GWh =**0.49g/kWh**
Thus the total CO_2 emission for its operational phases in CC-OTEC would be
= (0.8+0.49) = **1.29g/kWh**

Total CO_2 Emission from 100MW CC-OTEC
Hence, total CO_2 emission of the CC|-OTEC as par the Dutch model would be
= (27.18+1.29)g/kWh
=**28.47g/kWh**

Total CO_2 emission from 100MW OC-OTEC

The inventory items of OC-OTEC would vary from that of CC-OTEC, because OC-OTEC would require a much larger evaporator, requiring a larger amount of material inputs. On the other side, its use of DCC heat exchanger would cause much less material input than that used for metal surface heat exchangers, used in CC-OTEC. Hence it may be considered that the two inputs (positive and negative) would by and large, balance each other. Thus, CO_2 emission from material inputs of OC-OTEC may be considered to be more or less similar to that of the CC-OTEC.

Of course, CO_2 emission during operational stage of OC-OTEC would be quite high, 38.5g/kWh, as per studies of Green and Guenther (1990).

Thus the total CO_2 emission for 100MW OC –OTEC, may be considered to be
= (27.18+38.5)g/kWh = **65.68g/kWh**

Total emission from 100MW Hybrid OTEC

The Hybrid OTEC's CO_2 emission would be the total emission from material inputs of CC-OTEC (as estimated above) added with the input of Ammonia, plus the input of 11.7g/kWh from warm/cold sea water flow as noted by Green and Guenther(1990).

Thus the total CO_2 emission for 100MW Hybrid – OTEC, may be considered to be
= (27.18+0.49+11.7)g/kWh
= **39.37 g/kWh**

5.2.2.2 CO_2 emission of OTEC based from Bath University data source

Likewise, CO_2 emission of OTEC could also be estimated, based on the Bath University data source; with boundary conditions of 'cradle to gate' of LCA studies giving CO_2 emission in kg/kg of the inventory materials concerned (Hammond and Jones 2008).The results as estimated are shown below in table 5.3.

Table-5.3 CO_2 Emission of CC-OTEC estimated from Bath University data source

Inventory Materials	CO_2 emission kg/kg**	Mass of the material(kg)***	Total CO_2emission estimated, of the materials (kg)
Steel [includes different types]*	6.15	4157000	25565550
Copper	3.00	270000	810000
Iron	1.91	16817000	32120470
Concrete	0.95		
Plastics	2.53	14216000	35966480
Cement	0.83	75000000	62250000
Grand Total		110460000	155983500

* (mean values considered); **(Hammond & Jones 2008) *** (Tahara *et al*. 2000)

Thus the total CO_2 emission from the CC-OTEC device from table-5.3–excluding operational stage emission= 155983500kg/5913GWh
= **26.38 g/kWh**

The emissions during the operational phase of CC-OTEC would be the combined emission from Ammonia (the working fluid used) plus the emission caused from the flow of warm/cold sea water required for its operation, as per studies of Green & Guenther (1990) = 1.29 g/kWh, as shown in previous section (on the Danish model estimation)

Total CO_2 emission from 100MW CC-OTEC
Hence, total CO_2 emission of the 100MW CC-OTEC, as per the Bath University data source would be = (26.38+1.29)g/kWh
= **27.67g/kWh**

Total CO$_2$ emission from 100MW OC-OTEC

Following the same logic as put forward in previous section (on studies in the Danish model), total CO$_2$ emission from OC-OTEC would be input from materials of CC-OTEC, as explained in previous section + input as per studies of Green and Guenther(1990) in operational stage emission of OC-OTEC =(26.38+38.5)g/kWh
=**64.88 g/kWh**

Total CO$_2$ emission for 100MW Hybrid OTEC

As per discussions made in previous section, CO$_2$ emission from Hybrid OTEC would be: input from materials of CC-OTEC + input from Ammonia + Hybrid OTEC's warm/cold water flow CO$_2$ input = (26.38+0.49+11.7)g/kWh
= **38.57g/kWh**

5.2.2.3 Japanese model of CO$_2$ Emission

Tahara et al. (2000) determined CO$_2$ Emission for their proposed 100MW CC-OTEC, using the software NIRE –LCA (developed by National Institute of Resource and Environment), as shown below in table 5.4.

Table 5.4 CO$_2$ Emission of the OTEC device determined by Tahara *et al.* (2000).

Thus CO$_2$ emission for the Japanese model of 100MW CC-OTEC (considering 5913GWh, as life time power production) would be =142399600kg/5913GWh
=**24.08 g/kWh**;
whereas, CO$_2$ emission for 100MW CC-OTEC, from the Danish model & the Bath data source showed values of 28.47g/kWh & 27.67g/kWh, respectively.

Though the results of two European countries, the Danish model and Bath data, fairly conform to each other; but the results of Japanese researchers showed lower values for 100 MW CC-OTEC.

5.2.3.1 Emission of CO$_2$ from OTEC compared to coal fired power station

The indices for ascertaining advantage gained in CO$_2$ emission compared to coal power stations are as below (also shown in section 4.3.6.1, chapter 4):

CO_2 percent saved = 100- (W_e/C_e)*100; …………………………………..[5.1]
CO_2 payback period= ($L*W_e*P_a$)/(C_e*Pa); ……………………………….[5.2];
where , **C_e,** is the average CO_2 emission of a representative coal power station =**826.17g/kWh**; as deduced in section 4.3.6.2 of chapter 4.
'W_e' is CO_2 emission in g/kWh of concerned converter, with its annual power production 'P_a' and life period 'L.'

Based on the above 2 equations 5.1 & 5.2, percentage of CO_2 saved & CPBP could be determined from the values of W_e, as determined in previous section for the three types of 100MW OTEC plants. The results are shown below in tables 5.5 & 5.6, for CC-OTEC, Hybrid & OC-OTEC types.

Table 5.5 Percentage of CO_2 saved compared to a representative coal power station

OTEC plant type	CO_2emission model used	We in g/kWh	Percentage of CO_2 emission compared to coal	Percentage of CO_2 emission saved
100MW CC-OTEC	Dutch model	28.47	3.45	96.55
100MW CC-OTEC	Bath Univ.	27.67	3.35	96.65
100MW OC OTEC	Dutch model	65.68	7.95	92.05
100MW OC OTEC	Bath Univ.	64.88	7.85	92.15
100MW Hybrid OTEC	Dutch model	39.37	4.76	95.24
100MW Hybrid OTEC	Bath Univ.	38.57	4.67	95.33

Table 5.6 CO_2 Pay Back Period [CPBP] of different OTEC types

Type of OTEC plant	Model used	$L*W_e*P_a$ in kg/kWh	CPBP in yrs= $L*W_e*P_a$/ 162838107(*)
100MW CC-OTEC	Dutch model	168343110	1.03
100MW CC-OTEC	Bath Univ.	163612710	1.00
100MW OC-OTEC	Dutch model.	388365840	2.38
100MW OC-OTEC	Bath Univ.	383635440	2.35
100MW Hybrid	Dutch model	234568710	1.44
100MW Hybrid	Bath Univ.	228064410	1.40

(*)Since P_a*C_e= 197.1GWh* 826.17g/kWh = 162838107kg/kWh

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5.2.3.2 Emission of acid gas like SO_2

The above stated data gives CO_2 saving aspects, from the use of OTEC compared to the coal fired power stations. Likewise, the percentage saving as regards emission of acid gases like SO_2, may also be determined considering its emission from coal fired power stations to be 100%. The results determined from the above premise are shown below.

As shown in table 5.2 of the Dutch model of LCA, the above stated 100MW CC-OTEC unit in its life time produces 641521.62 kg SO_2 for its net power production of 5913GWh. Thus, its SO_2 production =0.11g/kWh

Coal fired power station is said to produce 7.8g/kWh SO_2 (Sorensen *et al.* 2003).

Hence percentage of SO_2 saving from the concerned CC-OTEC unit would be
100--(0.11*100)/ 7.8= 98.6 %.

5.2.4 Energy Accounting Studies

EPBP from energy accounting studies enables to determine in how many years the total energy required to manufacture the product can be recovered and can be determined as per the following equation:
EPBP $=\sum$ Ei Mi / Pa ……………………………………………………………[5.3].
where; Ei is embodied energy of 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.

The above data required for EPBP estimations, as obtained from different data sources - Danish model & Bath data- are shown below in table-5.7.

Table -5.7 Energy requirement data of 100MW OTEC for EPBP estimation

Inventory materials	Mass of materials (kg)*	Embodied Energy =Ei MJ/kg (Danish model)**	Embodied Energy =Ei MJ/kg (Bath data)***	Total embodied Energy =Ei*Mi MJ/kg (Danish model)	Total embodied energy=Ei*Mi (Bath data) MJ
Steel (includes different types)	4157000	25.65	56.7	106627050	235701900
Copper	270000	78.2	50	21114000	13500000
Iron	16817000	36.3	25	610457100	420425000
Plastics	14216000	45.7	80.5	649671200	1144388000
Cement	$75*10^6$	3.68	4.86	276000000	364500000
Grand Total	$11046*10^4$			1663869350	2178514900

* (Tahara *et al*. 2000); ** (Schleisner 2000); *** (Hammond & Jones 2008)

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The Energy Pay Back Period, estimated $==\sum$ Ei Mi / Pa
=1663869350 MJ/ (197.1*1000*3600)MJ =**2.35 years** (Danish model)
=2178514900 MJ / (197.1*1000*3600)MJ =**3.07 years** (Bath data)

5.2.5 Critical Appraisal of LCA & EA studies of OTEC

It is important to note that the OC-OTEC plant emits almost double the amount of CO_2 than that from CC-OTEC. Still it saves more than 90% emission than a coal fired power plant. However, there remains much scope of increasing CO_2 dissolution potential of surface ocean water, because of plankton inputs caused from the upwelling of cold water as discussed in section 5.2.1 (sequestering of CO_2) (Christopher & Barry 2008).

It could also be noted from the above studies that both GHG emission saving & CPBP values as well as EPBP results derived, depend on the type of model used for the study. This is because the LCA data derived depends on the process adopted, besides varying from country to country. In fact, wide variations in GHG emissions were observed for the Japanese model, though values of the two European countries like the Danish model or the Bath University data source were rather similar.

It is also to be added that the size of the OTEC plant would affect both GHG saving as well as the EPBP values, to a considerable extent.The inventory material requirement would not necessarily follow a linear relationship with the power generation capability. A 10MW plant's inventory materials are much more than $1/10^{th}$ of a 100 MW plant, though its power generation capability is $1/10^{th}$. This favours deployment of larger sized plants with higher power generation capability.

GHG emissions from LCA studies (not EPBP) would also vary widely, depending on the life of the plant considered. This invites important questions regarding the survivability of the OTEC plant, which has history of the entire plant being wiped out by tropical storms in small scale sea trials (Cohen 1982). If the life of OTEC with a 30 year life span is reduced to half (say 15 years), then its GHG saving would be affected accordingly with a doubling of CPBP value. This would also affect its economy to a great extent for lower life time power generation.

Thus there is a need for an optimization study for the size of the OTEC plant, with a larger power generation capability & at the same time ensuring its survivability to endure longer life of the plant.

5.3.0 Environmental Impact Assessment for OTEC deployment

The four environmental issues examined for studying EIA, are:

- The emission aspects.
- Effect on the Flora & Fauna.
- Hazards posed from OTEC's deployment (requiring preventive measures).
- Societal influences caused.

EIA tabulations made on above aspects are shown below in tables 5.8—5.11, for the above 4 environmental issues.

5.3.1 Emission Characteristics of OTEC.

The impacting parameters of the environmental issues which are of global concern are: the reduction that can be achieved for GHG emission like CO_2 and the acid gas like, SO_2. The effect of the former affecting global warming is global & rather permanent; whereas the effect of the latter is local & temporary (being washed down from acid rains). The results as obtained from LCA studies made in section 5.2.3 are shown below in table -5.8, given below.
.
Table-5.8 Emission characteristics of OTEC

Type of the OTEC	Emission Type	% emitted compared to Coal power plant.	% saved compared to Coal power plant
100MW CC-OTEC	CO_2	3.35	96.65
100MW OC-OTEC	CO_2	7.8	92.20
100MW Hybrid type	CO_2	4.7	95.30
100MW CC -OTEC	Acid gas like, SO_2	1.4	98.60

It is to be noted that the large scale application of OTEC reduces the CO_2 content of the atmospheric air widely. This is achieved not just by saving its emission with respect to fossil fuel power stations but it may increase the ocean's CO_2 dissolution potential appreciably. The cold water upwelling and thereafter discharging them in to the euphotic zone of the ocean with rich nutrients of plankton, would help CO_2 consumption in ocean's surface water appreciably, known as sequestering of CO_2 (vide also section 5.2.1, detailed discussions of which is made in section 5.5.4.1).

It may also be relevant to add that a little higher emission level from OC-OTEC (than that of CC-OTEC) can also be rectified by separating it with a scrubber at the de-aeration outlet point (where out gassed dissolved permanent gases O_2 & N_2, rich with $CO_2(g)$ are removed). This separated CO_2, dissolved in the scrubber can be fruitfully utilized in water bottling plants etc, (or other industrial products where CO_2 is required as one of the key raw materials).

Thus, it is evident that OTEC, being a renewable energy with the added phenomenon on the sequestration of CO_2, would have a great potential in reducing GHG emission levels, thereby addressing global warming problems to a large extent.

5.3.2 EIA on Flora and Fauna

In order to determine the influence of the large scale deployment of OTEC over ocean's flora and fauna, it is extremely important to identify the impacting parameters that are decisive in the growth of marine species.

The ocean may be considered to have overlapping temperature layers with varying water density extending to different depths in the ocean. Oceanic species of different types have their own preferred thermal zones of habitat. It is also a fact that most of the marine life thrives in the sunlit portion or euphotic zone in the ocean, though it constitutes a rather small portion of the bulk of ocean water.

The abundance of marine species would of course depend on the scope of availability of the nutrients in their habitat for survival and growth. Since the micro, nano and pico plankton- termed Phytoplankton, are building blocks in the food chain web of marine animals, the factors influencing their growth ultimately decides the growth and abundance of marine species in their concerned habitat (Quere *et al*. 2005). The growth of these plankton is facilitated in the upper euphotic zone of the ocean until a penetration of around 10% sunlight is availed. This extends to a depth of 20-80m from the surface depending on turbidity of the ocean concerned. The nutrients needed for the growth of Phytoplankton are dissolved nitrogen, phosphates and other mineral matters in the ocean water. Unless the nutrients are replenished, their growth stops (Quere *et al*. 2005).

Thus the impacting parameters influencing the growth of marine species would depend on:

- Temperature of the particular zone of the ocean water.
- Concentration of plankton with availability of sunlight.
- Availability of abundant nutrients such as dissolved mineral matter, nitrogen, phosphates etc. in the concerned zone of the ocean water.

The large production of shellfish was observed on the west coast of South America because of the upwelling of nutrient rich bottom cold water coming to the surface the Humboldt current of the ocean (Anderson 1998). Roels thereby could promote the production of fish by pumping water from 800m depth in the ocean (Roels 1980). He estimated that a 100MW OTEC plant, from its upwelling of 136m^3/sec of cold water, can yield a yearly production of 25, 000,000 kg shell fish meat (Roels 1980).
.
This single factor for the upwelling of cold water from depth, required for OTEC operation, would bring rich nutrients such as;, plankton and zoo-plankton, mineral matter, to the euphotic zone of the ocean. This would thereby facilitate the growth of all sea-animals, including fish population, which is a major protein food source for human consumption.

It is also to be noted that the upwelling of nutrient rich cold water may uplift some agents which might be toxic to certain marine species. They could be from harmful algal blooms (HABs) as well as from certain types of toxic Phytoplankton, depending on the site and seasonal variations (Pitcher *et al.* 2010). However, by and large the upwelling of cold water helps the overall growth of marine species (Takahashi 2003).

Chlorine feed in heat exchangers (to tackle the bio-fouling problem in OTEC plants), when spilled in to the ocean with mixed discharge of warm-cold sea water, might have a detrimental effect on marine life. But the required dose of Chlorine feed to a

maximum of 0.5 ppm, is well below the level prescribed by Environment Protection Agency's (EPA, USA) limit of chlorine pollution of species (Vega 1999).

In OC-OTEC as well as in Hybrid Type, evaporation of water to steam (though to a small extent) for availing potable water would enrich the mineral concentration of the outlet warm water in the mixed discharge. This makes OC-OTEC (& also Hybrid type) in rather more advantageous position for species growth than CC-OTEC, with the former providing a little more extra nutrients.

The running of 100MW OTEC requires a huge flow of warm and cold water feed (around $400m^3$/sec and $200m^3$/sec), which with its mixed discharge in the ocean has been compared as the "nominal flow of river Colorado in Pacific''(Vega 2002/3). This churning of the ocean with huge water flow at a temperature differential of around 20^0C round the clock is likely to create mist formation around the plant. This could then affect migratory birds and also of the bird population who are affected even from high wind towers if it falls in their migratory routes (Langton *et al*. 2011).

The laying of pipe lines for shore based plants may affect the Benthos population, which thrive in the ocean floor. But compared to the vast ocean floor area its effect would be marginal, in the vicinity of pipe line only.

The above points are kept in view in assessing the flora and fauna for CC-OTEC, OC--OTEC, as well as for Hybrid types. The flora and fauna thus considered for assessment are as below:

- Birds.
- Fish.
- Sea mammals.
- Plankton.
- Benthos community.

EIA impact assessment results for each of the above species, as derived from the above discussions on the influence of impacting parameters over them, are shown below in table 5.9 for all three types of OTEC devices.

Table-5.9 EIA score values of Flora and Fauna from OTEC deployment*

OTEC Type	Birds	Fish population	Sea mammals	Plankton	Benthos	Remarks
CC-OTEC	L-	M+	M+	H+	L-	OC-OTEC better growth than CC-OTEC, Hybrid in between
OC-OTEC	L-	M+	M+	H+	L -	
Hybrid type	L-	M+	M+	H+	L -	

*M+ = moderate positive; H+= high positive - may consist Phytoplankton of both types like, helpful (to species growth) as also toxic types; L - = low negative.

5.3.3 Hazard Posed from OTEC plants

In addition to the usual hazards as discussed in wave schemes,   the hazards posed particularly specific to OTEC system mostly originate from the following three sources:

- Inherent limitation in the construction of the OTEC device itself,   thereby off-setting its stability and survivability.
- Malfunctioning and/or failure of parts of the OTEC plant, requiring particular attention and periodic maintenance.
- Risk of causing huge damage to OTEC device, from extraneous factors like, natural disasters, sea storms /hurricanes/earthquakes etc; or collision of off-shore OTEC plant with other marine liners.

5.3.3.1 Preventive measures on hazards related to construction aspects of OTEC

The overhanging cold water pipes are to be attached through the central portion of the platform of the huge bodied OTEC plant, with the warm water and mixed discharge pipes fitted at two sides, ensuring stable C.G. of the structure (Bergman 1996). In fact, submersible OTEC devices with most of the structure submerged and C.G. below the ocean surface ensures better stability even in storms, though it involves higher cost with problems in O&M, and is still in the R&D stage of development (Takahashi 1999).

As per the norm of use in oil rigs-- the pipes should not to be rigidly attached to the OTEC platform, but should be kept flexible. It may then hang vertically, uncoupling from the platform which itself may swing violently in high storms (Anderson 1998). The construction of the pipes should be with flexible materials (rubber like substance known as elastomers) with jointed sections so that it does not yield from the stress of ocean currents (Cohen 1982).

The cable laying below a depth of 600 m poses a problem, for which in-situ manufacture of fuels like H_2, and/or NH_3, are recommended (Ryzin *et al*. 2005). This also saves the cost of long distance cables required and also averts transmission loss. But, this is still in the R&D stage.

Land-based plants are rather advantageous in this respect, requiring no mooring cost nor of cable laying for power transmission.

5.3.3.2 Malfunctioning of OTEC plant

The sources of malfunctioning of OTEC operation with measures to minimize them are enumerated below:

- Obviating bio-fouling of heat exchangers by chlorine injection as well as mechanical brushing periodically- minimizes the formation of scales so that the efficiency of heat exchangers are not affected.
- The Hazard from accidental leakage of $Cl_2(g)$ storage, may however affect plant workers for which in situ preparation for Cl_2 feed is suggested.

- Discharge of warm and cold water mix to be made to the right depth (> 60m), so that the heat availability resource of warm surface water layer is not affected by-cooler mixed water discharge.
- The NH_3 supply/storage (for CC-OTEC) should be properly secured, so that it does not cause leakages affecting plant workers.
- Adequate drainage/safety provision should be kept ready for sudden failures or leakages of the huge warm water /cold water pipe line. In case of pipe burst/leakage, plant's production as well as the safety of operational staff is affected.
- Usual precautions as used in usual steam power plants are to be maintained, though the risk in OTEC is much less even in OC-OTEC or Hybrid OTEC, since they only use low pressure steam.

It may be added that the above measures can only minimize the risk, if not altogether eliminating them.

5.3.3.3 Extraneous risk factors

The experience of construction with the operation and mooring of oil rigs, which are functioning without any break, despite storms and hurricanes in the ocean, is an important technological advancement, from which adequate countermeasure guidelines for OTEC schemes can be adopted. Of course there remains no fool-proof measure to counteract natural disasters. In fact, OTEC's early sea trial experiences are not encouraging with history of its earlier trial plants being wiped away by sea-storms. But land based plants provide better safety in this aspect.

Proper site selection should be made avoiding; earthquake prone zones and/or, storm prone zones, as far as practicable.

As regards averting collisions from the movement of ships, it is better to choose off-shore OTEC sites away from ship movement routes, as well as maintaining light signal for off-shore OTEC sites, with moving fog lights which could be visible and signalled from a distance.

5.3.3.4 Identification of all broad hazard types

Keeping in view the above perspective of impacting parameters as regards the hazards in OTEC deployment, the environmental hazard issues on OTEC, are identified as below:

- Survivability for land based plants [LB]
- Survivability for off-shore plants [OS]
- Survivability of submersible plants [SP]
- Malfunctioning of heat exchangers [HE]
- Leakages/failure in NH_3 storage [NH_3]
- Leakages /failure in warm/cold water pipe lines.[WP/CP]
- Leakages /failure of steam pipe line [SP]
- Leakages in the evaporator [Evaporator]
- Chance of collision for off-shore plant with other ocean liners [Collision]

- Failure in power production [Power failure]

EIA rating of above hazards posed over CC-OTEC, OC-OTEC and Hybrid OTEC plants, are tabulated below in table -5.10, keeping in view that the above stated preventive measures are adopted.

Table -5.10 EIA rating of Hazards posed for different OTEC types *

Environmental issues	CC-OTEC	OC-OTEC	Hybrid type	Remarks
Survivability LB	L -	L -	L-	Low/ marginal; for all 3 types
Survivability OS	M-	M-	M-	Moderate; same for all 3 types.
Survivability SP	L-	L-	L-	Better than [OS], but higher than [LB] plant; same for all types.
Malfunction HE	M-	L-	L-	DCC lowers HE of OC-OTEC; Hybrid in between OC-OTEC & CC-OTEC.
Leakage etc NH$_3$	L-	0	L-	None for OC-OTEC, rather lower in Hybrid than CC-OTEC.
Leakage etc WP/CP	M-	M-	M-	Same for all 3 types; moderate probability in its lower side.
Leakages etc SP	0	L-	L-	None for CC-OTEC, rather lower in Hybrid than OC-OTEC.
Leakages etc Evaporator	L-	L-	L-	Least for CC-OTEC; Hybrid rating in between OC-OTEC & CC-OTEC.
Collision	L -	L -	L -	Low/marginal; for all 3 types.
Power failure	L-	L -	L -	Lowest probability, but not zero.

* L- =low and negative; M- = moderately negative.

5.3.4 Societal Influence from OTEC's deployment

The societal impact from OTEC, in its various aspects should be judged both from a wider spectrum of global influence as well as from its local influence in the vicinity of OTEC plant deployment. Since OTEC opens up the availability of various by products, besides electricity, it also opens up the scope of employment generation, and making OTEC technology instrumental in improving the quality of life of the locality.

In addition, it ensures long term improvement in a much wider perspective with global implications from its environment friendly phenomenon, such as, an increase in sequestration of CO_2, as well as lowering the risk of coral bleaching.

The societal implication of the above input from OTEC, in addition to the aspects as regards noise pollution, visual impacts etc. have been discussed below.

5.3.4.1 Sequestering of CO_2

It has already been discussed in previous sections of LCA (section 5.2.1) as well as in flora & fauna (section 5.4.2), as to how the upwelling of cold water helps in increasing phytoplankton growth hugely. It then becomes instrumental in burying CO_2 deep in the ocean floor, with the carcass of dead marine species grown termed sequestering of CO_2. This phenomenon from the upwelling of water (needed for OTEC operation) could hugely increase the ocean's capacity for CO_2 consumption (Falkowski 1997) and thereby help in maintaining the CO_2 balance in a global atmosphere. It thus can help to address the global warming problem, much better than perhaps any other energy forms including other RE schemes.

It has been estimated that a suitably designed OTEC plant to up-well nutrient rich cold water to the maximum extent can sequester 10,000 metric tons of CO_2, per year per MW power generation (Christopher and Barry 2008).

5.3.4.2 Arresting Coral Bleaching

The increasing incidence of coral reef bleaching since the eighties, endangers many of the small island developing states [SIDS]. In fact, corals are sensitive to even small temperature changes and ocean level rises, with increasing trend of global warming. This phenomenon of coral bleaching is caused mainly from global warming, acid rains etc. any imbalance in the atmosphere. A sustained temperature rise of even 1—2 ^{0}C, causing a simultaneous sea level rise, may be lethal to most of the coral islands between 20-30°N (Buchheim n.d.). OTEC application has good potential to counter this problem of Coral Bleaching which is vital for the survival of SIDS (Binger n. d.).

It may be added that in addition to the saving of CO_2 as discussed in previous sections, saving of acid gas like SO_2 per year (vide also section 5.2.3.2 & table 5.2), from application of OTEC would be = net annual power generation of OTEC in kWh*(coal power's SO_2 emission/kWh- OTEC's SO_2 emission/kWh
= 197.1GWh*[(7.8-0.11)g/kWh*] = **1515.7 Mt.**

Such a lowering of acid gas formation, in addition to the CO_2 saving potential of OTEC plants, would be helpful in mitigating the problem of Coral Bleaching to a great extent (Binger n. d.).

5.3.4.3 Scope of Employment Generation from OTEC `

OTEC opens up the scope of a manpower requirement from the following four sources:

1. Construction of the huge bodied OTEC units, including its accessories, would require a large amount of manpower deployment. To cite an example it may be relevant to add that, even the global quantum of cable manufacture has to be increased if cable lines are to be accommodated for off-shore OTEC plants, for the transmission of power to the grid line from OTEC plant site (Cohen 1982).

2. OTEC, unlike most other RE systems, would require manpower deployment for running the plant - in addition to the maintenance, repair and manufacture of spare parts.

3. The potential of producing number of by-products that can be generated from the operation of OTEC, such as potable water, carbonated water offers scope for opening up a chemical hub on OTEC's operational sites. This would facilitate employment generation to a great extent. OC-OTEC and Hybrid OTEC would be more advantageous on this count.

4. Possibly an important point is the scope of increment of mariculture in quality and quantity offered from OTEC. This would have the potential of large employment generation, in addition to improving the quality of life in the locality.

It may also be added that power production itself opens up avenues for employment generation with economic growth.

5.3.4.4 Sources of Noise Pollution

In order to reduce the cost of cold water pipe (CWP) its diameter is kept on the lower side. But at the same time it is required to maintain huge water flow. This is achieved by increased water flow velocity, usually more than 6m/s (Takahashi 2003). Such high velocity water flow would cause vibrations in CWP causing appreciable noise, except in the case of submersible plants. In the case of the off-shore plants, the operational workers would experience same noise from CWP.

Source of noise experienced from Warm water pipe (WWP) lines may not initiate appreciable noise for CC-OTEC. But for OC-OTEC, or for Hybrid types, where warm water is used for steam formation, there could be appreciable noise caused from its sudden flush of huge masses of warm water through the narrow spouts of the evaporator. The discharge pipe line is another source of noise generation for all types of OTEC plants. The heat exchangers are however likely to create less noise.

It may be relevant to add that such noise pollution for high capacity OTEC plants, is likely to be experienced by the working staff,; but not by the people in the vicinity, even in the case of land based plants. In extreme cases a sound dampener may be required to be fitted at vulnerable sound producing points, for creating a tolerable work environment of the OTEC plant operators.

5.3.4.5 Visual Impact from OTEC implantation

It has been detailed in section 5.3.2 (paragraph 9) that the churning of ocean from OTEC operation is likely to cause a cloud of mist surrounding an OTEC plant, the intensity of which may be more for off-shore plants causing a visual impact. In fact, it would need fog lights for sighting the position of off-shore OTEC plants signalling to other vessels in the sea as a safe guard against collision.

But the above visual problem, for land-based plants is likely to affect tourist attraction to the sea-shore.

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5.3.4.6 EIA Rating on Societal Impact

Keeping in view the above impacting parameters, the different environmental issues over societal aspects could be identified as below:

- Increase in ocean's CO_2 dissolution capacity, from sequestering of CO_2 from cold water feed of OTEC and thereby maintaining balance in global warming [**CO_2 Seq.).**
- Arresting Coral Bleaching, particularly in the case of Small Island Developing States [**Reduction C.B. - SIDS**].
- Scope of improving the quality of life for the locality from increased marine and agricultural food production –both quality wise and quantity wise [**Food Production**].
- Possibility of destabilizing the eco-balance, like affecting the coastline mangroves etc. from unplanned mariculture extended to a large extent [**Destabilization Eco-balance**]
- Noise pollution from OTEC operation [**Noise pollution**].
- Visual Impact affecting the tourist economy for land based OTEC schemes [**Visual Impact**]
- Opening up scope for the abundant supplies for availing potable water/carbonized water with virtually no extra cost required [**Potable water**].
- Scope for developing chemical hubs nearby from availability of different by products with scope for the cheap supply of different chemicals [**By product chemicals**].
- Scope for employment generation [**Employment**].
- Scope for improving the quality of life with enhanced food production, improvement in tourism economy and power generation, particularly in SIDS [**SIDS –Quality life**].
- Scope for economic growth from the power generation availed from OTEC (**Quality of life**)

The EIA rating of the above issues, as determined from a societal perspective, are appended below in table -5.11, for all three types of OTEC schemes.

Table -5.11 EIA Score on impacting parameters on Societal Issues for OTEC*

Different societal issues affected	OC-OTEC	Hybrid Type	CC-OTEC	Remarks
CO$_2$Seq. GWP	M+	M+	M+	Same for all, moderate, +ve
Reduction CB - SIDS	H+	H+	H+	High for SIDS, +ve
Food production	H+	H+	H+	Potentially high for all, +ve
Destabilize eco-balance	L -	L -	L -	Low but -ve
Noise pollution	L-	L-	L-	Low -ve; lowest for CC-OTEC
Visual Impact	L -	L -	L -	Only for land based ones ,-ve
Potable water	H+	M+	0	+ve , high, Nil for CC-OTEC
By product chemicals	M+	M+	L+	Less in CC-OTEC +ve for all
Employment	M+	M+	L+	Moderate +ve, less in CC -OTEC
Quality life - SIDs etc	M+	M+	M+	Moderate +ve for all types

*H+=high positive; M+ =moderate positive; L- =low negative, L+ = low positive..

In fact, OTEC with its by product availability and massive power production capability, have immense potential for addressing many of the problems, and are required to be sorted out for sustainable development, with no pressure on land use.

5.4.0 Economic Issues involved

OTEC's economy, covering all three types of OTEC systems like, CC-OTEC, OC-OTEC or, Hybrid types, is required to be judged from the following two aspects of OTEC schemes. They are:

- Assessment with the commonly used economic tools developed for OE systems, from its power generation aspects.
- Scope of availability of the number of byproducts from OTEC schemes, besides electricity generation, which is particularly unique for OTEC systems.

The methodology adopted for the economic evaluation of OTEC schemes, from both the above two perspective are detailed below.

5.4.1 Economy evaluation on power generation aspects

The usual economic indices employed for wave schemes, based from NPV evaluation methods etc, are also used for OTEC schemes. The methodology of their

determination is shown from the case study of a 100 MW OTEC. This includes studies as regards the following indices:

- Present value of cost involved covering the operational costs in the entire life period.
- Present value of energy generated in its life time.
- Cost of electricity generated per kWh power generation.
- Net cash generated annually.
- Simple payback period of the money invested.
- Internal rate of return.
- Comparative studies with RPC (Relative Product Cost).

5.4.1.1 Case study of 100MW OTEC plant with economy tools on NPV concept

The capital cost of 100MW CC-OTEC was reported to be $242.1*$10^6$ (Ravindran 1999). On conversion to GBP this value would be = £ 242.1*10^6/1.88 =**£128.776*10^6**; since the average exchange rate of GBP to US dollar in August 2008 is: $1.88= £1 (x-rates.com 2008)

The operational and maintenance cost are reported to incur an annual expenditure of 1.5% of the capital cost (Vega 1992). The annual power generation of the said 100MW CC-OTEC has been shown to be 197.1 GWh, and life period to be 30 years, as per the estimations made in previous section 5.2.2.

Based on the above base data, the economic indices as determined considering 8% discount rate and 30 years life time, are given below.

Capital cost =Cc = £ 128, 776, 000
Annual O&M cost =Co= £ 128, 776, 000*0.015= £1931640
Annual Production of electricity =Ea =197.1GWh =197,100,000kWh
Discount factor =DF=$[(1+0.08)^{30}-1]/[0.08*(1+0.08)^{30}]$=11.25778, considering 8% discount rate with 30 years life.

Present value of cost =Cc+ Co*discount factor = £ 150,521,978
Present value of energy =197100000*11.25778=221,890,8438kWh
Cost/kWh =Present value of cost / Present value of energy
= **6.8 p/kWh.**

Net cash generated/year =Nc =£197,100,000*0.068 - £1931640 =£114,71160
Simple payback period = (Cc+ Co) **/** (Annual electricity production*cost /kWh)
=**9.8years**.

It may be relevant to add, that all these economic indices for the particular case of 100MW CC-OTEC are a function of the discount factor; since the mother data 'Cc', 'Co' and annual energy production, remain unaltered. Variation of this discount factor is caused from variations in 'discount rate 'R', and also of the life time "t''.

Hence, in order to determine and cross check the type of variations that can occur in these economic indices, data generation was made (following the above methodology

of estimating economy tools) by changing the discount rates, maintaining a constant life time period of 30 years; which is the supposed life period of OTEC.

On the other hand, economic indices were also determined at varied life periods of the OTEC, maintaining a constant discount rate of 8%. The results, of the former are tabulated in table 5.12 and of the latter in table 5.13, as shown below.

Table 5.12 Economy indices of 100MW CC-OTEC at varied discount rates with 30 yrs life.

Discount percent	NPV cost (£)	NPV energy (kWh)	Cost in p/kWh	SPBP (years)
5	158470039	3029909895	5.2	12.67
8	150521978	2218908438	6.8	9.77
10	146985404	1858044749	7.9	8.38
12	144335715	1587676766	9.1	7.29
15	141459109	1294154658	10.9	6.07
20	138393511	981348286	14.1	4.71

Table-5.13 Economy indices of 100MW CC-OTEC at varied life in yrs, at 8% discount rate.

Life in years	NPV cost (£)	NPV energy (kWh)	Cost in p/kWh	SPBP (years)
10	141737459	1322556768	10.7	6.19
15	145309834	1687073508	8.6	7.69
20	147741131	1935157365	7.6	8.69
30	150521978	2218908438	6.8	9.77
40	151810054	2350340631	6.4	1027
50	152406679	2411218908	6.3	10.49

It could be noted from the above tables that cost in p/kWh of power generation varied between 5p and 14p/kWh, with simple payback period (SPBP) varying between 5 and 12 years. SPBP obviously is related inversely with the cost/kWh.

The relationship between cost/kWh with discount rates as well as with different life periods, are shown below in fig.5.4 & fig. 5.5, respectively.
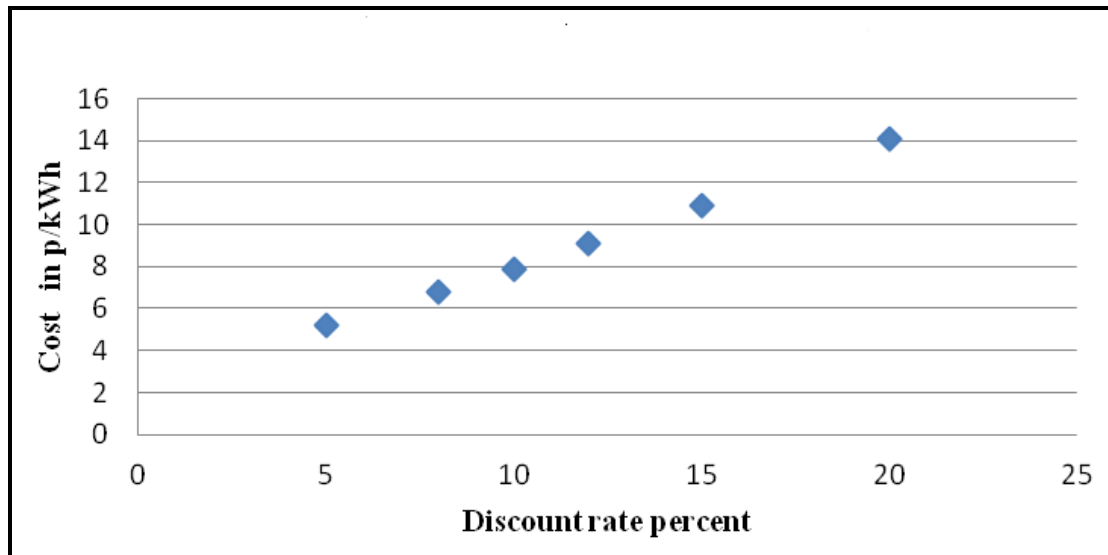
Fig. 5.4 Cost/kWh vs. discount rate percent of 100MW CC-OTEC at 30 years life.
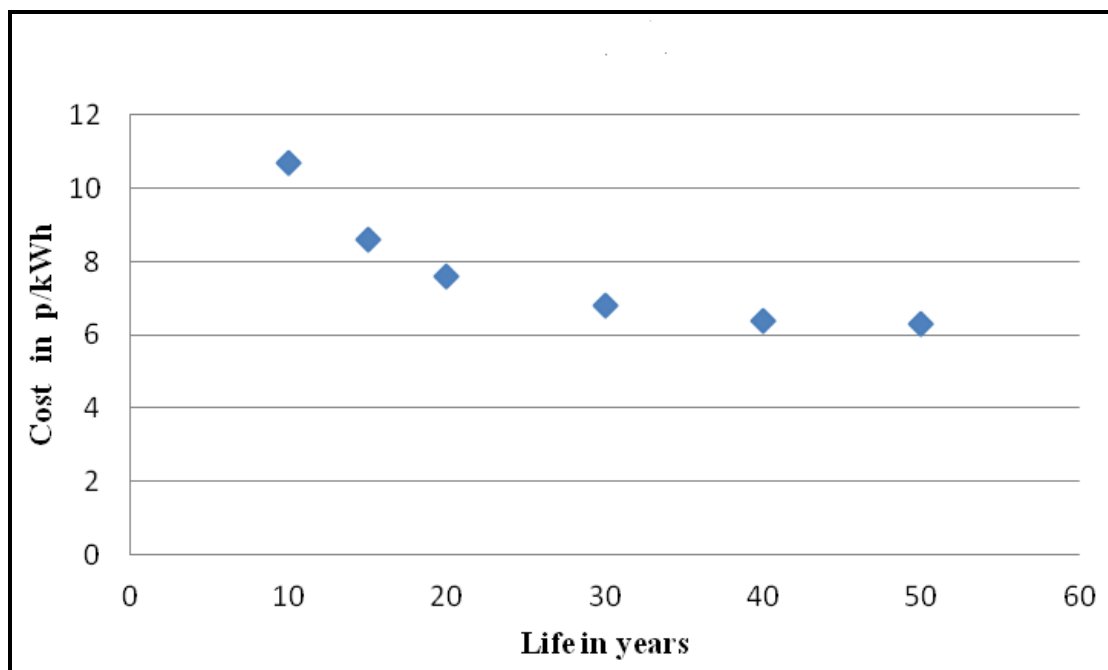
Fig.5.5 Cost in p/kWh vs. life in yrs for 100MW CC- OTEC at 8% discount rate.

It could be observed from fig.5.4 that like the WECs, costs in p/kWh show virtually a linear relationship with respective discount rates, showing higher cost/kWh with increase in discount rates, for obvious reasons.

As regards the relationship between life periods over cost/kWh is concerned, it is considered to be an important economic criterion, in view of the fact that OTEC plants have a history of entire plants being wiped away from tropical storms. Hence it was considered important to evaluate, the cut off limit of life period (if any), below which the cost/kWh would escalate sharply. Thus cost/kWh at life periods ranging from 10-50 years was evaluated, and the nature of change has been compared in fig.5.5. It could be noted from the above figure that, like the WECs, in the case of

OTEC also the break -even point may be considered to be of 30 years, below which the cost sharply escalates; but above which cost reduction/kWh power generation is not that sharp. This cut off limit of 30 years life may be considered to be an important data to the designers of OTEC plants.

Corroboration of the above cut off limit, giving the break-even point of life, was sought for from another important economic tool, IRR percent evaluations as well, the methodology of determination of which is shown below.

Based on the concept of IRR, NPV =0, at IRR (Appendix 2).
Thus $-Cc + Nc *DF = 0$ at IRR; where Nc is the net cash generated, DF is the discount factor.
By transposing, the above equation would assume the form:
At IRR, $DF – Cc/Nc =0$

By a trial and error method of estimating at different discount rates, if we get positive value for one, say V+, and negative value for the other, say V-; then by computation in between value of discount rate, at which NPV would be zero i.e. IRR can be determined.

Nc for 8% discount rate and life 30 years= £ 114, 71160 (previously determined).

V+ = 0.03172 at 8% discount rate, and V- = -1.79915 at 10% discount rate.

Hence the IRR% with zero value, would lie above 8% but below 10%; which computed from above values of V+ & V-, would be
=8+ 0.03172*(0.10-0.08)*100)/(1.2361-(-1.4079)= **8.03%**

Similarly, IRR% could also be determined for life times of 20 years, 40 years and 50 years as well; the results of which including the value of IRR shown for 30 years life, is tabulated in table 5.14, given below. The nature of change of IRR% with change in life period in years considered at 8% discount rate has also been shown below in fig.5.6.

Table 5.14 Life of CC-OTEC vs. IRR percent, computed at 8% discount rate

Life of CC-OTEC in years	IRR percent
20	6.403
30	8.03
40	8.76
50	9.03
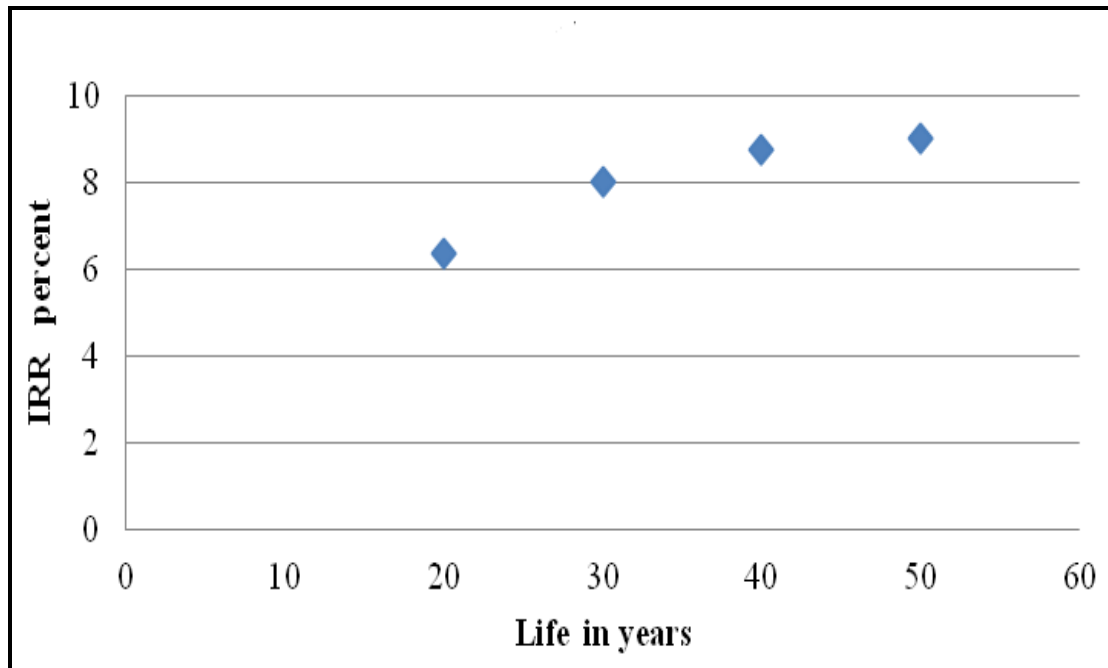
Fig. 5.6 Relationship of IRR% with life in yrs of 100MW CC-OTEC at 8% discount rate.

It would be evident from fig 5.6, that increment of IRR percent is quite sharp below 30 years life of 100MW CC-OTEC. But above 30 years life this increasing trend is not that sharp, suggesting 30 years to be the break-even point in deciding economic viability; as also shown in fig. 5.5 with the other economic index on cost/kWh vs. life. Both these economic indices, cost/kWh as well as IRR% thus confirm 30 years to be the break-even point in maintaining design life of OTEC for achieving economic viability.

It may be relevant to add here that in the case of WECs like, the Wave Dragon and Pelamis, not only a break-even point on economic viability was noted, but the value also coincided with the one noted for 100MW CC-OTEC, which is 30 years.

5.4.1.2 RPC ratios

As regards RPC values for use as an economic tool, it would have relevance only in undertaking comparative studies with other schemes. It does not give any absolute value, but indicates a ratio, comparing cost ratios with respect to relative annual power production for different types ocean energy (OE) systems.

Thus, it becomes independent of life period or, discount rates, or cost quotations made by concerned manufacturers, for respective OE devices. It broadly compares mark up cost (cost without profit) for different types OE systems.

The methodology adopted for estimating the RPC ratio in case of 100 MW OTEC devices is similar to the one as followed for Wave schemes, based only from annual energy production data and cost ratios of inventory materials. Thus the data employed are 100MW OTEC's net annual energy production of 197.1GWh; and cost ratios of different inventory items were estimated, as per table 4.32 (chapter 4), from the market survey]. The results as estimated are shown below in table-5.15.

Table-5.15 RPC ratios of 100MW OTEC.

Materials	*RPC ratios [I_{rpc}] (a)	*Mass in kg (b)	Relative product cost (a×b)
Steel (special)	2.5	4157000	10392500
Copper	3	270000	810000
Plastic/HDPE	1.6	14216000	22745600
Iron	1.3	16817000	21862100
Concrete	1	75000000	75000000
Grand Total		110460000	130810200
			0.66367428
Weight ratios/kWh		**0.56042618**	

* <www.metalprices.com> [26.12.2009] ** (Tahara et al 2000).

It may be presumed that the cost ratios compare the product cost of the OE systems, whereas weight ratios may be considered to make a broad comparison as regards transport and installation cost ratios for different type of OE devices.

5.5 Prospects on potential of by product availability from OTEC

The prospect of by-product availability from OTEC, if pursued with necessary R&D efforts, may perhaps prove to be more lucrative than the power generated from it. The scope of the variety of by products from OTEC with the possibility of deriving economic advantages, are listed as below:

1. Availability of desalinated potable water, from OC-OTEC or, Hybrid OTEC operation
2. Increasing scope of availability of mari-culture proteins, agricultural products etc. from cold water feed and/or mixed water discharge feed, to land or water bodies of concerned locality in OTEC deployment site
3. Utilizing cold water for air conditioning, or for refrigerant purpose with much less power requirement
4. Possibility for Production of Oxygen rich air, soda water / CO_2 dissolved water, etc. as by products
5. Scope of generation of Chemicals like Soda ash, Urea, CH_3OH & Hydrocarbons from OTEC power, in addition to H_2 type fuels and NH_3.

A brief description of above points giving their advantages and also of the technical challenges, are discussed in subsequent sections.

5.5.1 Potable water

It is known that considering OTEC's efficiency to be 2.5%, 40 units of thermal energy would be required to generate 1 unit of electricity. Thus warm water circulation of an amount $400m^3$/sec at around 20^OC temperature differential is required for a 100MW OTEC plant (Vega 2002b). With 1%--0.5% of this water being evaporated to steam (required for running the turbine of the 100MW OC-

OTEC's generator), it would have the potential to produce 4 m^3 to 2m^3 potable water per second, from the condensation of the steam in the condenser of the plant.

With this premise, production of potable water from 100MW OC-OTEC can be expected to be
= 0.005*400*24*3600 m^3/day, for round the clock plant operation.
=**172800 m^3/day** for round the clock operation.

It has been claimed that a 1.2MW OC-OTEC could yield desalinated water amounting to 2200m^3/day (Vega 1999). This by-product yield is said to be increased to nearly double the amount, diverting part of the generated power for potable water production, yielding a reduced net power generation of 1.1MW, but with an increased amount of the desalinated water as a by-product to an amount of5150m^3/day (Vega 1999). In case of a Hybrid plant, potable water production in its 1st stage of operation has been estimated to be 2281m^3/day for net power production of 5.1MW, which in the 2nd stage could yield 4 times the above amount (Vega 1999).

In fact, in an actual sea trial undertaken for OC-OTEC between1993-98, showed it could produce 0.4l /sec of desalinated potable water as a byproduct from its net electricity production of just 103kW net power (Vega 1999).

Considering the cost of potable water to be around $2/m^3 (Anderson 1998), the annual return from this by product of potable water alone, from a 100 MW OC-OTEC (or, Hybrid OTEC) can be considered to be = £172800*0.53*365
=**£66, 856320/year**; since $1=£0.53, as per the average exchange rate of August, 2008 <http://www.rates.com/d/USD/GBP/hist2008.html> [4.10.11]

5.5.2 Growth of mari-culture & agricultural products

All three types of OTEC plants (land based ones mainly), has the potential to improve considerable growth of both mari-culture and agricultural products, from their enriched nutrient laden up-welled cold water. This improvement could be achieved both in quality as well as in quantity.

As regards agricultural growth is concerned, the nutrient rich cold water feed may increase the quantity wise growth for different agricultural products. Particularly profitable are   the bio-pharmaceutical agricultural products and natural pigments like Carotoids, etc. (Anderson 1998).

As regards the mari-culture farming, it includes production of lobster, salmon, crabs, tilapia, shell fish etc (Binger n.d.)Studies conducted by University of West Indies Centre for Environment and Development (UWICED) showed that using up-welled nutrient rich water, the earning from mariculture could be increased more than 10 times than that earned from banana plantation and 30 times than that for sugar plantation, from equivalent land area used (Binger n. d.).

It had been estimated that annual growth of shellfish meat from the utilization of nutrient rich cold water of a 100MW OTEC plant, could be around 25,000,000 kg (Cohen 1982). It had also been estimated that implantation of 10,000 OTEC plants of 100MW capacity, would be able to meet the entire annual protein requirement for 2

billion people, considering an animal protein intake per person to be 35g/day (Takahashi 2003).

It needs however to be noted as a caution, that an unbalanced growth of mariculture, may be detrimental to the mangroves and other eco systems, vital for the stability of the coastal area (Ocean Thermal Energy Converter, Celestopia n.d.).

On the other side, simultaneous increased growth of algae/kelp, from nutrient rich cold water feed may affect certain species, and thus may affect the sea water's panorama. It is also a fact that along with mineral matter and other nutrients as may be up-welled from OTEC operations, simultaneous presence of certain toxic materials detrimental to certain marine species, cannot be completely ruled out; unless proven from commercial scale field trials.

Too high a productivity of species with too much cold water upwelling and altering atmospheric CO_2 level to too low a limit (from sequestering of CO_2) is also not desirable. It is the ocean's pH level and its surface water's CO_2 dissolution limit that strike a balance in global climate –arresting both global warming as well as cooling beyond a limit. This balance should not to be allowed to be disturbed too far.

5.5.3 Cold storage/Air conditioning with up-welled cold water

It has been suggested that up-welled cold water, availed free as by product from all types of OTEC plants, could be fruitfully used as chilling fluid for cold storage and/or, air conditioning plants.

In fact, in order to run a 1.1 MW OC-OTEC plant, the power requirement for up-welling the cold water feed of the amount 3085kg/sec at 4^0C = 313kW =313000J/s (Takahashi & Trenka 1996). The energy required to cool the above quantity of water from ambient level of 20^0C to 4^0C ≥3085*4.186*1000*(20-4) J/s ≥ 206620960J/s. This is more than 660 times the power required for upwelling the same amount of water to the same temperature level of 4^0C. Thus, if this cold water or part of it is utilised for chilling plants, like cold storage or air conditioning plants (cooling only), we save more than 600 times the power required for running the cold storage/air-conditioner or having a ready chilled fluid as OTEC's by product.

It has been shown by Vega that only $1m^3$/s of deep ocean water flow at 7^0C , requiring 360kWe power would be enough for air-conditioning 5800 rooms in a hotel, saving power to the extent of 5000kWe (Vega 1995a).

It would be obvious that such advantage of utilizing up-welled cold water for cold storage/air conditioning would be economic for land-based plants only.

5.5.4 Production of O_2 enriched air and CO_2 (g) as industrial raw material.

It may be of interest to examine the scope of availability of larger amounts of $CO_2(g)$ as a raw material of industrial products (water bottling plants etc) as well as oxygen enriched air as a by-product, from evolution of the gases like, O_2, N_2, and CO_2, from OTEC's operation.

In fact, in OC-OTEC and in Hybrid operations, water soluble gases are evolved from warm water feed, due to steam formation from it, which is usually 0.5% --1% of the total water feed. The other source is from the cold water feed in the condenser having DCC type heat exchangers, because of the elevation of the up-welled cold water temperature as well as from the release of pressure, being raised from the bottom of the sea. The released gases containing O_2, N_2 and CO_2, are sucked out in the de-aeration chamber, so that they do not impair the efficiency of the DCC heat exchanger of the condenser.

A typical hypothetical case study has been undertaken for a 100MW OC-OTEC, to determine the quantity and relative percentage of these gases which is virtually air, enriched with O_2 and CO_2, but with N2 percentage less than that of air. This is because of the fact that the dissolution of gases O_2, N_2 & CO_2 in the ocean remains in the proportion of 7mg/l, 12.5mg/l & 90mg/l, respectively (Floor 2006).

It is a fact that a 100MW OC-OTEC would require a warm & cold water feed of $400m^3$/s & $200m^3$/s, respectively; with around 0.5% of warm water being evaporated and sucked out in the de-aeration chamber (Vega 1999). Also part of the dissolved gases of up-welled cold water would evolve in the DCC condenser, from the release of pressure and elevation of temperature; the amount of which is presumed to be 0.4% of cold water feed.

Based on the above premise, relative production of the gases may be estimated from 100MW OC-OTEC operation/day, whose net power production/day would obviously be 0.54GWh (or 197.1GWh/365).

Gas release from warm water feed:

O_2 = 400*0.005*0.007*3600*24=1209.6kg/day=1209.6kg/0.54GWH= 2.24g/kWh
N_2 = 400*0.005*0.0125*3600*24=2160 kg/day= 2160kg / 0.54 GWh = 4g/kWh
CO_2= 400*0.005*0.09*3600*24 =15552 kg/day= 15552kg/ 0.54GWh=28.8g/kWh

Gas release from cold water feed:

O_2 =200*0.004*0.007*3600*24=483.84 kg/day = 483.84kg/0.54GWh =0..9g/kWh
N_2 =200*0.004*0.0125*3600*24 = 864   kg/day = 864kg/0.54GWh =1.6g/kWh
CO_2=200*0.004*0.09*3600*24=6220.8 kg/day =6220.8kg/0.54GWh = 11.52g/kWh

Total evolution of gases:

O_2=1209.6+483.84=1693.44kg/day=(2.24+0.9) =3.14g/kWh   = 0.098mole/kWh
N_2 =2160+864   = 3024kg/day   =(4+1.6)   = 5.6 g/kWh   = 0.2   mole/kWh
CO_2=15552+6220.8=21772.8kg/day=28.8+11.52= **40.32g/kWh** =0.916mole/kWh

Thus, the volume proportion of these gases are: O_2: N_2:CO_2:: 0.098:0.2:0.916 or,
 8.1%, 16.5% & 75.4%, respectively.

The high annual yield of CO_2 amounting to 21772.8*365 = **7947072kg/year,** can be utilised not only for water bottling plants etc. or the availed potable water from OC-

OTEC, but also in the manufacture of several by-products; - constructing necessary infra-structure; wherein CO_2 is one of the ingredient raw materials.

Oxygen enriched air, as obtained could also find application in various fields.

It may be also be relevant to point out that the results on CO_2 emission of 40.32g/kWh, obtained from the theoretical deductions made as above, conform well with that obtained from experimental studies of Green & Guenther (1990) using HMTSTA apparatus, whose CO_2 emission from OC-OTEC were observed to be 38.5g/kWh. In the case of Hybrid devices, CO_2 emission would only be from warm water feed; that too is nearly half the value produced from OC-OTEC. Thus it would be around 14.4g/kWh, whereas for CC-OTEC there is no scope for CO_2 evolution. These results also conform well to the values of Green & Guenther's results of 11.7g/kWh & <1g/kWh CO_2 emission in the operational stages for Hybrid & CC-OTEC types, respectively (Green & Guenther 1990).

5.5.5 Chemicals from OTEC

The above stated by-products availed from OTEC plants are produced as by-products because of the operational characteristic of OTEC. But there are certain products (chemicals), whose production is at the expense of electricity produced from OTEC, and are considered more profitable than just the production of electricity only. This includes production of fuels like H_2 and also chemicals like NH_3 etc from grazing type OTEC, which however, is in the conceptual stage (Ryzin *et al*. 2005). In fact CO_2 (g) availed from OC-OTEC can also be utilized to produce chemicals whose ingredient raw material is CO_2 (g)- like Urea, Soda ash, etc. Based on availability of H_2, it may also be useful for the production of Methyl alcohol with scope for synthesizing a host of different petrochemical products. A brief account of them is detailed below.
.
5.5.5.1 Soda ash

In addition to the prospect of using the concentrated form of CO_2 (g) in water bottling plants, the other application could be in manufacturing Na_2CO_3, obtained by scrubbing CO_2 (g) (as discussed in section 5.5.4) with Na OH, as per the reaction: $CO_2 + 2NaOH = Na_2CO_3 + H_2O$ or, 44g CO_2 would produce 106g. Na_2CO_3.

Thus 7947072 kg CO_2 produced /yr from a 100MW OC-OTEC (as estimated in section 5.5.4) could yield Na_2CO_3 to an amount =7947072×106/44 kg/yr =**19145219 kg/yr**

But such availability of soda ash can only be possible provided the concentrated form of CO_2 (g) is not used in water bottling plants or, for producing other chemicals.

They may be obtained only for OC-OTEC and to some extent from Hybrid types, but none from CC-OTEC.

5.5.5.2 Hydrogen

It has been reported that instead of transporting OTEC generated power, laying long sub-sea cables at 1000m depth, it may be a cheaper and better option to use that power to split water and make *in-situ* generation of hydrogen, considered the most environment friendly fuel (Ryzin *et al.* 2005). There have been many R&D studies suggesting that the electrical input for Hydrogen production by electrolysis from water splitting could be lowered with higher H_2 production. The advanced technology suggests using solid polymer electrochemical cell (SPE) with perfluorinated membrane as electrolyte (Nuttall 1977). Pure water (de-ionized water) is used to generate dry H_2 (g) from it.

It has been reported from a hypothetical deduction that a 64 MW OTEC plant-ship has the potential to manufacture 8270tons of H_2 / yr (Ryzin *et al.* 2005). In that case, it may be logical to deduce that a 100MW OTEC plant would have the potential for annual production of H_2 to an amount= $(100/64) \times 8270 \times 1000$kg /yr = **12921875 kg/yr =35402 kg/day** .

Obviously, such production of Hydrogen may be available from all 3 OTEC types, the amount of which is dependent solely on OTEC plant's net power production.

5.5.5.3 Ammonia

It is to be noted that the biggest challenge of hydrogen (g) production lies in its storage, so that there is minimum leakage during transportation and it reaching the end user. On the other side, the energy required for transporting liquefied Hydrogen would be nearly 10 times that of compressed hydrogen (g) (Ryzin *et al.* 2005). A r cheaper option suggests transforming this hydrogen(g) to NH_3(liq.) using Haber's synthesis as per the reaction: $N_2+3H_2=2NH_3$; in the presence of a suitable catalyst. nitrogen required for such ammonia production may be availed by stripping off oxygen from air.

This in-situ produced NH_3 (liq.) can then be transported as a hydrogen enriched chemical and/or as raw material for synthesis of various other chemicals.

Since as per stoichiometric equation in Haber's synthesis of NH_3 production, 6g of H_2 produces 2×17g. of $NH_3= 34$g of NH_3, hence its production from a 100MW OTEC would be $=34 \times 12921875/6$ kg /yr =**73223958kg/yr =200614 kg/day**

It may be needless to point out that, like the production of hydrogen(g), ammonia can also be availed for all the 3 types of OTEC plants: OC-OTEC, CC-OTEC as well as for the Hybrid types.

5.5.5.4 Urea

This huge production of NH_3 (liq.) can fruitfully be utilized to make *in situ* production of various other chemicals, like the nitrogen rich fertilizer urea, taking advantage of the production of a highly concentrated form of CO_2(g) produced as by product from OC-OTEC . In fact, the present practice for commercial production

of urea, requires ammonia and CO_2 (g) as raw materials. Both used to be derived from fossil fuel sources, like coal and/or natural gas.

Urea formation from these two raw materials proceeds as per the following reaction: $2NH_3 + CO_2 = H_2NCOONH_4$ [ammonium carbamate] = $(NH_2)_2CO$[urea] + H_2O [both reactions are exothermic in nature].

Thus, as per the above equation 44g CO_2 (g) interacting with 34g NH_3 can produce 60g Urea, in presence of suitable catalyst.

Since annual production of CO_2 (g) from OC-OTEC is 7947072 kg/year, as per estimations in section 5.5.4, it could interact with 7947072 × 34/44 kg of ammonia, or 6140919kg ammonia to produce 7947072×60/44kg urea
= **10836916 kg urea/year**

Since the cost/tonne of urea is $240/tonne.
<http://www.icis.com/V2/Chemicals/9076558/urea/pricing.html> [2nd March 2010].
i.e. £127 /tonne, considering $1 =£0.53 (vide section 5.5.1, last Para), hence annual revenue as may be earned from above amount of Urea production could be
=£127×10836916/1000/yr = **£1376288/yr**

The total production of ammonia from 100MW OTEC being 219671875 kg/yr (shown in previous section 5.5.5.3); the balance ammonia availed after Urea production would amount to:
=(219671875- 6140919)kg/yr =213530956 kg/yr after urea produced from it.

Price of ammonia (liq.)/ton being $230/ton availed from:
<http://www.icis.com/V2/chemicals/9075153/ammonia/pricing.html>
[6th March 2010] or, equivalent to £122/ton (considering $1=£0.53; vide section 5.5.1 last Para); in that case the price of surplus ammonia (liq.), left after urea production from OC-OTEC would be =£213530956×122/1000 = **£26050777/year**

Thus the total revenue that can be earned from100MW OC- OTEC from urea production and surplus ammonia production could be = £ (1376288+26050777)
= £27427065/year

However, such production of urea can only be availed from OC-OTEC and partly from Hybrid OTEC plants, but none from CC-OTEC having no by-product availability of concentrated form of CO_2 (g).

In the case of CC-OTEC, the revenue earned could be solely from Ammonia production, price of which could be= **£219671875×122/1000=26799969/year** which can however, be earned for all types of OTEC plants.

In the case of OC-OTEC however (and to some extent for Hybrid types), with the scope of the additional advantage for Urea production, it can earn an extra revenue of the amount
=£(28494719- 27898328) = **£ 627096 / year**

OC-OTEC (to some extent Hybrid Type as well) can also earn additional revenue from potable water production, as elucidated in section 5.5.1.

In addition to the above, all OTEC plants by virtue of their possibility of Hydrogen production can synthesize, host of chemicals including the petrochemicals, as discussed in subsequent section.

5.5.5.5 Methanol & other petrochemical products

Methanol can also be manufactured as another by product material from H_2, and this can be obtained by electrolysis of water utilizing the power generated from OTEC. The reaction would be the well known synthesis of methanol from interaction of Hydrogen with CO_2, as per the following reaction in presence of $Cu/ZnO/Al_2O_3$ catalyst, viz. $CO_2 + 3H_2 = CH_3OH + H_2O$. (Avery 1984). A US patent No-4476249; suggests it to be prepared from interaction of H_2 with CO, in presence of suitable catalyst; CO is said to be prepared processing CO_2 with carbon.

As per the above equation of methanol formation, 6g H_2 yields 32g methanol. Hence a 100 MW OTEC plant with annual hydrogen production of 12921875kg/yr, can yield methanol to an amount= 12921875×32/6kg/yr =**68916667 kg/yr**

Considering price of methanol to be $280/tonne:
<http://www.icis.com/V2/chemicals/9076034/methanol/pricing.html> [16.3.2010];
and presuming $1=£0.53, as per section 5.5.1, the price of methanol would be = £280*0.53 = £148/tonne. Thus revenue earning from methanol would be =£68916667×148/1000 =**£10199667/ year**

The prospect of such production of methanol is available for all types of OTEC. In the case of OC-OTEC & Hybrid types there remains the scope of availability of other reactants like concentrated form of $CO_2(g)$, which can be produced in the case of CC-OTEC by burning carbon.

Scope of such methanol production from OTEC, opens up the pathway of synthesizing a host of hydrocarbons and thereby the growth of the petrochemical industry.

Based on the above discussions, the prospect of revenue earning from various by-products of OTEC per kWh power generation, is shown below in table 5.15. These estimations however, exclude cost involvement of infrastructure facility build up of chemicals, that may be availed as OTEC's by products.

Table 5.16 Future prospect of revenue earning from By-products of 100 MW OTEC.

By Product	Daily production (kg) [a]	Production in g/ kWh =[a]kg/0.54GWh**	Revenue in p/kWh	Type of OTEC	Remarks
Hydrogen	35402kg	65g/kWh	--	All OTEC Types	1.**Net power generation/day =0.54GWh 2. H_2 being converted to NH_3; no revenue from H_2.
Ammonia	601840kg	1115g/kWh	14p/ kWh*	-do-	*Infrastructural costs of production excluded.
Methanol	188812kg	350 g/kWh	5.2p/ kWh*	-do-	-do-
Shell fish etc	68493kg	127 g/kWh	--	-do-	Earning on cost/kg
Potable water	172800m³	0.32m³/ kWh	17p/ kWh	None for CC-OTEC	For OC-OTEC 7& partly for Hybrid
$CO_2(g)$ (as can be availed)	21773kg	40 g/kWh	--	-do-	Water bottling plants/ Soda ash/ Urea production using NH_3 from H_2 production
Urea	29690kg	55g/kWh	0.7p /kWh*	-do-	* 1.Excludes infrastructural costs 2. Consuming all CO_2 & part of NH_3 produced from H_2
Excess NH_3 after availing Urea	585016	1083g/kWh	13.7p/ kWh*	-do-	*Excludes infrastructural costs.
Soda ash	52453	97	--	-do-	If CO_2 fully utilized

*Only earning from raw material production is considered, excluding cost involvement on infrastructural facilities of concerned production units.

5.6 Critical Appraisal on OTEC Economy

It would be obvious that by-product availability plays a major role in deciding the economic advantage of OTEC schemes. OC-OTEC or, Hybrid OTEC is in a more advantageous position than CC-OTEC.

As regards, the other economic tools, cost/kWh may be considered to be the key index. The life of OTEC should be so designed, so that its minimum life period should be 30 years, below which cost/kWh escalates.

However, RPC values are relevant for undertaking comparative studies with other OE devices, based only from their inventory material data. Even if the market price of the inventory materials fluctuates, the modus operandi of determining RPC and its importance for undertaking comparative studies of the relative economy of competing OE devices, remain unaltered.

In order to assess OTEC economy or for comparing it with other OE systems, all three economic indices, such as; - discounted factor oriented economy tools, RPC ratios and the future prospect on the scope of revenue earning from by-products availability – are required to be taken into account together.

However, power generation cost in p/kWh is considered an important index in economy evaluation.

5.7 Observations

1. The tools for assessing, the scope of exploitation of OTEC energy resource at suited sites could all be applied with necessary modification, for different types of OTEC schemes, from a hypothetical case study of 100 MW OTEC plant.

2. LCA & EA data determined from both Danish model and Bath University data source tallied fairly well with each other. Emission characteristics from LCA, inclusive of operational stage data, showed rather higher values for OC-OTEC and minimum for CC-OTEC, with Hybrid types having values in between. But GHG saving for all types showed more than 90% saving compared to coal fired station. SO_2 (g) gas savings showed more than 95% saving compared, to coal power station.

3. The operational stage CO_2 emission data, as estimated from theoretical computations conformed well to that as determined experimentally, using HMTSTA apparatus tried by Green and Guenther.

4. EPBP values showed values between 2-3 years.

5. The EIA estimation model, as developed could be applied for all three types of OTEC systems, identifying the impacting parameters influencing upon the different environmental issues like flora and fauna, different types of hazards posed and of various societal aspects. The upwelling of nutrient rich cold water had rather positive influence over flora and fauna. The mitigating measures for minimizing hazards posed could also be spelt out. The positive societal impact included- arresting coral bleaching in SIDS, better management of global warming particularly from sequestering of CO_2 (ocean's enhanced capability for CO_2 consumption and thereby assisting in minimizing global warming). The scope of employment generation and economic improvement are other advantages.

6. The most important positive impact of OTEC scheme lies in the scope of availability of various byproducts, like potable water (from OC-OTEC and Hybrid types only), increased mari-culture (also certain agricultural

products), scope of use for refrigeration/cold storage without additional power expenditure.

7. The tool for assessing economy, including cost/kWh power could be estimated for different discount rates. The influence of life period over economy could also be made from a hypothetical case study of a 100MW OTEC. Cost/kWh from NPV method varied between 5-14p/kWh, depending on the discount rates and life period. It was opined that in design planning of OTEC units, minimum life period be kept at 30 years.

8. Methodology on applicability of RPC, for comparing economy of different competing OE devices could also be spelt out, irrespective of the unit price quotation, nor of the requirement life periods or the discount rates etc.

9. The future prospect of a on the potential of host of by-product availability from OTEC schemes, including the scope of producing availing various chemicals from OTEC, with their prospect of revenue earning per kWh net power generation, could also be estimated from the case study of a 100MW OTEC.

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Chapter -6

ASSESSMENT OF TIDAL POWER

6.1 Introduction

It is considered useful to undertake an assessment as regards the scope & market acceptability of tidal energy, both for barrage construction as well as on Tidal In-Stream Energy Conversion (TISEC) systems.

Such an assessment has been made from the application of the tools including; Resource potential assessment, LCA & Energy accounting studies, Environmental Impact Assessment (EIA) and also evaluation of the Economic factors involved, as developed and applied for wave energy and OTEC systems. A brief account of them is discussed below.

6.2.0 Resource potential

The potential of global tidal energy has been estimated to be around 300 TWh per year (Elliott 2004). Its scope of power availability however is site specific. Suitable sites with significant annual average of tidal range (expressed in metres), as available on a global perspective, are shown below in figure 6.1 (NEEDS Project No. 502687)

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Fig. 6.1 Annual average of selected tidal range expressed in metres (NEEDS Project No. 502687).

Tidal barrages have been built at places for power production at some such sites. A few of these commercially viable tidal barrage schemes, that have been functioning for quite sometimes are:

- La Rance barrage scheme in France, with an annual average tidal range of 8m producing 480 GWh power/year since 1968, from 240 MW generator & with a basin area of 22 km^2 (Elliott 2004)..
- A 17.8 MW plant of 6m tidal range and basin area 6km^2 installed in 1984 at Annapolis in Canada (Duckers 2009).
- A 3.2MW tidal barrage plant at Jianxia, China, with tidal range 7.1m & basin area 2 km^2, installed in1980 (Duckers 2009).

6.2.1 Resource potential of Tidal Barrage

It has been explained and deduced before, in Chapter 2, that the power generated by a barrage from a rectangular basin area, may be estimated from the relationship:

$$P = \rho Ar^2 g/2T \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots[6.1]$$

where, P is the power generated, 'ρ 'is the density of water, 'A ' denotes the basin area, 'r' is the tidal range, 'T' is the tidal period & 'g' the acceleration due to gravity.

It would be obvious from the above equation that the higher the tidal range and basin area, the higher the power output in a barrage would be. But there must be an optimum value of making the basin area large enough to avail maximum power. Because, most of the cost involvement of a barrage scheme accrues from the dimension of the basin in its construction.

If 'T' could be hypothetically considered to be similar for all types of barrage schemes, then 'P/(Ar^2)' should have the same value for all barrage types; ρ and g being constant & since P/Ar^2 = ρg/(2T).

Considering the value of tidal period 'T' to be 12.5 hours/day, and presuming 'ρ' to be 1025 kg/m^3, the value of **ρg/2T** would have the constant value = **3.06*10^{-4}.**
since, 1025*9.81/ [2*(12.5*3600*365] = 3.06*10^{-4}.

But in practice, 'P/(Ar^2)' values varies from one barrage to the other. This variation is because of topographical diversities of the basin area, the variations in T values, as well as the modus operandi of power generation whether of ebb-tide, high -tide, or flood pumping methods adopted. This demands the introduction of a new index to determine the degree of deviation of 'P/Ar^2' from its standard value or threshold limiting value of '3.06*10^{-4}. This index, as may determined for the actual value 'P/Ar^2' of the barrage concerned, may be termed as the barrage index.

In fact, the higher the 'P' values with lower 'A' values involving lower barrage building cost, the better the quality of the barrage construction. Since, r is fixed for a site, P/Ar^2 values assume a significant role in deciding the optimization of barrage construction cost to derive maximum power with minimum cost involvement i.e. making minimum optimized dimension of 'A', the basin area.

Obviously, the higher the P/Ar^2 value, the better the quality of the barrage construction .This index, P/Ar^2, the barrage constant, could thus be advantageously used to compare relative barrage construction quality for different barrage schemes,

from its ratio with the threshold value of $3.06*10^{-4}$. It may also help as a guideline in undertaking an optimisation study as regards the dimensions of the barrage construction & power generation choice to be availed, for the concerned tidal range.

6.2.2 Barrage construction quality index

A few proposed barrage schemes, along with a functioning barrage at La Rance, France, have been compared as to the their barrage construction quality, as shown below in table 6.1.

Table -6.1 Barrage construction quality of a few proposed and functioing barrages compared.

Site/country *	Basin area Km² A	Mean Tidal Range [m] r	Power Produced TWh / yr P	Load Factor %	P/(Ar² = Barrage Index ×10⁻³	Optimized Barrage Construction quality = Barrage Index ×10⁻³/ 3.06×10⁻⁴
Severn, UK *	480	7.0	17	23	0.000722789	2.353
Mersey, UK*	60	6.5	1.3		0.000512821	1.667
Kutch, India**	170	5.23	2.41	22	0.000518	1.699
Gulf of Cumbay, ** India	1970	6.77	14.7	24	0.000163	0.523
Durga Duani Sundarbans, India ***	6***	2.97	0.016	23	0.000306	1.000
Cobequid, *Canada	240	12.4	14.0	30	0.000379379	1.242
Walcott Inlet* Australia	260	7.0	5.4	22	0.000423862	1.372
La Rance, France*	22	8.0	0.48	23	0.000341	1.114

[(N.B. *Data source as regards 'A','P, 'r' values, for countries other than India are from source ref -(Elliot 2004), **Data sources on A ,P & r values are from source ref (geda.org) ***Data source for P & r of Sundarbans are from source ref : (Chittora 2008).

It would be evident from above table that the barrage construction quality at the Gulf of Cumbay may require revision of its planning, since its barrage construction quality index shows a value less than the limiting value of '1', showing it to be 0.53. But in Sundarbans, India, which is still in the planning stage with an undecided basin dimension, it could be ascertained from the above premise that it cannot afford to increase its basin dimension to more than 6 km², to maintain its construction quality in attaining at least the threshold limit value of the proposed barrage, with the limiting Barrage construction quality to become '1'.

It is also shown from table 6.1, that the functioning La Rance barrage, with a higher annual average tidal range than that of the Severn barrage, shows the barrage construction quality index value of '1.114', against '2.353' for the Severn barrage.

This shows the proposed Severn barrage, UK, to be better planned than the functioning La Rance barrage, France. In fact, the Severn barrage shows the best optimised barrage construction quality index in its barrage planning (yet to be implemented).

It would be evident that for optimising planning, the barrage construction quality may not necessarily be considered to always be in tune with the tidal range. This could be observed in figure 6.2 given below, comparing barrage performance quality index vs. tidal range & the power available.
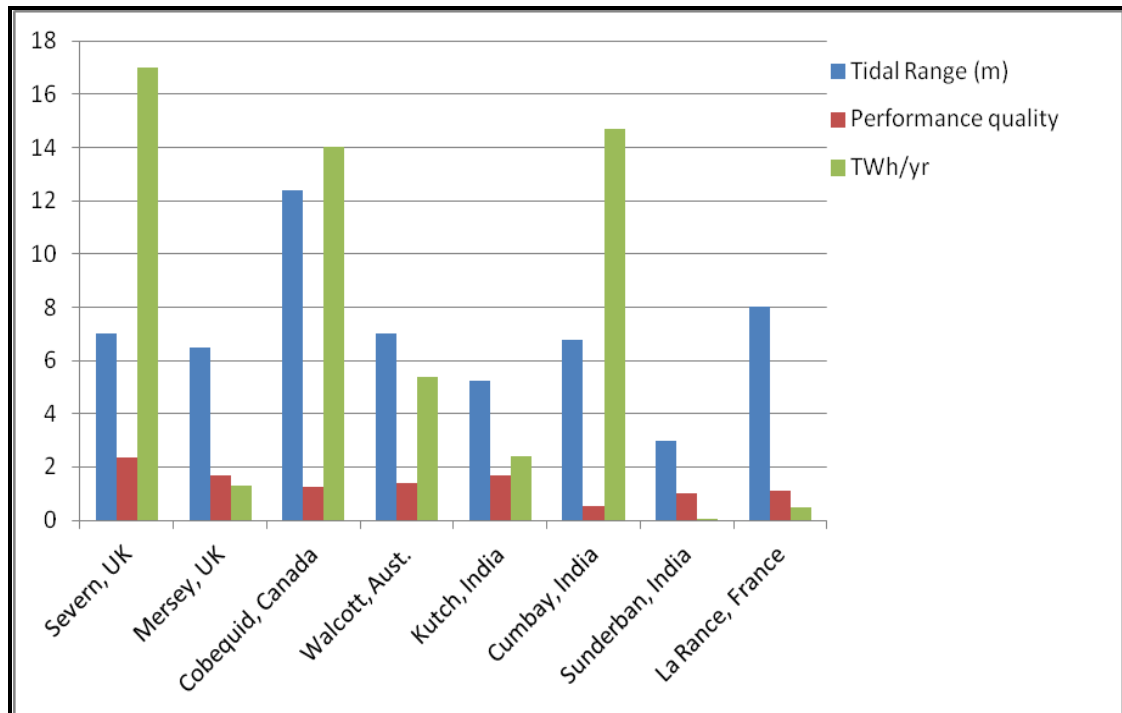
Fig. 6.2 Compared tidal range with power production & barrage planning quality index

6.2.3 Resource assessment of Tidal Current.

Total tidal current resources in the UK are reported to be 58 TWh/year. Out of this 58 TWh/year resource, 18 TWh / year has been opined to be technically extractable (Couch & Bryden 2006). A detailed account of the scope of availability of power from the tidal current energy, its efficiency, and application aspects of various innovative TISEC devices with their maximum safe limit for extracting tidal in-stream energy, without affecting estuary circulation and maintaining the ecological balance have been detailed in Chapter 2, along with its many advantages and limitations.

The power generation capability in the case of TISEC follows the equation $P/A = 1/2\rho u^3$, with P the power available, A the area swept by TISEC turbine, 'u' the water current speed and 'ρ' the water density. The exponential nature of the above equation shows 500-1000 W/m^2 are available at current speed 'u' between 1.3--2.5 m/sec. (Hagerman *et al*. 2006).

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In fact this water current speed can be predicted from the data on the amount of water surge from the ocean due to tidal range and the bed elevation from the estuary to the river as well as its constriction, employing Bernoulli's equation of the conservation of energy and conservation of the water mass flow to the constricted and elevated river bed.

Such sites suited for TISEC installation are normally ≥ 1km upstream of the estuary mouth with water depths of around 20-30m(Hagerman et al. 2006); so that 15-20m navigational clearance can be maintained from the top of the river, and around a 5 m clearance from the bottom to protect the benthic population and plankton (Meyers & Bahaj 2005).

TISEC technology holds a wide promise with many innovations being patented, some with ambitious planning for the generation of transport fuel like H_2, by splitting water (Elliott 2004), as proposed for the grazing type of OTEC systems. But like the OTEC system, this ambitious technology is also still in the R&D stage of development.

6.3.0 Life Cycle Analysis & Energy Accounting

It may be relevant to add that unlike other OE systems, the tidal Barrage construction in particular, [not TISEC] requires a long project completion period, starting from its planning stage to the construction completion and power generation. It also requires the transportation of materials during the construction period. For the Severn project, it required more than 3 decades for planning and is estimated to require 9 years for its construction, before it goes into production. After project completion, it requires virtually no effort for next century or, more except some minor repair works, which may be an average of 2 days per year (Sir Robert Mc Alpine & Sons Ltd. 1986). The turbine /generators may require replacement /repair, only once in 30 years for the barrage schemes (Woollcombe-Adams *et al*. 2009).

In the case of TISEC however, it would require rather more frequent maintenance against bio-fouling and time to time repair /replacements, as needed (Meyers & Bahaj 2005). TISEC's life period is also around 30 years.

Keeping in view the above perspective, the goal and scope of LCA & EA studies have been confined to the determination of the following:

- CO_2 emission / kWh power generation.
- Percentage of CO_2 emission saved, as compared to the coal-fired generator producing equivalent power.
- CO_2 emission payback period [CPBP], which is the number of years required for the coal power plant to produce life time equivalent CO_2 of the concerned Tidal scheme.
- Energy pay Back Period [EPBP] which is the ratio of the amount of energy required for production of the product, to the annual energy production of the system.

The estimations of the above were made following the Danish model of inventory data which were corroborated with Bath University data source as well, as per ISO 14040. This was needed in order to check the repeatability of results. In this context it may be relevant to mention that LCA is known to vary depending on the process followed etc. parameters. Hence the LCI data of inventory materials obtained from one source (Danish model) was required to be cross-checked with other data source, like Bath University data, as well.

LCI data (life cycle inventory data) on the same, giving the CO_2 emission characteristics as well as the embodied energy values, from the above two data sources, are given below in table 6.2.

Table -6.2 LCI data of inventory items relevant to Tidal schemes.

Inventory materials	CO_2 emission in kg/kg as per Danish model*	CO_2 emission in kg/kg as per Bath Univ. data**	Embodied Energy MJ/kg as per Danish model *	Embodied Energy MJ/kg as per Bath Univ. data**
Concrete /Cement	0.835	0.95	3.68	3.01
Copper	6.536	3.0	78.2	70
Steel/special steel	2.3065	2.83	25.65	25.4

*(Schleisner 2000); ** (Hammond & Jones 2008).

Based from the above data base, case studies made for barrages schemes like, the Severn & Mersey barrage as well as for Sea-Gen type TISEC schemes, are covered below.

6.3.1 Severn Barrage Scheme

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 the Severn river having a mean tidal range 7m (Sir Robert Mc Alpine & sons Ltd 1986). The annual power output from this barrage is expected to be 17 TWh, with a life time of over 100 years with a turbine life of over 30 years, requiring its replacement, around thrice in its life time. The LCI data of inventory materials of proposed the Severn Barrage, from both data sources, are shown below in table 6.3.

Table -6.3 CO_2 emission & Energy requirement of Severn barrage construction materials

Materials required	Mass (kt) *	CO_2 emission (kt) (Danish model)	Energy (MJ) (Danish model)	CO_2 emission estimated(kt) (Bath Univ. data source)	Energy (MJ) estimated (Bath Univ. data source)
Concrete (consisting cement/sand)	3800	3173	$13984*10^6$	3610	$11438*10^6$
Copper	43.2	461.4	$3378.24*10^6$	129.6	$3024*10^6$
Steel (covering barrage & turbines)	588.8	1358.36	$15102.72*10^6$	1666.30	$14955.52*10^6$
Grand Total	4432	4992.76	$32464.96*10^6$	5405.9	$29417.52*10^6$

 * (Woolcombe-Adams *et al*. 2009)

Based on the above table-6.3, life time CO_2 emission characteristics as well as the energy payback period estimations, from both the Danish model & Bath University data are estimated below for the Severn barrage scheme.

6.3.1.1 Danish model

CO_2 emission value of 2% from transportation added with 2 days/yr as O&M, gives the value = 0.02*4992.76+ 200*4992.76 / (365*100)=127.21kt

Thus total CO_2 emission =(4992.76+127.21) kt = 5119.97kt=$5119.97*10^9$g
Annual power production = 17 TWh =$17*10^9$ kWh
Life time power production (100 years life) =1700TWh =$1700*10^9$kWh
CO_2 emission per kWh power production would be =$5119.97*10^9$g / $1700*10^9$kWh
= **3.01 g/kWh**.

By definition the CO_2 payback period [CPBP], may be determined, by estimating the life time total production of CO_2 of the barrage, and then determining its ratio with that of the representative coal power station's average CO_2 emissions for the equivalent annual power generation of the barrage. Since CO_2 emission from such coal power plants is 826.17g/kWh as per determinations made in section 4.3.6.2, chapter 4. Then for 17 TWh power generation it would emit $826.17*17*10^9$g =$14045*10^9$ g

Thus **CPBP** = 5119.97/ 14045 years
=**0.36 years** [since life time CO_2 emission from barrage is $5119.97*10^9$g)

% CO_2 saved (considering 826.17g/kWh from coal plant as 100% emission)
= (100- 3.01*100/826.17)%
=**99.63 %**

Total amount of energy required to produce the barrage scheme from table 6.3
= $32464.96*10^6$ MJ.

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EPBP would hence be=$32464.96*10^6/(17*10^6*3600)=$ **0.53 years**

6.3.1.2 Bath University data

CO_2 emission value of 2% from transportation added with 2 days/yr as O&M, gives the value = $0.02*5405.9+ 200*5405.9 / (365*100)=137.74$ kt

Thus total CO_2 emission = $(5405.9+137.7)$ kt $=5543.6*10^9$ g
CO_2 emission per kWh power production, would be $=5543.6*10^9$ g $/ 1700*10^9$ kWh $=$ **3.26 g/kWh**

CPBP=5543.6/14045 years =**0.39 years**
% CO_2 saved =100-3.26*100/826.17 =**99.61%**
EPBP = 29417.52/ $(17*10^6* 3600)=$ **0.48 years**

6.3.2 Mersey Tidal Barrage scheme

In order to capture the annual average tidal range of 6.5 m of the river Mersey, UK, 1.8km long barrage construction in the Mersey estuary (between New Brighton and Huskisson Dock), has been proposed making an impounded basin area of around 60 km^2, to produce the targeted net annual power production of 1.48 TWh (Mersey Barrage company 1991). The life of the barrage has been considered to be 120 years in a feasibility study report of the said company (1991).

CO_2 emission & energy requirement data of the Mersey barrage, as per the Danish model as well as from Bath University data, based from table 6.2 are given below in table 4

Table 6.4. CO_2 emission & Energy requirement for Mersey barrage construction.

Materials Required	Mass (kt) *	CO_2 emission(kt) (Danish model)	Energy (MJ) (Danish model)	CO_2 emission(kt) (Bath data)	Energy (MJ) (Bath data)
Concrete	3480	2905.8	12806.4 $* 10^6$	3306	10474.8*10^6
Steel	128.8	297.142	3303.72*10^6	364.50	3271.52*10^6
Copper	3.8	24.837	297.16 *10^6	11.4	266*10^6
Grand Total		3227.78	16407.28 *10^6	3681.9	14012*10^6

* (Mersey barrage company 1991).

6.3.2.1 Danish model

CO_2 emission value of 2% from transportation added with 2 days/yr as O&M, gives the value = $0.02*3227.78+ 240*3227.78 / (365*120) =82.23$ kt

Thus total CO_2 emission =$(3227.78+82.23)$ kt = 3310.01 kt =$3310.01 *10^9$ g .
Net annual Power production from Mersey =1.48TWh =$1.48*10^9$ kWh

Total power production in its 120 years life period $=120*1.48*10^9$kWh $=177.6*10^9$kWh

CO_2 emission per kWh power production would be $=3310.01*10^9$g / $177.6*10^9$kWh =**18.63 g/kWh**

In order to determine % CO_2 saved & also CPBP values, it is required to compare the CO_2 emission from the representative coal power station's emission at 826.17g/kWh, considering it to be of 100%; and also to determine its production of CO_2 at that rate, for power generation of 1.48TWh, being annual power generation for proposed Mersey project.

Emission of CO_2 from such a coal power station in power production of 1.48TWh $=1.48*10^9*826.17$g = $1222.73*10^9$g.

CPBP =3310.01/ 1222.73 years
=**2.70 years**
% CO_2 saved =100--18.63*100/826.17 =**97.74%**
EPBP = $16407.28*10^6$/ ($1.48*10^6$ *3600) = **3.08 years**

6.3.2.2 Bath University data

CO_2 emission value of 2% from transportation added with 2 days/yr as O&M, gives the value = 0.02*3681.9+ 240*3681.9 / (365*120)= 92.81kt

Thus total CO_2 emission =(3681.9+92.81) kt = 3773.71.kt=$3773.71*10^9$g ......[d]
CO_2 emission per kWh power production, would be =$3773.71*10^9$g / $177.6*10^9$kWh =**21.25 g/kWh**
CPBP=3773.71/1222.73 years = **3.09 years**
% CO_2 saved =100—21.25*100/826.17 =**97.42%**
EPBP = $14012*10^6$/ ($1.48*10^6$* 3600)= **2.63 years**

6.3.3 Sea Gen type TISEC converter

This TISEC device is proposed to be deployed at Strangfold Lough in Northern Ireland, and would be the first full type commercial proto turbine to utilise the power from the kinetic energy of tidal current. The proposed annual power output of the assembly of such turbines is claimed to be 4736 MWh, presuming 94% availability of power (Douglas *et al*.2008). Its CO_2 emission has been claimed to be 15 g/kWh, and EPBP around 14 months (Douglas *et al*. 2008).

From the above data can be estimated % CO2 saved as well as the CPBP values, as shown below:

Total CO_2 produced for Sea Gen in its life time of 30 years =0.015*4736000*30 kg =2131200 kg.
Average annual CO_2 produced =0.015*4736000 kg =71040kg
(Annual power generation being 4736000kWh).
CO2 produced from coal power station from generation of 4736000kWh
(The annual power production of Sea Gen) =826.17*4736000g = 3912741.12 kg

CPBP=2131200/ 3912741.12years =**0.54 years**
% CO$_2$ saved =100—15*100/826.17 =**98.2%**

6.3.4 Appraisal of results of LCA & EA studies

LCA estimations are known to be country specific as well as process specific. Obviously some discrepancies of values observed, for different models of LCA estimations may crop up. It was therefore considered useful to recheck the results from both the Danish models as well as from Bath University data source. The results obtained from LCA & EA studies however, corroborated with both the Danish model as well as of Bath University data sources.

It is apparent from the above results of the emission and energy requirement values of the Severn & Mersey projects, that the efficacy of the Severn is much better than the Mersey project. In fact, the Severn project proved even better than the Sea Gen type TISEC l, perhaps because of the high power capture capacity of the Severn scheme with its high barrage planning efficiency.

In Sea Gen type TISEC device, it could be estimated as regards the carbon payback period and percentage CO$_2$ saved, from the data available as regards its CO$_2$ emission in g/kWh and power production values.

Comparative results, as regards CO$_2$ saving percentage for all three tidal schemes are shown below in Table 5.

Table 6.5 CO$_2$ saving compared for different tidal schemes

Tidal scheme	Severn Barrage	Mersey Barrage	Sea Gen TISEC
% CO$_2$ saved	99.6	97.7	98.2

In addition to LCA & EA studies, environmental impact assessments of Tidal schemes are required to be assessed, as discussed below.

6.4.0 EIA studies

There remains a basic difference in the assessment of the environmental consequences for Tidal schemes with that of other OE systems such as, Wave and OTEC. The latter examines the eco-balance disturbance if any, in high seas. But for the former the concern is of the estuary mouths with rivers meeting the oceans, as well as the changes caused if any, of the river upstream flowing through the landscape, with the possibility of immediate fall outs over the surrounding landscapes . Hence the stake as regards environmental issues are more in the case of utilising Tidal power, the effects being experienced both directly and immediately. EIA for tidal schemes thus require closer examination, both for Barrage construction and also for TISEC installations. It is therefore considered important to examine whether the 'EIA model', as has been developed and applied for Wave and OTEC, may be applicable for Tidal schemes or, would it require necessary modifications.

In other OE systems, the model developed was used for the identification of four environmental issues such as; emission characteristics, flora and fauna, hazards

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posed and social aspects. The same environmental issues could be applicable for tidal schemes, as well. But the impacting parameters influencing upon the above four issues would of course be quite different. These would be more pronounced for barrage projects than for TISEC installation. Some of the most important impacting parameters that influence the above environmental issues in case of tidal schemes are:

- Affecting the water flow and water current of the river, both upstream and downstream, of the of the project site.
- Causing changes of water quality in the estuary such as, salinity, turbidity etc. influencing upon the sedimentation pattern, making landscape changes at places.

The barrage construction in particular has a tendency to even out the tidal ranges. It lowers down the highest water level for high tides, but elevates the lowest water level during ebb tides. A specific example has been shown below in Figure 3, citing the case of the proposed Severn Barrage scheme (Elliott 2004).

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Fig.6.3 Tide level curves, with & without the proposed Severn barrage (Elliott 2004).

This change in tide water level, as shown in figure 6.3, results in less churning of water-affecting the water quality change in the estuary and also in upstream, as regards their salinity and turbidity. Less water flow from ocean reduces the salinity upstream. Also a decrease in water flow fluctuations, lessens the churning of the water flow, reduces the turbidity which in turn affects sedimentations patterns. Thus all these interdependent impacting parameters change the quality of water differently in the estuary and in upstream. It would thereby influence the environmental issues involving; flora and fauna, hazards posed and societal aspects. Some of them may have positive and some a negative impact, depending upon the degree of changes

caused, and of the characteristics of the specific site concerned. The EIA estimations are thus site specific as well as the barrage specific, depending on its magnitude and construction scheduling.

In fact, reducing the turbidity ensures more penetration of sunlight in deeper water layers facilitating the growth of species and therefore availing food for birds and fish, encouraging their growth as well (Elliott 2004). At the same time, reduced exposure of mud flats upstream [for elevation of minimum water level caused, as shown in fig.6.3] & carrying less silt, due to the reduced ebb-tide variation, may adversely affect some species-including certain fish types whose preferred growth zone is the mud flats upstream. Likewise, salinity reduction zone extending downstream of the barrage construction site, would encourage growth of species that thrive in fresh water, with impoverished shrinking populace of the ones whose preferred growth zone is saline water.

In fact, ecological changes could be observed in the post construction period of La Rance barrage in France, constructed as early as 1966 (Pelc and Fujita 2002). It has been observed that there was a reduced intertidal area with a reduction in salinity zone and species growth. Of course in the case of constructing of La Rance barrage, the estuary had been kept closed from the ocean for 2-3 years (Pelc & Fujita 2002), which is discouraged with present advancement of technology being planned with partial blocking only.

It is to be noted that there always remains a risk of causing irreversible damage to the local eco system of the estuary, and blockage/partial blockage of tidal water, as may be caused during barrage construction, covering a long project completion period. La Rance barrage construction led to the partial collapse of the then eco system of the estuary (Elliott 2004). The extent of eco-imbalance that had occurred then is not known because no monitoring was maintained in the sixties.

The eco system changes during the long period of barrage construction, is hence considered a very important impacting issue to be considered, along with the other impacting parameters like, water flow/current change, sedimentation pattern changes, or water quality (salinity/turbidity etc.) changes.

The blockage/partial blockage of tidal water for barrage construction covering a large basin area may at times become a serious hazard, from the emission of foul smelling pollutant gases like H_2S, CH_4, etc. This occurs, if the basin is allowed to be left stagnated with stratification of thick slimes at the bottom because of no flow, and left in an anaerobic condition for a longer period (Elliott 2004). Such pollutant gases would pose a big hazard, if it is emitted in huge quantity from the thick slime of stratified mud-pools, collected at the bottom of the basin (Elliott 2004).

As regards the hazards concerned, the barrage construction would help reduce floods in landscapes (from elevation made of river banks). But without thorough planning (adequate elevation of embankments etc.) to tame a river, constructing the barrages may be counterproductive inviting erosion of soil, and affecting the landscapes (Banerjee 1999).

In TISEC implantation however, the water flow and current variation is not that marked, as may occur in cases of barrage construction. It is however required to maintain adequate spacing in installation of TISEC units. These aspects have been covered in chapter 2. They include-

- The right spacing that is required to be maintained for establishing TISEC farms.
- Choosing the right site as would be suited for installation of TISEC farm.
- Maintenance of adequate spacing from bottom to safe guard benthic populace.
- The right allowance of space from the top for navigational clearance.

Keeping in mind the above perspectives, the EIA model developed for tidal schemes, are outlined below with identification of each impacting parameter affecting the four environmental issues; emission characteristics, flora and fauna, hazards posed and the societal issues involved. Quantitative scoring as regards high, moderate or low, have also been attempted, also indicating whether they would have a positive impact for sustainable growth or a negative impact. They are outlined below, identifying the impacting parameters to be reckoned with for each environmental issue, as well as considering the zones that would be affected.

6.4.1 Emission characteristics

As regards the emissivity aspects, % CO_2 saving is considered and shown below in table 6.6, citing case studies of barrage schemes like the Severn & the Mersey and of a TISEC project like, Sea Gen. In fact CO_2 savings for tidal barrage proves to be very effective for its long life of more than 100 years and for its potential for building power plants of very high capacity.

Table 6.6 Score values of GHG emission on Tidal Schemes.

Tidal project/ Emission % of CO_2	Severn Barrage	Mersey Barrage	Sea Gen TISEC
% CO_2 emission	0.4	2.3	1.8

6.4.2 Flora and Fauna

The type of species considered for quantitative assessment of flora and fauna are as below:

- Fish populace –both for fresh water fishes (**FW**) as well as saline water (**SW**)ones;
- Birds – both for the migratory birds(**MB**) and those feeding with worms and invertebrates in mud-flats(**MFB**) created at shallow water zones;
- Species like Benthic community(**BC**)
- Plankton and sea –weeds (**P**);
- Various other Sea-mammals (**SA**).

The zones considered are:

- The project site – basin area in case of barrage, and installation sites for TISEC projects **(Basin etc).**
- Downstream towards the estuary meeting the ocean (**DE**).
- Upstream in the river from the barrage /TISEC project site (**UP**).

The impacting parameters considered for each of them are as below:

- The degree of the lowering of the water flow quantity /river-current.
- Reduction of salinity of water with extension of lowered saline watery zone.
- Turbidity reduction caused.
- Sedimentation pattern changes, creating new landscapes or mudflats.
- Scope of restriction of free water flow during the construction period of barrage (applicable for barrage only, not for TISEC projects).

Assessment of flora and fauna, made from above perspectives, as discussed in section 6.4.0, are shown below in table 6.7; putting in score values of each species at specific zones, caused from the impacting parameters stated above, in section 6.4.2.

Table -6.7 .Flora and Fauna from Tidal projects (*)

Site/ Species	Fish/ FW	Fish /SW	Birds /MB	Birds / (MFB)	Benthos (BC)	Sea mammals (SA)	Plankton & Weeds (P)
Barrage Construction Period							
Estuary/ DE	M -	L+	L-	L-	L-	L-	L-
Upstream/ UP	0	M-	0	L-	L- -	L-	0
Post Construction							
Basin	L+	L+	M+	L-	L+	L-	L+
Estuary/ DE	L-	L+	M+	L-	0	0	L+
Upstream/ UP	M+	L-	L+	L-	0	0	L+
TISEC Projects							
Site / implantation	M-	M-	L-	L -	L -	L -	0
Upstream	0	0	0	0	0	L+	L+
Downstream	0	0	0	0	0	0	0

 * L - =low -ve; M- =moderate negative; L+= low +ve; M+ = moderate +ve;
0=no effect.

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6.4.3 Hazards posed

The construction of a barrage would always restrict the natural seawards flow of a river, allowing it to flow in a controlled manner operated through sluice gates. The immediate hazard posed from it is - affecting the navigational access, particularly during the construction period that takes years to complete. Of course ship locks are created with prior planning taking into account the volume of ship movement for the site concerned.

In addition to it, the number and dimension of the openings of sluices and lock gates are required to be optimized, not only for achieving the best economy but also to minimize chocking of the openings from sedimentation. Of course, periodic dredging and necessary maintenance work of the turbines /generators is needed to avoid the hazards, as regards malfunctioning of the power generation equipment as well as its accessories.

The other hazards, as may be anticipated are the soil erosion of the landscape and floods, for the mean minimum water level being elevated from barrage construction [shown in figure 6.2]. But, with proper planning and implementation of preventive measures to mitigate such hazards with measures like elevating the upstream embankments, barrage construction would rather help in lowering these hazards. (Environment Council, UK)

Since the barrage life is more than 100 years, adequate mitigating provision is required to be kept in view as regards the possibility of futuristic changes in wave climate, besides natural disasters like storms or, surging waves like Tsunamis, etc. They would adversely affect the grid power line, with sudden bursts of many times more power for the connecting grid to accommodate. These can be avoided with the provision of power shedding devices, as safety measures for such emergency.

In the case of TISEC implantation however, the only problem that may pose as hazard is malfunctioning of equipment from bio-fouling etc. and corrosion with requirement of regular and periodic maintenance. Of course, adequate precautions for site selections of TISEC farm installations are needed (discussed in chapter -2), so that power tapping does not appreciably affect the tidal current.

Based on the above discussions, the impacting parameters identified as regards the hazards posed from tidal schemes along with mitigating measures to be followed are as below:

- Affection of navigational access, mainly during construction – minimised keeping provision of sluice gates / ship locks, etc.
- Chocking of sluice gates /ship locks from sedimentation –can be minimised with periodic dredging.
- Malfunctioning of equipment –tackled with periodic maintenance.
- Soil erosion or, sudden floods in landscapes – mitigated with prior planning from heightening of embankments.
- Data analysis as regards the scope of periodic change in tidal range and tidal current characteristics, and keeping preventive provisions accordingly, with

       adoption of measures in advance (barrage construction would thus be rather helpful in lowering these hazards on flood and/or soil erosion).

- Bio-fouling etc, mainly for TISECs – can easily be resolved with periodic maintenance.
- Sudden power upsurge from natural disasters, like future changes of wave climate from global warming, sudden storms - mitigated keeping provision of power shedding.

The scoring made of above hazards for tidal schemes, keeping provision of proper adherence to the above mitigating measures, are shown below in table 6.8

Table 6.8 Scoring of Hazards posed from tidal projects –on adoption of remedial measures*

Impacting Parameters	Remedial measures	Score Values	Remarks
During Barrage Construction			
Blocking of the Navigational access	To maintain ship locks & adequate prior planning	M-	At times blockage may occur, despite prior planning.
Barrage functioning –-post construction			
Blocking Navigational Access	Ship locks & due Monitoring	L -	Minimal –but not zero
Chocking of sluice gates caused from sedimentation etc.	To follow periodic dredging & maintenance work	L -	Can be brought to near zero level
Equipment malfunctioning	Periodic maintenance /repair work /replacement of equipment, as per requirement.	0	Can be brought down to zero failure with proper scheduling / monitoring of maintenance etc. jobs.
Flood /Soil erosion Upstream	Proper planning, like heightening barrage embankments etc. be followed	L +	It rather helps mitigating these hazards; if followed with data monitoring etc.
Natural disasters like, storms etc	Precautions like- shedding high power surge, so that main grid line remain unaffected	L -	It can be brought down to low risk level, without effecting much damage.
TISEC projects			
Equipment malfunctioning	Periodic scheduling of cleaning of bio-fouling agents over turbines & their maintenance /repair etc be regularly & routinely followed	L -	Can be minimised to near zero level.
Lowering of tidal current etc from power capture	Due precautions as regards site selection and TISEC density be maintained as discussed in chapter 2.	L -	Can be brought down to near zero level, if not to zero level of the hazard posed.

  * L - =low negative; L+ =low positive; M- =moderately negative, 0= no effect.

6.4.4 Societal Issues

Tidal schemes generating power helps improve the economy of the locality, facilitating more energy availability. Besides, the barrage schemes in particular helps in getting access roads etc facilitating tourism. The huge quantity of materials required and their transportation for making gigantic barrage construction generates employment potential in large numbers, during the construction period mainly. This continues later also (to a lessened degree) after the barrage goes into production, from the maintenance/repair work being continued.

More or less similar advantages are achieved for TISEC projects, though of much less magnitude.

The negative effect in barrage construction is that, the calmness and tranquility of the otherwise isolated area is disturbed for making it a hub of vigorous activity. Also, very high capital outlay is required for barrage construction and remains a financial burden to the stakeholders, until it is repaid from the profit earned from power generation. But once constructed, the long life of barrage is a virtual insurance of providing unhindered power supply with very little recurring cost involvement.

Keeping in view the above perspective, identification of impacting parameters, as regards societal issues are given below in table 6.9. The score values are attributed based from the degree of influence of impacting parameters over the concerned societal issues.

Table 6.9 Score values attributed on societal issues of tidal schemes.

Societal issues/ Construction phases	Local economy improvement	Tourist attraction	Employment generation	Financial burden
During construction	M+	L-	H+	H-
Post barrage construction	H+	M+	L+	M-
TISEC projects	M+	L+	L+	L-

6.4.5 Critical appraisal

Quantitative assessment of the environmental consequences for tidal schemes could be applied from the EIA model, with modification of impacting parameters than that of wave and OTEC systems.

In the case of tidal schemes, the impacting parameters were required to be spelt out & identified for each of the environmental issues including;, flora and fauna, hazards posed and societal aspects. The score values for each of them could also be put in from subjective assessments of the magnitude of the influence of impacting parameters, over the sub-section of individual environmental issues.

But it only gives a generalized guideline, since all tidal schemes are site specific having their own specialties. Besides, even for the same project, the project size is also a determining factor as regards the environmental fall out. Hence, smaller barrage sizes and TISEC projects are encouraged, for their lesser environmental uncertainties as well as for less financial burden.

As regards to GHG saving, tidal schemes show rather better efficiency than other OE systems.

6.**5.0 Economic issues involved**

There is a basic difference between the economy of other OE systems and tidal barrage schemes (not applicable for TISEC schemes). In the case of other OE systems, there remains much scope for cost-reduction from third or fourth generation of new devices of OE set ups, with improvement in technology. Whereas barrage construction technology is mature enough with not much scope for cost reduction for its future construction.

But every site for barrage construction opens up a new challenges, with a long period of planning from necessary data analysis of the site. This is required for optimisation of construction details, as regards the optimum barrage dimension and planning of sluices / ship locks /accommodating number of turbines etc, to derive maximum efficiency from minimum cost involvement. Suitable construction site selection from alternatives, is also an important issue in barrage planning.

Since the barrage construction expenditure is so decisive in power production cost from barrages, Baker derived a relationship between the barrage dimensions and power production cost involvement, from analysis of nearly 20 sites globally, as shown below (Baker 1986):

$$\log U = k \log \left(\frac{L^{0.8} (H+2)^2}{A(R-1)^2} \right) \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \quad [6.2];$$

where, U=cost of electricity [p/kWh]; L=barrage length,[m]; H=barrage height [m]; A=basin area [km^2]; R =tidal range [m]; K=constant, determined to be around **0.69**.

It could however, be observed from analysis of a number of proposed barrage projects sites globally along with an operational barrage, shown in section 2.1 table 6.1, that power production values do not necessarily conform to the basin area and its annual average tidal range only. In fact, every barrage project has its own barrage constant and performance quality, depending on the power generation mode followed, tidal period utilised for power capture and the topography of tidal basin chosen.

It thus requires meticulous planning before going for barrage construction, to derive the best economy. This planning as regards feasibility studies of barrage construction has a long lag period for barrage construction, and also involves huge capital investment with no return till the barrage goes for production. In construction of La Rance barrage in France, which is the biggest tidal project to date, it took 25 years of

long and meticulous studies in various fields, prior to its inauguration on 26th Nov. 1966 (Frau 1993).

Attempts have however been made to apply the usual economy tools as below, for assessing the barrage economy, which is also applicable for TISEC projects as well. They are:

- Evaluating the Present Value of cost of the total investments made for barrage construction (or for TISEC implantation), covering the O&M cost in its entire life time.
- Determining the cost of electricity / kWh power generation.
- Determining the payback period (simple payback period) for the total investment made.
- Estimating the Internal Rate of Return which highlights the scope of profitability of the project.

The methodology of determining the above indices have been detailed from a case study of the proposed Severn Barrage, shown below.

6.5.1 Case study on economy evaluation of Severn barrage

It has been reported from detailed examination of the Severn Barrage that construction cost of the barrage would be =£4,896,000,000. But with provision of 15% contingency expenditure and 7% engineering & management cost it comes to a total cost involvement of £5,239,000,000 (anon. Severn Barrage Project 1989). This cost estimate made in 1989, is based with the presumption that the construction would be completed by seven years time, after which it was to start power production. It considered that an assured annual power production of 17 TWh is achievable.

It is known that barrages once constructed have a long life of 100 years with nominal O&M cost of 1% of the capital cost (Woolcombe-Adams *et al*. 2009).

Based on the above premise the usual economy evaluating tools, may be determined following the usual methods of economy evaluation as per NPV concept. The results are shown as below:

Capital expenditure = Cc = £ 5,239,000,000
Annual O&M cost =Co = Cc*0.01= £5,239, 0000
Annual energy production =17,000,000,000 kWh

Discount factor considering 8% discount rate = $[(1+0.08)^{100}—1]/ [0.08*(1+0.08)]^{100}$
= 12.49
Present value of cost =Cc+ Co*Discount factor =5,239, 000,000 +5,239, 0000*12.49
= £(5,239,000,000+654351100) =5893,351,100
Present value of energy =annual energy production*discount factor
=17 000, 000, 000*12.49=21233, 000, 0000 kWh
Cost/kWh =Present value of cost/present value of energy=**2.8 p/kWh**

Nc = Net cash generated annually =Annual energy production*cost/kWh--Annual O&M cost
 = £(17000,000,000*0.028—5239,0000)=£423,610,000
Simple payback period = (Cc+ Co)/(Annual energy production *cost/kWh)
=**11.11 years**

In order to determine IRR percent, considered at 8% discount rate for life period of 100 years, the concept as elucidated in Appendix 2, stating NPV = 0, at IRR, is utilised (as per estimations made for wave and OTEC schemes in previous chapters).

Thus, -Cc + Nc* discount factor (DF) =0, at IRR, where Nc = £423, 610,000.

Transposing the above equation, DF- Cc/Nc =V (say). If two values of discount rates are so chosen that one value of V would be positive (V+), and the other negative (V-); then IRR would lie between these two discount rates, where V=0.

Using the above Nc, at 8% discount rate, the value of V+ = 0.126809; whence at 10% discount rate V- = -2.368233. Thus, in order to make V=0; IRR would be
=8+ 100*(0.126809*(0.1-.08))/[(0.126809-(0.126809-(-2.368233)]
= **8.1%**

It may be relevant to point out here that cost/kWh, as determined to be 2.8p/kWh when considered at 8% discount rate (for 100 years life), would vary if the discount rate is changed to say, 15%, as shown below:

DF at 15 % discount rate for 100 years life= [(1+0.15)^100 -1] / [0.15*(1+0.15^100)
=6.67
Net Present Value (NPV) of cost ==£(5239000000+52390000*6.67)=£558,844,1300
NPV of energy=17 000, 000, 000*6.67 kWh=11339, 000, 0000 kWh
Cost/kWh= £ 558, 844, 1300 / 11339, 000, 0000 kWh = **4.9p/kWh**

6.5.2 Critical appraisal on economy evaluation

The cost/kWh of power from barrage made from above premise, shows, values between 3-5 p/kWh, depending on the discount rate considered. But this could have been obtained provided the barrage started functioning 2 decades ago, when the costing was made (1989). In fact it took more than 3 decades for planning itself which still remains in planning stage only. This adds up the NPV value and cost, as well as the discount rate affecting the economy of Barrages. It has hence been suggested that instead of the larger barrage projects, requiring huge capital with elaborate planning and increased lag period for project completion, it is better to opt for smaller ones requiring less financial burden and also lessening the time needed to reach the project completion period (Frontier Economics Ltd 2008).

In TISEC devices however, the factor of project completion period, is not of much significance. TISEC economy can however, be compared with other OE systems from Relative Product Cost (RPC ratios)/kWh estimations of inventory items, as had been developed & used for comparative study of wave and OTEC systems.

6.5.3 Comments on Tidal Economy

Economically viable tidal sites, for the barrage in particular, are quite limited from a global perspective (Hammons 1993). It requires meticulous planning considering all aspects to construct a barrage, that would derive maximum power with minimum cost involvement. But once constructed with proper optimisation study, the barrage is a virtual insurance to provide huge energy for next century with very little recurring cost involvement.

On the other side, TISEC projects have immense possibility of providing cheap power with the advancement of its technology.

6.6 Observations

The following information generation could be made alongside inferences reached, for tidal schemes covering both barrage and TISEC projects.

- A methodology could be derived for determining the barrage performance quality for ensuring optimisation in barrage planning; so that maximum power is availed with minimum basin dimension, lowering the cost of barrage construction. This could be achieved from case studies of a few proposed, as well as operational, barrage sites. This index proved useful to assess the scope of improvement for the barrage concerned, with its particular tidal range and basin area. It could be a useful guide in prior barrage planning, making an assessment for the best and optimized alternative.

- Suitable sites for implantation of TISEC projects, as well as the maximum packing density to be maintained of TISEC farms, as determined from information retrieval on the topic, could also be specifically spelt out.

- Based from LCA & EA studies with case studies for barrage and TISEC projects, the CO_2 emission percentage saved were determined and carbon payback period compared to coal fired power station, as well as energy pay back periods. Such studies performed following the Danish model could be corroborated with the Bath University data sources as well.

- Quantitative assessment, as regards environmental consequences on flora and fauna, hazards posed and societal aspects, as made for wave schemes, could also be extended for application in tidal power as well. The impacting parameters influencing upon the different environmental issues could also be identified, which are especially important for tidal schemes. Guidelines to be followed for minimizing the different types of hazards posed for tidal schemes, could also be spelt out.

- The tools for assessing the economy of tidal schemes could also be identified and determined from case study of the proposed Severn barrage. This included cost in p/ kWh power production, at different discount rates.

- It could be observed that power generation cost for barrages with their long life of a century, showed rather lower cost / kWh power generation.

- The technology of barrage construction is mature enough with scope of immediate implementation, but its limitations are its long project completion period as well as of limited suited sites globally; in addition to high capital outlay required. TISEC projects however have wide scope of future application.

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CHAPTER – 7

DEVELOPING INTEGRATED ASSESSMENT METHODOLOGY (IAM) FROM COMPARATIVE STUDIES OF OE SCHEMES

7.0 Introduction

Development of the Integrated Assessment Methodology of ocean energy systems (OE) would help in the decision making process as regards choosing the right type of OE schemes, like wave, OTEC or, tidal scheme at the appropriate site. It should also enable the evaluation of the degree and status of acceptability on the sustainable development of the particular device. Thus, comparative studies of different competing energy converters as are proposed by different organizations can be done. Therefore, tools or assessment criterion to evaluate the relative merits of competing OE devices should be identified and well defined

In fact, a detailed examination of such studies has already been undertaken separately from case studies on wave, OTEC and tidal schemes. This is achieved by the application of the four assessment tools; resource analysis, LCA & EA studies, EIA, and Economy evaluation. The results of such studies have been detailed in Chapters 4, 5 & 6 respectively. But, it would need a paradigm shift for development of the IAM encompassing all three OE systems under one canvas. In fact, it then becomes a multi-criterion decision making (MCDM) approach with identification of major assessment tools or priority quality elements along with the broader based ones.

Since the 1980's, the growing environmental concerns with increased awareness of social causes, have embarked upon the decision making process in RE sector to go beyond the single criterion of cost-benefit analysis (CBA) to the multi criteria decision making (MCDM) process by addressing these social concerns for sustainable development (Pohakar & Ramchandran 2004). Such a MCDM approach with the formulation of IAM should not only enable choosing the right type of OE device for deployment at the right site, but also to rank the competing OE devices from a sustainable development point of view. It may also be useful to identify the scope of improving upon the device concerned.

Based on the above perspectives as well as on the data availed from the case studies made in chapters 4, 5 & 6; studies carried out in developing the IAM with its application in ranking of OE devices are, as below:

- Examination of the decision making aspects of site deployment site for OE systems.
- Studies on aspects of survivability of these devices.
- Comparative studies of OE systems with data generated from scope of resource tapping, LCA & EA studies, EIA, and economy evaluation.
- Identification of Tasks needed for defining the IAM.
- Development of the composite IAM applicable for all OE systems.
- Examination of the IAM for ranking OE devices from sustainable development point of view.

- Development of mathematical model of IAM**s** with well defined approach in assessing the viability of an energy device, for sustainable development.

An account of the above studies developing the IAM & IAM**s** has been covered in the subsequent sections.

7.1 Deployment site of OE devices

The sub-criterions as regards the decision making on site selection, for placement of OE devices are:

1. Availability of proper resource of the particular OE systems like, wave, OTEC and Tidal schemes.
2. Availability and distance of grid line /transmission of power from placement site.
3. Facilities with cost component as regards their constructability with scope of easy access for periodic maintenance work, as needed.
4. Environmental impacts caused.

The above points as regards choosing the right deployment site for the right OE device have been detailed below.

7.1.1 Resource availability

The resource availability at the deployment site is an important criterion for choosing the right type of OE device. Comparative studies of resource availability shown in fig. 2.1 (Chapter 2) & fig.5.1 (Chapter 5) have depicted that high latitude regions mostly with higher wave density resource potential, makes wave schemes the preferred choice in these regions. OTEC resources are more favoured in equatorial seas of low latitude regions. Tidal schemes have their own specific, but limited sites suitable for the construction of barrage or TISEC schemes, and have been shown in fig. 6.1(Chapter 6).

There are options of choosing land based, near shore or off-shore sites during the decision making for the deployment of wave or OTEC schemes. In the case of wave schemes, the off-shore sites are preferred having a higher wave density than land based or near shore ones. Off-shore sites for wave schemes are also considered to be economically beneficial (Westwood 2004).

But unlike the wave schemes, in the case of OTEC- off-shore sites are not necessarily the preferred choice. Land based OTEC plants are rather helpful in deriving better benefits in terms of by product availability, like utilization of up-welled cold water for mariculture, and in cold storages/air conditioning etc, without expending power (Takahashi & Trenka 1996). On the other side, in the case of land based OTEC plant, costs involved for the cold water pipe is nearly 3 times than that for off-shore ones, as detailed in section 2.2.4.1 of chapter 2. Thus the ultimate decision making in choosing deployment site would be decided from the overall economic gains achieved, considering all these parameters. If however from R&D studies, grazing OTEC plant with in situ hydrogen production becomes successful

(Ryzin *et al* 2005), then that would be best option with no involvement on expenditure of mooring or cost of cable laying for power transmission.

High tidal range availability is not the sole criteria for choosing sites of tidal barrages. Adequate planning to derive maximum power with minimum barrage dimension, for deriving maximum economic benefit is required prior to deployment.

TISEC sites with high tidal ranges should be such; so that they have river current velocity between the ranges 1.0—2.5m/sec should be available for more than 5000 hours all year round 8760 hour period (Hagerman et al. 2006). TISEC placement sites should have a clearance of 5m depth from the estuary bed to safe guard benthic population, and 10-15m clearance from the top to allow navigational access (Bryden et al. 2004). Such sites are normally available around 1 km upstream, the estuary mouths of rivers with high tidal range (Westwood 2004). A maximum 10-15% of the estuary width can be utilised for the placement of TISEC assembly, thus ensuring that the main river current is not affected appreciably (Bryden *et al.* 2004).

Though resource potential is an important criterion in choosing the deployment site for an OE device, there are other parameters to be considered. These have been discussed in subsequent sections.

7.1.2 Scope of Gridline availability

All OE systems, whether wave, OTEC or, Tidal schemes (both barrage and TISEC units), are to be connected with the gridline connection for delivering power to the consumer. This involves additional cable costs which include its material cost, laying out cost from the implantation site to the grid line and the cost for its periodic maintenance. Thus, the availability of the shortest distance of gridline from implantation site would be the preferred site of choice.

In-situ generation of fuels like H_2 etc, utilizing electricity production from OTEC schemes (Ryzin *et al* 2005) as well as for some types of TISEC projects [Elliot 2004), are being considered as an alternative to transmitting power through long cable lines. But such ambitious projects (of H_2 generation etc.) are still in the R&D stage and they hold wide promise as alternate transport fuel by replacing oil (Kane 2005).

7.1.3 Facilities of construction and O&M of OE devices

The technology of off-shore construction for wave energy converters is the preferred choice with availability of high wave density climate. This is no longer a technical challenge but means a much larger financial cost than the land based ones.

But for OTEC schemes, it remains a technical challenge with high cost involvement for cable line laying and maintenance, reaching 1000m below the ocean surface (Cohen 1982).

In the case of barrage construction, there should be access road/passage for transporting the large volume ofconstruction materials to the site. If such infra

structural facilities in terms of access to site are not available, extra expenditure would be incurred for its build costs.

7.1.4 Environmental Impacts over deployment sites

Land based wave (also OTEC) schemes may have a negative eco-impact from noise pollution during the construction phase and in addition will have a negative visual impact especially in places of tourist importance. It would also affect the bird population and fishing community (though minor) during its construction phase, particularly if the breeding period of the birds coincides with the construction period (Sorensen 2003).

In off-shore sites, of both wave and OTEC schemes, sites of archeological importance or sites of naval exercises etc should be avoided.

Barrage schemes open up tourist economy from construction of approach roads etc but earthquake prone zones or, zones with zeological disturbance should be avoided in making barrage site selection.

Apart from the environmental consideratons, economic gains are also to be taken into account prior to making a site selection for all types of OE devices.

7.2 Stability and survivability of OE device

The minimum requirement of accepting a wave or OTEC device is its sea-worthiness or, survivability withstanding the rough ocean conditions including storm waves. No wonder off-shore wave energy converters or OTEC plants need to be built robustly enough to withstand the high density off-shore waves including storm waves. Hence huge amounts of construction materials are required for such energy schemes, affecting their economy and this invites survivability vs. cost optimization.

It is a fact that higher material requirements to make the devices rugged play a negative impact on their economy. But, on the other side assuring a higher life time for them makes a positive impact on the cost input. It may be relevant to add that sensitivity analysis on design aspects of devices, like replacement with cheaper construction materials without compromising the quality and/ or, making design improvements/ adjustments may help to reduce the cost component due to the large amount of construction material required to ensure survivability.

Based from the above discussions the assessment criterion as could be identified the on survivability aspect of OE systems, is detailed as below:
.
- Adjustment of design parameters of devices to ensure better survivability keeping the cost component in view.
- Examining the effect on cost component vs. life expectancy of the devices.

A brief outline of the above points has been described below.

7.2.1 Adjustment in design parameters of OE devices

Economic improvement in the construction of OE devices may be made in three ways. It could either be by replacing costlier construction materials (even partly) with cheaper options, without compromising the quality; like, the suggested part replacement of steel with concrete in the body construction of Pelamis. In OTEC plants, replacements of costlier Titanium heat exchangers with cheaper aluminum alloy are being considered, although this is still in R&D stage (Anderson 1998). For constructing cold water pipes of OTEC schemes, scope of use of soft pipes made of reinforced elastomeric fibers are considered. They are as effective with better survivability in rough seas and are the cheaper option compared to HDPE pipes (Vega 1999).

The other method could be by performance improvement of converters. A typical example is the suggestion of making the Wave Dragon a Hybrid type, tagging the off-shore Wind farms over its huge platform and using the same mooring. Thus there is increased power generation with proportionately less load of construction materials. In the case of OTEC it could be from using Solar collectors to increase the temperature of working fluid in CC-OTEC. However this is still in R&D stage (Yamada *et al.* 2006).

The third alternative, which also is still in R& D stage, is to employ devices that need not encounter ferocity of waves using point absorber type WECs, placed at seabed, like linear generators (Legion *et al*. 2006). For OTEC schemes submersible OTEC plants (Takahashi 2000) or, grazing ship type OTEC plants (Ryzin *et al*. 2005) could be considered.

These schemes of wave and OTEC are in R&D stage and hold wide promise of economic improvement in these sectors, besides ensuring survivability. All these points have been examined in the subsequent chapter (Chapter 8) discussing the scope of improvement

7.2.2 Cost component vs. Life expectancy

From necessary case studies of both wave and OTEC schemes it could be noted that life expectancy below a certain level (around 30 years) causes a sharp rise in their cost (vide fig.4.15 & fig.4.16 of chapter 4, and fig.5.5 & fig.5.6 of chapter 5; respectively). In this context it may be relevant to add that the life expectancy of tidal barrages is quite high, around 100 years (section 2.3.8 chapter 2). But the life of its turbines as well as for TISEC units is around 30 years.

Obviously R&D to increase the life expectancy of OE schemes would derive economic benefit. On the other side no compromise on design life below the breakeven point of wave or OTEC scheme would be desirable.

7.2.3 Comments on survivability of WECs & OTEC devices

From the above analysis on the assessment criterion, on survivability, it is evident that an adequate safety factor should be maintained in the construction design of

off-shore WECs or OTEC schemes, to ensure survivability from storm waves etc (also in the eventuality of higher wave regime for future global warming etc).

Preference should be given to devices that have the potential of cost reduction with the replacement of cheaper construction materials without compromising on quality. Preferred designs are those that can facilitate design adjustments for cost reduction ensuring survivability.

Promise with higher life period (minimum 30 years for wave & OTEC schemes), with economic advantage achievable would be the preferred choice of the device.

7.3 Comparative studies on data obtained from four assessment tools of OE schemes

Data generated from the examination of OE systems covering; wave, OTEC & tidal schemes, employing 4 assessment tools including resource analysis, LCA & EA studies, EIA studies and economic evaluations (as made in Chapters 4, 5 & 6, respectively), are compared for developing the composite model as could be made applicable for all the OE systems. The results obtained for each of the above 4 assessment tools are detailed in subsequent sections.

7.3.1 Resource analysis

It would be obvious that though broadly the resource to be exploited is the energy of the ocean, each system harnesses energy in a different form. Wave schemes utilise the energy density of the waves, whereas OTEC schemes utilise the temperature differential of the surface and bottom layer temperature differential of ocean. Barrage & TISEC both utilises the upsurge of tidal range. Naturally the technology employed to utilise the respective enegy systems is different and would need separate treatment for each in their resource analysis studies, as are discussed below.

7.3.1.1 Resource analysis of wave schemes

Depending on the design characteristics and technology used, different types of WECs have their own characteristic power generation capability from the same site possessing a particular wave density. The annual power production from the same type of WEC (with definite capacity factor) would vary at different sites with varied wave density. Thus, annual power production **P** showing the annual energy production from a wave schemes, may be considered to be a function of the capacity factor of design characteristics of the WEC (C_w) & site's wave density (S_w). Mathematically it can be expressed as:

$P = f (C_w, S_w)$……………………………[7.1]

Thus both the capacity factor of the WEC concerned as well as the site's resource density is important (as is seasonal variation) in determining the annual energy production of a device. The results can only be obtained from actual sea-trials of the concerned device at the particular site. A classic example of which may be cited from trial runs made of 750kW Pelamis. It showed an annual energy production of 2.5GWh with capacity factor of 38% when placed on the coast of Ireland but was reduced to nearly half with capacity factor of less than 20% when tried on the coast

of Portugal (Dalton *et al*. 2010). Such results showing the importance of both wave density and WEC design characteristics, is also evident from results of tables 4.1-4.4, shown in chapter 4.

Thus both the technology of the device and also the wave density are important criterion in deciding annual power generation of a WEC which can only be availed from on-sea prototype trial runs.

7.3.1.2 Resource analysis of OTEC schemes

Resource density of OTEC is solely dependent on the degree of temperature differential between the ocean surface and up-welled cold water from the depth below. This temperature differential is quite small to run a turbine and therefore a high mass of water flow with large sized heat exchangers and condensers are needed to make OTEC a viable proposition. It has been estimated that a 100MW OTEC plant with a resource potential of temperature difference around 20^0C would require a 400m^3/sec of hot surface water flow with corresponding cold water flow from a depth to be around 200m^3/sec (Vega 2002/2003a). This resource density of OTEC can be increased manifold for CC-OTEC, by the Hybrid system of SOTEC, increasing working fluid temperature of OTEC with a solar collector. This scheme is however, still in the R &D Stage (Yamada *et al*. 2006).

In fact, there can only be 3 options as regards the designs of OTEC schemes. They can be CC-OTEC, OC-OTEC or Hybrid OTEC. Of course they may be of a varied in-built power production capability, from a few kW to 100MW or more. As regards the size of OTEC plants, it has been estimated that mooring cost per unit power output for a 20MW plant can be lowered 10 times if the plant size is increased to 100MW capacity (Vega 1999). Also the percentage of net power availability from gross power is more for larger capacity plants. This makes larger capacity plants the preferred choice.

Land based OTEC plants run the risk of exhausting the resource of warm surface water feed, unless care is undertaken to drain out the mixed discharge of warm and cold water from the condenser, to a sufficient depth so that the surface water temperature is not lowered.

If however, grazing type plant-ship with scope of in-situ production of H$_2$ etc. type fuels is successful, it would then revolutionize the OTEC industry with scope of utilising the warmest sea surface temperature points grazing around the best hot spots, with no mooring cost and little for cable line layout cost for power transmission. Of course net energy availed may be a little less as part of the gross energy would be spent in ship movement besides operations on OTEC power generation.

7.3.1.3 Resource analysis for tidal schemes

Tidal schemes involve two systems-barrage schemes and TISECs' deployment. Cost/kWh is the important assessment tool for both. But an important criterion to

assess the economic advantage for barrages is the tidal range as well as effective barrage planning.

In the case of TISECs, it is the innovative design characteristics in addition to tidal current resource, which is of importance. A brief outline defining the quality elements in design characteristics of both schemes are discussed below.

7.3.1.3.1 Resource analysis on barrage schemes

Tidal barrage has proved to be a viable commercial proposition, running profitably for decades. La Rance Barrage in France is making uninterrupted production of 480 GWh/yr since 1968 (Frau 1993). But suitable barrage sites with availability of high tidal ranges are limited globally. Each barrage site however, has its own specific construction constraints. This includes the high cost involvement for barrage construction and also the risk of causing irreversible damage to the local eco system during the construction phase (Kane 2005).

These constraints demand a long and meticulous planning for undertaking barrage construction. The test for efficient planning lies with the availability of maximum power production from minimum basin area constructed. High tidal range of course gives some benefit for availing higher power but effective planning helps in deriving better economic advantage. These two factors, tidal range and effective planning are hence considered decisive, for any barrage scheme.

In order to undertake effective barrage planning the important considerations are:

- Selecting the right construction site in estuaries which could deliver maximum power production from minimum basin area.
- Optimization of sluice gate dimensions and their numbers accommodating maximum numbers of turbines/generators.
- Selecting proper power production modes and duration for running the turbines utilizing tidal heights in the basin (best performance achieved for flood pumping mode of power generation).

A methodology to ascertain the barrage efficiency could be evolved from case studies of some of the proposed as well as functioning barrage projects.

It had been noted (Chapter 6, section 6.2.1) that P/Ar^2, would have the minimum value of 3.06×10^{-4}, termed threshold value or, limiting value of barrages; where P denotes annual power production. 'A' is the basin area and 'r' is the tidal range (considering the barrage to function 12 hrs 25mins /day). It followed logically that all barrages would have its own specific value of P/Ar^2, which may be termed the barrage constant. The ratio between barrage constant with the threshold value of 3.06×10^{-4}, would obviously denote the barrage efficacy, and is an important tool, irrespective of the tidal range, to categorize achieved barrage planning efficacy. Based on the above assessment tool, categorization could be made as regards design efficacy of different proposed, as well as the functioning La Rance barrage, having varied tidal ranges and is shown below in fig.7.1.
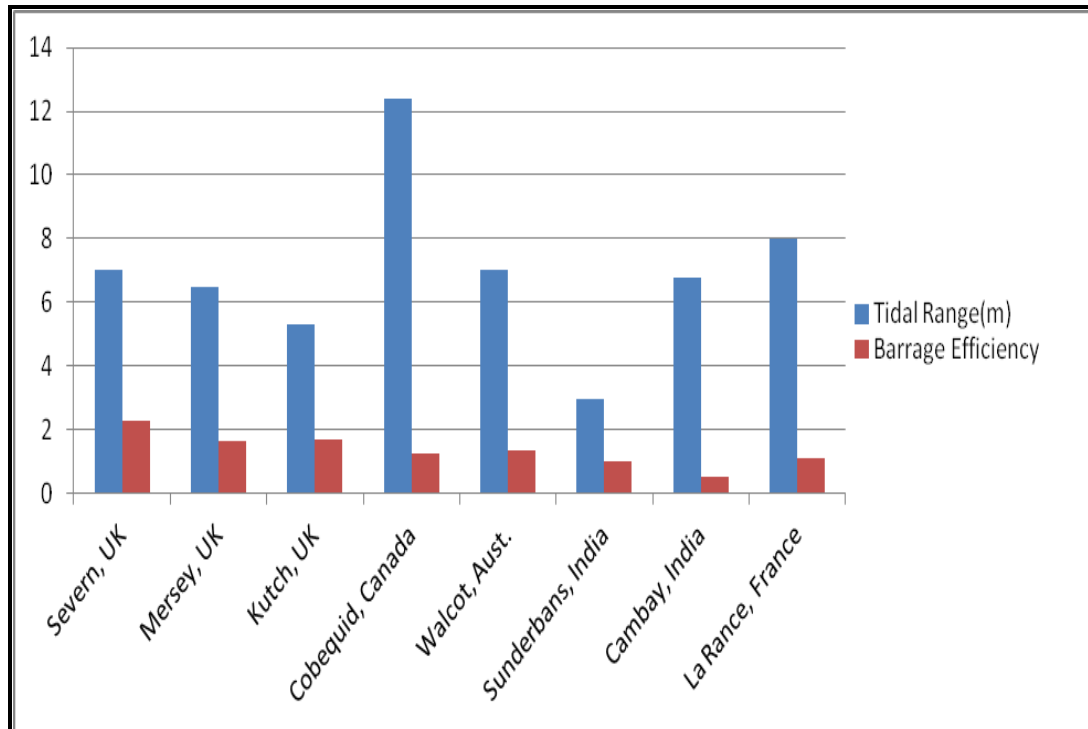
Fig.7.1 Tidal range vs. barrage efficacy of some proposed & functional tidal barrages

It could be observed that tidal ranges do not necessarily give better barrage planning efficiency. The functioning La Rance barrage, France, with higher tidal range, had lower barrage efficiency than the proposed Severn Barrage scheme, which shows best planning efficiency.

This barrage index also helps in revising the barrage planning and/or determining suited barrage dimension. It would be obvious from above fig.7.1, that the Gulf of Cambay (India) needs revision of its planning, with poor efficiency despite reasonably high tidal range. On the other side in Sundarbans (India) with undecided basin area, the limiting value of the basin area could be spelt out so that its barrage constant does not fall below the threshold value of $3.06*10^{-4}$. This has also been detailed in section 6.2.2 & table 6.1, in Chapter 6.

7.3.1.3.2 TISEC schemes design parameters in resource tapping

Full scale commercial runs of TISEC prototypes, whose resources are high tidal current, are yet to take off with Sea Gen and some such other prototypes showing promise. Many of them hold the potential to produce huge power from TISEC farms, with scope for generating H_2 fuel, and are also considered for grazing type OTEC plants. Both these ambitious schemes are however in the R&D stage but hold wide promise.

The only criterion however, in assessing design excellence for TISEC devices would be its capability of power production vs. cost involved including the O&M costs.

7.4 Assessment on the efficacy for global warming abatement of OE schemes

It is more or less an accepted fact that high CO_2 emission from fossil fuel is mainly responsible for global warming, despite its low GWP value of just '1' compared to the rather higher GWP values of other gases. Other emitting gases like CH_4 and oxides of N_2 do contribute to global warming, though proportionately much less compared to the much higher quantity of CO_2 emission from fossil fuel combustion. Hence, the term CO_2 equivalent of global warming potential is used, since CO_2 (g) emission is the principal contributor.

Unlike fossil fuels, OE systems like all other renewable energy systems have very little emission during the O&M stage, most of the evolution being in its construction stage. Thus a life cycle analysis with boundary conditions of 'cradle to gate' is adopted for estimating its total life time emission. These values if compared with the huge emission from fossil fuels could be an indicator for making a quantitative assessment of OE devices in minimising global warming by saving CO_2 emission.

Based on the above premise a number of criterions/sub-section assessment tools of the broad-based criterion on 'efficacy for minimising global warming' have been evolved. These assessment tools, as can be determined from LCA studies are as below:

- Emission of CO_2 in g/kWh power generation.
- Emission of GHG equivalent of CO_2 in g/kWh power generation.
- Percentage of CO_2 saved compared to its evolution from equivalent power generation of fossil fuel generator, say from a coal-fired power generator.
- CO_2 payback period in years (CPBP), compared with its emission from equivalent annual power generation from coal fired generator.

Energy loss for construction /installation etc covering life cycle analysis can be estimated from Energy payback period and determined from Energy Accounting (EA) studies.

The specific results of all the above indices can be determined from LCA & EA studies, but only if their inventory data is made available along with the annual power production and assured life. Of course there may be minor variations in the results depending on the model used in LCA & EA studies. Provided the same model is used for comparison the relative efficacy of different OE schemes in their global warming abatement, would not be largely affected.

A comparative study of the above indices, as derived from the results of LCA & EA estimations of chapters 4, 5 & 6 covering wave, OTEC & Tidal schemes, have been shown below in table 7.1 (vide sections: 4.3 & 4.4; 5.2; and 6.3; of Chapters 4, 5 & 6, respectively). The results obtained from the Danish data source have been shown in the table and these results tally fairly well with the Bath University data source.

Table7.1Comparative study on LCA & EA studies of different OE devices

Indices / OE device	CO_2 g/kWh	CO_2 eqv. g/kWh	% CO_2 saved	CPBP in yrs	EPBP in yrs	Remarks
Wave Schemes						
Wave Dragon	28.23	28.25	96.58	1.71	1.75	Considered 50yrs life as per the design.
Pelamis	19.49	19.68	97.64	0.49	1.22	Considered 20 years life, as per the design.
OTEC Schemes**[Inventory data for 3 OTEC types are considered more or less the same]						
100MW CC-OTEC	28.47	28.64	96.55	1.03	2.35	Operational input with NH_3 as working fluid considered,
100MW OC-OTEC	65.68	65.85	92.05	2.38	2.35	Release of dissolved CO_2 from evaporation (partly) of warm water in the evaporator in its operational phase, contributes to higher CO_2.
100MW Hybrid OTEC	39.37	39.54	95.24	1.44	2.35	Obviously, CO_2 values are in between CC-OTEC & OC-OTEC.
Tidal Schemes						
Severn Barrage	3.01	---	99.63	0.36	0.53	Better planning with proposed high power production gives the advantage in reduced CO_2 emission over other OE devices,
Mersey Barrage	18.63	--	97.74	2.71	3.08	CO_2 emission much more than Severn; proportionately had less power generation.

Amongst the above indices on global warming abatement tools, the two indices - 'CO_2 emission in g/kWh' and 'percentage of CO_2 saved' (compared to an average coal power generator) - are of overriding importance. OE devices could be categorised from their 'global warming abatement' criterion, based on the above two assessment tools, as shown below in fig.7.2.

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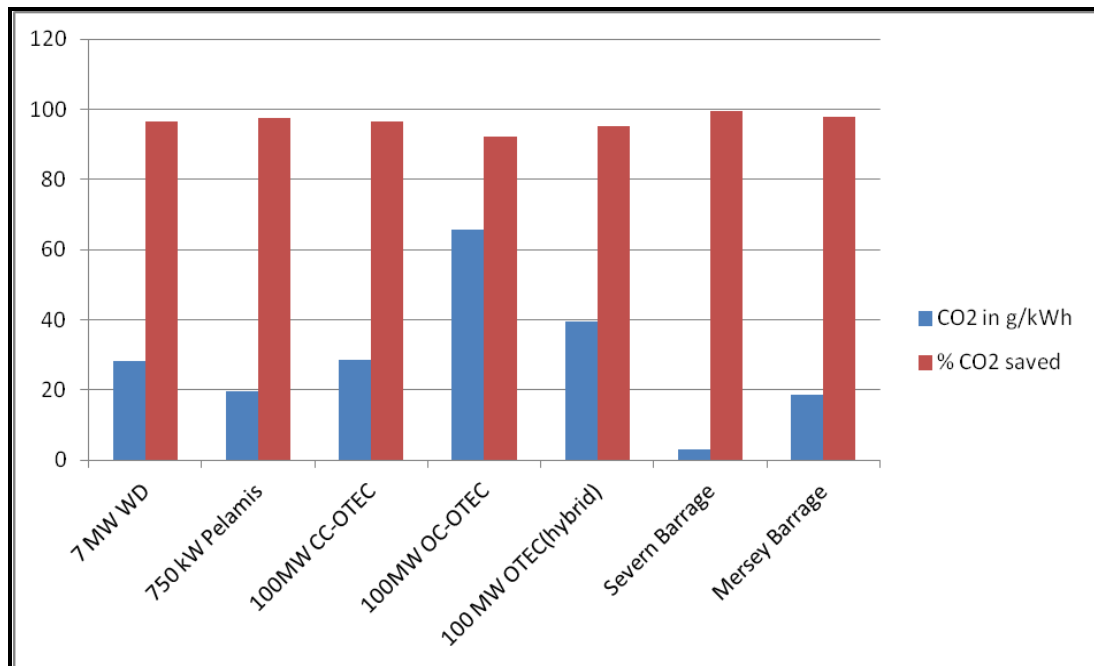
Figure 7.2 Compared OE systtems from global warming abatement criterion

In addition to the emission characteritics, comparative study of different OE systems based on other environmental issues such as; flora and fauna, hazards posed and societal issues, are detailed   in the subsequent section.

7.5 EIA on OE systems

Environmental Impact Assessment (EIA) of OE systems, have already been examined in detail and narrated in sections 4.5, 5.3 & 6.4, of chapters 4, 5 & 6, for wave, OTEC and tidal schemes, respectively. In these analyses, quantitative estimations for different environmental issues including; flora and fauna, hazards posed, and societal issues, have been categorised into three broad subdivisions. As per the degree of impacting parameters influencing upon the subsets of these individual environmental issues, they have been grouped to be; high, medium or low category. The qualitative characteristics are determined from the nature of influence of the impacting parameters over the environmental issues, whether favourable or detrimental to sustainable development. This model, as developed in chapter 3 spelling out the logic for quantitative and qualitative environmental impact assessment (EIA) of OE systems, could be applied individually and separately for all three OE systems, wave, OTEC and tidal schemes, shown in Chapters 4, 5 and 6, respectively.

In the present study, the results obtained in the above sections (4.5, 5.3 & 6.4) have been compared together. Based from Pastakia and Jensens RIAM studies of EIA (1998), as discussed in section 3.8 of Chapter 3, it may be presumed that low value would be indicative of around 5-20% shift, medium values around 20-40% changes and high values to cause > 40% influence than the original scenario of the ocean (in the vicinity of deployment site), that existed before deployment of the OE devices/farm.

It may be relevant to add, based from observations of the relevant sections of EIA studies made in the concerned chapters that the influence of wave schemes over flora and fauna are rather benign (provided sensitive periods are avoided for constructing land based WECs). This makes a higher positive impact (better than wave) or, moderate positive impact for tidal schemes; but appreciably higher positive impact (higher than tidal) for OTEC schemes.

As regards the apprehension of hazards, it is presumed that all the mitigating measures spelt out as deployment guidelines for respective OE schemes, are strictly adhered to. The risk ratings given are only hazard rating from accidental failures, despite the adoption of mitigating measures. However, as spelt out in respective sections of the concerned chapters, hazards and scope of operational failures are highest for OTEC, and less high for tidal schemes, provided of course all preventive measures are strictly adopted.

Keeping the above perspective in view- EIA rating for; the environmental impact on flora and fauna, hazards posed from deployment and societal issues involved- have been compared, respectively in figures 7.3.7.4 and 7.6 respectively, and are given below.

7.5.1 Flora &Fauna

The results on flora and fauna based from the results obtained from tables 4.21, 5.9 & 6.7, of chapters 4, 5 & 6, have been compared below in fig. 7.3.
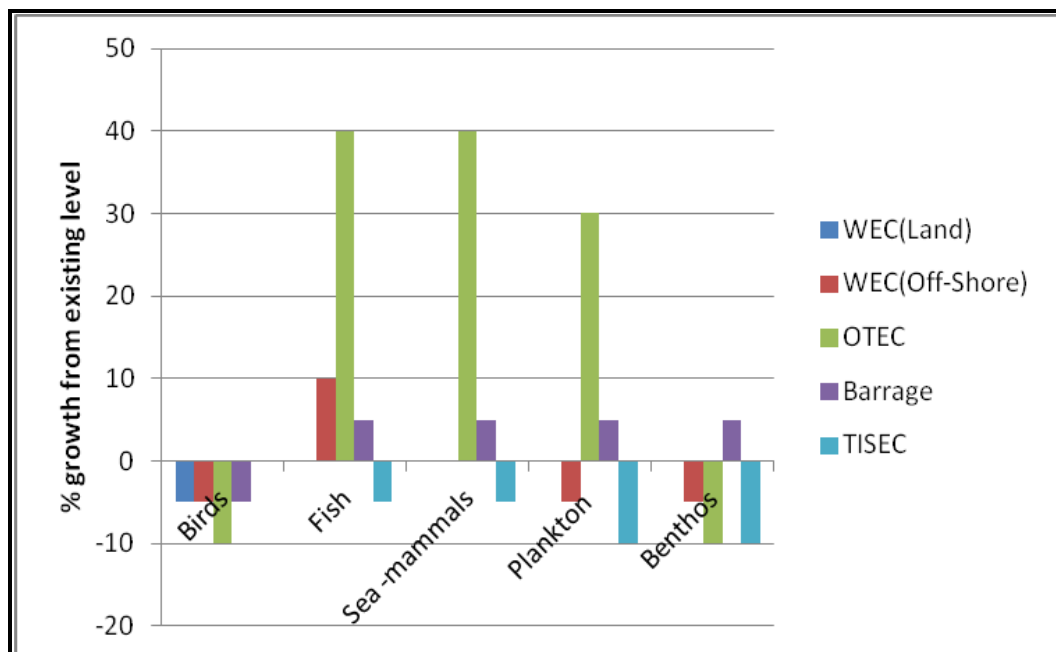
Fig. 7.3.Effects on flora and fauna for different OE systems.

7.5.2 Hazards posed

As regards the hazards posed for different OE schemes, the following observations in regards to the concerned environmental issues are relevant. They are as below:

- For wave systems the issues to be addressed are: survivability, collision with ships/liners, malfunctioning of equipment from bio-fouling, oil spillage from converters affecting the coastline from large scale energy capture from WEC farms, etc.
- For OTECs, in addition to hazards of wave schemes, particular mention should be given to survivability from tropical storms, malfunctioning of equipment caused from its various operational failures and/or bio-fouling, with sudden power failure blocking its operation.
- For Tidal barrage schemes they are mainly on: blocking navigational access, choking of sluice gates (from sedimentation etc), floods and/ or soil erosions aspects, and also on malfunctioning of equipment etc. caused from bio-fouling, particularly for TISEC schemes. In fact, flood or soil erosion problem are reduced from barrage construction, if adequate measures like heightening embankments and such measures are adhered to.

The assessments made are based from the presumption that adequate mitigating measures are adhered to. The results (as obtained from tables 4.22, 5.10 & 6.8 of chapters 4, 5 & 6, and also considering the premise stated above) have been depicted in fig. 7.4. Positive hazard value indicates scope of reducing the concerned hazard, whereas negative value is indicative of enhancement of the particular hazard item.
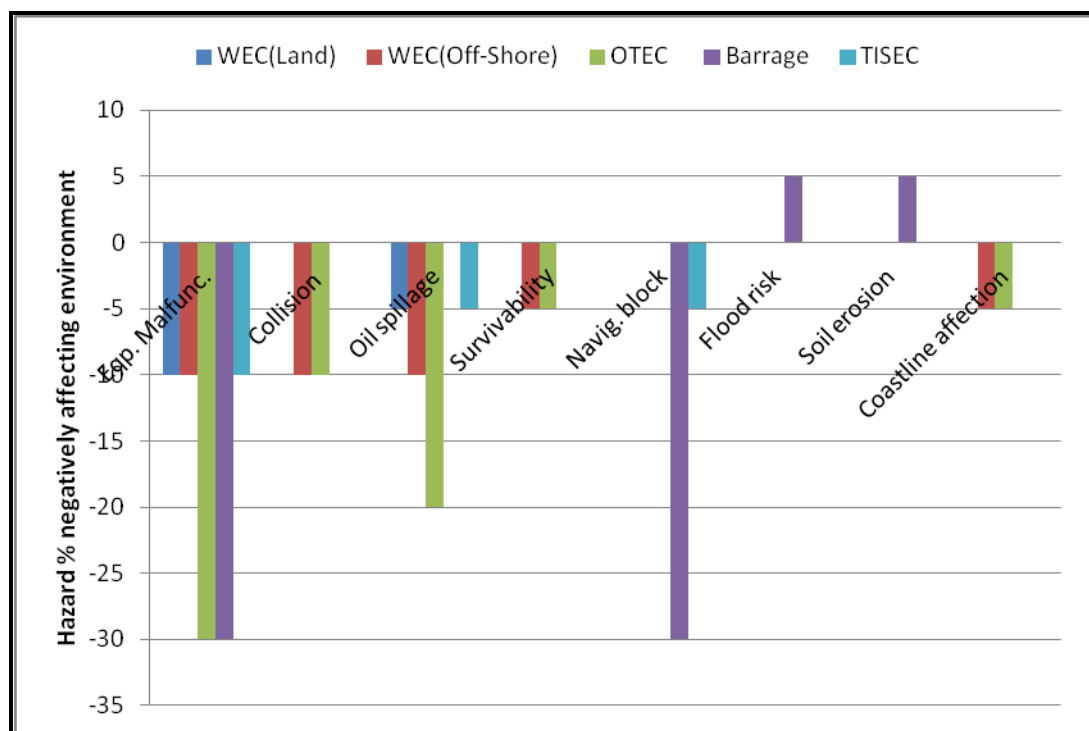
Fig. 7.4 Comparison of the hazards of OE systems.

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7.5.3 Societal Issues

It may be added that societal issues for wave, OTEC or Tidal Schemes are not exactly similar. Social acceptance for not allowing sites of naval exercises or of archeological importance, or avoidance of shipping routes in deployment site, may be important for off-shore waves or OTECs. Whereas, for land based projects noise pollution during construction phase or visual impact, could be an important issue to be reckoned with.

The unique advantage of by- product availability and food growth (fish/plankton) as also sequestering of CO_2 and scope of arresting coral bleaching, is not availed for by other OE systems. On the other side, in case of barrage schemes, financial burden is a big problem which is not at all relevant for TISEC schemes.

However, barrage scheme improves tourist economy by opening up access road facility also creates job particularly in its construction stage which is usually prolonged.

However, it is a fact that all energy production schemes improve the local economy. Keeping the above perspective in view and based on results availed from tables 4.23, 5.11 & 6.9, of chapters 4, 5 & 6, for wave, OTEC and tidal schemes, the societal issues affected from deployment of these OE schemes, have been compared in table 7.5 and is given below.
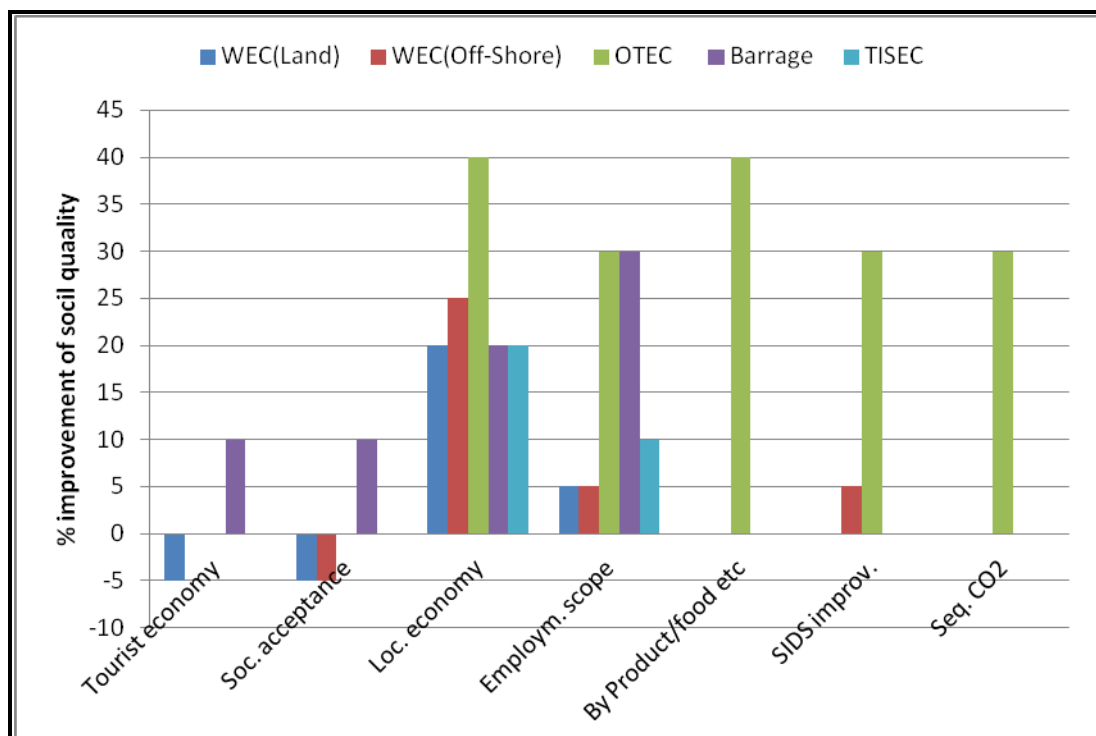
Figure 7.5 Comparison of the societal issues from deployment of different OE devices.

It may be relevant to add that the societal issues conform to the scope of improving upon the quality of life in the vicinity of the concerned site, caused by the deployment of different types of OE devices.

7.6 Evaluation from Economic assessment tools /indices

Evaluation of the economic advantages is considered to be the most important tool in assessing the market acceptability of an OE device. In fact, all other decision making criterion or tools such as; site selection aspects, scope of survivability, resource utilization capability, degree of 'CO$_2$ emission saving' in averting global warming, and other environmental impact assessments, are all indirectly related to the economic fallout affecting sustainable development.

However, there are a few tools for the direct evaluation of the economy of a process or a system. These tools of economy assessment for OE systems are as below.

- Cost of power generation in p/kWh from the concerned device, based on the Net Present Value concept.
- Cost Payback period in years.
- Percentage of Internal Rate of Return on the cost component.
- Relative product cost ratios (RPC) of different OE devices, comparing the ratios of their mark up costs (i.e. cost without the profit margin maintained by the concerned device manufacturer).

In estimating these costs of different OE systems- additional costs like insurance, carbon tax, local taxes etc. have not been considered. It is presumed that the results are mainly meant for comparing the relative economy of different competing OE devices; hence it would not affect much in making the comparative studies.

All estimations for the concerned OE devices (excepting RPC ratio criterion) were made on the basis of the price of the device, quoted by respective companies.

It was also thought useful to compare the mark up cost ratios from international price of the raw materials needed for the construction of respective OE devices. This ratio termed RPC ratio / kWh (relative product cost ratio) was used to compare the relative economic merits of competing OE devices; even if its capital cost involvement or designed life period is not known. This is considered useful particularly for R&D studies of different competing devices, during the stage of their development, and also in the efforts to improve upon it, to lower the capital cost involvement. Successful application of this has been discussed in chapter 8.

In the estimations of discount factor for determining indices based from NPV concept, the   discount rate maintained was 8%, and life period considered was the designed life of respective devices. Thus for the wave dragon the designed life was 50 years (Tedd 2007), for Pelamis 20 years (Dalton *et al* 2010), for CC-OTEC 30 years (Tahara *et al*. 2000) and 100 years life period for the proposed Severn barrage (Woolcombe-Adams *et al*. 2009).

Results of case studies as made for the three OE systems, estimating the above stated economic indices, have been compared in table 7.2 & figure 7.6 given below.

Table 7.2 Economy Indices of different OE systems compared.

Economy Indices / OE devices	Cost in p/kWh	IRR %	Cost Pay back period in years (simple payback period)	(Relative Product Cost Ratios) RPC ratios / kWh	Remarks
7MW Wave Dragon	6.8	8.2	9.22	1.64	Considered design life of 50 years.
750 kW Pelamis	6.4	7.96	7.81	0.398	Considered design life of 20 years.
100MW CC-OTEC	6.8	8.03	9.8	0.664	Considered 30 years life.
Proposed 18km Severn Barrage	2.8	8.1	11.11	-	Considering life of 100 years.
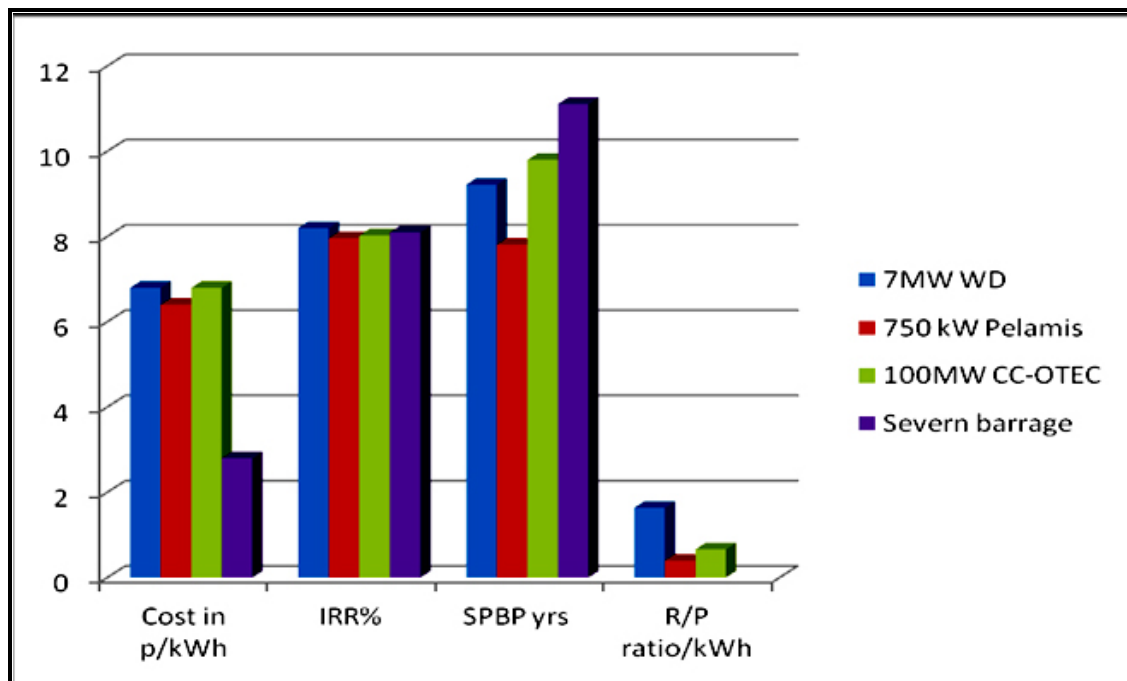
Fig.7.6 Economy indices of OE systems compared as per their design premises

The RPC values of barrage construction was not considered, since its long project completion period, with huge capital investment, with no return during its long construction period, is of overriding importance. The long project completion period appreciably affects the valuation of capital cost involvement (Elliot 2004).

The other important criterion that is considered decisive in the economy of OE system is its designed life period. There remain a sharp cut off life period, below which cost/kWh power generation increases sharply. This cut off life period or, breakeven point is important for the concerned companies in designing their

respective OE devices. Typical examples showing such break even points in the life of wave and OTEC schemes have been detailed in figs. 4.15 & 4.16 of section 4.6 in chapter 4, and fig. 5.5 & fig.5.6 of section 5.4.5.1 in chapter 5, respectively.

7.6.1 Comments on economic index

Amongst all the above stated sub-criterion or, economic assessment tools for OE systems, the most important assessment tool is the cost in p/kWh, the trend of which conforms fairly well with RPC cost ratio/kWh, for the OE schemes studied.

7.7.0 Development of Integrated Assessment methodology of OE schemes (IAM)

In order to develop the IAM**,** it is all the more important to comprehend the purpose and also the scope of its application. It should be a complete package to include all aspects on the scope of deployment, as well as of judging the relative merits and demerits as may be accrued from the deployment of the concerned OE device. In addition, it should also act as a guide to the manufacturer accordingly, including the device's status on scope for commercial application and also of its utility in the efforts for improving upon the device from R&D efforts.

In fact, the assessment tools as are developed and tried from case studies of OE schemes, in chapters 4, 5, 6 and compared from section 7.1-7.6 in the present chapter- is only a part in fulfilling the job for developing the IAM. In addition to the identification of the assessment tools with their application modality, as detailed above, there also remain certain specific tasks to be performed for developing the IAM, which need to be specified and well-defined.

Such tasks may be defined as below:

- Task 1- Identification of areas of data collection on certain specific aspects of the device, from the concerned manufacturer.
- Task 2- Defining necessary guidelines for OE device's deployment status for advising the concerned device manufacturer, accordingly.
- Task 3- Identification of the assessment tools and their application examining the scope for commercial deployment of the device, based from the primary data collected from the manufacturer; as spelt out in task 1.
- Task 4- Examining the OE device from application of the assessment tools identified in task 3, with a view to determine its relative merits and demerits, compared to other devices opening up scope of R&D areas for performance improvement of the same.

It would be obvious that these tasks are interdependent. It may require simultaneous operation of the different tasks, and also of one following the other, depending on the status of development of the concerned device. These tasks with their interrelationship and scope of operations are detailed below.

7.7.1 Data Collection (task 1).

There is a four-fold approach to the data collection aspect as stated below, which may be considered to be the first task required for the development and application of the IAM.

1. The precondition of accepting a WEC device or OTEC unit for study should be its passing the test of sea-worthiness. For TISEC unit it should be able to withstand the high river current pressure. In fact, the survivability safety factor required should accommodate future global climate changes and/or storm waves etc; even if it can be at the cost of apparent economic stakes.

2. The most important data requirement, as the first step of examination of a sea-worthy OE device is its detailed inventory data. This data not only helps categorising respective OE devices from their quality in addressing global warming etc. (LCA & EA studies etc), but could also help in comparing their economy, with other OE devices from the index of RPC ratios. Such inventory data would also be useful to examine design improvement options; undertaking   sensitivity analysis from the scope of the replacement of costlier inventory items with cheaper options (without compromising on the quality/performance) and thereby can assess the possibility of economic gains, as may be achievable.

3. The next important data requirement for examining an OE system is its designed power generation capability with capacity factor and designers assured life period.

4. It may be relevant to add that in the case of a WEC, the power generation data availed from the sea trials of prototype units and its capacity factor as obtained is useful to predict its annual power production capability. For an OTEC unit the power generation capacity would help operational efforts as regards the quantity of hot water and cold water feed required. Additionally it would help to assess the quantity of by product availability and thus ascertaining the economic prospect. However in the case of barrage, power generation data (tidal range data being fixed at a site) can advantageously be used in planning the basin dimension, so that the barrage efficacy does not fall below the threshold value. This could help in the optimization study for barrage planning.

7.7.2 Guidelines for OE device deployment (Task 2)

The guidelines for deployment as regards wave and OTEC systems would have to address two problems. In the first place, it has to ensure the appropriate type of OE unit with scope for of availing maximum power availability is deployed at the correct location. This brings in considerations on assessment tools like, resource potential of the implantation site, as well as designers claim of resource tapping capability of the device. In the case of tidal schemes there are only limited and specific sites globally with adequate tidal ranges making it an economically viable proposition.

The second important problem required to be addressed in OE deployment, is its assured survivability and other hazard mitigation in addition to respecting local social issues. Thus earth quake prone zones or, sites of heritage importance /naval exercise sites etc., are to be avoided as far as practicable. Survivability for off-shore devices is to ensure they are sea-worthy of the implantation site's wave density and should maintain adequate safety factor with assured life period. The safety factor should accommodate an eventual uncertainty of facing higher density waves.

Other usual precautions as are needed to be maintained for OE systems are the mandatory hazard mitigation aspects. To cite a few examples: adequate lighting/warning/signaling arrangement in off-shore wave /OTEC plants to avoid collisions from ships, avoiding ship routes on implantation sites to avoid collisions etc. On the other side, routine precautions in barrage construction such as;, river bank elevation to avoid floods, dredging in basin area to maintain proper functioning of sluice gates, etc. are required as mandatory guidelines. In addition to this, maintenance work is required for all OE systems, to avert their malfunctioning and should be carried out periodically.

Normally off-shore sites are the preferred choice for WECs. But the preferred site for OTEC projects would be decided on a case by case basis, comparing the relative economic gains as could be derived between shore line devices with that of the off-shore devices, depending on; the scope of the byproduct availability provision, maintained in the project concerned. Barrage construction sites should check up for achieving best economy from comparing barrage constant derived of the concerned basin area, with that of the threshold value ($3.06*10^{-4}$). TISEC sites should ensure adequate and cut off river current resource availability for a major period round the year.

In fact, all these guidelines for OE implantations are derived as a logical outcome from closer examination of the different assessment tools identified. They are outlined in the following task, which in fact is the essence of the IAM. Detailed treatment of the application methodology has been discussed in sections 7.1 -7.6, undertaken for different OE devices. Based on such studies, the following 6 assessment tools could be identified, as mentioned below.

7.7.3 Assessment tools identifying the priority assessment criterion (Task 3)

There are 6 broad assessment tools for ascertaining the relative merits and demerits of the concerned OE devices. Broadly they are as below:

1. Examination mainly in terms of economic as regards the OE device's deployment site analysis.

2. Its status of survivability including provisions of accommodating future uncertainty factors in wave density etc. so that the device's designed life period is maintained.

3. The scope of resource capture of the device proposed for application with analysis on its resource utilisation capability and scope for economic improvement.

4. Its scope for addressing global warming issues and quantification thereby, compared to fossil fuels, as estimated from LCA & EA studies.

5. Environmental Impact Assessment (EIA) on the device's application towards promoting or annulling sustainability development, as the case may be.

6. Economic evaluation with usual economy indices for comparing the relative economy of competing OE devices.

A detailed treatment of all the above 6 indices have already been discussed and compared in sections 7.1-7.6, from case studies of all types of typical OE systems. However, some of the relevant and important points of them are reiterated in the subsequent sections as well.

7.7.3.1 Deployment site selection for OE device

As regards choosing the deployment site, the primary criteria to be considered is the availability of resource potential as well as the economic potential for utilizing power. Based on the examination of the above two assessment criterion, it would be decided whether, wave OTEC or, tidal scheme is the best option at the site concerned. Then comes the question of choosing whether on-shore, off-shore or near shore device would be the better option, and for this economic evaluation is an important deciding factor. For tidal schemes basin area should be chosen and planned amongst different options that assure best economy.

7.7.3.2 Survivability of OE device

The condition on survivability of the device in the ocean is the bare minimum required to be fulfilled, before a WEC or OTEC device is subjected to assessment for adjudging its relative merits. It is to be evaluated that adequate safety factor are maintained to complete the device's designed life period, (should not be less than the breakeven point of 30 years), as estimated for wave and OTEC schemes.

7.7.3.3 Scope of Resource Capture from application of OE device

It would be dependent on the technology employed in developing the device, and also on the available energy density of the concerned deployment site. The latter in the case of wave schemes would be wave density and the tidal range for the tidal schemes. For OTEC, it would be the available temperature differential between surface water and the up-welled bottom layer of cold water. A detailed analysis of these has already been covered from case studies of all three OE systems, in previous sections (section 7.3, and Chapters 4, 5 and 6).

It may be relevant to add that there remains ample scope for technology improvement in this parameter on resource capture aspect of IAM, where many innovative ideas are in progress. In the case of WECs it has been attempted to enable them so as to utilise power even from wave density as low as a few kW/m only, using linear generators etc. (Leijon *et al*. 2006). On the other side, in the case of OTEC, attempts are in progress to increase the resource density itself manifold, using solar collectors etc. (Yamada *et al*. 2006). In TISEC a number of innovative ideas are being floated with much increased scope for power capture. In fact, the scope of application for IAM pin-pointing the areas of R&D in advancing OE technology

have been dealt with in subsequent chapter (Chapter 8) with detailed elucidations identifying the grey areas of research.

7.7.3.4 Scope of addressing global warming.

As regards addressing the aspect of global warming, the priority assessment criterion identified are the emission of CO_2 in g/kWh from power generation; as well as the percentage of CO_2 saved, compared to a typical and average coal power plant, as determined from LCA studies. It also included the loss of energy caused from the manufacturing etc of the particular device, as determined from EA studies estimating energy payback period (EPBP) of the concerned device.

Thus, considering coal power stations emission in producing equivalent power to be 100% -the input caused from CO_2 emissions from a particular OE device in its entire life time, may be expressed in percentage.

Likewise, energy loss caused during the manufacture of the device in its entire life cycle may also be estimated from the ratio of its energy payback period for its entire life (producing the power), and expressing the fraction in percentage.

7.7.3.5 Environmental Impact Assessment on deployment of OE farms

Apart from the aspects of emission which could be accurately determined from LCA studies, the other environmental issues considered in the application of the large scale deployment of OE farms are the impact on; oceans flora and fauna, hazards posed and societal issues that might be impacted. To date there is no definite data available on the quantitative effects caused by the above issues that might be accrued from the large scale application of OE devices. This is because of the fact that the large scale commercial application of OE device is yet to happen. However, qualitative effects and to some extent quantitative effects also, with three categorization on the impacts as to 'high', 'moderate' or 'low' category, could be made from a literature review as shown, as well as from the logical development of the topics involved, developing the EIA model for OE systems. A detailed treatment of the same has been covered in Chapter 3.

The degree of impact generated by the impacting parameters over the above environmental issues (from large scale OE device application) decides the quantitative character. On the other side, the nature of impact favouring sustainable development or declining it, gives the qualitative character of the environmental issues involved. These have been observed from detailed case studies of wave, OTEC and tidal schemes, shown in sections 4.5 (tables 4.21-4.23), section 5.3 (Tables 5.9-5.11) & sections 6.4 (tables 6.7-6.9); respectively. As per the premise made in section 7.5 (paragraph 2) assignment of score values maintained in the present study on environmental issues were considered to be around 5-20% for low effects, 20-40% for moderate, and >40% effect for high category effects (as per section 7.5, paragraph 2). Obviously such effects were considered for the localized area in the vicinity of the OE device application site.

The other aspect of the above EIA model developed was forecasting the hazards as could be considered inherent in the application OE devices. The mitigating measures could also be suggested as guideline to be followed in the application of OE devices. The risk rating values as assigned in tables 4.22, 5.10 and 6.8 of chapters 4, 5 & 6,

for wave, OTEC & tidal schemes were considered in the eventuality of accidental failures, despite taking recourse to the prescribed mitigating measures, as had been identified for respective OE schemes.

It may be stressed upon that the above EIA model may be improved upon by making it more objective oriented, as and when large scale application OE devices come into force.

7.7.3.6 Economic evaluation on application of OE devices
The priority assessment tools directly deciding the economy of OE systems are the indices like, cost in p/ kWh as well as RPC values (Relative Product Cost Ratios /kWh). If the designed life period of the device is below the cutoff point (break-even point), the cost escalates rather sharply (vide figs. 4.15 & 5.5.

The comparative study with fossil fuel, as regards cost/kWh denoting the acceptability index of the concerned OE device may also be considered an important economic assessment tool. Such Acceptability Index (AI) may be estimated from the index of Cost in p/ kWh of fossil fuel **/** Cost in p/ kWh of the concerned OE device.

Relative Product cost ratios are helpful in comparing the relative economy of OE devices, amongst different competing OE devices, where the capital cost involvement data and life of the device is not available. However, it only compares the relative economy, and does not give the absolute value on economy index.

7.7.4 Application of the 6 assessment tools over OE devices (Task 4)

This is the final stage of IAM development indicating its utility, where 6 assessment tools (as identified and well defined in task 3) are applied. This is based on data collected from task 1 and also adhering to the guidelines to be followed, in making their application as highlighted in task 2. The detailed modality of such application of the 6 assessment tools have already been covered in sections 7.1-7.6, making comparative studies of all three OE schemes, including wave, OTEC and tidal schemes.

In fact, the entire scheme of development of the Integrated Assessment Methodology **(IAM)** as developed, is based on the above stated 4 interrelated tasks and direct application of 6 assessment tools. This could be outlined as schematic diagrams and shown below in figs. 7.7 & 7. 8.
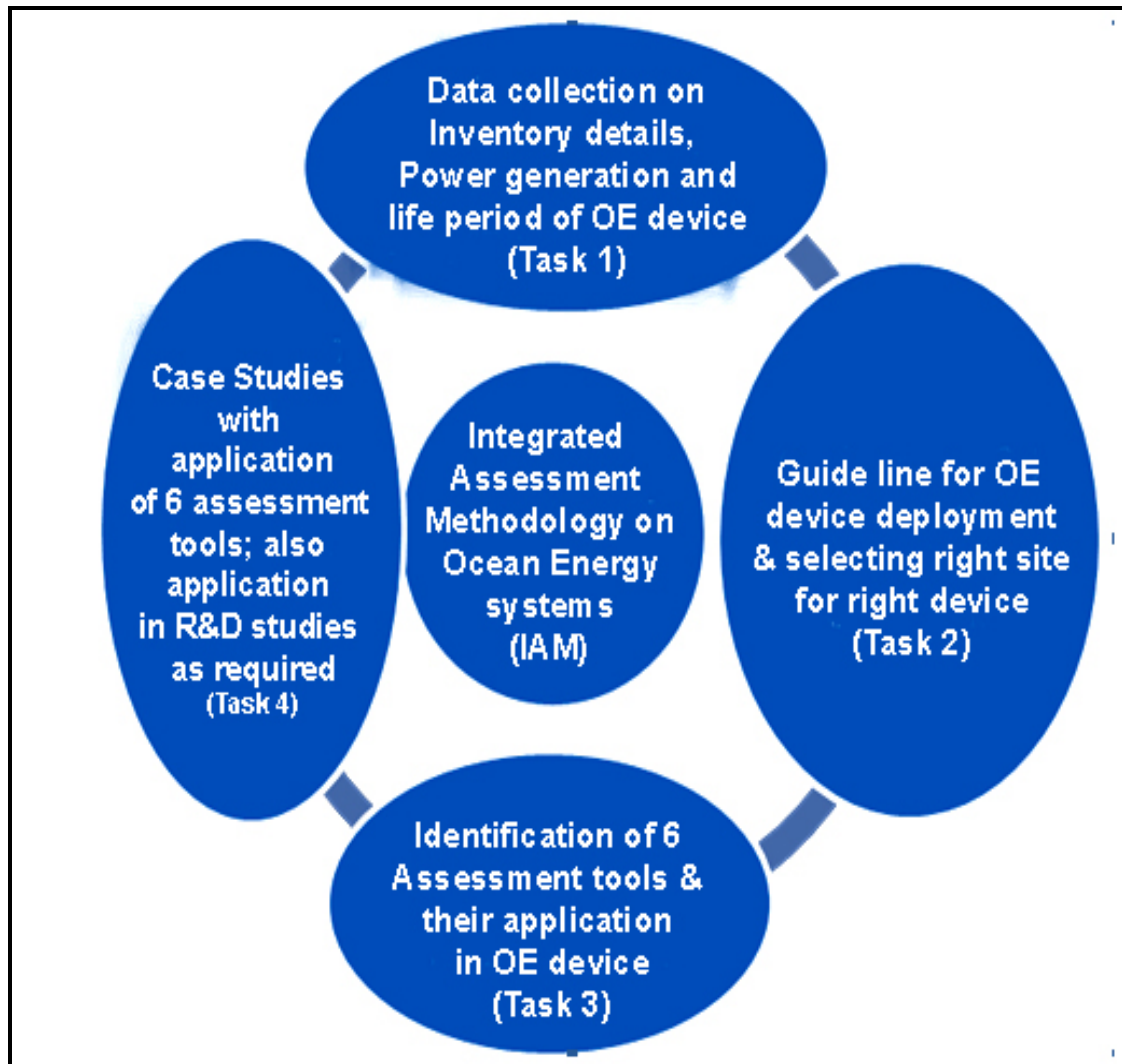
Fig. 7.7 Interrelationship of 4 tasks required in developing the IAM.

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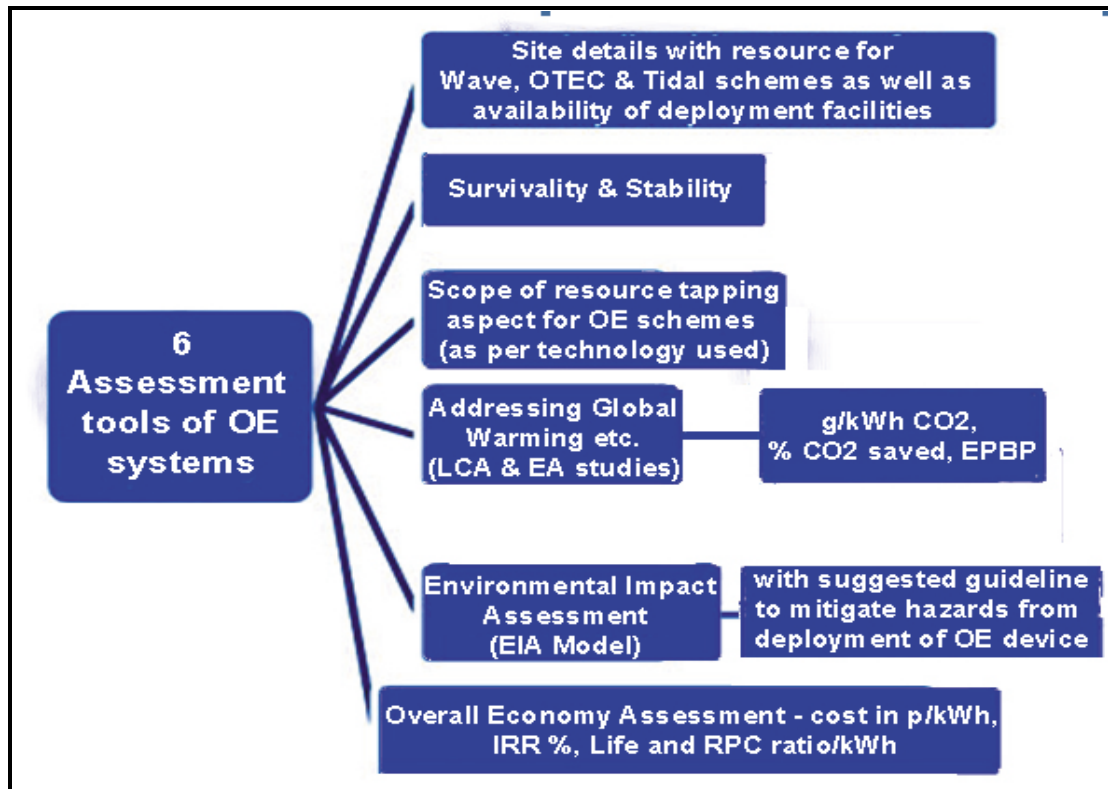
Fig. 7.8 Six Assessment Tools of the IAM has been shown schematically.

7.7.5 Critical appraisal of IAM

It may be added that the application of IAM as developed, has two components that may be considered. The first one is its scope of assessment on the status of the OE device examined, along with other OE devices, showing the relative merits and demerits of the concerned OE devices. The other is the feasibility of an improved device as might be achieved from R&D studies determining the degree of improvement that might be achieved thus helping in improving upon the device design. A detailed examination of this aspect on scope of applying IAM, as an important tool in R&D studies of grey areas, has also been taken up and discussed subsequently in chapter 8.

But the limitation of IAM is its multi-dimensional assessment criterion and absence of a common unified scale. This multidimensional criterion makes it difficult to judge the competing OE devices and rank them. There are two approaches to convert the multidimensional assessment criterion into one common unified scale. It could be either by converting to monetized scale and is considered neither feasible nor rational. The other approach could be by converting the different assessment criterion, to their scope of contributing to or, declining sustainable development. In this effort the Integrated Assessment Methodology (IAM) of OE systems is to be remodelled labelling it to IAMs which is redefined as the Integrated Assessment Model for ascertaining sustainable development (IAMs) of OE devices.

The methodology of developing this model IAM**s,** enabling the ranking of competing OE devices from their scope of sustainable development, has been covered in subsequent sections.

7.8 Application of IAM for developing IAMs for ranking OE devices

Energy Indicator for Sustainable Development (EISD) in their 2005 resolution identified 30 indices (inclusive of economy, energy and environment) for assessing the sustainable development of a country (Tsar 2010). For competing OE devices and their prospect of achieving sustainable development,- 7 indices could be evolved. This would help in the rank wise categorisation of such devices. The assessment technique employed and the indices identified, were based mainly on the assessment tools introduced in the development of the IAM of OE systems. Thus IAM**s** may be considered to be the modified IAM, meant for application in ranking competing OE devices, from the point of view of their scope of achieving sustainable development.

The methodology adopted consisted of the following five fold operations:

1. Identification of sustainable development indices (SDI).
2. Development of the scale of sustainable development of the energy system.
3. Methodology of estimating contribution from each of the SDI**s** contributing to sustainability development, termed sustainability development load score (SDLS).
4. Case studies estimating sustainable development including sensitivity analysis in perfecting the application methodology.
5. Mathematical model developing IAM**s** for scope of wider application for any energy system.

The methodology of developing IAM**s**, from above scheme has been outlined below.

7.8.1 Identification of sustainable development indices (SDI)

It is well recognized that sustainability development is mainly threatened from three negative inputs; global warming caused from emission of CO_2 (mainly), depletion of fuel resource (fossil fuels) and species loss caused, if any. In addition to this, the risks on inherent hazards, as may be caused from the application of the OE system included, are also detrimental to sustainable development. On the other side, economic improvement, or food growth and other social infra structure improvements which helps improve the quality of life, are always helpful for sustainable development of the society. Of course the magnitude of such sustainable development, whether favourable or detrimental to it, would depend on the degree of respective inputs.

Thus, the following 7 SDIs could be considered important indicators in assessing any OE device, from its scope of achieving sustainable development (SD). They are identified as below:

1. **Sustainability loss from input to global warming (SDIgw)**
   It can be estimated from LCA studies of CO_2 emission expressed as percentage emission, considering the emission from coal power plant (emission of 826.17 g/kWh from a typical and average coal plant, as shown in section 4.3.6.2 of chapter 4), to be of 100 percent.

The percentage input to global warming from respective OE devices, may be computed based on the values of CO_2 percentage saved, shown in table 7.1 of the present chapter.

2. **Sustainability loss caused from energy/fuel loss (SDIen)**
    It is related to the energy expended in constructing etc of the OE device. There is no loss of fossil fuel incurred in its operational stage (not even from OTEC) and it can be determined from the ratio of the energy payback period (EPBP) determined from EA studies to that of the life of the energy device. The ratio of the same is expressed as percent loss of energy from the device concerned.

    EPBP values were considered as per the table 7.1 of the present chapter. For considering its life period (of energy production), the designed lifetime of the concerned OE device was considered.

3. **Sustainability loss from the species loss caused, if any (SDIsp).**
    Quantitative estimations of EIA accrued from deployment of the particular OE device can help in the estimation of negative input percentage on the flora and fauna. The overall loss of flora and fauna, if any, as derived from EIA model of chapter 3, and subsequently derived in tables 4.21, 5.9 & 6.7; of chapters 4,5 & 6, respectively; are considered in assessing species loss, if any from application of OE devices.

    The percentage estimations are made as per section 7.5 (paragraph 2); stating the low category evaluation to be of 5-20%, moderate >20-40% and high to be of >40%, changes, that may occur in the vicinity of deployment site of OE device concerned.

4. **Sustainability loss from Intrinsic Hazard/ Vulnerability (SDIv)**
    It is estimated from the EIA model's negative score values due to accidental failures, despite adopting hazard mitigating measures. The overall values considered for different types of OE systems, could be estimated from the overall considerations of negative inputs shown in tables 4.22, 5.10 & 6.8 of chapters 4,5 & 6, respectively.

    Percentage estimations were made as per section 7.5 paragraph 2 of the present chapter- for low, moderate and high category scores made in respective tables as above.

5. **Sustainability gain from scope on the growth of food items (SDIgf)**
    It can be estimated from the positive input percentage on fish growth and plankton's growth if any (from deployment of the concerned OE device). It is estimated from the EIA on flora and fauna (tables 4.21, 5.9 & 6.7 of chapters 4,5 & 6, respectively). In contrast to species loss, it is estimated only if there is any positive input on fish growth and plankton growth.

    Percentage estimations were made as per section 7.5 paragraph 2 of the present chapter - for low, moderate and high category scores, made in

respective tables, as above. It may be reiterated that only positive inputs, if any, on fish & planktons growth are considered, for obvious reasons.

6. **Sustainability gain from economic growth derived (SDIeg)**
It is estimated from the ratio of the cost in p/kWh power generation, to that of the minimum cost in p/kWh power generation, expressed as percentage. The minimum cost of power generation, say 1p/kWh, is considered to derive 100% economic benefit. Percentage estimations on economic benefits derived for respective OE devices are made accordingly.

In estimating the cost in p/kWh of concerned OE device from NPV concept, the respective design life with 8% discount rates were considered, as per the results shown in table 7.2 of the present chapter.

7. **Sustainability gain from quality improvement in of life (SDIqi)**
It is estimated from the overall inputs (combined inputs of both positive and negative ones, if any) on societal issues, as shown from the deployment of OE device, and estimated from EIA model's societal scores, shown in tables 4.23, 5.11 & 6.9 of chapters 4, 5 & 6, respectively.

The percentage determinations are estimated as per section 7.5, paragraph 2 of the present chapter.

In order to determine the total SD score, covering all the above 7 indices, it is needed to develop a sustainability development scale, based on which the total percentage on sustainability loss or gain for a particular OE device can be estimated.

7.8.2 Development of sustainability scale

The first requirement of SD scale is a reference indicator giving zero values and also of 100 score value, so that the actual SD score of a device could be estimated, as per that scale of 0-100. Amongst the above 7 SDIs, first 4 are sustainability loss items, and the last 3 are sustainability gain items. If all the above 4 SDI loss items have zero values, with no loss at all; and all 3 SDI gain items have 100% gain value, in that case the concerned hypothetical device would obviously have 100% SD. On the other side, if all 4 SDI loss items show 100% loss, and all 3 SDI gain items show zero percent gain, then the SD of such a hypothetical device would have zero percent sustainability. But, in actual practice all devices would have sustainability in between these two extremes. Thus one can conceive of a SD scale 0-100, with the above two hypothetical extremes.

The next stage of the scale development is assigning sustainability load score values (**SDLS**) to each SDI, such that the combined sum total of SDLS of all 7SDIs would be 100. Of course, the assigned value of SDLS, to each of these 7SDIs, may be put in as per their relative importance towards achieving sustainability development. Since assignment of the relative importance towards assigning SDLS to each SDI is subjective, hence sensitivity analysis with different sets of SDLS values were made and studied for repeatability and standardizing the methodology of determining SD.

The relative weightage of SDI indices, in influencing SD, is also required to be considered in defining the individual SDI indices.

7.8.3 Methodology of estimating SD of OE devices

Three steps are followed for estimating the total SD percentage of a particular OE device, which is the sum total of percentage contribution from each of the 7 SDIs. The first step is defining the weightage factor required to be put in to the individual SDIs, spelling out the rationality of the same. The second step is assignment of SDLS values to each SDI, such that their sum total is 100. Of course, sensitivity analysis should be made in such assignment of SDLS values to individual SDIs, so that the rationale of SDLS value assignments could be developed. The third step is computing the percentage of the individual SDIs, based on the data of the individual SDIs as per the IAM. In this computation only a contribution percentage towards achieving SD are made. The total SD percentage achieved for the device concerned can be obtained by adding up the individual percent contributions of SD from each of these SDIs.

The above premise of SD evaluation has been explained below.

7.8.3.1 Weightage of individual SDIs and its rationale

It may be relevant to add that sustainablity loss from global warming (SDIgw) due to CO_2 emission (estimated from LCA studies) and energy loss (SDIen) caused from construction etc. of the energy system (estimated from EA studies), are known to affect globally, causing an irreversible permanent impact. These loss indices are hence required to be multiplied with '3', logically attributed as the weighting factor to these two indices, considering their weighting on input loss towards achieving SD.

On the other side growth of the economy (SDIge) though helps the concerned locality, the economic input helps in yeilding rather permnent results by enrichment from development of infrastructural faclities. It may thus be considered to have weigtage factor '2', to give justice to the relative importance of the index concerned. Thus its results should be multiplied with '2'.

But the other 4 indices like, species loss (SDIsp), inherent vulnerabilty/hazards (SDIv) caused from the application of the device, scope on the growth of food materials (SDIgf) and quality improvement(SDIqi) of life, estimated from impacts over societal issues - have only a local effect in the vicinity of application site and have a temporrary effect, since it ceases as soon as the device applicator is withdrawn. Hence their weighting factor would be only '1', suggesting the concerned values to be multiplied with '1'.

7.8.3.2 Assignment of SDLS values to each SDIs with sensitivity analysis

Amongst all 7 SDIs, the three SDIs like, SDIgw, SDIen and SDIeg would be decisive in contributing to the overall status of SD of the OE device in a major way. Hence it may be reasonable to presume that more than a 50% contribution would be caused from these 3 SDIs. Thus, SDLS values assigned to these 3 indices were 20% each, which together makes 60% of the total SD of 100%. The other 4 SDIs, like SDIsp, SDIgf, SDIv, SDIqi- could be assigned SDLS values of 10% each, making total SDLS values from all 7 indices to come up to the value of 100%.

However, sensitivity analysis was undertaken in order to cross check the results. Thus, 3 new sets with different distribution pattern of SDLS values, in addition to the above stated **Prime set** (of SDLS distribution pattern), was studied as per the scheme shown below:

Set 1- SDLS values of all SDIs were maintained having more or less equal values of 15% each, excepting SDIsp having 10% SDLS value; making the sum total to be 100% covering all SDIs

Set 2- SDLS values of SDIgw, SDIen was kept 20% each; SDIeg & SDIqi with SDLS values of 15% each; rest 3 like SDIsp, SDIv & SDIgf had SDLS values of 10% each; making the sum total to be of 100% covering all.

Set 3- SDLS values of SDIgw, SDIen, & SDqi was kept 20% each, making their sum total 60%, with 10% each for rest 4 SDIs, like, SDIsp, SDIv, SDIgf & SDIeg; making the sum total to be 100%, covering all..

The methodology of estimating them has been developed accordingly from case studies for all the above 4 sets, having differently assigned SDLS values for each.

7.8.3.3 Computation on contribution to sustainability from each SDI

The data as available from IAM for individual SDIs are expressed as percent contribution to SD, taking into account their weightage factors in making the computation. Their percentage contribution is decided with respect to the assigned SDLS values of individual SDIs.

In order to estimate SD gain percent achieved from the loss items like, SDIgw, SDIen, SDIv & SDIsp - the loss percent is subtracted from the total SDLS value assigned. On the other side, values obtained from SD gain items, like SDIgf, SDIeg & SDIqi, are the contributions to sustainability from respective SDIs. These values obtained in percentage with respect to concerned SDLS values, are the direct contributions to sustainability gain percent achieved.

The total SD gain contributed from individual SDIs are then added up to give the total SD percent achieved in its scale of 100. The results derived from the above premise developed, have been shown below making case studies,

7.8.4 Case Studies showing SD gain percent achieved from OE devices

Estimations of total SD gain percent achieved were examined developing case studies of 7MW Wave Dragon, 750kW Pelamis, and 100MW CC-OTEC and of the proposed Severn Barrage scheme. As per the methodology adopted in previous section 7.8.3, the data obtained from IAM for respective SDIs were multiplied with their weightage factor and the values obtained were expressed in percentage contributing to sustainability, in terms of respective SDLS values assigned. The computations made for respective OE devices, for different SDLS percentage distribution pattern of the 4 sets as above, are shown below in tables 7.3 to 7.9. Values for a typical and average coal fired power plant & a hypothetical utopian device of 100 percent SD, are also included.

Table -7.3 SD gain percent of devices from SDIgw under different SDLS values.

Devices	CO$_2$ Emission (from table 7.1) (%) [a]	Input GW [a]*3 (%) [b]	Input GW at SDLS 20: [b]%* 20 [c]	Input GW at SDLS 15: [b]%* 15 [d]	Input GW at SDLS 10 [b]%*10 [e]	Saving GW at SDLS 20: 20-[c] (%)	Saving GW at SDLS 15: 15-[d] (%)	Saving GW at SDLS 10: 10-[e] (%)
7MW WD	3.42	10.26	2.05	1.54	1.03	17.95	13.46	8.97
750 kW Pelamis	2.36	7.08	1.42	1.06	0.71	18.58	13.94	9.29
100MW CC-OTEC	3.45	10.35	2.07	1.55	1.04	17.93	13.45	8.96
Severn Barrage	0.37	1.11	0.22	0.16	0.11	19.78	14.84	9.89
Coal (average)	100	100	20	15	10	0	0	0
Utopian Energy)	0	0	0	0	0	20	15	10

Table 7.4- SD gain percent of devices from SDIen under different SDLS values

Devices	EPBP/ Device life (from table 7.1) [a]	Energy loss [a]*3 in (%) [b]	Energy Loss at SDLS 20: [b]%*20 [c]	Energy Loss at SDLS 15: [b]%*15 [d]	Energy loss at SDLS 10: [b]%*10 [e]	Saving energy at SDLS 20: 20-[c] (%)	Saving energy at SDLS 15: 15-[d] (%)	Saving Energy at SDLS 10: 10-[e] (%)
7MW WD	1.75/50	3.5	0.7	0.525	0.35	19.3	14.475	9.65
750 kW Pelamis	1.22/20	6.1	1.22	0.915	0.61	18.78	14.085	9.39
100MW CC-OTEC	2.35/30	7.83	1.56	1.175	0.78	18.44	13.825	9.22
Severn Barrage	0.53/100	0.53	0.106	0.079	0.01	19.9	14.921	9.99
Coal plant (typical Average)	-	100	20	15	10	0	0	0
Utopian scheme	-	0	0	0	0	20	15	10

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Table 7.5- SD loss percent of devices from SDIsp under different SDLS values.

Devices	Species loss % from flora & fauna as per respective tables (%) [a]	Species loss [a]*1 (%) [b]	Species loss at SDLS 20:: [b]%*20 [c]	Species loss at at SDLS 15: [b]%*15 [d]	Species loss at SDLS 10: [b]%*10 [e]	SD saving at SDLS 20: 20-[c] (%)	SD saving at SDLS 15: 15-[d] (%)	SD saving at SDLS 10: 10-[e] (%)
7MW WD	<5 *	5	1.25	0.75	0.5	18.75	13.25	9.5
750 kW Pelamis	<5*	5	1.25	0.75	0.5	18.75	13.25	9.5
100MW CC-OTEC	<10**	10	2	1.5	1	19	13.5	9
Severn Barrage	<10***	10	2	1.5	1	19	13.5	9
Coal plant	<5****	5	1.25	0.75	0.5	18.75	13.25	9.5
Utopian energy	0	0	0	0	0	20	15	10

*Loss marginal (vide table-4.21); ** migrating birds loss low (vide table 5.9); ***loss low, construction stage only (vide table 6.7); **** Coal plants - marginal loss.

Table 7.6- SD loss percent of devices from SDIv under different SDLS values

Devices	Hazards percent as per respective tables (%) [a]	SD Loss from Hazards [a]*1 (%) [b]	SD Loss at SDLS 20: [b]%*20 [c]	SD loss at at SDLS 15: [b]%*15 [d]	SD loss at SDLS 10: [b]%*10 [e]	SD saving at SDLS 20: 20-[c] (%)	SD saving at SDLS 15: 15-[d] (%)	SD saving at SDLS 10: 10-[e] (%)
7MW WD	20	20	4	3	2	16	12	8
750 kW Pelamis	20	20	4	3	2	16	12	8
100MW CC-OTEC	25	25	5	3.75	2.5	15	11.25	7.5
Severn Barrage	15	15	3	2.25	1.5	17	12.75	8.5
Coal plant (typical average plant)	50	50	10	7.5	5	10	7.5	5
Utopian energy scheme	0	0	0	0	0	20	15	10

It may be relevant to add that wave schemes have low hazard as per table 4.22. OTEC have higher hazards (moderate) as per table 5.10 & Barrage have the least as per table 6.8. But coal power plants have the probability of high hazards because of the high pressure turbines etc & also from risks of coal stack fires (spontaneous combustion of coal) in coal power plants. Hazard ratings in table 7.6, have been assigned accordingly.

Table 7.7- SD gain percent of devices from SDIgf under different SDLS values

Devices	Food Growth percent as per respective tables (%) [a]	SD Gain percent [a]*1 (%) [b]	SD Gain percent at SDLS 20: [b]%*20 [c]	SD Gain percent at SDLS 15: [b]%*15 [d]	SD Gain percent at SDLS 10: [b]%*10 [e]	Remarks
7MW WD	5	5	1	0.75	0.5	Fish growth though marginal is expected in huge WD tank & in the vicinity around WD site; as per table 4.21.
750 kW Pelamis	1	1	0.2	0.15	0.1	Fish growth if at all in the vicinity would be marginal; as per table 4.21.
100MW CC-OTEC	50	50	10	7.5	5	High growth of fish & planktons from upwelling of nutrient rich cold water & from mixed discharge with enriched nutrient; as per table 5.9.
Severn Barrage	20	20	4	3	2	Enhanced fish growth, though not much pronounced, from growth of fresh water fish etc, as per table 6.7.
Coal plant	0	0	0	0	0	No scope of food growth, rather; destroys crop field from open cast coal mines, etc. required for making coal supply in coal plants
Utopian energy scheme	100	100	20	15	10	Utopian schemes have 100% scores.

It may be relevant to add that the cheaper the power generation cost, the better the economic growth would be for the concerned area. Thus, the hypothetical minimum power generation cost of 1p/kWh, could be considered to favour maximum economic growth of 100%. Obviously, the percentage on SD gain from SDIeg, might be estimated from the fraction of power generation cost with that of 1p/kWh.

In order to determine the above, the values on cost/kWh of power generation of OE devices were taken up from table 7.2, considered at 8% discount rate with their respective design life.

Cost/kWh quoted by Royal Academy of Engineering (2004) for a coal power plant is 2.5 p/kWh (for pulverised-fuel steam plant). Based on the above premise, SD gain achieved from SDIeg is shown below in table 7.8.

Table 7.8- SD gain percent of devices from SDIeg under different SDLS values

Devices	Economic Growth as per table 7.2 & premise stated before [a]	Economic Growth percent [a]*2 (%) [b]	SD Gain percent at SDLS 20: [b]%*20 [c]	SD Gain percent at SDLS 15: [b]%*15 [d]	SD Gain percent at SDLS 10: [b]%*10 [e]	Remarks
7MW WD	1/6.8	29.41	5.88	4.41	2.94	Results in percentage. Weightage factor is 2
750 kW Pelamis	1/6.4	31.25	6.25	4.69	3.12	-do-
100MW CC-OTEC	1/6.8	29.41	5.88	4.41	2.94	-do-
Severn Barrage	1/2.8	71.43	14.28	10.71	7.14	-do-
Coal plant	1/2.5	80	16	12	8	Results of coal plants cost in p/kWh being 2.5
Utopian energy scheme	100	100	20	15	10	Considered 100% gain of SD

Table 7.9- SD gain percent of devices from SDIqi under different SDLS values

Devices	Quality Improvement of life as per EIA model's societal impact data (%) [a]	SD gain on QI percent [a]*1 (%) [b]	SD Gain percent at SDLS 20: [b]%*20 [c]	SD Gain percent at SDLS 15: [b]%*15 [d]	SD Gain percent at SDLS 10: [b]%*10 [e]	Remarks
7MW WD	20	20	4	3	2	SDIqi for OTEC is quite high for its huge scope of by product availability, including food items.
750 kW Pelamis	20	20	4	3	2	
100MW CC-OTEC	40	40	8	6	4	
Severn Barrage	30	30	6	4.5	3	Barrage with 100 years unhindered power supply and rather enhanced fish growth improves SDIqi moderately.
Coal plant	50	50	10	7.5	5	
Utopian energy scheme	100	100	20	15	10	Coal plants with cheapest power improve SDIqi in a major way. Whence WEC, because of power availability also improves SDIqi to some extent.

Justification of the values put in for SDIqi, in table 7.9, -are considered based on the overall sustainability gain input from societal issues concerned.

Necessary computation may be made to determine the **total SD gain percent** of the above stated energy systems, for all 4 sets with different distribution patterns of SDLS percentages (Prime Set, Set 1, Set 2 & Set 3), based on the data availed from the above 7 tables (7.3-7.9). SD gain percent achievable from all 7 SDIs, at respective SDLS values, added together gives the total SD gain percent.

Studies have also been made with coal power plant, ascertaining its status of sustainability in comparison to the OE devices. A utopian hypothetical energy system has also been included, citing the sustainability scale of 100, showing it attaining 100 percent sustainability.

The results on total SD gain percentages achievable for different OE systems, as obtained making sensitivity for the above 4 sets, have been shown below in tables 7.10-7.13.

Table -7.10 SD gain percent achievable for OE systems of the Prime Set.

SDIs	SDLS values	SD gain percent achievable from different devices						Remarks giving data source of columns from tables 7.3-7.9
		7MW WD	750kW Pelamis	100MW CC-OTEC	Severn Barrage	Coal power plant	Utopian device	
SDIwg	20	17.95	18.58	17.93	19.78	0	20	As per col. 7 of table 7.3
SDIen	20	19.3	18.78	18.44	19.9	0	20	Col. 7 of table 7.4
SDIsp	10	9.5	9.5	9	9	9.5	10	Col. 9 of table 7.5
SDIv	10	8	8	7.5	8.5	5	10	Col. 9 of table 7.6
SDIgf	10	0.5	0.1	5	2	0	10	Col. 6 of table 7.7
SDIeg	20	5.88	6.25	5.88	14.28	16	20	Col. 4 of table 7.8
SDIqi	10	2	2	4	3	5	10	Col. 6 of table 7.9
Grand total	100	62.13	63.21	66.75	76.46	35.5	100	

Thus it could be observed that both WECs attained more than 60% sustainability, with OTEC above 65% and the Severn Barrage attaining above 75% sustainability. But the coal power plant though the cheapest scheme with the best economic viability, shows least sustainability, <40%.

SD percent have also been studied for the above energy systems, undertaking a sensitivity analysis with 3 more sets. The results are shown below in tables 7.11-7.13.

Table -7.11 SD gain percent achievable for OE systems of Set 1

SDIs	SDLS values	SD gain percent achievable from different devices						Remarks giving data source of columns from tables 7.3-7.9
		7MW WD	750kW Pelamis	100MW CC-OTEC	Severn Barrage	Coal power plant	Utopian device	
SDIwg	15	13.46	13.94	13.45	14.84	0	15	As per column 8 of table 7.3
SDIen	15	14.48	14.08	13.82	14.92	0	15	Column 8 of table 7.4
SDIsp	10	9.5	9.5	9	9	9.5	10	Column 9 of table 7.5
SDIv	15	12	12	11.25	12.75	7.5	15	Column 8 of table 7.6
SDIgf	15	0.75	0.15	7.5	3	0	15	Column 5 of table 7.7
SDIeg	15	4.41	4.69	4.41	10.71	12	15	Column 5 of table 7.8
SDIqi	15	3	3	6	4.5	7.5	15	Column 5 of table 7.9
Grand total	100	57.60	57.36	65.43	69.72	36.5	100	

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Table -7.12 SD gain percent achievable for OE systems of Set 2

SDIs	SDLS values	SD gain percent achievable from different devices						Remarks giving data source of columns from tables 7.3-7.9
		7MW WD	750kW Pelamis	100MW CC-OTEC	Severn Barrage	Coal power plant	Utopian device	
SDIwg	20	17.95	18.58	17.93	19.78	0	20	As per column 7 of table 7.3
SDIen	20	19.3	18.78	18.44	19.9	0	20	Column 7 of table 7.4
SDIsp	10	9.5	9.5	9	9	9.5	10	Column 9 of table 7.5
SDIv	10	8	8	7.5	8.5	5	10	Column 9 of table 7.6
SDIgf	10	0.5	0.1	5	2	0	10	Column 6 of table 7.7
SDIeg	15	4.41	4.69	4.41	10.71	12	15	Column 5 of table 7.8
SDIqi	15	3	3	6	4.5	7.5	15	Column 5 of table 7.9
Grand total	100	62.66	62.65	68.28	73.39	34	100	

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Table -7.13 SD gain percent achievable for OE systems of Set 3

SDIs	SDLS values	SD gain percent achievable from different devices						Remarks giving data source of columns from tables 7.3-7.9
		7MW WD	750kW Pelamis	100MW CC-OTEC	Severn Barrage	Coal power plant	Utopian device	
SDIwg	20	17.95	18.58	17.93	19.78	0	20	As per column 7 of table 7.3
SDIen	20	19.3	18.78	18.44	19.9	0	20	Column 7 of table 7.4
SDIsp	10	9.5	9.5	9	9	9.5	10	Column 9 of table 7.5
SDIv	10	8	8	7.5	8.5	5	10	Column 9 of table 7.6
SDIgf	10	0.5	0.1	5	2	0	10	Column 6 of table 7.7
SDIeg	10	2.94	3.12	2.94	7.14	8	10	Column 6 of table 7.8
SDIqi	20	4	4	8	6	10	20	Column 4 of table 7.9
Grand total	100	62.29	62.08	68.81	72.32	32.5	100	

It could be noted from the tables 7.10-7.13, that the trend of values showed the Severn Barrage to have attained around or above 70% SD, from different SDLS distribution patterns, made in sensitivity analysis. Next in order comes OTEC having attained more or less around 65% SD values, whereas two WECs SD gain percentages were more or less similar, between 58-63% SD gains.

These findings besides proving to be effective in ranking the OE devices; also validate the logic on the adhoc presumptions made on SDLS distribution patterns made. The trend of values conforms fairly well even under different sets of SDLS percent distribution patterns.

Another feature of this SD study is the fact that coal power, under all sets indicated sustainability less than 40%, despite its economic viability being the cheapest power source.

Relative merits of OE devices, based on their scope of attaining SD percent gain, at different SDLS percentage distribution patterns (along with coal power plant), have also been compared in fig 7.9 as given below.
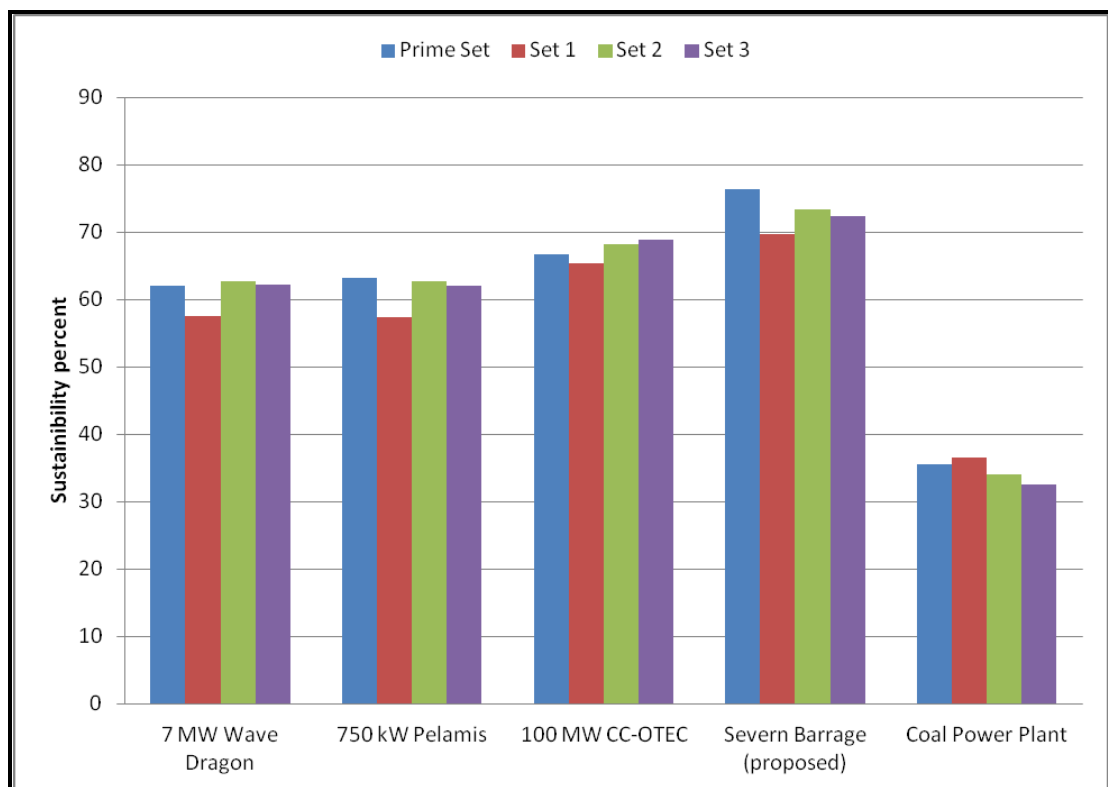
Fig. 7.9 Results of OE devices from SD gain percent made at varied SDLS sets

7.8.4.1 Critical appraisal on SD estimations of OE devices

The results obtained on sustainability indices, are quite significant showing coal power to be the last choice from sustainable development point of view; showing always much less than 50% SD score values. The advantage gained by OTEC schemes over wave schemes, may be assigned because of its scope of availablity of huge byproducts (food growth from mariculture etc). The Severn barrage has the best sustainability score, because of its efficient planning and optimized barrage schemes at suited site, with high power generation scope. Its high life period for an assured 100 years, unhindered power supply, with minimal eco-disturbannce; low maintenance costs are other salient features which gives it an edge over the others.

The scope of the applicability of the 'Integrated Assessment Methodology'(IAM) having multidimensional assessment criterion; can thus be extended for ranking the competing energy devices under a unified scale, of their efficacy in achieving sustainable development. This is undertaken by formulating a new model **IAMs,**

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indicating the Integrated Assessment Model for ascertaining sustainable development of OE schemes.

It may be pointed out that in the development of this model IAM**s**, there are only two presumtions, though they are quite logical and validated from a literature review and also from sensitivity analysis which was undertaken.

The first one is about percentages assigned on impact estimations of environmental issues as made from EIA model, and the 2nd one is on presumtions of SDLS distribution patterns attributed for individual SD indices.

EIA model's percentage estimations of some of the environmental issues, considered for some of the SD indices, the values assigned have been broadly corroborated from the literature review.

As regards the presumtions made on SDLS distribution patterns with varied relative importance to SD indices, the presumptions made can be considered to be justifiable. The corroboration of the trend of results under different SDLS distribution patttern, developed through a sensitivity analysis, validate the logic of presumtions made in assigning SDLS values in the prime model.

However, a **mathematical model** without making any presumtions, which would be a generalised formulae applicable for all energy systems in ascertaining its degree of viability for sustainable develoment, could also be developed and has been detailed in the subsequent section.

7.8.5 Mathematical model of IAMs in assessing SD gain for an energy device

Based on the above case studies made, IAMs as determined, may be expresssed in the following equation:

IAMs =SD loss from CO_2 emission (SDIgw)+SD loss from Energy depletion (SDIen) + SD loss from species depletion(SDIsp) + SD loss from inherent hazards/vulnerability on device application(SDIv) + SD gain from growth of food materials (SDIgf) +SD gain from the degree on growth of economy(SDIge) + SD gain from quality improvement of life (SDIqi) …………………………. [7.2]

Depending on the importance of the above 7 SDIs shown in above equation, their individual contribution percentages over sustainability load score (SDLS) values may be assigned, such that all indices combined together would make 100, so that the combined percentage contribution to sustainability gain from all these SDIs could be estimated. But instead of making presumptions on assigning SDLS values to individual SDIs, non-numerical percentage contributions are attributed. Thus SDLS value distribution pattern of respective SDIs could be designated with non-numerical values like, α, β, γ, δ,ε, ζ, and Ψ, for the respective 7 indices. The only condition attributed to these non-numerical percentage inputs is that, their sum total should be 100%, making thereby: **α+β+γ+δ+ε+ζ+Ψ =100.**

Thus the SDLS values, which represents the percentage distribution of sustainability in the scale of 100, (meaning 100% sustainability for a hypothetical & utopian

energy systems), the above stated non-numerical SDLS values for respective SDIs would be as below:

- **α** represents SDLS gain percent in addressing global warming.
- **β** represents SDLS gain percent in reduction of energy loss.
- **γ** represents SDLS gain percent in stopping decline of species loss.
- **δ** represents SDLS gain percent in lessning vulnerability/ hazards as may be accrued from OE deplyment.
- **ε** represents SDLS gain percent in helping growth of food items.
- **ζ** represents SDLS gain percent in growth of economy.
- **Ψ** represents SDLS gain percent in improving upon the quality of life.

Based on the above premise and considering the weightage factors of respective SDIs, the above equation equation [7.2] indicating total sustainability gain achievable for an energy system (IAMs), may be written as below:
:

IAMs = α*[1-3*CO_2 emission % compared to fossil power] +β*[1- 3*Energy loss%]
+ γ*[1- species loss%]+δ*[1- inherent hazard%]+ε*[food growth%]
+ζ*[2*Economy growth %]+ Ψ*[quality of life improvement %]……….… [7.3]

The individual SDI values of the above 7 indices, multiplied with respective weightage factors, may be evaluated as below:

1. CO_2 emission % compared to fossil fuel (determined from LCA studies):
   =3 *[{$\sum$ Gi × Mi / P_L + Go}*100}/ Gc] …………………………..[7.3.1]
   where, Gi denotes emission of GHG / unit mass, Mi denotes the mass of inventory materials, P_L is the life time power generation (kWh) of the device concerned, and Go is the emission during O&M stages (which is perceptible for OTEC systems only); while Gc, the CO_2 emission from fossil fuel (coal) power plant / kWh power generation (operational stage only), is considered to be of 100 percent.

2. Energy loss%, may be considered as the ratio of the energy payback period of the device (determined from EA study) with respect to its life; expressed in percentage:
   =3*[EPBP/L]*100 =3*[{$\sum$ Ei Mi / Pa}/L]*100……………………[7.3.2]

   where, Ei is the embodied energy of inventory items of the device expressed in MJ/Kg, and Pa is its annual power production also expressed in |MJ/Kg, L is the device life period.

3. Species loss % is determined from the negative impact on flora and fauna, as may be caused from application of the energy device, in the vicinity of the concerned zone. If the negative impact of species thus affect is expressed in percentage change than that as existed prior to the application of the energy device, then it can be expressed as per the following equation:
   Species loss = 1*$\sum$Fn% ……………………………………..…..[7.3.3]

   where, $\sum$ Fn gives the overall flora and fauna depletion percentage than that existed prior to application of energy device, in the concerned area.

4   Hazards rating %, covering different types of it, if grouped together   and expressed as the overall negative input percentages towards sustainable development (caused from accidental failure of the mitigating measures as are prescribed in application of the concerned energy device); then it may be expressed as:
Vulnerability of the energy device $=1*\sum H\%$ ……………………..[7.3.4]

where, $\sum H$ gives the total rating of all types of hazards, that may be caused on the accidental failures, of the preventive measures on EIA model's hazard mitigating guidelines.

5   Food Growth % is estimated from the positive score values of fish and planktons, as the direct fall out experienced from the application of the energy device, compared to the concentration that existed prior to energy device application in the concerned zone. Expressed in percentage it would cause SD gain percent as below:
Food growth $=1*\sum Fp$ % ……………………………………… .[7.3.5]

where, $\sum Fp$ gives the total positive rating   on fish and plankton growth experienced from application of the energy device.

6   Economy percentage gain is determined from ratio of the cheapest power cost/kWh with that of the actual cost/kWh incurred (ratio expressed in %). Considering minimum power cost with 100% economic growth to be of 1p/kWh, the Economy gain percentage would be
$=2*(1p/kWh/$ actual power cost in p/kWh$)$ %
$=2*1$ / $[(Cc +Co*DF) / (Pa*DF)]$ %. …………………………….[7.3.6]

where, Cc is the capital cost involved, Co is O&M cost of the device, which may be x percentage of the capital cost Cc, Pa is the annual power production from the device; DF is the discount factor determined as:

$DF = [(1+r)^{L} - 1] / [r*(1+r)^{L}]$; where r is the discount rate, and L is the device life.

7   Improvement in Quality of life is decided from the aggregate positive score percentage as may be attributed to the social issues concerned. The percentage gain in quality of life as favourable for sustainable development is expressed as:
Social impact improving upon the quality of life $= 1*\sum Qs\%$ ……… [7.3.7]

where, $\sum Qs$ gives the aggregate positive impact in improving quality of life in various social aspects, as a result of application of energy device.
.

It would be obvious from the very premise adopted on SDLS values that all SDIs are to be expressed in percentage with relation to the percentage distribution share of its assigned SDLS values. Also subtracting respective percentages of SD loss item from its parent SDLS values, gives the SD gain achieved on these SDIs. However for SD gain indices the values derived as such, expressed in percentage gives SD gain input. Of course all SDI percentages are to be multiplied with their respective weightage factors.

Based on the above premise, and substituting the values of SDIs as deduced in equations 7.1.1 - 7.1.7, the mathematical model on IAMs, which always determines percentage of sustainability gain achieved, may be deduced as below:

IAMs
$$= \alpha\,[\,1\text{--}\,3\,\{(\textstyle\sum Gi \times Mi\,/\,P_L + Go)*100\}/\,Gc\}\%]\ +\beta[1\text{-}\,3*\{(\,EiMi/Pa)*100/L\%\}]$$
$$+\,\gamma[1\text{--}\,(\textstyle\sum Fn\%)] + \delta[1\text{--}(\textstyle\sum H)\%] + \varepsilon\,[(\textstyle\sum Fp)]\% + \zeta\,[\,2*(Cc+Co*DF)/\,(Ea*DF)]\%$$
$$+\,\Psi[\,\textstyle\sum Qs]\%\ ....[7.4]$$

IAMs ≥ 50%,   ensures sustainability of the device. Ranking of devices depends on the values achieved.
< 50% of the above equation [7.4], indicates device concerned to be rejected being an unsustainable one.

The above equation [7.4], deduced without making any presumption,   may be considered to be applicable not only for all types of OE systems; but can prove to be useful to decide the viability of sustainable development for different forms of all energy systems, as well.

The SDLS percentage distribution of the coefficients α, β, γ, δ, ε, ζ, Ψ, depends on socio-economic parameters of the country and the device concerned. For all practical purposes of OE systems however, values of α, β & ζ, may be considered to have values of 20% each, and 10% for the rest 4 coefficients, like γ, δ, ε, & Ψ - as considered in the Prime set of OE device.
.
Also, the value Gc of the 1st index, is normally considered to be 826.17 g/kWh, as noted from review of literature on various types of coal power plants, giving the average of the representative value, shown in section 4.3.6.2 of chapter 4. Go of the 1st index, is neglected for wave and tidal schemes, but has values of around 40 g/kWh for OC-OTEC, around 10g/kWh for hybrid types, but <1g/kWh for CC-OTEC schemes, as noted from theoretical deduction, as well as confirmed by HTMSTA apparatus, as well (chapter 5, section 5.2.2).

7.9 Observations

1. An Integrated Model for Assessment (IAM) of Ocean Energy Systems, covering wave, OTEC and tidal schemes, could be developed with identification of 6 broad based and well defined assessment tools and four interrelated tasks.

2. Ranking the OE devices from sustainable development could also be made developing an Integrated Assessment Model for ascertaining sustainable development (IAM**s**) of OE devices. It was based on identification of seven Sustainability Indices, which were based on the assessment tools of the IAM developed.

3. The assessment tools of IAM, developed with the identification of priority criterion   that were considered useful for multi-criterion decision analysis (MCDA), in assessing OE devices were as below:

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a. Examination and analysis on placement sites of OE devices, with resource availability as an important criterion.

b. Safety factor from survivability, taking cognizance of ensuring stability in storm waves, for off-shore WECs and OTEC schemes, in particular.

c. Scope of resource tapping capability of the device concerned, which is dependent on technology used as also of resource availability of the deployment site.

d. Scope of addressing global warming and emission aspects, with the important criterion of emission of CO_2 in g/kWh and the percentage CO_2 saved, compared to coal generator; as also the energy payback period. They are determined from LCA & EA studies.

e. EIA model as could be suggested for qualitative & quantitative assessment of environmental impact; from deployment of wave, OTEC and Tidal schemes. Each environmental issue had its own specific impacting parameters, influencing the common environmental issues on –emission aspects, flora and fauna, hazards posed and societal issues.

f. Economy evaluation with identification of main criterion to be the cost/kWh and RPC ratios/kWh (comparing the mark up cost). Of course, designed life period is also an important criterion. For tidal barrages however gestation period was considered to be of overriding importance.

4. Four inter-related tasks that were considered to be needed for assessment of OE devices for application of the IAM, could be spelt out as below:

a. Data collection of the concerned device that is required to be assessed, mainly from the context of the inventory items, power generation scope and life period.

b. Defining the guidelines to be followed as safety measures and preventive norms, required in case of deployment of the concerned OE systems.

c. Application of the 6 assessment tools for ranking the concerned device with its relative merits and demerits amongst the competing OE devices, helping in making multi criterion decision making.

d. Scope of application of IAM for assessing sustainability & in R & D studies on performance improvement to achieve better economy and safety.

5. The IAM developed for making multi-criterion assessment of OE systems, could be extended in the development of IAM**s**, for ranking OE devices on the single criterion basis of achieving sustainable development.

6. IAMs development could be developed with the identification of 7 sustainability indices (SDI) based on the assessment tools of IAM; a sustainable scale development of 100; and attributing sustainable load score (SDLS) values to each SDIs, depending on their relative importance in achieving sustainability. The sensitivity analysis of the same, with varied

SDLS distribution percentage, corroborated the premise made for assessing sustainability development, used for ranking OE devices.

7. It could be observed from comparative studies of IAMs that Severn Barrage scheme had nearly 75% sustainability, with OTEC having around 65% sustainability and WEC like WD & Pelamis showed above 60% sustainability; whereas coal power plant despite its best economic viability showed least sustainability of less than 40%.

8. Mathematical modeling of IAMs for assessing viability of sustainable development could be formulated, which was applicable not only for OE devices in making their ranking, but a generalised formulae considered applicable for all energy systems.

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CHAPTER 8

DISCUSSIONS ON SCOPE OF APPLICATION OF IAM & IAMs FOR R&D STUDIES OF OE DEVICES

8.0 Introduction

The scope of application of IAM lies in making assessment of OE devices from examination of the various assessment tools, and adjudging relative merits and demerits of competing OE devices from multi-criterion-analysis of them. On the other side, IAM**s** helps in assessment of competing OE devices accurately from a single criterion, which is based on their respective potential of achieving sustainability, and thereby making ranking of the devices.

All these exercises would also be relevant in R&D efforts as well, for betterment of the OE devices, so that the improved versions with commercial prospect could be identified and duly assessed. It may be relevant to add that other than Tidal barrage construction, which is a matured technology making commercial runs since decades (La Rance, France), all other OE devices including WECs, OTEC & TISEC devices have immense scope of improving upon their performance efficiency. In such efforts both the models developed, on IAM & IAMs, can be fruitfully employed not only in adjudging relative merits of competing OE device concerned, but would also be useful in deciding relative merits of the different types of innovative R&D projects.

It is hence considered important to identify a few R&D areas, over which the assessment tools of both IAM & IAM**s**, can find use in assessing their relative merits. Some of these schemes proposed for performance improvement of OE devices & in which IAM & IAMs might play important role are as below:

- Material development research -for achieving economic gains of Pelamis type WECs etc.
- Hybrid schemes -as may be taken up for Wave Dragon & tagging it with off-shore wind farms, making the Hybrid type WD. Likewise, Hybrid OTEC with solar collector could increase the power generation efficiency of OTEC schemes making the Hybrid SOTEC
- Application of new information - generated in course of development of IAM & IAMs, for making feasibility studies of the innovative ideas and projects of OE devices in the planning stage itself.

A brief resume of the above topics have been elucidated below.

8.1 Cost reduction of OE systems from material development research

The cost reduction of OE systems may be done by altering the construction material with cheaper options without compromising the quality, as far as practicable. The scope of making such improvement over a wave scheme, like Pelamis, has been suggested elucidating prospective improvements that may be effected from sensitivity analysis of inventory materials required for construction of Pelamis.
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8.1.1 Case studies with Pelamis

It may be noted that the life and survivability of Pelamis having steel as the major component of its body construction, would not get much compromised if its steel component is partly replaced with concrete. Of course the proportion of replacement that can be allowed should be to the extent that its quality is not appreciably compromised.

It may be noted that even a part replacement of steel with concrete would lower down its cost appreciably, and also life time emission of GHG gases as well as the energy payback period. Since, emission of CO_2 in kg/kg of steel is 2.3065 kg/kg and its embodied energy is 25.65 MJ/kg; whence for concrete they are 0.835 kg/kg and 3.68MJ/kg respectively, as per Danish model data source (Schleisner 2000).

An attempt has hence been made to assess the degree of lowering of CO_2 emission by replacement of steel with concrete, making only part replacement, say 25% of steel with concrete, maintaining total weight the same.

The lowering of CO_2 emission, energy payback period and, cost in p/kWh power generation is shown below in table 8.1. Its annual power generation is considered to be 2.5GWh, as per the data availed for its deployment in Ireland coast (Dalton *et al*. 2010) In estimating cost/kWh power generation, advantage is taken from application of RPC ratio of inventory materials, estimating the percentage of lowering of cost, which seem to be applicable for comparing same type of devices. Such estimations from RPC ratio of inventory items could be a useful index in such R&D studies, where the capital cost data or the life period is not known, and only comparative values are needed.

Table-8.1 LCA, EA & RPC values of 25% concrete replaced Pelamis (Improved one)

Inventory Items	Mass (kg)	CO_2 (kg)	MJ	RPC ratios	Cost ratio ofInventor materials	Original Pelamis
Steel	285000	657352.5	7310250	2.5	712500	Steel (kg): 380000**
Copper	15000	98040	1173000	3.0	45000	Cu(kg):** 15000
Concrete	95000	79325	349600	1.0	95000	nil
Grand Total	395000	834717.5	8832850		852500	395000kg
CO_2 in g/kWh		**16.69g/kWh**				19.49g/kWh *
EPBP in yrs			**0.98yrs**			1.21years*
RPC ratio/kWh					**0.341/kWh**	0.398/kWh

* Values of parent Pelamis as per the table 7.1 of chapter 7. **(Taylor 2006)

It would be obvious from table 8.1, that CO_2 in g/kWh was reduced to 14.37% from the parent Pelamis (value being reduced by 2.8 g/kWh); whence EPBP value getting reduced to 0.23 years, got reduced to 19%, and cost/kWh from RPC ratio with value difference 0.057, from the parent Pelamis' value of 0.398, was reduced to 14.32% on cost/kWh of its parent Pelamis (the value of RPC ratio/kWh of parent Pelamis, is taken from table 7.2, of chapter 7).

It may thus be presumed that the power generation cost of the Improved Pelamis (*25% steel replaced Pelamis*) would be less than 14.32% of .6.4p/kWh, which is the cost/kWh of the parent Pelamis (as per table 7.2 of chapter 7). Thus its power generation cost on cost reduction can be considered to assume the value of **5.48p/kWh.**

Sustainability percentage of the Improved Pelamis (25% steel replaced Pelamis) can also be determined putting in the above values of sustainability indices in equation 7.4 of chapter 7, which gives the generalized & mathematical model of IAMs. It would be obvious that the SD indices like SDI_{sp}, SDI_{gf}, SDI_{v} & SDI_{qi}, would remain unaltered, since the mode of functioning of Pelamis, with power generation capability also remain unaltered. It is also considered that the SDLS distribution percentage is considered at 20% for SDI_{gw}, SDI_{en} & SDI_{ge}, with rest 4 indices as 10% each (as per the prime model of table 7.10, of chapter 7). Thus IAMs for the Improved Pelamis as per equation 7.4 of chapter 7 would be as below:

$=20[1- \{3*(16.69+0)*100/826.17\}\%] + 20[1- (3*0.98/20)\%] +10 (1-5\%)+ 10*(1-20\%)+ 10*1\% + 20*2*(1/5.48*100)\% +10*20\%$

$=18.79+19.97+9.5+8+0.1+7.3+2$
$= 65.6\%$

This value makes a 3.73% improvement on sustainability percentage, from the parent Pelamis, which had a sustainability percentage of 63.21 as per table 7.10 of chapter 7.

8.1.1.1 Limitations

It is however to be kept in view that such a replacement of steel with concrete has the disadvantage that unlike steel, concrete cannot be recycled on expiry of its life. Also, the quality of the concrete is to be so chosen as to ensure its shear stress is comparable to that of the steel, so that the device is not affected by the impact of the surging waves.

8.1.2 Material development research on OTEC devices

The above methodology (illustrated from case study of Pelamis in section 8.1) enables to determine the quantum of benefits derivable on sustainability, economy, etc, as may be accrued from material replacements of construction materials for all types of OE schemes. This approach may also find use in cases of OTEC or TISEC devices in addition to WECs.

Example may be cited for various such R&D schemes for OTEC systems. Studies are in progress to develop Alcan type rather cheaper alloys over costly Titanium heat exchangers, which alone incurs nearly 40% cost input in OTEC plants (Takahashi 2000). It has also been suggested to use steel or concrete pipes for upwelling cold water in place of FRP, which are normally considered for use in off-shore technology. Scope of use of soft pipes, made of reinforced elastomeric fibers are also being suggested considering its efficacy for better survivability in rough seas, besides being rather the cheaper option (Vega 1999). The tools of IAM & IAMs, developed can be of advantage in making feasibility study for all these options in OTEC schemes, based on the methodology followed in case study of Pelamis, shown in previous section 8.1.1.

8.2 Hybridization of OE schemes for making performance improvement

In addition to material development research, hybridization is another area of research that helps in improving upon OE devices. Studies have been made of a proposal on hybridisation by tagging Wind Farms over the huge platform of 7MW Wave Dragon, using the same mooring. A case study on the same is shown below.

8.2.1 Case study of Hybrid Wave Dragon (WD)

It has been suggested that off-shore Wind Turbine farms, if fitted over the huge platform of WD, the Hybrid WD thus developed would then have better performance in economy, since wind energy is the cheapest option amongst all renewable energies (EWEA report 2004). Besides, use of the same mooring and cable lines would be of further advantage.

A case study has been made to examine the advantages gained, if any as regards emission characteristics, energy payback period, and sustainability aspects of the 7MW WD. This type of WD having annual power production of 20 GWh & life of 50 years, and thereby of lifetime production of 1000GWh (as per Section 4.2.3, item 1 of chapter 4) is proposed to be tagged with off-shore wind farm. The lifetime power production of such wind farms would be 250GWh, using the same mooring etc (Schleisner 2000). Thus the life time power production of the Hybrid device with 50 years life would be 1250GWh, having annual production of 25GWh. The efficacy of power generation in WD thus improves upon 25%, making use of its huge

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platform to install off-shore wind farms on board, and thereby capturing the strong off-shore wind power as well.

It is however important to make an estimation of LCA & EA studies of the installed wind farms to assess the combined effect of CO_2 emission from this additional wind farm in its entire life period, alongside the parent WD, as also of energy payback period gained. Economy index on cost of power generatioin in p/kWh could also be estimated from RPC ratios of inventory materials. Thus, as detmined in case of improved type Pelamis (25% steel replacement with concrete), sustainability gain percent if any, could also be determined.

In order to estimate cost of power generation of the hybrid device, inventory data with cost ratios of inventory items, as per RPC ratio estimations are needed. The results on the same are shown in table 8.2, given below.

Table 8.2 Inventory data of WD & Wind farms estimting the RPC ratios of hybrid device

Inventory materials	Inventory of Wind farm(kg)*	Inventory of 7 WM WD (kg)**	Inventory Hybrid (kg)	RPC ratios	RPC Ratios of Hybrid device
Steel	527000	553000	1080000	2.5	2700000
Al	14000	24100	38100	1.9	72390
Copper	3500	69300	72800	3	218400
Glass	11000	-	11000	1.6	13200
Plastic	20000	31540	51540	1.2	82464
Iron	-	120920	120920	1.3	157196
Concrete	-	31068000	31068000	1	3106800
Grand total	575500	31866860	32442360		**34311650**

*(Schleisner 2000)   ** (Russel 2007)

In order to estimate the emission charactrristics & EBPB of the Hybrid device, it was first needed to determine the total CO_2 emission of the inventory materials of the concerned wind farm (excluding moorings etc), from LCA studies as well as of the total embodied energy involved. These data were then added up with those of the parent WD (table 4.9 & 4.17 of chapter 4, gives the data for the parent 7MW WD) to estimate the results of the hybrid device. These results are tabulated below.

Thus, the RPC/kWh of the Hybrid device, based from table 8.2 would be =34311650/25GWh= **1.37;** whence RPC/kWh estimated for the parent WD as per table 4.33, chapter4 =1.64. This gives the advantage of 16.46% lowering of cost from the parent WD. The power generation cost of WD has been estimated to be =6.8p/kWh, shown in table 7.2 of chapter 7. Hence the power generation cost, based

from results of RPC concept suggest reduction of 16.46% of 6.8p/kWh = **5.68p/kWh.**

Table 8.3 Inventory data of the Wind farms for LCA & EA studies [as per Danish model]

Inventory materials of Wind farm (Schleiner 2000)	Amount *(kg)	CO_2 emission (kg)	Embodied Energy MJ .
Steel	527000	11215525.5	13517550
Aluminium	14000	48069.0	548100
Copper	3500	22876.0	273700
Glass	11000	11088.0	89100
Plastics	20000	62260.0	914000
Grand Total	575500	1359818.5	15342450

* Inventory items and their quantity exclude moorings etc (Schleisner 2000)

Table 8.4 Comparative study of the hybrid device with the parent 7MW WD

Device concerned	7MW WD	Wind Farm	Hybrid Device	Gain percent achieved in the Hybrid device, compared to the parent 7MW WD, in respect of power availability, CO_2 emission & EPBP are shown below.
Mass (kg)	31866860	575500	32442360	
CO_2 emission(kg)	28227695.55	1359818.5	29587514.55	
Embodied Energy (MJ)	126523789	15342450	141866239	
Annual energy	20GWh	5GWh	25GWh	25 % gain achieved
Life time energy	1000GWh	250GWh	1250GWh	25 % gain achieved
CO_2 in g/kWh	28.23g/kWh	5.44g/kWh	23.67g/kWh	16.15 % gain achieved
EPBP in years	1.75 years	0.85 years	1.57 years	10.28 % gain acheved

IAM**s** giving sustainability percent could also be estimated, based on the above results of CO_2 emission characteristics, EPBP & cost/kWh power generation data availed for the Hybrid device. It is however presumed that SDIsp, SDIv, SDIgf & SDIqi, remain unaltered and would have similar values of the parent WD; considering off-shore Wind farm to have no additional inputs on these environmental issues.

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Thus considering SDLS distribution pattern as per the prime set (shown in table 7.10 of chapter 7), sustainability percent of Hybrid device would assume the value as below:

IAMs =20[1- {3*(23.67+0)*100/826.17}%] + 20[1- (3*1.57/50)%] +10 (1-5%)+ 10*(1-20%)+ 10*1% + 20*2*(1/5.68*100)% +10*20%

= 18.28 +19.91+9.5 +8 +0.1+7.1+2
=**64.89%**

Its parent WD had sustainability of 62.13%. Thus the increment in sustainability achieved of the hybrid device is: 4.25%.

8.2.1.1 Limitations

It may be relevant to add that adequate measures are needed to ascertain stability and survivability of the WD, in tagging off-shore wind farms over its huge platforms; for constructing the hybrid device. It may thus be needed to examine maintaining optimum tower heights of wind tower, so that the C.G. of the parent WD does not get destabilised.

8.2.2 Hybridisation of OTEC with solar collector (SOTEC)

It has been suggested to increase the temperature of the working fluid of OTEC attaching a solar collector & thereby making the hybrid device SOTEC. This would cause increment of temperature differential of OTEC, and thereby can increase its power generation efficiency manifold (Yamada *et al.* 2006). This project however, is in R&D stage only.

The economic viability of the project along with prospect of sustainability percent, can be estimated following the methodology as followed for hybrid WD. This is based on the knowledge of the inventory data of the solar collector, along with the parent OTEC device, as well as of the temperature rise of working fluid that can be achievable (giving increment in power generation data),

The scope of advancements of Pelamis & WD, as could be achievable following the R&D proposals as above (sensitivity studies and/or hybridisation), and estimated from tools of IAM & IAMs, is shown below in fig. 8.1, comparing the benefits derived from respective proposals.
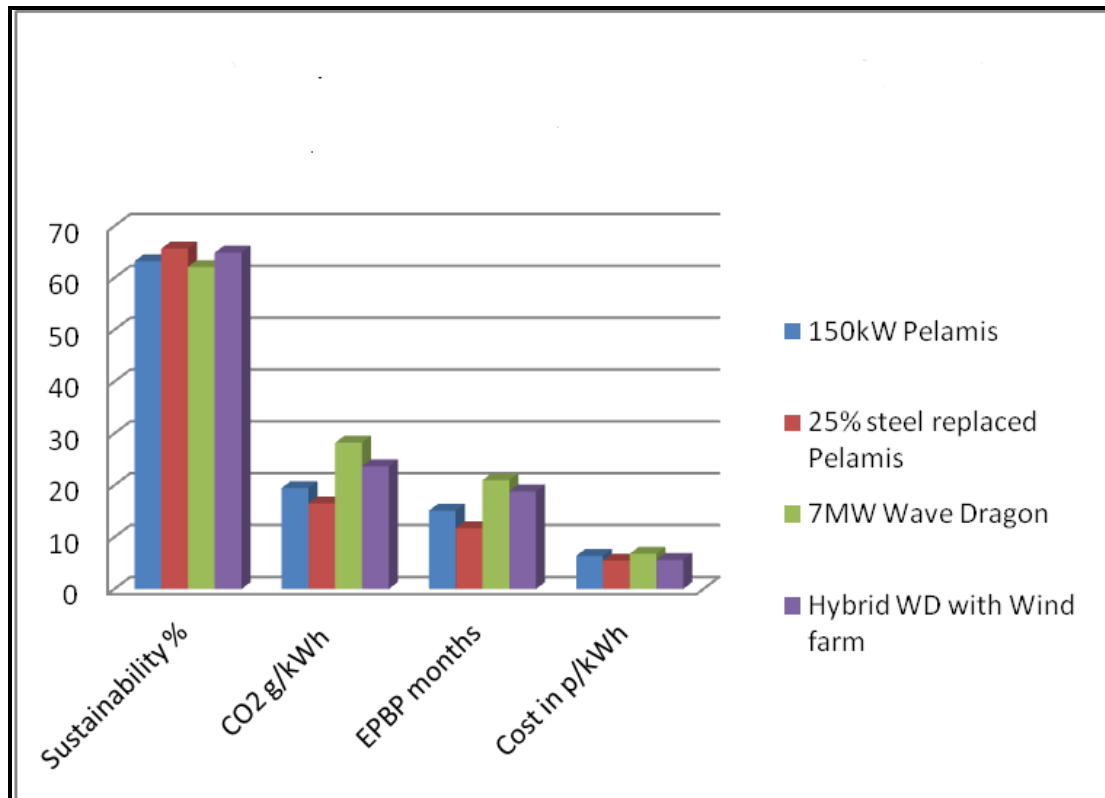
Fig.8.1 Improvements of Pelamis & WD estimated from the tools of IAM &IAMs

8.3 Application of IAM & IAMs tools in new innovations of OE devices

It may be added that in course of developing IAM & IAMs, quite a few new concepts could be introduced, which along with the other tools of IAM & IAMs, could be considered useful in feasibility study of innovative projects, as identified for wave, OTEC & Tidal schemes. They are as below:

1. **RPC ratio concept introduced** - would be helpful in design improvement research, by making prior assessment on scope of economy improvement or liabilities, in the planning stage itself, as shown in case studies of section 8.1 & 8.2

2. **The barrage efficiency index developed**- (with threshold limiting value of $3.06*10^{-4}$) - could be advantageously used in making optimization study in barrage planning to choose the right alternative giving the best economy etc.

3. **Detection of breakeven point on life of WECs & OTEC -**would be helpful in design research, to assign mandatory minimum lifetime required to be maintained, for concerned devices; below which cost of power generation for wave & OTEC schemes escalate sharply.

The utility of the above concepts, along with the tools developed on integrated assessment methodology and sustainability percentage estimations, as may be applied for certain new innovative proposals on wave, OTEC & Tidal schemes, are briefed below in subsequent sections.

8.3.1 Wave Schemes

Novel innovative ideas are being floated to develop sea-worthy Linear Generator type WECs, that can ensure power generation from wave density as low as a few kW/m only (Szabo *et al.* 2007). It is claimed that this device being embedded in sea-bed has no problem of survivability (section 2.1.5.6 of chapter 2). It would need much less inventory material; and thus is expected to be more economic. From inventory and power generation data, the extent of economic gains, if any and as also its ranking on sustainability can be estimated, as per the methodologies shown in case studies of sections 8.1 & 8.2. RPC cost ratio and other assessment tools of IAM, would be quite useful in making the feasibility studies of such ideas, as also trying different options from sensitivity analysis.

It may also be noted that the designed life of WECs, like Pelamis or WD should not be kept below 30 years, which has been noted to be the break-even point for such wave schemes.

Likewise, the feasibility study of Coventry clam (as also for other devices) with various designs, dimensions and inventory materials can also be made for developing the optimised device. This may be done by sensitivity analysis following the methodology cited in sections 8.1 & 8.2. RPC concept along with other assessment tools developed on IAM would be of help in such efforts.

It is to be stressed, that the economy evaluation from studies of RPC cost ratios, could be of advantage from comparative study of only such devices that operate using similar technique and design.

8.3.2 OTEC schemes

An ambitious concept on OTEC has been suggested of *in-situ* generation of hydrogen, by splitting water from the power generated through OTEC has been suggested. Thereafter ammonia manufacture can be generated in the grazing type OTEC plant-ship (Ryzin *et al.* 2005). Thus, a host of chemicals suggesting possibility on growth of chemical hub with scope of chemical industry and economic gain/kWh power generated from these by products could also be estimated in table 5.15 of chapter 5.

The feasibility study of such ambitious scheme can be tested, provided only the inventory material inputs on *infrastructural facilities* required for availing such by products, are available. In other words, the tools developed in IAMs can successfully be applied to test the feasibility of such ambitious project in the planning stage itself. With the currently available technology itself, based only from theoretical estimations.

8.3.3 Tidal schemes

Tidal barrage scheme has attained matured technology, with commercially viable project running since 1966, like La Rance Barrage in France ((Andre 1978). But every Barrage planning poses challenge of its own, and needs elaborate long planning so that maximum economic benefit is derived with minimum cost

involvement. In making Severn Barrage quite a number of alternate basin sites were examined to derive the best benefit. Ultimately the site chosen was 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 and with estimated annual power generation of 17TWh (Sir Robert Mc Alpine & sons Ltd 1986; Frontier Economics Ltd. 2008).

In fact, many such barrage proposals, including the functional La Rance barrage, France, .have been listed in table 6.1 of chapter 6. Data as regards their basin dimension, power generation etc. have also been spelt out in each proposal. But it could be noted from the Barrage efficiency concept introduced, that their planning efficiency varied from Barrage to Barrage, independent of the tidal range.

The introduction of threshold barrage construction efficiency concept enabled assignment of the maximum basin area that can be allowed (6 km^2) for the undecided basin area of Sundarbans (India). It could also be suggested to revise the barrage planning of gulf of Cumbay (India), which showed barrage efficiency much less than the threshold limit. Severn Barrage was noted to be the best planned Barrage with highest barrage planning efficiency of the value of 2.35, nearly double than that of the functioning La Rance barrage having barrage efficiency value 1.11.

In IAMs examinations of OE devices as well, it could be noted that Severn Barrage proposal showed highest sustainability around >75% (Tables-7.10, of Chapter 7), corroborating its attainment of the highest planning efficiency, as noted in table 6.1, of chapter 6.

It may be pointed out that such high sustainability percent achieved for Severn barrage not only excelled other OE device (OTEC & Wave scheme); but it also showed much higher sustainability percent from another barrage proposal, like Mersey barrage, which had barrage efficiency 1.66 (table 6.1). A case study on the sustainability percentage a of Mersey barrage, compared to the Severn scheme, in the subsequent section.

8.3.3.1 Case study with Mersey Barrage on sustainability percent

Like Severn scheme, Mersey barrage project also remains in the proposal stage. But unlike Severn scheme, capital investment data of Mersey scheme was not available. However, economy assessment as regards cost/kWh could be estimated for Mersey barrage, based from RPC ratio of its inventory data and making comparative study with that of Severn barrage. The methodology adopted in estimating cost/kWh for Mersey barrage, despite non-availability of its capital cost involvement data, is shown below in table 8.5. The values as regards their emission characteristics & EPBP was availed from table 6.3.& 6.4, of sections 6.3.1.1 & 6.3.2.1 of chapter 6.

Table 8.5 RPC ratios of inventory items of Severn & Mersey barrage schemes

Inventory Items	Severn Barrage* (kt)	Mersey Barrage** (kt)	RPC ratio	Cost ratios of Severn Barrage	Cost Ratios of Mersey Barrage
Steel	588.8	128.8	2.5	1472	322
Copper	43.2	3.8	3	129.6	11.4
Concrete	3800	3480	1	3800	3480
Grand Total	4432	4172.6		5401.6	3813.4
Annual Power (TWh)	17	1.48			
RPC ratio/kWh	0.32	2.57			

* (Woolcombe-Adams *et al*. 2009)   **(Mersey Barrage company 1991).

For the Mersey scheme its value from above estimations would be =2.57;
Cost in p/kWh of Severn Barrage would hence be   = (2.57-0.32)/2.57
=87.548% less than the cost in p/kWh of Mersey scheme.

Since cost in p/kWh of Severn scheme is 2.8 p/kWh (shown in table 7.2, chapter 7), the power generation cost of Mersey Barrage would be
= 2.8+2.8*87.548/100=**5.25p/kWh**

The values of CO_2 emission in g/kWh & EPBP of Mersey scheme, as per table 7.1 of chapter 7 shows, **18.63g/kWh** and **3.08 years**, respectively. Putting these values in equation 7.4 of chapter 7, and considering SDLS distribution percentage to be as per the prime set of table 7.10, and also presuming SDIsp, SDIv, SDIgf & SDIqi, to have identical values as of the Severn barrage, the sustainability percentage (IAMs) for Mersey barrage would be as below:

IAMs =20[1- {3*(18.63+0)*100/826.17}%] + 20[1- (3*3.08/120)%] +9+8.5+2+
 20*2*(1/5.25*100)% +2
(Putting in the values of SDIsp, SDIv, SDIgf & SDIqi, similar to that of the Severn scheme, as per table 7.10. Life of Mersey is said to be120 years; it has accordingly been incorporated in the above equation).

=18.64+18.46+9+8.5+2+7.6+2= **66.2%**

It may be relevant to add that IAMs for Severn Barrage of the same scheme is 76.34%, which is 15.3% higher than the sustainability percentage of Mersey project (as estimated). In fact, OTEC shows better sustainability of 66.75% (as per table 7.10) than the Mersey scheme.

The highest sustainability of Severn scheme is in conformity with the concept introduced to judge barrage planning efficiency, which showed the Severn's Barrage

planning efficiency to be the best amongst all other proposals, evaluated in table 6.1 of chapter 6.

In fig. 8.2 as given below, is compared Severn & Mersey scheme's respective barrage efficiency with sustainability percent achievable, along with other OE schemes, (SDLS distribution pattern are as per the prime set of table 7.10, of Chapter 7)

.
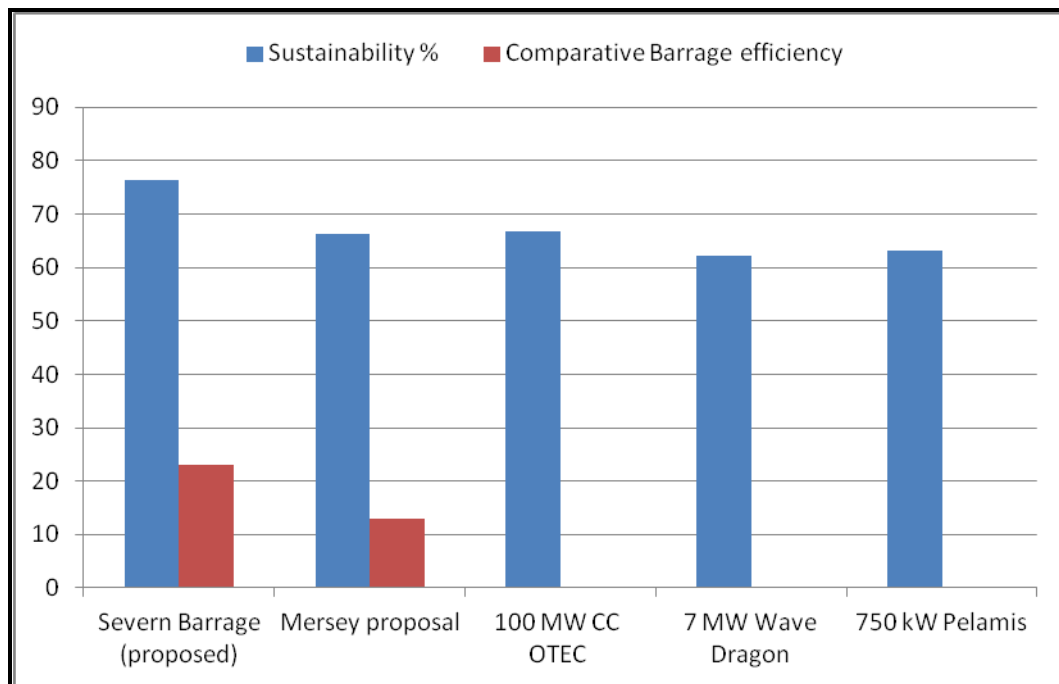
Fig. 8.2 Sustainability of OE devices compared along with Barrage efficiency

8.4 Observations

1. It had been established that IAM & IAMs decide the scope of application with guidelines on placement for sea-worthy competing OE devices, and to their rank them. It has now been shown that these instruments developed can also be used in efforts of advancing the OE devices, in their planning stage itself. It would be of help as an important instrument in R&D efforts of design improvement of the devices.
2. It could be shown from case studies of two WECs and one barrage scheme, that based only from inventory and power generation data, the sustainability percent including cost/kWh of power generation of similar type of devices could be evaluated, by the comparative studies of RPC ratio concept introduced.
3. The scope of improving upon the OE device in making their performance improvement as also achieving better economy could be identified. It is mainly through two types of R&D efforts, material development research, as also from hybridisation by adjoining the OE device with suitable other energy systems.

4. It could also be proved that the with introduction of threshold limit value of barrages and the concept of barrage constant value not only helps in judging the quality of the barrage planning, but also suggests the scope of revision of the barrage scheme to achieve desired efficiency.

5. Such barrage constant with threshold limiting value of barrage could be corroborated from sustainability percent achievable for the best planned barrage (Severn) that excels in assuring highest sustainability with best economic benefit.

6. Several grey areas of innovative ideas in WECs and OTEC schemes could also be suggested highlighting as to how the tools of IAM & IAMs, along with RPC values could play an important role in the planning stage itself, before undertaking capital investment.

7. Apart from the tools developed in IAM & IAMs, the new concepts introduced like, comparative studies on RPC ratio, and the identification on break-even point in the life of WECs & OTEC device, below which cost of power generation escalates sharply. The concept of threshold limiting values of barrages used in judging optimisation in barrage planning - could be useful instruments in R&D efforts on improving upon the barrage schemes.

CHAPTER 9

CONCLUSIONS

9.0 Preamble

The Integrated Assessment Methodology (IAM) for OE systems was developed, meeting the objective of the study taken up. This multi-criterion assessment tool (IAM) could thereafter be advanced to the single criterion model, IAMs, for ascertaining sustainable development of competing OE devices. The scope of applicability IAM & IAMs in ranking competing OE devices as well as its scope of use in R&D studies, could also be shown from case studies made.

In course of developing the above IAM & IAMs, the broad conclusion and new information generated from the study, may be grouped into 4 types of derivations, as shown below:

1. Observations from literature review on the current status of OE devices, in the perspective of the challenges for their commercial application.
2. Standardization of certain assessment tools with new information generation.
3. Development of the IAM and extension of it developing the IAM**s**
4. Applicability of IAM & IAM**s** for advancing OE systems from R&D studies,
   .

The conclusions as reached on above are briefed below.

9.1 Observations on status of OE systems for their commercial application

- It is only the Barrage scheme that has attained maturity; whereas all other OE systems have a wide scope for further advancement.
- Both wave and OTEC schemes may have scope for cost reduction from sensitivity analysis, with relevant material development research (replacing costly inventory items with cheaper ones), and also from hybridisation of them, like adding solar collectors in OTEC device; wind farms with WD, etc.
- The point absorber type WECs, like linear generator installed on the sea bed, enabling resource capture from a few kW/m with little problem in survivability, and also of grazing type OTEC plant-ship with *in-situ* production of hydrogen and ammonia (with a host of other chemicals as well) have good potential of economic viability.

9.2 Tools & new concepts developed

Some of the concepts as could be developed and standardised while developing the IAM are as below:
- Development of the EIA model for qualitative and quantitative assessment of environmental fall outs on application of OE systems.
- Computation methodology for assessing the benefits on emission aspects (addressing global warming etc) from the application of OE devices.
- Introduction of 'threshold limit' value of barrages, as an aid to make optimised barrage planning.

- Estimating the possibility of revenue earning/kWh power generation from the by-products of OTEC schemes.
- Introduction of Relative Product cost ratio concept enabling to compare relative economy of similar type of OE devices.
- Breakeven point in the life of OE devices, below which power generation cost escalates sharply.

Their methodology of application with the conclusions reached is given below.

9.2.1 Development of the EIA model for application in OE systems

In its scheme of development, the entire environmental aspects relevant for OE systems were divided into two groups, labelled as Set A & Set B. Both these sets were divided with different subsets, each having number of subset elements as well. Set A, signifies all the environmental issues, like emission aspects, flora and fauna, hazards posed and societal issues. Each has different subset elements. For example flora and fauna would have six subset elements, like birds, fish population, sea mammals, planktons and benthos. Likewise all environmental issues have their specific subset elements, as could be identified.

Set B and its subset elements, influencing the environmental issues (set A), are however, device specific. For example, noise during construction phase (a subset element of set B) is an important impact parameter for flora and fauna (set A) of wave schemes. But in case of OTEC it would be the up-welling of nutrient rich cold water; whereas for barrages it would be the shift in carrying capacity of water flow affecting turbidity that would affect the flora and fauna.

The nature of influence of subset elements B over subset elements A, would decide the qualitative character over each subset element of set A; whether of positive impact supportive of sustainable development or, of negative impact. On the other side, the degree of influence (as also of time period persisting) with number of subset elements of set B, influencing the subset elements of set A, would decide the quantitative character over the subset elements of set A. All the subset elements of Set A as also of Set B could be identified and their effects ascertained, making case studies of wave, OTEC and tidal schemes (sections 4.5 of chapter 4; section 5.3 of chapter 5 & section 6.4 of chapter 6).

The nomenclature used in categorizing the nature and degree of impact of (set B) over the environmental issues (set A) were - high, low, moderate or very low/negligible. The positive inputs were suggestive of favouring the sustainable development and negative in cases of declining it.

Based on the above model, it could be inferred that the overall impact on flora and fauna for wave schemes, are rather benign. In case of OTEC schemes there would be abundant species growth (despite favouring certain toxic species growth as well); whereas in barrage it favours post construction species growth (but with some reduction of saline water fish upstream).

It may be added that in the environmental issue category on 'hazard posed', the mitigating measures of all the possible hazards could also be spelt out, giving the

guideline on deployment of respective OE systems. The score values on subset elements of set A, indicating different types of hazards for respective OE schemes, were based in the eventuality of accidental failure towards adopting the suggested hazard mitigating guidelines. It is to be noted that unlike wave or OTEC schemes, hazards from tidal schemes directly and immediately affect the landscape, like soil erosion/floods etc. Taking recourse to adequate precautionary measures in barrage construction like, heightening of basin embankment etc. rather helps in reducing these risks.

In societal issues, it was not only the criterion on improving the economy that was important, but also aesthetics like visual impact (influencing tourist industry and local economy) are also to be taken into consideration. The scope of different by product availability from OTEC schemes as well as sequestering of CO_2 from OTEC operations, proved to have additional positive impact on societal issues for OTEC schemes.

9.2.2 Methodology developed in estimating benefits from emission aspects

The emission characteristics are estimated presuming typical coal power plants emission to be of 100 percent. Accordingly, GHG emission percentage saved from the deployment of OE device could be estimated from the following relationship:

$$\sum [G_i \times M_i / P_L + G_o\}*100] / 826.17 \qquad [9.1]$$

where, G_i is emission of CO_2 / unit mass (as per LCA data source concerned), M_i is the mass of inventory materials, P_L is the life time power generation (kWh), and G_o is the emission during O&M stages, (perceptible for OTEC systems only); while 826.17, the average CO_2 emission from coal power plant / kWh power generation (as shown in section 4.3.6.2, chapter 4), is considered to be of 100 percent.

Similarly, SO_2 emission percent saved could also be determined with respect to coal power stations SO_2 emission, the value of which is 7.8 g/kWh (section 4.3.6.4 of chapter 4). SO_2 saving for WD was >99% and for Pelamis >98% (Table 4.15, chapter 4).

The other indices, like CO_2 payback period **(CPBP)** & energy payback period **(EPBP)** could also be estimated from equations, as below.

CPBP) $=\sum G_i \times M_i / (826.17 *P_a) \qquad [9.2]$
where, P_a = annual power generation of the device concerned.

EPBP $==\sum E_i M_i / P_a \qquad [9.3]$
where, E_i is the embodied energy of inventory items, expressed in MJ; the annual energy production of device, P_a, is also expressed in MJ.

In these estimations, the values on G_o, the operational stage emission characteristics for OTEC schemes, were included.

Some of the important data as could be generated from the above studies are as below:

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- % of CO_2 emission saved were around 96.5 - 97.5% for the wave and CC-OTEC schemes, and between 92% and 95% for the OC-OTEC & Hybrid types, respectively. Proposed Severn barrage showed the maximum CO_2 saving, which was > 99%; but around 98% saving for the Mersey scheme.

- EPBP values were found to be between 1- 2 years for wave schemes (Pelamis much less than Wave Dragon); whereas it was > 2years for OTEC. Proposed Severn barrage showed the lowest EPBP values of < 1 year; whereas Mersey scheme showed the highest value >3 years.

9.2.3 Introduction to the concept of threshold limit value of barrage

Based on data analysis of a number of barrage proposals, including the functioning La Rance barrage of France, the threshold limiting value of the barrage constant could be determined. This is expressed as $[P/AR^2]*10^{-3} \geq 3.06*10^{-4}$ (section 6.2.1 chapter 6); where P is the power generation, A is the basin area & r denotes the tidal range.

Based from the above concept as was logically developed, it could be predicted that the undecided basin area of Sundarbans barrage project, India, cannot afford to make it more than 6 km^2. Also, the proposed barrage in the Gulf of Cambay, India, would need revision of its barrage planning for achieving economic viability (section 6.2.2 chapter 6). It could also be noted that the proposed Severn barrage showed best planning, even better than the functioning La Rance Barrage of France (table 6.1, chapter 6).

This concept of threshold limit value of barrage helps in checking up optimization of barrage planning.

9.2.4 Scope of revenue earning from by products of OTEC

OTEC schemes have the unique advantage on their scope of availability of various by products, which were estimated as below (section 5.5, chapter 5):

- Availability of desalinated potable water, from OC-OTEC or, Hybrid OTEC operation. Estimated scope of revenue earning from it would be 17p/kWh.
- Increased scope of mari-culture proteins from cold water feed and /or mixed water discharge feed, to land or water bodies of concerned locality in OTEC deployment site.
- Scope of utilisation of up-welled cold water for air conditioning, or for refrigerant purpose with much less power requirement. The power saving achievable by diverting part of up-welled cold water for chilling plants was noted to be more than 600 times the power required for effecting equivalent cooling.
- Prospect of producing H_2 type fuels (*65g/kWh*) & NH_3, (*1115g/kWh*), as proposed for production in grazing type OTEC (requiring no mooring or cable lines etc; still in R&D stage). The potential revenue earning in such cases, from production of different chemicals could be estimated(table 5.15, chapter 5) as below:

1. NH_3 = 14p/kWh – for all types of OTEC.
2. Urea = 0.7p/kWh for OC-OTEC & Hybrid only.
3. Excess NH_3, as saved after Urea production = 13.7p/KWh – only for OC –OTEC & Hybrid types. Thus they gain over CC-OTEC by an amount of 0.4p/kWh (13.7+0.7= 14.4)
4. Methanol= 5.2 p/kWh – applicable for all types of OTEC.

- It may be relevant to add that such wide scope of chemical production opens up the possibility of developing chemical hub with scope of onsite set up of petrochemical industry in OTEC plants (R&D stage). However, the revenue earning estimated for chemicals, excludes the infra-structural development costs of such chemical plants.

9.2.5 Introduction of RPC ratios for comparing economy of OE devices

The concept of Relative Product Cost (RPC) ratios could be introduced, as an economy evaluation index, for comparing relative economy of competing OE devices. This index is particularly suited for OE schemes, which require huge inventory materials for construction of concerned devices.

This index used mainly for comparative study, can be estimated from the mathematical relationships as given below:

RPC ratio of an OE device $= \sum I_m * I_{rpc}$ [9.4];
where, I_m is the mass of respective inventory items of the product, with cost ratios I_{rpc} for each of the individual inventory items; which can be made available from market survey.
For comparative study, the index used is: RPC ratio/kWh $= \sum I_m * I_{rpc} / Pa$ [9.5];
where, Pa is the annual energy production of respective devices.

This index is useful for R&D efforts in making sensitivity analysis on material development research as well as for hybridisation studies, undertaken for improving upon the respective OE devices. In such cases it enables economy evaluation, without the need of knowledge on capital cost data, or of device life- which are not available in the early developmental stages of respective devices.

9.2.5.1 Sensitivity Analysis

It was proposed to replace 25% of steel body of 750 kW Pelamis, with cheaper concrete (without compromising the performance). By knowing the cost/kWh power generation of the parent Pelamis (6.4p/kWh) and comparing its RPC ratio with that of the modified Pelamis, the cost /kWh of the modified Pelamis could be estimated and found to be 5.48p/kWh; thereby showing 14.32% improvement in economy. (table 8.1, Chapter 8).

Thus, RPC ratios could be useful in cost estimations on R& D efforts for material development research of OE schemes.

9.2.5.2 Hybridisation studies of WEC

7MW Wave Dragon was proposed to be tagged with off shore wind farms, using the same mooring and increasing its annual power generation by 25% (Table 8.4, chapter 8). Based from the cost/kWh power generation of the parent WD (6.8p/kWh) and estimating the RPC ratios of WD and wind farm the cost/kWh power generation of the hybrid device could be estimated and found to be 5.68p/kWh; showing 16.46% improvement in economy (Chapter 8).

Thus, based on RPC ratios, cost estimations could be made for hybridisation studies (undertaken for performance improvement of OE devices)   only from the inventory data and making comparative studies with the mother device.

9.2.5.3 Economy evaluation of similar device from RPC ratio/kWh

Based on the knowledge of cost in p/kWh of power generation of Severn Barrage (2.8p/kWh, estimated from its capital cost, O&M cost, as also of its life period), it was possible to estimate the cost in p/kWh of power generation of proposed Mersey Barrage, only from its inventory items and annual power generation data, without the knowledge of capital investment costs etc. This was possible from comparative study of their RPC values, showing that the cost of power generation of Mersey barrage would be 5.68p/kWh, giving around 87.5% higher cost than the Severn proposal.

RPC ratio comparison could thus be a useful tool for R&D studies in the preliminary stage of developing an advanced OE device, where capital cost involvement or design life data are not available.

9.2.6 Break-even point in life of OE devices

Cost of power generation in p/kWh is an important economy evaluation index, which is determined from the relationship as below:

Cost in p/kWh = Cc + Co * DF/ (P_a*DF)   [9.6]
where, Cc is the capital cost, Co is O&M cost, P_a is annual power generation of device and DF is the discount factor expressed as:
$DF = [(1+r)^L -1] / [(r*(1+r)^L]$ [9.7]
where, r is the discount rate and L is device life.

Based on cost /kWh estimations and by varying the device life years, case studies of 750 kW Pelamis, 7MW Wave Dragon & 100 MW CC-OTEC were made. It could be observed that 30 years life for all these device seem to be the break-even point, below which cost in p/kWh escalates sharply (as per fig 4.21 for Pelamis & fig.4.15 for WD of chapter 4; and fig. 5.6 for OTEC of chapter 5; respectively). Thus 30 years life can be considered to be the minimum mandatory design life for such devices.

9.3 Development of IAM

The Integrated Assessment Methodology developed for evaluating the relative merits and demerits of OE devices, that is to say wave, OTEC and tidal schemes- consists in identification of four interdependent tasks and standardization of six assessment tools. They are elucidated as below.

9.3.1 Tasks identified

The interdependent tasks, as are needed for applying the assessment tools are as below:

- Task 1- Identification on areas of data collection on certain specific aspects of the device. Usually it should be on details of inventory items, power generation data, including survivability from on-sea trial runs of prototype units, for wave & OTEC schemes. Capital cost involvement data with design life are also required to be sought for, if available.
- Task 2- Defining necessary guidelines for OE device's deployment status for advising the concerned device manufacturer including identification of the hazard mitigating measures of respective systems.
- Task 3- Identification of the assessment tools and their application examining the scope for commercial deployment of the device, based on the primary data collected from the manufacturer; as spelt out in task 1 & 2. .
- Task 4- Examining the OE device from application of the assessment tools identified in task 3, with a view to determine its relative merits and demerits, compared to other devices. This helps in identifying R&D areas for making performance improvement of the concerned device.

The assessment tools of IAM, developed, with identification of priority criterion that were considered useful for multi-criterion decision analysis (MCDA), in assessing competing OE devices are as below:

1. Examination and analysis on deployment sites of OE devices, with resource availability and scope of economic gains achievable.
2. Safety factor from survivability, taking recognition of ensuring stability in storm waves; particularly for offshore WECs and OTEC schemes.
3. Scope of resource tapping capability of the device concerned.
4. Scope of addressing global warming and emission aspects, with the criterion like, emission of CO_2 in g/kWh and the percentage CO_2 saved, compared to coal generator.
5. Qualitative & quantitative assessment of the environmental impact accrued from deployment of concerned OE device.
6. Economy evaluation giving the cost in p/kWh and RPC ratios/kWh (comparing the mark up cost).

It could be noted from case studies of wave, OTEC and barrage schemes that cost/kWh varies depending on the life of the device as also of the discount rate. From studies carried out at discount rates varying between 5 and 20 percent the cost /kWh for 750 kW Pelamis for deployment in Ireland coast varied between 5 and 13 p/kWh at its designed life of 20 years. 7MW Wave Dragon with its design life of 50 years varied between 5 and 14p/kWh; 100MW CC-OTEC with life of 30 years

varied between 5 and 15 p/kWh, and the proposed Severn Barrage with its life of 100 years showed values of 3 and 5p/kWh.

The IAM developed for making multi-criterion assessment of OE systems, was thereafter extended developing of **IAMs**, for ranking OE devices from the **single criterion** of achieving sustainable development. The scheme of development of IAMs based on IAM developed is shown below.

9.4 IAMs for ascertaining sustainability development of OE devices

IAM**s** development was made following the scheme as below:
1. Identification of 7 sustainability development indices (SDI).
2. Developing a sustainable scale from 0 to 100.
3. Attributing sustainable development load score (SDLS) values to each SDIs, as also making sensitivity analysis of the same.
4. Computation of sustainability gain input from all the SDIs, and thereafter estimating the total sustainability achievable from deployment of the concerned device.
5. Mathematical modeling of determining IAM**s** based from case studies.

The above scheme, as developed is briefed below.

9.4.1 Identification of sustainability development indices (SDIs)

7 SDIs based on tools of IAM could be identified; which included four sustainability loss items (1st 4 items) and three gain (last 3) items.

They are: Input to global warming **(SDIge)**, energy loss **(SDIen),** species loss **(SDIsp)**, inherent hazards posed from device deployment **(SDIv)**,scope of food growth**(SDgf)** economy improvement made **(SDIeg)** and the scope of improving upon the quality of life **(SDIqi)**.

SDI values are to be multiplied with their assigned weightage factor. This factor is '3' for SDIge and SDIen , the effect being global and permanent; '2' for SDIeg, the effect being local but permanent; and '1' for the rest four SDIs, whose effects are local and temporary.

9.4.2 Sustainability scale development

The sustainability scale of 0-100 was developed, considering two types of hypothetical systems. The one with all loss and no gain in sustainability results in zero percent sustainability; the other with no loss and all gain would achieve 100 percent sustainability. In actual practice however, the values are in between these two extremes.

9.4.3 Attributing SDLS distribution pattern & estimating sustainability percent

In order to determine sustainability percent of an energy device, sustainability load score distribution values are attributed as per their relative importance. The

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sustainability input from the loss items of SDIs are estimated subtracting the loss incurred from the SDLS values attributed to it and expressed in percent

Whereas for the gain items, the values achieved are considered as their individual input to sustainability. The sum total of all the input to sustainability gives the total sustainability achieved for the device concerned.

9.4.4 Case studies of estimating sustainability percentage for OE devices

Case studies were made of different OE devices, with varied distribution pattern of SDLS. It was found that percentage gain of sustainability of WECs, like 7MW WD & 750 kW Pelamis varied between 57 and 63%; between 66 and 68% for 100MW CC-OTEC, whence above 70% for Severn barrage scheme.

Comparative studies with coal plant, which is known to be an unsustainable energy system, showed sustainability between 32 and 36%.

However, SDLS value distribution pattern of respective SDIs could be designated with non-numerical values like, α, β, γ, δ,ε, ζ, and Ψ, for the respective 7 indices. The only condition attributed to these non-numerical percentage inputs was that, their sum total should be 100%, making thereby: **α+β+γ+δ+ε+ζ+Ψ =100.** Thereby a mathematical model of IAM**s** could be developed and is shown below.

9.4.5 Mathematical model of IAMs

The non-numerical values of SDLS based from which respective SDIs are determined would be as below:

- **α** represents SDLS percent in addressing global warming **(SDIge)**
- **β** represents SDLS percent in energy loss **(SDIen)**.
- **γ** represents SDLS percent in decline of species loss **(SDIsp).**
- **δ** represents SDLS percent in vulnerability/ hazards as may be accrued from OE deployment **(SDIv)**
- **ε** represents SDLS percent in helping growth of food items **(SDIgf)**.
- **ζ** represents SDLS percent in growth of economy **(SDIeg)**.
- **Ψ** represents SDLS gain percent in improving upon the quality of life **(SDIqi)**.

Thus expressing the SDI items from their basic equations, with necessary multiplication of weight-age factors, the IAM**s** may be written as below, from which sustainability percent of any device may be estimated.

IAMs = α*[1-3*CO_2 emission % compared to coal power] +β*[1- 3*Energy loss%] + γ*[1- species loss%]+δ*[1-inherent hazard%]+ε*[food growth%]+ζ*[2*Economy growth%]+ Ψ*[quality of life improvement %]   [9.8]

= α [1-- 3 {(∑ Gi × Mi / P$_L$ + Go)*100}/ 826.17}%] +
β[1- 3*{(EiMi/Pa)*100/L%}]+ γ[1-- (∑ Fn%)] + δ[1--(∑H)%]+ ε (∑ Fp)% +
ζ [2*(Cc+Co*DF)/ (Ea*DF)]%+ Ψ (∑Qs)%   [9.9]

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where, $\sum$ Fn indicates overall species loss expressed in percent from negative score values of flora and fauna as per EIA model; $\sum$ **Fp** denoting food growth is estimated from positive score values of fish population and planktons, as per EIA model; $\sum$**H** denotes hazards posed as determined from EIA model, $\sum$**Qs** is estimated from overall positive score values of societal issues as per EIA model; with all expressed in percentage. The remaining nomenclature has usual values noted in previous sections.

IAMs $\geq$ 50% gives viability to the sustainability of a device**.**

The above stated mathematical modeling of IAMs for assessing viability of sustainable development could be applicable not only for OE devices, but a generalized formulae considered applicable for all energy systems.

9.5 Application of IAMs for feasibility studies in R&D efforts

IAM**s** can be used for making feasibility studies of R&D efforts of OE devices. A few such results obtained from theoretical studies are cited below.

- In case of Pelamis, it could be estimated that replacement of its steel body with 25% concrete makes an increment of 3.73% sustainability than the parent Pelamis.

- Likewise, sustainability improvement could be estimated in efforts of improving upon WD from Hybridization study, tagging it with off-shore Wind farm. It could be estimated that there was increment of 4.13% sustainability from such efforts.
- The sustainability of Mersey Barrage could also be estimated and found to be 66.2% (after availing the economy data comparing its RPC ratio data with that of Severn barrage).

Thus, IAMs with other indices developed, could prove to be effective in making feasibility studies of all three areas of R&D efforts like material development research, hybridization study as well as design technology improvement from R&D efforts- based only on theoretical estimations, prior to making capital investment.

9.6 Comments.
.
It may be added that future wide scale commercial application of systems from their further improvements may need revision of the specific values obtained on different aspects of the IAM & IAMs. But the basic tenets of the models with their broad application modality would remain unchanged.

In fact, the above model could be applicable not only for the OE systems alone (for ranking devices as also for making feasibility studies on R&D efforts), but with adequate adjustments of the application modality it has the scope of making it useful for all types of RE systems.

APPENDIX 1

SCOPE OF APPLICATION OF LCA & EA FOR OE SYSTEMS

1.0 Introduction

The green house gas emission of renewable energy systems is mainly during their manufacturing stage only and virtually none during their operations, unlike the fossil fuels. Hence, in order to assess the environmental burden of a RE system, it is important to determine the life cycle emission characteristics of the system, covering all its phases of development and operations. This starts from excavation of the inventory raw materials, product construction, and operations to the disposal stage of the finished product after serving lifetime service. Such assessment system, from "cradle to gate" of a product or a process, has been termed, life cycle assessment or LCA of the product or the process concerned.

Likewise, if the energy requirement for building up the power-generating unit is more than the energy it can produce in its lifetime, then certainly such power generation system serves no meaningful purpose. This has brought in the concept of making energy accounting to determine the period, by which the unit can pay back the energy it required for its production. This is termed energy accounting that helps in determining the energy payback period of the product. In this energy accounting studies, energy requirement for the product construction is evaluated in terms of the number of years that the energy generator would require to pay back the energy it required for its construction etc.
.
2.0 Developmental stages

Previously some form of LCA was used as a corporate strategy in USA and after that, as an aid for developing public policy towards promoting sustainable development. But such application of LCA & EA, got momentum from the Brundlant commission in 1987 appointed by the World Commission of Environment and Development (WCED) and from the United Nations stressing upon sustainable development of human society (SETAC 1990). Sustainability development is defined as "the development that meets the needs of the present, without compromising the ability of the future generations to meet their own needs" (SETAC 1990).

It would be obvious from the very scope of   LCA & EA   studies, that they provide us a basis to assess the environmental burden on resources and energy. Besides, it provides background information, to choose the best option amongst alternative processes and/or competing products (Helias et al. 2007). Hence such studies for all products or processes are considered helpful in assessing the most efficient alternative, for   achieving sustainable development. Also, it helps ascertaining the scope for the   products or process that can co-exist in balance with nature, without causing a burden to it.

Importance of LCA in the assessment of GHG emission is particularly stressed upon, for countering global warming problem. With this in view,   a policy decision was taken in 2005, by the European Emission Trading Scheme [EUETS] to set a carbon emission price for tackling the GHG emission problems (British Standard Institute

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2006). This brings in the importance of assessing CO_2 emission, or rather GHG emission characteristics from LCA studies, besides energy payback period from EA studies.

The boundary conditions in such cases may be defined to be a *'cradle to site'* approach. This includes the transportation of the product, right from extraction to reaching the site of construction, added with future O&M operations required during its life time, following the standard of ISO 14040 (Gagon et al 2002).

In fact, for all the ocean energy schemes--covering wave, OTEC and tidal systems – huge raw material inputs are required for their construction itself, to make them robust enough to assure survivability. Hence, for OE systems- LCA & EA studies are considered particularly important to assess their environmental burden if any, or the benefits accrued from the degree of saving GHG emission.

The methodology of estimating such GHG emission and energy payback period estimations from LCA & EA studies are briefed below in subsequent sections.

2.0 Methodology of LCA Estimations

LCA evaluates the environmental burden associated with a product, process or activity by *identifying as well as quantifying* the energy use and material release to the environment. It also suggests implementations to make environmental improvements, identifying the scope of opportunities for the same (Gunilla 1996). Such LCA assessment identifies the environmental problems involved in the whole life cycle, categorize them and then assign priority in finding the solution. It is rather a cradle to grave system, which can assess hidden impact of the environmental burden. The four generally accepted steps for LCA studies, as presented in ISO 14040 are as below (Khan et al. 2005):

1. Goal and scope definition
2. Inventory analysis
3. Impact assessment
4. Interpretation and improvement assessment

Goal and scope definition is the first step of LCA study. It specifies the purpose for which LCA study is carried out. It includes the scope, functional unit and assumptions. After the goal and purpose is spelt out, the boundary conditions of the study is determined.

For Inventory *Analysis study*, the material input, wastes and emission data are collected and environmental data are quantified.

Impact assessment provides the potential and actual environmental and human health effects from the use of resources and environmental releases. This third step of impact assessments again consist of two parts.

Classification:
In this process, the results from the inventory analysis are assembled into Impact categories, namely:

- Environmental ecosystem.
- Quality of human life.
- Natural resource utilization.
- Social welfare.

Characterization:
Here an assessment of the magnitude of the potential and impact that is exerted by a specific input is made.

The 4th step, Interpretation *and Improvement assessment*, enables the identification of the areas where the environmental burden can be reduced.

The above stated the 4 steps for LCA are however , interrelated with each other , as shown below in figure 1 (Khan et al. 2005).
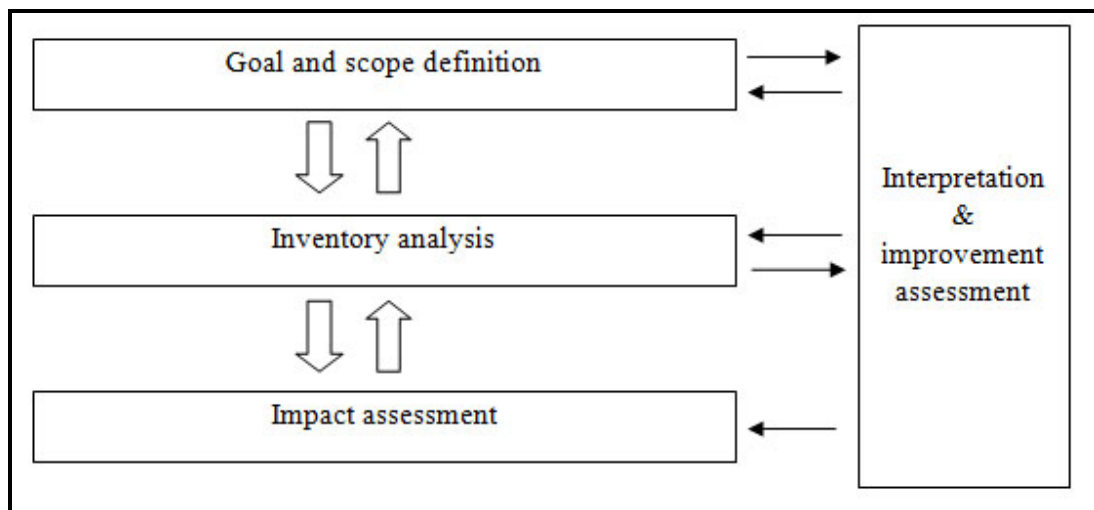
Figure 1 Four interrelated steps of LCA and their relationship is shown
(Khan et al. 2005; Gunilla 1996)

In fact, LCA is a continuously developing concept. It is mostly used for product design and development, and the selection of processes, or waste management systems. Industry is a major user of LCA. Such assessment of LCA include the entire lifecycle of the product, process, or activity encompassing—extraction and processing of materials; manufacturing, transportation and distribution; use, reuse, maintenance; recycling and final disposal.

A typical example of the stages considered for a particular raw material, steel, which is the most important constituent inventory item for OE system, is shown below in fig.2

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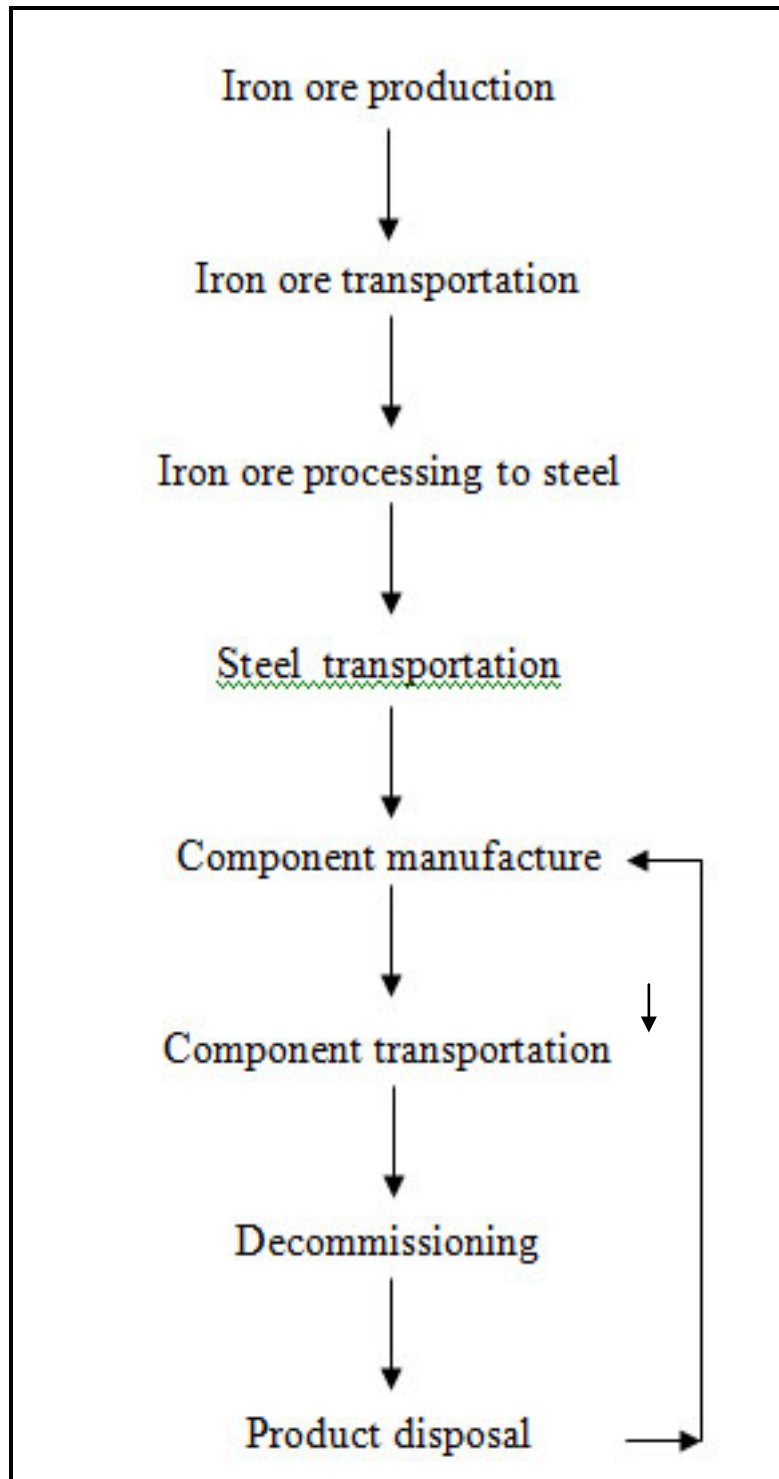
Fig 2 various stages in the lifecycle of steel being in use for OE schemes.

It thus enables us to study the *raw materials used* and *type of energy utilized*. It helps us to find out the discharge in the air, water arising from a specific process and the damage to the human health. It is also a framework and methodology for *spotting out even environmentally friendly products*. LCA thus enables the decision makers in identifying the methods to reduce environmental disturbance

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3.0 LCA & EA Models used for OE systems

Two sources of base data on emission characteristics have been followed in making the LCA studies of OE systems. The emission characteristics of inventory items from above two sources are followed in making the LCA estimations.

These sources are the Danish model (Schleisner 2000), as well as of the Bath University data sources (Hammond and Jones 2008), as shown below in tables 1 & 2 respectively.

Table 1 Emissions in kg/kg of construction materials from Danish model (Schleiner 2000)

Materials	CO_2 (kg/kg)	NO (kg/kg)	N_2O (kg/kg)	CH_4 (kg/kg)	SO_2 (kg/kg)
Steel/Stainless steel etc.	2.3065	0.0095	0.00007	0.00004	0.0145
Aluminium	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	0.00000	0.00000	0.00001

Table 2 CO_2 emission from Bath University data source (Hammond and Jones 2008)

Inventory Materials	Steel	Copper	Iron	Concrete	Plastics	Aluminium
CO_2 emission Kg/kg	2.83	3.0	1.91	0.95	2.53	8.26

Likewise embodied energy in MJ/kg of the inventory materials for OE systems, based from above two data sources are shown below in table 3.

Table 3 Embodied energy of inventory items of OE systems

Materials	Steel	Iron/ Cast iron	Cu	Al	Glass	Concrete /Cement	Plastic
Embodied Energy MJ/kg- (Danish model) *	25.65	36.3	78.2	39.15	8.1	3.68	45.7
Embodied Energy MJ/kg --(Bath Univ. Data)**	25.4	25	70	34.1	18.50	3.01	45.7

*(Schleisner 2000) ** (Hammond and Jones 2008).

Based from the above 3 tables could be estimated emission characteristics as well as energy payback period for different OE schemes, elaborated in respective chapters (Chapters 4, 5 & 6). It may be added that LCA & EA values being process specific may vary from country to country, or for different models /softwares used.

In ocean energy systems have been determined emission in g/kWh, carbon payback period, & percentage of CO_2 saved, compared to coal fired plant, as well as the energy payback period for different OE systems. The results obtained from the Danish model could be compared with Bath University data source, as well.

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APPENDIX 2

**METHODOLOGY FOR ECONOMY EVALUATION
OF OCEAN ENERGY SYSTEMS**

1.0 Introduction

Economy is the key issue in deciding the market acceptability of a product or project. Thus, even if an *energy system* achieves technical viability with its prospect of becoming environment –friendly, it has to ensure *economical viability* as well, to invite investment for its commercial application. It is more important for Ocean Energy systems, which require huge capital outlay in its initial stage, for its successful commercial application with foolproof safety and survivability. Based on cost – benefit assessment it may not yield profit in the initial years during the construction and commissioning stage of the energy system concerned, which may rather show a negative benefit then. But unless in later years of its energy production stage, the net benefit derived from its *lifetime* estimation does not prove to be positive, the project cannot be considered to be economically viable.

It is important to note that in making such estimations as regards *net benefit derived* in its long life time, the factors like *depreciation* of the money value of the profit earned is to be considered. This profit, as might be earned in later years covering the long life of the energy system, is to be adjudged comparing it with the benefit, which could have otherwise been earned from interest of the capital invested. Keeping the above perspective in view, it becomes necessary to have adequate economy-tools for ranking different designs of ocean energy devices, along with the fossil fuel system, for assessment of their market acceptability.

In fact, such tools of economy assessment of different competing energy systems would also be helpful in identifying scope of design improvement, for cost reduction of energy converters without compromising their quality.

It may be noted that the basic difference between conventional fossil fuel energy systems and ocean energy (OE) systems is that, the recurring expenditure for the latter is very little for their operation and maintenance (O&M). This is particularly because of the fact that they involve zero fuel cost like, other renewable energy (RE) systems. But, unlike most other RE systems, the OE systems require *huge initial capital outlay* with massive material requirement (inventory items) for its construction etc. to withstand the rough ocean climate. Of course, its resources are also very high with possibility of large scale energy productions.

Keeping in view the above perspectives, the tools identified for evaluating the economic benefits as could derived from application of different competing energy converters (for OE systems in particular), are as below:

- Evaluating the Net Present Value of the investments made in lifetime of converters.
- Determining the cost of electricity / kWh power generation.
- Estimating the percentage of Internal Rate of Return.

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- Estimating the (Simple) Cost Payback period in years, for the capital invested.
- Comparing *Relative Product Cost Ratios (RPC)* of Energy converters, for assessing their mark up cost ratios (cost ratios without profit).
- Comparison with fossil fuel economy.

A brief resume of above, giving the methodology for their determination and their respective economic significance as assessment tools for competing OE systems, are discussed below.

2.0 Evaluating Net Present Value (NPV) of the investments

Net Present Value (NPV) estimation is useful when the benefits from investments are derived a long time after the investment is made (Mathew 2006:209-231). Thus in its estimation, the *lifetime* is required to be specified. It also indicates the actual present value of money, taking into account the *depreciation of money* value that occurs after the specified time. Thus, it is required to be specific about the interest rate as well, to take care of the depreciation of money value with respect to the present value. For example £ 1000, if deposited in bank (without investing etc) at 5% simple interest, it would amount to £1500 after 10 years-- making the net present value of that £1500 to be just £1000, at that simple interest rate of 5% in 10 years time period.

Thus, having specified these two factors of *time* and the *interest rate*, the *NPV* value of cash flow in future periods can be estimated: by multiplying it with the annual cash flow 'C' with the *discount factor* $=1/(1+r)^t$; where t= time period, r=the interest rate/yr.
Thus, NPV $=\sum_0^t C/(1+r)^t$; where, C=cash flow each year, t=time period (total life time covered); r=rate of interest.

The initial investment made is to be realised from the integrated value of the above cash flow discounted with the above rate 'r' covering the time period 't.' Projects with positive values of cash flow against the investments made can only be considered economically viable. In other words for economically viable projects, the Net Present value of *benefit* minus Net Present value of *cost,* has to become positive. If negative, the project would then be considered to be running at a loss. If both are the same then the project would have just balanced with 'no profit and no loss basis.'

NPV thus becomes a good instrument to compare relative benefits derived from different systems under *identical 't' and 'r' values*. With varied 't' or 'r' values, NPV values would of course be different. Obviously, higher the NPV greater would be the benefit.

In the case of Ocean Energy Converters, if the construction & installation cost including spares is 'Cc;' and annual maintenance and operational cost 'Co' is 'x' percent of 'Cc;' then the *total cost involvement* for the converter concerned from NPV concept, in its life period 't' and considering the money value discounted with rate 'r; would be:
$=Cc +\sum Co = Cc +\sum_0^t [0.01x*Cc/(1+r)^t]$ ....(1)

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The profits earned each year (selling electricity generated etc.) has also to be multiplied with the discount factor $1/(1+r)^t$, for estimating the total benefits derived in its lifetime 't.'

In order for a OE system to become profitable, its NPV of total benefit (covering specified time periods for the particular discount rate) has to be positive, after its subtraction from above cost involvement. If negative the system would run at loss.

Hence it becomes a good instrument to compare relative benefits of different OE systems.

3.0 Estimating the cost/kWh of electricity production

The above NPV concept can be fruitfully utilized to determine the cost of electricity production as well, by knowing the annual production of electricity of the OE system concerned, as well as the life of the system.

Thus, if the annual electricity production of the device is 'E' kWh, it would earn each year an amount say p*E, where p/kWh =cost/kWh of power generated. Multiplying this with the discount factor $1/(1+r)$, we can derive the present value of money considering the discount rate of 'r.'

The Net present value of total money earned in its entire lifetime of 't' at discount rate 'r' would obviously be:
$= \sum_0^t [p*E/(1+r)^t]$ ....(2)

As per equation (1) above, NPV of total cost $= Cc + \sum_0^t [0.01x*Cc/(1+r)^t]$.

The cost of electricity production =Net Present Value of the cost of production /Net Present Value of the energy availed.

Thus, cost of electricity production /kWh
=p/kWh
$= \{Cc + \sum_0^t [0.01x*Cc/(1+r)^t]\}/ \{\sum_0^t [E/(1+r)^t]\}$.per kWh ....(3)

Since NPV varies with 't' and 'r', 'p' would also vary accordingly.

Also, cost of electricity production is directly related to the profitability, hence comparative study of *profitability* for different OE systems can be made from the above index of *cost of electricity production/kWh*. Of course, comparative studies can only be made under identical 't' and 'r' values.

4.0 Estimation of Internal Rate of Return (IRR)

Internal Rate of Return (IRR) may be said to be the discount rate of a venture, at which the benefit gained is just neutralised against the cost incurred (Khalib 2003:57-59). Thus, based from NPV equation as above, it would follow that 'r' attaining IRR value:
$\sum C_n/(1+r)^n = \sum B_n/(1+r)^n$; ....(4)

Where Cn=stream of cost involvement, Bn= stream of benefits derived, n=life time.

In order to satisfy the above equation, to make 'r' value such, as could make NPV of cost equal to the NPV of benefit i.e. to make zero NPV; trial and error method is adopted with varied values of 'r.' In this way one value comes up positive whence the other negative. Exact 'r' value to make zero NPV can easily be made thereafter with necessary computation or, graphically plotting the two points and finding the zero crossing value of 'r.'(Khalib 2003:57-69). Obviously this value of 'r' giving zero NPV, lying in between the above two positive and negative values, gives the *IRR* which may be irrespective of presumptions of discount rate, but based from NPV value estimations.

Thus, at the discount rate coinciding with IRR:
Net cash flow*discount factor-- Capital cost = 0;
[Net cash flow =power cost/kWh*annual power in kWh—O&M cost etc]
Or, Discount factor= capital cost/Net cash flow
Or, Discount factor—capital cost/Net cash flow=0;

But, at the discount rate much higher than IRR, say Rn, the above equation may yield negative value, say Vn. If however, the discount rate is much lower than IRR, say at Rp, then the above value may be positive, say Vp.

At IRR value of V is zero; and IRR should be higher than Rp, but lower than Rn, whose value would be:
=[Rp + (Rn --Rp)*Vp /{Vp—(--Vn)}]*100

In fact, IRR value gives the minimum return from the project that can be acceptable, below which it should be rejected; since it would then incur loss. It is widely used to assess competing energy system's economical viability.

Obviously, higher the IRR value better is the investment

5.0 Payback period estimations

Simple payback period is defined as the ratio between total cost of the project and the net annual savings that can be earned from the annual power production of the concerned energy converter unit.
Total cost involvement for the OE system, converted to NPV would be:
= Cc +$\sum_0^t$ [0.01x*Cc/(1+r)^t] .... ……. (1)
[equation (1) as above].

For a OE unit of 'E' KW, its annual electricity production covering entire 8760 hours/yr
=E*(capacity factor) *8760 KWh.................................. (4)

Cost of electricity per kWh
= {Cc +$\sum_0^t$ [0.01xCc/(1+r)^t]}/ {{$\sum_0^t$ [E/(1+r)^t] } per kWh, ...(3)
[equation (3) as above].

Net annual savings as could be derived from annual production of electricity

=Annual production of electricity in kWh*cost of electricity per kWh
=equation (4) $\times$ equation (3)
= E*(capacity factor) *8760 $\times[\{$ Cc $+\sum_0^t [0.01xCc/(1+r)^t]\}/\{\sum_0^t [E/(1+r)^t]\}]$ ....(5)

Payback period in years would thus be
=equation (1)/Equation (5)
= $\{Cc +\sum_0^t [0.01xCc/(1+r)^t]\}/[E*$(capacity factor) *8760 $\times\{Cc + \sum_0^t \{0.01xCc/(1+r)^t \}/ \{\sum_0^t [E/(1+r)t \}]$.years ....(6)

Obviously higher the value cost/kWh, the lower is the simple payback period.

6.0 Determining the Relative Product Cost (RPC) of OE converters

The robustly built large sized ocean energy converters would require huge quantity of raw materials like, Steel/Stainless Steel, Aluminum, Copper, Plastic, Iron, Concrete /Cement, Glass, Plastics (HDPE), etc. This involves high cost for the raw materials alone, besides the cost of construction with subsequent installation for power generation. The financial liability of such large capital outlay credited from stakeholders remains a financial burden with inherent risk of survivability, till the unit goes into production..The profit margin is hence likely to be maintained enough by production companies, to pay back the money invested, besides taking care of the depreciation of the money value as determined from NPV estimation and IRR.

Thus, in estimations of cost involvement of units, it is always associated with the profit component and there is no tool available to know the *mark up cost*, which is the actual cost involved excluding the profit margin of units. For comparative purpose also, varied profit margins by different manufacturers makes it difficult to compare the relative cost component for individual converters. In fact, in comparing relative economy the *mark up cost* (cost without profit /margin) of the energy converter units is also a decisive factor. But it difficult to collect data regarding *mark up cost* of respective generators, made by different companies.

Also for R&D studies it is not always possible to know the exact capital investment needed in the initial stage of developing the product as also its life period.

An attempt has therefore been made to introduce an index of *Relative Product Cost (RPC) ratios,* for comparing the relative economy for different types of OE devices. It may be considered to be particularly important for OE type energy systems, most of which involve huge raw materials, unlike many others RE systems; and in R&D work for improving upon the concerned product.

The following logical presumptions are made for developing the above tool, *RPC ratio* for comparing relative economy. They are:

- The average cost of the different inventory materials /constituents, required for constructing the OE devices,   are considered to maintain (with a reasonable approximation) a definite ratio, which could be determined from market survey, as shown in table -1 given below. This enables to make comparative studies of RPC ratios of raw material cost --though not of the actual cost involved.

- The cost involvement of the components (and their assembly) made from respective raw materials, may be approximated to be directly proportional to the cost of the raw materials concerned.

- By and large, the transportation & installation cost is likely to be dependent on the respective weights of products, on transportation/ installation (not the actual cost involvement, but relative ratios only).

The above presumptions would make it possible to compare the relative product cost for different OE devices, as regards their financial credit requirement--towards meeting their respective raw materials cost for component parts, their manufacture, assembly-- including transportation / installation.

In table -1 shown below, is given the *relative product cost ratios* (RPC ratios) of usual raw materials that are normally used for OE converters, based from current market survey; [on line]. availed from <http://www.metalprices.com/> [13th December 2011]

Table-1 RPC ratios of various inventory items, as observed from market survey. (availed from <http://www.metalprices.com/> [13th December 2011])

Inventory items	Stainless Steel/ Special steel	Al	Cu	Plastic/ HDPE	Glass	Iron / Steel	Concrete
RPC ratios	2.5	1.9	3.0	1.6	1.2	1.3	1.0

The cost ratio of the respective converter units may be made multiplying mass requirement of each item with the RPC ratios of respective inventory items; and thereafter adding them up to make the *grand total cost ratio* for each converter types. This grand total cost ratio divided by annual power generation for respective generators, would give the *cost ratio/kWh* which could be an important *index to compare* the relative advantage gained from different types of converters.

It would also help in making sensitivity analysis for performance improvement, identifying scope of replacement of costly inventory materials, and/or tagging up cheaper type converters to make hybrid converter types, for performance improvement.

Obviously, the *ratios of installation and transport cost* can be compared from the grand total of mass of all inventory items divided by the annual power generation, giving transport/installation cost ratios per kWh

These *RPC ratios* of construction cost & transportation/installation costs however can only be useful in making *comparative study* and do not give the actual cost component. The advantage derived from this index is that it is *irrespective of price quotations* of manufacturers for their respective converters.

It would however be more useful for comparing identical type of converters in assessing their relative efficacy from different competing manufacturers, just by

knowing the market ratios of inventory items and quantity required for each of these materials.

Obviously, economy assessment from this *RPC ratio index* would be more accurate for comparing identical types of OE systems than those of different types.

7.0 Comparison with fossil fuels economy.

Ocean energy systems, like all other RE systems are yet to take off for large scale commercial production, mainly because of the fact that cost/kWh power generation from conventional fossil fuels seem to be *apparently cheaper* than most of the RE systems. Of course, some applications are being reported in Solar power sector for small scale power supply in inaccessible places. Some use of Bio-fuels and Wind energy or, Hydro power and Tidal Barrages at suitable sites, are also reported. But by and large, the stake holders across the globe are not much encouraged for large scale commercial investments in RE sectors, not to speak of the OE systems, despite their bright prospect of assuring sustainable development.

But the *indirect cost* involvement covering the *environmental fall outs including carbon tax etc.,* as termed *external costs,* should be taken into account in fossil fuels' economy evaluation with considerations on sustainable development(Olav Hohmeyer 1988:8) An approach may be made to evaluate this indirect cost termed external cost, as are incurred by fossil fuels.

In that case can be compared economy of fossil fuel from the following relationship of Acceptability Index, which may be defined as:

Acceptability Index (AI) = Price of conventional power /Price of concerned OE device; inclusive of external cost for both systems. In fact, this relationship holds good for other RE systems as well for comparison with fossil fuel sectors.

8.0 Observations

1. It is obvious from the above discussions that combination of all the economy instruments, like *NPV estimation*, cost *estimation of electricity/kWh*, *IRR%* , *simple payback period* estimations as well as *RPC ratio comparisons-–*are to be used together for comparing respective financial advantage, achieved for different competing energy converters of OE systems.

2. The first 4 indices are interlinked with profit component and discount rates. But the fifth one, the RPC ratio estimation, gives a comparative study excluding the profit component or of the discounted money values. It compares the relative economy of the different competing OE devices (identical types mainly), irrespective of their life & their price quoted from different companies.

3. All these indices are likely to assist in R&D endeavours for search of cheaper options.

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4. The efficacy of these financial indices can of course be checked up and standardized for assessment, on availing updated field data from large scale commercial application of the different types OE systems.

APPENDIX 3

List of Publications: Journals / Presentations in Seminars/ Summit & conferences/ Posters

1. Subhashish Banerjee, Dr Les Duckers and Dr Richard Blanchard- Challenges and Prospect of Ocean Energy Systems with case study of ascertaining their sustainability development, Presented at Low Carbon Earth Summit-2011, held at Dalien, China, October 19-26, 2011.

2. Subhashish Banerjee, Dr. Les Duckers, Dr. Richard Blanchard, and Dr B. K. Choudhury- Economy Evaluation of Ocean Energy Systems with a case study on Wave scheme. Published in October, 2011, in 'Encyclopedia of Energy Engineering and Technology' journal.

3. Subhashish Banerjee, Dr. Les Duckers, Dr. Richard Blanchard and Dr B. K. Choudhury Ocean Thermal Energy Conversion (OTEC): By-Product Availability. (Published in October, 2011, in 'Encyclopedia Energy Engineering and Technology' journal.

4. Subhashish Banerjee, Dr. Les Duckers, Dr. R. E. Blanchard and Dr. B. K. Choudhury-Assessment of Tidal power; World Energy Engineering Congress, Nov. 4-6, 2009. Washington Convention Centre, Washington DC, USA.

5. Subhashish Banerjee, Dr. Les Duckers, Dr. R. E. Blanchard and Dr. B. K. Choudhury- Comparative study of Wave energy, OTEC and Tidal Schemes; 3rd Annual International conference on Management & Social Welfare, Dec, 14-15 2009. IISWBM, India.

6. Subhashish Banerjee, Dr. Les Duckers, Dr. R. E. Blanchard and Dr. B. K. Choudhury–Life Cycle Analysis of Selected Solar and Wave Energy Systems, Proc. 1st National Conference on Advances in Energy Research, IIT Bombay, India [AER 2006], Dec 2006, p143.

7. Banerjee, S., Duckers L. J, Blanchard R. E.– Development of assessment tool for wave energy systems, World Renewable Energy Conference, Florence, August, 2006.

8. Poster presentation- Subhashish Banerjee and Dr. Les Duckers– Application of Pelamis for Power Generation, Coventry University. June, 2006.

9. Subhashish Banerjee *et al*- Towards commercialization of a low cost solar cooker, Proc. 23rd National Renewable Energy Convention, Indore. India. Dec, 1999, pp: 481-84. (Prior to admission in Coventry University, UK).

Bibliography

Achievements in OTEC Technology, National Renewable Energy Laboratory. Availed from <http://www.nrel.gov/otec/achievements. html> [12.05.2012]

Adams, C. W., Watson, M. and Shaw, T. (2008) 'Severn Barrage tidal project: Implication for carbon emission'. *Water & Environment journal*. 23(1), 63-68

AEA Energy & Environment on the behalf of Sustainable Energy Ireland for the IEA's Implementing Agreement on Ocean Energy Systems. (2006). *Review and analysis of ocean energy systems Development and supporting policies*. Availed from <http://www.iea-oceans.org/_fich/6/Review_Policies_on_OES_2.pdf [12.12.2011]

Alderson, S.G. (1992) 'Solution by operational calculus to the problem of the optimization of tidal power'. *IMA journal of Applied Mathematics*, 49, 123-138

Almeida, E., Diamantino, T. C., de-Sousa, O. (2007). 'Marine paints: The particular case of antifouling paints'. *Progress in organic coatings*.59(1)2-20.

Anderson, J.H. (1998) *Ocean thermal power, The coming energy revolution*. Unpublished Booklet. York, Pennsylvania: Sea Solar Power, Inc, 1-38. Availed from < http://www.otecnews.org/library/publications_list.html> [1.6. 2009]

Andre, H.(1978) 'Energy from the seas: Ten years of experience at the "La Rance" tidal power plant', *Ocean Management*, 4(2-4), 165-178.

Avery, W.H. (1984), *Low cost method for producing methanol utilizing OTEC plant ships*, United States Patent 4476249. Available from <http://www. freepatentsonline.com /4476249.html> [7.12 2011]

Bahaj A. S. (2011) Generating electricity from the oceans, *Renewable and Sustainable energy reviews*, Elsevier, April 2011, (15) 3399-3416

Baker, A.C. (1986) 'The development of functions relating cost and performance of tidal power schemes and their application to small-scale sites, *Proc. of symposium held by Institution of Civil Engineers*, held 8-9th October 1981, at London, London: Thomas Telford Ltd.

Banerjee, M. (1999) *A report on the impact of Farakka barrage on the human fabric. A submission for world commission of dams: Thematic review of flood control and many other thematic reviews,* New Delhi, India: South Asia network on dam rivers and people.

Baroni, M. (2011). World Energy Outlook: 2010 Key message and focus. *OECD Annual meeting with the economics and security committee of NATO parliamentary assembly,* held at Paris, Feb 2011.

Subhashish Banerjee

Bechtel, M. and Netz, E. (n.d.) 'OTEC–Ocean Thermal Energy Conversion' 1-12, available from <http://www.exergy.se/ftp/cng97ot.pdf>, [1.7 2009].

Bedard, R., Previsic, M., Polagye, B., Hagerman, G. and Casavant, A. (2006) *North America tidal in-stream energy conversion technology feasibility study*, *Tech. Rep. EPRI TP-008-NA*. USA:EPRI.

Bedi, E, Cancee, and Falk, H. "Energy Saving Now" availed from<http://energy. saving. nu /hydroenergy/wave.shtml > [12.05.2012].

Beer, J.M. (2009) 'Higher efficiency power generation reduces emission' *National coal council issue paper 2009* available from < http://web.mit.edu/mitei/ docs/reports/beer-emissions.pdf> [7.12 2011].

Bergman, G., B. (1996) Ocean Thermal Energy Conversion Platform. US Patent No 5,555,838. Date of patent: Sept. 17, 1996.

Binger, A.(n.d) *Potential and Future Prospects for Ocean Thermal Energy Conversion (OTEC) in Small Islands Developing States (SIDS)*, available from <http://www.sidsnet.org/docshare/energy/20040428105917_OTEC_UN.pdf> [27.5 2009].

Blengini, G.A. (2008) 'Using LCA to evaluate impacts and resources conservation potential of composting: A case study of the Asti District in Italy' *Resources, Conservation and Recycling*,; 52(12),1373-1381.

Booras, G. and Holt, N. (2004), 'Coal, P. and IGCC plant Cost and Performance Estimates', *Gasification Technologies Conference*, at Washington D.C.

British Bio energy news (2010) 'The world's largest bio-mass project takes shape at Drax power station.UK'. *UKERC*. September 2010, issue 11.

British Standards Institute (2006) *Environmental management, Life cycle assessment, Principles and framework*. ISO 14040:2006. London: British Standards Institute.

Brooke, J. (2003) *Wave energy conversion: Chapter 3*. Oxford, UK: Elsevier Science Ltd, 27-35.

Bryden, I.G., Grinsted, T. and Melville, G.T. (2004) 'Assessing the potential of a simple tidal channel to deliver useful energy'. *Applied Ocean Research*, 26, 198—204.

Buchheim, J. n.d. Coral Reef Bleaching, Odyssey Expeditions, availed from <http://www.marinebiology.org/coralbleaching.htm> [3.7. 2009]

Cambell, L., *et.al*. Ed. Gray, A. (1992) 'The Ecological impact of estuarine barrage' *British Ecological Society*, Ecological Issue no 3, U.K: British Ecological Society by Field Studies Council.

(Anon), *Celestopea gateway to a sustainable future.Ocean Thermal Energy Converter (OTEC)* available from <http://www.celestopea.com/OTEC.htm> [2.7. 2009].

Chapter 8, Fundamentals of Physical Geography, 2nd edition, availed from <http://www.physicalgeography.net/fundamentals/8p.html> [14.7.2012].

Chisholum S. W. (1992) 'What limits Phytoplankton growth', *Fisheries Biology*, 35(3), 36-46.

Chichao, L. and Chicharo, M.A. (2001) 'Effect of environmental conditions on planktonic abundances benthic recruitment and growth rates of the bivalve mollusk, ruditapes, decussates in a Portuguese coastal lagoon', *Fisheries Research*, 53, 235-250.

Chittora, M., (2008), *India's first tidal power project coming up, Durgaduani Creek of Sundarbans.* availed from <http://www.projectsmonitor.com/ detailnews.asp?newsid=17114> [7.12. 2011].

Christopher, G., (1972) 'Tidal Resonance in the Bay of Fundy and Gulf of Maine'. *Nature*, 238, 441-443.

Christopher, D., Barry, P.E. (2008) 'Ocean Thermal Energy Conversion and CO2 Sequestration', *Renewable Energy World.com* 1st July 2008. Availed from <http://www.renewableenergyworld.com/rea/news/article/2008/07/ocean-thermal-energy-conversion-and-co2-sequestration-52762> [7.12. 2011].

Cohen, R. (1982) 'Energy from the ocean.' *Phil. Trans. R. Soc*, A307, 405-437.

Colombe, J., and Kydd, P. (2010) Dept. of Energy & Climate Change, S*trategic environmental assessment of proposals for tidal power development in the Severn estuary, options definition report, version 3, volume 1, Job No : FSE97051A* U.K: Department of Energy and Climate Change.

Couch, S.J. and Bryden, I. (2006) 'Tidal current energy extraction: hydrodynamic resource characteristics'. *Proc. I Mech. E*, 220(Part M: J Engineering for the maritime environment, special issue paper), 185—194.

Crest Flexible and distance learning series, Wave Power, Unit 9 (2004/05). *M. Sc in Renewable Energy systems, Study notes for Hydropower,* Loughborough University.

Crest Flexible and distance learning series, Tidal Power, Unit 8 (2004/05a). *M. Sc in Renewable Energy systems, Study notes for Hydropower,* Loughborough University, 15-26.

Douglas, C.A., Harrison, G P. and Chick, J. P. (2008). 'Life cycle assessment of the Seagen marine current turbine', *Proc. I. Mech. E. J. Engineering for the Maritime Environment*, 222(M), 1—12.

Dalton, G. J., Alcorn, R., Lewis, T.(2010), 'Case study feasibility analysis of the Pelamis wave energy converter of Ireland, Portugal and North America', *Renewable Energy*, 35, 443-445.

Douglas, C.A., Harrison, G P. and Chick, J. P. (2008). 'Life cycle assessment of the Seagen marine current turbine', *Proc. I. Mech. E. J. Engineering for the Maritime Environment*, 222(M), 1—12.

Dickson, A.G., and Goyet, C. (1994) *Handbook of Methods for the Analysis of the Various Parameters of the Carbon Dioxide System in Sea Water,* version 2.1. U S Department of Energy Special Research Grant Program 89-7A, US available from<www.vliz.be> [7.12. 2011].

Dincer, I. (2000). Renewable energy and sustainable development: a crucial review. *Renewable and sustainable energy reviews.* 4(2) 167-175.

Douglas, C.A., Harrison, G. P. and Chick, J. P. (2008). 'Life cycle assessment of the Sea Gen marine current turbine', *Proc. I. Mech. E. J. Engineering for the Maritime Environment*, 222(M), 1—12.

Dov, R. and Roy, R. (2004) 'A Paradigm Change in Replacing Fossil Fuel with Solar Energy. *Presented at the Solar Energy Conference*, held February 2004 at Sdeh Boker, Israel. Availed from <http://shebacss.com/rd/docs/rdresrs001.pdf>
 [12.12. 2011].

DTI report (2003) on OUR Energy Future: creating a low carbon economy *Presented to Parliament by the Secretary of State for Trade and Industry by Command of Her Majesty*, February, 2003.

Duckers, L.(2004) 'Wave Energy.' in *Renewable energy*. ed. by Boyle, G.
Oxford University Press, 297-340.

Duckers, L. (2009a) *Report of Coventry University on the topic "Renewable energy sources,"* id/rep/res/ak. 1-30.

Duckers, L.J., Lockett, F.P., Loughridge, B.W., Peatfield, A.M., West, M.J. and White, P.R.S. (1994) 'Optimisation of the clam wave energy converter', *Renewable Energy*, 5(5-8), 1464-1466.

Duckers, L., J. (1999). 'Reinforced rubber membrane for the clam wave energy converter'. *Proc. 9th International offshore and polar engineering conference* held: May 30-June 4, 1999, at France.

Duckers, L. (2006) 'Environmental impact assessment of wave energy systems', *World Maritime Technology Conference*, held 2006 in London.

Subhashish Banerjee

ELARD (2004). Earth link and advance resources development, Environmental Impact Assessment, Solid Waste Treatment Center, JBEIL-HBALINE.

Elder, S.A. and Williams, J. (1996) *Fluid Physics for Oceanographers and Physicists*, Oxford: Butterworth Heinemann, 290.

Elliott, D. (2004) 'Chapter-6, Tidal Power.' in *Renewable energy*. ed. by Boyle, G. Oxford University Press, 196-242.

Engineering toolbox, Pressure and boiling points of water, availed from <http://www.engineeringtoolbox.com/boiling-point-water-d_926.html > [12.05.2012].

Englander, D. and Bradford, T. (2008) *Forecasting the future of Ocean Power,* Availed from <http://www.greentechmedia.com/researchreport/forecasting-the-future-of-ocean-powe> [12.12.2011].

Enrick, M.R. and Scott, M.K. (1990) 'CO_2 solubility in water and brine under reservoir conditions', *Chemical Engineering communications*, 90(1), 23-33.

European Commission (2007:112). Guidelines for the establishment of the Natura 2000 network in the marine environment. *Application of the Habitats and Birds Directives.*2007; in Langton *et al* 2011.

EWEA Report. (2004) *An analysis of Wind Energy: Wind Characteristics and Resources..* in. Manwell James F., *et al*. Wind energy explained: Theory, Design, and Application (Google book), Art.2 pp 23- 87.

Falkowski P., G.(1997). Evolution of the nitrogen cycle and its influence on the biological sequestration of CO_2 in the ocean. *Nature (Letters to Nature)*, 387, 272-274.

Floor, A.J.(2006) 'The chemical composition of sea water', Available from <www.seafriends.org.nz.oceano/seawater.htm> [1.12. 2009].

Floor, A.,J. (2000) 'Waves theory and principles of waves, how they work and what causes them'. *Oceanography*, Availed from <http://www.seafriends.org:nz/oceano /waves.htm> [24.7. 2009].

Folley, M. and Whittaker, T.J.T.(2009). 'Analysis of near shore wave energy', *Renewable Energy*, 34(7), 1709-1715.

Frau, J. P. (1993) 'Tidal Energy - promising projects: La Rance a successful industrial scale experiment'. IIEE Transactions on Energy conversion; 1993; 8(3) 552-558.

Friis-Madsen, E.,Christensen, .L, Kofoed, J.P. and Tedd, J. (2006) 'Worlds Largest Wave Energy Project 2007 in Wales' *Powergen Europe Conference Proceedings*, at Cologne. Availed from
<http://www.wisions.net/files/tr downloads/Aquaret_Wave_Dragon.pdf>
[14.9. 2011]

Frontier economics Ltd, London, (2008) *Analysis of a Severn Barrage, A report prepared for the NGO Steering Group,* Frontier Economics, 1-47.

Gagon, L., et al. (2002) 'Life-cycle assessment of electricity generation options: the Status of research in year 2001', *Energy Policy*, 30, 1267-78.

Garcia, L. National Museum of WWII, availed from <http://www.ww2sci-ech.org/lessons/lessons2.html> [13th May, 2012].

Glasson, J., Therivel, R. and Chadwick, A. (2005) *Introduction to Environmental Impact Assessment*. 3rd Edition, Routledge Publisher

Glickson A. (2009) *Submission to the Senate Inquiry into the exposure drafts of the legislation to implement the Carbon Pollution Reduction Scheme*. Availed from

<http://wopared.parl.net/Senate/committee/economics_ctte/cprs_09/submissions/sub 34_web.pdf> [25.1.2012]

Goldberg, E.D. (1993) *Coastal zone space: sites for conflict*, [Presentation] held 22nd January 1993 at Tokyo: United Nations University, Japan. Available from <http://www.unu.edu/unupress/lecture3.html> [6.7. 2009].

Gray, A.(1992) 'The Ecological impact of estuarine barrage' *British Ecological Society.* Ed. Alan Gray; Ecological Issue No3, (published by field study council).

Green, H.J. and Guenther, P.R. (1990) 'Carbon Di-oxide release from OTEC cycles'. *International conference on ocean energy recovery*, Report -SERI/TP-253-3594; UC category: 262 DE 89009504, held 28-30th November 1989 at Hawaii.

Gunilla, J. (1996) *LCA a tool for measuring environmental performance*. Surrey, UK : Pira International.

Hagerman, G., Polagya, B., Bedard, R. and Previsic, M. (2006) EPRI REV 2 DRAFT *Methodology for Estimating Tidal Current Energy Resources and Power Production by Tidal In-Stream Energy Conversion [TISEC] Devices.* EPRI-TP-001 NA Rev 2, EPRI North American Tidal In stream Power Feasibility Demonstration Project.

Hammond, G and Jones, C. (2008) *Data on LCA & EA* [Communication from Dept of Mechanical Engineering, University of Bath, UK] available from <www.bath.ac.uk/mech-eng/sert/embodied> [1.8. 2009].

Hammons, T.J. (1993) 'Tidal Power, (Invited paper)' *Proc. of the IEEE*, 8(3), 419—433.

Helias, A., Udo de, H. and Reinout, H. (2007) 'Life Cycle assessment for energy analysis and management', *Applied Energy*, 84: 817-827

Khan, F.I., Hawboldt, K. and Iqbal, M.T. (2005) 'Life Cycle Analysis of Wind –fuel cell integrated system', *Renewable Energy*, 30(2), 157—177.

Hardisty, J. (2009). *The analysis of tidal stream power.* Wiley and sons, 2009, 57.

Helias, A., Udo de, H. and Reinout, H. (2007) 'Life Cycle assessment for energy analysis and management', *Applied Energy*, 84: 817-827.

Hemmingsen, E. (2010) At the base of Hubert's Peak: Grounding the debate on petroleum scarcity. *Geoforum* 41(4) 531-540.

Heydt, G.T. (1993) 'An assessment of ocean thermal energy conversion as an advanced electric generation method', *Proc. IIEE*, 81(3), 409-418.

<http://www.pelamiswave.com/media/pelamisbrochure.pdf> [29.7. 2009].

<http://www.fujitaresearch.com/reports/tidalpower.html> [13.7. 2012].

<http://www.x-rates.com/d/USD/GBP/hist2008.html> [2.1. 2011].

<http://www.metalprices.com> [14.8. 2009].

<http://www.icis.com/V2/Chemicals/9076558/urea/pricing.html>
[2.2. 2010]

<http://www.icis.com/V2/chemicals/9075153/ammonia/pricing.html>
[6.3.2010]

<http://www.icis.com/V2/chemicals/9076034/methanol/pricing.html>
[16.3. 2010]

<http://www.freepatentsonline.com/4476249.html>[12.3.2009]
US patent no 4476289

<http://aquarius.nasa.gov/prop_fresh_sea.html>[12.6.2011]

Huang, J.C., Krock, H.J. and Oney, S.K. (2003) *An OTEC overview,* 1-20 available from <http://library.greenocean.org/oteclibrary/otecpapers/revisitedotec>
[20.4. 2007].

Ikegami, Y., Inadomi, J., Yasunaga, T. and Asou, H. (2008) 'Experimental Study of OTEC using Ammonia/Water Mixture as Working Fluid'. *Proc. of the Eighteenth International Offshore and Polar Engineering Conference,* held 6-11 July, 2008 at Vancouver, BC, Canada.

Subhashish Banerjee

International Energy Outlook, (2011), US Energy Information, Report no DOE/EIA-0484(2011). Availed from <http://www.eia.gov/totalenergy/data/annual/pdf/aer.pdf> (Release date 19.9.2011).

Jayashankar, V., Purnima, J., Ravindran, M., Mitsumori, M., lkegami, Y. and Uehara, H. (1998) 'The Indian OTEC Program', *Paper Number 8905-MS*, 'Offshore Technology Conference', held 4-7th May 1998 at Houston, Texas.

Kane, M. (2005) *California small hydropower and ocean wave energy resources*. Presented as staff paper in California Energy Commission, held 9th May 2005 at Sacramento: California.

Kato, S. and Widiyanto, A. (2005) 'Environmental impact consolidated evaluation of energy systems by an LCA-NETS scheme' *Energy*, 30, 2057-2072.

Kaur, R. (2004-5) *Environmental impacts of wave energy*. M70ENV, M.Sc. Dissertation. Coventry University, U.K.

Kennish, M.J. (1998) *Pollution impacts on marine biotic communities*. New York: CRC Press, 80–83.

Khalib, H. (2003) *Economic evaluation of projects in the electricity supply industry, Chapter -5,* 57—69, London, U.K.: The Institution of Engineering and Technology.

Khan, F.I., Hawboldt, K. and Iqbal, M.T., (2005) 'Life Cycle Analysis of Wind –fuel cell integrated system', *Renewable Energy*, 30(2), 157—177.

Khan, J. and Bhuyan, G.S. (2009) *Ocean Energy: Global technology development status*, IEA-OES Document No T0104. Report prepared by Power tech Labs for the IEA-OES. available from:
<http://www.iea- oceans.org/_fich/6/ANNEX_1_Doc_T0104.pdf> [12.12. 2011].

Kofoed, J.P., Frigaard, P. Friis-Madsen, E., Sørensen, H.C., (2006) 'Prototype testing of wave energy converter wave dragon', *Renewable Energy*, 31(2), 181-189.

Kumpel, A.H.J. (1971) 'Experimental Results on the tidal resonance effect of the liquid core'. *Geophysical and Astrophysical Fluid Dynamics*, 13(1), 253-261.

Langton, R., Davies, I.M. and Scott, B.E. (2011) 'Seabird conservation and tidal stream and wave power generation: Information needs for predicting and managing potential impacts', *Marine Policy,* 35, 623-630.

Leijon, M., Danielsson, O., Erikson, M. and Thorburn, K. (2006) 'An electrical approach to wave energy conversion'. *Renewable Energy* 31, 1309-1319.

Lenard, D.E. and Johnson, F.A. (1988) 'British OTEC Programmes 10MW floaing and 0.5 MW land based'. *Proc. OCEANS '88. A Partnership of Marine Interests* held 31st October - 2nd November 1988 at Baltimore, MD.

Link, H. (1989) 'Operational Experiences of the OC-OTEC experiments at NELH'. *SERI/TP-253-3480, UC category:262, DE8900877*, '11. annual American Society of Mechanical Engineers solar energy conference' held 2-5th April 1989 at San Diego, CA (United States).

Margheritini, L., Hansen, A.M., Frigaard, P. (2011) 'A method for EIA scoping of wave energy converters-based on classification of the used technology', *Environmental Impact Assessment Review*, 32(1), 33-34.

Marcuse, H. (2005) Historical Dollar-to-Marks Currency Conversion Page. Availed from <http://www.history.ucsb.edu/faculty/marcuse /projects/currency.htm> [13.12.2011].

Millar, D.L., Smith, H.C. M. and Reeve, D.E. (2007) 'Modeling analysis of the sensitivity of shore line change to a wave farm' *Ocean Engineering*, 34(5-6), 884-901.

Mirco, P., Bedard, R. and Hagarman, G., (2004) *E2I EPRI Assessment, Offshore Wave Energy Conversion Devices,* E2I EPRI WP – 004 – US – Rev 1, USA: Electricity Innovation Institute. Availed from
<http://www.energy.ca.gov/oceanenergy/E2I_ EPRI_Report_Wave_Energy.pdf>
[5.12. 2011].

Mathew, S. (2006) *Wind Energy: Fundamentals, resources analysis and economics, Chapter 7.* Berlin Heidelberg: Springer, 209-231, availed from
<http://www.albadr.org/www/pdf/library/495.pdf > [13.12. 2011].

Musial, W. (2008) National Renewable Energy Laboratory Technical Report (NREL/TP-500-43240), *Status of Wave and Tidal Power Technologies for the United States*, U.S.: NREL.

McCormick, M. E. (1981) *Ocean wave energy conversion*. John Wiley and sons, 1-2.

McCormick, M. E.(1981a) *Ocean wave energy conversion*. John Wiley and sons, 10-11.

McCormick, M. E.(1981b) *Ocean wave energy conversion*. John Wiley and sons, 23-26.

Mersey Barrage Company, (1991) *Tidal Power from the River Mersey: A Feasibility Study Stage 2 report*, ETSI TID 4071, Department of Energy, 1-379 & 22-24.

Meyers, L. and Bahaj, A.S. (2005) 'Simulated electrical power potential harnessed by marine current turbine array in the Alderney Race'. *Renewable Energy*, 30, 1713-1731.

Subhashish Banerjee

Mirco, P., Bedard, R. and Hagarman, G. (2004) *E2I EPRI Assessment, Offshore Wave Energy Conversion Devices,* E2I EPRI WP – 004 – US – Rev 1, USA: Electricity Innovation Institute. Availed from: <http://www.energy.ca.gov/oceanenergy/E2I_EPRI_Report_Wave_ Energy.pdf> [5th December 2011]

Morimoto, R. and Hope, C. (2006) 'The impact of Electric supply on Economic growth in Sri Lanka', *Proc. Energy and Power systems*, 526.

Mueller, M. and Wallace, R. (2008) 'Enabling science and technology for marine renewable energy', *Energy Policy*, 36(12), 4376-4382.

Nadeau, M. (2007) 'Ocean Energy Systems Implementing Agreement An International Collaborative Programme (IEA--OES)' *OREG Fall Symposium,* held 25-26th October 2007.

NEEDS, Project No.502687, "Report on technical specification of reference technologies (wave and tidal power plant)" [28.11. 2008].

Nendza, M. (2007) *Hazard assessment of silicone oils (polydimethylsiloxanes, PDMS) used in antifouling-/foul-release-products in the marine environment.* [Marine Pollution Bulletin 54:1190-1196].

Nuttal L. J. (1977) Conceptual design of large scale water electrolysis plant using solid polymer electrolyte technology. *International Journal of Hydrogen Energy* 2(4), 395-403.

Ocean Energy Technology Overview (2009) *Prepared for the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Federal Energy Management Program* , July 2009. DOE/GO-102009-2823.

Odeh, N. A., Cockerill, T.T. (2008) 'Life Cycle analysis of UK coal fired power plants', *Energy conversion and Management*, 49, 212-220.

Olav Hohmeyer, (1988) *Social cost of energy consumption*. Heidelburg, Berlin: Springer Verlag, 8.

Palha, A., Mendes, L., Juana Fortes, C.O., Brito-Melo, A., Sarmento, A. (2010) 'The impact of wave energy farms in the shoreline wave climate: Portuguese pilot zone case study using Pelamis energy wave devices' *Renewable Energy*, 35, 62-77.

Parker R. P. M., Harrison, G. P. and Chick, J. P. (2007) 'Energy and carbon audit of an off-shore wave energy converter' *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy,* 221, 1119-1131.

Pastakia, C., M., R., and Jensen, A. (1998) 'The Rapid Impact Assessment Matrix (RIAM) for EIA', *Environmental Impact Assessment Review*,18, 461-482.

Subhashish Banerjee

Paul, J.T.S., Wilfred, G.J.H.M. and van Sark. (2008) 'A new hybrid ocean thermal energy conversion-Offshore solar pond (OTEC-OSP) design: A cost optimised approach'. *Solar Energy*, 82, 520-527.

Pelc, R. and Fujita, R.M. (2002) 'Renewable energy from the ocean'. *Marine Policy*, 26, 471-479.

Peter, C., Rebecca, K. and Lauren, K. (2003). *Tidal Energy; Cause 2003: Final Project Nov. 13, 2003* availed from:
<http://www.libertyparkusafd.org/lp/NatureFirst%20USA/Special%20Reports%5COcean%20Energy%5CTidal%20Energy%20-%202003.pdf > [5.12. 2011].

Pitcher, G. C., Figueiras, F. G., Hickey, B. M., and Moita, M. T. (2010) 'The physical oceanography of upwelling systems and the development of harmful algal blooms'. *Progress in Oceanography* 85(1-2) 5-32.

Pohekar, S.D. and Ramachandran, M. (2004) 'Application of multi-criteria decision making to sustainable energy planning—A review', *Renewable energy and sustainable energy reviews,* 8(4), 365-381.

Pontes, M.T. and Falcao, A. (2001) 'Ocean energies: resources and utilisation'. *World Energy Council 18th Congress*, held October 2001 at Buenos Aires.

Previsic, M. and Bedard, R. (2005) *Methodology for Conceptual Level Design of Tidal In Stream Energy Conversion [TISEC] Power Plants*, EPRI–TP-005 NA, North American Tidal In Stream Power Feasibility Demonstration Project.

Quere, C.L., *et al*. (2005) 'Ecosystem dynamics based on plankton functional types for global ocean biogeochemistry models'. *Global Change Biology,* 11 (doi:10.1111/j.1365--2486.2005.01004.x), 2016-204.

Ravindran, M. (1999) *The Indian 1 MW floating OTEC plant-An overview*, [Key note address], The international OTEC/DOWA conference, 31 Oct-2nd November 1999, Japan: Imari.

Rai, G .D. (1997) 'Chapter 9', in *Non-Conventional Energy source*. Delhi: Khanna Publishers, 509.

Roels, June. (1980). 'Food, Energy, and Fresh Water from the Deep Sea', *Mechanical Engineering*, 37.

Rosmin, N. and Zakaria, M. P. (2006).'The Feasibility of electrical generation by using Tidal Method'. *ELEKTRIKA*. 8(2) 27-31.

Rourke, R.O., Boyle, F., Reynolds, A. (2010) **'**Tidal energy update 2009'. *Applied energy*, 87(2) 398-409.

Royal Academy of engineering(2004); availed from: <http://www.raeng.org.uk/news/publications/list/reports/Cost_Generation_Comment ary.pdf> [16.12. 2011].

Russel, I. (2007) *Inventory materials of 7MW Wave Dragon* [Personal communication from Wave Dragon farm].

Ryzin, J.V., Grandelli, P., Lipp, D. and Argall, R. (2005) 'The Hydrogen Economy 2050: OTEC Driven'. *Proc. of MTS/IIEE, Oceans 2005.*

Sakhashiri (2007). 'Gases of The Air' *Chemical of the week, Chemistry*, 103(1).

Schleisner, L. (2000) 'Life cycle analysis of a wind farm and related externalities'. *Renewable Energy*, 20, 279—28.

(Anon.) (1989), 'Severn barrage project: Detailed report. 1989', Vol-3A, *Civil Engineering including site investigations: Contractor report,* ETSU TID 4060—P3A (Parts A &B), Chapter 20, 5-6.

SETAC (Anon.) (1990) 'A Technical Framework for Life-Cycle Assessment, 1991', *Workshop Report of Society of Environmental Toxicology and Chemistry (SETAC),* 'SETAC Foundation for Environmental Education, Inc.' held 18-23th August 1990 at US: Pensacola, Florida.

Shaw, R. (1982), *Wave energy: a design challenge*. New York: Halsted Press.

Shier, S.H. (1990) *Electricity in the American Economy: Agent of Technological progress*. US: Green Wood publisher. Availed from:
 < http://scifun.chem.wisc.edu/chemweek/pdf/airgas.pdf> [4.8. 2010]

Sieber, M., Malchow, H. and Schimansky-Geier, L. (2007) 'Constructive effects of environmental noise in an excitable prey–predator plankton system with infected prey', *Ecological Complexity*, 4, 223–233.

Sir Robert Mc Alpine & Sons Ltd. (1986) *Tidal Power from the Severn, Engineering and Economic Studies: Cardiff Weston Scheme,* Severn Tidal Power Group, Chapter 4, 4-74.

Sir Robert Mc Alpine & Sons Ltd. (1986a) *Tidal Power from the Severn, Engineering and Economic Studies: Cardiff Weston Scheme,* Severn Tidal Power Group, Chapter 8, 1-16.

Smith, M.R. (2007) 'Resource depletion: modelling and Forecasting oil production', *Modelling the Oil Transition: A Summary of the Proceedings of the DOE/EPA Workshop on the Economic and Environmental Implications of Global Energy Transitions,* 'Modeling Global Energy Transition & their Environmental effects' held February 2007, at Oak Ridge, Tennessee, USA, 107-113.

Sneddon, C., Howarth, R.B., and Norgaard, R.C. (2006) 'Sustainable development in a post-Brundtland world'. *Ecological Economics*, 57(2), 253-268.

Subhashish Banerjee

Sorenson, H.C. (2008) '*Report on technical specification of reference technologies (wave and tidal power plant)*' Project No 502687, NEEDS. Availed from < http://www.needs-project.org.Tidal.pd> [14.12. 2010].

Sorensen, H. C. *et al*. (2003) *European thematic net work on wave energy*, NNES - 1999-00438; WP 3.3-Final Report - Environmental Impact. (n.a.).

Sorensen, H.C.(2006) *Wave Dragon – from the 20 kW to the 7 MW prototype device* [Presentation] EU Contractors' meeting, October 2006. Availed from: <http://ec.europa.eu/research/energy/pdf/gp/gp_events/ocean_energy/1010_wave> [15.2.2010].

Szabo, L., Oprea, C., Viorel, I.A. and Biro, K.A. (2007) 'Novel permanent magnet tubular linear generator for wave energy converter' *Electric Machines & Drives 07, conference* 2007, IEMDC ', held 3-5th May 2007 at IIEE International, 983-987 Takahashi, P. and Trenka, A. (1996) *Ocean Thermal Energy Conversion*. John Wiley and sons, 49-77.

Tahara, K., Kojima,T. and Inaba, A. (2000) ' Estimation of Ocean Thermal Energy Conversion System by using LCA Methodology'. *OTEC*, 8, 31-41 [In Japanese].

Takahashi, M.M. (2000), 'Chapter 3 OTEC is not a dream'. in *Deep ocean water as our next natural resource*, Tokyo:Terra Scientific publishing Co, 31-44.

Takahashi, P. (2003) *Energy from the sea: The Potential and Realities of Thermal Ocean Energy Conversion (OTEC.)*, Anton Bruun Memorial lecture, 30th June 2003. Paris: UNESCO House, availed from <http://library.greenocean.org /oteclibrary/ otecpapers/energy_from_the_sea.pdf> [1.6. 2009].

Takahashi, P. and Trenka, A. (1996) *Ocean Thermal Energy Conversion*. John Wiley and sons, 49-77.

Takahashi, M.M. (2000) 'Chapter 3 OTEC is not a dream'. in *Deep ocean water as our next natural resource*, Tokyo: Terra Scientific publishing Co, 31-44.

Taylor, C. (2006) *Inventory materials of 750 kW Pelamis* [Personal communication from Pelamis farm, OPD].

Tedd, J., *et al*. (2006) *Wave Dragon prototype wave power production* in 'World Renewable Energy Conference'. held August 2006 at Florence, Italy.

Tedd, J. (2007) *Testing, analysis and control of wave dragon wave energy converter.* 'PhD Thesis (101207)', Denmark: Aalborg University.

Tsar, W.T. (2010) 'Energy sustainability from analysis of sustainable development indicators: A case study in Taiwan' *Renewable and sustainable energy reviews*, 14(7), 2131-2138.

Teng H., Masutani S. M., Kinoshita, C. M.., and Nihous G.C. (1996). Solubility of CO_2 in the ocean and its effect on CO_2 dissolution, *Energy Conversion & Management*. 37(6-8) 1029-1038.

(Anon.) *Tidal energy physics and resource*, available from <http://www.thew 2o.net/events/oceanenergy/images/tidal_energy.pdf> [3.9.2008].

Titel, C. L., Madsen, E. F., Kofoed, J. P. and Tedd, J. (2006) *World's largest wave energy project, 2007 in Wales,* 'Power Gen Europe: Meet the Future ' held 30th May to 1st June 2006 at Cologne, Germany.

Anon. (2010) 'The world's largest bio-mass project takes shape at Drax power station' *British Bio energy news (UKERC)*, 11, 2. Availed from <http://www. supergen-bioenergy.net/Resources/user/Bio-energy%20Newsletter%20Issue% 2011.pdf> [7.12. 2011]

Thorpe, T. W. (1999) *A brief review of wave energy*, ETSU-R120, UK: Department of Trade and Industry.

Thorpe, T. W.(1999a) *An overview of wave energy technologies: Status, performance and Wave power: moving towards commercial viability,* Broadway house, Westminster, London: ETSU. Availed from:
<http://waveberg.com/pdfs/overview.pdf> [21.11. 2011].

Thresher, R. and Musial, W. (2010) 'Ocean Renewable Energy's Potential role in supplying future electrical needs', *Special issue on Marine Renewable Energy, Oceanography*,23(2).

Twidell, J. and Weir, T. (2006) *Renewable Energy Resources.* London: E & FN Spon. Availed from <http://ecosustainablevillage.com.ip01- eb23.net/tidal_energy_ production. html> [14.5. 2012].

United Nations General Assembly, *96th Plenary meeting* 1987. Report No-A/Res/42/187.Availed from:
<http://www.un.org/documents/ga/res/42/ares42-187.htm> [6.8.2010]

UN resolutions No- A/58/484/Add.1, 58th session of agenda 94(a), for achieving sustainable development. Availed from:
<http://www.renewables2004.de/pdf/UNRes_promotion_re_sources.pdf> [4.8.2008]

UN resolution (No- A/C.2/58/L.26 and A/C.2/58/L.59) suggest switching over to RE sources, for achieving sustainable development. Availed from:
<http://www.un.org/esa/dsd/dsd_aofw_ene/ene_index.shtml> [12.12. 2011]

UN Atlas of the oceans: Ocean Thermal Energy Conversion (OTEC), Availed from:
<http://www.oceansatlas.com/servlet/CDSServlet?status=ND0zMDYzLjIwOTQwJj Y9ZW4mMzM9d2ViLXNpdGVzJjM3PWluZm8> [15.4. 2006].

Subhashish Banerjee

US Report to Congress. (2009) *Potential Environmental Effects of Marine and Hydrokinetic Energy Technologies, December 2009; prepared in response to the energy independence and security act of 2007*, SECTION 633(B).

Valério, D., Beirão, P, Costa, J.S.D. (2007) 'Optimisation of wave energy extraction with the Archimedes Wave Swing' *Ocean Engineering,* 34, (17-18) , 2330-2344.

Vega, L. A. (1999) 'Ocean Thermal Energy Conversion', *OTEC*, 1—22.

Vega, L. A. (2002/2003a) 'Ocean Thermal Energy Conversion Primer'. *Marine Technology Society Journal*, 6(4), 25-35.

Vega L.A. (1995) 'Economics of Ocean Thermal Energy Conversion', USA: PICHTER, Honolulu. Availed from <www.seafriends.org.nz.oceano/seawater.htm> [1.7. 2009].

Vega, L.A. (1992) *Economics of ocean thermal energy conversion (OTEC)* in 'Chapter 7 of Ocean Energy Recovery: The State of the Art' Published in Ocean Energy Recovery, ASCE (1992), 152-181.

Varotsos, C. (2004) Atmospheric pollution and remote sensing: implications for the southern hemisphere ozone hole split in 2002 and the northern mid-latitude ozone trend. *Advances in space research.* 33(3) 249-153.

Vining, J.,G. (2005) Report submitted to Muetze, A., *Ocean Wave Energy Conversion*, ECE 699, US: University of Wisconsin-Madison. Availed from <http://homepages.cae.wisc.edu/~vining/JVining_WaveEnergyConversion.pdf> [12.12. 2011].

Westwood, A. (2004) 'Ocean power: wave and tidal energy review'. *Refocus,* 5(5) 50-55.

Westwood, A. (2004a) 'Ocean Power: Wave and Tidal Energy Review', *Refocus*, 5(5) 1-11.

Wolf, J., Walkington, I.A., Holt, J. and Burrows, R. (2009) 'Environmental impacts of tidal power schemes', *Proceedings of the Institution of Civil Engineers-Maritime Engineering*, Volume: 162, Issue: December, Publisher: Thomas Telford Publishing, 165-177.

Woollcombe-Adams C., Watson M., and Tom S. (2009) Severn Barrage tidal project: Implication for carbon emissions. *Water &Environment journal*, 23(1), 63-68.

Yamada, N., Hoshi, A. and Ikegami, Y. (2006) 'Thermal efficiency enhancement of ocean thermal energy conversion (OTEC) using Solar energy'. *AIAA2006-4130*, '4th International energy conversion engineering conference and exhibit (IECEC)' held 26-29th June 2006 at San Diego, California, 1-9.

Yung, C.S., Grace, T.R., Lin, K., Pin, L. and Benjamin, J.C.Y. (2010) 'An assessment of exploiting renewable energy sources with concerns of policy and technology', *Energy Policy*, 38(8), 4604-4616.

Zabihian, F., and Fung, A.S. (2011) 'Review of marine renewable energies: Case study of Iran' *Renewable and Sustainable Energy Reviews*, 15, 2461-2474.

Zolfagharifard, E., (2011) 'Solar Energy: Tropical Idea' *Engineer (London)*, 26-27.

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